Aviation Electronics Technician (Intermediate)

(ADI)

NAVEDTRA 14029A

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PREFACE

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THE MANUAL: This manual is organized into subject matter areas, each containing learning objectives to help you determine what you should learn, along with text and illustrations to help you understand the information. The subject matter reflects day-to-day requirements and experiences of personnel in the rating or skill area. It also reflects guidance provided by Enlisted Community Managers (ECMs) and other senior personnel, technical references, instructions, etc., and either the occupational or naval standards that are listed in the Manual of Navy Enlisted Manpower and Personnel Classifications and Occupational Standards, NAVPERS 18068(series).

THE QUESTIONS: The questions that appear in this manual are designed to help you understand the material in the text. The answers for the end of chapter questions are located in the appendixes.

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THE INTERACTIVITY: This manual contains interactive animations and graphics. They are available throughout the course and provide additional insight to the operation of equipment and processes. For the clearest view of the images, animations, and videos embedded in this interactive rate training manual, adjust your monitor to its maximum resolution setting.

VALUE: In completing this manual, you will improve your military and professional knowledge. Importantly, it can also help you study for the Navy-wide advancement in rate examination. If you are studying and discover a reference in the text to another publication for further information, look it up.

June 2015 Edition Prepared by

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Sailor’s Creed

"I am a United States Sailor.
I will support and defend the Constitution of the United States of America and I will obey the orders of those appointed over me.

I represent the fighting spirit of the Navy and those who have gone before me to defend freedom and democracy around the world.

I proudly serve my country’s Navy combat team with honor, courage and commitment.

I am committed to excellence and the fair treatment of all.”
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CHAPTER 1
SERVO SYSTEMS

As an aviation electronics technician (ATI), you will encounter various types of servo systems. The particular type (electromechanical, electrohydraulic, pneumatic, etc.) will depend upon the type of load for which it was designed. One of your tasks may be the control of radar antennas from a remote control station. Antenna control is discussed later in this chapter.

This chapter does not provide detailed presentations of any one servo system but will discuss basic systems, identify their essential components, and explain the function of each component. For details concerning the theory and operation of a particular system, you should refer to the applicable technical manuals for that system. Before continuing, you should review the basic theory of synchros and servomechanisms discussed in Navy Electricity and Electronics Training Series (NEETS), Module 15, Principles of Synchros, Servos, and Gyros, NAVEDTRA 14187A.

LEARNING OBJECTIVES

When you have completed this chapter, you will be able to do the following:

1. Identify the concepts and components of a basic servomechanism to include a data transmission system, servo control amplifier, and servomotor.

2. Identify factors affecting servomechanism oscillations to include damping, integral control, and the relationship of gain, phase, and balance.

3. Recognize the importance of zeroing transmitting and receiving synchro units.

4. Explain the procedures for the application of servomechanisms to include positioning a radar antenna and supplying information to the weapons system.

BASIC SERVOMECHANISMS

The essential components of a servomechanism are a data transmission system, a servo control amplifier, and a servomotor. These components are shown in the block diagram of Figure 1-1 and are discussed in the following paragraphs.

The functions of the data transmission system are as follows:

- Measures the servo output
- Transmits or feeds back a signal that is proportional to the output, to the error detector (a differential device for comparing two signals)
- Compares the input signal with the feedback signal

Figure 1-1 — Simplified block diagram of a servomechanism.
Transmits a signal that is proportional to the difference between the input and output to the servo amplifier.

The signal obtained by comparing the servo input and output is called the servo error and is represented by the symbol E. Servo error (E) is the difference between the input ($\theta_i$) and the output ($\theta_o$). This is stated mathematically as $E = \theta_i - \theta_o$.

In many servo systems, the physical location of the servo input device and output device are remotely located from each other and may also be remotely located from the servo amplifier. This requires some means of transmitting the output information back to the device receiving the input command and transmitting the servo error to the servo amplifier. This system of transmission, as well as the comparing device, called an error detector, is part of an overall data transmission system. Data transmission is discussed later in this chapter. The function of the servo amplifier is to receive the error signal from the error detector, amplify it sufficiently to cause the output device to position the servo load to the commanded position, and transmit the amplified signal to the servomotor.

The servomotor positions the servo load. The motor must be capable of positioning the load within a response time based on the requirements of the system.

### Error Detectors

The component of the data transmission system that compares the input with the servomechanism output is the error detector. Error detectors can be either mechanical or electrical devices. A simple form of a mechanical error detector is the differential. However, in aircraft weapons systems, most error detectors are electrical devices because of their adaptability to widely separated or remotely installed components. Most of the electrical devices used are of either the potentiometer (resistive) or one of several magnetic devices.

Electrical error detectors may be either alternating current (ac) or direct current (dc) devices, depending upon the requirements of the servo system. An ac device used as an error detector must compare the two input signals and produce an error signal. The phase and amplitude of the error signal will indicate both the direction and the amount of control necessary to accomplish correspondence. A dc device differs because the polarity of the output error signal determines the direction of the correction necessary.

Error detectors are also used extensively in gyroscope (gyro) stabilized platforms and rate gyros. In stabilized platforms, synchros are attached to gimbals. Any movement of the platform around the gyro axes is detected by the synchro and an error voltage is sent to the appropriate servo system.

In rate gyros, an E-transformer is commonly used to detect gyro precession. It is extremely sensitive to very slight changes, but its range of motion is limited to a very small amount. Therefore, they are extensively used within constrained gyro systems.

### Potentiometer

Potentiometer error detector systems are generally used only where the input and output of the servomechanism have limited motion. They are characterized by high accuracy, small size, and the ability to produce an ac or dc voltage as an output. Their disadvantages include limited motion, a life problem resulting from the wear of the brush on the potentiometer wire, and that the voltage output of the potentiometer changes in discrete steps as the brush moves from wire to wire. A further disadvantage of some potentiometers is the high drive torque required to rotate the wiper contact.

An example of a balanced potentiometer error detector system is shown in Figure 1-2. The purpose of the circuit is to give an output error voltage that is proportional to the difference between the input
and output signals. The command input shaft is mechanically linked to R1, and the load is mechanically linked to R2. An electrical source of 115 volts ac is applied across both potentiometers.

When the input and output shafts are in the same angular position, they are in correspondence and there is no output error voltage. If the input shaft is rotated, moving the wiper contact of R1, an error voltage is developed and applied to the servo control amplifier. This error voltage is the difference of the voltages at the wiper contacts of R1 and R2. The output of the amplifier causes the motor to rotate both the load and the wiper contact of R2 until both voltages are equal. When equal, there is no output error voltage.

In the example shown R1 and R2 are grouped together, although in actual practice, the potentiometers may be positioned remotely from each other, with R2, the output potentiometer, being located at the output shaft or load. The remote location of one of the components does not remove it from being a part of the error detector.

**E-Transformer**

The E-transformer is a type of magnetic device used as an error detector. Its application is useful in systems that do not require the error detector to move through large angles. A simplified drawing, which illustrates one of several possible devices in this category, is shown in Figure 1-3. The primary excitation voltage is applied to coil A on the center leg of the laminated core. The coupling between coil A and the secondary windings, coils B and C, is controlled by the armature, which is displaced linearly by the input signal. When the armature is positioned so the coupling between the windings is balanced (null), the output voltage is minimal because of the series-opposing connections of the secondary windings. The phase of the output voltage on either side of the voltage null differs by 180 degrees. By proper design of the transformer, the amplitude can be made proportional to the displacement of the armature from its null voltage position. This type of error detector has the advantages of small size and high accuracy. It has the disadvantage of permitting only limited input motion.
Control Transformer

Synchros have been developed to a point of relatively high accuracy, low noise level, reasonably small driving torques, and long life. These qualities also apply to synchro control transformers. A primary advantage of the synchro control transformer over other types of error detectors is its unlimited rotation angle; that is, both the input and the output to the synchro control transformer may rotate through unlimited angles. Among the disadvantages of synchros (including the synchro control transformer) are the large size necessary to maintain high accuracy, the power consumed, and the output supplied to the servo control amplifier is always ac modulated with the servo error.

You may use ac if the following conditions are met:

- The frequency of the ac used must be greater than the maximum frequency response of the measuring devices used
- If negative values of the variables are allowed, the devices used can be phase-sensitive

A dc signal and the same function represented by an ac voltage are shown in Figure 1-4. The instantaneous value of the ac signal does not indicate the value of the function, but the average value of the ac signal may be used to represent the value of a function. If the ac signal is the input to a servomotor, for example, the motor must not attempt to follow every variation of the ac signal, but must follow the average value. The second condition is essential because a negative ac signal does not exist. However, negative values can be indicated by a change in phase of the signal. Note that during the period when the dc signal is positive, the positive peaks of the ac signal correspond to the positive peaks of the ac reference. During the period when the dc signal is negative, the positive peaks of the ac signal correspond to the negative peaks of the reference and the signal is 180 degrees out of phase with the reference. Servomotors are available that use ac. These servomotors will rotate in one direction when the input signal is in phase with a reference voltage and in the other direction when the signal is out of phase with the reference voltage.

Figure 1-4 — AC modulated with the servo error.

Figure 1-5 — Control transformer as an error detector.
A synchro data transmission system is comprised of a synchro transmitter, a synchro control transformer, and, in some cases, a differential transmitter for additional servo inputs. The synchro transmitter transforms the motion of its shaft into electrical signals suitable for transmission to the synchro control transformer, which comprises the error detector shown in Figure 1-5.

The stator of the transmitter consists of three coils spaced 120 degrees (electrically) apart. The voltage induced into the stator windings is a function of the transmitter rotor position. These voltages are applied to the three similar stator windings of the synchro control transformer. The voltage induced in the rotor of the synchro control transformer depends upon the relative position of this rotor with respect to the direction of the stator flux.

The variation of the synchro control transformer output voltage as a function of the rotor position relative to an assumed stator flux direction is shown in Figure 1-6. While there are two positions of the rotor, 180 degrees apart, where the output voltage is zero, only one corresponds to a stable operating position of the servo.

When a synchro differential transmitter is used for additional inputs to the servo system, it is connected between the synchro transmitter and the synchro control transformer illustrated in Figure 1-7.

When the synchro differential rotor is in line with its stator windings, the differential transmitter acts as a one-to-one ratio transformer, and the voltages applied to the synchro control transformer

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**Figure 1-6** — Induced voltage in synchro control transformer rotor.

**Figure 1-7** — Synchro differential transmitter used for additional input.
are the same as the voltages from the synchro transmitter. If the synchro differential transmitter rotor is displaced by a second input, the voltages from the synchro transmitter to the control transformer are modified by the synchro differential transmitter by the amount and direction of its rotor displacement. Thus, the two inputs are added and fed to the synchro control transformer as a single input.

**Flux Gate**

A flux gate element may be used to drive or excite a control transformer and is usually used in compass systems. The flux gate operates on the principle of using the earth’s magnetic field to produce a second harmonic current flow in the element. This, in turn, produces a voltage in the stator windings of the control transformer that is in direct proportion to earth’s magnetic north. Because it is desirable to use only the horizontal component of the earth’s field, a gyro is used to hold the element level with the earth’s surface. Another method is to suspend the element by a spring and use the properties of a pendulum to rigidly mount it to the aircraft so that it turns in an azimuth direction as the aircraft turns.

**Multiple-Speed Data Transmission Systems**

The static accuracy (how accurately the load is controlled) of a servomechanism is frequently limited only by the accuracy of the data transmission system. The accuracy of the data transmission system may be increased considerably by employing a multiple-speed data transmission system along with a single-speed system. The error detector elements of the multiple-speed transmission system rotate at some multiple of the shaft being controlled. The elements of the single-speed transmission system operate one to one with respect to the controlled shaft.

The schematic diagram of a multiple- and a single-speed system is shown in Figure 1-8. If a system can transmit data at two different speeds, it is referred to as a dual-speed system. In this example, if the input shaft turns through 1 degree, the single-speed transmitter is also rotated 1 degree, while the multiple-speed unit is rotated 10 degrees. The synchro control transformer associated with each of these transmitters is geared in similar ratios with respect to the servo output shaft.

An error of 1 degree between the position of the input and output shafts produces a relative rotor displacement of 1 degree in single-speed synchros and 10 degrees in multiple-speed synchros. If the relation between the rotor displacement and output voltage is linear, the error signal from the multiple-speed system is 10 times that from the single-speed system. This amplification of the error signal in the data transmission link reduces the signal amplification required in the servo controller. If the
synchro has an inherent error of 0.1 degree with respect to its own shaft, the consequent servo error introduced by a single-speed data transmission system will be of corresponding magnitude. The consequent servo error introduced by a 10-speed data transmission system will be only one-tenth as great, or 0.01 degree.

A disadvantage of using a multiple-speed error detector lies in the possibility of the system falling out of step. If this happens, it will synchronize in a position differing from the correct position by an integral number of revolutions of the multiple-speed synchro. If the output shaft was held stationary and the input shaft rotated 36 degrees, the 10-speed synchro transmitter would turn one complete revolution. At this point, the error signal from the multiple-speed error detector would be zero. If the output shaft were then released, the system would operate in a stable fashion with a 36-degree error between the input and output shafts. The purpose of using a 1-speed detector is to prevent this ambiguous synchronization.

An error signal selector circuit is provided that switches control of the servo to the 1-speed data transmission system. This occurs whenever the servo error becomes large enough to permit the multiple-speed system to synchronize falsely.

An example of a simple device that could control an error-selector circuit is shown in Figure 1-8. It is essentially a single-pole, double-throw relay actuated by the output of the 1-speed error detector. The relay is shown in the de-energized position. When the output of the 1-speed synchro is high, the relay is energized and the 1-speed circuit controls the servomotor. When the output is low, the relay opens and the 10-speed synchro controls the circuit. Keep in mind that the synchro output is high only when there is a large error.

The relationship of the coarse (1-speed) synchro output and the fine (10-speed) synchro output is shown in Figure 1-9, view A. The shaded portion represents the area where control can be switched from the 1-speed circuit to the 10-speed circuit. With the selector circuit shown, it is still possible to have a single ambiguous position of the 1-speed (coarse) synchro. At this point the 1-speed (coarse) and 10-speed (fine) shafts are nulled (but are 180 degrees out of phase) and control is switched to the 10-speed circuit.

One way of eliminating this false synchronization position is to drive the multiple-speed synchro at any odd multiple of the 1-speed synchro. The phase relationship of a 1-speed and 7-speed system is shown in Figure 1-9, view B. Although there is still a null of both synchros at the 180-degree position of the 1-speed synchro, their outputs are in phase. This position is an unstable one, and the servo will not remain at this point.

The system shown in Figure 1-8 is not found in operating equipment due partly to the load the relay places on the 1-speed synchro. In actual practice, the relay could be controlled by an electronic circuit operated by the synchro voltages. A method commonly used feeds the outputs of the synchros to an
electronic circuit biased so that the fine-synchro voltage is not used when the coarse-synchro voltage is high. This method does not require a relay.

The disadvantage of using multiple-speed error detectors is the need for an additional synchro system and switching circuit. This additional equipment is needed if increased servo accuracy accounts for the wide use of these multiple-speed data transmission systems. This results from the amplification of the error signal and the effective reduction of inherent synchro errors.

**Servo Control Amplifiers**

As earlier stated, the output of an error detector (error voltage) can be fed to a servo control amplifier. This type of signal is small in amplitude and requires sufficient amplification to allow actuation of a prime mover. In addition to amplification, the servo control amplifier must, in some cases, transfer the error signal into a suitable form for controlling the servomotor or output member. It may also include provisions for special characteristics necessary to obtain stable, fast, and accurate operation.

Servo amplifiers used in aircraft weapons systems are limited to electronic and magnetic types. The operation and explanation of electronic amplifiers and their circuits are discussed in NEETS, Module 8, Amplifiers, NAVEDTRA 14180A.

In addition to the requirements of basic amplifiers, servo amplifiers must also meet certain additional requirements as follows:

- A flat gain versus frequency response for a frequency well beyond the frequency range used
- A minimum of phase shift with a change in level of input signal. Zero phase shift is desired, but a small amount can be tolerated if constant
- A low output impedance
- A low noise level

Servo amplifiers may use either ac or dc amplifiers or a combination of both. The application of dc amplifiers is limited by such problems as drift and provisions for special bias voltages needed in cascaded stages. Drift, a variation in output voltage with no change in input voltage, can be caused by a change in supply voltage or a change in value of a component. Consequently, many servo amplifiers use ac amplifiers for voltage amplification.

**Modulators**

As discussed previously, ac amplifiers are the best to use for amplifying an error signal. They do not need well-regulated power supplies and costly precision components; however, some aircraft weapons systems use a dc voltage for an error signal. The dc error voltage may be changed to an ac signal by the use of a modulator (sometimes called a chopper). Modulator circuits used in servo control amplifiers must be phase sensitive and produce an ac output signal whose amplitude is proportional to the dc input signal and whose phase is indicative of the polarity.

**Vibrator Modulators**

A modulator may be either an electromechanical vibrator or an electronic circuit. An example of a vibrator modulator is shown in *Figure 1-10*. An ac supply voltage is employed to vibrate the contacts of the vibrator in synchronism with the supply voltage. The dc error voltage is applied to the center contact of the vibrator. Assume that the reference voltage will cause the cycle at point A during the first half and point B during the second half cycle. The output is represented by waveform B if the error voltage is positive and by waveform C if it is negative.
Electronic Modulator

An example of an electronic modulator circuit is shown in Figure 1-11. The circuit shown is a diode ring modulator and works by causing a changing current to flow through one-half of the primary of transformer T2, and then through the other half at a 400-hertz (Hz) rate. Each half-cycle of changing current produces a half-cycle of sinusoidal output voltage. The phase of this output voltage compared to the 400 Hz carrier depends upon the direction of current through each primary half. Diodes CR1 and CR4 are forward biased when the dc control voltage is positive. Diodes CR2 and CR3 are forward biased when the dc control voltage is negative. When two of the diodes are forward biased by the dc control voltage, the other two are reversed biased and cut off. As long as the instantaneous amplitude of the carrier voltage is less than the dc control voltage, the reverse biased diodes remain cutoff and current flows through one of the half windings.

When one of the reverse biased diodes becomes forward biased (the amplitude of carrier voltage exceeds the dc control voltage), the diode conducts. This interrupts the current flowing through the half winding. The result is that the output voltage amplitude is clipped at the value it had when the current was interrupted.

The capacitor connected across the primary of T2 filters any high frequency components associated with the clipped half-cycle of the sine wave so that a nearly sinusoidal output half-cycle occurs. The output’s amplitude is approximately equal to the output voltage at the time of clipping.

The capacitor operates by coupling the high frequency components of the clipped voltage through the nonconducting half windings. The high frequency components are canceled because they produce currents that flow in opposite directions in both halves of the center tapped primary windings; that is, they produce magnetic fields that cancel each other.

The amplitude of each half-cycle of the 400 Hz carrier voltage is modulated by the dc control voltage. The polarity of the control voltage determines the phase of the modulated carrier voltage output relative to the unmodulated carrier voltage input. This is done as a result of the direction of current.
flow through the half winding. This direction depends upon which diode is forward biased as a result of the polarity of the dc control voltage.

**Phase Detectors**

As discussed, an ac amplifier has inherent advantages over a dc amplifier, a dc error voltage can be changed into an ac signal, and the ac signal can be amplified and applied to an ac servomotor. However, some systems use dc servomotors that necessitate converting the ac signal to dc. To do this, they use a phase detector, sometimes called a demodulator.

**Bridge Phase Detectors**

A basic phase detector using a bridge circuit is shown in *Figure 1-12*. With no error input signal and only the reference voltage applied, CR1 and CR2 would conduct in series when point C is on its positive half-cycle. When point C is on its negative half-cycle, CR3 and CR4 would conduct in series. Assuming the drops across the diodes and resistances are equal, points A and B would be at ground potential on both half-cycles and the output voltage would be zero.

When an error signal is applied to the bridge in phase with the referenced voltage and points A and C are both on their positive half-cycle, electron flow will be from point G on the reference transformer T2 to point D, through CR2 to point A, from point A to the center tap on T1, and to E through to G. On the next half-cycle, both points A and C will change polarity and the electron flow will be from point G to point C, through CR3 to point B, through T1 to the center tap, to the right to point E, and through R<sub>L</sub> to G. On both half-cycles of reference and error voltage, the electron flow was down through R<sub>L</sub> to ground, developing a negative dc output voltage.

If the error signal is applied out of phase with the reference voltage and positive at points A and D, electron flow will be from point G up through R<sub>L</sub>, left to the center tap of T1, down to point B, through CR4, down to point D, and left to point G. On the next half-cycle, both points A and D will have G up through R<sub>L</sub> to the center tap of T1 up to point A, through CR1 to point C, and right to the center tap to point G. On both half-cycles of the error and reference voltages, electron flow was up through R<sub>L</sub>, developing a positive

![Figure 1-12 — Bridge phase detector.](image1)

![Figure 1-13 — Triode phase detector.](image2)
voltage output at point E. The magnitude of the dc produced at point E in both instances was dependent on the amplitude of the ac error signal, and the polarity of the dc was dependent on the phase of the ac error signal. \( C_L \) is used to filter the pulses and provide smooth dc.

**Triode Phase Detectors**

A phase detector that uses Negative-Positive-Negative (NPN) transistors and also provides amplification of the error signal in addition to phase detection is depicted in *Figure 1-13*. In this circuit, the collectors of the transistors are supplied with the ac reference voltage in such a manner that the collector voltages are in phase. For the purpose of explanation, assume that no error signal is present at T2. When the collectors of Q1 and Q2 are positive, the two transistors conduct equally. The collector current that flows sets up magnetic fields in the dc motor exciter windings that are equal in amplitude and opposite in polarity; therefore, the fields cancel and produce no output. When the collector voltages are on a negative half cycle, C1 and C2 discharge through their respective exciter windings to maintain a constant dc through the windings.

If an error signal is introduced into the primary of T2 with a phase relationship that causes the base of Q1 to be positive at the same instant that the collector of Q2 is positive, the following conditions exist:

1. On this half cycle, the conduction of Q1 is increased above its no-error signal condition.
2. The heavier collector current causes a stronger field to be created in the upper exciter winding.
3. At this same instant, since the base of Q2 is on a negative half cycle, its average conduction is reduced to a level below that of its no-error signal condition.
4. The lower level of collector current causes a weaker field to be produced in the lower exciter winding.
5. Since the magnetic fields produced in the exciter windings are no longer of equal amplitude, they no longer cancel each other.
6. The exciter produces an output voltage of a polarity controlled by the polarity of the resultant field and of an amplitude controlled by the relative strength of this resultant field.
7. The exciter output causes the proper mechanical actions necessary to reduce the amplitude of the error to zero.
8. As the error signal is reduced to zero, the current conduction through Q1 and Q2 is again balanced. Also, the exciter fields are equal and opposite, canceling each other, reducing the exciter output to zero, and stopping the mechanical action. Resistors R1 and R2 prevent excessive base current when the error angle is large.

**Special Circuits**

It has been shown how a servo control amplifier may have provisions for changing a dc error signal to an ac signal, and how an ac error signal may be detected to supply a dc voltage to a servomotor or controller. In the following paragraphs, other special amplifier circuits are discussed.

**Two-Stage Direct Current Servo Control Amplifier**

If more power is required by a servomotor than can be supplied by the servo amplifier, a push-pull dc amplifier can be inserted between the phase-sensitive transistors and the servomotor illustrated in *Figure 1-13*. In the schematic diagram shown in *Figure 1-14*, the output of the phase detector transistors is now taken across the parallel RC networks in the collector circuit.
The bias source, $E_{cc}$, for the dc amplifier is connected with its positive terminal on the base side. This positive voltage subtracts from the highly negative voltage across the capacitor to give a resulting negative voltage that allows the transistor to operate on the linear portion of its characteristic curve.

When there is no signal input from the error detector, the collector currents of the phase sensitive rectifiers are equal. The outputs of Q1 and Q2 are applied to the base of Q3 and Q4, respectively. Equal output from Q1 and Q2 causes equal currents to flow in Q3 and Q4. With R5 and R6 equal in resistance and current, the voltage across the motor is zero. Consequently, the motor does not turn.

For an analysis of a signal output from the error detector, assume that the error signal makes the base of Q1 positive and the base of Q2 negative. The collector current of Q1 increases and the collector current of Q2 decreases. An increasing collector current in Q1 increases the charge on capacitor C1; conversely, a decreasing collector current in Q2 decreases the charge on capacitor C2. As a result of the change in error signal, the voltage on the base of Q3 is now more negative than the voltage on the base of Q4. This increased negative voltage on the base of Q3 decreases its collector current and the voltage e3 decreases. The decreased negative voltage on the base of Q4 increases its collector current, and the voltage e4 increases. As a result, a voltage difference appears across the motor armature and the motor rotates.

When the output signal from the error detector reverses in phase, the sequence of events that follow causes the motor to reverse its direction of rotation.

**Magnetic Amplifiers as Servo Control Amplifiers**

The servomotor used in conjunction with the magnetic amplifier shown in *Figure 1-15* is an ac type. The uncontrolled phase may be connected in parallel with transformer (T1) by using a phase shifting capacitor, or it may be connected to a different phase of a multiphase system. The

*Figure 1-14 — Two-stage dc servo control amplifier.*

*Figure 1-15 — Magnetic amplifier servo control amplifier.*
controlled phase is energized by the magnetic amplifier, and its phase relationship is determined by the polarity of the dc error voltage.

The magnetic amplifier consists of a transformer (T1) and two saturable reactors, each having three windings. Note that the dc bias current flows through a winding of each reactor and the windings are connected in series-aiding. This bias current is supplied by a dc bias power source. A dc error current also flows through a winding in each reactor; however, these windings are connected in series-opposing.

The reactors Z1 and Z2 are equally and partially saturated by the dc bias current when no dc error signal is applied. The reactance of Z1 and Z2 are now equal, resulting in points B and D being at equal potential. There is no current flow through the controlled phase winding.

If an error signal is applied, causing the current to further saturate Z2, the reactance of its ac winding is decreased. This current through Z1 tends to cancel the effect of the dc bias current and increase the reactance of its ac winding. Within the operating limits of the circuit, the change in reactance is proportional to the amplitude of the error signal. Hence, point D is now effectively connected to point C, causing motor rotation. Reversing the polarity of the error signal causes the direction of rotation to reverse, since point D is effectively connected to point A. The basic magnetic servo amplifier discussed above has a response of approximately 6 to 20 Hz. In some applications, this delay would be excessive, creating too much error. However, this delay can be reduced to about 1 Hz by using special push-pull circuits.

**Amplifier Integrator**

A servo system in a steady-state condition will have a constant positional displacement between input and output, which is called the error. The only way to reduce this error is to increase the drive torque. Thus, a new signal must be introduced that is related to the error. The error is not changing; therefore, it cannot be a derivative signal, nor can it be proportional to the error, because it would then decrease as the error decreases and a new condition would be met without removing the error. The only alternative is to produce a signal proportional to the integral of the error. Then, if a torque proportional to the time integral of the error is added to the normal torque that is proportional to the error, the error will eventually be reduced to zero. A circuit that is used for this purpose is called an amplifier integrator. A simple and commonly used integrator (*Figure 1-16*) consists of two circuit elements: a resistor and capacitor.

![Figure 1-16 — Simple integrator.](image)

The voltage across the capacitor is proportional to the integral of the charging current. It can be explained by considering that the voltage across a capacitor is

\[ E = \frac{Q}{C} \]

For any given capacitor (C), the voltage depends directly on the charge (Q), which is the imbalance of electrons on the two capacitor plates. The amount of this charge depends on the current flow and the time that this flow exists.
Because the voltage is proportional to the integral of the charging current, it allows the resistive-capacitive (RC) circuit to be used as an integrator output. Provision must be made to supply a charging current that is proportional to the input information. The purpose of the resistor is to produce this proportional current from an input signal voltage ($e_i$). At the instant this voltage is applied, the charging current becomes

$$i = \frac{e_i}{R}$$

Unfortunately, this proportionality does not continue to exist. As the capacitor becomes charged, the capacitor voltage opposes the charging current, and the charging current becomes less proportional to the input signal. This results in an error in the output. The ideal output for a constant input signal is a steadily increasing output. This steady increase is attained only when the signal voltage is first applied and the capacitor has not become appreciably charged.

A remedy to this error in the RC integrator is to use a circuit with a long time constant. Such a circuit delays the charging of the capacitor. The result is a more accurate integration of an input signal. The ideal output would be a perfect triangular wave. Although a long time constant produces more accurate results, it also provides a much lower output for the same input signal. Better integration is possible by the use of a high gain, feedback amplifier.

An amplifier integrator is illustrated in Figure 1-17. The circuit arrangement uses a high gain amplifier and is known as the Miller integrator. The amplifier produces an output that is not limited by the input signal as it is in the simple RC integrator. The amplifier also supplies any energy that is required in the output. The function of the input signal is to control the charging current. The operation can be explained by assuming a constant input, as shown in Figure 1-17, view A. At the start, assume the initial condition is zero, that is,

$$e_i = e_g = e_o = 0.$$  

Also assume that the capacitor is discharged. The positive voltage to be integrated, $e_i$, is then applied. The capacitor charges with a polarity as shown, since electrons are attracted from the left plate. The charging path is shown in Figure 1-17, view B.

A voltage measured at the amplifier input, $e_g$, tends to rise in the positive direction since this point is directly coupled to $e_i$. However, this rise tends to be opposed by the degenerative feedback voltage from the output. The output will be $-Ae_g(e_o)$. The letter (A) stands for amplifier gain. The minus sign indicates that the output polarity or phase is opposite to the input. The output changes (A) times faster or steeper than $e_g$. The output voltage is negative and aids the charging of the capacitor.

For a certain input voltage, the charging current is limited to a particular value that tends to keep $e_g$ practically zero. If the current should exceed this value, $e_g$ would decrease a small amount due to the
increased voltage drop across R. The $e_o$ would decrease, and the charging current would decrease to the original value. If the initial charging current should decrease, the opposite action would occur. The value of the charging current is therefore stabilized to a specific value proportional to the input voltage. This eliminates the error caused by $e_i$ and the charging current not remaining proportional in the fundamental RC integrator.

This constant charging current must be produced by $e_o$ despite the fact that the steadily increasing capacitor voltage opposes the charging current. To do this, $e_o$ must also steadily increase. This steady increase in $e_o$ is exactly the integrator output voltage desired for a constant signal input.

Similar action would be produced for a condition in which the input signal suddenly became negative. Polarities would then be in reverse to those shown in the example given. Remember that simple examples are used for explanation on the assumption that the desired result will also be produced for a more complicated signal input. Removal of $e_i$ would produce little effect upon the output that existed at that instant, since the amplifier output would oppose the tendency for the capacitor to discharge.

The limits for $e_o$ are determined by the amplifier and not by $e_i$ or the range of $e_g$. The output range would be designed to produce an increasing output for any probable input amplitude and period of application. The exception to this would be an integrator that was designed to function also as a limiter.

**Output Devices**

The output of the servo control amplifier is fed to an output device. The functions of this device, usually a servomotor, are to supply torque, power, and dynamic characteristics required to position the servo load. Ideally, the power device should require small power from the control amplifier, accelerate rapidly, be of small size and weight, be of lasting endurance, have small time lags, and have an adequate speed range. In aircraft weapons systems, the electric motor is most frequently used as an output device. However, electromagnetic clutches, hydraulic devices, and pneumatic devices are also used.

**Electric Motors**

In aircraft weapons systems, electric motors are primarily used to drive the servo load. The type of electric motor used within particular equipment is determined by power factors such as type of power available, output power, speed range, inertia, and electrical noise.

**Alternating Current Motors**

Frequently, ac motors are used in low power servo applications because of their rapid response. However, they have a disadvantage of having a narrow speed range characteristic. The detailed theory of operation of ac motors is discussed in NEETS, Module 5, Generators and Motors, Navedtra 14177A. Basic types of motors used with servo systems are briefly discussed in this chapter.

The two-phase induction motor is the most widely used ac servomotor. The stator of the motor consists of two similar windings that are positioned at right angles to each other. The rotor may be wound with short-circuited turns of wire or it may be a squirrel cage rotor. The squirrel cage rotor is the type most frequently encountered. It is made up of heavy conducting bars, which are set into armature slots, the bars being shorted by conducting rings at the ends.

Two ac voltages 90 degrees out of phase must be applied to the stator windings for the motor to turn. These out-of-phase voltages generate a rotating magnetic field which induces a voltage in the rotor. This induced voltage generates a magnetic field in the rotor that is displaced 90 degrees from the stator magnetic field. The interaction of these two magnetic fields causes the armature to rotate.
As previously stated, the voltage to the two stator windings must be 90 degrees out of phase to cause the rotor to turn. The direction of rotation is determined by the phase relationship of the stator windings, which, in turn, is determined by the servo error detector. One phase is connected directly to one of the stator windings while the other phase is used to energize an error detector. The resulting error voltage is either in phase or 180 degrees out of phase with the signal applied to the error detector. This will cause the controlled phase to either lead or lag the uncontrolled phase by 90 degrees.

Most induction motors have low starting torque and high torque at high speed. For servo applications, it is desirable to have high starting torque so that the system may have a low time lag. This may be accomplished by increasing the armature resistance with the use of materials such as zinc for the conducting bars. This increased torque at low speed results in decreased torque at high speed. However, increased stability of the servo system is a desirable result of this change.

Split-phase ac motors are similar to the two-phase induction motor. It differs only in that a phase shifting network is used to shift the phase of the voltage supplied to one of the windings by 90 degrees. This is usually accomplished by connecting a capacitor in series with the uncontrolled winding of the stator. Direction of rotation and reversal is accomplished in the same manner as in the two-phase motor discussed above.

Other types of motors that may be used with an ac power supply are shaded pole, universal, and repulsion motors. They use various methods of obtaining rotation reversal. However, they are seldom found in aircraft weapons systems.

**Direct Current Motors**

Some advantages of dc motors are their higher starting torque, reversing torque, and less weight for equal power than ac motors.

Series motors are characterized by their high starting torque and poor speed regulation with a change in torque. Higher torque can be obtained on reversal of direction with a series motor than any other type. However, it is a unidirectional motor and requires special switching circuits to obtain bidirectional characteristics. This is normally done by switching either the armature or field connections, but not both.

A variation of the series motor that has bidirectional characteristics is the split-series motor. The motor has two field windings on its frame, only one of which is used for each direction of rotation. This reduces the number of relay contacts required for reversing by one-half. This double winding also reduces the torque capabilities of the motor as compared to a straight-series motor wound on the same frame.

The most frequently used dc servomotor is the shunt motor. Its direction of motion is controlled by varying the direction of flow of either the armature or field current. The uncontrolled current is usually maintained constant to preserve a linear relationship between the motor output torque and the voltage or current input. The field windings are usually two differentially wound coils to aid in direction control of the field current by the servo control amplifier. The larger armature currents require thyristors or generators as current regulators, but are not normally found in aircraft weapons systems.

**Magnetic Clutches**

Any device using an electrical signal that may be used to control the coupling of torque from an input shaft to an output shaft is a magnetic clutch. This coupling may be accomplished by the contact between friction surfaces or by the action of one or more magnetic fields. A magnetic clutch is used only to couple the input torque to the output shaft. Thus, it is capable of controlling large amounts of power and torque for its size and weight. The magnetic clutch may be used with a large flywheel.
driven at high speed by a small motor. This allows the flywheel to impart very large acceleration to the load when the magnetic clutch is energized.

There are two distinct types of magnetic clutches. Some transmit torque by physical contact of frictional surfaces. Others use the action of magnetic flux produced by two sets of coils, or one set of coils and induced eddy currents resulting from rotating the one set of coils near a conducting surface. The frictionless eddy current type of clutch offers smoother operation because there is no physical contact between torque surfaces. Thus, it has no problem of wear due to friction. Both types have suitable control characteristics and are found in servomechanisms.

**Hydraulic Devices**

Hydraulic systems used in servomechanisms are found in aircraft weapons systems. Hydraulic power devices, such as motors and associated control valves, have advantages comparable to the best electric motors and magnetic clutch systems. They also require minimum maintenance, have very high accuracy, and are adapted to heavy loads.

The essential components of a hydraulic system are as follows:

- A source of high-pressure oil and sump to receive discharge oil
- A control valve and means of employing an actuating signal
- An actuator (motor or cylinder)

The theory of operation of a hydraulic system is discussed in Fluid Power, NAVEDTRA 16193 (series).

The source of high-pressure oil serves as a source of power to operate the actuator. However, this source of power is controlled by the control valve. This valve is actuated by the output from the servo control amplifier. This control is normally accomplished by feeding the error signal to a solenoid-controlled valve. However, the error signal could be used to drive an electric motor, which, in turn, would actuate the control valve. The actuator is usually in the form of an axial motor, which must be a reversible and variable speed type. Some applications may employ a cylinder where linear motion is required for positioning.

**Servomechanism Oscillation**

In aircraft weapons systems, servomechanisms are used for various functions and must meet certain performance requirements. These requirements not only concern such things as speed of response and accuracy, but the manner in which the system responds in carrying out its command function. All systems contain certain errors; the problem is keeping them within allowable limits.

As discussed previously, the servomotor must be capable of developing sufficient torque and power to position the load in a minimum of time. The servomotor and its connected load have sufficient inertia to drive the load past the point of command position. This overshooting results in an opposite error voltage, reversing the direction of rotation of the servomotor and the load. The servomotor again attempts to correct the error, and again overshoots the point of correspondence, with each reversal requiring less correction until the system is in correspondence. The time required for the oscillations to die out determines the transient response of the system and can be greatly reduced by the use of damping.

**Damping**

The function of damping is to reduce the amplitude and duration of the oscillations that may exist in the system. The simplest form of damping is viscous damping. Viscous damping is the application of
friction to the output load or shaft that is proportional to the output velocity. The amount of friction applied to the system is critical and will materially affect the results of the system. When just enough friction to prevent overshoot is applied, the system is said to be critically damped. When the friction is greater than that needed for critical damping, the system is over-damped. However, when damping is slightly less than critical, the system is said to be slightly underdamped, which is usually the desired condition. The application of friction absorbs power from the motor and is dissipated in the form of heat.

A pure viscous damper would absorb an excessive amount of power from the system. However, a system having some of the characteristics of a viscous damper with somewhat less power loss is used in actual practice. The first of this type of damper to be discussed uses a dry friction clutch to couple a weighted flywheel to the output drive shaft. A flywheel has the property of inertia, which may be defined as that property of matter by which it will remain at rest or in uniform motion in the same straight line or direction unless acted upon by some external force.

Since the flywheel is coupled to the output shaft with a friction clutch, any rapid change in velocity of the output member causes the clutch to slip. This slipping effectively disconnects the flywheel, instantaneously, but allows sufficient power to be coupled to the flywheel to overcome its inertia. As the inertia is gradually overcome, the flywheel gains speed and approaches the velocity of the output member. As the point of correspondence is neared and the error signal is reduced, the inertia of the flywheel gives up power to the system, causing the load to increase its overshoot. When the system attempts to correct for this overshoot, the inertia of the flywheel adds to the output load, reducing the effect of the correcting signal. The effect dampens the oscillations in the system, reducing its transit time.

Another type of damper used is the eddy current damper. This damper uses the interaction of induced eddy currents and a permanent magnet field to couple the output shaft to a weighted flywheel.

The effect of damping is shown in Figure 1-18. The solid line shows the action of the load without damping. The time required to reach a steady state condition without damping should be noted. This time is greatly reduced although the initial overshoot is increased.

A viscous damper (Figure 1-18) effectively reduces transient oscillations, but it also produces an undesired steady-state error.

How well the load is controlled is a measure of the steady-state performance of a servo system. If the load is moved to an exact given position, then the servo system is said to have perfect steady-state performance. If the load is not moved to an exact position, then the system is not perfect and the difference in error is expressed as the steady-state error. Steady-state error may be either velocity lag or position error. Velocity error is the steady-state error due to viscous drag during velocity operation. Position error is the difference in position between the load and the position order given to the servo

![Figure 1-18 — Effect of friction damper.](image)
system. Since the friction damper absorbs power from the system, its use is normally limited to small servomechanisms.

To overcome the disadvantages of the viscous dampers and still provide damping, error-rate damping is used. This type of damping consists of introducing a voltage that is proportional to the rate of change of the error signal. This voltage is fed to the servo control amplifier and combined with the error signal. The effect of error-rate damping on the torque output of the servomotor is shown in Figure 1-19. Curve A shows the torque resulting from the error voltage, curve B shows the torque resulting from the error-rate damper, and curve C depicts the resultant of curves A and B. It should be noted that torque resulting from the damper increases the total torque as long as the error component is increasing. Once the error component starts to decrease, the error-rate damper produces a torque in an opposite direction, reducing the transit time of the system.

There are two methods of generating an error rate voltage normally found in aircraft weapons systems—tachometer and electrical networks. The tachometer error-rate damper uses a device that is essentially a generator having an output voltage proportional to its shaft speed. The tachometer is connected to the shaft of the output member, giving a voltage proportional to its speed. The output voltage is fed to a network that modifies this voltage so that it is proportional to a change in input voltage. This voltage is fed back to the servo control amplifier and added to the error signal.

Electrical networks used for error-rate damping consist of a combination of resistors and capacitors used to form an RC differentiating network. For a detailed explanation of RC circuits, refer to NEETS, Module 2, Alternating Current and Transformers, NAVEDTRA 14174A. These networks, sometimes referred to as phase advance or lead networks, vary in design, depending on the type of error signal. However, in practice, networks are normally limited to the dc type (Figure 1-20) because of the unstable results that would be caused by a small change in frequency of the power source. An ac system may use a dc network by first using a demodulator (detector) prior to the network. However, the output of the network must be modulated for use in the remainder of the ac system. Like the tachometer, the output of the network is fed to the servo control amplifier.
Integral Control

Servomechanisms used in aircraft weapons systems are sometimes required to follow an input function, the magnitude of which changes at a constant rate with time, such as an antenna system tracking a target. Thus, if the input is the angle of a shaft, the velocity of the shaft may be constant for a substantial percentage of time. The servomechanism may be required to respond to this type of input with substantially zero error. The error that characterizes the servo response to a constant velocity input is known as the velocity error.

To correct for velocity error or an inaccuracy due to a steady-state error, an integral control may be used. This control modifies the error voltage in such a manner that the signal fed to the servo control amplifier is a function of both the amplitude and time duration of the error signal. This is accomplished by the use of a variable voltage divider, whose output is increased with time for a constant input. As in all voltage dividers, the output is only a portion of the input that effectively reduces the amplitude of the error signal. To compensate for the loss of amplitude, additional amplification must be used either in the form of a preamplifier or a higher gain servo control amplifier. With the overall gain of the system now increased to give a normal output for transient error signals, small velocity or steady-state error signals of long duration will result in somewhat increased output to the servomotor due to the action of the integral control.

The integral control (Figure 1-21) consists of a combination of resistors and capacitors connected to make an integrator circuit for a dc error signal. The values of its components are such that the capacitor does not have sufficient time to change with fluctuations in error voltage. Only that portion of the transient error signal developed across R1 is impressed on the amplifier. However, with a velocity error or steady-state error of longer duration, the capacitor (C1) charges, increasing the amplitude of the amplifier input.

Networks shown in are not limited to dc systems, as a demodulator maybe used prior to the integrator and its output modulated for easier amplification.

Gain, Phase, and Balance

The overall system gain has a most important effect on the servomechanism response characteristics and is one of the more easily adjustable parameters in electronics servo controllers. Increasing the system gain reduces the system velocity errors and those steady-state errors resulting from restraining torques on the servo load or misalignment in the system. An increase in system gain also increases the speed of response to transient inputs. Excessive gain always decreases the rate at which oscillatory transients disappear. Continued increase in the system gain eventually produces instability.

Servo systems using push-pull amplifiers must be balanced to ensure equal torque in both directions of the servomotor. This adjustment should be checked periodically as a change in value of a
component may cause an unbalanced output. Balancing is accomplished by adjusting the system for zero output with no signal applied.

A phase control is included in some servo systems using ac motors. The two windings of the ac servomotor must be energized by ac signals that are 90 degrees apart. A phasing adjustment is normally included in the system to compensate for any phase shift in the amplifier circuit, resulting in unstable operation of the system. This adjustment may be located in the control amplifier, or in the case of a split-phase motor, it may be in the uncontrolled winding.

**ZEROING SYNCHRO UNITS**

Throughout this chapter, servomechanism accuracy has been stressed at every point. In any servomechanism using synchro units, it is also very important that the units be zeroed electrically (Figure 1-22, view A).

For a synchro transmitter or receiver to be in a position of electrical zero, the rotor must be aligned with S2, the voltage between S1 and S3 must be zero, and the phase of the voltage at S2 must be the same as the phase of the voltage at R1.

The most common methods of zeroing synchro transmitters and receivers are the ac voltmeter method and the electrical lock method. The method used to zero a synchro depends upon how the synchro is used. Where the rotor is free to turn, the electrical lock method can be used. This is accomplished by connecting S1 and S3 to R2 using a jumper wire and connecting S2 to R1 (Figure 1-23). When power is applied, the rotor will position itself in the zero position. After the synchro is zeroed, the pointer is adjusted to indicate zero.

The great majority of synchros used in aviation systems have their rotor gear driven or mechanically coupled to a driving member. In these cases it is necessary to use the ac voltmeter method, zeroing the synchro by rotating the stator or housing until its electrical zero is reached. Before you zero the synchro, the mechanical unit that positions the synchro must be set to its indexing or zero position. This is done by aligning the unit to its index and installing its indexing pins in the holes provided for this purpose. The pins hold the unit to its index and keep it from moving.

![Figure 1-22 — Synchro electrical zero positions.](image)

![Figure 1-23 — Electrical lock method of zeroing a synchro.](image)
The ac voltmeter method is done by connecting the meter and jumper wires, as shown in Figure 1-24, view A. Rotate the energized synchro until a zero reading is obtained on the voltmeter. Since rotor positions of 0 degree and 180 degrees produce this zero reading, it is necessary to determine if the phase of S2 is the same as that of R1. Make the connections as shown in Figure 1-24, view B. If the proper polarity relationship exists, the voltmeter indicates less than the excitation voltage being applied to the rotor. If the indication is greater than the rotor excitation voltage, the rotor (or stator) must be rotated 180 degrees and the previous step must be performed again.

**Differential Transmitter**

The electrical zero position of a synchro differential transmitter or receiver is when the three windings of the rotor are in correspondence with their respective stator windings and their respective voltages are in phase (Figure 1-22, view B). Because the differential transmitter synchro is normally used to insert a correction into a synchro system, it is usually driven either directly or through a gear train. Before you zero the differential transmitter synchro, the unit whose position the differential synchro transmits should first be zeroed. After this has been accomplished, connect the differential synchro as shown in Figure 1-25, view A. Turn the synchro in its mounting until the voltmeter shows a minimum indication. After you complete this step, make the connections shown in Figure 1-25, view B. Again, turn the synchro slightly in its mounting until a minimum voltage is indicated by the voltmeter.

**Differential Receiver**

Electrical zero for a differential receiver is illustrated in Figure 1-22, view B. To zero a differential receiver synchro, make the connections shown in Figure 1-26. As soon as the power is applied to the synchro, the rotor assumes a position of electrical zero. The dial can then be set at zero, and the unit reconnected to its circuit.
Control Transformer
The synchro control transformer is normally zeroed by using the ac voltmeter method. You should remember that the electrical zero position of the control transformer is 90 degrees from that of a receiver, since the rotor winding must be perpendicular to the stator’s resulting magnetic field to have a zero output (Figure 1-22, view C). The coarse adjustment is made by connecting the meter and unit as shown in Figure 1-27, view A. The rotor is rotated to give a minimum or null reading on the voltmeter. The final adjustment is made by connecting the unit as shown in Figure 1-27, view B, and displacing the rotor a few degrees in both directions to determine the null or electrical zero position. Once the zero position has been determined, the unit must be locked, as discussed previously.

ANTENNA POSITIONING SERVO SYSTEM
In this section, the application of a servomechanism to position a radar antenna and supply target information to the weapons system is discussed. However, before discussing the servo system, consider the scan pattern of a basic aviation fire control radar.

The antenna radiator and reflector form a conical pattern of circular symmetry with beam dimensions, as shown in Figure 1-28. The antenna assembly contains a spinner motor that rotates the beam about the antenna axis to produce a 7-degree conical scan. While the radar is in the search mode of operation, the rotating cone scans both horizontally and vertically, covering an area of 10 degrees vertically by 90 degrees horizontally (Figure 1-29). The search pattern may be positioned vertically from a positive 30 degrees to a negative 30 degrees by the antenna positioning level.

The operator normally observes the targets, identifies each as friend or foe, and determines which target, if any, to pursue. Since the antenna uses its 7-degree conical pattern only during track operation, some means must be provided for positioning the antenna on the selected target to begin the track operation. This is accomplished by bracketing the selected target with strobe lines. When the target has been selected and bracketed, a lock-on switch is depressed, positioning the antenna on the predetermined target, and placing the equipment in the automatic track mode of operation. The antenna is now positioned by the radar receiver output, keeping the target centered in the 7-degree beam.
A block diagram of a typical fire control antenna servo system is shown in Figure 1-30. It should be noted that the azimuth channel of the antenna control system has been omitted, as its operation is similar to the elevation channel. Since the antenna servo system uses different components during search and track operation, the system used in each mode of operation is discussed separately.

**Search Operation**

The main components of the antenna servo system used during a search operation are as follows:

- Error detector and its ac voltage source
- Servo amplifier
- Servomotor
- Data transmission system

The ac generator supplies voltage to the input and feedback potentiometers of the balanced potentiometer error detector. However, the voltage fed to the input potentiometer is fed through a gyro space stabilizer and scan generator.

The function of the gyro space stabilizer is to cause the antenna to scan a selected area 90 degrees horizontally and 10 degrees vertically, regardless of any roll or pitch of the aircraft. As in all fire control equipment of this type, the amount of correction that can be made by the gyro space stabilizer is
limited by the limits of the radar scanner. The output of the gyro space stabilizer is an ac voltage, the amplitude of which is a function of the roll and pitch of the aircraft. The principles of operation of gyros are discussed later in this manual.

The function of the vertical scan generator is to automatically position the antenna in the vertical geometric plane. Note that the antenna scans horizontally and vertically in Figure 1-29. The scan generator provides the necessary voltage change to cause the antenna to change its angle of elevation by 3 degrees when the antenna reaches its azimuth limits.

The error detector has three inputs that are summed and compared against the antenna’s position. The gyro space stabilizer and scan generator constitute two inputs by controlling the amplitude of the voltage supplied to the input potentiometer. The third input is the control handle, which positions the wiper contact of the input potentiometer. The output of the error detector is an ac voltage, whose amplitude and phase is determined by the voltages on the wipers of the potentiometers.

The error signal is fed to the servo amplifier, where it is amplified and compared with the phase of the reference voltage. The phase of the output voltage causes the servomotor to rotate in a direction reducing the error voltage.

The data transmission system is the mechanical linkage necessary to drive the wiper of the feedback potentiometer, indicating the actual position of the antenna in the vertical plane at all times.

**Track Operation**

The main components of the servo system employed during track operation are as follows:

- Radar receiver and 50 Hz amplifier
The radar receiver functions as the error detector, supplying a 50 Hz error voltage and provides the error signal. As stated previously, the antenna axis is centered approximately on a target prior to going into track operation. The antenna is rotating at 50 revolutions per second while the radar transmitter is transmitting a pulse of energy 450 times per second. When the antenna axis is pointing directly at the target, both the target return and the receiver video output remain at a constant level. However, if the target were above the antenna axis, as shown in Figure 1-31, the amplitude of the video would vary as the antenna rotated about its axis. It should be noted that the video amplitude is maximum when the beam axis is at its highest elevation and minimum when the beam axis is at its lowest elevation. The video output from the receiver is filtered, leaving only the 50 Hz envelope to be employed as an error voltage.

**Figure 1-31 — Derivation of elevation error signal.**

The function of the servo amplifier is to amplify the 50 Hz error voltage and compare its phase with the phase of the 50 Hz reference voltage originating in the 50 Hz spin generator. The phase of the output voltage to the servomotor causes the motor to rotate in the direction that reduces the amplitude of the error signal.

**Theory of Search Operation**

The schematic diagram of the antenna servo system described above is shown in Figure 1-32. As in the case of the block diagram, the system’s search mode of operation is discussed first.
Figure 1-32 — Servo system schematic diagram.
Scan Generator

The elevation scan generator is used during automatic search only. It consists of two resistors and one double-pole relay. Since only one resistor is in the circuit at a time, they serve alternately to unbalance the voltage applied to the error detector potentiometer R3. The input to the scan generator is an ac voltage with its center point grounded by a resistor network. With both R1 and R2 shorted, the center of R3 would also be at ground potential. Inserting R1 in the circuit would cause the center of R3 to be at some potential, just as though the wiper of R3 has been moved to the right. Shorting R1 and inserting R2 should have the same effect as moving the wiper of R3 to the left.

The relay is actuated by a cam attached to the azimuth limit mechanism. The cam operates when the antenna reaches either azimuth limit.

Error Detector

The balanced potentiometer error detector consists of potentiometers R3 and R35. Potentiometer R35 is supplied with a 400 Hz reference voltage of approximately 32 volts amplitude while the reference voltage applied to R3 is modified in the manner described. This voltage source is center tapped and grounded, thus reflecting an apparent ground at approximately the center of each potentiometer. A control handle displacement causing a change in the wiper contact of R3 results in an unbalanced voltage condition with an error signal being fed to the search contact of relay K2. With the equipment on search, the error signal is applied to the servo amplifier.

Servo Amplifier

The servo amplifier consists of the following stages:

- Preamplifier
- Phase shifter amplifier
- Amplifier
- Demodulator driver
- Demodulator
- Cathode followers
- Search/track network
- Magnetic amplifier drivers
- Magnetic amplifier

Preamplifier V1 receives the error voltage from relay K2 and amplifies it. The preamplifier output is coupled through C1 to the grid of V2 and to the relay K3.

Phase shifter amplifier V2 is bypassed during search operation; it is discussed under track operation.

Amplifier V3 provides an additional stage of amplification of the error signal. Its output is coupled through C4 to the gain control R15. The gain control determines the amplitude of the error signal fed to the demodulator driver. Thus, the gain of the antenna servo system is controlled by R15.

The demodulator driver provides the final amplification of the error signal prior to demodulation. As pointed out above, the amplitude of the signal applied to the grid can be controlled by the gain potentiometer (R15). The gain of the stage is stabilized by degenerative feedback. The feedback is accomplished by two means—an unbypassed cathode resistor R22 and a plate-to-grid feedback loop.
consisting of C5, C6, and R17. In addition to gain stabilization, the plate-to-grid loop provides the characteristic of an error-rate damper.

The full-wave demodulator employs two dual triodes, V5 and V6. Its operation is somewhat similar to that of a triode demodulator. The input error signal from the demodulator driver is applied to either the plate or cathode of the demodulator triodes. The reference voltage, which is 400 Hz during search operation, is supplied to the grids through either T1 or T2 with the primary-secondary phase relationship, as shown in Figure 1-32. (The small black rectangles on the input and output leads of the transformers in Figure 1-32, are polarity marks.) Instantaneous voltage polarity at the transformer primary polarity mark corresponds to the same polarity at the secondary polarity mark.

Figure 1-33 shows a synchrogram of the voltages existing in the demodulator. When the error signal and reference voltage are in phase, V5A conducts on the first half-cycle and V6A conducts on the second half-cycle. Since V5B is cut off during the time V5A is conducting, V5A draws electrons from the top plate of C8, giving it a positive charge. During the second half-cycle, electrons flowing through V6A are deposited on the lower plate of C9, giving it a negative charge. This action results in a push-pull output being supplied to the cathode followers.

When the error signal is 180 degrees out of phase with the reference voltage, V5B and V6B conduct on alternate half-cycles, charging C8 and C9 to the opposite polarity.

The cathode followers, V7 and V8, isolate the dc output of the demodulator from the low impedance of the search network (Figure 1-32). Potentiometer R25 is provided to balance the outputs of V7 and V8 when no error signal is present.

The search/track network consists of two RC band-pass filter networks that have fairly long time constants. The search filter networks pass a 5 Hz signal while sharply attenuating lower frequencies. This action counteracts the high gain of the magnetic amplifiers, giving a flatter overall response for the servo system.

The magnetic amplifier drivers are dc amplifiers that control the current through the magnetic amplifier’s control windings. The dc error signal is applied directly to the control grids of the drivers. The amplified dc error signal is applied to the control windings, controlling the output of the magnetic amplifier.

Figure 1-33 — Synchrogram of demodulator waveform.
The magnetic amplifier provides the final stage of amplification of the error signal prior to the servomotor or output member. The amplifier consists of four amplifier sections: A, B, C, and D. Each amplifier section has three windings on its core—control, bias, and load. Referring to Figure 1-32, note that the control and bias windings of sections A and B are connected in series. The bias level is determined by the setting of potentiometer R30, and the control current is determined by the output of magnetic amplifier driver V9.

The C and D sections are connected in a similar manner with the bias level determined by potentiometer R33 and control winding current determined by the output of magnetic amplifier driver V10. The load winding of each section has a rectifier connected in series with it, allowing current to flow only in one direction. The polarity of the magnetic field resulting from current in each winding is indicated on the schematic by the direction of the arrows.

A synchrogram of waveforms illustrating the operation of the magnetic amplifier is shown in Figure 1-34. With a zero error signal applied to the grids of V9 and V10, conduction in all sections of the amplifier is equal. Waveforms showing the amount and time of conduction of each amplifier section under zero error signal conditions are shown in column A of Figure 1-34. Waveforms (4) and (6) are equal in amplitude in column A but 180 degrees out of phase, resulting in zero output to the servomotor.

Column B of Figure 1-34 illustrates the operation of the amplifiers with a positive error (an error signal that would cause the antenna elevation angle to be increased) applied to the magnetic amplifier drivers. The positive voltage applied to the grid of V9 increases the degree of core saturation, reducing the impedance of amplifier sections A and B. The negative voltage applied to the grid of V10 decreases the degree of core saturation, increasing the impedance of amplifier sections C and D. Since the output of a magnetic amplifier varies inversely with its impedance, the output of sections A and B is increased in amplitude while the output of sections C and D is reduced in amplitude. Waveform (5) shows the algebraic sum of the two waveforms, which is fed to the servomotor.

Column C of Figure 1-34 illustrates the operation of the amplifiers with a negative error signal applied. The output amplitudes have been reversed, causing the signal applied to the servomotor to be 180 degrees out of phase with that in column B.

**Servomotor**

The servomotor is a split phase ac induction motor whose field windings are excited by voltages that are 90 electrical degrees out of phase. The output of the servo amplifier determines whether the
controlled winding is leading or lagging the uncontrolled winding. This phase relationship also determines the direction of rotation of the servomotor.

**Theory of Track Operation**

The purpose of the antenna servo system during track operation is to position the antenna based on the video output of the radar system. Again referring to Figure 1-32, note that relay K2 disconnects the error detector and control handle from the servo loop. The 50 Hz envelope of the video output constitutes the error signal and is fed to the servo amplifier.

**Servo Amplifier**

The 50 Hz error signal is amplified by the preamplifier and fed to the phase shifter. The phase shifter amplifies the error signal and also provides an adjustment, R13, to compensate for any phase shift of the error signal through the servo amplifier (Figure 1-32). The output of the plate is coupled through C2 to R13, with the other end of R13 connected to the junction of R1 and R12. The plate and cathode voltages are 180 degrees out of phase, and regenerative current flows in R12, resulting in regenerative feedback. The shifting of the error signal’s phase is accomplished by varying the resistive-reactive ratio of the plate-to-cathode feedback loop. This varies the phase of the regenerative feedback, controlling the phase of the output error signal.

The operation of the amplifier and demodulator driver stages is identical under both modes of operation. However, the demodulator must now employ a 50 Hz reference voltage. Relay K4 is energized by the track/search switch, disconnecting the 400 Hz reference and connecting the 50 Hz reference supplied by the 50 Hz spin generator.

The outputs of the demodulator are fed through the cathode followers to the track section of the search/track networks. The track section is composed of two identical RC bandpass filters, which pass 2 Hz signals and attenuate all other signals. A signal from the elevation rate gyro is also used to control the error signal amplitude during track operation.

Since the magnetic amplifier drivers and the magnetic amplifier use dc error signals only, their operation is unchanged when switched to track operation.

**Spin Generator**

The 50 Hz spin generator is a permanent magnet ac generator that is driven by the spin motor. Its only function is to furnish a reference voltage for the demodulator during track operation.

**MAINTENANCE AND ADJUSTMENTS**

The maintenance of the antenna servo system is normally covered during phased inspections of the entire system. However, this section of the chapter will discuss maintenance pertinent to a typical antenna servo system.

**Lubrication**

The lubrication of the antenna system should follow the procedure set forth in the maintenance instruction manual (MIM) for the equipment. The lubricants and the time interval between lubrications should also be in accordance with standards established by the maintenance instructions. Instructions are normally issued by the squadron, supplying supplemental maintenance information and establishing schedules to be followed by maintenance personnel.
Alignment

The procedure for alignment of the antenna servo system is also found in the MIM for each piece of equipment. However, for illustration purposes, the alignment procedures applicable to a basic antenna servo system will be discussed here.

The first adjustment to be made is the balance control, R25 (Figure 1-32). Its purpose is to ensure there is no output from the servo amplifier when no error signal is applied. Connect a dc voltmeter between the grid of V9 and the grid of V10. Place a jumper between the grid of V7 and the grid of V8, shorting out any error signal and allowing any imbalance of the cathode followers to be determined. Adjust R25 until there is a zero voltage reading on the voltmeter. Remove the voltmeter from the circuit, but do not disconnect the jumper, as it is required for the next adjustment.

Bias adjustments in magnetic amplifiers are made by connecting an appropriate multimeter in the load winding of each amplifier and adjusting the bias controls, R30 and R33, to the current specified by the MIM. A current jack is normally incorporated in the equipment so you can use a standard multimeter. Remove the jumper from the grids of the cathode followers and disconnect the meter.

Gain adjustments are made by inserting a voltage of a specific amplitude and frequency at the input of the preamplifier and measuring the output of the demodulator driver V4, which is the last ac amplifier stage. The MIM will normally specify the amplitude and frequency of the input signal and the output stage.

Make phase adjustments when the equipment is in track operation and locked on a strong target. Disable the antenna azimuth channel per instructions in the MIM. With the equipment operating as specified above, manually rotate the antenna in azimuth. Any change in the elevation of the antenna indicates an undesirable phase shift in the amplifier. Vary the phase adjustment until any movement of the antenna in azimuth causes no change in its elevation.

The simplified radar antenna system used in this lesson is for illustration purposes only and not indicative of the systems you will encounter in naval aviation today. A representation of an APG-73 radar servo electronics gimbal assembly that is currently in service is shown in Figure 1-35.

Figure 1-35 — APG-73 Servo electronics gimbal assembly.
End of Chapter 1
Servo Systems

Review Questions

1-1. What data transmission system component compares the input with the output of the servomechanism?

A. Servomotor  
B. Servo follow-up  
C. Error detector  
D. Servo amplifier

1-2. In the figure below, the error signal is proportional to the signal of the _______.

A. input less the signal of the output.  
B. output divided by the signal of the input.  
C. input divided by the signal of the output.  
D. output less the signal of the input.

![Simplified block diagram of a servomechanism.](image)

1-3. Which of the following is the main advantage of using a synchro control transformer as an error detector?

A. Its high accuracy  
B. Its driving torque requirements are small  
C. Its low noise level  
D. Its unlimited input and output rotation angles

1-4. A multiple-speed data transmission system is used with a single-speed system in a servomechanism for what purpose?

A. To compensate for a wide range of rotation rates  
B. To step down the frequency of the error signal  
C. To eliminate the need for a servo-control amplifier in the system  
D. To increase the accuracy of control of the servomotor load
1-5. Which of the following system characteristics is a primary cause of servo system oscillations?

A. Inertia
B. Friction
C. Low-speed gain
D. High-speed gain

1-6. When just enough damping to prevent overshoot of the commanded position is applied to a servo system, the system can be described as being in what condition?

A. Critically damped
B. Slightly overdamped
C. Slightly underdamped
D. Proportionally damped

1-7. Error rate voltage is produced in a network by the tachometer error-rate damper. This is done by using a device that is essentially a generator, which produces a steady state voltage proportional to _______.

A. the change in the damper input voltage.
B. the servomotor torque.
C. the shaft rotation speed.
D. the current through the demodulator.

1-8. In the figure below, the integrator circuit consisting of R2, R1, and C1 is designed so that the transient error signal delivered to the amplifier is only that portion which is _______.

A. developed across R1.
B. developed across R2.
C. the combination of the R1 and R2 voltage.
D. the charge developed by R2 and C1.

1-9. In balancing a servo system, the circuit is adjusted to obtain which of the following results?

A. Maximum output when no error signal is applied
B. Compensation for variations in line voltage
C. Zero output when no signal is applied
D. The fastest response without hunting
1-10. Electrically zeroing a synchro transmitter or receiver requires the rotor be aligned with S2, the phase of the voltage at R1 be same as the phase of the voltage at S2, and _______.

A. the voltage at R1 and R2 be zero.
B. the voltage at S1 and S3 be zero.
C. R1 and R2 be disconnected from power.
D. R1 and R2 be jumpered.

1-11. When using the electrical lock method of zeroing a synchro transmitter, what is the next step after the rotor positions itself at zero?

A. Remove jumper wires
B. Find the null position
C. Adjust the pointer to zero
D. Calculate the error rate voltage

1-12. In the figure below, the first step in electrically zeroing a control transformer synchro is to _______.

A. jumper S3 and R2 and find null.
B. perform fine-tuning adjustment.
C. lock the unit’s position.
D. connect voltmeter between S1 and R1 for coarse adjustment.

Electrically zeroing a control transformer synchro.

![Diagrams A and B showing connections and labels for zeroing a control transformer synchro.](image-url)
1-13. In the figure below, when a positive voltage is applied to the grid of V9, the resulting circuit action causes which of the following actions relative to the antenna?

A. The antenna’s elevation angle to decrease only  
B. The antenna’s elevation angle to increase  
C. Damping of antenna oscillations only  
D. Damping of antenna oscillations and the antenna’s elevation angle to decrease

1-14. In the figure below, when the tracking mode is selected, adjustment of R13 performs what function?

A. It compensates for any phase shift of error signal as the signal passes through the servo amplifier circuits.  
B. It improves the linearity of V2 by controlling the amount of degenerative feedback applied to V2’s input circuit.  
C. It reduces any error signal to zero by supplying the correct amount of regenerative feedback to V2’s cathode.  
D. It eliminates any phase shift or error signal caused by feed through from the gyro stabilizer or because of control handle movement.

Servo system schematic diagram.
1-15. The function of the 50 Hz spin generator in the antenna servo system is to furnish a reference voltage for the ______.

A. modulator during both track and search operations.
B. demodulator during track operation.
C. demodulator during search operation.
D. radar receiver during search operation.

1-16. Which of the following potentiometers is the first to be adjusted in the alignment procedure?

A. Phase adjust R13
B. Gain adjust R20
C. Balance control R25
D. Bias adjust R30
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CHAPTER 2
LOGIC DEVICES

As an aviation electronics technician (AT) in the U.S. Navy today, you have to understand solid-state devices if you are to become proficient in the use, maintenance, and repair of electronic equipment. Both analog and digital circuits are used in this chapter. First, semiconductor theory is covered to give you an overview of their operation and application. Then, transistor fabrication and integrated circuits (ICs) are discussed to give you an insight into the manufacturing methods. The functions of some ICs are discussed in detail to give you a working knowledge of their uses.

LEARNING OBJECTIVES

When you have completed this chapter, you will be able to do the following:

1. Describe the basic operation of a semiconductor diode.
2. Identify the different types of transistor configurations.
3. Recall the basic concepts of transistor theory and the operation of transistors.
4. Describe the purpose and use of thyristors.
5. Describe the purpose, fabrication, and operation of ICs.
6. Describe the purpose and use of transistor-transistor logic (TTL).

SEMICONDUCTORS

Semiconductors have electrical properties somewhere between those of insulators and conductors. The use of semiconductor materials in electronic components is not new. Some devices are as old as the electron tube. Two of the most widely known semiconductors in use today are the junction diode and transistor. These semiconductors fall under a more general heading called solid-state devices. A solid-state device is nothing more than an electronic device that operates by virtue of the movement of electrons within a solid piece of semiconductor material.

Since the invention of the transistor, solid-state devices have been developed and improved at an extremely high rate. Great strides have been made in the manufacturing techniques, and there is no foreseeable limit to the future of these devices. Solid-state devices made from semiconductor materials offer compactness, efficiency, ruggedness, and versatility. Consequently, these devices have permeated virtually every field of science and industry. In addition to the junction diode and transistor, a whole new family of related devices has been developed, including thyristors and field-effect transistors. One development that has dominated solid-state technology, and probably has had a greater impact on the electronics industry than either the electron tube or transistor, is the IC. The IC is a minute piece of semiconductor material that can produce complete electronic circuit functions.

Semiconductor devices are all around us. They can be found in just about every commercial product you touch, from the family car to the smart phone. Semiconductor devices are contained in television sets, portable radios, stereo equipment, and much more. Science and industry also rely heavily on semiconductor devices. Research laboratories use these devices in all sorts of electronic instruments to perform tests, measurements, and numerous other experimental tasks. Industrial control systems (such as those used to manufacture automobiles) and automatic telephone exchanges also use semiconductors. Even today, heavy-duty versions of the solid-state rectifier diode are being used to convert large amounts of power for electric railroads. Of the many different applications for solid-state
devices, space systems, computers, and data processing equipment are some of the largest consumers.

Various types of modern military equipment are literally loaded with semiconductor devices. Radar, communication, and navigation systems all contain solid-state equipment. Data display systems, data processing units, computers, and aircraft guidance-control assemblies are also good examples of electronic equipment that use semiconductor devices. All of the specific applications of semiconductor devices make a long, impressive list.

**Junction Diode**

If you join a section of positive (P)-type (positively charged, holes) semiconductor material with a similar section of negative (N)-type (negatively charged, electrons) semiconductor material, you obtain a device known as a positive/negative (PN) junction. The junction diode, referred to as a diode, is nothing more than a two-element semiconductor device that makes use of the rectifying properties of a PN junction to convert alternating current (ac) into direct current (dc) by permitting current flow in only one direction. In addition, they have special properties that make them particularly useful for bias and voltage stabilization. A diode is normally identified as a crystal rectifier (CR) on schematic drawings. If only one diode is on the drawing, it is labeled CR1. The symbol of a diode is shown in Figure 2-1. The heavy, dark line shows electron flow. Notice it is against the arrow. For further clarification, a pictorial diagram of a PN junction and an actual semiconductor (one of many types) is also illustrated.

Because diodes can be made of the same material as the transistor and have the same temperature coefficient and resistance, they will efficiently operate over the same temperature range, providing nearly ideal thermal compensation. Likewise, application of the avalanche breakdown phenomena provides a special voltage-stabilizing (zener) diode.

The junction diode has four important ratings that must be taken into consideration when used in a power supply. They are the maximum:

- Average forward current
- Repetitive reverse voltage
- Surge current
- Repetitive forward current

These ratings are important to you, as a technician, when it becomes necessary to troubleshoot a power supply or select junction diodes for replacement if the desired one is not readily available.

The maximum average forward current is the maximum amount of average current that can be permitted to flow in the forward direction. This rating is usually given for a specified ambient temperature and should not be exceeded for any length of time because damage to the diode will occur.

---

**Figure 2-1 — The PN junction diode.**
The maximum repetitive reverse voltage is that value of reverse bias voltage that can be applied to the diode without causing it to break down.

The maximum surge current is that amount of current allowed to flow in the forward direction in nonrepetitive pulses.

The repetitive forward current is that value of forward bias voltage that can be applied to the diode without causing it to break down.

All of the ratings mentioned above are subject to change with temperature variations. If the temperature increases beyond normal operating parameters, the ratings given on the specification sheet may not be accurate.

Transistors

Semiconductor devices that have three or more elements are called transistors. The term “transistor" was derived from the words transfer and resistor. A transistor is an active component of an electronic circuit that may be used as an amplifier, detector, or switch. There are many different types of transistors (Figure 2-2), but their basic theory of operation is all the same. The operation of a transistor is similar to the operation of a diode except that now two such PN junctions are required to form the three elements of a transistor. The two-junction transistor has three elements: the emitter, which gives off, or emits, current carriers (electrons or holes); the base, which controls the flow of current carriers; and the collector, which collects the current carriers.

This term was adopted because it best describes the operation of the transistor—the transfer of an input signal current from a low-resistance circuit to a high-resistance circuit. Basically, the transistor is a solid-state device that amplifies by controlling the flow of current carriers through its semiconductor materials. Transistors are of two general types; bipolar and field-effect. The bipolar type involves excess minority current carrier injection. The field-effect type involves only majority current carriers. Historically, the bipolar type was developed before the field-effect type; both are widely used today. An unmodified transistor usually refers to the bipolar type.

Bipolar Transistor

In a bipolar transistor, at least one contact is ohmic (nonrectifying), and at least one contact is rectifying. Usually, there are two closely spaced rectifying contacts and one ohmic contact.

The operation of a simple transistor consists of the control of the current flowing in the high-resistance direction through one rectifying contact (called the collector) by the current flowing in the low-resistance direction in the other rectifying contact (called the emitter). The third contact, which is ohmic, is called the base contact.

These contacts usually consist of two or more regions. The regions in which the actual rectification processes take place are called the emitter barrier and collector barrier. The region between these
two barriers is called the base region, or simply the base. The regions outside these barriers are called the emitter and collector regions.

**Classification of Transistors**

Transistors are classified chiefly by four criteria: (1) the type and number of structural regions of the semiconductor crystal; (2) the technology used in fabrication; (3) the semiconductor material used; and (4) the intended use of the device. A typical designation following this scheme would be negative/positive/negative (NPN) double-diffused silicon switching transistor. It is not necessary to include all of the above criteria in a single designation or to rigidly follow this order.

A common transistor type is the NPN double-diffused silicon planar passivated transistor (Figure 2-3). The term “double-diffused” refers to the fabrication technique in which the base region is formed by diffusion through a mask into the body of the silicon wafer, which forms the collector region.

In turn, the emitter region is formed by diffusion through a second mask into the previously formed base region. The term “planar” refers to the fact that all three electrical connections are found on a single surface of the device. The term “passivated” means that the surface to which all junctions return is protected by a layer of naturally grown silicon oxide, which, together with an overcoating of glass or other inert material, passivates the surface, electrically minimizing leakage currents. The double-diffusion process allows very close control of narrow base widths. The base diffusion provides a resistivity gradient in the base region, which has an associated electric field. In this field, charge transport is by drift. Such transistors have been called drift transistors to distinguish them from most other transistors in which the charge transport is by a diffusion process. Silicon planar transistors have power ratings in the 100 milliwatt (mW) to 50 watt (W) range with characteristic frequencies between 50 and 2,000 megahertz (MHz), usually of the NPN type. The designation NPN stands for the conductivity type of the emitter, base, and collector regions, respectively. The n stands for negative because the charge on an electron is negative, and electrons carry most of the current in a region of type conductivity. In a region of P-type conductivity, most of the current is carried by electron vacancies called holes, which behave as if they were positively charged.

A historically important type was the NPN alloy-junction germanium transistor. This type was widely used in the first decade of the solid-state electronics era. The term “alloy-junction” in this transistor designation refers to the fabrication method. The emitter and collector regions were produced by recrystallization from an alloy of some suitable metal infused with a P-type impurity to increase current flow efficiency. The process of adding these impurities to crystals is referred to as “doping.” When the alloy that had previously been infused made contact with the opposite surfaces of the original N-type semiconductor body, it dissolved some of the semiconductor material and its junction was fused. Fused-junction is equivalent terminology. A wide variety of transistors are made depending on the desired application, function, and power requirements.

**Transistor Action**

To explain transistor action in more detail, some of the basic properties of a semiconductor material are presented first. As previously discussed, an N-type semiconductor contains electrons, and a P-type semiconductor contains holes. These electrons and holes are called the majority carriers of the two types. Actually, a small number of holes are always present in N-type semiconductors, and a small number of electrons are always present in P-type semiconductors. These electrons and holes are called the minority carriers of the two types. At a given temperature with a given material, the product of the densities of the majority and minority carriers is a constant. This means that if there is a high density of majority carriers (low-resistivity material) present, there will be a correspondingly low density of minority carriers.
The emitter current controls the collector current in a simple NPN transistor. To understand this concept, first consider the magnitude of the collector current in the absence of emitter current. In normal operation, the collector barrier is biased in the high-resistance (reverse) direction. Under this condition of bias, the majority carriers are stopped by the barrier, and only the minority carriers are free to flow. If the collector barrier is a silicon PN junction, the minority-carrier diffusion current is negligible, and the reverse-bias leakage current will consist of thermally generated carriers and be in the nanoampere range. If emitter current is present, the portion consisting of carriers entering the base will continue across the collector barrier, and thus control the collector current.

**Injection**

The emitter controls the density of minority carriers by injecting extra minority carriers into the base region when the emitter is biased in the low-resistance (forward) direction. This is the fundamental process of simple transistor action. Whenever a rectifying barrier is forward-biased, extra minority carriers are added to the semiconductor near the barrier. Because the source of these minority carriers is the majority-carrier density on the other side of the barrier, it is clear that the largest part of the forward current will be carried by those carriers that come from the largest majority density. A PN junction will have a high injection efficiency for electrons if the n region has a much larger density of carriers (lower resistivity) than the p region. Therefore, in the NPN transistor, the emitter n region should have a low resistivity compared to the P-type base region. Also, the phenomenon of minority-carrier injection is observed in rectifying metal semiconductor contacts, and such contacts may be used as emitters as well as PN junctions.

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**Figure 2-3 — Sections of a planer NPN double-diffused silicon transistor.**
Current Gain

The current gain of a simple transistor may be expressed as the product of three factors: (1) the fraction \( \gamma \) (gamma) of the emitter current earned by the injected carriers, (2) fraction \( \beta \) (beta) of the injected carriers that arrive at the collector barrier, and (3) the current multiplication factor \( \alpha^* \) (alpha) of the collector. For a double-diffused transistor, typical values of these factors are \( \gamma = 0.985 \), \( \beta = 0.999 \), and \( \alpha^* = 1.000 \), giving \( \alpha = 0.984 \). From these values you can see that most of the current that flows into the emitter flows right on through the base region and out the collector, while only a small fraction (here 0.016) flows out the base connection.

For a fixed value of emitter current \( (I_e) \) there is a fixed value of collector current \( (\alpha I_e) \) added to the collector-barrier leakage current \( (I_{co}) \), giving a total collector current, \( (I_c) = I_{co} + \alpha I_e \). This means that the slope of the dc characteristics should be the same as the slope of the collector-barrier leakage current curve for \( I_e = 0 \). The typical characteristics shown in Figure 2-4, views A and B, illustrate collector and emitter leakage current, respectively. The slope of the collector leakage curve is very low because the collector voltage does not influence the relatively fixed number of minority carriers carrying the current.

![Figure 2-4 — Transistor dc characteristics.](image)

High-Frequency Effects

High-frequency effects originate in three distinct properties of transistors: the transit time of injected carriers across the base region, the charging time of the collector- or emitter-barrier capacitance through the base region and collector-region resistance in series, and the time required to build up the proper density of injected carriers in the base region (called storage-capacity effect). In alloy-junction transistors with a base region of uniform resistivity, the transport of injected carriers across the base is usually the limiting factor. Base transit time alone (Figure 2-5, view A) introduces only a phase shift between the emitter and collector signals (Figure 2-5, view B), but this time also gives a chance for injected carriers, bunched by the emitter signal, to diffuse apart, and therefore degrade the signal.

In double-diffused (drift) transistors, the base transit time is usually negligible compared to the charging time of the collector or emitter capacitance. In some units, the storage capacity (often called diffusion capacity) seems to be an appreciable limitation.

Storage capacity also shows up in another way in transistors used as switches. Here it introduces a time delay in both turning on and turning off the transistor. The turn-off delay is usually longer than...
the turn-on delay because the density of injected carriers in the base region has had time to build up to large values during the time the transistor was on, and therefore takes a long time to subside to the level where the transistor can turn off. These delays are only slightly related to the actual time of rise or fall of the collector level, which is determined primarily by the collector-capacitance base-resistance time constant.

To minimize the storage capacity effects in high-speed transistors, a fabrication technique called epitaxial growth is used. In this process, a transistor structure is formed entirely in a thin skin of good semiconductor material grown upon the surface of a wafer of heavily doped material. The heavily doped material has low lifetime for excess carriers and, therefore, a low storage effect, as well as a low series resistance. The collector junction of such a transistor is close to this low-lifetime material but is formed in the high-quality, epitaxially grown skin so that its properties are not degraded by the heavily doped material. Such transistors are called epitaxial transistors.

Close control of the injection ratio $\gamma$, is afforded by the fabrication technique of ion implantation. In this technique, a beam of ions composed of the desired dopant material is accelerated to a specific kinetic energy and caused to strike the surface of the region to be doped. The ions penetrate the surface and remain embedded in the semiconductor material. By controlling the ion-beam current and the time of bombardment, a very accurate control of the total number of dopant ions in the region is achieved. After heating the semiconductor to diffusion temperature, the ions move on into the material, creating the emitter and base regions of the double-diffused structure. These regions now have precisely controlled doping, and hence, show a $\gamma$-factor within ±1 percent of the design value.

Transistor Noise

Noise is quite low if low source impedance is used. With source impedances of about 1,000 ohms, a good junction transistor will have a noise factor of about 4 decibels (dB). The noise factor is independent of the connection but rises with source impedances above 10,000 ohms and with frequencies below 1,000 Hz.
Temperature Effects

Temperature effects are most often marked in connection with the collector-barrier leakage current with no emitter current flowing $I_{co}$. This current increases exponentially with temperature and leads to a phenomenon called “thermal runaway.” If a transistor is operated at a given ambient temperature and a given initial power dissipation, this power will soon raise the temperature of the collector barrier, which then draws more current, and, in turn, increases the dissipation. The process is cumulative, and precautions must be taken to stabilize against it. Current gain increases slightly with increased temperature in most NPN transistors, but this gain is a small effect unless the current gain is unusually close to unity.

Power Switching

Several transistor structures are that are used for power switching also make use of current gains greater than unity. This type of device, is commonly called the thyristor, is discussed later in this chapter. These devices are often called “four-layer” devices because they usually contain four regions of alternating N- and P-type semiconductor material. Connections are made to the end regions and to one of the interior regions. The end regions are oppositely biased so that the center junction is reverse-biased. The connection to the interior region is then the control and is usually called the “gate.” When the gate is biased to cause injection of excess carriers across the junction between it and the nearest end connection, the device is triggered on, and a saturation current is drawn between the two end connections, normally called anode and cathode. Such devices are normally classified as rectifiers, but, in reality, they are a form of transistor.

Field-Effect Transistor

In contrast to the bipolar transistor, which uses bias current between base and emitter to control conductivity, the field-effect transistor (FET) uses voltage to control an electrostatic field within the transistor. There are two major types of field-effect transistors—the junction-gate FET (JFET) and the insulated-gate FET (IGFET). The IGFET is more commonly known as a metal-oxide-semiconductor (MOS) FET, MOSFET, or MOS transistor, which describes, in order, the structure of the device from the gate toward the channel. The JFET, developed first because it involved no technology beyond that of the planar bipolar silicon transistor, functions similar to a voltage-controlled vacuum tube. The MOSFET is used in applications that require high input impedance combined with high current gain, such as amplifiers, mixers, and test equipment.

Junction Field-Effect Transistor

A cross-section of a JFET is shown in Figure 2-6, view A. The channel consists of relatively low-conductivity semiconductor material sandwiched between two regions of high-conductivity material of opposite type. When these junctions are reverse-biased, the junction depletion regions encroach upon the channel, and finally, at a high reverse bias, pinch it off entirely. The thickness of the channel, and hence its conductivity, is controlled by the voltage on the two gates. Therefore, this device is normally on and may be switched off. It is called a “depletion-mode” FET. In practice, this FET has an input impedance several orders of magnitude greater than that of a silicon bipolar transistor. JFETs are made in both N- and P-channel types. They are used in amplifiers, oscillators, mixers, and switches. The general performance limits are about 500 MHz, 1 W, 100 volts (V), and 100 milliamps (mA) (saturation drain current). They also find application in ICs employing bipolar transistors because their technology is compatible.
A cross-section of a MOSFET is shown in Figure 2-6, view B. Here the source and drain regions consist of n diffusion in a P-type substrate. The gate is a metal film evaporated on a thin silicon dioxide (SiO₂) insulator spanning the separation between the source and drain. With no voltage on the gate, the source and drain are insulated from each other by their surrounding junctions. When a positive voltage is applied to the gate, electrons are induced to move to the surface of the P-type substrate immediately beneath the gate, producing a thin surface of induced N-type material, which now forms a channel connecting the source and drain. Such a surface layer is called an inversion layer because it is of opposite conductivity type to the substrate. The number of induced electrons is directly proportional to the gate voltage, so that the conductivity of the channel increases with gate voltage. This device is called an N-channel enhancement-mode MOSFET. It is normally off at zero gate voltage.

Because of the quality of the SiO₂ gate insulator, the input impedance of a MOSFET is several orders of magnitude greater than that of a JFET. Typical MOSFET dc characteristics are shown in Figure 2-7. The low-drain voltage channel resistance is inversely proportional to \((V_{gs} - V_{th})\), where \(V_{gs}\) is the gate source voltage and \(V_{th}\) is the threshold voltage, and the saturation drain current is proportional to \((V_{gs} - V_{th})^2\).

MOSFET devices are fabricated in both P- and N-channel types, as well as for both depletion (normally on) and enhancement (normally off) modes of operation. In a MOSFET, the mode of operation is determined by a threshold voltage of the gate at which the device changes from off to on, or vice versa. In modern technology, this threshold voltage can be set for a wide range of values by the use of ion implantation through the gate oxide.

MOSFET discrete devices are used for ultrahigh-input impedance amplifiers, such as electrometers where the input leakage current is less than \(10^{-14}\) amps (A). Dual-gate depletion types can be used as mixers up to 1,000 MHz, and power-switching types are good to 25 W, 2 A, or 100 V. Most integrated circuits using MOSFETs are called complementary metal-oxide-
semiconductor (CMOS) integrated circuits. These circuits use N- and P-channel types together to achieve digital logic. Typical propagation delay time through small-scale integrated (SSI) building-block circuits is about 20 nanoseconds (ns) for a 20-picofarad load. At a 100 MHZ clock rate, the power dissipation for such a gate is about 10 mW. For large-scale integration, typical 16-kilobit random-access memory has an access time as low as 20 ns, an active power of 500 mW, and a standby power of 20 mW. Technological advances have dramatically decreased access times and power consumption even beyond these parameters.

There are a number of variations of the MOS technology. Two of particular interest are the VMOS (V for vertical) and silicon on sapphire (SOS). The VMOS device is fabricated by etching a notch down through a planar double-diffused structure similar to that of an NPN bipolar transistor. The surface of the notch is first oxidized and then covered with the gate metallization. The source contact bridges the n+-p junction near the surface, and the drain connection corresponds to the collector contact of the bipolar structure. The channel length is now determined by the thickness of the p region allowing short channels and gives both high-current and high-voltage capability.

The SOS device is fabricated in a very small silicon body grown epitaxially on a sapphire substrate. MOS/SOS 64,000-bit memory has shown a standby power of only 1 microwatt.

Transistor Manufacture

The manufacture of transistors has required a whole new field of exacting technology. Good semiconductor material requires the maintenance of chemical purities far beyond the spectroscopic range. A few years ago a purity of 1 part in $10^8$ was not unusual. Today, raw materials slated for use in the semiconductor manufacturing process start at a purity level greater than 99.9999 percent. Electronic-grade silicon (EGS) or semiconductor-grade silicon (SGS) contains individual impurity levels in the parts per billion (ppb) range, with gold being near the smallest at less than 0.00001 ppb. Most devices must be made from oriented single crystals of semiconductor material and are highly susceptible to the effects of structural defects caused by impurities during the growth process.

Physical tolerances of the high-frequency transistor structures are microscopic; the separation of emitter and collector junctions must be of the order of a few nanometers in these units. In fact, it is possible for more than 30 million transistors to fit on a pin head in some microcomputer applications.

To solve these problems new techniques have appeared. Purity is achieved by melting a small zone of a bar, or ingot, and gradually passing this molten zone from one end of the bar to the other. Impurities in the material remain in the liquid phase and are earned along with the molten zone, leaving high-purity material behind.

Tolerances are achieved by a collection of new techniques, such as epitaxial growth, solid-state diffusion, ion implantation, and the photolithographic delineation of diffusion masks.

Transistor Configurations

It is important for you to understand the method of connecting a transistor into a circuit. Bipolar transistor connections and FET connections are discussed in the following text.

Bipolar Transistor Connections

A transistor may be connected in any one of three basic configurations (Figure 2-8): (1) common emitter, (2) common base, and (3) common collector. The term “common” is used to denote the element that is common to both input and output circuits. Because the common element is often grounded, these configurations may be referred to as grounded emitter, grounded base, and grounded collector.
Each configuration has particular characteristics that make it suitable for specific applications. An easy way to identify a specific transistor configuration is to follow two simple steps: (1) Identify the element (emitter, base, or collector) to which the input signal is applied, (2) Identify the element (emitter, base, or collector) from which the output signal is taken. The remaining element is the common element and gives the configuration its name.

Common-Emitter Configuration

The common-emitter configuration shown in Figure 2-8, view A is the arrangement most frequently used in practical amplifier circuits because it provides good voltage, current, and power gain. The common emitter also has a somewhat low input resistance (500 to 1,500 ohms) because the input is applied to the forward-biased junction and has a moderately high output resistance (30 to 50 kilohms or more), and because the output is taken off the reverse-biased junction. Because the input signal is
applied to the base-emitter circuit and the output is taken from the collector-emitter circuit, the emitter is the element common to both input and output.

When a transistor is connected in a common-emitter configuration, the input signal is injected between the base and emitter, which is a low-resistance, low-current circuit. As the input signal swings positive, it also causes the base to swing positive with respect to the emitter. This action decreases forward bias, which reduces collector current \( I_c \) and increases collector voltage \( V_c \) making \( V_c \) more negative. During the negative alternation of the input signal, the base is driven more negative with respect to the emitter increasing forward bias and allowing more current carriers to be released from the emitter. The result is an increase in collector current and a decrease in collector voltage (making \( V_c \) less negative or swing in a positive direction). The collector current that flows through the high-resistance, reverse-biased junction also flows through a high resistance load, resulting in a high level of amplification.

Because the input signal to the common emitter goes positive when the output goes negative, the two signals (input and output) are 180 degrees out of phase. The common-emitter circuit is the only configuration that provides a phase reversal.

The common emitter is the most popular of the three transistor configurations because it has the best combination of current and voltage gain. The term "gain" is used to describe the amplification capabilities of the amplifier. It is basically a ratio of output versus input. Each transistor configuration gives a different value of gain, even though the same transistor is used. The transistor configuration used is a matter of design consideration. However, as a technician, you will become interested in this output-versus-input ratio (gain) to determine whether or not the transistor is working properly in the circuit.

The current gain in the common-emitter circuit is called “beta” \( \beta \). Beta is the relationship of collector current (output current) to base current (input current). To calculate beta, use the following formula:

\[
\beta = \frac{\Delta I_c}{\Delta I_b} \quad (\Delta \text{ is the Greek letter delta; it is used to indicate a small change})
\]

For example, if the input base current \( I_b \) in a common emitter changes from 75 to 100 microamps (uA) and the output current \( I_c \) changes from 1.5 to 2.6 mA, the current gain \( \beta \) will be 44:

\[
\beta = \frac{\Delta I_c}{\Delta I_b} = \frac{11 \times 10^{-3}}{25 \times 10^{-6}} = 44
\]

This simply means that a change in base current produces a change in collector current that is 44 times as large.

The resistance gain of the common emitter can be found in a method similar to the one used for finding beta:

\[
R = \frac{R_{out}}{R_{in}}
\]

Once the resistance gain is known, the voltage gain is easy to calculate because it is equal to the current gain \( \beta \) multiplied by the resistance gain \( E = \beta R \). Also, the power gain is equal to the voltage gain multiplied by the current gain \( \beta \) \( P = \beta E \).

**Common-Base Configuration**

The common-base configuration shown in Figure 2-8, view B is mainly used for impedance matching because it has a low input resistance (30 to 160 ohms) and a high output resistance (250 k to 550 kilohms). However, two factors limit its usefulness in some circuit applications: (1) its low input resistance and (2) its current gain of less than 1. Because the common-base configuration will give
voltage amplification, there are some additional applications, which require both a low input resistance and voltage amplification, that could use a circuit configuration of this type, for example, some microphone amplifiers.

In the common-base configuration, the input signal is applied to the emitter-base, the output is taken from the collector-base, and the base is the element common to both input and output. Because the input is applied to the emitter, it causes the emitter-base junction to react in the same manner as it did in the common-emitter circuit. For example, an input that aids the bias will increase transistor current, and one that opposes the bias will decrease transistor current.

Unlike the common-emitter circuit, the input and output signals in the common-base circuit are in phase. To illustrate this point, assume the input to the NPN version of the common-base circuit in Figure 2-8, view B is positive. The signal adds to the forward bias because it is applied to the emitter, causing the collector current to increase. This increase in $I_c$ results in a greater voltage drop across the load resistor $R_L$, thus lowering the collector voltage $V_c$. The collector voltage, in becoming less negative, is swinging in a positive direction and is therefore in phase with the incoming positive signal.

The current gain in the common-base circuit is calculated in a method similar to that of the common emitter except that the input current is $I_E$, not $I_B$, and the term “alpha” ($\alpha$) is used in place of beta for gain. Alpha is the relationship of collector current (output current) to emitter current (input current). Alpha is calculated using the formula:

$$\alpha = \frac{\Delta I_c}{\Delta I_e}$$

For example, if the input current ($I_e$) in a common base changes from 1 to 3 mA and the output current ($I_c$) changes from 1 to 2.8 mA, the current gain ($\alpha$) will be 0.90, or:

$$\alpha = \frac{\Delta I_c}{\Delta I_e} = \frac{18 \times 10^{-3}}{2 \times 10^{-3}} = 0.90$$

This is a current gain of less than 1. Because part of the emitter current flows into the base and does not appear as collector current, collector current will always be less than the emitter current that causes it. (Remember that $I_e = I_B + I_c$.) Therefore, alpha is always less than 1 for a common-base configuration.

Many transistor manuals and data sheets only list transistor current gain characteristics in terms of beta. To find alpha when given beta, use the following formula to convert beta to alpha for use with the common-base configuration:

$$\alpha = \frac{\beta}{\beta + 1}$$

To calculate the other gains (voltage and power) in the common-base configuration when the current gain alpha is known, follow the procedures described earlier under the common-emitter section.

**Common-Collector Configuration**

The common-collector configuration shown in Figure 2-8, view C is used mostly for impedance matching. It is also used as a current driver because of its substantial current gain. It is particularly useful in switching circuitry because it has the ability to pass signals in either direction (bilateral operation).

In the common-collector circuit, the input signal is applied to the base-collector, the output is taken from the emitter-collector, and the collector is the element common to both input and output. The common collector has a high input and low output resistance. The input resistance for the common collector ranges from 2 to 500 kilohms, and the output resistance varies from 50 to 1,500 ohms. The current gain is higher than that in the common emitter, but it has a lower power gain than either the
common base or common emitter. Similar to the common base, the output signal from the common collector is in phase with the input signal. The common collector is also referred to as an emitter-follower because the output developed on the emitter follows the input signal applied to the base.

Transistor action in the common collector is similar to the operation explained for the common base, except that the current gain is not based on the emitter-to-collector current ratio, alpha. Instead, it is based on the emitter-to-base current ratio called “gamma” (\(\gamma\)) because the output is taken off the emitter. Because a small change in base current controls a large change in emitter current, it is still possible to obtain high current gain in the common collector. However, because the emitter current gain is offset by the low output resistance, the voltage gain is always less than 1 (unity), exactly as in the electron-tube cathode follower. The common-collector current gain, gamma, is defined as

\[ \gamma = \frac{\Delta I_e}{\Delta I_b} \]

and is related to collector-to-base current gain, beta, of the common-emitter circuit by the formula:

\[ \gamma = \beta + 1 \]

Because a given transistor may be connected in any of three basic configurations, there is a definite relationship, as pointed out earlier, between alpha, beta, and gamma. These relationships are listed again for your convenience:

\[ \alpha = \frac{\beta}{\beta + 1} \quad \beta = \frac{\alpha}{1 - \alpha} \quad \gamma = \beta + 1 \]

Take, for example, a transistor that is listed on a manufacturer’s data sheet as having an alpha of 0.90. We wish to use it in a common-emitter configuration. This means we must find beta. The calculations are:

\[ \beta = \frac{\alpha}{1 - \alpha} = \frac{0.90}{1 - 0.90} = \frac{0.90}{0.10} = 9 \]

A change in base current in this transistor will thus produce a change in collector current that will be 9 times as large. If you wish to use this same transistor in a common collector, you can find gamma by:

\[ \gamma = \beta + 1 = 9 + 1 = 10 \]

To summarize the properties of the three transistor configurations, a comparison chart is provided in Table 2-1 for your convenience.

<table>
<thead>
<tr>
<th>Amplifier Type</th>
<th>Common Base</th>
<th>Common Emitter</th>
<th>Common Collector</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input/Output Phase Relationship</td>
<td>0°</td>
<td>180°</td>
<td>0°</td>
</tr>
<tr>
<td>Voltage Gain</td>
<td>High</td>
<td>Medium</td>
<td>Low</td>
</tr>
<tr>
<td>Current Gain</td>
<td>Low ((\alpha))</td>
<td>Medium ((\beta))</td>
<td>High ((\gamma))</td>
</tr>
<tr>
<td>Power Gain</td>
<td>Low</td>
<td>High</td>
<td>Medium</td>
</tr>
<tr>
<td>Input Resistance</td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td>Output Resistance</td>
<td>High</td>
<td>Medium</td>
<td>Low</td>
</tr>
</tbody>
</table>
Field Effect Transistor Configuration

The largest use of FETs today is in the large-scale integration of computer memory and logic circuits. Inverter circuits most commonly use N-channel MOSFET technology (NMOS), shown in Figure 2-9, view A. In this circuit, a depletion-mode MOSFET is used to load an enhancement-mode MOSFET switching device. The switching device is designated Q and is shown at the bottom of Figure 2-9, view A. The load device is designated L and is shown at the top of Figure 2-9, view A. The grounded arrows indicate that the substrates of both devices are grounded. The two states of the inverter are given in Figure 2-9, view B and are shown in the loaded drain characteristic diagram shown in Figure 2-9, view C.

![Diagram of inverter circuit](image)

**Figure 2-9 — Typical N-channel MOSFET inverter.**

The nature of an inverter circuit is that if the input voltage goes up, the output voltage goes down, and vice versa (Figure 2-9, view B). Considering the circuit of the inverter (Figure 2-9, view B), it can be seen that Q and L are in series between the supply voltage $V_{DD}$ and ground. The load device is always conducting because it is a depletion-mode device and its gate is permanently connected to its source. The switching device may be either conducting or nonconducting, depending on the input signal $V_i$ on its gate terminal. When $V_i$ is positive, electrons are collected in the channel of Q, and it is conducting. When conducting, the channel resistance of Q is much lower than that of L and the output voltage $V_O$ is held just above ground. When $V_i$ is nearly zero, the switching device is not conducting and the conducting channel of L holds $V_O$ just below the positive supply voltage $V_{DD}$. The circuit thus fulfills the criterion for inverter action. This behavior is illustrated in Figure 2-9, view C.

Here, the drain characteristic of the load device is drawn as a nonlinear load line on the drain characteristic curves of the switching device. This load line is marked L. The intersection of the load line with the operating characteristic of the Q device determines the quiescent point of the circuit. For a switching inverter, there are two quiescent points. One, where the Q device is not conducting, is designated A in Figure 2-9, view C, and is called the off-state. The second, where the Q device is conducting, is designated B in Figure 2-9, view C, and is called the on-state. There is a single load line, while there are several curves in the family of the switching characteristics. The reason for this is that the gate of the load device is connected to its source and cannot change its voltage relative to
the source, whereas the gate of the switching device can take on any value of input (gate-source) voltage. In the circuit shown, however, the Q device gate voltage moves between the limits of zero and +VDD. Some intermediate gate voltage curves are shown as a reminder that there are a multiplicity of states of the inverter between the off-state and the on-state, and that considerable power may be dissipated during the switching process. The off-state (A) has negligible standby power drain. The on-state (B) dissipates typically about 0.1 mW. The switching time ratio (pull-up time to pull-down time) is about 4 to 1, and the total switching delay time of a pair of inverters is approximately 20 nanoseconds.

In small-scale integrated circuit chip components, it is customary to use complementary MOSFET devices (CMOS). In such circuits, both N- and P-channel devices are used together, one as the load of the other. The use of complementary devices this way greatly reduces standby power to about 10 nanowatts.

**Thyristors**

A semiconductor thyristor is a three-terminal semiconductor switching device with separate input (control) and output (load) circuits. Relatively low control current causes the output section of the thyristor to be turned on, allowing high current to flow in the load. Once the device is turned on, the input section no longer has control of the device. Turn-off is controlled only by the output circuit supply voltage. The two major components in the thyristor family are the silicon-controlled rectifier and the bidirectional triode ac switch. Thyristors are generally called ac switches and are used in a variety of power applications. Whereas diodes use two alternate layers of PN-type semiconductor material and transistors use three such layers, thyristor devices use four layers, forming three or more junctions within a slice of silicon semiconductor material. Thyristor devices exhibit regenerative, or latching-type, switching action in one or two quadrants of their volt-ampere characteristic. They can be switched into the on state (conducting condition) but must usually be restored to their off state (voltage-blocking condition) by circuit action.

**Silicon-Controlled Rectifier**

The silicon-controlled rectifier (SCR), is one of the family of semiconductors that includes transistors and diodes. A drawing of an SCR and its schematic representation is shown in *Figure 2-10, views A and B*. Not all SCRs use the casing shown, but this example is typical of most of the high-power units.

Although it is not the same as either a diode or a transistor, the SCR combines features of both. Circuits using transistors or rectifier diodes may be greatly improved in some instances through the use of SCRs.

![Silicon-Controlled Rectifier Diagram](image-url)
The basic purpose of the SCR is to function as a switch that can turn on or off small or large amounts of power. It performs this function with no moving parts that wear out and no points that require replacing. There can be a tremendous power gain in the SCR. In some units, a very small triggering current is able to switch several hundred amperes without exceeding its rated abilities. The SCR can often replace much slower and larger mechanical switches. It even has many advantages over its more complex and larger electron-tube equivalent, the thyratron.

The SCR is an extremely fast switch. It is difficult to cycle a mechanical switch several hundred times a minute, yet some SCRs can be switched 25,000 times a second. It takes just microseconds (millionths of a second) to turn on or off these units. Varying the time that a switch is on as compared to the time that it is off regulates the amount of power flowing through the switch. Because most devices can operate on pulses of power (alternating current is a special form of alternating positive and negative pulse), the SCR can be used readily in control applications. Motor-speed controllers, inverters, remote switching units, controlled rectifiers, circuit overload protectors, latching relays, and computer logic circuits all use the SCR. The SCR is made up of four layers of semiconductor material, arranged PNPN. The construction is represented in Figure 2-11, although the regions are not drawn to scale. In function, the SCR has much in common with a diode, but the theory of operation of the SCR is best explained in terms of transistors.

Consider the SCR as a transistor pair, one PNP and the other NPN, connected as shown in Figure 2-12. The anode (A) is attached to the upper p-layer; the cathode (C) is part of the lower n-layer; and the gate terminal (G) goes to the p-layer of the NPN triode.

In operation, the collector of Q2 drives the base of Q1, while the collector of Q1 feeds back to the base of Q2. Beta 1 (β1) is the current gain of Q1, and beta 2 (β2) is the current gain of Q2. The gain of this positive feedback loop is their product, β1 times β2. When the product is less than 1, the circuit is stable; if the product is greater than unity, the circuit is regenerative. A small negative current applied to terminal G will bias the NPN transistor into cutoff, and the loop gain is less than unity. Under these conditions, the only current that can exist between output terminals A and C is very high.
When a positive current is applied to terminal G, transistor Q2 is biased into conduction, causing its collector current to rise. Because the current gain of Q2 increases with increased collector current, a point (called the breakover point) is reached where the loop gain equals unity and the circuit becomes regenerative. At this point, collector current of the two transistors rapidly increases to a value limited only by the external circuit. Both transistors are driven into saturation, and the impedance between A and C is very low. The positive current applied to terminal G, which served to trigger the self-regenerative action, is no longer required because the collector of PNP transistor Q1 now supplies more than enough current to drive Q2. The circuit will remain on until it is turned off by a reduction in the collector current to a value below that necessary to maintain conduction.

The characteristic curve for the SCR is shown in Figure 2-13. With no gate current, the leakage current remains very small as the forward voltage from cathode to anode is increased until the breakdown point is reached. Here the center junction breaks down, the SCR begins to conduct heavily, and the drop across the SCR becomes very low.

![Figure 2-13 — Characteristic curve for an SCR.](image)

The effect of a gate signal on the firing of an SCR is shown in Figure 2-14. Breakdown of the center junction can be achieved at speeds approaching a microsecond by applying an appropriate signal to the gate lead while holding the anode voltage constant. After breakdown, the voltage across the device is so low that the current through it from cathode to anode is essentially determined by the load it is feeding.

The important thing to remember is that a small current from gate to cathode can fire or trigger the SCR, changing it from practically an open circuit to a short circuit. The only way to change it back again (to commutate it) is to reduce the load current to a value less than the minimum forward-bias current. Gate current is required only until the anode current has completely built up to a point sufficient to sustain conduction (about 5 microseconds in resistive-load circuits). After conduction from cathode to anode begins, removing the gate current has no effect.

The applications of the SCR as a rectifier are many. The multiple applications as a rectifier give the SCR its name. When alternating current is applied to a rectifier, only the positive or negative halves of the sine wave flow through. All of each positive or negative half cycle appears in the output. When an SCR is used, however, the controlled rectifier may be turned on at any time during the half cycle, thus controlling the amount of dc power available from zero to maximum, as shown in Figure 2-15. Because the output is actually dc pulses, suitable filtering can be added if continuous direct current is
needed. Thus, any dc-operated device can have controlled amounts of power applied to it. Notice that the SCR must be turned on at the desired time for each cycle.

When an ac power source is used, the SCR is turned off automatically because current and voltage drop to zero every half cycle. By using one SCR on positive alternations and one on negative, full-wave rectification can be accomplished, and control is obtained over the entire sine wave. The SCR serves in this application just as its name implies—as a controlled rectifier of ac voltage.

Anode voltage applied to the SCR significantly in excess of the voltage rating of the SCR can trigger the device into conduction, even in the absence of a gate signal. Excess reverse voltage, however, can permanently damage the SCR, such as in the case of the silicon junction diode. SCRs, similar to the junction diode and all power semiconductors, have a failure mechanism called “thermal fatigue.” Thermal fatigue failure is due to the thermal stresses induced during repetitive temperature changes occurring in the normal operation of the device. These stresses are inherent in all devices undergoing substantial temperature

Figure 2-14 — SCR characteristic curve with various gate signals.

Figure 2-15 — SCR gate control signals.
changes that contain dissimilar metals. When power semiconductors, such as rectifier diodes and SCRs, are properly applied to take into account their thermal fatigue limitations, they can be expected to perform their function faultlessly for the life of the equipment in which they are used.

Current ratings of SCRs range from under 1 to 5,000 amperes. Blocking voltage capability of commercially available devices typically extends to 4,400 V for the higher power types, with voltages up to 6 kilovolts (kV) having been achieved.

Like most semiconductor devices, SCRs are dependent on temperature in some of their characteristics. Usual operating junction temperatures are 125 degrees Celsius (°C) (257 degrees Fahrenheit [°F]), and some devices are available up to 150 °C (302 °F).

The mounting considerations for SCRs are similar to those for diodes. Small devices handling between 2-4 amps are lead-mounted to radiating fins or some type of heat sink for adequate cooling of the semiconductor junction.

Manufacturing techniques used in SCRs are similar to those of silicon diodes. In addition to alloy and diffusion processing technology, epitaxial processing is sometimes used. In small devices, a planar structure, such as that developed for signal transistors and monolithic integrated circuits, is used. Higher power SCR structures are of a mesa type of construction, with the edges of the pellet often shaped in a manner to reduce the surface field across the blocking junction for higher voltage-blocking capability.

**Triode for Alternating Current**

For specialized ac-switching power control, such as in lamp dimmers and heating controls, the bidirectional triode thyristor, popularly called the triode-alternating current (TRIAC), is in widespread use.

The TRIAC is a three-terminal device similar in construction and operation to the SCR. The TRIAC controls and conducts current flow during both alternations of an ac cycle instead of only one. The schematic symbols for the SCR and the TRIAC are compared in Figure 2-16. Both the SCR and the TRIAC have a gate lead. However, in the TRIAC, the lead on the same side as the gate is main terminal 1, and the lead opposite the gate is main terminal 2. This method of lead labeling is necessary because the TRIAC is essentially two SCRs back to back, with a common gate and common terminals.

Each terminal is, in effect, the anode of one SCR and the cathode of another, and either terminal can receive an input. In fact, the functions of a TRIAC can be duplicated by connecting two actual SCRs, as shown in Figure 2-17. The result is a three-terminal device identical to the TRIAC. The common anode-cathode connections form main terminals 1 and 2, and the common gate forms terminal 3.
The difference in current control between the SCR and the TRIAC can be seen by comparing their operation in the basic circuit, shown in Figure 2-18. In the circuit shown in Figure 2-18, view A, the SCR is connected in the familiar halfwave arrangement. Current will flow through the load resistor (R_L) for one alternation of each input cycle. Diode CR1 is necessary to ensure a positive trigger voltage.

In the circuit shown in Figure 2-18, view B with the TRIAC inserted in the place of the SCR, current flows through the load resistor during both alternations of the input cycle. Because either alternation will trigger the gate of the TRIAC, CR1 is not required in the circuit. Current flowing through the load will reverse direction for half of each input cycle. To clarify this difference, a comparison of the waveforms seen at the input, gate, and output points of the two devices is shown in Figure 2-19.

**Thyristor Variants**

Thyristors come in a variety of specialized applications. Among them are the asymmetrical silicon-controlled rectifier (ASCR), reverse-conducting thyristor (RCT), and gate turn-off (GTO) devices shown in Figure 2-20.

These devices are all in the thyristor family and are mainly used in place of SCRs in power circuits requiring operation from a dc source. The ASCR (Figure 2-20, view A) and RCT (Figure 2-20, view B) have the advantage of faster turn-off time than the SCR and thus require a less costly auxiliary circuit to effectively turn-off. The RCT has an added circuit advantage because it has a built-in reverse rectifier diode in parallel with the device. (The RCT is the integrated equivalent of a discrete ASCR in
Along with faster turn-off times, the ASCR and RCT devices have lower forward-voltage drops for comparable forward-blocking voltage ratings and silicon area, thus increasing the device’s efficiency.

The GTO (Figure 2-20, view C), is also a thyristor. Like the SCR, it is a symmetrical reverse-blocking triode thyristor (unlike the ASCR and RCT, which cannot block reverse voltages), but it has the added advantage of being able to turn off current when a negative signal is applied to the gate. Thus, the GTO does not require an auxiliary circuit to communicate it off as do the SCR, ASCR, and RCT devices.

It is necessary to operate thyristors from a dc supply in order to achieve power conversion from the dc (battery or rectified ac line) supply to a load requiring an alternating supply (dc to ac inversion) or to a load requiring a variable-voltage dc supply (dc to dc conversion). Because the rate of switching the thyristors in dc circuits can be varied by the control circuit, a thyristor inverter circuit can supply ac load with a variable frequency. An important application of this mode of operation is for adjustable speed operation of ac synchronous and induction motors.
A battery source can be converted to a variable-voltage dc source for a dc motor by “chopping” the dc source voltage either at a variable rate at constant pulse width (frequency power modulation) or by operating the chopper circuit at a constant frequency and varying the pulse width (pulse-width power modulation).

### INTEGRATED CIRCUITS

Miniature electronic circuits are produced within and upon a single semiconductor crystal, usually silicon. Integrated circuits range in complexity, from simple logic circuits and amplifiers to large-scale applications containing millions of transistors and other components that provide computer memory circuits and complex logic subsystems, such as microcomputer central processor units.

Integrated circuits are the primary components of most electronic systems. Their low cost, high reliability, and speed have been essential in advancing and miniaturizing the use of digital computers. Microcomputers have spread the use of computer technology to instruments, personal electronic devices, automobiles, and other equipment. For analog signal processing, integrated subsystems such as frequency modulated stereo demodulators and switched-capacitor filters have been developed to bridge the digital divide.

Integrated circuits consist of the combination of active electronic devices, such as transistors and diodes, with passive components, such as resistors and capacitors, within and upon a single semiconductor crystal. The construction of these elements within the semiconductor is achieved through the introduction of electrically active impurities into well-defined regions of the semiconductor. The fabrication of integrated circuits thus involves such processes as vapor-phase deposition of semiconductors and insulators, oxidation, solid-stage diffusion, ion implantation, and vacuum deposition.

Generally, integrated circuits are not straight-forward replacements of electronic circuits assembled from discrete components. They represent an extension of the technology by which silicon planar transistors are made. For this reason, transistors or modifications of transistor structures are the primary devices of integrated circuits. Methods of fabricating good-quality resistors and capacitors have been devised. However, the third major type of passive component, inductors, must be simulated with complex circuitry or added to the integrated circuit as discrete components.

Simple logic circuits were the easiest to adapt to these design changes. The first of these circuits, such as inverters and gates, were produced in the early 1960s primarily for miniaturization of missile guidance computers and other aerospace systems. Analog circuits, called linear integrated circuits, did not become commercially practical until several years later because of their heavy dependence on passive components, such as resistors and capacitors. Today, integrated circuits are everywhere, including in the Common Access Card you may be using to access this course.

### Types of Integrated Silicon Circuits

Basically, there are two general classifications of integrated circuits: monolithic and hybrid. In the monolithic integrated circuit, all elements (resistors, transistors, and so forth) associated with the circuit are fabricated inseparably within a continuous piece of material (called the substrate), usually silicon. The monolithic integrated circuit is made very much like a single transistor. While one part of the crystal is being doped to form a transistor, other parts of the crystal are being acted upon to form the associated resistors and capacitors. Thus, all the elements of the complete circuit are created in the crystal by the same processes and in the same time required to make a single transistor. This process results in a considerable cost savings over the same circuit made with discrete components by lowering assembly costs. A typical packaging sequence is shown in Figure 2-21.
Hybrid integrated circuits are constructed somewhat differently from the monolithic devices. The passive components (resistors and capacitors) are deposited onto a substrate (foundation) made of glass, ceramic, or other insulating material. Then the active components (diodes and transistors) are attached to the substrate and connected to the passive circuit components on the substrate using very fine (.001 inch) wire. The term “hybrid” refers to the fact that different processes are used to form the passive and active components of the device. Hybrid circuits are of two general types: (1) thin film and, (2) thick film. Thin and thick film refers to the relative thickness of the deposited material used to form the resistors and other passive components. Thick film devices are capable of dissipating more power, but are somewhat more bulky. Integrated circuits are being used in an ever-increasing variety of applications. Small size and weight and high reliability make them ideally suited for use in airborne equipment, missile systems, computers, spacecraft, and portable equipment. They are often easily recognized because of the unusual packages that contain the integrated circuit. These tiny packages protect and help dissipate heat generated in the device. One of these packages may contain one or several stages, often having several thousand components. Some of the most common package styles are shown in Figure 2-22.

The design of the circuits within these packages provides further classification into two sub-groups. Bipolar, when the principal element is the bipolar junction transistor, and linear when the principle element is the metal oxide semiconductor (MOS) transistor. Both depend upon the construction of a desired pattern of electrically active impurities within the semiconductor body, and upon the formation of an interconnection pattern of metal films on the surface of the semiconductor.
Bipolar circuits are generally used where highest logic speed is desired, and MOS for largest-scale integration or lowest power dissipation. Additionally, MOS ICs are simpler to fabricate and more cost effective. Linear circuits are mostly bipolar, but MOS devices are used extensively in switched-capacitor filters.

**Bipolar Circuits**

A simple bipolar inverter circuit using a diffused resistor and an NPN transistor is shown in Figure 2-23, view A. The input voltage $V_{in}$ is applied to the base of the transistor. When $V_{in}$ is zero or negative with respect to the emitter, no current flows. As a result, no voltage drop exists across the resistor, and the output voltage $V_{out}$ will be the same as the externally applied biasing voltage, +5 volts in this example shown in Figure 2-23, view B. When a positive input voltage is applied, the transistor becomes conducting. Current now flows through the transistor, hence through the resistor; as a result, the output voltage decreases. Thus, the change in input voltage appears inverted at the output. The change in the output voltage occurs slightly later than the change in the input voltage. This time difference, called propagation delay, is an important characteristic of all integrated circuits. Much effort has been spent on reducing it, and values less than one-billionth of a second have been achieved.

Most simple digital circuits can be fabricated, much as the inverter circuit described above. As an example, a photomicrograph of an early logic gate circuit is shown in Figure 2-24. This circuit is one of the earliest digital integrated circuits. For comparison, the field-programmable gate array shown in Figure 2-25 contains up to 1,124,022 gates, 51,000 slices, and 16 megabits of integrated block memory on a 5-layer 0.22 micrometer CMOS process, surface-mounted package.
This tendency toward increased complexity is dictated by the economics of integrated circuit manufacturing. Because of the nature of this manufacturing process, all circuits on a slice are fabricated together. Consequently, the more circuitry accommodated on a slice, the cheaper the circuitry becomes. Because testing and packaging costs depend on the number of chips, it is desirable, to keep costs down, to crowd more circuitry onto a given chip rather than to increase the number of chips on a wafer.

Linear Circuits

Integrated circuits based on amplifiers are called “linear” because amplifiers usually exhibit a linearly proportional response to input signal variations. However, the category includes memory sense amplifiers, combinations of analog and digital processing functions, and other circuits with nonlinear characteristics. Some digital and analog combinations include analog-to-digital converters, timing controls, and data communications modulator-demodulator units (modems).

A long-standing drawback in these circuits was the lack of inductors for tuning and filtering. That shortcoming was overcome by the use of resistor-capacitor networks and additional circuitry. For low-frequency circuits, the resistor in these networks is being replaced by the switched capacitor. At the higher frequencies, an oscillator-based circuit known as the phase-locked loop provides a general-purpose replacement for inductors in applications such as radio transmission demodulation.

At first, the development of linear circuits was slow because of the difficulty of integrating passive components, and also because of undesirable interactions between the semiconductor substrate and the operating components. Thus, much greater ingenuity was required to design and use the early linear circuits.

In addition, manufacturing economics favors digital circuits. A computer can be built by repetitious use of simple inverters and gates, while analog signal processing requires specialized linear circuits.
MOS Circuits

The other major class of integrated circuits is called MOS because its principal device is a MOSFET. It is more suitable for very large-scale integration (VLSI) than bipolar circuits because MOS transistors are self-isolating and can have an average size of less than a millionth of a square inch \((5 \times 10^{-5})\). This technological advance has made it practical to use over 1 million transistors per circuit. Because of this high-density capability, MOS transistors are used for high-density, random-access memories (RAMs), read-only memories (ROMs), and microprocessors. An example of radiation-hardened RAM is shown in Figure 2-26.

Several types of MOS device fabrication technologies have been developed. Among them are (1) metal-gate P-channel MOS (PMOS), which uses aluminum for electrodes and interconnections; (2) silicon-gate P-channel MOS, employing polycrystalline silicon for gate electrodes and the first interconnection layer; (3) NMOS, which is usually silicon gate; and (4) CMOS, which employs both P- and N-channel devices. NMOS and CMOS became the dominant technologies, with CMOS using silicon gates and becoming the most attractive for new designs. Both conceptually and structurally, the MOS transistor is a much simpler device than the bipolar transistor. In fact, its principle of operation has been known since the late 1930s, and the research effort that led to the discovery of the bipolar transistor was originally aimed at developing the MOS transistor. This simple device was kept from commercial use until 1964 because it depends on the properties of the semiconductor surface for its operation, while the bipolar transistor depends principally on the bulk properties of the semiconductor crystal. Hence, MOS transistors became practical only when understanding and control of the properties of the oxidized silicon surface had been perfected to a great degree. While the basic technical knowledge has been around for years, advances in manufacturing processes and materials have made MOS technology extraordinarily effective in the electronic world.

CMOS Circuits

A simple CMOS inverter is shown in Figure 2-27, view A, and a circuit schematic is shown in Figure 2-28, view A. The gates of the N- and P-channel transistors are connected together as are the drains. The common gate connection is the input node, while the common drain connection is the output node. A capacitor is added to the output node to model the loading expected from the subsequent stages on typical circuits.

When the input node is in the “low state,” at 0 V (Figure 2-27, view B), the N-channel gate-to-source voltage is 0 V, while the P-channel gate-to-source voltage is -5 V. The N-channel transistor requires a positive gate-to-source voltage, which is greater than the transistor threshold voltage (typically 0.5-1 V), before it will start conducting current between the drain and source. Thus, with a 0 V gate-to-source voltage, it will be off and no current will flow through the drain and source regions. The P-channel transistor, however, requires a negative voltage between the gate and source, which is less than its threshold voltage (typically -0.5 to -1.5 V). The -5 volt gate-to-source potential is clearly less
than the threshold voltage, and the P-channel will be turned on, conducting current from the source to the drain, and thereby charging up the loading capacitor. Once the capacitor is charged to the “high state” at 5 V, the transistor will no longer conduct because there will no longer be a potential difference between the source and drain regions.

When the input is now put to the high state at 5 V (*Figure 2-27, view C*), just the opposite occurs. The N-channel transistor will be turned on, while the P-channel will be off allowing the load capacitor to discharge through the N-channel transistor. The resulting in the output voltage drops from a high state at 5 V to a low state at 0 V. Again, once there is no potential difference between the drain and source (capacitor discharged to 0 V), the current flow will stop, and the circuit will be stable.

*Figure 2-27 — CMOS inverter cross-section.*
This simple circuit illustrates an important feature of CMOS circuits. Once the loading capacitor has been either charged to 5 V or discharged back to 0 V (Figure 2-28, view B), there is no current flow, and the standby power is very low. This simplicity is the reason for the high popularity of CMOS for battery-based systems. None of the other MOS technologies offers this feature without complex circuit techniques, and even then, they will typically not match the low standby power of CMOS. The bipolar circuits discussed above require even more power than these other MOS technologies. The additional fabrication steps required (10 to 20 percent more) are the price for CMOS’s lower power, compared to NMOS.

**Sampled-Data Device Circuits**

In addition to the digital logic applications discussed above with the simple CMOS inverter circuit, MOS devices also offer unique features for some analog circuit applications. These features include signal-processing applications that are based on sampled-data techniques. The charge-coupled device (CCD) is such an application.

In CCDs, the stored charge at the semiconductor surface can also be made to propagate along the surface via potential wells created by a series of these MOS structures. You may have noticed digital camera manufacturers advertise CCD pixel count as an indication of image quality.

Digital cameras incorporate an electronic component known as an image sensor. In most digital cameras, that sensor is a CCD that converts light into current. CCD sensors are made up of tiny components known as pixels. Each pixel is actually a photodiode that is sensitive to the intensity of the light that it comes in contact with and passes a corresponding amount of current to a processor that converts that signal into a digital image.

**Transistor-Transistor Logic Devices**

Perhaps the best-known and most widely used implementation of logic switches is the bipolar TTL. Shown schematically in Figure 2-29, the basic TTL not AND (NAND) gate (turned on only if one input is low) is formed by a multi-emitter transistor, followed by an output transistor that acts as a pull-up/buffer. Thus, the first transistor performs an AND (turned on when all inputs are high) operation on the inputs, and the second transistor completes the NAND by performing an inversion.
TTL transistors are operated in the saturation mode; in other words, the transistors are driven hard to either the cutoff or the saturation limits. This overdriving introduces a time delay that does not exist if the transistors are operated in the non-saturated mode. Such non-saturating logic, while inherently faster, is more susceptible to noise because it is biased in the linear region.

The 7400 designation is a family of TTL devices that has a useful temperature range of 0 to 70 °C. Military-grade equipment required a greater range to handle the extreme temperature variations, and the 5400 series was developed that operated in the -55 to +125 °C range. Typical numbering systems for military- and commercial-grade TTL are shown in Table 2-2.

Several varieties of TTL have specific and special uses. Table 2-2 lists the military and commercial identifiers.

<table>
<thead>
<tr>
<th>Types</th>
<th>-55° to +125°C</th>
<th>0° to +70°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regular</td>
<td>5400</td>
<td>7400</td>
</tr>
<tr>
<td>High-Power</td>
<td>54H00</td>
<td>74H00</td>
</tr>
<tr>
<td>Low-Power</td>
<td>54L00</td>
<td>74L00</td>
</tr>
<tr>
<td>Schottky</td>
<td>54S00</td>
<td>74S00</td>
</tr>
<tr>
<td>Low-Power</td>
<td>54LS00</td>
<td>74LS00</td>
</tr>
</tbody>
</table>

**Regular TTL**

Regular TTL is normally the widest available and the lowest priced type of TTL, and it has by far the greatest variety and second-sourcing. A typical gate-propagation time is 10 nanoseconds, the time it takes for a logic change at a gate input to appear as a logic change on the output. Typical TTL requires around 10 milliwatts per gate with counting flip-flops operating at speeds of 40 MHz and higher.
Low-Power TTL

Low-power TTL exchanges power consumption for speed and is identified by an “L” in the part number. For instance, a 74L00 is a low-power, commercial version of the 7400 regular TTL NAND gate. There is roughly a 10:1 tradeoff in the low-power version, one-tenth the speed to counters at one-tenth the power, although the simpler gates run one-fourth the speed on one-tenth the power. Flip-flops and counters have a maximum toggle frequency of 3 MHz or so. Within the low-power subfamily, the output-drive remains 10, but a low-power TTL gate can drive only one regular TTL gate. While the 54L00 and 74L00 series TTL do offer low-power consumption, their advantages are preempted by the CMOS logic families.

High-Power TTL

The high-power TTL devices are designated with an “H” in the part number; 74H00 is the equivalent of a 7400 gate, and so on. Typically, you get twice the speed for twice the power. Counters are good to 50 MHz. Within the high-power subfamily, the output-drive remains at 10, but the input is typically 1.3 times regular TTL loads. Thus, a regular TTL gate can drive at most only seven high-power TTL inputs. High-power TTL is normally handled by the Schottky TTL, which is faster and draws less supply power. Quite a few high-power devices remain available. One advantage they do have over the Schottky devices is that the outputs are “electrically quieter,” a handy feature in high-speed digital-to-analog converters.

Schottky TTL

Schottky TTL is an improved version of TTL that has a better speed/power tradeoff than the older types. To do this, Schottky diodes (a fast diode with a 0.3-volt forward drop) are placed across most of the transistors in the basic TTL gate. This arrangement prevents the transistors from saturating, and thus eliminates any storage-time delays inside the transistors. The part numbers have an “S” in them, as in 74S00. Propagation delays of 3 nanoseconds are combined with flip-flops that can run at 125 MHz.

Where high speed is essential, Schottky TTL is a logical choice. Its competitor is the emitter-coupled logic (ECL) families that in general are much faster, but considerably more difficult to use.

A high-speed, unsaturated logic family, such as Schottky TTL, presents serious restrictions in the type and quality of test equipment you must have to work with it intelligently. A 60 MHz triggered oscilloscope is essential, and a 120 MHz oscilloscope is preferable. As might be expected, Schottky devices are much more critical as to layouts and supply decoupling than ordinary TTL because of their higher speed. Nevertheless, where high speed is essential, they are often the simplest solution to system problems in the 30 to 120 MHz range.

Low-Power Schottky TTL

Devices such as the 74LS00 are emerging as a more recent variation on TTL. The low-power Schottky TTL family is slightly faster than regular TTL but requires only one-fifth the power. It does this by using the Schottky diodes to eliminate storage-time effects, but then raises the circuit impedance levels to slow things down to normal and pick up power savings. For many applications, this capability represents a near-optimum combination of values.

Emitter-Coupled Logic Devices

The basic ECL gate, shown in Figure 2-30, is composed of current-steering transistors that perform an operation on the inputs. Typically, the gate output is amplified by an emitter-follower transistor, and both the true and complement signals can be made available with no added delays at the output. This circuit makes the switching of the transistors very fast by never allowing them to turn all the way on, a
condition known as saturation, resulting in propagation delays of less than 1 nanosecond. This configuration is not normally used in large, complex chips due to its characteristic of drawing large amounts of current, which produces large power dissipation.

**Types of Integrated Gallium Arsenide Circuits**

Integrated circuits based on gallium arsenide (GaAs) have been in use since the late 1970s. Gallium arsenide is a compound made up of the elements gallium and arsenic. While gallium is not generally considered toxic, arsenic, alone, is highly poisonous. GaAs has several advantages over silicon. It is relatively insensitive to heat, resistant to radiation, and versatile, with applications ranging from logic devices to solar panels.

The major advantage of these GaAs circuits is their fast switching speed.

**Gallium Arsenide FET**

The gallium arsenide field-effect transistor (GaAs FET) is a majority carrier device in which the cross-sectional area of the conducting path of the carriers is varied by the potential applied to the gate (Figure 2-31, view A). Unlike the MOSFET, the gate of the GaAs FET is a Schottky barrier composed of metal and GaAs. Because of the difference in work functions of the two materials, a junction is formed. The depletion region associated with the junction is a function of the difference in voltage of...
the gate and the conducting channel, and the doping density of the channel. By applying a negative voltage to the gate, the electrons under the gate in the channel are repelled, extending the depletion region across the conducting channel. The variation in the height of the conducting portion of the channel caused by the change in the extent of the depletion region alters the resistance between the drain and source. Thus, the negative voltage on the gate modulates the current flowing between the drain and the source (Figure 2-31, view B), as shown by the linear region of operation in Figure 2-31, view C. As the height of the conducting channel is decreased by the gate voltage or as the drain voltage is increased, the velocity of charge carriers (electrons for N-type GaAs) under the gate increases (similar to water in a hose when its path is constricted by passing through the nozzle). The velocity of the carriers continues to increase with increasing drain voltage, as does the current, until their saturated velocity is obtained (about \(10^7\) centimeter per second or \(3 \times 10^5\) feet per second for GaAs). At that point, the device is in the saturated region of operation; that is, the current is independent of the drain voltage.

The high-frequency operation of a device is limited by the transit time of the carriers under the gate. The time during which the velocity of electrons (output signal) is modulated by the voltage on the gate (input signal) must be short compared to any change of the input voltage. Because electrons in gallium arsenide have a high saturated velocity, GaAs FETs operate at very high frequencies. The high-frequency performance is also improved by decreasing the gate length (the length of the path of the electrons under the gate) by using special lithographic techniques to define the gate during processing. GaAs FETs with gate lengths as short as 0.1 micrometer (\(\mu\)m) \((4 \times 10^{-5}\) in\) have been fabricated, resulting in a potential frequency of operation of approximately 100 gigahertz (GHz).

As noted above, the major advantage of gallium arsenide integrated circuits over silicon integrated circuits is the faster switching speed of the logic gate. The reason for the improvement of the switching speed of GaAs FETs with short gate lengths (less than 1 \(\mu\)m or \(4 \times 10^{-5}\) in) over silicon FETs of comparable size has been the subject of controversy. In essence, the speed or gain-bandwidth product of a FET is determined by the velocity with which the electrons pass under the gate. The saturated drift velocity of electrons in gallium arsenide is twice that of electrons in silicon; therefore, the switching speed of gallium arsenide might be expected to be only twice as fast.

However, this simplified model neglects several important aspects of the problem. One way to determine the switching speed of a logic circuit is to calculate the total capacitance that must be charged or discharged as the logic level is switched, and the current drive available. The larger the current drive and the smaller the capacitance, the faster the switching speed. Because gallium arsenide integrated circuits are fabricated on semi-insulating substrates, the parasitic capacitance to ground is much smaller than for silicon integrated circuits. The only comparable small-capacitance silicon technology is CMOS/SOS (silicon on sapphire). Also, because of the higher mobility, the transconductance of a GaAs FET is much higher than for a silicon FET, and the associated parasitic resistances are lower. Thus, there is more current change for a given amount of input voltage. Finally, the mobility of gallium arsenide is six to eight times that of silicon, and even though the saturated velocities of gallium arsenide and silicon are within a factor of 2, the electrical field necessary for the carriers to reach velocity saturation in gallium arsenide (about 4 kV/cm) is much less than in silicon (about 40 kV/cm). Therefore, when operating at the low voltages typical of GaAs FETs, similar gallium arsenide and silicon FETs have a speed ratio that is approximately proportional to their low-field mobilities. At higher voltages, the speed ratio decreases because the carrier velocity (current) continues to increase in silicon, whereas the carriers are saturated in gallium arsenide; however, this increase in speed is at the expense of increased power dissipation. This effect explains the experimental results plotted in Figure 2-32, where the power-delay products of silicon and gallium arsenide inverters with 1 \(\mu\)m gate length \((4 \times 10^{-5}\) in\) FETs are plotted as functions of power dissipation. There are several device choices for high-speed gallium arsenide integrated circuits, each with certain advantages and disadvantages.
Depletion-Mode FET

Depletion-mode FET (DFET) is the most mature of the device technologies (Figure 2-33). The DFET has the largest current drive capacity per unit device width for an all GaAs FET devices. This capacity contributes to its high speed and high power dissipation. The pinchoff voltage of the DFET is determined by the channel doping and thickness under the Schottky barrier gate. This voltage can be made quite large (about –2.5 V) in order to improve the noise immunity of logic gates in which they are used.

Enhancement-Mode FET (ENFET)

This low-current, low-power device is realized by increasing the pinchoff voltage to zero or above. The logic swing for the enhancement-mode FET (ENFET) is limited to the difference between the pinchoff voltage (approximately 0 V) and the forward turn-on voltage of the Schottky barrier gate (approximately +0.5 V), thus providing a significantly lower noise immunity for logic gates using ENFETs. The realization of medium-scale integration (MSI) and large-scale integration (LSI) chips in which the noise margins are small requires stringent process controls to fabricate devices across the wafer with small variations in pinchoff voltage.

Enhancement-Mode Junction FET (E-JFET)

In this device, the Schottky barrier of the ENFET is replaced with an implanted p region that forms a PN junction for the gate (Figure 2-34). The enhancement-mode junction FET (E-JFET) has all the advantages of the ENFET with respect to low power, plus the additional advantage of a slightly larger logic swing due to the larger turn-on voltage of the PN junction. The ultimate speed of the E-JFET will be less than an ENFET of similar dimensions because the added side wall gate capacitance of the PN-junction gate is a significant fraction of the total gate capacitance at sub-micrometer gate lengths.
LOGIC GATE CONFIGURATIONS

Three different logic gate configurations (Figure 2-35) are presently the most popular approaches to high-speed gallium arsenide logic circuits. The buffered-FET logic (BFL) gate (Figure 2-35, view A) is the fastest gate for reasonable fan-outs (the number of identical logic gates it must drive) but dissipates the most power (approximately 5 to 10 mW per gate). The Schottky diode FET logic (SDFL) gate (Figure 2-35, view B) dissipates about one-fifth the power of the BFL; however, it is slower by about a factor of 2. Finally, direct-coupled FET logic (DCFL) gates (Figure 2-35, view C) using ENFETs have the lowest power consumption (about 50 μW per gate) at gate delays two to four times those of BFL for complex logic circuits.

The BFL gate using DFETs requires level shifting to make the input and output logic levels compatible. This extra circuitry adds both delay to the switching time of the gate and extra power consumption; however, it provides buffering to the next stage, and therefore, has very good fan-out and on-off chip drive capabilities. Because of the high power dissipation and the huge device count per gate, BFL will not be suitable for circuits with the complexity of LSI (greater than 1,000 gates).
The SDFL gate incorporates very small Schottky barrier diodes to perform the input logical OR (high output if either input is high) function and to provide level shifting. The invert function is performed by the DFETs in the second stage. Because of the lower power dissipation and small diodes, packing densities of more than 1,000 gates/mm² (645,000 gates/in²) are achievable. Large fan-in (number of inputs a logic gate can handle) does not require any significant chip area because of the small diodes; however, SDFL gates are extremely fan-out sensitive, and for fan-outs (number of outputs a logic gate can feed) of greater than three, either buffers or much wider DFETs must be incorporated to maintain the speed. Because of the medium power dissipation and high packing density, SDFL is suitable for large-scale integration applications, but not for circuits with the complexity of very large-scale integration (VLSI) (more than 10,000 gates).

DCFL incorporating ENFETs is inherently much simpler than BFL or SDFL because there is no need for level shifting. The very low power consumption and circuit simplicity lead to high packing density (more than 5,000 gates/mm² or $3.2 \times 10^6$ gates/in²) at only slightly slower speeds.

Table 2-3 lists the projected applications for each of the three logic gates, along with the competing silicon technology.

<table>
<thead>
<tr>
<th>Gallium Arsenide Technology</th>
<th>Applications</th>
<th>Feasibility Issues</th>
<th>Competing Silicon Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buffered Field Effect Transistor logic (BFL)</td>
<td>Small-Scale Integration (SSI), Medium-Scale Integration (MSI), superfast logic-prescalers, multiplexers, demultiplexers, fast cache memory</td>
<td>Most producible, uses large logic swings with good noise margins; tolerant of FET threshold variations; least area efficient</td>
<td>Emitter-coupled logic (ECL) and submicrometer Metal Oxide Semiconductor (MOS)</td>
</tr>
<tr>
<td>Schottky diode FET logic (SSDFL)</td>
<td>High-speed large-scale integration (LSI), for example, $8 \times 8$ multiplexer; arithmetic-logic unit (ALU), gate arrays</td>
<td>Replaces FETs with diodes for logic function; usually smaller noise margin than BFL, but still fairly tolerant of threshold variations; circuit design complicated by fan-out sensitivity</td>
<td>Bipolar LSI; 1 μm MOS LSI</td>
</tr>
<tr>
<td>Direct-Coupled FET logic (DCFL)</td>
<td>Low power or very large scale integration (VLSI) applications, memory, gate arrays</td>
<td>Uses enhancement FETs; low noise margin; requires excellent threshold control</td>
<td>1 μm MOS VLSI</td>
</tr>
</tbody>
</table>

Digital Counter

A digital counter is an instrument that, in its simplest form, provides an output that corresponds to the number of pulses applied to its input.

Counters may be categorized into two types: the Moore machine or the Mealy machine. The simpler counter type, the Moore machine, has a single count input (also called the clock input or pulse input), while the Mealy machine has additional inputs that alter the count sequence. Digital counters take many forms, such as geared mechanisms (operating time counters and older odometers are
examples), relays (old telephone switching systems), and solid-state semiconductor circuits (most modern electronic counters). This section stresses solid-state electronic counters.

Most digital counters operate in the binary number system because binary is easily implemented with electronic circuitry. Binary allows any integer (whole number) to be represented as a series of binary digits, or bits, where each bit is either a 0 or 1 (off or on, low or high, and so forth).

Four-bit binary counters (Figure 2-36) count from 0 to 15; the 16th count input causes the counter to return to the 0 output state and generate a carry pulse. This action of the counter to return to the 0 state with a carry output on every 16th pulse makes the 4-bit binary counter a modulus 16 counter. The four binary-digit outputs \( Q_D, Q_C, Q_B, \) and \( Q_A \) are said to have an 8-4-2-1 “weighting” because, if \( Q_D \) through \( Q_A \) are all ones, then the binary counter output is \( 1111_2 = 1 \times 2^3 + 1 \times 2^2 + 1 \times 2^1 + 1 \times 2^0 = 8 + 4 + 2 + 1 = 15_{10}, \) where the subscripts indicate the base of the number system. In Figure 2-36, view A, the counter state-flow diagram is shown. Each possible state is represented by the numerical output of that state. Upon receiving a count pulse, the counter must change state by following an arrow from the present state to the next state. In Figure 2-36, view B, a table is given showing the counter output after a given number of input pulses, assuming that the counter always starts from the 0 state. The counter
output is listed in binary, octal, decimal, and hexadecimal. Figure 2-36, view C, shows a block diagram of the counter built with \( T \) flip-flops, and Figure 2-36, view D, shows the counter waveforms through time, with a periodic count input. The \( T \) flip-flop is a device that has either a 0 or a 1 on its \( Q \) output at all times. When the count input \( T \) moves from the 1 state to the 0 state, the flip-flop output must change state, from a 0 to a 1 or a 1 to a 0. The carry output produces a 1-to-0 transition on every 16th count input, producing a divide-by-16 function.

The four bits of the counter of Figure 2-36 can be grouped together and used to represent a single hexadecimal digit; in Figure 2-36, view B, each counter output state represents one hexadecimal digit. A two-digit hexadecimal counter requires two sets of four-bit binary counters, the carry output from the first set of counters driving the count input of the second set of counters.

A decimal counter built from four binary counters is shown in Figure 2-37. Let four bits of data from the binary counter represent one decimal digit. The counter will work in the same way as the counter shown in Figure 2-36, except that all the flip-flops are reset to the 0 state when the counter moves from the \( 1001_2 = 9 \) state, instead of advancing to the \( 1010_2 = 10 \) state. Besides the AND gate that is now used to detect the \( 1001 \) state of the counter and enable the resets, the circuit block diagram shows a new type of flip-flop. The \( SR \) flip-flop acts like a \( T \) flip-flop with an additional input that forces the \( Q \) output to a 1 state when the \( S \) (set) input is high and the \( T \) input has had a 1-to-0 transition applied. An \( R \) (reset) input acts as the \( S \) input does, except that the \( Q \) output goes to 0. This example decimal counter has an 8-4-2-1 weighted output that is known as binary-coded decimal (BCD). A seven-segment display is easily interfaced to the binary-coded decimal counter using a widely available decoder/driver circuit that is binary coded decimal to seven segments.

Digital counters are found in much modern electronic equipment, especially equipment that is digitally controlled or has digital numeric displays. A frequency counter, as a test instrument or a channel frequency display on a radio tuner, consists simply of a string of decade counters that count the pulses of an input signal for a known period of time, and display that count on a seven-segment display. A digital voltmeter operates by using nearly the same idea, except that the counter counts a known frequency for a period of time proportional to the input voltage.
Digital computers may contain counters in the form of programmable interval timers that count an integral number of clock pulses of a known period, and then generate an output at the end of the count to signal that the time period has expired. Most of the counters in a microprocessor consist of arithmetic logic units (ALUs) that add one many-bit number to another, storing the results in a memory location. The program and data counters are examples of this kind of counter.

Counters have progressed from relays to light-wavelength-geometry, very large-scale ICs. There are several technologies for building individual digital counters. Single counters are available as integrated circuit chips in ECL, TTL, and CMOS. The three technologies are often used together in order to keep production costs down. In some applications, ECL or TTL is used towards the input end of a counter and CMOS towards the output where speed is critical, thus putting less expensive logic devices where the signal will never operate at a high-enough frequency to require an expensive CMOS circuit. Standard, high-volume production NMOS LSI can implement a one-bit binary counter in a 100 × 100 μm² (39 × 3.9 mil²) area that will operate to 10 MHz. A gallium arsenide metal semiconductor field-effect transistor (MESFET) master-slave JK flip-flop has been reduced that operates at 610 MHz in a 390 × 390 μm² (15 × 15 mil²) surface area while consuming the power of an NMOS.

Comparator Circuit

A comparator circuit is an electronic circuit that produces an output voltage or current whenever two input levels simultaneously satisfy predetermined amplitude requirements. A comparator circuit may be designed to respond to continuously varying (analog) or discrete (digital) signals. Its output may be in the form of signaling pulses that occur at the comparison point or in the form of discrete dc levels.

Linear Comparator

A linear comparator operates on continuous, or nondiscrete, waveforms. Most often one voltage, referred to as the reference voltage, is a variable dc or level-setting voltage, and the other is a time-varying waveform. One common application of the comparator is in a linear time-delay circuit. Inputs consist of a sawtooth waveform of linearly increasing magnitude (ramp function) and a variable dc reference voltage. The reference voltage can be calibrated in units of time, as measured from the beginning of the sawtooth.

A clipper and a coincidence amplifier, together with a resistance-capacitance (RC) differentiating circuit, can perform the function of comparator. In Figure 2-38, the series clipper, usually called a pick-off diode for this application, does not conduct until the input reaches level \( V_R \). The diode input is a sawtooth as shown. Consequently, only the portion of the sawtooth above \( V_R \) appears at the output of the clipper. This output is applied to the RC differentiating network, which passes only the initial part of the rise. This short pulse is then amplified to produce the resultant output waveform.

The particular amplifier illustrated is a two-transistor, high-gain amplifier with a relatively high input impedance and a low output impedance. A sharper pulse can be obtained if the amplifier is made regenerative. It may even take the form of a multivibrator or blocking oscillator to increase the gain at the point of coincidence.

Regenerative Comparator

Multivibrators can be used in several ways directly as comparators without need for the pick-off diodes; such comparators sense the required coincidence accurately and introduce little additional delay. A simple type is the direct-coupled bistable circuit, sometimes known as the Schmitt circuit, as shown in Figure 2-39. This example employs enhancement-mode P-channel field-effect transistors and can be made to function from either negative- or positive-going input waveforms. The example compares a negative-going input waveform with reference voltage \( V_R \).
Under a variety of choices of supply voltage and resistances, the circuit will be bistable; that is, either of the two transistors can be conducting for a particular voltage at input gate G1. Until a predetermined value of reference voltage is reached, Q1 is nonconducting, and at time $T$, it switches from nonconducting to conducting, while Q2 simultaneously switches from conducting to nonconducting. With dc coupling, as shown in Figure 2-39, three outputs of differing dc levels and polarities are produced. If RC differentiating circuits are added as indicated, sharp pulses can then be obtained. When the input waveform ends, all points in the circuit return to their initial states.

Direct-coupled regenerative comparators, such as the Schmitt circuit, are usually bidirectional, responding to inputs approaching the reference level $V_R$ from either the positive or the negative side. If the input starts at a value lower than $V_R$, the output voltage $V_1$ will be at its high value until $V_R$ is
reached, and it then shifts to its low value. Polarities of the other output signals will be correspondingly reversed. Thus, at the voltage coincidence of $V_i$ and $V_R$, one of two possible output states, definable as logic level (1) or logic level (0) in digital terminology, will be generated. Because of design limitations in practical circuits, the input voltage at which the bistable circuit changes state is slightly less or greater than $V_R$, depending upon whether the input signal is positive- or negative-going. This slight difference in level is referred to as the hysteresis of the circuit.

**Integrated Circuit Comparators**

High-gain dc operational amplifiers operated in the nonfeedback mode are often used to perform the comparator function, and many such amplifiers are classified as comparators because they are specifically designed to meet the needs for accurate voltage comparison applications. Such "op-amps" have two inputs, the output being inverting with respect to one and noninverting with respect to the other, as shown in *Figure 2-40*. The voltage gain (amplification) of the amplifier is so high that its output will swing through its entire dynamic range, $V_{\text{min}}$ to $V_{\text{max}}$, for very small changes in input voltage. Thus, for $V_{im} < V_R$, the amplifier will be cut off and the output voltage will be at $V_{\text{max}}$, and for $V_i > V_R$, the amplifier will saturate and the output will be at $V_{\text{min}}$. For digital system applications, the output levels may be designed to coincide with logic level (0) and logic level (1) of the specific digital system, and thus be suitable for converting a specific level in a continuously varying signal to a specific logic number assigned to the level. Arrays of such comparators connected to a common input, each designed to respond at a distinct reference voltage and with the outputs connected to appropriate logic gates, may be used to convert a range of signal levels to a specific digital code, and as such form the basic building block of analog-to-digital converters.

The voltage gain, and hence the timing precision of the operational amplifier comparator, can be increased by converting it to a regenerative comparator, as shown in *Figure 2-41*.

**Digital Comparator**

The term "digital comparator" has historically been used when the comparator circuit is specifically designed to respond to a combination of discrete level (digital) signals; for example, when one or more such input signals simultaneously reach the reference level that causes the change of state of the output. Among other applications, such comparators perform the function of the logic gate, such as the AND, OR (turned on when either input is high), and NAND functions. More often, however,
digital comparator is used to describe an array of logic gates designed specifically to determine whether one binary number is less than or greater than another binary number. Such digital comparators are sometimes called magnitude comparators or binary comparators.

Comparators may take many forms and can find many uses in addition to those that have been discussed. For example, the electronically regulated dc voltage supply uses a circuit that compares the dc output voltage with a fixed reference level. The resulting difference signal controls an amplifier, which, in turn, changes the output to the desired level. In a radio receiver, the automatic gain control circuit may be thought of broadly as a comparator; it measures the short-term average of the signal at the output of the detector, compares this output with a desired bias level on the radio-frequency amplifier stages, and changes that bias to maintain a constant average-level output from the detector.

Analog-to-Digital Converter

The analog-to-digital converter (sometimes called A-to-D converter) is a device for converting the information contained in the value or magnitude of some characteristics of an input signal, compared to a standard or reference. This input is compared to information in the form of discrete states of a signal, usually with numerical values assigned to the various combinations of discrete states of the signal.

A-to-D converters are used to transform analog information, such as audio signals or measurements of physical variables (for example, temperature, force, or shaft rotation) into a form suitable for digital handling, which might involve any of the following operations: (1) processing by a computer or by logic circuits, including arithmetical operations, comparison, sorting, ordering, and code conversion; (2) storage until ready for further handling; (3) display in numerical or graphical form; and (4) transmission.

If a wide-range analog signal can be converted, with adequate frequency, to an appropriate number of two-level digits, or bits, the digital representation of the signal can be transmitted through a noisy medium without relative degradation of the fine structure of the original signal.

Conversion involves quantizing and encoding. The term “quantizing” means partitioning the analog signal range into a number of discrete quanta and determining to which quantum the input signal belongs. The term “encoding” means assigning a unique digital code to each quantum and determining the code that corresponds to the input signal. The most common system is binary, in which there are $2^n$ quanta (where $n$ is some whole number), numbered consecutively; the code is a set of $n$ physical two-valued levels or bits (1 or 0) corresponding to the binary number associated with the signal quantum.

A typical three-bit binary representation of a range of input signals, partitioned into eight quanta, is shown in Figure 2-42. For example, a signal in the vicinity of 3/8 full scale (between 5/16 and 7/16) will be coded 011 (binary 3).
Conceptually, the conversion can be made to take place in any kind of medium—electrical, mechanical, fluid, optical, and so on (for example, shaft-rotation to optical). By far the most commonly employed form of A-to-D converters comprises those devices that convert electrical voltages or currents to coded sets of binary electrical levels (for example, +5 V or 0 V) in simultaneous (parallel) or pulse-train (serial) form, as shown in Figure 2-43. The serial output is not always made available.

![Figure 2-43 — A-to-D converter, showing parallel and serial (return-to-zero) output formats for code 10110.](image)

The converter depicted in Figure 2-43 converts the analog input to a five-digit “word.” If the coding is binary, the first digit, the most significant bit (MSB), has a weight of 1/2 full scale, the second 1/4 full scale, and so on, down to the \( n \)th digit, the least-significant bit (LSB), which has a weight of \( 2^{-n} \) of full scale (1/32 in this example). Thus, for the output word shown, the analog input must be given approximately by the following equation:

\[
\frac{16}{32} + \frac{0}{32} + \frac{4}{32} + \frac{2}{32} + \frac{0}{32} = \frac{22}{32} = 0.6875 \times 16 \text{FS (full scale)}
\]
The number of bits, \( n \), characterizes the resolution of a converter.

A commonly used configuration of connections to an A-to-D converter is shown in Figure 2-43. Note the analog signal and reference inputs, the parallel and serial digital outputs, and the leads from the power supply that provide the required energy for operation. Additionally, two control leads—a start-conversion input and a status-indicating output (busy) indicate when a conversion is in progress. The reference voltage or current is often developed within the converter.

Second in importance to the binary code and its many variations is the BCD, which is used rather widely, especially when the encoded material is to be displayed in numerical form. In BCD, each digit of a radix-10 number is represented by a four-digit binary subgroup. For example, the BCD code for 379 is 0011 0111 1001. The output of the A-to-D converter used in digital panel meters is usually BCD.

Many techniques are used for A-to-D conversion, ranging from simple voltage-level comparators to sophisticated closed-loop systems, depending on the input level, output format, control features, and the desired speed, resolution, and accuracy. The two most popular techniques are dual-slope conversion and successive-approximations conversion.

Dual-slope converters have high resolution and low noise sensitivity; they operate at relatively low speeds, usually a few conversions per second. They are primarily used for direct dc measurements requiring digital readout; the technique is the basis of the most widely used approach to the design of digital panel meters.

A simplified block diagram of a dual-slope converter is shown in Figure 2-44, view A. The input is integrated for a period of time determined by a clock-pulse generator and counter (Figure 2-44, view B). The final value of the signal integral becomes the initial condition for integration of the reference in the opposite sense, while the clock output is counted. When the net integral is zero, the count stops. Because the integral “up” of the input over a fixed time \( (N_o \text{ counts}) \) is equal to the integral “down” of the fixed reference, the ratio of the number of counts of the variable period to that of the fixed period is equal to the ratio of the average value of the signal to the reference. Successive-approximations

![Figure 2-44 — Example of dual-slope conversion block diagram and output.](image_url)
conversion is a high-speed technique used principally in data-acquisition and computer-interface systems. The simplified block diagram of a successive-approximations converter is illustrated in Figure 2-45, view A. In a manner analogous to the operation of an apothecary’s scale with a set of binary weights, the input is “weighed” against a set of successively smaller fractions of the reference, produced by a digital-to-analog (sometimes called a DAC) converter that reflects the number in the output register.

First, the MSB is tried (1/2 full scale). If the signal is less than the MSB, the MSB code is returned to zero; if the signal is equal to or greater than the MSB, the MSB code is latched in the output register (Figure 2-45, view B). The second bit is tried (1/4 full scale). If the signal is less than 1/4 or 3/4, depending on the previous choice, bit 2 is set to zero; if the signal is equal to or greater than 1/4 or 3/4; bit 2 is retained in the output register. The third bit is tried (1/8 full scale). If the signal is less than 1/8, 3/8, 5/8, or 7/8, depending on previous choices, bit 2 is set to zero; otherwise, it is accepted. The trial continues until the contribution of the LSB has been weighed and either accepted or rejected. The conversion is then complete. The digital code latched in the output register is the digital equivalent of the analog input signal.

The earliest A-to-D converters were large rack-panel chassis-type modules using vacuum tubes, requiring about 1.4 ft³ (1/25 m³) of space and many watts of power. Since then, they have become smaller in size and cost, evolving through circuit-board, encapsulated module, and hybrid construction, with improved speed and resolution. Single-chip A-to-D converters with the ability to interface with microprocessors are now available in small IC packages.

Digital-to-Analog Converter

A digital-to-analog converter (DAC) is a device for converting information in the form of combinations of discrete states or a signal, often representing binary number values, to information in the form of the value or magnitude of some characteristics of a signal, in relation to a standard or reference. Most often, it is a device that has electrical inputs representing a parallel binary number, and an output in the form of voltage or current.

The structure of a typical DAC is shown in Figure 2-46. The essential elements, found even in the simplest devices, are enclosed within the dashed rectangle. The digital inputs, labeled $u_i$, $i = 1, 2, ..., n$, are equal to 1 or 0. The output voltage $E_0$ is given by the following equation, where $V_{REF}$ is an analog reference voltage and $K$ is a constant.

$$E_0 = KV_{REF}(u_12^{-1} + u_22^{-2} + u_32^{-3} + \ldots + u_n2^n)$$
Thus, for a five-bit binary converter with latched input code 10110, the output is given by the following equation.

\[ E_0 = \left( \frac{16}{32} + \frac{0}{32} + \frac{4}{32} + \frac{2}{32} + \frac{0}{32} \right) KV_{REF} = \frac{11}{16} KV_{REF} \]

Bit 1 is the MSB, with a weight of 1/2; bit \( n \) is the LSB, with a weight of \( 2^{-n} \). The number of bits \( n \) characterizes the resolution.

DACs are used to present the result of digital computation, storage, or transmission, typically for graphical display or for the control of devices that operate with continuously varying quantities. DAC circuits are also used in the design of A-to-D converters that employ feedback techniques, such as successive-approximations and counter-comparator types. In such applications, the DAC may not necessarily appear as a separately identifiable entity.

The fundamental circuit of most DACs involves a voltage or current reference; a resistive "ladder network" that derives weighted currents or voltages, usually as discrete fractions of the reference; and a set of switches, operated by the digital input, that determines which currents or voltages will be summed to constitute the output.

An elementary three-bit DAC converter is shown in Figure 2-47. Binary-weighted currents developed in \( R_1 \), \( R_2 \), and \( R_3 \) by \( V_{REF} \) are switched either directly to ground or to the output summing bus (which is held at zero volts by the operational-amplifier circuit). The sum of the currents develops an output voltage of polarity opposite to that of the reference across the feedback resistor \( R_f \). The binary relationship between the input code and the output, both as a voltage and as a fraction of the reference, is shown in Table 2-4.

The output of the DAC converter is proportional to the product of the digital input value and the reference. In many applications, the reference is fixed, and the output bears a fixed proportion to the digital input. In other applications, the reference, as well as the digital input, can vary; a DAC converter that is used in these applications is thus called a multiplying DAC. It is principally used for

Figure 2-46 — Typical A-to-D convertor.
imparting a digitally controlled scale factor, or gain, to an analog input signal applied at the reference terminal.

![Digital Opamp Circuit](image)

**Figure 2-47 — Elementary three-bit DAC.**

Except for the highest resolutions (beyond 16 bits), commercially available DACs are generally manufactured in the form of dual in-line-packaged (DIP or DIL package) ICs, using bipolar, MOS, and hybrid technologies. A single chip may include just the resistor network and switches, or it may also include a reference circuit, output amplifier, and one or more sets of registers (with control logic suitable for direct microprocessor interfacing).

<table>
<thead>
<tr>
<th>Digital Input Code</th>
<th>Analog Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu_1$</td>
<td>$\mu_2$</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
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</tbody>
</table>

Table 2-4 — Input and Output of Converter
End of Chapter 2
Logic Devices

Review Questions
2-1. How many charged regions make up a basic PN junction diode?
A. Two  
B. Three  
C. Four  
D. Six

2-2. What junction diode rating indicates maximum average current that can be permitted to flow for any length of time before damage will occur?
A. Repetitive reverse voltage  
B. Average forward current  
C. Surge current  
D. Repetitive forward current

2-3. You are selecting a diode from the parts-expended bin for one that has failed due to high heat conditions. Which of the following ratings should you look for in your replacement diode?
A. Average forward current, surge current, peak current, and repetitive reverse voltage  
B. Surge current, repetitive forward current, average inductance, and repetitive reverse voltage  
C. Average reference voltage, surge current, repetitive forward current, and repetitive reverse voltage  
D. Average forward current, surge current, repetitive forward current, and repetitive reverse voltage

2-4. What functional property is most commonly associated with a junction diode?
A. Amplification  
B. Rectifying  
C. Passivation  
D. Diffusion

2-5. What term describes a transistor that has all three electrical connections found on a single surface?
A. Bipolar  
B. Planar  
C. Passivated  
D. Double-diffused
2-6. What term refers to the method in which a transistor’s active material is fabricated?

A. Bipolar  
B. Passivated  
C. Planar  
D. Double-diffused

2-7. Which of the following characteristic accounts for the time delay in turning off and on a transistor when it is used as a switch?

A. Phase shift  
B. Transit time  
C. Charging time  
D. Storage capacity

2-8. What term refers to the control connection of a four-layer power switching transistor?

A. Source  
B. Emitter  
C. Gate  
D. Base

2-9. What transistor normally operates conducting and must be cut off by a voltage on the gate?

A. Junction gate field-effect transistor  
B. Insulated-gate field-effect transistor  
C. Metal-oxide-semiconductor field-effect transistor  
D. Bipolar

2-10. Which of the following transistor configurations is most commonly used?

A. Common-collector  
B. Common-base  
C. Common-emitter  
D. Common-gate

2-11. What is the (a) input and (b) output of a common-emitter connected transistor?

A. (a) Base to collector (b) base to emitter  
B. (a) Base to emitter (b) collector to emitter  
C. (a) Emitter to base (b) collector to base  
D. (a) Base to collector (b) emitter to collector
2-12. Refer to the figure above. What happens to the output voltage ($V_o$) of the inverter circuit shown if the input voltage ($V_i$) goes to nearly 0 volts?

A. $V_o$ increases to one-half the value of $V_{DD}$.
B. $V_o$ increases to a value almost equal to $V_{DD}$.
C. $V_o$ decreases to 0 volts.
D. $V_o$ stays constant.

2-13. Thyristors are most commonly used in which of the following applications?

A. Mixer
B. Impedance matcher
C. Switch
D. Oscillator

2-14. Which of the following transistor devices is most commonly used for power controls?

A. Junction gate field-effect transistor
B. Metal-oxide-semiconductor field-effect transistor
C. Triode alternating-current
D. Silicon-controlled rectifier

2-15. What thyristor is a symmetrical reverse-blocking triode that is able to turn off current with a negative gate input signal?

A. Gate turn-off
B. Asymmetrical silicon-controlled rectifier
C. Resistive turn-off device
D. Silicon-controlled rectifier

2-16. What term describes the method of obtaining a variable-voltage direct current from a battery source?

A. Latch switching
B. Phase controlling
C. Voltage chopping
D. Reverse blocking
2-17. Which of the following discrete electronic components is the most difficult to fabricate as an integrated circuit?

A. Inductor  
B. Capacitor  
C. Resistor  
D. Transistor

Refer to the figure to the right in answering questions 2-18 and 2-19.

2-18. What is the (a) input node and (b) output node of the basic complementary metal-oxide-semiconductor (CMOS) inverter?

A. (a) Drain (b) gate  
B. (a) Gate (b) drain  
C. (a) Source (b) gate  
D. (a) Drain (b) source

2-19. With no input signal to the complementary metal-oxide-semiconductor (CMOS) inverter, what is the (a) state and (b) voltage of the loading capacitor?

A. (a) Discharged (b) 0 volts  
B. (a) Charged (b) 0 volts  
C. (a) Charged (b) 5 volts  
D. (a) Discharged (b) 5 volts

2-20. What is the designation for a military-grade Schottky transistor-transistor logic (TTL) device?

A. 5400  
B. 54S00  
C. 54L00  
D. 54H00

2-21. What is the major advantage of gallium arsenide integrated circuits over silicon integrated circuits?

A. Faster switching speed  
B. Lower power requirement  
C. Reduced output noise  
D. Higher audio fidelity
2-22. A particular logic gate can drive four following logic gates. What is the logic gate term that best describes this characteristic?

A. Flip-flop  
B. Fan-in  
C. Fan-out  
D. Reset-set

2-23. What number system is the simplest that can be directly implemented with electronic circuitry?

A. Binary  
B. Octal  
C. Decimal  
D. Hexadecimal

2-24. What circuit changes an audio signal to a numerical display?

A. Comparator  
B. Logic gate  
C. Digital to analog converter (DAC)  
D. Analog to digital converter (A-to-D)
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2-53
CHAPTER 3

COMMUNICATIONS

As an aviation electronics technician (AT), you will be tasked to operate and maintain many different types of aircraft communications equipment. This equipment will differ in many respects, but in other respects, it will be much the same. For example, there are numerous models of amplitude-modulated (AM) and frequency-modulated (FM) radios that function and operate on the same basic principles. It is beyond the scope of this chapter to discuss all radios or to present information that relates to all of the many different pieces of communications equipment. Therefore, only representative communication receivers and transmitters will be discussed, along with a brief overview of fiber optics. You will also be given a basic understanding of equipment repair at the intermediate level (I-level) of maintenance.

LEARNING OBJECTIVES

When you have completed this chapter, you will be able to do the following:

1. Explain the testing procedures for communication transmitters, to include frequency and modulation measurements and intermediate frequency (IF) and radiofrequency (RF) amplifier measurements.
2. Explain the testing procedures for communication receivers, to include receiver sensitivity, bandwidth response and measurements, squelch, modulation and automatic frequency control (AFC) measurements, and typical receiver alignment.
3. Describe fiber optics to include a basic system, advantages, and light transmission.
4. Describe fiber types, cables construction, and couplings.

RADIOFREQUENCY COMMUNICATIONS

When the wireless (radiotelegraph) was invented, the Navy saw a possible use for it: For communications from shore stations to ships along the coast. In 1899, the first official naval radio message was sent from ship to shore. It only traveled a distance of 20 miles but that was a start. The next advance was in 1916 when the Navy first used the radiotelephone between ships. Three years later the first airborne radio was used to communicate with a ground station. In the early years, communications were not the best because of poor tuning techniques. Receivers often did not pick up the signal. This problem was almost eliminated in 1931 when the first superheterodyne receivers were installed in the fleet. As previously mentioned, while the technology has greatly improved, the basic principles of RF communications still apply today. The fundamental equipment used to communicate are the transmitter and receiver.

Transmitters and receivers must each perform two basic functions. The transmitter must generate a RF signal of sufficient power at the desired frequency and have some means of varying (or modulating) the basic frequency so that it can carry an intelligible signal. The receiver must select the desired frequency you want to receive and reject all unwanted frequencies. In addition, receivers must be able to amplify the weak incoming signal to overcome the losses the signal suffers in its journey through space.
TRANSMITTER AND TRANSCEIVER TESTING

When testing communications transmitters and/or transceivers, the configuration in which the equipment is installed must be considered. In the newer installations, system monitoring is used (more so than equipment monitoring). Newer configurations employ built-in test equipment (BITE) to perform system monitoring and to a varying degree, fault isolation. In the past, front panel meters and dials were relied upon for equipment monitoring and some fault isolation. A number of pieces of equipment can be placed in either installation, while other equipment is unique to either the system concept or the individual equipment concept. In both instances, however, the same parameters are monitored. Only the monitoring method is changed.

Temperature is another consideration in transmitter/transceiver maintenance. High-powered transmitters emit a great deal of heat in their power amplifier and driver stages. If the heat is poorly dissipated, premature failure of equipment will occur. Two factors that contribute significantly to poor heat dissipation are water and dirty filters/heat exchanges. Although the first factor is usually unpredictable, the latter is always avoidable with routine maintenance. In addition, routine maintenance can usually prevent most circulatory system failures. If forced air (blower) circulation is employed to dissipate the heat in a high-powered transmitter, dust settling in the equipment can contribute to problems. Because dust forms a film that absorbs moisture, insulation resistance is lowered to a point where the insulation fails and the resulting arc causes its near-simultaneous ignition known as flashover. Flashover can be described as an electrical arc that can produce temperatures exceeding the surface temperature of the sun and vaporize surrounding materials. Strict adherence to scheduled maintenance is mandatory if the equipment is to be cooled effectively.

Military aircraft operate in wide-ranging operational environments presenting a myriad of challenges for today’s technicians. Equipment must be wiped down, corroded metal parts cleaned, and inspections performed to detect degraded material conditions. A good visual inspection is the starting point of every maintenance evolution. It is possible to detect poor contacts by inspecting for evidence of local overheating or arching. Such contacts must be thoroughly cleaned and tightened.

Frequency Generation

On any given day, several thousand different frequencies may be used simultaneously by several transmitting units. Because atmospheric conditions dictate which frequency will best be propagated at any given time, the transmission frequency in use may need to be changed quite often so that the individual units may maintain efficient and reliable communications. Regulations require that each transmitted frequency be precise and comply with both harmonic frequency and sideband emission limits. To meet these rigid standards, crystal oscillators and frequency synthesis are employed to generate the required transmission frequency. When frequency synthesis is used, a calibrated frequency standard with a very high degree of accuracy serves as the basic oscillator. This standard is external to the transmitter or transceiver, and its output is fed to each transmitter or transceiver via a frequency standard distribution system, as shown in Figure 3-1.

A back-up internal standard is incorporated in each transmitter/transceiver for use in case of primary standard malfunction. The output of the primary standard is multiplied and/or divided in the transmitter to obtain the desired frequencies for use in the frequency synthesis process. An example of a high-frequency (HF) transmitter’s frequency synthesizer is shown in Figure 3-2. In the example, all of the output operating frequencies are derived from the 5 megahertz (MHz) primary standard input frequency. This method ensures each operating frequency is as accurate as the primary standard.
Figure 3-1 — Frequency standard distribution system.

Figure 3-2 — Frequency synthesizer.


**Frequency Measurement**

The primary standard used in the frequency standard distribution system requires routine calibration. The standard must be more accurate than any other general-purpose test equipment maintained aboard ship. Stable power must be applied to the standard at all times to ensure proper operation. When power is removed from the standard for any reason or it is turned off, sufficient warm-up time must be permitted to allow it to stabilize for accuracy. This warm-up time is noted in the particular equipment’s technical manual.

Older standards required as much as 24 hours to become stable. Although the frequency accuracy of the primary standard cannot be checked realistically, a check with a calibrated frequency counter will indicate whether or not the standard is grossly off frequency. Harmonic distortion of the primary standard’s frequency must be guarded against because of the unwanted changes this frequency will undergo during the frequency synthesis process in the transmitters and transceivers. Spectrum analysis is used to measure harmonic distortion because low-level distortion will not appear in the time-domain display of an oscilloscope. Such distortion will show up, however, in the frequency domain display of the spectrum analyzer (*Figure 3-3*). High-level distortion will show up in either display. If more than 0.2 percent of distortion is encountered in the standard’s output, the standard must be sent to a shore facility for repair and/or calibration.

![Oscilloscope and Spectrum Analyzer](image)

*Figure 3-3 — Harmonic distortion displays.*

The two best means of measuring a transmitter’s output frequency are the frequency counter and the spectrum analyzer. The frequency counter is more accurate of the two because its output is derived from the counting of discrete events (cycles) over a specific period of time. The spectrum analyzer can measure second and third order harmonic emissions, sideband emissions, and intermodulation distortion, as well as output frequency. When used in conjunction with a directional coupler and calibrated attenuators, it can also measure power output and reflected power. The spectrum analyzer can thus provide a better indication of transmission quality than can a frequency counter.

**Amplitude Modulation Measurements**

If an AM signal is applied to the vertical input of an oscilloscope, the oscilloscope will display a wave-envelope pattern of the AM signal (*Figure 3-4*). When the modulation voltage is used as an external sweep voltage, a trapezoid pattern (*Figure 3-5*) is displayed. In this display, the amplitude-modulated carrier is plotted as a function of modulation rather than of time. The resultant pattern in *Figure 3-5* will remain stationary, and its shape is determined by the percent of modulation.
Distorted trapezoid waveforms caused by certain circuit malfunctions are shown in Figure 3-6. An AM waveform and its corresponding trapezoidal display that results from excessive drain voltage applied to the RF power amplifier in a radio transmitter is shown in Figure 3-6, view A. The reverse situation is shown in Figure 3-6, view B, where insufficient voltage was applied to the drain of the transmitter power amplifier. The effects obtained from imperfect neutralization in a radio transmitter power amplifier are shown in Figure 3-6, views C and D. There is nonuniform density in the AM waveform. Light and dark bars represent spurious oscillation. To calculate the percent of modulation, the trapezoid pattern provides the most convenient form to use. The horizontal and vertical gain

![AM carrier](image1)

![Trapezoidal AM carrier pattern](image2)

![Distorted AM waveforms](image3)
controls are adjusted for a suitable display on the screen, such as shown in Figure 3-7. The modulation percent is then calculated, using the formula

\[ \frac{H_1 - H_2}{H_1 + H_2} \times 100. \]

H1 is the greatest vertical height (amplitude) and H2 is the lesser vertical height. Using Figure 3-7 as an example, the percent of modulation would be

\[ \frac{5-1}{5+1} \times 100 = \frac{4}{6} \times 100 = 66.6 \text{ percent.} \]

The longer side or the trapezoidal pattern represents modulation peaks, or crests. The shorter side indicates modulation troughs, or low points, at 100-percent modulation. The wedge-shaped pattern assumes a point on the shorter side. Modulation over 100 percent causes this point to extend and form a horizontal line or tail, as shown in Figure 3-8. Because the trapezoid type of display retains its triangular characteristic even with varying degrees of modulation, it provides a more easy discernible indication of overmodulation as well as the modulation percentage. To obtain correct results, you should take care to avoid stray RF pickup that may distort the oscilloscope presentation.

**Frequency Modulation Measurements**

The concept of percentage of modulation (as discussed in connection with amplitude modulation) does not apply to frequency modulation. The amplitude of the FM waveform is constant. The extent of modulation must be described in terms other than those of the amplitude-modulated wave. In regards to a class of stations, a certain maximum frequency swing is established as representing 100-percent modulation. For example, in the case of FM broadcast stations, a frequency swing of plus or minus 75 kilohertz (kHz) from the unmodulated center frequency (frequency deviation) is commonly considered as being the equivalent of 100-percent modulation. However, the more widely accepted method of
describing the extent of modulation is to state the value of the modulation index. This index \( (m) \) is the ratio of the amount by which the transmitted frequency swings from its average frequency (frequency deviation \( [Fd] \)) to the frequency of the modulating signal \( (FM) \). The relationship of these quantities is shown by the following equation:

\[
m = \frac{Fd}{FM}
\]

where:

- \( m \) = modulation index,
- \( Fd \) = frequency deviation, and
- \( FM \) = frequency of modulating signal

By means of this basic relationship, it is possible to determine the frequency deviation when the modulation index and the modulating frequency are known. It should be carefully noted (in describing the extent of frequency modulation) that the modulation percentage and the modulation index are defined in a different manner. The percentage is proportional to the frequency swing.

The modulation index is also directly proportional to the frequency swing, but in addition, it is inversely proportional to the highest modulating frequency. Thus, in contrast to amplitude modulation, the modulation index of a FM wave is not the decimal equivalent of the modulation percentage. The modulation index of a FM waveform, for example, will exceed 1 (unity) by many times when the frequency swing is large and the modulating frequency is low. The FM output is the sum of a center frequency component and numerous pairs of sideband frequency components. The center frequency component has the same frequency as the unmodulated carrier. The two components of the first sideband pair have frequencies respectively higher and lower than the center frequency by the amount of the modulating frequency, just as in amplitude modulation. In frequency modulation, however, there are additional pairs of sideband components that can have appreciable amplitude. For example, the second pair of sidebands (having frequencies that are higher and lower than the center frequency by twice the amount of the modulating frequency) can also be important. The same can be true of the third pair of sidebands. These sidebands are removed from the center frequency by three times the modulating frequency, and even higher orders of sideband pairs, whose frequencies differ from the center frequency by correspondingly greater amounts. When the modulation is only slight, only the pair of sidebands nearest in frequency to the carrier frequency component will have sufficient amplitude to be important. Under this condition, the bandwidth required is no greater than that for an AM wave. As the frequency modulation is increased, however, more pairs of sidebands acquire appreciable amplitude, and the bandwidth requirements become greater than the amplitude modulation.

The actual amplitudes of the FM waveform sidebands and carrier, as compared with an unmodulated carrier amplitude of 1, may be read directly from Table 3-1 for modulation indices up to 6. To find the amplitude of any sideband pair, determine the modulation index \( (m) \), read the corresponding amplitude factor for the sideband pair, and multiply this factor by the amplitude of the unmodulated carrier. The amplitude of the carrier during modulation is found in the same manner, taking the amplitude factor from the \( J_0(m) \) column. Where no value is given in a column, the amplitude factor is less than 0.005, and the sideband pair will not be important for normal considerations. The values of \( J_0(m) \), \( J_1(m) \), and \( J_2(m) \) over the range \( m = 0 \) to \( m = 16 \) are shown plotted in Figure 3-9. A study of these curves reveals some interesting facts about the composition of FM waves. \( J_0(m) \) is less than 1 for all values of \( m \) greater than zero. This situation indicates that as sideband components appear with modulation, the amplitude of the center frequency component is less than its amplitude in the absence of modulation. This fact is evident if you remember that the amplitude of a FM waveform is constant. The average power during each RF cycle is the same as the power during any other RF cycle. If the power in the wave will not change when frequency modulation causes sideband currents to appear, then the amplitude of the center frequency component must decrease sufficiently to keep the total of the \( I^2R \) products of all the components equal to the power of the unmodulated wave.
Table 3-1 — Bessel Factors for Finding Amplitudes of Center and Sideband Frequency Components

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<th>$F$</th>
<th>$J_0(m)$</th>
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Frequency Deviation Measurements

Regardless of the differences between amplitude modulation and frequency modulation, it is possible to make an analogy between percentage of amplitude modulation and frequency deviation. Specifically, frequency deviation is proportional to the amplitude of the modulating signal, as is the percentage of amplitude modulation. Because of this analogy, it is convenient to extend the concept of percentage of modulation to frequency modulation by arbitrarily designating the maximum allowable frequency deviation of a class of operation as 100-percent modulation. An important distinction to remember is that no distortion results from modulation percentages greater than 100 in FM transmission. However, any percentage larger than the amount sanctioned by the proper authorities will produce excessive channel width, making interference with other stations possible. For example, the maximum frequency deviation for commercial FM stations is limited to 75 kHz; for military applications, the maximum deviation is limited to 40 kHz, and is classed as narrow-band FM transmission. The sound transmission of television stations is restricted to a deviation of 25 kHz.
It was stated earlier that the modulation index determines the relative amplitude of the carrier and sideband frequencies emitted by an FM transmitter. The modulation index may be measured by using the fact that the carrier amplitude becomes zero whenever the modulation index is such that $J_0(m) = 0$, where $J_0$ is a Bessel function of the zero order. The values of the modulation index for these conditions are given in Table 3-2. Specifically, the carrier component disappears completely for certain values of $m$; that is, $m = 2.405, 5.52, 8.654$, etc. (Note that $J_0(m) = 0$ in Figure 3-9 for these values of $m$) For these specific values of $m$, all of the transmitter power is contained in the sidebands. This fact allows the measurement of specific values of the modulation index by measuring the amplitude of the carrier component only. The level of modulation on the FM carrier is increased from zero to the first point at which the detected carrier disappears. The point at which the carrier first disappears corresponds to $m = 2.405$.

Table 3-2 — Values of Modulation Index for Which a Carrier Wave has Zero Amplitude

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<th>Order of Carrier Zero</th>
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<td>$m(m6)$</td>
<td>$18.07 + \pi(m - 6)$</td>
</tr>
</tbody>
</table>

Figure 3-9 — Variation of FM waveform component with degree of modulation.
Upon increasing the modulation further, the carrier reappears and then disappears a second time. The second vanishing of the carrier corresponds to $m = 5.52$. Further increases in modulation will produce the higher carrier zeros (or null points). For example, the frequency deviation at the first null point is

$$F_d = 2.405 \, F_m$$

This means of determining frequency deviation is generally known as the “Bessel zero method.” Modulation indices between carrier zero-points would involve considerable interpolation, leaving room for large error if the Bessel zero method were used. In addition, the modulating frequency must be started at zero amplitude to determine which zero point is being displayed.

A more accurate method involves comparing the carrier amplitude with respect to the sideband amplitudes. A spectrum analyzer display of an FM signal where deviation has caused the carrier to be at 30 percent of its unmodulated level is shown in Figure 3-10, view A. In Figure 3-10, views B and C, the carrier is in the negative region of its curve. The spectrum analyzer will still display the carrier level as 30 percent, but by measuring sideband levels (two or three should prove sufficient), the correct index can be determined, as shown in Figure 3-10, view D. From this procedure, the precise frequency deviation can be readily determined.

**IF and RF Amplifiers**

There are three basic methods used to obtain a transmitter’s operating frequency. One method mixes the output of various crystal oscillators of different frequencies. Another method involves multiplying the basic crystal frequency by certain factors. A third method employs frequency synthesis, whereby the basic oscillator’s frequency is used to generate harmonics, which are then amplified and mixed. On occasion, more than one method is used. In each method, intermediate and output frequencies are developed that require amplification to attain the rated output power of the transmitter. Both IF and RF-type amplifiers can distort a modulated signal if the amplifiers are not operated in the linear portion of their characteristic curve. Linear operation is not always the most efficient or desirable method of operating an amplifier. The output power requirements and the type of modulation used will be the determining factor in the design of IF and RF amplifiers.
**IF Gain Measurement**

When the gain factor of an IF signal is the main consideration and the IF stage is not amplifying an AM or single sideband (SSB) signal, nonlinear amplification is used for maximum efficiency. Since the IF is not amplitude-modulated, distortion products can be eliminated by installing fixed or tunable filters in the output stage on each amplifier. You should keep two prime considerations in mind when testing this type of IF amplifier—the gain of the amplifier and the selectivity (response) of the filter. In general, the undesired, out-of-band signals should be reduced by more than 40 decibels (dB) because IF gain will vary by each piece of equipment. You should consider the technical manual for each piece of equipment to determine what the IF gain factor should be. A basic setup for measuring IF gain is shown in Figure 3-11.

![Figure 3-11 — IF gain and distortion measurement, test equipment arrangement.](image)

**FM Requirements**

In FM transmissions, the basic frequency is modulated. It is this frequency that is mixed, translated, or multiplied to obtain the transmitter’s output frequency. Since the distortion generated in nonlinear amplification primarily affects the amplitude of the carrier more than the frequency, FM is less susceptible than AM to the distortion created in nonlinear amplification. Therefore, the IF and RF amplifiers of an FM transmitter can be operated for maximum efficiency. The primary consideration in FM is that the IF filter’s response be broad enough to pass the required frequency deviation of the FM signal with sufficient amplitude. The test setup for checking an FM transmitter’s IF stages is similar to that for testing an AM transmitter’s IF stages except that a sweep generator is used as a signal source instead of a continuous-wave (CW) signal generator.

**AM/FM Considerations**

Both AM and FM transmitters are rated in terms of average power. In AM transmitters, the power contained in the carrier does not change with an increase or decrease in the percent of modulation. Sideband power can increase the power output of a transmitter by as much as 50 percent at 100-percent modulation. In FM transmitters, the dispersing of power is averaged throughout the sidebands and the carrier; therefore, there is neither increase nor decrease in power as modulation changes.

**RECEIVER TESTING**

Communication receivers are generally composed of a series of selective RF and audio frequency (AF) circuits, each stage of which is designed to amplify the output of the preceding stage. The lowered efficiency of any amplifier, or a change in any one circuit parameter, usually results in lowered overall efficiency of the receiver. The sensitivity of the receiver may also be decreased by the misalignment of the successive circuits, although each of which may function in a suitable manner as a unit. The sole function of a communication receiver is to receive (selectively) a weak signal.
Therefore, an objective overall test of sensitivity is the most significant single check that can be made on the condition of a receiver. Some receivers include a built-in output meter. Others require an external indicator, such as a dB meter or a spectrum analyzer to facilitate testing. The only other equipment needed for a sensitivity check is a calibrated signal for the excitation of the receiver on its various bands. You should correct any decrease in sensitivity.

In addition to sensitivity checks, you should perform qualitative checks, as outlined in the maintenance instruction manual or the equipment’s technical manual. Adjustment and servicing methods for a specific receiver are discussed in detail in its associated technical manual. When attempting to isolate receiver faults, first test the most accessible or vulnerable parts. Because a receiver can operate for years with reduced sensitivity before trouble is detected or a complete failure occurs, performing the maintenance prescribed in the equipment’s technical manual is a necessity.

Receiver Characteristics

Sensitivity, noise, selectivity, and fidelity are important receiver characteristics. These characteristics will be useful to you when performing receiver tests. They can help you to determine whether a receiver is working or not or in comparing one receiver to another.

Sensitivity

The ability of a receiver to reproduce weak signals is a function of the sensitivity of a receiver. The weaker a signal that can be applied to a receiver and still produce a certain value of signal output, the better the sensitivity rating. Sensitivity of a receiver is measured under standardized conditions. It is expressed in terms of the signal voltage, usually in the microvolts that must be applied to the antenna input terminals to give an established level of the output. The output may be an alternating current (ac) or direct current (dc) voltage measured at the detector output or a power measurement (measured in decibels or watts) at the loudspeaker or headphone terminals.

Noise

All receivers generate a certain amount of noise, which must be considered when measuring sensitivity. Receiver noise may originate from the atmosphere (lightning) or from internal components (transistors). Noise is the limiting factor of sensitivity. Sensitivity is the value of input carrier voltage (in microvolts) that must be applied from the signal generator to the receiver input to develop a specified output power.

Selectivity

Selectivity is the degree of distinction made by the receiver between the desired signal and unwanted signals. The better the ability of the receiver to reject unwanted signals, the better its selectivity. The degree of selection is determined by the sharpness of resonance to which the frequency determining circuits have been engineered and tuned. Selectivity is usually measured by taking a series of sensitivity readings. While taking the readings, you step the input signal along a band of frequencies above and below the circuit resonance of the receiver; for example, 100 kHz below to 100 kHz above the tuned frequency. As you approach the tuned frequency, the input level required to maintain a given output level will fall. As you pass the tuned frequency, the required input level will rise. Input voltage levels are then compared with frequency. They can be plotted on paper or you might view them on an oscilloscope. They would appear in the form of a response curve. The steepness of the response curve at the tuned frequency indicates the selectivity of the receiver.
Fidelity

The fidelity of a receiver is its ability to accurately reproduce, in its output, the signal that appears at its input. Usually, the broader the band passed by frequency selection circuits, the greater your fidelity. You can measure fidelity by modulating an input frequency with a series of audio frequencies and then plotting the output measurements at each step against the audio input frequencies. The resulting curve will show the limits of reproduction.

Good selectivity requires that a receiver pass a narrow frequency band. Good fidelity requires that the receiver pass a broader band to amplify the outermost frequencies of the sidebands. Receivers in general use are a compromise between good selectivity and high fidelity.

Receiver Sensitivity

Noise-figure measurements are a ratio of the signal-to-noise power ratio of an ideal receiver to the signal-to-noise power ratio of the receiver under test. Sensitivity measurements, however, are relative measurements that are arbitrarily calculated to be the 30-percent, 1,000-hertz (Hz) modulated signal input required to raise the detected audio 10 dB or greater above the receiver's noise level. Sensitivity is measured in microvolts, or in dB below 1 volt. This arbitrary reference value was selected because a 10 dB change represents a change in voltage by 10 times. Therefore, the detected output, as measured across a given resistance with zero signal input to the receiver, can be increased by a factor equal to or greater than 10. This increase can be achieved by increasing the input modulated signal level (in microvolts) to a predetermined level. Note that sensitivity (and selectivity) may be affected by alignment in all types of receivers.

As receivers become more complex, alignment becomes more of a problem. In AM receivers, improper alignment may result in the loss of weak signals through loss of sensitivity, and through inability to select the desired signal. Tracking error produces a varying IF, which results in a loss of signal over portions of the frequency range of the receiver. In FM receivers, the discriminator tuning becomes somewhat critical. In phase-modulated receivers, phasing of the carrier must be correct, adding to the alignment problem. Proper alignment procedures must be followed when automatic gain control (AGC) and AFC are added to receivers. In equipment employing crystals, as reference generators, oscillators, or filters, the alignment must center on the crystals since, the frequencies of crystals are not variable. As a result, because of the wide variations in circuitry between models of receivers, the actual alignment procedures and specifications provided in the applicable technical manual must be closely followed if the sensitivity check indicates a need for alignment.

Single Sideband Sensitivity Measurement Considerations

Sensitivity measurements for SSB receivers are determined in a manner similar to that used for other AM equipment. However, take the following considerations into account when performing measurements.

FM (F-3) Sensitivity Measurement

The procedures for measurement of FM (F-3) receiver sensitivity are analogous to those for AM receivers; however, an FM signal generator must be used. The modulation signal is a 1,000 Hz tone with 2,500 Hz deviation. The modulation-on/ modulation-off reference is still used as in AM, and the minimum signal required to obtain a 10 dB drop is a measure of the receiver’s sensitivity.

Pulse-Modulation Sensitivity Measurement

CW generator methods of measuring sensitivity do not provide an accurate indication of the ability of a receiver that is designed for the reception of pulse-modulated signals to receive weak pulse transmissions. A better method of determining the sensitivity of a pulse-modulation receiver involves
performing a minimum-discernible signal measurement. This type of measurement consists of measuring the power level of a pulse whose level is just sufficient to produce a visible receiver output. Because of the relatively wide bandwidths associated with pulse-modulation receivers, an even better performance indication can be obtained by determining quantitatively how much noise is inherent in the receiver. Noise is the limiting factor in the determination of maximum sensitivity. This method of checking sensitivity uses a noise generator for a signal source. The noise in the receiver is related to a calculable noise figure.

Determining IF Bandwidth Response

A graph showing the bandwidth response of an IF amplifier can be constructed by plotting frequency horizontally (from left to right) and signal amplitude vertically. This method is ideal for record retention purposes, but it is not necessary for receiver checks and adjustments. For such checks and adjustments, a spectrum analyzer is used in conjunction with a tracking generator as illustrated in Figure 3-12. The voltage control oscillator (VCO) feeds both the spectrum analyzer’s mixer and the tracking generator’s mixer. Because of this simultaneous precision tracking, the tracking generator’s output frequency acquires the same scan capabilities as the spectrum analyzer. Therefore, the analyzer’s calibrated scan widths, which range from broadband to extremely narrow, are acquired by the tracking generator and can be applied to various IF strips. This configuration makes identification of any point on the display easy and unambiguous. The 3 dB point, 60 dB point, center frequency, or any point on the display can be measured by stopping the scan (either electronically or manually) at the point of interest and reading the indication on the tracking generator.

![Figure 3-12 — Equipment arranged to obtain visual IF bandwidth response.](image)

Selectivity and Bandwidth Measurements

As previously discussed, selectivity is the property that enables a receiver to discriminate against transmissions other than the one to which it is tuned. It is usually expressed in the form of a curve obtained from a plot of the strength of a standard modulated carrier signal required to produce a constant (standard) output, versus off-resonance frequency. A typical selectivity curve with the carrier signal strength at resonance used as a reference is shown in Figure 3-13.
The bandwidth of a receiver is usually employed to define that portion of the selectivity curve that represents the frequency range over which the amplification is relatively constant. For most receivers, the bandwidth represents the usable portion of the curve, and has a direct relation to the fidelity of the modulated intelligence. Practically, the bandwidth is measured at the half-power down (3 dB down) or, for certain applications, at the 60 dB down points. This measurement is represented by the frequency range between the two points on a response curve expressed as relative response in dB versus frequency, as shown in Figure 3-14. The bandwidth at the 3 dB (or often the 6 dB) points, when compared with the bandwidth at the 6 dB down point, gives a good indication of the selectivity of the receiver. The character of the skirts of the curve becomes apparent. This comparison is referred to as the bandwidth or selectivity ratio. In most receivers, the overall bandwidth is determined by the IF amplifiers. Therefore, bandwidth is sometimes considered a fundamental IF characteristic measurement.

**Overall Selectivity**

Since the RF stages of a receiver are also of some importance in determining the selectivity, and are of fundamental importance in determining the image rejection characteristics, the selectivity factor is most often plotted as overall selectivity. The term “overall selectivity” usually refers to the frequency selectivity of a receiver as measured from (and including) the antenna to the input terminals of the final detector. It does not normally include any elements of the audio system. The overall selectivity of a superheterodyne receiver may be difficult to measure accurately with the equipment available in most operating installations, especially at frequencies above 1 MHz. If the lowest signal frequency is at least several times that of the lowest IF used in the receiver, the overall selectivity is very likely to be practically the same as the lowest IF selectivity. Therefore, the lowest IF selectivity curve may suffice, and it is much easier to obtain.

**Bandwidth**

When making bandwidth measurements, the receiver’s AGC should be disabled (grounded), connected to a source of fixed bias or turned off, and the volume control set to maximum. Bandwidth
curves can be obtained with the test setup illustrated in Figure 3-12. This procedure can be used for narrow or wide-band receivers employing any type of demodulation. When making IF bandwidth measurements, the spectrum analyzer is set to the IFs center frequency. The scan width and scan speed controls are then adjusted to achieve an undistorted display. If the scan time is too short with respect to the scan width of the spectrum analyzer, the response curve will appear wider than it actually is and the amplitude will be greatly reduced. This condition is illustrated in Figure 3-15.

**Automatic Gain Control Measurements**

An AGC circuit reduces the effect of signal strength fading by maintaining a constant carrier level at the detector input of an AM receiver, despite variations of the in-signal carrier level. To determine the effectiveness of the AGC circuit, its characteristic should be measured at the center frequency of each band covered by the receiver. A curve can be plotted to compare the change of the receiver output to input signal levels.

The standard method of measuring the AGC of amplitude-modulated receiver is to set the signal generator for 30 percent, 1,000 Hz modulation at carrier frequency. The receiver gain is set to maximum, and the carrier level is then varied over a wide range, such as .4 microvolts (μV) to 50 μV. The relative output is then plotted in dB as a function of carrier input voltage, which is also presented in terms of dB. Either a vacuum tube voltmeter (VTVM) or a spectrum analyzer can be employed to obtain the output measurement. A typical plot of carrier signal versus power output with different percentages of modulation is illustrated in Figure 3-16. In SSB receivers, the procedure transmission is similar except that the carrier is unmodulated.

**Delayed AGC Considerations**

Delayed AGC circuits are often incorporated in a receiver because even the weakest signal received in conventional AGC circuits tends to reduce the gain of the receiver somewhat. The delayed AGC adaptation incorporates a separate diode (AGC diode) in addition to the detector diode. Part of the signal fed to the detector diode is coupled to the AGC diode by a small capacitor. The AGC diode is maintained at a suitable bias; this bias keeps the diode until the peak voltage of the amplified signal voltage equals the bias introduced to the diode. For very weak signals that do not produce enough
voltage on the anode of the AGC diode to overcome the existing negative potential, no AGC voltage is developed. Thus, the sensitivity of the receiver remains constant, just as if the AGC were not being used. When normal strength signals are being received and they do not need the maximum sensitivity of the receiver, enough signal voltage will be coupled to the AGC diode to overcome the bias applied. AGC voltage will thus be developed normally for these stronger signals. Measurements on delayed AGC circuits are made in the same manner as described for conventional AGC circuits; however, particular attention should be given at the low-input portions of the curve.

**Receiver Standard Measurements**

In the measurement of single sideband reception, it is imperative that the standard oscillator used be precise. Two methods are used to determine the precision of the frequency standard. One method involves measuring the output of the standard against a frequency counter. The frequency counter must therefore be more accurate than the standard to be measured. The other method, used in most SSB receivers, compares an extended primary standard with the internal receiver standard. The two signals are fed to a difference network, whose output is fed to either a meter with zero center swing or to a light that blinks on and off. In both instances the receiver’s standard is compared against the primary standard input or a minimum zero change. Any adjustments are made only after the receiver has had time to warm up thoroughly. Receiver standard adjustments are done in very small increments. At no time will any adjustments be made to calibrated standards.

**Squelch Circuit Measurements**

FM and high-frequency receiver circuits inherently have a high noise level when no signal is being received. During communications, where a receiver is tuned to a specific frequency for long stand-by periods in anticipation of signals that may appear at any time, the continuous roar of noise is annoying to anyone in the vicinity of the receiver. To silence the audio output during these periods, a squelch (or silencer) circuit has been incorporated. This circuit eliminates unwanted signal noise and other disturbances during periods of inactivity (no signal). Squelch circuits block the input to the audio stage of the receiver whenever the signal voltage is very low or is entirely absent at the detector. The squelch circuit accomplishes this silencing effect by applying a very large cutoff bias to the first audio amplifier, by actuating a relay to open the audio line, or by gating open the audio line with a field-effect transistor (FET), as shown in Figure 3-17. The high-pass filter removes all low-frequency signal components and passes the high-frequency noise components. The high-frequency noise increases with a decrease in signal strength, thus providing a gate control signal to the audio output gate FET and cutting it off in low to no signal condition.

When cutoff bias squelch is required, it must be in excess of cutoff to prevent the noise output from the intermediate amplifiers from causing current to flow in the first audio amplifier stage, even
momentarily, on the noise peaks. To determine the squelch characteristic, set the signal generator to a frequency with 1,000 Hz, 30 percent modulation. With the signal generator RF output control set for zero output, note the receiver output, which should be essentially zero. Gradually increase the signal generator RF output until the squelch circuit operates. A sudden increase in the radio receiver output indicates operation of the squelch circuit. You can record the signal generator RF output required for the operation of the squelch circuit as representing the squelch characteristic.

Modulation Distortion Measurements

The distortion produced in the RF, IF, and detector stages of a receiver can increase significantly as a result of increases in the percentage of modulation. One method for determining the distortion of a receiver in terms of the percentage of modulation is to connect a signal generator to the receiver input, and to shunt a suitable resistor across the receiver output. The distortion meter should be connected across the resistor. The distortion meter will not respond to the resonant frequency, which is suppressed, but will provide the root mean square (RMS) value of the other components of the distorted output signal. The meter will provide an indication of the amounts of distortion for calibrated percentages or modulation. The signal generator should be modulated at 1,000 Hz and set for an output of 50 microvolts (μV). The receiver volume control should be adjusted for a low-level output of 50 milliwatts (mws). This level should be maintained throughout the test. Maintaining this low power output level keeps the distortion contributed by the audio section to a low, constant level.

The percentage of modulation at the generator is then increased in convenient steps from 10 to 100 percent, and the results are plotted on linear graph paper, with the modulation percentage appearing horizontally and the value of distortion vertically. This test should then be repeated for different RF gain settings to determine whether the RF and the IF amplifiers affect the modulation.

Automatic Frequency Control Characteristic Measurements

AFC circuits are most often found in FM receivers and in very-high-frequency (VHF) and ultra-high-frequency (UHF) receivers because of the high degree of oscillator frequency stability required. Thus, FM receivers incorporate discriminator circuits, whose output voltage and polarity are contingent upon the direction and deviation from a center, or mean value. For purposes of oscillator frequency control, a sampling of this voltage is filtered to remove any ac component. The resulting variation in dc voltage is applied to the local oscillator, which is a VCO. The VCO varies frequency as a function of the direction and magnitude of the applied correction voltage. The voltage-sensitive component of the VCO may be in the form of a saturable reactor or a varicap. Either component varies the reactance of the oscillator tank circuit, thus changing the oscillator’s frequency. The use of this technique can decrease the amount of frequency drift as much as 100 to 200 percent in an uncontrolled receiver.

To determine the locking range of the AFC circuit, connect a signal generator to the input of the receiver at some suitable level at the center frequency. Tune the signal generator both above and below the center frequency and note the break-off points.

RECEIVER ALIGNMENT

Sensitivity and selectivity are critical factors in alignment of all types of receivers. Improper alignment in AM receivers using conventional full-carrier signals will result in degraded selectivity. As previously discussed, AGC and AFC are complicated circuits that require particular attention during receiver alignments. Procedures contained in specific maintenance instruction manuals will provide detailed initial set-up procedures to ensure their ability to affect sensitivity and selectivity as part of their normal operation does not affect receiver alignment. When multiple conversion is incorporated in the receiver with two or more heterodyne oscillators, additional variables are introduced, further complicating alignment. In equipment employing crystals as either reference generators, oscillators, or
filters, as previously discussed, the alignment must center on the crystals because the frequencies of individual crystals are not variable.

Alignment of Crystal Filter Circuits

Crystal filters are incorporated in communications receivers that require an extremely high order of selectivity. These filters are usually located between the receiver-mixer and intermediate amplifier stages. The crystal is the major component of the filter. It is used because of the extremely high Q (sharpness of a resonant circuit), stability, and accuracy that they exhibit during operation. The filter is adjustable so that a variation in bandpass can be obtained. Crystal filters are often used as wave traps, and are extensively used in SSB equipment because of the sharp frequency-cutoff property required for this type of equipment. However, filters are generally of the crystal-lattice type; they are usually hermetically sealed or potted and should not be tampered with. Some lattice or half-lattice crystal filters have adjustable trimmers, accessible as potentiometer adjustments. Some adjustments are labeled as factory adjustments and should never be disturbed. Consult the manufacturer’s technical manual before making any adjustments.

Schematic diagrams of crystal filters usually indicate variable capacitors and variable inductances. Such diagrams may be misleading to those unfamiliar with filter circuits. Capacitors in parallel with filter crystals are usually of very small value, on the order of 1 to several picofarads. These capacitors frequently consist only of leads given a slight wrap or twist. They may be a piece of wire bent near the crystal holder or electrode. Such capacitors are factory-adjusted, and are usually not accessible without dismantling the filter. The schematic symbols for a crystal and its equivalent electrical circuit are shown in Figure 3-18, view A.

A crystal in its holder is actually a combination of both series and parallel resonant circuits. As such it has two resonant frequencies, as shown in Figure 3-18, view B. The series-resonant frequency occurs at the point where the reactance curve crosses the zero-reactance line. The parallel-resonance (anti-resonance) frequency occurs at the point where the reactance curve rises to a high inductive reactance. The frequency then falls sharply through the zero-reference line to a high capacitive reactance. In most crystals, the two resonant frequency points will occur within a few hundred cycles of each other. The points can be spread (or narrowed) by shunting them with a lump constant so that a suitable filter network can be designed. Phasing controls on interference filters are examples of capacitance introduced into the filter circuit to shift the crystal rejection slot (parallel-resonant frequency) so that specific unwanted signals can be rejected.

When filter circuits are aligned, the circuit in which it is integrated must be considered. When connected in the IF amplifiers of a communications receiver, either conventional AM or SSB, the alignment will consist principally of properly tuning the resonant input circuit to the filter and to the

Figure 3-18 — Equivalent electrical circuit and reactance curve of a quartz crystal.
resonant circuit at the output of the filter (Figure 3-19) for maximum output. The points of parallel resonance must be aligned for sharp cutoff (maximum attention) at the design frequency. This is an especially important consideration for equipment containing AFC circuits. If sufficient response is not allowed, the carrier may be severely attenuated at a slightly too low (or too high) frequency. This condition will cause the AFC circuit to drop control. Thus, the desired limits of AFC operation are also considered in the bandpass of the filter and vice versa.

Alignment of Wave Traps

The term "wave trap" usually refers to a resonant element used as an auxiliary device to provide additional frequency selectivity in a radio circuit. It may take a distributed form (resonant stub or cavity), or it may consist of a lumped reactor combination (inductor and capacitor) (Figure 3-20). A trap normally provides a means of rejecting (or accepting) signals over only a relatively narrow band of signal frequencies. The width would depend on the effective Q of the trap circuit. The trapping desired may result from the shorting effect of a series-resonant circuit shunted across the
signal path; from the selective opposition to the flow of current afforded by a high value of resonant impedance in series with the path; from selective degeneration in an amplifier, produced by using resonant circuits to provide frequency-dependent feedback, etc.

Some of the more common lumped-reactor wave-trap applications are shown in Figure 3-20. In addition to those shown, many other forms of wave traps may be incorporated in radio equipment. In some applications, a wave trap is used to suppress response at a frequency not desired in one channel. The resulting trap resonance at that frequency is used as a means of supplying the signal to a second channel. Resistance capacitance (RC), resistance-inductance (RL), and inductance-capacitance (LC) networks, affording high-pass and low-pass characteristics, are also employed to provide band elimination or bandpass effects for wave-trapping purposes.

The operating frequencies and apparent effects of wave traps differ from one type of equipment to another. In general, leave the traps until the last steps in a prescribed alignment procedure because of their auxiliary corrective nature. On the other hand, you should usually adjust wave-trap trimmers at very specific frequencies and under particular conditions, which you should rigidly observe. If adequate instructions for wave-trap alignment are lacking in an equipment technical manual, take immediate steps to obtain further instructions. An incorrectly adjusted trap circuit may produce serious shortcomings in equipment operation that are not apparent to the operator under ordinary conditions. The signal generator and output indicator commonly employed in the alignment of receiver-tuned circuits will usually serve for wave-trap alignment in receiving equipment. Other forms of radio equipment employing traps, such as field-strength meters and oscilloscopes, may require special instrumentation.

**Alignment of Beat Frequency Oscillators**

Beat frequency oscillators (BFOs) are incorporated in communications receivers to provide an audible indication of received continuous-wave transmission. They are also used to calibrate dials in receivers containing internal crystal calibration oscillators. Figure 3-21 shows a schematic diagram of a typical manually operated BFO that is heterodyned against the IF. The procedure for aligning this type of oscillator requires feeding an unmodulated signal into the input of the receiver, with the receiver switched to the CW mode of operation. A frequency counter is connected to the phone jack to record the frequency of the detected signal caused by heterodyning the BFO with the incoming IF signal. Then L1 is adjusted so that the BFO vernier control will cause a readout of the frequency counter of 6,000 Hz above and below the zero beat.

![Figure 3-21 — Beat frequency oscillator circuit.](image)
AM Receiver Alignment

Prior to the alignment of an AM receiver, the automatic gain control (if possible) should be turned off. The gain should be adjusted by means of the manual RF gain control. The gain level should be set to give the standard 6 mws of audio output with about 100 to 1,000 microvolt of signal input at the receiver antenna terminals. This alignment condition is desirable to reduce the detuning effect of receiver gain variations as reflected in changes of overall selectivity. It ensures the circuits will be resonated under average load conditions at approximately the middle working value or amplifier’s input reactance and with freedom from serious regeneration. With most receivers, this condition also reduces receiver noise to a degree that renders it unnecessary to quiet the receiver by removing the amplifier stage preceding the point of alignment-signal injection.

Disabling Automatic Gain Controls

AM receiving equipment that operates with automatic gain control as a permanent condition (with a built-in provision for the alternative manual control of RF and IF gain) may present a problem, especially if considerable regeneration is normally present at full gain. It may not be feasible to disable the automatic gain control in order to add a temporary battery-biased manual gain control potentiometer in its place. In such cases, it will be necessary to align each section of the receiver (with suitable signal-input levels at the various points of signal injection) to produce final detector operation below the threshold of AGC action. Disable the amplifier stage preceding the point of alignment signal injection to preclude the presence of unwanted signals and noise.

Disabling Local Oscillators

Do not disable the heterodyne oscillator or oscillators when aligning a receiver, except for the BFO, which is used to provide tone output from the final detector in CW reception. The heterodyne oscillator injection voltage is ordinarily a major factor controlling the mixer’s operating bias and impedance, with consequent influence on gain and both mixer input and output circuit resonance. In some cases, adjustment of heterodyne oscillator tuning may not be possible as a means of preventing undesired beats or random signals that may result from the interaction of the alignment signal and the heterodyne injection voltage. The oscillator must then be disabled. Stopping an oscillator by short circuiting its input to ground or by shorting its tank circuit may cause serious damage to the oscillator and to other electronic parts. Therefore, removal of the oscillator output is the safest way to disable the oscillator. The receiver’s technical manual will detail the procedure for oscillator removal if it is required for alignment.

Beat Frequency Oscillator Considerations

The BFO injection voltage in a properly designed CW receiver usually produces a large fixed bias at the final detector and will mask its rectified voltage changes. This masking is objectionable when the rectifier signal voltage is employed as an output indication for alignment. Before starting the actual alignment, disable all auxiliary functions provided in the receiver that may interfere with proper output indication or circuit resonance including the squelch circuits and noise limiters.

IF Amplifier Alignment

With a few exceptions, such as some trap circuits, IF resonant circuits are aligned by adjusting their trimmers to produce maximum signal voltage. The IF trimmers of a typical AM receiver are thus adjusted to produce maximum final-detector signal input voltage, using the input signal frequency or frequencies prescribed in the technical manual for the equipment. In many cases, this will be the nominal band center frequency of the particular IF amplifier. In other instances, usually involving relatively wide IF bandpass, “peaking” of some or all trimmers for maximum response at one or more
frequencies off the band center will be specified. In general, align the last IF transformer preceding
the detector first, unless the equipment technical manual specifies a different order.

The input from the signal generator should be adjusted to adjust the input from the signal generator to
produce a signal output level that is well above the noise level at the output indicator, but also well
below the saturation level of the amplifier stages. As needed, progressively reduce the signal input as
more circuits are brought into proper alignment. The progression of circuit adjustment should move
toward the mixer stage. After completing the first round of alignment adjustments of the IF amplifier
stages, perform an overall check of the IF alignment. Use a similar procedure for the alignment of the
preceding IF amplifier(s) in receivers employing more than one frequency conversion. The IF signal
input should, in each case, be injected at the input electrode of the mixer preceding that particular IF
amplifier. This ensures inclusion of the transformer located in the output circuit of the mixer. Disable
the associated conversion oscillator if necessary, as previously discussed.

**RF Stage Alignment**

In addition to a suitable signal generator, use the dummy antenna specified by the receiver instruction
book to simulate an ideal antenna for the receiver. Adjust the signal generator (modulated as
required) to the upper alignment frequency specified for the particular receiver tuning band, using an
external frequency standard if necessary. If an antenna trimmer control is provided on the front panel
of the receiver, set it to the middle of its range. Tune the receiver to that signal frequency and the
generator output to produce the desired maximum (or other specified optimum detection on the
receiver output indicator).

The control panel frequency indication should coincide with the signal frequency being supplied. If it
does not, reset the control panel to indicate the proper frequency. Adjust the high frequency (shunt
capacitance) trimmer of the oscillator tank circuit to produce optimum output from the test signal.
Following these adjustments, adjust the inter-stage and antenna circuit shunt-capacitance trimmers
for optimum output, with the test signal input level reset, as needed, to avoid receiver saturation
effects.

Oscillator shunt trimmers occasionally have an unusually wide range of adjustments. For this and
other reasons, it is possible to misalign the circuit so the heterodyne oscillator is on the wrong side of
the signal frequency. In many instances, this mistake will be revealed as an inability to obtain good
circuit tracking over the tuning band. Sometimes, however, the mistake will not be so clearly
apparent. Therefore, always ensure that the oscillator is being trimmed on the proper side of the
desired signal frequency. Determination of the proper relationship from the equipment instruction
book, together with careful observations of shunt trimmer positioning (whether its capacitance is
increasing or decreasing relative to the two positions of heterodyne response that it produces), will
help to prevent error. Next, you should check the oscillator alignment at some specified frequency
near the low-frequency end of the tuning band.

In many military receivers, iron core or eddy current trimmers are used in the RF coils to permit tank
inductance adjustments for optimum low-frequency tracking of all RF circuits. Make the inductance
adjustments on all coils except the oscillator coil before checking the oscillator series padder (a tuning
capacitance circuit). Then trim the series padder to produce optimum output while the receiver tuning
control is “rocked” back and forth through the region test signal response.

If oscillator tracing relative to the other RF circuits is poor over the band as the tuning control is
operated throughout its range (indicated by abnormal variations of gain and/or output noise), you may
need to adjust the oscillator tank inductance trimmer. You can determine the correction needed to
produce better tracking by trial readjustment of the oscillator shunt capacitance trimmer. If the
tracking (check by tuning from the high-frequency to the low-frequency alignment points) is improved
as you increase the shunt-trimmer capacitance, the oscillator tank inductance is low. If you must
decrease the shunt-trimmer capacitance to obtain improvement, the tank inductance is high. Correction adjustment of oscillator tank induction will necessitate some changes in oscillator series padders and shunt-trimmer adjustments. Also, you must repeat the preselector alignment procedure. In either case, you must repeat the entire preselector alignment procedure. If the control panel indications are still in error over part of the band, it may be possible to correct the calibration to some degree by further slight readjustments to the oscillator and other trimmers. Only undertake this realignment after careful study of the tracking discrepancies and calibration errors over the entire band. Ensure that you fully understand the superheterodyne tracking problems if adequate directions are not available.

It is not acceptable to sacrifice receiver gain and selectivity for the convenience of accurate control box calibration. Check receivers that incorporate IF traps in their RF circuit by applying a signal, at the IF, to the receiver input. The trimmers for such traps are usually adjusted for minimum output at the center frequency of the first IF amplifier, and may require large input signal amplitude at that frequency.

**FM Receiver Alignment**

The basic difference between receivers used for the reception of frequency or phase-modulated signals and those used for the reception of AM signals lies in the types of demodulator and IF amplifier circuit employed. In an FM receiver, a frequency-sensitive demodulator is used. IF amplifiers are designed to cause, rather than avoid, amplitude limiting. When testing several amplifier stages that have similar operating functions, such as successive IF stages, it is possible (but not recommended) to test immediately for an “overall” response curve such as that shown in Figure 3-22. You may see this curve at the output of the last IF stage or at the grid of the limiter.

When using an FM signal generator for testing wide-band equipment, such as an FM receiver, you can see the response curve directly on the screen of an oscilloscope. Improperly applied, this procedure could consist of randomly varying the different adjustments in all the stages until the overall response curve appears to be satisfactory. But, this good-looking curve may result from a compromise. This generally means that a poor alignment in one stage is compensated by overemphasized and shifted alignment in other stages. The reason for this is that one stage may be peaked unsystematically, another stage may have a center peak, and the remaining stages may have two response peaks. This situation refers to all IF stages—no stage by itself satisfies the condition required for linear networks with respect to amplitude and phase. Distortion is bound to result.

Regardless of the method of aligning the receiver, the recommended practice is to first align the discriminator. You must have a sufficient signal source, the sensitivity of the indicator must be high, and the IF transformers must not be excessively detuned. The remainder of the set, up to the

---

**Figure 3-22 — FM versus AM resonance curves.**
discriminator, is then aligned. Always make the correct IF alignment by first aligning the IF stage ahead of the limiter, then the preceding IF stage, walking through the process in a “two steps forward, one step back” method. Regarding the RF stage or stages before the mixer, ordinary single peaking is generally practiced. To align the receiver most conveniently, use an FM signal generator. However, if such a generator is not available, you can use an AM generator. You can employ a meter on an oscilloscope as an output indication. Normal receiver alignment consists of the following sequence:

1. Alignment of the demodulation (discriminator) stage
2. Alignment of the limiter stage
3. Alignment of the IF amplifier stages
4. Alignment of the RF stages

Limiter-Type Discriminator Alignment

A typical schematic diagram of a limiter-type detector is shown in Figure 3-23. In the double-tuned circuit shown, the primary and secondary are tuned to the carrier frequency. At the carrier frequency, the voltages developed across the diodes are equal to each other, and the diode currents are also equal. Thus, the opposing voltages developed across the output diode resistors are equal and therefore cancel. As a result, no voltage is developed at point A. At frequencies lower than that of the carrier frequency, there is more current flow through the lower diode than through the upper diode resulting in a negative voltage to be developed at point A. Conversely, at frequencies higher than that of the carrier frequency, there is more current flow through the upper diode causing a positive voltage to be developed at point A. Within the range of carrier-frequency swing, the dc output changes in proportion to the frequency change.

![Figure 3-23 — Limiter-type discriminator circuit.](image-url)
The signal generator is then set above and below the IF. The voltmeter should indicate equal but opposite direct voltages for equal but opposite frequency deviations. If you obtain unequal voltages, the setting of primary trimmer capacitor C2 is incorrect. Adjust the setting until equality is obtained. If necessary, repeat these operations until the proper indications are obtained. You can determine the linearity over the entire range by plotting the values obtained for steps of frequency deviation, as shown in Figure 3-24, view A. The output of the generator should be constant, or the limiter should be in full operation. A visual method of aligning the discriminator, using an FM signal generator and an oscilloscope, has an advantage over the meter method in that the discriminator curve may be observed. Since the effects of the adjustments are visible, no guesswork is involved.

There are two methods of setting the discriminator to its proper center frequency. The first method is more accurate and has more easily observed results. Start by applying an AM RF signal of the correct center frequency to the discriminator. Then, adjust the discriminator’s secondary for minimum signal output. The output signal will disappear if the discriminator characteristic measurements are symmetrical because the output will be zero at the center frequency. To use the AM signal method for aligning the discriminator to its center frequency, connect an AM signal generator to point B (Figure 3-23) and the oscilloscope vertical input to point A. Set the signal generator for 400 Hz amplitude modulation, and adjust the oscilloscope controls for a convenient pattern size. When the discriminator secondary trimmer capacitor (C1) is not adjusted to the current frequency but is close to it, a pattern similar to Figure 3-24, view B, will appear. To align the discriminator to the correct center frequency, adjust the secondary trimmer capacitor slowly in one direction, and then in the other direction until the 400 Hz signal disappears and then reappears with a further movement of the trimmer. Set the capacitor midway between these points. Then connect an FM signal generator to point B (Figure 3-23). Leave the oscilloscope vertical input at point A and connect the horizontal input to the modulation circuit of the signal generator. Adjust the signal
generator for full frequency deviation and set the oscilloscope controls for a convenient pattern size. Then, adjust the primary trimmer capacitor, C2, (Figure 3-23) for a symmetrical curve similar to the one shown in Figure 3-24, view A.

In the second method, insert a marker pip on the discriminator response curve. The pip should be set for the crossover point at the center frequency. The center frequency is determined by noting where the marker disappears and reappears. Because of the difficulty in observing the exact points of appearance of this pip, this method sometimes leads to inaccurate results. When using the marker method, connect the FM signal generator and oscilloscope as described above. Then couple point A, marker generator or wavemeter with the signal generator output to point B (Figure 3-23) to produce a pip on the discriminator response curve. With the marker signal generator or wavemeter set at the discriminator center frequency, adjust the secondary trimmer capacitor until the marker disappears at the crossover point at the center of the response curve. Then, adjust the primary trimmer capacitor for a symmetrical curve.

**Ratio Detector Alignment**

Another type of FM detector (Figure 3-25) is called a “ratio detector.” This circuit is based on changes in the ratio of the voltage across the two diodes rather than on differences in voltage. A ratio detector is virtually insensitive to amplitude variations. The tuning and coupling provisions are about the same as in a limiter-type discriminator. As a result, the RF voltage developed across the diode at any instant depends upon the amount of frequency deviation from the carrier center frequency. Unlike the arrangement in the limiter-type discriminator, however, the diodes are connected to conduct simultaneously, so that a negative voltage is developed across the load resistor. A filter capacitor connected across the load resistor has enough value to hold the voltage constant even at the lowest audio frequencies to be reproduced. The voltages across the diodes differ according to the instantaneous frequency of the carrier. The rectified voltages across capacitors C3 and C4 are proportional to the corresponding diode voltages. Although each of these voltages vary, their sum is held constant by the filter. As a result of this reaction, an audio output is developed across C4. Many modified versions of the ratio detector are in common use. However, the operation and alignment procedures are similar to those described for the ratio detector.

To align a ratio detector, connect an FM signal generator between point B and ground, and connect the input to the oscilloscope between point A and ground (Figure 3-25). Set the generator to the center frequency, with maximum frequency deviation. Adjust the discriminator, the primary trimmer
capacitor, C2, for a curve of maximum amplitude. The curve will appear somewhat S-shaped if the secondary trimmer capacitor C1 is not excessively detuned. Keep the generator attenuation control set for an output below the level where limiting occurs. Next, adjust the secondary trimmer capacitor until the S-shaped curve is symmetrical (Figure 3-24, view A). Set the curve to exact center frequency as described previously for discriminators. If necessary, retune the detector primary trimmer for a symmetrical response of maximum amplitude.

**IF Amplifier Alignment**

Specific alignment procedures are included in technical manuals for particular receivers. Specific response curves for each transformer may be given so that a particular overall response curve may be obtained. However, in general, you can align the IF amplifiers by feeding an FM signal from the generator to the IF amplifier just preceding the limiter, while observing the discriminator output. Then adjust the secondary of this IF amplifier for a symmetrical S-shaped curve that has a proper frequency response of maximum amplitude. Repeat the procedure to tune the primary. If the output can be kept below the threshold of limiting by reducing the generator output, adjust each IF secondary and primary in sequence, proceeding from the last IF stage curve of maximum amplitude. Should limiting occur, observe the response curve of the amplifier at the grid of the limiter and tune the IF amplifiers for proper bandpass (Figure 3-22).

**RF And Oscillator Stages Alignment**

The RF and oscillator stages may also be aligned by using of an FM signal generator and an oscilloscope. To align these stages, connect the output from the generator to the antenna terminals of the receiver through a matching network. Connect the oscilloscope input to the discriminator output. Set the generator to a frequency in the approximate center of the band being tested. Set the frequency deviation greater than the receiver bandpass. Observing the receiver output response, tune the shunt (high-frequency trimmer capacitor) for maximum output.

An oscilloscope may also be used to check the response of the RF and mixer sections of a receiver. Connect the FM signal generator to the receiver input through a matching network. Connect the oscilloscope vertical input to the mixer plate decoupling network or, by means of a high-frequency detector probe, to the mixer’s output. The first IF amplifier is disabled during this test to reduce the loading effect of the oscilloscope input. Couple a marker signal-generator with the FM signal generator to the receiver input to determine the frequency points of the response curve. Set the FM signal generator for the desired frequency deviations. In many communications receivers, the front-end response curve is from 150 to 200 kHz wide. The bandwidth of the front end is largely fixed by the number and Q of the RF circuits, since all of the circuits are usually tuned to identical frequencies. Usually, the bandwidth of the RF circuits is considerably greater than the IF bandwidth, so that the latter mainly determines the bandwidth of the entire receiver. When making any adjustment of the front end, both the RF and overall response must be considered, since it is important that the RF response be wide enough to pass all of the important frequency components of the signal. Follow the previous procedure for measuring the RF response to perform this check.

**FIBER OPTICS**

Fiber optics is the branch of optical technology concerned with the transmission of radiant power (light energy) through fibers.

The difference between conventional electronic systems and fiber optic systems is how the data is sent. Fiber optics transmits light (photons) through glass fibers. Electronic systems send electrons through wire. Microwave and RF communication (including satellite links) rely on microwaves and radio waves traveling through open space.
In electronic systems, the data is sent using analog technology. If a computer uses a 5 volt logic state, then five volts represents a logic high or “1” and zero volts represents a logic low or “0”. The combination of highs and lows (1’s and 0’s) is the data (binary code) sent. In an optical system light ON is a “1” and light OFF or dark is a “0”. This type of transmission is called pulse code modulation (PCM). The data (pulses of light) is sent through fiber optic glass from the transmitter to the receiver. Data can be transmitted digitally (the natural form for computer data) rather than analogically.

Fiber optics revolutionized the telecommunications industry and has become the preferred norm of aviation and electronics technology. The cumbersome myriad of wires, connections, and cabling used today are being replaced by advanced, lightweight optical fiber lines. Airframe weight will be reduced and capabilities greatly increased. Fiber optic systems are increasingly being integrated into aircraft systems and support equipment.

The concept of fiber optics is not new. In the 1880s, William Wheeler patented a device for lighting a home by piping light from an electric lamp in the basement to rooms throughout in “light pipes.” Similarly, sailing ships funneled light from the main deck into below-deck compartments using glass deck prisms. Today, the F-35 Joint Strike Fighter’s central computing system integrates sensors, communications, and flight-control systems using high-speed fiber optic data buses.

Basic System

The principles of fiber optics follow the basic properties of light, including refraction and reflection. Light traveling within a fiber obeys the laws of propagation. Fiber optics is the technique of sending data in the form of light through long, thin, flexible fibers of glass, plastic, or other transparent materials. A basic system (Figure 3-26) consists of a data source, transmitter, optical fiber, detector, and data output device. The purpose of the transmitter is to convert an electrical waveform or digital data stream to the best optical signal for transmission through an optical fiber. The fiber or fibers guide(s) the light to a light detector that converts the light back into an electrical signal. The detector serves the opposite function from the transmitter: it converts optical energy to electrical energy. The output circuitry of the receiver amplifies and accurately reproduces the original digital signal.

Advantages of Fiber Optic Systems

Fiber optic systems have many attractive features that are superior to electrical systems. These advantages include improved system performance, immunity to noise, safety, and overall system economy. Table 3-3 lists the main advantages of fiber optic systems.

![Figure 3-26 — Basic fiber optic system.](image-url)
### Table 3-3 — Advantages of Fiber Optics

<table>
<thead>
<tr>
<th>System Performance</th>
<th>Greatly increased bandwidth, data transmission speed, and capacity</th>
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<tbody>
<tr>
<td>Immunity to Electrical Noise</td>
<td>Immune to noise (electromagnetic interference (EMI), high altitude electromagnetic pulse (HEMP), and RF interference (RFI))</td>
</tr>
<tr>
<td>Electrical Configuration</td>
<td>No common ground required. Used near fuel tanks because light, not an electrical pulse, is the energy sent</td>
</tr>
<tr>
<td>Size and Weight</td>
<td>Reduced size and weight cables</td>
</tr>
<tr>
<td>Environmental Conditions</td>
<td>Resistant to radiation and corrosion</td>
</tr>
<tr>
<td></td>
<td>Resistant to temperature and moisture variations</td>
</tr>
<tr>
<td></td>
<td>Improved ruggedness and flexibility</td>
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</table>

### Optical Fiber Structure

The basic structure of an optical fiber consists of three parts: the core, the cladding, and the coating or buffer. The basic structure of an optical fiber is shown in Figure 3-27. The core is a cylindrical rod of dielectric material. Dielectric material conducts no electricity. Light propagates mainly along the core of the fiber. The core is generally made of glass. The core is described as having a radius of \( a \) and an index of refraction \( n_1 \). The core is surrounded by a layer of material called the cladding. Even though light will propagate along the fiber core without the layer of cladding material, the cladding does perform some necessary functions.

The cladding layer is made of a dielectric material. The index of refraction of the cladding material is less than that of the core material. The cladding is generally made of glass or plastic. The cladding performs the following functions:

- Reduces loss of light from the core into the surrounding air
- Reduces scattering loss at the surface of the core
- Protects the fiber from absorbing surface contaminants
- Adds mechanical strength

For extra protection, the cladding is enclosed in an additional layer called the coating or buffer. The coating or buffer is a layer of material used to protect an optical fiber from physical damage. The material used for a buffer is a type of plastic. The buffer is elastic in nature and prevents abrasions.

![Figure 3-27 — Basic structure of an optical fiber.](image)
Light Transmission

The light injected into a fiber travels in a series of reflections from wall to wall between the core and cladding. The reflections depend on the cone of acceptance and resulting angles of refraction and reflection propagation (Figure 3-28). The cone of acceptance is the area in front of the fiber that determines the angle of light waves it will accept. The acceptance angle is the half-angle of the cone of acceptance. The light enters the core and refracts to the interface of the core and cladding. The light reflects at the same angle of impact. The light, reflecting from wall to wall, continues at the same angle to the end of the fiber at the detector. As in the physics of light, the maximum critical angle is that angle that, when surpassed, won’t reflect; in this case, it is lost in the cladding of the fiber. As long as the light wave is at a lesser angle than the maximum critical angle of the fiber (as determined by the function of the fiber’s core and cladding indexes of refraction), light will travel to the receiver.

Types of Optical Fibers

Optical fibers are characterized by their structure and by their properties of transmission. Optical fibers are classified into two types. The first type is single-mode fibers. The second type is multi-mode fibers. As each name implies, optical fibers are classified by the number of modes that propagate along the fiber. Single-mode fibers can propagate only the fundamental mode. Multi-mode fibers can propagate hundreds of modes. The structure of the fiber can permit or restrict modes from propagating in a fiber. The basic structural difference is the core size. Single-mode fibers are manufactured with the same materials as multi-mode fibers. Single-mode fibers are also manufactured by following the same fabrication process as multi-mode fibers.

Single-mode Fibers

The core size of single-mode fibers is small. The core size (diameter) is typically around 8 to 10 micrometers (μm). A fiber core of this size allows only the fundamental or lowest order mode to propagate around a 1,300 nanometer (nm) wavelength. Single-mode fibers propagate only one mode, because the core size approaches the operational wavelength (λ). This propagation is achieved by using a laser as a light source.

Single-mode fibers have a lower signal loss and a higher information capacity (bandwidth) than multi-mode fibers. Single-mode fibers are capable of transferring higher amounts of data due to low fiber dispersion. Basically, dispersion is the spreading of light as light propagates along a fiber.

Multi-mode Fibers

As their name implies, multi-mode fibers propagate more than one mode. Multi-mode fibers can propagate over 100 modes. The number of modes propagated depends on the core size and numerical aperture (NA). As the core size and NA increase, the number of modes increases.
A large core size and a higher NA have several advantages. Light is launched into a multi-mode fiber with more ease. The higher NA and the larger core size make it easier to make fiber connections. During fiber splicing, core-to-core alignment becomes less critical. Another advantage is that multi-mode fibers permit the use of light-emitting diodes (LEDs). Single-mode fibers typically must use laser diodes. LEDs are cheaper, less complex, and last longer. LEDs are preferred for most applications.

**Fiber Refractive Index Profile**

An optical fiber's refractive index profile and core size further distinguish single-mode and multi-mode fibers. The refractive index profile describes the value of refractive index as a function of radial distance at any fiber diameter. Fiber refractive index profiles classify single-mode and multi-mode fibers as follows:

- Multi-mode step-index fibers
- Multi-mode graded-index fibers
- Single-mode step-index fibers

Step-index fibers have large differences in the core and cladding indexes of refraction. When held constant these differences cause light to reflect from the interface back through the core to its opposite wall. Graded-index fibers have a decreasing core refractive index as the radial distance from the core increases. This arrangement causes the light rays to continuously refocus as they travel down the fiber. Both types operate in either single-mode or multi-mode. Single-mode accepts a specific wavelength, otherwise large attenuation will result. The multi-mode type operates over a range of wavelengths with minimum signal loss (Figure 3-29).

**Optical Fiber Cable Construction**

Manufacturers design fiber optic cables for specific applications. Navy systems require that fiber optic cables meet stringent environmental conditions. A design that will meet the harsh conditions that fiber optic cables are expected to be exposed to is the tight-buffered breakout. A tight-buffered breakout cable consists of individual single fiber cables, called Optical Fiber Cable Components (OFCCs). OFCCs are a tight-buffered core fiber surrounded by aramid yarn and a low-halogen outer jacket. The OFCC outer diameter is typically 2 millimeters (mm). The fiber is typically buffered with a polyester elastomer to a total diameter of 900 μm. Typical design of an OFCC is shown in Figure 3-30.
The size of the OFCC limits the amount of fibers contained within an individual breakout cable. A breakout cable generally contains less than 36 fibers (OFCCs). An isometric view of a breakout cable is shown in Figure 3-31. In this multifiber cable design, the OFCCs surround a flexible central member in a helical manner. The central member may add to cable strength or only support the OFCCs. For additional protection, two layers of aramid yarn strength members encase the OFCC units. These strength members are stranded in opposing layers to minimize microbending of the fibers. The aramid yarn strength members may be treated with polymers that are water absorbing, blocking, and sealing. This treatment eliminates the need for additional water blocking protection. Finally, a low-halogen, flame-resistant outer jacket is extruded over the strength members.

Properties of Optical Cables

Optical cables are affected by many physical properties. Among the most significant to you are the numerical index, dispersion, and attenuation.

Numerical Index

The numerical index of optical cables deals with the sine of the angle of acceptance. The numerical aperture (NA) (or numerical index) can be found using the formula shown below:

\[ NA = \sin i = n_1^2 - n_2^2 \]

where \( i \) = acceptance angle, \( n_1 \) = Core Index of Refraction, and \( n_2 \) = Cladding Index of Refraction.

The acceptance angle is a measure of the numerical aperture (NA) or numerical index of a fiber. This coding lets the manufacturer select the proper fiber for the desired specific light waves and for optimum power coupling. NA is a measure of the light capture angle (half-acceptance angle). It describes the maximum core angle of light rays that will be reflected down the fiber by total reflection.
The refractive index of a material is the ratio of the speed of light in a vacuum to the speed of light in the material. The higher the refractive index of a material, the lower the velocity of light through the material. Also, there will be more refraction or bending of the light when it enters the material.

If the NA increases, angle $i$ must have increased, and the fiber sees more light. NA can never be greater than 1.0; normal values are low (0.2 and 0.6).

**Dispersion**

Dispersion is the spreading or widening of light waves due to the refractive index of the material and the wavelength of the light traveling in the fiber. There are two types of dispersion—intermodal and intramodal.

- Intermodal (multi-mode) dispersion. The propagation (travel) of rays of the same wavelength along different paths through the fiber. These wavelength rays arrive at the receiving end at different times.
- Intramodal dispersion. A condition due to variations of the index of refraction in the core and cladding.

**Attenuation**

Attenuation is the loss or reduction in amplitude of the energy transmitted. These losses are due to differences of refractive indexes and imperfections in fiber materials. Also, man-made scratches or dirt and light scattering within the fiber cause unwanted losses. Efforts to reduce these losses include the forming of the following standard parameters:

- Bandwidth parameters. Bandwidth parameters include attenuation curves, which provide all designers the ability to choose the best fiber. These parameters are plotted in decibels per kilometers (dB/km). They measure the efficiency of the fiber as a comparison of light transmission to light loss through a fiber.
- Rise time parameters. These parameters set speed requirements for operation.
- Fiber strength parameters. These parameters set tensile strength standards to help reduce flaws and micro-cracks in the fiber.

**Fiber Coupling**

One important aspect of a fiber optic system is the connection between the fiber and the other components. Fiber optic connectors permit easy coupling and uncoupling of optical fibers. Fiber optic connectors sometimes resemble familiar electrical plugs and sockets. Systems may also divide or combine optical signals between fibers. Fiber optic couplers distribute or combine optical signals between fibers. Couplers can distribute an optical signal from a single fiber into several fibers. Couplers may also combine optical signals from several fibers into one fiber.

In a fiber optic system, minimizing loss at connection points is critical to performance. Every connection in the system is a possible point of failure. Take extreme care when terminating and connecting connectors. Splicing will not be covered in this lesson.

Fiber optic connection losses may affect system performance. The number one problem in maintaining a fiber optic system is contamination. A single contaminant particle mated in the core of an optical fiber can cause significant back reflection, insertion loss and even equipment damage (Figure 3-32). The average dust particle is 2 to 5 microns in diameter (.000002 to .000005um), which is not visible to the human eye. The typical filter size used in heating, ventilation, and air conditioning (HVAC) systems both commercially (in buildings) and onboard naval vessels is 5 microns. Most dust
particles flow right through them. Hence, the dust in your house. Typical HVAC filters were not designed to remove dust, just the big stuff. It would be like expecting a screen door to keep out the wind. Standard filters in were not designed with optics in mind.

Therefore, a 4 micron dust particle sitting on the core of an 8 micron single-mode fiber has the potential to create at least a 50 percent loss of power in the system. If a class 3a laser is the light source, it has enough power to burn the dust particle into the glass core causing permanent damage. Also, if it is a single-mode system, the back reflection caused by this particle can create bit errors and lower system performance to the point where the laser will shut itself down in order to protect itself. Good cleaning processes are critical to system performance. Before any optical connection is made, you should inspect the end face before mating the connector up. Also, since a dust particle has a negative charge and the glass and ferrule on the end face are dielectrics, the dust particle is attracted to the end face of the connector. Once the dust particle makes contact with the end face an ionic bond is made. In order to break the ionic bond, you should use a fiber optic preparation fluid with static-dissipating properties to clean the end face.

Cross contamination is also a major problem. If one side of the connection is dirty and is connected to a clean end face. The dirty one will cross contaminate the clean end face. That means you have to clean both end faces of the connectors being mated together before the connection can be made. A simple but effective practice for ensuring maximum performance from fiber optic systems is shown in Figure 3-33.

Follow this simple "Inspect Before You Connect" process to ensure Fiber End faces are clean prior to mating connectors.

![Diagram of cleaning process]

Figure 3-33 — Inspection and cleaning process.
Review Questions

3-1. Which of the following practices contributes to the accumulation of moisture and the premature failure of transmitting equipment?

A. Improper operation  
B. Premature changing of filters  
C. Operating at very high frequencies  
D. Poor routine maintenance

3-2. Which of the following types of equipment provides a better indication of transmission quality?

A. Spectrum analyzer  
B. Oscilloscope  
C. Frequency counter  
D. Digital tracker

3-3. To provide a distortion-free modulated signal, transmitter intermediate frequency (IF) and radiofrequency (RF) amplifiers must operate in what portion of their characteristic curve?

A. Saturated  
B. Linear  
C. Nonlinear  
D. Logarithmic

3-4. To test an intermediate frequency (IF) amplifier in a transmitter section, what are the two prime considerations?

A. Selectivity and gain  
B. Sensitivity and frequency  
C. Frequency and modulation  
D. Modulation and selectivity

3-5. What is the most significant single check that can be made to evaluate the condition of a receiver?

A. Qualitative  
B. Sensitivity  
C. Frequency  
D. Modulation
3-6. What type of receiver uses a minimum-discernible signal measurement as the best way to perform a sensitivity check?

A. FM receiver  
B. AM receiver  
C. Pulse-modulation receiver  
D. SSB receiver

3-7. In most receivers, the overall bandwidth is determined by which of the following components?

A. RF amplifier  
B. IF amplifier  
C. Oscillation detector  
D. Image detector

3-8. Which of the following circuits eliminates unwanted signal noise in a receiver?

A. RF amplifier  
B. First IF stage  
C. Squelch  
D. Detector

3-9. Which of the following devices is used in a fiber-optic system to convert the light into an electrical signal?

A. Detector  
B. Transmitter  
C. Receiver  
D. Core

3-10. Why is the use of fiber optics for the transmission of data particularly beneficial in naval aviation applications?

A. Increase weight and stability  
B. Susceptible to electromagnetic pulses  
C. Attracts electromagnetic interference  
D. Reduced size and lightweight

3-11. What is the name of area in front of the fiber that determines the angle of light waves that will enter the core?

A. Dielectric insulator  
B. Strengthening member  
C. Cone of acceptance  
D. Low halogen jacket
3-12. In a fiber optic cable, light refracts to the interface between the core and what other component?

A. Aramid yarn  
B. Cladding  
C. Cone of acceptance  
D. Low halogen jacket

3-13. What two types of optical fibers are classified by their transmission capabilities?

A. Single and multi-mode  
B. High and low speed  
C. Reflective and non-reflective  
D. Amplitude and frequency

3-14. Which classification of optical fiber accepts a signal at a specific wavelength?

A. Non-attenuated  
B. Multi-mode graded-index  
C. Multi-mode step-index  
D. Single-mode step-index

3-15. Which component is capable of distributing or combining optical signals between fibers?

A. Detector  
B. Coupler  
C. Intermodal amplifier  
D. Intramodal amplifier

3-16. What critical step of fiber optic system maintenance must be performed before any connection is made?

A. Operational test  
B. Self-test  
C. Contamination inspection  
D. Decoupling inspection
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CHAPTER 4

NAVIGATION SYSTEMS

Airborne navigation systems encompass various equipment and instruments that are used to determine an aircraft’s position, altitude, and heading. Your portion of this equipment includes Automatic direction finder (ADF) systems, very high-frequency (VHF) omnidirectional range (VOR) systems, instrument landing systems (ILS), tactical air navigation (TACAN) systems, inertial navigation systems (INS), Doppler navigation systems, navigational computer systems, global positioning systems (GPS) and electronic altimeter systems.

You will be tasked with operating and maintaining navigational systems. It is beyond the scope of this manual to discuss all of the specific equipment; therefore, only representative equipment will be discussed. This chapter will provide you with the basic concepts, capabilities, and operating principles of various types of navigation sets. Although there may be newer and more sophisticated equipment in use than those depicted as examples in this chapter, keep in mind they all operate on the same basic principles.

LEARNING OBJECTIVES

When you have completed this chapter, you will be able to do the following:

1. Explain ADF theory and operation of a typical system.
2. Explain VOR theory and operation of a typical system.
3. Explain ILS theory and operation of a typical system.
4. Explain TACAN theory and operation of a typical system.
5. Explain Doppler theory and operation of a typical system.
6. Explain INS theory and operation of a typical system, including accelerometers, integrators, stable platforms, and navigation computers.
7. Explain GPS theory and operation of a typical system.
8. Explain navigational computer theory and operation of a typical system, including sensors, computer, and navigation panels.
9. Explain electronic altimeter theory and operation of a typical system.

AUTOMATIC DIRECTION FINDER SYSTEM

An ADF is a radio receiver equipped with a directional antenna, which is used to determine the direction from which a radio signal is received. ADF receivers are able to tune in to nondirectional beacons (NDBs) with bearing information displayed on an indicator. Older models (Figure 4-1) use analog displays with servomotors driving an indicator pointer (needle), while digital displays have become the standard for modern aircraft. The pointer will point toward the radio station, giving the pilot or operator, referred to as aircrew, a relative bearing to the station with respect to aircraft heading. By using a map and knowing the location of the radio station, an ADF operator can determine the aircraft’s relative position from the location. By plotting a two-station fix (relative bearings (Figure 4-2), the aircrew can determine the aircraft’s exact position on the map.
In most applications today, ADF is used in conjunction with other equipment and is not the primary means of navigation. For example, F/A-18 aircraft have their ADF functions incorporated into their very high frequency/ultra-high-frequency (VHF) communications system. The station is selected by VHF/UHF receiver-transmitter (RT) No. 1 or No. 2. The system operates in the 100- to 400-megahertz (MHz) range. The bearing is displayed on the horizontal situation indicator (HSI)/display.

**Basic Principles**

When a conductor is cut by magnetic lines of force, or lines of flux, a voltage is induced in the conductor. In order to cut lines of flux, the conductor must be perpendicular or have a component that is perpendicular to the lines of flux. The relative motion between flux and conductor must have a component in a direction that is perpendicular to both the lines of flux and the conductor.

A vertically polarized wave has a vertical electric (E) field and a horizontal magnetic (H) field. The wave induces voltage in vertical conductors only. A vertical wire, or monopole, is the simplest type of antenna. When a vertically polarized radio wave induces voltage in a monopole (Figure 4-3), the induced voltage is in phase with the incident wave and is the same for all horizontal angles of incidence. This similarity in response pattern, in all directions simultaneously, suggests the name omnidirectional for this antenna. The term “omnidirectional” means receiving signals from all directions in this case. Likewise, it also applies antennas that transmit in all directions.

The response of a loop antenna is different from that of a vertical monopole. The vertical monopole antenna is also known as a sense antenna. A rectangular, single-turn loop with dimensions that are small compared to the wavelength of an incident radiation field is shown in Figure 4-4, view A. As the loop is rotated about the XX axis, the angle between the plane of the loop and the direction of propagation of the wave is changed.

Figure 4-1 — Typical analog ADF indicator.

Figure 4-2 — Two-station ADF fix to determine aircraft’s position.
At any instance, the voltage induced in arm AB is slightly different from the voltage induced in arm CD. Arms BC and AD are not affected by the H lines of a wave polarized at right angles to them. The arms do not contribute to the induced voltage in the loop because the horizontal members are parallel to the H lines.

If the loop is turned so that its face is perpendicular to the direction of arrival of the wave, sides AB and CD are cut by the incoming wave, that is, $\theta = 90^\circ$. Sides AB and CD are cut by the H vector at the same instant. The voltages induced in arms AB and CD are then the same magnitude and phase. They neutralize each other, so no current flows in the antenna loop.

Because the magnetic field of the radio wave alternates at the frequency of the wave, the instantaneous flux density at any point along the path of arrival varies sinusoidally. Sinusoidal voltage is voltage that varies with the sine function of the phase angle. Thus, the voltage induced into arms AB and CD are sinusoidal voltages with a phase difference of $\theta$. The total loop voltage is the sinusoidal voltage, which represents the integration of the sums of all the instantaneous voltages induced into the two arms. It may be shown mathematically that this resultant voltage is proportional to the cosine of $\theta$. The pattern of the response is similar to the figure eight in Figure 4-5. All medium-frequency, direction-finding equipment obtains bearing information using the response as shown in this figure.

The directional characteristic of the loop antenna is called a cosine, or figure pattern. When the loop is oriented so that the received signal is at maximum strength, a small change in orientation produces a small change in signal. When the orientation of the loop is such that the received signal is at minimum strength, a large change occurs in output voltage. Furthermore, there is a reversal in phase of the signal as the loop passes through a null point. For these reasons, the null points, rather than the maximum-response points, are used in radio direction finding to obtain a line bearing or line of arrival of a radio wave.
Because the two null positions are 180 degrees apart, the loop can give a line of bearing (the actual bearing or its reciprocal). The absolute direction of the transmitter from the direction finder is not determined directly from the loop antenna. The determination of absolute direction, or sense, is obtained by adding the output of a vertical sense antenna (monopole antenna) to that of the loop antenna. It is essential the two antennas are properly connected for a correct combined response.

Signal Comparison

The figure-of-eight pattern of a loop (Figure 4-5) has two null positions for one incident radio wave. If the outputs of a loop and a sense antenna are combined in phase, the response of the two antennas is the algebraic sum of their individual diagrams. This figure shows four possible responses caused by differences in the relative amplitudes of the sense and loop outputs. In Figure 4-6, view A, the sense amplitude is not great enough to produce a null when combined with the loop input. In Figure 4-6, view B, the algebraic sum of the two inputs is approaching the desired null with the optimum response—one sharp null in a cardioid shape—shown in Figure 4-6, view C. The shape of the resultant curve is called a cardioid because of its similarity to a Valentine heart. The sense input in Figure 4-6, view B, is large enough to flatten the combined response.
The output of the sense antenna is independent of the horizontal direction of arrival of the wave, so it may be considered to have a positive polarity. The phase of the loop voltage changes as the loop passes through a null. One-half of the figure-of-eight pattern has a positive polarity, and the other half has a negative polarity. The addition of the loop and sense curves gives the responses shown.

The output of the sense antenna is in phase with the radio wave. The output of the loop antenna, however, is 90 degrees out of phase with the radio wave. This difference means that the loop output voltage is maximum when the sense output is zero, and vice versa. The cardioid pattern produced by the combined loop and sense antenna can also be produced by a rhombic antenna. This type of antenna is used without a sense element.

**Typical Direction Finder Set**

A typical direction finder set is a low-frequency radio navigation device that operates at frequencies between 90 and 1,800 kilohertz (kHz). It is capable of receiving both amplitude modulated (AM) and continuous wave (CW) transmissions within its operating range. We will use this set as a representative direction finder set.

The direction finder has three modes of operation that are selected remotely at the control unit. In the antenna (ANT) mode, the radiofrequency (RF) input to the receiver is from the sense antenna. The direction finder in this mode operates as a nondirectional, low-frequency receiver. The RF input in the loop mode is from the loop antenna. To use the loop mode for manual direction finding, rotate the loop for an audio output null or a tuning meter null. A 180-degree ambiguity in direction is possible in the loop mode because the loop antenna pattern has two nulls 180 degrees apart. Aircrew can manually choose from the control box the direction from which signals are best received by positioning the loop. In the ADF mode, the loop antenna’s signal determines whether the loop is pointed to the left or to the right of the signal source. The receiver commands clockwise rotation of the loop if the loop axis is pointed to the left of the signal source. Counterclockwise rotation is commanded if the loop axis is to the right of the signal source. Rotation ceases when the loop axis is pointed directly at the signal source.

The position of the loop is continuously transmitted to the bearing indicator. The bearing indicator reads the bearing to the station in the ADF mode because the loop is kept pointed directly at the station. The bearing indicator combines the bearing information from the direction finder with navigation data received from other equipment. Audio signals in all three modes are supplied to the intercommunication system (ICS) in the aircraft. The audio level to the ICS is varied manually from the control box.

**Theory of Operation**

To understand the theory of operation of an ADF, refer to the simplified block diagram of Figure 4-7.
Figure 4-7 — Typical ADF simplified block diagram.
Antenna Mode

RF signals from the sense antenna are coupled to the RF amplifier through the impedance-only signal input to the RF amplifier in the ANT mode. The loop amplifier and the balanced modulator are disabled. The oscillator and mixer convert the output of the RF amplifier to 455.7 hertz (Hz), the intermediate frequency of the receiver. The tuning servo tunes the oscillator from the control box. One of two mechanical fibers passes the desired signal and attenuates the undesired signals. The broad filter provides selectivity of 3.1 kHz, and the sharp filter provides receiver selectivity of 1.5 kHz. The narrow band output of the mechanical filters is amplified by the intermediate frequency (IF) amplifier, and it is applied to the detectors. The output of one detector is used as the automatic volume control (AVC) signal to limit the gain of the RF and IF amplifiers. The AVC signal is also applied to the tuning meter. The output of the other detector is applied to the audio amplifier. The audio gain control is bypassed in the ANT mode, and the receiver gain is manually controlled by using the RF gain control. The audio amplifier increases the output of the detector to the level required by the ICS in the aircraft.

Loop Mode

The loop switch on the control box controls rotation of the loop antenna. The loop switch applies either of two phases of 400 Hz from the receiver to the loop. The aircrew uses the loop switch to drive the loop antenna to the position of minimum reception of the received signal. This position of minimum reception, which occurs when the loop antenna is pointed directly at the signal source, is called the null position. The angle of the transmitting station, with respect to aircraft heading, can then be read accurately on the bearing indicator. The RF output of the loop antenna is applied to the balanced modulator through the loop amplifier. The balanced modulator is unbalanced during loop operation, and it couples the output of the loop amplifier to the RF amplifier. Signals from the balanced modulator are the only input to the RF amplifier in the loop mode. The input to the RF amplifier is the same as in the antenna mode of operation.

Automatic Direction Finder Mode

The RF output of the loop antenna has either of two phases relative to signals from the sense antenna. Phase A, as shown in Figure 4-8, occurs when the loop antenna is to the right of the null position. Phase B occurs when the loop is to the left of the null position. The loop antenna has no output when in the null position. Either output phase of the loop antenna is modulated by a 47 Hz signal in the balanced modulator stage. The RF amplifier adds the output of the balanced modulator to signals from the sense antenna. Note that there is a 180-degree difference in phase between the envelope of A, present when the loop antenna is to the right of the null position, and envelope B, present when the loop antenna is to the left of the null position. The output of the IF amplifier is amplified and detected.

Figure 4-8 — Typical UHF ADF system block diagram.
The output is applied to the audio amplifier. The output of the audio amplifier is processed and applied to the 47 Hz amplifier.

The amplified 47 Hz component of the output of the audio amplifier is applied to the discriminator. The discriminator compares the phase of the 47 Hz signal from the 47 Hz amplifier with the reference phase from the 47 Hz oscillator. If the two are in phase, the discriminator applies a positive direct current (dc) level to the 400 Hz modulator. If the two are out of phase, the discriminator applies a negative dc level to the 400 Hz modulator.

The 400 Hz modulator applies either a phase A or phase B 400 Hz signal to the loop servo amplifier, which is connected to one winding of the loop antenna drive motor. Phase A applies if the dc level from the discriminator is positive. The signal that drives the loop antenna motor will always cause the loop antenna to rotate toward the null position.

The bearing indicator, electromechanically coupled to the loop antenna by synchros, reads the position of the loop, and thus the direction to the signal source.

In the ADF mode, the RF gain control is inoperative. The audio gain control is used to vary the audio output level of the receiver.

**ADF Bearing Limitations**

Various factors contribute to inaccuracy in radio bearings. As a maintenance technician, you should keep these factors in mind when analyzing reported ADF discrepancies. Some of the more important factors are discussed in the following text.

**Night Effect**

Night effect is caused by the reflection of sky waves from the ionosphere. Night effect is most noticeable for about 1 hour, around sunrise and sunset. At these times, the height of sky waves varies in intensity and range. This fluctuation interferes with the reception of the ground wave. Because the operation of the ADF depends on the reception of ground waves, the loop antenna tends to hunt, causing the bearing needle to fluctuate.

**Electrical Disturbance**

Radio waves are distorted by electrical storms. This distortion results in extremely erratic hunting of the loop antenna and bearing needle towards the direction of the electrical storm.

**Precipitation Static**

Aircraft may accumulate a static charge when moving through air, especially air that is laden with particles (dust, ice crystals, etc.). These particles may have a charge on them or create one through frictional contact with aircraft surfaces. These charges tend to discharge from surface to surface or off into the air. In so doing, these changes intermittently cause interference with the ADF equipment.

**Quadrantal Error**

When incoming radio waves strike an aircraft’s surface, a number of reradiated fields are created around the metallic portions of the aircraft. These fields bend the radio waves prior to reception by the loop antenna. This error, known as quadrantal error, is maximum when incoming radio signals must cross the wings or stabilizer surfaces before striking the loop antenna. Quadrantal error is usually adjusted for by compensating circuits installed in the loop antenna unit. Whenever a new loop antenna unit is installed in an aircraft, it must be calibrated in accordance with the maintenance manual for the equipment.
TYPICAL UHF ADF SYSTEM

The total typical UHF ADF system comprises an ADF antenna, a coaxial relay (to select either normal UHF antenna or the ADF antenna), a control amplifier (to drive the ADF antenna), a UHF transceiver that is wired for ADF, and a bearing indicator. A block diagram of a typical UHF ADF system is shown in Figure 4-8. If you place the mode selector switch to the ADF position, it will actuate the coaxial relay, shown in Figure 4-8. The control amplifier module contains the circuitry to steer the ADF antenna, much the same as the unit previously discussed drove its loop antenna.

The heart of a UHF ADF system is the directional antenna. Because of the design of the typical antenna, no sense antenna is required as with the loop antenna. A typical antenna is flush-mounted and receives signals in the range of 225.0 to 400.0 MHz.

The antenna unit (Figure 4-9) consists of a directional receiving element, an antenna drive motor, a rate generator, a lobing switch, and the associated gear assembly necessary to mechanically link the items. The antenna is a cavity-backed complementary slot radiator that is formed by the position of a rhombic-shaped metal plate. The antenna element is terminated alternately at either end by use of the antenna lobing switch G1. This action allows the antenna field, which is a cardioid, to be reversed 180 degrees, 155 times each second, by a signal from the control amplifier module. It is this switching of the field that prevents ambiguous 180-degree readings of the received signal and eliminates the need for a sense antenna.
Figure 4-9 — Typical antenna schematic diagram.
The switching of the cardioid antenna pattern causes the received RF signal to be square-wave modulated. The degree of modulation received by the antenna element is shown in Figure 4-10. The antenna develops the modulation as follows: Assume that a signal is received from the direction OX₁ (Figure 4-10, view B). The resulting modulated input to the control amplifier module (Figure 4-9), after being detected in the UHF receiver, is of the form shown in view C of Figure 4-10. A motor control
voltage proportional to the difference between \( O_{A1} \) and \( O_{B1} \) is then applied from the control amplifier module to the antenna drive motor \( B1 \) (Figure 4-9). \( B1 \) drives the antenna element toward the null position indicated by \( OX_0 \) (Figure 4-10, view B). When a signal is received along this null axis, the difference in modulation resulting from the switching of the antenna field pattern is zero. Under these conditions, the motor control voltage applied to \( B1 \) is zero, and the antenna ceases to rotate. Synchro transmitter \( B2 \) (Figure 4-9) transmits antenna position to the bearing indicator needle.

A rate feedback voltage proportional to the speed of the antenna rotation is developed by the rate generator \( G2 \) (Figure 4-9) and fed to the control amplifier module, where it combines with the input from the UHF receiver to prevent oversteering of the antenna and similar problems.

The electronic lobing switch \( G1 \) (Figure 4-11) uses four diodes to perform the switching function. In the simplified schematic diagram shown in Figure 4-11, the ADF antenna element is represented as a diamond-shaped plate, the ends of which are connected to \( J3 \) and \( J4 \), respectively. To examine the operation, assume a 6.3-volt (V) square-wave voltage at 155 Hz is incoming from the control amplifier module and applied between points A and B. A positive voltage at point B places forward bias on \( CR3 \) and \( CR5 \) (through the antenna element), causing both diodes to conduct and appear as a low-value RF impedance. The same potential will bias \( CR6 \) and \( CR4 \) in the reverse direction, so they are nonconducting. Under these conditions, the \( J3 \) end of the antenna element is connected through the resistance of \( CR5 \) to the terminating network, which consists of \( R4 \) and \( C2 \). The RF signal is coupled from the \( J4 \) end of the antenna element, through \( CR3 \) to \( J5 \). When the input square wave drives point B negative with respect to point A, \( CR3 \) and \( CR5 \) are biased off, and \( CR6 \) and \( CR4 \) are conducting due to the forward bias. The \( J4 \) end of the antenna element is then connected to the terminating network \( R4 \) and \( C2 \), while the signal is passed from \( J3 \) through \( CR4 \) and \( C3 \) to \( J5 \). Inductors \( L1 \), \( L2 \), and \( L3 \) isolate the RF energy from the 155 Hz control amplifier circuits. Capacitor \( C2 \) offers a low impedance to the high-frequency RF signals, effectively placing the end of \( R4 \) at RF ground while isolating the 155 Hz circuitry by the relatively high reactance at 155 Hz.

Although the typical UHF ADF antenna is better than the standard loop sense antenna, it is still vulnerable to some of the factors that can cause bearing inaccuracies. Radio signals experience minimal night effect errors while operating in the UHF frequency spectrum, but they are subject to quadrantal and electrical disturbance errors.
VHF OMNIDIRECTIONAL RANGE SYSTEM

A VOR facility (Figure 4-12) is a radio range station whose transmitting radiation patterns produce directional courses on “tracks” by having special characteristics in its emissions, recognizable as bearing information. These courses or tracks remain stationary with respect to the surface of the Earth. The operation of a VOR bearing function may be compared to that of an airport beacon light. If the beacon light, rotating at a known speed, blinks each time it sweeps past magnetic north, and the time from that blink until the beam sweeps past an aircraft is measured, the magnetic bearing from the beacon can be determined. For example, if the beam revolves at 1 degree per second and 120 seconds are counted between the reference blink (magnetic north) and the time the beam strikes the aircraft, the aircraft is on the 120-degree radial (track) from the beacon.

Transmission Principle

The transmission principle of the VOR station is based on the creation of a phase difference between two simultaneously transmitted RF signals in the frequency band of 108.00 to 117.95 MHz. Magnetic north is used as the base for measuring the phase relationship. One of the two RF signals transmitted is nondirectional and has a constant phase throughout 360 degrees of azimuth. It is called the reference phase signal. This signal is transmitted on a 9.96 kHz subcarrier, frequency modulated at 30 Hz, and is applied to the center loop. The second signal is a rotating signal with a speed of 1,800 RPM. It is called the variable phase signal. The relationship between these two signals is illustrated in Figure 4-13.

The VOR transmitter is modulated both by a 9.96 kHz subcarrier and by an additional component, either of voice or the station identification code characters, as shown in Figure 4-14. The subcarrier is frequency modulated at 30 Hz and generated by a notched tone wheel rotating in a magnetic field. The purpose of the subcarrier is to...
provide a means for separating the 30 Hz tone of the reference phase from the variable tone of the same frequency.

The modulated output of the transmitter is applied to both a modulation eliminator and to the center loop antenna of a five-element array. There it is radiated to form the reference phase signal. The modulation eliminator is a clipper that removes the amplitude modulation from the carrier. The unmodulated output is fed to a capacity goniometer, which serves as a mechanical sideband generator. The goniometer is a motor-driven, double capacitor in which one set of stator plates is displaced 90 degrees from the other set. The rotor plates to which the RF signal is applied are driven at 1,800 rpm.

Two outputs are derived, one from each set of stator plates. These two signals contain modulation components (30 Hz) that differ in phase by 90 degrees because of the capacitor plate relationship. One output is fed to one pair of diagonally opposite loop antennas, and the other is fed to the remaining pair of loops in the square array. Each pair of corner antennas produces a figure eight radiation pattern. These two patterns are displaced from each other by 90 degrees in both the space and time phase. The resultant pattern is the sum of the two crossed figure-of-eight patterns and consists of the rotating field. The transmitter is designed so that the 30 Hz, frequency-modulated component reaches its positive maximum at the same time that the rotating pattern maximum passes magnetic north (in phase). As a result of the rotation of the variable phase pattern, the signal induced in the airborne VOR receiver is amplitude modulated with 30 Hz variations. The receiver develops this tone and compares it with the reference signal. The amount of phase difference between the two signals depends on the location of the aircraft with respect to the transmitting station. Although the VOR provides an infinite number of courses from the station, for simplicity it is referred to as providing 360 courses 1 degree apart. These courses are called radials. Any radial may be selected and flown, or may be used to obtain a line of position at any time.

**Typical Aircraft VOR System**

A typical aircraft VOR (omnidirectional) system consists of a receiver, control box, course deviation indicator (CDI), course indicator (CI), and an antenna. A simplified block diagram of a typical VOR receiver is shown in Figure 4-15. An illustration of an analog CDI and CI is shown in Figure 4-16. A typical VOR control box is shown in Figure 4-17.

The VOR control box contains an ON-OFF power switch that applies power to the complete system, two tuning controls (1 and 0.05 MHz) to select the receiver’s frequency, a frequency indicator, a volume control for adjusting the VOR audio feed to the ICS, and a LOC (localizer)-VOR function.
select switch. The localizer function will not be discussed, but a representative system will be
discussed under the ILS heading.

Figure 6-15 — Typical airborne VOR receiver simplified block diagram.
Figure 4-16 — Typical analog VOR Indicators.

Figure 4-17 — Typical VOR control box.
This receiver is tunable in increments of 0.3 MHz from 329.3 to 335.0 MHz, and it can be tuned simultaneously with the VOR control box with the appropriate localizer frequency. Various frequencies and their uses are shown in Table 4-1.

The control box tuning controls enable the aircrew to select any ILS or VOR station frequency. Most VOR receivers tune higher than 117.95 MHz; that is, either to 135.95 MHz or to 151.95 MHz. Due to this added capability, the VOR receiver may be used as a secondary VHF communication receiver. As a result of antenna polarization, the signal may be degraded, but still usable.

The control box electrically operates the receiver’s autopositioners, which mechanically tune the RF amplifier circuits, local oscillators, and mixer stages to the desired frequency.

As in any superheterodyne receiver, the received signals are processed by the RF amplifiers and converted to a lower IF frequency for demodulation. The portion of the received signal that contains voice or station identification is detected and fed to the audio circuits and out to the aircraft’s ICS.

The portion of the received signal that contains omnibearing information (30 Hz modulated variable phase and 9.96 kHz subcarrier, 30 Hz frequency modulated reference phase) is fed to the instrumentation circuits. The instrumentation section of the receiver is divided into two channels, which are referred to as the reference phase channel and the variable phase channel. The reference phase channel is concerned with the 9.96 kHz subcarrier frequency that is modulated by the 30 Hz reference signal. The subcarrier signal passes through a 9.96 kHz bandpass filter and is amplified and applied to an FM (frequency modulated)-AM translator. The output of the translator is an AM signal modulated with a 30 Hz component. It also still contains the original FM signal. This signal is fed to an AM demodulator bridge circuit, and the resulting 30 Hz output is amplified and applied to a manual resolver located in the CDI. It is also amplified by an automatic resolver amplifier and applied to windings of a resolver located in the CI. This signal will be mixed with a 30 Hz signal from the variable phase channel to drive the pointer to the correct bearing to the station.

The reference phase signal, applied across the CDI manual resolver, re-enters the receiver and is again amplified and applied as one input to a phase comparator. The variable phase channel accepts the 30 Hz variable phase signal obtained at the output of the detector, amplifies it, and applies the signal as the second input to the phase comparator. It also applies the signal to the course indicator phase signal and drives the pointer to the correct bearing of the received station.

The output of the phase comparator is a vector summation voltage (at), which is applied to three different places. First, it is applied to the CDI flag alarm circuit to drive the ON-OFF flag to indicate adequate station signal reception. Second, it is also applied to resolver windings in the CDI. The reference phase signal in the CDI manual resolver is compared with the variable phase signal, and the resulting vector summation voltage will drive the vertical bar either left or right of center, depending on whether the course to the station is left or right of the course set in the CDI selection window. By turning the course set knob, the vertical bar can be centered, and the reading in the course selection window should be the same as that bearing indicated by the pointer of the CI.

Another use of the CDI is illustrated in Figure 4-18. Aircrew may select a desired course to a known station and fly the aircraft in a direction so as to center the vertical bar, thus ensuring that the aircraft is on the desired course.

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Use</th>
</tr>
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<tbody>
<tr>
<td>108.00 – 117.95 MHz</td>
<td>VHF Omni Range (VOR)</td>
</tr>
<tr>
<td>108.1 – 111.9 MHz</td>
<td>ILS Localizer</td>
</tr>
<tr>
<td>116.00 – 1,151.95 MHz</td>
<td>VHF Communications</td>
</tr>
</tbody>
</table>
Figure 4-18 — CDI presentations at various positions in relation to the VOR station.
The third output of the phase comparator is fed to a TO-FROM phase comparator and a 90-degree phase shifter circuit, and to the TO-FROM phase comparator. The vector summation voltage output of the TO-FROM phase comparator is applied to the CDI TO-FROM to drive the TO-FROM indicator flag. If a received signal is from the course selected in the course selection window, the TO-FROM flag will read "FROM." If the course set is to the station, the TO-FROM flag will read "TO." As shown in Figure 4-18, the combination of the CDI vertical crossbar position, the course selected in the course selection window, and the TO-FROM indication will inform the aircrew just where the aircraft is located with respect to the received VOR station.

INSTRUMENT LANDING SYSTEM

The ILS is a radio and radar system that enables aircraft to land in low visibility. While ILS system operation is fundamentally the same in all naval aircraft, there are significant differences in equipment and indicator displays. In this section we will discuss the AN/ARA-63 (Figure 4-19) as a representative system.

Principles of Operation

The AN/ARA-63 is an all-weather aircraft approach guidance system, which consists of ground and airborne equipment. Receiving-Decoding Group AN/ARA-63 is the airborne portion of the aircraft approach control system (AACS). This equipment receives coded microwave transmissions from ground or carrier-based azimuth and elevation transmitters, and decodes these signals for display on a crosspointer indicator in the aircraft cockpit. Some aircraft incorporate an all-attitude indicator (AAI) (Figure 4-20). In addition to pitch and roll, this indicator shows compass information along the horizon bar. It also shows turn-and-bank information on the bottom. A centerline display of both elevation and azimuth on the AAI depicts the flight path the pilot must follow to line up accurately with the airport runway or carrier deck. By consecutively scanning through azimuth and elevation, the system provides continuous measurement of the lateral and vertical aircraft deviations from the optimum approach line in space.
As you can see from Figure 4-21, proportional angle information in elevation is displayed ± 1.4 degrees from the glide slope.
Azimuth and proportional angle information is displayed between ±6 degrees, as shown in Figure 4-22. The normal azimuth course is along the runway centerline. The normal glide slope is 3 degrees, but, by means of jumper wires in the airborne decoder, the glide scope can be adjusted from 2 to 5 degrees in 0.5-degree increments. (The glide slope can also be adjusted on the ship’s transmitter.)

Input Signal Characteristics

The ground equipment transmits a complete series of elevation and azimuth signals five times per second using sector scanners in simple harmonic motion, illustrated in Figure 4-23. Because the mechanical scan rate is 2.5 Hz, the 5 Hz signal rate is achieved by transmitting during a portion of the left-to-right azimuth scanning time, and transmitting again during a portion of the right-to-left scanning time. A similar but interlaced two-way scan is used for elevation.

The azimuth and elevation transmissions share time on the same frequency; that is, the on-and-off periods are governed by the synchronized scans of the two antennas. Each transmission consists of a series of paired pulses, by means of which the transmission is encoded with either azimuth or elevation identification and with angle information. The signal pulses are 0.3 microsecond (μsec) wide.
Pulse coding is shown in Figure 4-24. The time between the first two pulses in the data group identifies the group as being from the elevation or azimuth transmitter. The two pulses in each pair are spaced 12 μsec apart during elevation transmission, and either 10 or 14 μsec apart during azimuth transmission. These spacings can be increased by 1 μsec to provide an additional channel at each frequency.

The time between pulse pairs represents a value of angle data. As the antenna scans, the angle data changes at 1/8-degree intervals (0.25 μsec). The variation of angle data spacing with time is illustrated in Figure 4-25.

Controls and Indicators
Controls and indicators are shown in Figure 4-26. These illustrations show receiver control C-7949/ARA-63 (Figure 4-26, view A), radio receiver R-1379/ARA-63 (Figure 4-26, view B), and pulse decoder KY-651/ARA-63 (Figure 4-26, view C).
Figure 4-26 — Receiver Control C-7949, Radio Receiver R-1379, and Pulse Decoder KY-651/ARA-63.
Radio Receiver R-1379/ARA-63

A simplified block diagram of the radio receiver is shown in Figure 4-27. RF input signals intercepted by the antenna are mixed with the local oscillator (LO) to produce an IF output of 150 MHz. The mixer is a conventional balanced wave guide mixer. The LO is a crystal-controlled, solid-state unit employing multipliers, amplifiers, and filters to obtain the required output. The outputs from the mixer are amplified by the IF amplifier. The input of the amplifier is filtered to reject spurious signals. The detector is a single diode, with the video output filtered to remove the IF component. The detector output is amplified by a video amplifier. The stages are direct-coupled and designed for preservation of the pulse signal. The receiver also contains a built-in-test (BIT) module.

Pulse Decoder KY-651/ARA-63

The decoder is composed of two basic units. They are the logic module assembly and the power supply assembly. The power supply furnishes all dc voltages necessary for the operation of the AN/ARA-63 (both receiver and decoder), except for 28 volts direct current (Vdc) aircraft power.

The logic module assembly converts the video pulses from the receiver to dc voltages to drive the indicator. It also generates an automatic gain control (AGC) voltage for the IF amplifier. Signal flow and layout are illustrated in Figure 4-27.

Receiver Control C-7949/ARA-63

The receiver control controls system power, channel selection, and the BIT function, as shown in Figure 4-28.

The function of the BIT is to provide the pilot with a degree of confidence of the system’s operation. The pilot activates the BIT by pressing and holding the BIT PRESS (Figure 4-26, view A) switch on the receiver control. Correct functioning of the system gives the following readings on the AAI:

- Vertical needle—oscillating one-third scale fly right and one-third scale fly left at a 4-second-per-cycle rate
- Horizontal needle—on the glide slope in elevation (center scale)
A malfunction detected by the BIT turns on failure indicators in the receiver, the decoder, or both. When the BIT is activated, a video train of pulses is generated from the clock/BIT-flag module in the decoder. These pulses are used to modulate the 150 MHz BIT oscillator in the BIT module in the receiver. The output of the oscillator is connected to input jack J3 of the IF amplifier. The output of the IF amplifier is fed back to the BIT module. If no output is detected by the BIT module because of IF amplifier failure, both failure indicators (on the receiver and decoder) will appear.

The BIT module also checks the mixer crystal voltage. Inadequate mixer crystal voltage inhibits the 150 MHz BIT oscillator so that the flags on the AAI are in view, and both failure indicators are on. The BIT monitor in the memory module evaluates the decoder response to the BIT simulated input and generates a decoder failure indicator signal when a malfunction is detected. Failure of the power supply also results in a decoder failure indicator signal.

**Theory of Operation**

The front end of the radio receiver consists of the LO, mixer, and IF amplifier subassemblies. The subassemblies are repairable only at the factory. Therefore, the repair of these subassemblies is not covered in this chapter. For reference, characteristics of these units are shown in Figures 4-27, 4-28, and 4-29.

The BIT module contains a 150 MHz oscillator and logic circuitry. This circuitry is used to detect the video output, evaluate the mixer crystal voltage, and drive the receiver failure indicator. The decoder consists of the logic module assembly and the power supply assembly.

**Logic Module Assembly (General Description)**

The logic module assembly consists of five two-card modules. The five modules shown in Figure 4-29 are video-identity, error, memory, AGC, and clock/BIT-flag modules.

The video-identity module receives video from the IF amplifier and performs a three-level threshold detecting process. It also identifies the intrapair (identity) pulse spacing being received. This module consists of a video decoder board and an identity shift register board. Each board is described separately later in this chapter.

The error module receives the quantized video from the video-identity module and compares the spacing of the angle data pulses with reference timing signals. This condition allows the error module to produce an error pulse that is proportional to the angular error of the aircraft from the glide path.
Figure 4-29 — Logic module assembly.
The memory module converts the error pulse from the error module into a dc voltage. This dc voltage is proportional to the error pulse width. The memory module averages all valid error pulses received during a beam. It then averages the result of the last beam with the present beam. The output signal is a dc voltage proportional to the average angular offset of the aircraft from the glide path.

The AGC module develops a dc voltage that is a logarithmic function of the received signal strength. This voltage is used to control the gain of the IF amplifier.

The clock/BIT-flag module supplies the basic clock frequencies needed throughout the decoder for timing purposes, and also produces the pulse signal to modulate the 150 MHz BIT oscillator. The flag board determines if sufficient video information is being received for proper tracking. It also senses if unwanted information is being decoded. The output signals are go/no-go indications.

**Video Decoder Board**

The video decoder board (Figure 4-30) receives the IF video pulses from the IF amplifier. It can be subdivided into four basic sections. They are the video quantizer, the track video detector, the AGC video detector, and the beam gate generator sections. If the IF video pulses exceed 0.57 V, the video quantizer will produce two output signals—identity shift register drive and identity video. These signals are used in the identity shift register board to decode the identity pulses. If the IF video pulses exceed 1.2 V and an azimuth or elevation beam gate is present, the track video detector will produce an output pulse track video that is used to decode the angle data information.

If the IF video pulses exceed 3.2 V and AZ + EL (azimuth/elevation) video is present, the AGC video detector will produce an output pulse that is used to determine the respective AGC voltage.

The beam gate generator receives azimuth video and elevation video pulses from the identity shift register unit. These pulses have been identified as having the correct identity spacing for either azimuth video or elevation video. If three azimuth video pulses are received, none of which are spaced more than 512 seconds apart, an azimuth beam gate (ABG) signal is generated. If three elevation video pulses are received, none of which are spaced more than 512 sec apart, an elevation beam gate (EBG) signal is generated.

**Identity Shift Register Board**

The identity shift register is the digital equivalent of a delay line. Its function is to decode properly spaced elevation and azimuth identity pulse pairs. The identity shift register can be divided into six basic sections. The sections are the high-low channel select circuit, the 1 sec delay, the 4 sec video inhibit circuit, the shift register, the identity decoder, and the side-lobe counter reset circuit sections.
The function of the high-low channel circuit is to allow the pulse going down the shift register to pass through undelayed or to delay the pulse by 1 sec. The pulse is controlled by the channel selector signal, which doubles the number of operating channels without adding RF channels. This doubling is accomplished by using two different identity spacings with the same frequency. Thus, one channel can use 15.412 gigahertz (GHz) and $x \mu$sec spaced identity pulses, and a second channel can be 15.412 GHz and $(x + 1) \mu$sec spaced identity pulses. The 4 sec video inhibit circuit generates a 4 sec video inhibit pulse. The video inhibit pulse inhibits the video quantizer (on the video decoder) from generating identity video to ensure that no reflected signals will be picked up within 4 $\mu$sec of a valid signal.

The shift register is a series of 8-bit shift registers connected in series. The output taps of the shift register are shown in Figure 4-31 with the high-low channel in the undelayed (channels 1 through 10) position. The information is clocked through the shift register by the 4 MHz clock.

The basic decoding principle used in the shift register is to delay the first pulse of an identity pulse pair a period of time equal to the time expected between the pulses. When the delayed pulse and the second pulse of the pulse pair are compared at a not-and (NAND) gate, an output will be produced if they are in time coincidence. For each tap on the shift register, a pair of identified pulses can be decoded. There are taps at 10, 12, and 14 sec corresponding to left azimuth, elevation, and right azimuth.

A side-lobe counter reset signal will be sent to the video counter on the flag board 64 milliseconds (ms) after the start of a beam gate. The counter is also reset if the type of beam gate changes.

**Error Board**

The function of the error board (Figure 4-32) is to produce a pulse output (late EL/AZ gate, early/late gate), the width of which is proportional to the spacing between the angle data pulses. The maximum width of this pulse is limited to prevent the crosspointer needles from being driven off scale. The error board also produces three other signals. These signals are the track quantizer, the read, and the video reset signal.

**Track Quantizer Signal**

The function of the track quantizer is to generate a pulse that has a fixed width of two clock pulses. This signal is called quantized track. It also produces a reset pulse (video reset), which goes to the video decoder board, and a pulse called 2nd video (if error gate is present). If a series of angle data pulses is received, only the second and succeeding pulses are allowed to pass.
The early elevation gate circuitry will produce a pulse output that is proportional to the angle data pulse spacing if the following conditions are present:

- EGB signal is present.
- A 59.25 μsec signal has been received, but an elevation glide-slope reference signal has not been received.
- The pulse is initiated by the 2nd video pulse, and it is terminated by elevation glide slope reference or by a maximum elevation error signal, whichever occurs first.
- This circuit also generates an inhibit signal, which prevents a late EL/AZ gate from being generated during an early elevation gate.

The late EL/AZ gate will produce a pulse output that is proportional to the angle data pulse spacing if the following conditions are present:

- ABG present:
  - If an ABG signal is present, the gate is initiated by the 60 sec delayed pulse and terminated by a 2nd video pulse or a maximum azimuth error pulse, whichever occurs first.
- EBG present with the following conditions:
  - No early elevation gate was generated.
  - Elevation glide-slope reference provided.

If an EBG signal is present, the gate is initiated by elevation glide-slope reference and terminated by the 2d video pulse or by maximum elevation error signal, whichever occurs first.

The maximum error limiter sets a limit to the pulse width of the early elevation gate and the late EL/AZ gate. The maximum gate widths are as follows:

- Late EL/AZ—14.25 μsec
- Early elevation—4.25 μsec

**Read Signal**

The read pulse generator circuit generates a pulse whenever a 2nd video pulse is received during a late EL/AZ error gate, or when a glide-slope reference is generated in the case of an early elevation.
The function of the tapped delay board (Figure 4-33) is to generate timing signals referenced to the quantized track signals. The tapped delay board I circuit receives the quantized track signal from the error board. The tapped delay board I circuit is a ripple-through counter used as a timer. An output pulse called 59.25 is produced 59.25 μsec after a quantized pulse is received. This pulse goes to the error board and to the tapped delay board II circuit.

**Video Reset Signal**

The reset I circuit resets the tapped delay board I circuit whenever a 59.25-μsec signal is generated.

The tapped delay board II is another ripple-through counter used as a timer circuit. The tapped delay board II circuit produces four output signals:

- Error gate starting 59.25 μsec after quantized track and terminated by the read signal or by the 140-sec count
- A signal called 60, which occurs 60 μsec after the tapped delay board I receives a quantized track signal
- A signal called elevation glide-slope reference, which can be adjusted to occur between 64 and 70 μsec (in 1 μsec intervals) after the quantized track signal is received.
- A signal called 140, which occurs 140 μsec after a quantized track signal is received

The reset II circuit resets the tapped delay board II whenever a read signal or a 140 signal is generated. It also produces a reset signal that goes to the error board to reset the maximum error counter.

**Memory Module**

The memory module consists of two boards called memory I and memory II.

**Memory I Board**

The function of the memory I board is to convert the pulse width of the early/late gate (generated on the error board) into a dc signal that is proportional to the early/late gate pulse width, starting from zero volts each time a new gate is received (Figure 4-34). Memory I also generates a read gate signal and a discharge drive signal.
The temporary error integrator generates the temporary error signal, which is proportional to the pulse width of the early/late gate each time a valid error signal is received. This signal starts from ground each time a new early/late gate is received.

The temporary error inverter inverts the temporary error signal if a late azimuth video (fly right) signal is present or if an early elevation gate (fly up) is generated.

The read gate generator produces two output signals—the read gate and a control signal to the discharge drive generator.

The read gate is either 16 or 32 μsec wide, depending on the level of the wide-beam/narrow-beam control. If the wide-beam/narrow-beam signal is high (47 count signal present—see AGC I), the read gate is 16 μsec wide. If the wide-beam/narrow-beam signal is low (narrow beam being received), the read gate is 32 μsec wide. This signal goes to memory II and gates the temporary error signal into memory.

The discharge drive generator produces a signal called discharge drive. Its purpose is to discharge the temporary error integrating capacitor. The discharge drive signal is generated whenever any one of the following signals is present:

- End of read gate
- End of either azimuth or elevation beam
- 140 μsec after quantized track

The temporary error integrating capacitor is allowed to charge 59.25 μsec after quantized track.

**Memory II Board**

The function of memory II board (Figure 4-35) is to receive the temporary error signal from memory I board to produce output signals called azimuth deviation and elevation deviation, which drive the AAI. The amplitude of the output signal is the average of the latest computed deviation and the computed deviation of the previous beam.
The temporary error signal goes to the feedback network. This signal is multiplexed between azimuth and elevation to permit the memories to be updated on a beam-to-beam basis so that an average correction may be made during beam scan time.

The output selector switch selects the proper signal to be fed into the feedback network. This selection is determined by either ABG´ or EBG´.

The input selector switch connects the output of the feedback network to the proper integrator. This selection is determined by ABG´ and EBG´.

The azimuth integrator integrates the signal from the feedback network with stored dc voltage. The signal from the feedback network is the sum of the temporary error signal and the signal from the azimuth sample/hold network. The feedback ratio is determined by the feedback network and is integrated for a time equal to the read gate signal. Thus, the azimuth integrator is updated each time a read gate is generated. At the end of a beam, it should contain the average error decoded in that beam.

At the beginning of an azimuth beam, the voltage stored by the azimuth integrator is stored in the azimuth sample/hold network.

The azimuth summation and scaler network has two functions: to average the output of the azimuth integrator and to average the azimuth sample/hold. The elevation integrator is identical to the azimuth integrator. The elevation sample/hold is identical to the azimuth sample/hold. The elevation summation and scaler is identical to the azimuth summation and scaler. The function of the main beam gate generator circuit is to produce an ABG´ or an EBG´ to prevent the circuits in memory II board from responding to beam gates generated from side lobes.

The BIT monitor evaluates the decoder response to the BIT simulated input and generates a decoder failure indicator signal when a malfunction is detected. Failure of the power supply also results in a decoder failure indicator signal. The AGC module (Figure 4-36) develops AGC bias signals, depending on signal strength for both elevation and azimuth, and generates a wide-beam/narrow-

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**Figure 4-35 — Memory II board.**
beam signal. The eight-count circuit counts the AGC video pulses. When eight pulses are received, a signal is sent to the azimuth AGC circuit and the elevation AGC circuit. The azimuth AGC circuit generates a dc signal, which is dependent upon the received signal. The AGC circuit will raise the dc level (desensitize the IF amplifier) if a pulse is received from the eight-count circuit, or lower the dc level if a two-count pulse is received. The eight- and two-count circuits, by varying the dc levels, ensure that pulses are being received in the top center portion of the beam (not side lobe or less than 16 pulses). The elevation AGC circuit is identical to the azimuth AGC circuit.

The function of the AGC multiplexer is to select the proper AGC voltage. If an ABG signal is present, the azimuth AGC voltage or the noise level AGC is selected, depending on which one is more positive. Similarly, if an EBG signal is present, either the elevation AGC or the noise level AGC is selected, depending on which one is more positive. The wide-beam/narrow-beam control determines whether more than 47 or less than 47 pulses within the beam are being received. Because this receiver is able to fly against 1- and 2-degree-wide beams, a method of detecting which beam width is being received is necessary. This situation allows the memory to make unity correction in one beam passage. Unity correction corresponds to critical damping in a servo system.

**Clock/BIT-Flag Module**

The clock/BIT-flag module consists of the clock/BIT board (Figures 4-37) and the flag board (Figure 4-38).

The function of the clock/BIT board is to produce clock pulses of various frequencies, which are used as timing pulses throughout the decoder. It consists of a 4 MHz crystal oscillator, which produces the basic 4 MHz clock pulse, and a ripple-through counter, which divides down the 4 MHz oscillator pulse to produce 1, 2, 4, 8, 16, 32, 64 microseconds, etc. The BIT (Bit) signal is modulated using these timing pulses.

**Figure 4-37 — Clock/BIT board.**

**Figure 4-36 — AGC module.**
MHz clock to lower clock frequencies that are used throughout the logic module assembly. The board also produces the pulse train used to modulate the 150 MHz BIT oscillator.

The function of the flag board (Figure 4-39) is to determine if sufficient information is being received to permit tracking and to supply the following output signals:

- Azimuth flag
- Elevation flag
- Azimuth side-lobe AGC
- Elevation side-lobe AGC
- 16/beam count (a count of 16 pulses per beam)
- Azimuth 2 count (a count of two azimuth video pulses)
- Elevation 2 count (a count of two elevation video pulses)
- 47 count (a count of 47 azimuth/elevation video pulses)

The 16/beam circuit counts the read gate pulses. If 16 read gate pulses in 1 beam are received, the information within that beam is considered valid and a signal is sent to the azimuth flag circuit or to the elevation flag circuit, depending on which beam gate has been generated. If 3 beams having more than 16 pulses per beam are counted in the azimuth flag circuit, the 3-counter in the azimuth flag circuit sets the azimuth flag signal to the high level. The azimuth flag circuit also contains a...
counter that serves two functions. The first is to determine if the 16 pulses per beam received by the azimuth flag circuit are within 1 sec of each other. If they are not, the 3-counter is reset, and counting starts again from zero. The other function is to change the azimuth flag signal from a high to a low level, if no valid beams are received within 2.1 seconds. The elevation flag circuit is identical to the azimuth flag circuit. The video counter counts $AZ + EL \text{ VIDEO}$ pulses. If two pulses are counted, an output pulse is generated to put the AGC buss into a discharge mode. If 47 pulses are counted, an output pulse is generated. This pulse goes to the wide-beam/narrow-beam control located on the AGC I board. If 144 pulses are counted (too many for normal tracking), an azimuth side-lobe AGC or an elevation side-lobe AGC signal is generated. This signal is sent to the AGC board and is used to raise the azimuth or elevation AGC voltage, thereby reducing receiver sensitivity. The 144 count also makes the flags on the AAI visible. The video counter is enabled by the presence of an $ABG + EBG$ signal.

**Figure 4-39 — Flag board.**

### TACTICAL AIR NAVIGATION SYSTEM

A TACAN system is a polar coordinate navigation system. It is used to determine the relative bearing and/or slant-range distance to a TACAN ground station or cooperating aircraft. Therefore, only distance data is supplied to the interrogating aircraft. The TACAN system operating range limit is line of sight and depends on aircraft altitude and type of terrain.

The TACAN system operates on a selected channel from the 252 TACAN channels available. The 252 channels are equally divided: 126 X-channels and 126 Y-channels. Both X- and Y-channels are spaced at 1 MHz intervals. The TACAN channels provide airborne transmit (interrogation) frequencies from 1,025 to 1,150 MHz. The TACAN airborne receive frequencies are from 962 to 1,213 MHz.

The typical TACAN system operates in the following ground-to-air modes: receive (REC) and transmit-receive (T/R). It also operates in air-to-air (A/A) modes: air-to-air transmit-receive (A/A T/R), air-to-air receive (A/A REC), and self-test (in-flight confidence test). The system produces both digital
and analog data that can drive digital HSI, analog HSI, and computer systems. It can also drive bearing distance-heading indicators (BDHIs), CDIs, distance indicators, and radio magnetic indicators (RMIs). A TACAN beacon, either surface or airborne, is required for operation of a TACAN system.

**Receiver Section**

A simplified block diagram of a TACAN receiver section is shown in Figure 4-40. The binary-coded decimal (BCD) channel data and the high-/low-band (low level = low band) signal from the input control circuit is supplied to synthesizer A15A2. The BCD channel data is used to produce the voltage-controlled oscillator (VCO) voltage that is supplied to variable voltage controlled (VVO) A15A3. The high-/low-band signal and the BCD channel data are used to produce a digital-to-analog output that is supplied to curve shaper A14A4. The synthesizer produces a specific control voltage and digital-to-analog output for the selected channel.

The control voltage supplied to VCO A15A3 causes the VCO to produce a fundamental frequency. The frequency is for the selected channel that is between 256.25 and 287.50 MHz. The fundamental frequency is supplied to RF driver A15A4.

**Figure 4-40 — Receiver section operation.**
RF driver A15A4 multiplies and amplifies the fundamental frequency to produce a local oscillator frequency between 1,025 and 1,150 MHz. The specific frequency depends on the selected TACAN channel. The local oscillator signal is supplied to RF amplifier/mixer A14A2. Curve shaper A14A4 uses the digital-to-analog output from A15A2 to produce a tuning voltage that is supplied to preselector A14A1. The tuning voltage produced by A14A4 varies nonlinearly with channel selection but is a specific voltage for each selected channel.

The external antenna select and antenna lobe enable signals are supplied to the antenna lobe (switching) circuit on bearing control Al. The bearing search signal and the pretrack signal are supplied to the antenna switching circuit. The antenna select signal allows either antenna 1 or antenna 2 to be manually selected. The antenna lobe enable signal allows the transmit and receive signals to be switched between antennas 1 and 2.

The antenna switching takes place at 5-second intervals until a usable signal is located. The bearing search and/or pretrack signals inhibit the switching when the bearing circuits are receiving a usable bearing signal. They also inhibit the switching when the distance circuits switch to the pretrack submode.

When switching is inhibited, the transmit and receive signals are received from the antenna that provides a usable receive signal. The antenna modulation (switching) signal is applied from the antenna switching circuit to diplexer A17. The internal suppressor signal from A11 is supplied to the antenna switching circuit. The suppressor inhibits antenna switching during the transmission of the interrogation pulses.

Diplexer A17 receives the TACAN station signal from either antenna 1 or antenna 2, depending on the antenna modulation signal from the antenna switching circuit. The 962 to 1,213 MHz receive signal is supplied from diplexer A17 to preselector A14A1. The preselector circuit is composed of one two-pole preselector and one four-pole preselector. The preselectors are broadband filters that pass frequencies in the spectrum of the selected TACAN station channel. The tuning voltage from curve shaper A14A4 controls the selection of the frequency spectrum.

The receive signal is applied from the preselector circuit to RF amplifier mixer A14A2. The RF amplifier is actually located between the two preselectors and is used to amplify the output of the two-pole preselect. The amplification takes place before the signal is supplied to the four-pole preselector. The mixer portion of A14A2 heterodynes the receive signal with the 1,025- to 1,150 MHz local oscillator signal from RF driver A15A1.

A 63 MHz IF signal is then produced. The 63 MHz signal is supplied to IF amplifier A14A3. After amplification and application of AGC, the 63 MHz IF is converted to a 12.6 MHz second IF. Then, the 12.6 MHz IF is amplified and detected to form the IF video signal that is supplied to the decoder circuit and to the AGC receiver circuit on pulse pair decoder A5.

The decode circuits and the receiver AGC circuit on pulse pair decoder A5 process the IF signal, producing an AGC receiver signal that is supplied to the diplexer AGC circuit on burst decoder A6 and to IF amplifier A14A3. The decoded video signal from the decoder circuit is supplied to the AGC circuits on burst decoder burst decoder A6. The AGC circuits on burst decoder A6 determine the number of decoded video pulses received per second. The circuits also determine when internal suppressor pulses occur and when the channel is reset. The AGC circuit produces an AGC control voltage that is supplied to the receiver AGC circuit.

When over 680 decoded video pulses are received per second or an internal suppressor pulse occurs, the control voltage changes. The voltage changes the AGC receiver signal so that the IF amplifier is reduced to minimum gain. When a channel reset signal is received from output control A4 (new TACAN channel), the AGC circuit on burst decoder A6 produces an AGC control voltage, causing the AGC receiver signal to increase the IF amplifier gain to maximum in order to acquire the
new TACAN station’s signal. The AGC circuits on burst decoder A6 produce a diplexer AGC signal that is supplied to A17 and controls the diplexer output. When an internal suppressor pulse occurs, the diplexer AGC signal inhibits the receive signal from being supplied to the preselector circuit.

**Transmitter Section**

The transmitter *(Figure 4-41)* is used only in the T/R and A/A T/R modes of operation.

The BCD channel data and high/low signal from the input control circuit contains selected channel data supplied to stabilized master oscillator (SMO)/VCOs A15A2 and A15A3. The channel data tunes the SMO/VCO so that the fundamental frequency is produced for the selected channel. The SMO/VCO produces a 256.25 to 287.50 MHz fundamental frequency that is supplied to RF driver A15A4.

![Transmitter section operation](image)

**Figure 4-41 — Transmitter section operation.**
The X- and Y-channel data from the input control circuit and the AA/TR mode signal are supplied to interrogator All. The X and Y and AA/TR signals cause A11 to produce driver trigger and modulator trigger pulse pairs. The pulse pairs have the correct spacing between pulses for the selected channel and mode of operation.

The driver trigger pulse pairs are supplied to RF driver A15A4, and the modulator trigger pulses are supplied to transmitter A16. Interrogator A11 produces an internal suppression pulse during the time the driver and modulator trigger pulses are produced. The internal suppression pulse is supplied to the internal receiver-transmitter circuits to prevent the transmit interrogation pulse pairs from being applied to the receiver section and the decoder circuits.

RF driver A15A4 multiplies and amplifies the fundamental frequency from the SMO/VCO circuit to produce a 1,025 to 1,150 MHz pulse pair at the same time as the driver trigger pulse pair occurs. The specific frequency of the pulse pair depends on the channel selected. The 1,025 to 1,150 MHz pulse pair is supplied to transmitter A16 as the RF driver signal.

Transmitter A16 amplifies and modulates the 1,025 to 1,150 MHz RF driver signal, producing a 1,025 to 1,150 MHz transmit pulse pair that is supplied to diplexer A17.

The antenna lobe circuit operates the same as described in the receiver section discussion. The antenna select signal manually selects antenna 1 or 2. Antenna lobing circuits switch between antennas 1 and 2 at 5-second intervals until a usable signal is located. The diplexer directs the transmit pulse pairs to the correct antenna. The internal suppression signal from interrogator A11 is applied to the decode circuits, producing an AGC diplexer signal that is supplied to diplexer A17. The AGC diplexer signal switches diplexer A17 to prevent the transmit pulse pair from being applied to the receiver section.

The transmit pulse pair power is sampled and supplied to the power monitor circuit A12 as a power monitor output signal. The monitor circuit checks that the transmit pulse pair power is above a predetermined minimum. It also supplies the RF power output signal to the monitor and flag circuit on output control A4. If the transmitter power is insufficient, the RF power output signal from A12 causes monitor and flag circuit A4 to produce a flag warning. When the RT is initially turned on, a nominal 90-second time-delay signal is supplied to the transmitter inhibit circuit on distance control A7.

The transmitter inhibit circuit applies a transmitter inhibit signal to interrogator A11 that causes the modulator and driver trigger pulses to be inhibited. The transmitter pulse pair is inhibited for the 90-second period to allow the transmitter to warm up. When the REC mode or A/A REC mode is selected, a receive mode signal is applied to the transmitter inhibit circuit.

The inhibit circuit produces an inhibit signal that keeps the modulator trigger pulses inhibited on interrogator A11. If the SMO does not lock on the selected channel frequency, the SMO lock signal causes an inhibit signal from A7. The modulator trigger pulses are inhibited until the SMO locks on the correct frequency. The SMO lock signal prevents the transmitter from transmitting on an incorrect frequency while the SMO is locking on the correct frequency.

**Decoder Circuit**

The decoder circuits (Figure 4-42) decode the IF video signal to produce a shaped video signal and a detected envelope signal. They also produce a decoded north burst pulse, a decoded auxiliary burst pulse, and a burst eliminated video signal.

The IF video signal from the receiver section is supplied to the decode circuits on pulse pair decoder pulse pair decoder A5. The X and Y channel and the AA/TR mode signals from the input control circuit are supplied to pulse pair decoder A5. They are also supplied to burst decoder A6.
The signals from the input control circuit switch the decode circuits to decode only the data for the selected channel and mode of operation.

The decode circuits on pulse pair decoder A5 produce a decoded video signal. The signal is a pulse for each received pulse pair with the correct spacing for the selected channel and mode of operation. The decoded video signal is supplied to the burst decoder circuits on A6. The decode circuits also produce a peak memory signal that is the amplitude of each pulse received. The memory signal is supplied to the envelope detector circuit on A6.

The burst decode circuits on A6 process the decoded video to provide a shaped video signal with uniform width pulses. The shaped video signal is supplied to distance control A7. The decode circuit produces a decoded north burst pulse that is a bearing pulse that represents magnetic north. It also produces a decoded auxiliary burst pulse that is the bearing pulse that divides the 360-degree bearing circle into 40-degree sectors.

The decoded burst pulses are supplied to bearing reference loop A3 for calculating the aircraft relative bearing with respect to the TACAN station. A burst eliminated video signal is produced by the burst decode circuit and supplied to the envelope detector circuit. The signal is also supplied to the identification circuits on A12. The envelope detector circuit uses the peak memory signal and the burst eliminated video signal to produce a detected envelope signal that is applied to bearing control A1.

The detected envelope signal is a 135 Hz signal modulated with the 15 Hz signal. The 15 Hz portion of the signal is the coarse bearing data. The 135 Hz portion of the signal is the tine bearing signal. The burst eliminated video signal is used to produce the detected envelope signal because the bursts would distort the envelope detector.

**Bearing Measurement Circuit**

The bearing measurement circuit (Figure 4-43) calculates the aircraft relative bearing with respect to the selected TACAN station. The data is calculated from the detected envelope signal and the north
and auxiliary burst pulses from the decode circuit. The bearing data is supplied to the output control circuit as digital data.

The detected envelope signal from the decode circuit is supplied to the bearing filter circuit on bearing control A1. The A/A T/R mode signal from the input control circuit is also supplied to the bearing filter circuit.

The filter circuit separates and filters the detected envelope signal producing 15/135 Hz filtered signals that are supplied to the bearing presence on A1. They are also supplied to the modulation detector circuit on A1 and to the variable phase-lock loop circuit on bearing variable loop AZ. The 135 Hz signal is inhibited in the A/A mode.

The bearing presence and modulation detector circuit checks the 15/135 Hz filtered bearing signals to determine if the modulation of the signals exceeds a predetermined minimum. It also determines if a sufficient signal is present for correct bearing calculations. The bearing presence and modulation detector circuit supplies 15/135 Hz present signals and 15/135 Hz dump signals to AZ.

The present signals are supplied to bearing variable loop A2 when the bearing signals are usable. When the signals are not usable, the detector circuit applies 15/135 Hz dump signals to bearing variable loop A2 inhibiting the 15/135 Hz filtered bearing signals from being applied to the phase-lock loop circuit on A2. When the A/A mode of operation is selected, the 135 Hz presence detector is forced to indicate that 135 Hz data is not available. The 135 Hz dump signal is then produced.

The bearing variable phase-lock loop circuit on bearing variable loop A2 is a 90-degree phase-lock loop that is locked when the output of the loop is 90 degrees out of phase with the input. The loop locks with three different inputs. Before a usable bearing signal is received, a bearing search signal from bearing reference loop A3 is applied to the variable phase-lock loop. The 15 Hz variable search signal from the reference phase-lock loop circuit is used to lock the variable phase-lock loop.

The bearing search signal is supplied to the antenna switching circuit on A1, allowing antenna lobing until a usable signal is obtained. When a usable bearing signal is received, the variable phase-lock loop locks on the 15 Hz coarse bearing signal first. During the 15 Hz lock-on, the variable phase-lock loop applies a wide-band signal to the reference phase-lock loop. This signal switches the loop to a wide passband for locking on the decoded north burst from the decode circuit. The bearing data during and after lock-on is supplied to the bearing data circuit on A3 as a 15 Hz variable 90-degree signal.

When the variable loop is locked on the 15 Hz signal, a variable lock signal is supplied to the bearing lock. The lock is also supplied to a memory circuit on output control A4. When the reference loop locks on the decoded north burst, a reference lock signal is supplied. The lock signal is supplied to the bearing lock and memory circuit. After both loops are locked, the bearing lock and memory circuit supplies a bearing lock signal to the variable and reference loops. The lock signal is also supplied to the self-test circuit on A4.

The bearing lock signal switches the variable loop to lock on to the 135 Hz (fine) bearing signal. The variable loop supplies a 135 Hz operation signal to the reference loop. This signal causes the reference loop to lock on the decoded auxiliary burst. The lock-on to the 135 Hz bearing signal and the decoded auxiliary burst finely adjusts the phase-lock loop circuit. This adjustment provides an accurate bearing calculation. The bearing data is still supplied to the bearing data circuit by the 15 Hz variable 90-degree signal.

The bearing lock and memory circuit uses the variable lock signal, the reference lock signal, and the 15 Hz present signal to control the memory circuit. If the 15 Hz present signal is lost or if either of the phase-lock loops unlocks, the memory circuit applies a memory switch enable signal to the reference phase-lock loop. The reference loop supplies a memory switch signal to the variable phase-lock loop.
Figure 4-43 — Bearing measurement circuit operation.
The memory signals cause both loops to remain locked on the last valid bearing data. The memory signals last for a nominal 3 seconds after a lock or present signal is lost. The memory circuit supplies a bearing memory signal that indicates when the bearing circuits are in bearing memory. The input control circuits on A10 receive this indication. The input control circuit incorporates the bearing memory data in the frequency word, which provides the area navigation system with bearing memory data.

The variable phase-lock loop contains a frequency divider that provides specific frequency signals to the gate circuit. The gate circuit is on A2 and produces an 8,640 Hz ship clock that is used throughout the RT. The 8,640 Hz ship clock is used to ship serial data between circuits and to ship the data out of the RT. The gate circuit produces a bearing data gate, a modified ship gate, a parity gate, a distance data gate, and a 135 Hz, variable, 270-degree signal. All of these signals go to output control A4.

The bearing and distance data gates are used to determine the status of the bearing and distance data. This information is sent out of the RT. The parity gate is used to check the parity of the bearing and velocity serial words. The modified ship gate is used as the word synchronizer pulse for the 6-wire serial data shipped out of the RT. The 135 Hz, variable, 270-degree signal is used to clock a label circuit. The circuit produces labels for the serial words shipped out of the RT.

When the 15 Hz variable 90-degree signal makes a positive zero crossing, the bearing data circuit loads a shift register. This process is done by a continuous running counter that is clocked by a data clock signal from the reference phase-lock loop. Bearing status bits 30 and 31 are applied from output control A4 to the shift register in the bearing data circuit. Bits 30 and 31 are added to bearing data.

The shift register stores 24 bits of data. Bearing data is in bits 18 through 29, status data in bits 30 and 31, and bit 32 is a logic 0 parity bit. The parity bit logic can be changed when the parity is checked in the data output circuits.

When the bearing ship gate is supplied to the bearing data circuit, the 24-bit serial bearing data is sent to A4 at the 8,640 Hz ship clock rate. When the 32-bit bearing word is sent out of the RT, the word is supplied back to the shift register in A4. The word reloads the shift register with the same data that was sent out of the register. The register must be reloaded with the same data because it is sent out faster than it is updated.

The bearing data circuit produces a bearing load gate when the bearing data is loaded into the shift register. The load gate is supplied to output control A4 for use in the bearing status circuit.

Distance Control Circuit

The distance control circuit (Figure 4-44) is part of the distance measurement circuits. Due to the complexity of the distance measurement circuits, the distance control circuit is discussed separately. The distance control circuit determines the mode of operation for the distance measurement circuits. It monitors the distance reply pulse to determine if the distance circuits are locked on the reply pulse or an echo pulse.

The shaped video signal from the decoder circuit is supplied to the composite video circuit on A7. The composite video circuit supplies the composite video pulses to the hit sensor circuit, the echo monitor circuit, and the distance servo loop.

The range gate from the distance servo loop is supplied to the hit sensor circuit. The hit sensor circuit determines when hits occur within the range gate, indicating that the distance circuits have located the distance reply target. When a hit occurs in the range gate, the hit sensor circuit supplies a range hit signal. This hit signal is supplied to the distance servo loop and to the distance mode circuit.
When hits do not occur in the range gate, the hit sensor circuit applies an offset correction signal to the distance servo loop, causing the servo loop to move the range gate in search of the distance reply target. The hit sensor circuit is timed by a pulse repetition frequency (PRF) pulse from interrogator A11. The pulse occurs at the beginning of each interrogation period. The hit sensor circuit looks for a hit in the range gate during each interrogation period.

The PRF pulse and encoder timing pulses are supplied to the distance mode circuit from A11. The distance mode circuit keeps the distance circuits in the search submode. The circuits remain in this mode until at least seven hits occur in the range gate within 15 consecutive PRF periods. When the seven hits occur, the distance mode circuit switches the distance circuits to the pretrack submode. A pretrack signal is then supplied to the output control circuits and to the antenna switching circuit.

The pretrack signal applied to the antenna switching circuit inhibits antenna lobing and keeps the RT signals connected to the last antenna used. The pretrack signal supplied to the output control circuit enables the automatic self-test function in the self-test circuits.

After a nominal 7 seconds, if hits continue to occur in the range gate, the distance mode circuit switches to track submode. A track signal is supplied to the distance servo loop circuit and to the distance memory circuit. The track signal enables the memory circuit to keep the distance circuits in memory if the distance signal is lost.

If hits stop occurring in the range gate and the distance circuits are in the track submode, the distance memory circuit locks the distance circuits. The circuits are locked with the last valid distance data, but the memory circuit updates this data with the last known velocity data for a nominal 15 seconds. At the end of the 15-second period, a distance memory runout signal is applied to the distance reset circuit. This signal causes the reset circuit to supply a distance reset signal to the distance servo loop circuit. The reset signal is also supplied to the hit sensor circuit and to the echo monitor circuit.

The distance reset signal resets the distance circuits to the search submode. A distance memory signal is supplied to the input control circuit. The memory signal provides the memory data used in the frequency word. The frequency word is supplied to the area navigation system and indicates the distance memory status.

The echo monitor circuit determines if the distance circuits are locked on an echo pulse instead of the distance reply target. The circuit searches outbound from 0 to 300 nautical miles (nmi) or the range gate, whichever occurs first. An echo pulse occurs outbound of a distance reply pulse because of delayed interrogation of the TACAN station by the reflected interrogation pulse.

If the echo monitor locates a distance reply pulse inbound of the pulse that the distance circuits are locked on to and tracking, the distance circuits are locked on an echo pulse. When this condition occurs, an echo monitor reset pulse is supplied to the distance reset circuit. A distance reset signal is produced and resets the distance circuits to the search mode to look for the distance reply target.

The maximum range of the distance circuit is 389.9 nmi. When the maximum range is reached and exceeded, a range limit reset signal is supplied from the distance servo loop circuit to the distance reset circuit. The distance reset circuit resets the distance circuits to search submode of operation.
Figure 4-44 — Distance control circuit operation.
Distance Servo Loop

The distance servo loop (Figure 4-45) uses the range reply (target) pulse contained in the composite video signal. The video signal from the distance control circuit is used to calculate the distance (range) to or from the selected TACAN station. It also calculates the velocity (range rate) at which the aircraft is approaching or flying away from the station. The servo loop supplies the range and range rate data to the output circuit as 24-bit serial words. The range data is also supplied to the output circuit as an analog distance pulse pair.

The composite video signal consists of squitter and target pulses. The offset correction signal indicates when hits are not occurring in the range gate. The range gate hit status signal indicates when hits are occurring in the range gate. These three signals are supplied to the 4K modulus counter circuit. Encoder timing pulses from interrogator A11 and the range gate pulse from the range gate generator circuit are supplied to the counter circuit.

At the beginning of each interrogation period, an encoder timing pulse presets the 4K modulus counter to a count of 3,958. The counter is clocked at a 0.1 nmi rate and produces a gated distance clock signal that is supplied to the distance counter circuit. The 4K counter operates in the search, pretrack, and track submodes. The first 42 counts, or from 3,958 to 4,000 (0), are used to produce gate pulses. These pulses are for distance circuit operation and a T1 pulse that is supplied to the pulse pair generator circuit.

The offset correction and range gate hit status signals control the operation of the gated distance clock signal. When the distance circuits are in the search submode, the distance circuits search outbound. The search starts from 0 nmi to locate a range reply target pulse.

The offset correction signal causes the 4K modulus counter circuit to produce four up-distance clocks and a 4K modulus down-distance clock. The down-distance clock is inhibited from the trailing edge of the range gate to the next composite video pulse. This pulse can be either a squitter or range reply composite video pulse causing the range gate to be moved outbound in search of the range reply target pulse.

When a hit occurs in the range gate, the range gate hit status signal from the distance control circuit inhibits the four up-distance clock pulses. During the prior interrogation period, the four up-distance clock pulses were used to center the range reply pulse in the range gate. After the range gate hit status signal occurs, only the down-distance clock is supplied to the distance counter circuit. If the hit in the range gate is a squitter pulse and not a range reply pulse, the pulse does not occur in the same position. The distance circuit again supplies the offset correction signal to the 4K modulus counter circuit. Finally, the distance circuits search for another target pulse outbound.

The distance reset signal occurs when the distance memory runs out or when the 389.9 nmi distance range limit is reached. It also occurs when the distance circuits are locked on an echo pulse. The reset signal is then supplied to the distance counter circuit. The distance reset signal presets the distance counter to 399.00 nmi. On initial turn-on, the distance counter is preset to 399.00 nmi. The counter is preset by a timing pulse from interrogator A11, which occurs at the beginning of an interrogation period.

Either the distance reset or the timing pulse causes the distance circuits to be placed in the search submode. The search submode requires the distance counter to be set to 399.00 nmi. The distance counter is counted up four 0.1 counts and down 4,000 counts each interrogation period. The only time it does not count is the period from the trailing edge of the range gate to the next composite video pulse. The 4K modulus down-distance clock is inhibited. The inhibiting of the down-distance clock causes the range gate to move outbound from the previous position to the next composite video pulse.
Figure 4-45 — Distance servo loop operation.
The distance count produced by the distance counter circuit is supplied to the distance data circuit and to the range gate generator circuit. When the range reply hit occurs in the range gate and the distance circuits are in the track submode, the distance counter is counted down 4,000 clock pulses, causing the counter to count down from the number stored in the distance counter through zero to the same number again each interrogation period.

The digital zero signal from interrogator A11 is applied to the distance counter circuit. The digital zero signal synchronizes the counter to digital zero, which is adjustable to allow for internal delays of the receive signal. The outbound from velocity counter and distance update signals from the update circuit are supplied to the distance counter circuit. The distance update signal corrects the counter in 0.01 nmi increments for the range rate.

The outbound signal is used to count the distance counter up or down in 0.01 nmi increments. The direction, up or down, depends on whether the aircraft is flying to or from the station. The distance counter circuit produces a variable synchronizer signal from the 0.01 nmi data. It applies the signal to the 4K modulus counter circuit synchronizing the start of the 4K modulus counter with the 0.01 nmi because the counter is clocked in 0.1 nmi increments.

The range gate generator circuit produces a range gate 96 that is 0.8 nmi wide during each interrogation period in the search mode. The range gate is produced when the distance counter output is being counted down from 3,987 to 3,979 during each interrogation period. Therefore, the range gate is always produced at the same time in the distance count. The down-distance clock is inhibited during the search submode for the period from the trailing edge of the previous range gate to the next composite video pulse. The counter does not count down a full cycle, which causes the range gate to be produced outbound of the previous range gate.

The range gate is supplied to the error sensor circuit and the update circuit on distance servo A9. Range gate 96/25 is supplied to the error sensor, distance control, and the 4K modulus circuits. Range gate 96/25 is 96 Hz in the search submode and 25 Hz in the subtrack mode. The range gate generator circuit produces a range gate center pulse that is supplied to the error sensor circuit. The pulse is also supplied to the pulse pair generator circuit.

The range gate center pulse leading edge occurs in the center of the range gate. The trailing edge occurs at the same time as the trailing edge of the range gate. The range gate generator circuit senses when the distance circuits reach their maximum range of 389.9 nmi. A range limit reset signal is then produced. This signal is supplied to the distance control circuit, which resets the distance circuits to the search submode.

The track signal indicates when the distance circuits are in the track submode. The signal is applied from the distance control circuit to the pulse pair generator circuit. When the distance circuits are in the track submode, the pulse pair generator circuit uses the T1 pulse from the 4K modulus counter circuit. The generator uses the pulse as the first pulse of the pulse pair produced by the circuit.

The pulse pair generator circuit produces a pulse pair. The time between pulses is equal to 50 sec + [12.359 sec (radar mile) × distance (nmi)]. The T1 pulse occurs at 50 sec before zero nmi and is the first pulse of the pulse pair. The range gate center (actual distance to the station) is used to produce the second pulse of the pulse pair. The pulse pair is supplied to the output control circuit.

The offset correction and track signals from the distance control circuit are supplied to the error sensor circuit. The offset correction signal inhibits the circuit until the track signal is supplied to the sensor circuit. The track signal enables the sensor circuit to check the position of the range gate hit in the range gate. The sensor circuit produces a no-error velocity counter clock signal. The signal is supplied to the velocity counter circuit when the hit is centered in the range gate.
When the hit is not centered in the range gate, the sensor determines if the error is small or large. If the error is large, the error sensor supplies a high-frequency clock signal to the velocity counter. If the error is small, the error sensor supplies a low-frequency clock signal to the velocity counter.

The velocity counter circuit produces a velocity count from 1 to 8,163 knots. The distance circuits can only track a range reply target at a maximum of 4,800 to 5,000 knots. The counter is clocked either up or down to the correct velocity. It remains set at that velocity until an error is sensed. The circuit produces a velocity times 10 signal. The signal is supplied to the update distance circuit. A velocity count signal is supplied to the velocity data circuit.

The update circuit converts the velocity times 10 signal to 0.01 nmi distance update data that is supplied to the distance counter circuit. The 0.01 nmi update data causes the distance counter to increase or decrease proportionately with the aircraft velocity. Therefore, during the search and pretrack submodes, the distance counter is clocked by the 4K modulus counter. After the distance circuits switch to the track submode, the distance counter is updated in 0.01 nmi increments by the distance update signal.

The 8,640 Hz ship clock signal from the bearing circuits is supplied to the distance data, velocity data, and output circuits. The distance count from the distance counter circuit is supplied to the distance data circuit on distance generator A8. The distance ship gate and distance status bits are 31 and 32. The distance data circuit converts the distance count and status bits to a 24-bit serial word. This word is shipped to the output circuit during the distance ship gate.

The 24-bit word is shipped to the output circuit at the 8,640 Hz ship clock rate. The output ships the 32-bit distance word out of the RT. The 32-bit serial word is also supplied to the distance data circuit as serial data at this time. The distance data circuit does not use the first 8 bits of the word but stores the last 24 bits.

The last 24 bits of the serial word is the same data that was shipped out as the 24-bit distance serial word. The same data must be stored in the distance data circuit. The distance count signal does not update the distance data as often as the 24-bit serial word is shipped to the output circuit.

The velocity data circuit operates in the same way as the distance data circuit. The difference is that the velocity data is shipped to the output circuit. Also, the distance status bits are used to establish the status of the velocity data.

**Data Output Circuit**

The data output circuit (Figure 4-46) converts the data from the bearing, distance, and input control circuits to serial data. The information is shipped out of the RT to indicators and/or other systems requiring the data.

The 24-bit bearing, frequency, distance, and velocity serial words are supplied to the data output on output control A4. The parity gate and modified ship gate pulses from the bearing circuits are supplied to the data output circuit. The output circuit uses the parity gate to produce odd 1’s parity which is used for the bearing and velocity serial words shipped out of the circuit. The output circuit produces the required label for each serial word and converts the serial word to ternary serial words. These words are supplied to indicators and/or systems requiring the data.

The ternary data is supplied to a ternary bus that carries the four different ternary words. The data is shipped out of the output circuit in 32-bit words separated by 32-bit spaces. The following information sequence follows: distance serial word, space, frequency serial word, space, bearing serial word, space, velocity serial word, and space. The cycle is then repeated.
Figure 4-46 — Data output circuit operation.
The data is also shipped out of the RT as 6-wire serial data. The 6-wire data consists of 32-bit, 6-wire serial data; a 6-wire word synchronizer pulse; and 8640 Hz, 6-wire clock. The synchronizer pulse occurs as the eighth pulse of the 32-bit serial word. The 6-wire distance serial data is produced in the same sequence as the ternary data.

The data output circuit amplifies the analog pulse pair from the distance circuit. The output also supplies the data to any external system requiring the data.

The circuit produces serial data that is identical to the 6-wire serial word data. This data is supplied to the RT adapter as a 32-bit, serial-data, high-level signal. The distance data contained on the serial bus is the only data from the bus that is used by the adapter. The adapter also receives a gated distance clock high-level signal from the output circuit. The gated distance clock is an 8640 Hz, 32-bit clock that occurs only when the distance data is shipped from the RT.

When the serial data is shipped from the RT, the 32-bit serial data is shipped back to the bearing input control and to distance circuits for storing the data in the circuits. It is stored until the circuits update the data.

**Monitor and Flag Circuit**

The monitor and flag circuits (Figure 4-47) check the validity of the data calculated in the bearing and distance circuits. They also monitor receiver-transmitter operation.

The TACAN control signal from the input control circuit is supplied to the control rate monitor circuit. It is supplied with the frequency ship gate pulse from the data output circuit. The control rate monitor is enabled by the TACAN control signal and operates only when the RT is controlled by an external system, such as the radio-navigation (RNAV) system. The monitor checks that the control data is updated at a sufficient rate to ensure correct operation of the RT. The control rate signal is supplied to the signal control search (SCS) circuit.

The shaped video pulses from the decoder and the PRF, modulation control, low-level signal, and T1 pulse from interrogator A11 are supplied to the SCS circuit. The circuit checks for at least six shaped video pulses each interrogation period, or between T1 pulses. At least six pulses must be received each interrogation period to ensure accurate bearing and distance data. When at least six pulses are received, the circuit supplies a control rate (SCS) signal to the bearing monitor and distance monitor circuits.

If control data from the RNAV system is not being updated at a sufficient rate, the control rate signal that is applied to the monitor circuits is removed.

The bearing lock, the 15 Hz reference 90-degree bearing load gate, and bearing data gate signals are supplied to the bearing monitor. The SMO lock signal, the SCS signal, and the sample self-test signal are also supplied to the bearing monitor circuit.

When the bearing circuits are locked, the 15 Hz reference signal is present, the SMO is locked, and when the SCS signal is present, the bearing monitor circuit supplies a valid bearing signal to the bearing status and the RT flag circuits. The signals are supplied to the circuits when the sample self-test signal from the self-test circuit occurs.

The sample self-test signal occurs when the distance circuits switch from pretrack to track submodes. If any one of the input signals indicates a malfunction, the monitor circuit supplies an invalid signal to the status and RT flag circuits. The bearing status circuit uses the bearing data from the monitor circuit to produce status bits 30 and 31 of the 32-bit bearing serial word. When both bits 30 and 31 are logic 0, the bearing data is valid. Also, the bearing indication is in the 0- to 180-degree range.
When bit 30 is a logic 1 and bit 31 is a logic 0, the bearing data is invalid due to a failure. When bit 30 is a logic 0 and bit 31 is a logic 1, the status indicates that no computed data is available. When both bits 30 and 31 are logic 1, the bearing data is valid. The bearing indication is then in the 180- to 360-degree range.

Bearing status bits 30 and 31 are supplied to the bearing circuit and to the bearing flag circuit. The status bits become part of the 24-bit serial data. When the status bits indicate a failure or that no computed data is available, the bearing flag circuit produces a bearing flag signal. The signal is applied to the system indicator and causes the indicator flag to come in view.

Figure 4-47 — Monitor and flag circuit operation.

When bit 30 is a logic 1 and bit 31 is a logic 0, the bearing data is invalid due to a failure. When bit 30 is a logic 0 and bit 31 is a logic 1, the status indicates that no computed data is available. When both bits 30 and 31 are logic 1, the bearing data is valid. The bearing indication is then in the 180- to 360-degree range.

Bearing status bits 30 and 31 are supplied to the bearing circuit and to the bearing flag circuit. The status bits become part of the 24-bit serial data. When the status bits indicate a failure or that no computed data is available, the bearing flag circuit produces a bearing flag signal. The signal is applied to the system indicator and causes the indicator flag to come in view.
The distance circuits operate in a manner similar to the bearing monitor and flag circuits, except the distance data gate and the pretrack signal are supplied to the monitor circuit. The pretrack signal is from the distance control circuit. When the distance circuits switch to track and all monitor inputs are normal, the monitor supplies a distance valid signal to the distance status and flag circuit. The status circuit produces distance bits 31 and 32 of the 32-bit distance serial word.

Bits 30 and 31 indicate the status of the distance data contained in the word. When both bits 31 and 32 are a logic 0, the distance data is valid. When bit 31 is a logic 1 and bit 32 is a logic 0, there is a failure in the distance circuits. When bit 31 is a logic 0 and bit 32 is a logic 1, no computed distance data is available. The status with bits 31 and 32 at a logic 1 level is not used. Distance bits 31 and 32 are supplied to the distance circuits for insertion into the 24-bit distance serial data word.

Distance bits 31 and 32 are supplied to the distance flag circuit. They cause the flag circuit to produce a distance flag signal when a distance failure occurs or no computed data is available. The flag signal is supplied to a distance indicator and causes the indicator to pull the distance flag in view.

When a bearing or distance failure occurs or the transmitter power is below a predetermined minimum, the flag circuit produces indicator RT flag signals. The indicators warn the flight crew that the RT is malfunctioning.

**Receiver-Transmitter Adapter**

RT adapters (*Figure 4-48*) convert digital outputs from the RT into analog signals. They are converted for use by horizontal indicator (HI) or HSI (*Figure 4-49*), RMI, CDI, and BDHI (*Figure 4-50*). However, during discussion of the adapter theory of operation, the HSI is used as the indicator receiving the outputs.

The distance data from the RT is applied to distance No. 1 card A1. The distance data, in serial BCD format, is converted to parallel format in the shift register with a serial-to-parallel bit converter. The 100’s distance data is converted to analog synchro-type voltages and applied to driver card A7. Card A7 is a power amplifier, and the 100's distance data, in synchro format, is supplied to the HSI.

The 0.1’s distance data is converted from BCD to sine/cosine format and applied to distance No. 2 card, A2. On card A2, the 0.1’s and 1’s distance data is combined. The sine/cosine 1’s distance data output is applied to driver card A5. Card A5 converts the sine/cosine 1’s data to analog synchro format that is supplied to the HSI.

The 10’s and 1’s distance data is processed similarly and is converted and amplified by driver card A6. The Geneva switch causes the 1’s and 10’s indicators on the HSI to move at the same time when the 1’s indicator is between 9 and 10.

The RMI bearing data and the HSI to-from and lateral deviation signals are derived from the 15 Hz inputs from the RT. Bearing No. 1 card, A3, converts the 15 Hz inputs to dc sine/cosine data that is applied to bearing No. 2 card, A4. The X-Y magnetic compass input is converted to sine/cosine data on A4, where it is combined with the TACAN bearing data. The 4-quadrant multiplier and summing networks produce analog synchro X1 and Y1 outputs that are applied to card A8. Synchro driver power supply card A8 provides the RMI X and Y bearing outputs to the HSI.

The omnibearing selector (OBS) signal generator (*Figure 4-48*) on card A3 produces the D-, E-, F-, and G-outputs for the course resolver in the HSI. The HSI NAV flag is controlled by the RT NAV flag input.

The OBS B input from the HSI is phase detected on card A4 to produce the HSI lateral deviation signal. The OBS A input from the HSI is also phase detected on card A4 to produce the to-from output to the HSI.

4-53
Figure 4-48 — Receiver-transmitter adapter, block diagram.
INERTIAL NAVIGATION SYSTEM

The INS is a critical part of any military aircraft’s general navigational system for two reasons:

- An inertial system neither transmits nor receives any signal, so it is unaffected by enemy countermeasures.
- Theoretically, there is no accuracy limitation in an inertial system. Technology and manufacturing precision can be considered as the factors affecting accuracy.

An inertial navigator can measure ground speed in the presence of wind and is completely independent of operating environments. The need for a system with these properties has spurred development to the point where the inertial navigator is as good as other automatic navigation systems. The inertial navigator provides accurate velocity information instantaneously, as well as accurate attitude and heading reference, for all maneuvers.

INS technology has advanced very rapidly within the past few years. Inertia is the basic element around which advanced navigation systems are designed. INSs with excellent reliability and present position errors of less than .6 nmi per hour are currently employed in operational aircraft. While not a true autonomous INS, circular error probability accuracies of 7 meters or less are possible when the INS is integrated with global positioning equipment.

Principles of Operation

The basic principle of inertial navigation is the measurement of acceleration or displacement rather than the measurement of airspeed and wind velocity, as is necessary in the use of dead reckoning. This measuring of displacement is done with accelerometers. The four basic components in any INS are as follows:

- The accelerometers arranged on the platform to supply specific components of acceleration.
• The integrators to receive the output from the accelerometers and to furnish velocity and distance

• A stable platform oriented to maintain the accelerometers horizontal to the Earth and to provide azimuth orientation

• A computer to receive the signals from the integrators and to change the distance traveled into position in the selected coordinates

A basic inertial system is illustrated in Figure 4-51. Accelerometers are maintained horizontal to the Earth by means of a gyrostabilized platform. A signal is transmitted from the accelerometer to the integrators, which perform a double integration. Distance is fed into the computer, where two operations are performed. First, a position is determined in relation to the reference system used, and second, a signal is sent back to the platform to reposition the accelerometer.

![Figure 4-51 — Basic inertial system.](image)

**Accelerometer**

The primary data source for the INS is the accelerometer. Three accelerometers are mounted on the stable element between the gyros. They provide output signals proportional to total accelerations experienced along the three axes of the stable element. The system uses these accelerations to produce aircraft velocities and changes in position.

An accelerometer (Figure 4-52) consists of a pendulous mass that is free to rotate about a pivot axis in the instrument. It has an electrical pickoff that converts the rotation of the mass about the pivot axis to an output signal. An acceleration of the device to the right causes the pendulum to swing to the left. This motion provides an electrical pickoff signal, which causes a torquer to restrain the pendulum. The pickoff signal goes to a high-gain amplifier. The output of the amplifier connects to the torquer on the accelerometer. During an acceleration, this feedback loop sends a voltage to the torquer. This voltage holds the pickoff signal at a null under the influence of the measured acceleration. This voltage is proportional to the measured acceleration. It also provides the electrical output acceleration signal that goes to the computer.
Accelerometers cannot distinguish between the actual acceleration and the force of gravity. Acceleration, to be meaningful, must be computed relative to the Earth. This means that the accelerometers must be kept level in relation to the Earth’s surface (perpendicular to the local vertical) if acceleration in the horizontal plane is to be measured. The gyroscopes keep the accelerometers level and oriented in a north-south and east-west direction.

In an aircraft, acceleration must be measured in all directions. To do this, three accelerometers are mounted mutually perpendicular (orthogonal) in a fixed orientation. To convert acceleration into useful information, the acceleration signals must be processed to produce velocity, and then the velocity information must be processed to get the distance traveled. It is true that if acceleration is integrated with respect to time, velocity results. It is also true that if velocity is integrated with time, the result is distance. Any inertial system is based on the integration of acceleration to obtain velocity and distance. Acceleration is a vector quantity, and has not only magnitude but also direction.

**Integrator**

The integration of both acceleration and velocity is very critical, and the highest accuracy is essential. There are two types of integrators (Figure 4-53): the analog and the digital. One of the most used analog integrators is the resistive-capacitive (RC) amplifier, which uses a charging current stabilized to a specific value proportional to an input voltage. Another analog integrator is the ac tachometer-generator, which uses an input to turn a motor. In this system, the motor physically turns the tachometer-generator, producing an output voltage. The rotation of the motor is proportional to an integral of acceleration. Simply stated, the processing of acceleration is done with an integrator.

![Figure 4-52 — Accelerometer.](image)

![Figure 4-53 — Integrator.](image)
Integrators produce outputs equal to the mathematical integral of the input; in other words, the input signal multiplied by the time it was present.

**Stable Platform**

Gyros are mounted on a platform with the accelerometers and control the orientation of the platform. All inertial systems use a gyrostabilized platform to maintain accelerometer orientation. Each platform must contain a minimum of two gyros. If rate gyros are used, three gyros are needed. Each gyro must have its own independent operating loop. The effectiveness of the platform is determined by all parts of the platform, not just the gyros, to include torque motors, servomotors, pickoffs, amplifiers, and wiring. The gyro presents a major problem, particularly concerning precession. Many later developments have appeared, including the air-bearing gyro, which has only one ten millionth the friction of a standard gyro. Other types of gyros have real precession rates of less than 360 degrees in 40 years. The air-bearing gyro has little or no precession.

Platforms have been used for years in bombing and fire control systems; autopilots use a basic platform. Inertial navigation simply requires a stable platform with higher specifications of accuracy.

A gyrostabilized platform on which accelerometers are mounted is called a stable element. It is isolated from the aircraft’s angular motions by gimbals. A simple diagram of a 2-degree freedom gyro mounted on a single-axis platform is shown in (Figure 4-54).

A gyro tends to remain in its original position when it is up to speed. Any displacement of the stable element from its frame of reference is sensed by the electrical pickoffs in the gyroscopes. These electrical signals are amplified and used to drive the platform gimbals (Figure 4-55) to realign the stable element.

Most INS have a four-gimbal platform in a three-axis configuration. The order of gimbal axis is as follows, starting with the innermost axis: azimuth, inner roll, pitch, and outer roll.
The four-gimbal mounting provides a full 360-degree freedom of rotation about the stable element, thus allowing it to remain level with respect to local gravity and orientated to true north. True north is established by the gyros and accelerometers, regardless of the in-flight attitude of the aircraft. The azimuth, pitch, and outer roll gimbals have 360-degree freedom of rotation about their own individual axis. The fourth gimbal, or inner roll gimbal, has stops limiting its rotation about its axis. This gimbal is provided to prevent gimbal lock, which is a condition that causes the stable element to tumble. Gimbal lock can occur during flight maneuvers, such as a loop when two of the gimbal axes become aligned parallel to each other, causing the stable element to lose one of its degrees of freedom.

**Measuring Horizontal Acceleration**

The key to a successful inertial system is absolute accuracy in measuring horizontal accelerations. As previously discussed, an accelerometer (Figure 4-56, view A) cannot distinguish between the acceleration of the vehicle and gravitational acceleration. Therefore, if the accelerometer tilts off level as in Figure 4-56, view B, its output includes a component of gravitational acceleration as well as vehicle acceleration.

To get the correct vehicle acceleration in the horizontal plane, hold the sensitive axis of the accelerometer normal to the gravitational field, as shown in Figure 4-56, view C.

The accelerometer mounts on a platform (stable element) in a way that it is always level. In this position, the accelerometer measures true aircraft acceleration in a horizontal direction along its sensitive axis. Mounting another level accelerometer perpendicular to the first one gives you the X- and Y-axes. The system can now determine total true acceleration in a horizontal plane for any movement in any direction.

Keeping the accelerometers level is the job of the feedback circuit. The computer calculates distance traveled and, via the feedback link, moves the accelerometer through an equivalent arc. The problem of aligning the accelerometer using this method is complicated by the following factors:

- The Earth is not a sphere, but an oblate spheroid or geoid.
- The rotation of the Earth produces a centrifugal force, which deflects the specific force of gravity.
- Because the Earth is not a smooth surface, there are local deviations in the direction of gravity.

The feedback circuit operates on the premise that the arc transverse is proportional to distance traveled. Actually, the arc varies considerably because of the Earth’s shape; the variation is greatest at the poles. The computer must solve for this irregularity in converting distance to arc.

The accelerometers are kept level relative to astronomical, rather than geocentric, latitude. The accelerometers are kept aligned with the local horizon and also with the Earth’s gravitational field by
using the astronomical latitude. The Earth’s rotation produces a centrifugal deflection that causes gravity to be perpendicular to astronomical latitude, as illustrated in Figure 4-57.

Local abnormalities in the Earth’s gravitational field are of minor concern. They are compensated for only in vehicles with short inertial guidance terms, such as ballistic missiles.

Accelerometers are kept level by feedback from the computer. Feedback is needed because of apparent precession. As the Earth rotates or as a gyro is flown from one position on the Earth to another, the spin axis remains fixed in space. However, to an observer on the surface of the Earth, the spin axis appears to change its orientation in space. Either the Earth’s rotation (Earth rate precession, Figure 4-58) or transportation of the gyro from one geographical fix to another (Earth transport precession) may cause apparent precession. A comparison of Earth rate and transport precession is illustrated in Figure 4-59. The movement of the stabilized platform requires constant correction to keep the accelerometers level. For a local horizontal system in which the accelerometers are maintained directly on the gyro platform, the gyro platform must be processed by a signal from the computer to keep the platform horizontal.

To overcome the problems that arise from platform tilt, the system uses the gyroscopic principle of precession. By using this principle as the aircraft flies over the rotating Earth, it is possible to apply a continuous torque to the proper gyro axis. This continuous torque reorients the gyros to maintain the stable element horizontal to the Earth’s surface and pointed north.
A comparison of gyros is shown in Figure 4-60, without torqueing in view A and with torqueing applied in view B. An animation of both conditions is shown in Figure 4-61.

A computer develops the signals necessary to properly torque the gyros. The corrections for Earth rate depend on the aircraft’s position on the Earth’s surface. To maintain the stable element oriented to the north reference, torqueing corrections rotate the platform. The rotation is about the vertical axis compensating for vehicle velocity.
Schuler Pendulum

A pendulum is any suspended mass that is free to rotate about at least one axis. However, its center of gravity is NOT on the axis of rotation. Therefore, any pivoted mass that is not perfectly balanced is, by definition, a pendulum. The inertial platform is a pendulous device and, therefore, behaves as all pendulums behave. It aligns to the dynamic vertical when at rest. The pivot axis and the center of gravity align with the gravity vector. The center of gravity will be on the bottom. Also, it tends to break into its natural period of oscillation whenever the aircraft accelerates.

Pendulous oscillation is periodic angular motion with the gravity vector as its midpoint. Periodic motion around the local vertical produces obvious errors from an inertial platform. This motion happens because misalignment about the horizontal plane introduces gravity components on accelerometer inputs. The system will interpret gravity accelerations as horizontal acceleration of the aircraft. The Schuler pendulum is a specially constructed pendulum without the unwanted oscillatory motions of non-Schuler pendulums. It is a special case of both the simple and the compound pendulums, which are discussed in the following paragraphs.

The simple pendulum consists of a small body suspended by a weightless string. The motion of the simple pendulum is both periodic and oscillatory. The period of the simple pendulum is given by the mathematical formula

\[ T = 2 \pi \sqrt{\frac{L}{g}} \]

where,

- \( T \) = time of one oscillation in seconds,
- \( L \) = length of the string, and
- \( g \) = local gravity.

The formula shows that the period of a simple pendulum is proportional to the square root of the length of the suspending string; the longer the string, the longer the period.

One property of the simple pendulum that is very useful in the construction of an inertial stable element is shown in Figure 4-62. Two pendulums are suspended by strings of different lengths. Equal forces horizontally accelerate the suspension point of each pendulum. The inertia of the bob resists
the change in its state of motion. This action causes the bob to lag the point of suspension. It also produces an angular motion of the pendulum about the local gravity vector. Figure 4-62 shows that the length of pendulum B is longer than pendulum A. It also shows angular motion of pendulum B is less than pendulum A for a corresponding linear motion of the suspension point. Therefore, the longer the suspending string, the less the angular motion of the pendulum for a given linear motion of the suspension point.

Consider what would happen in the following case. The suspending string is long enough to maintain the bob at the center of the Earth. The suspension point is transported horizontally along the Earth’s surface (Figure 4-62, view B). The bob is hypothetically at the center of the Earth, the seat of the Earth’s gravity field. Accelerating the suspension point along the Earth’s surface merely realigns the suspending string with the new local gravity vector. Therefore, the angular motion of the pendulum about the gravity vector for any horizontal acceleration of the suspension point is zero. This particular pendulum is the Schuler pendulum, shown in Figure 4-62, view B. This pendulum gets its name from the German engineer Maximilian Schuler.

Schuler solved the problem of oscillating shipboard gyrocompasses in the early 1900s. Of course, Schuler could not use the simple pendulum itself to solve this oscillating problem. He used the principle of the simple pendulum to construct a pendulum that reacted like a simple pendulum. The length of his pendulum equals the radius of the Earth, which is about 3,440 nmi long. The period of oscillation for this pendulum is about 84.4 minutes. Remember, the period of oscillation of a pendulum is proportional to the square root of its length. Therefore, any pendulum constructed to oscillate with a period of 84.4 minutes would have an equivalent length of about 3,440 nautical miles. Such a pendulum is the Schuler pendulum, a special case of the compound or physical pendulum. Figure 4-63 shows three examples of compound pendulums.

In Figure 4-63, view A, the pivot point, P, is farthest away from the center of gravity, represented by distance d. In view B, the pivot point is closer to the center of gravity than in view A. However, it is farther away than the one shown in view C, which pivots at the center of gravity.

The pivot point of each pendulum in Figure 4-63 is given the same acceleration. Therefore, each pendulum has the same linear motion at its pivot point. Yet, each pendulum has a different angular motion. As distance d decreases, the angular motion of the pendulum about the local vertical (gravity vector) decreases and distance L increases. Distance L is the distance from pivot point P to the
center of oscillation, point \( O \). Also, the pivot point and the center of gravity come closer together, and equivalent length \( L \) of the pendulum becomes longer. Figure 4-63, view \( C \), shows the pendulum pivoted at the center of gravity. In this case, there is no angular motion of the pendulum and the equivalent length \( L \) is infinite. Therefore, it is not a pendulum; it is a perfectly balanced mass that has an infinite period of oscillation. Thus, it is possible to construct a pendulum of infinite equivalent length and period. It is also possible to construct one that has an equivalent length of 3,440 nmi. Such a pendulum would be pivoted at some distance \( d \) from the center of gravity. This distance would be greater than the one in Figure 4-63, view \( C \), but less than the one in Figure 4-63, view \( B \). When pivoted at a point where the period of oscillation is found to be 84.4 minutes, it becomes a Schuler pendulum.

![Figure 4-63 — Compound pendulums.](image)

The stable element is essentially a Schuler pendulum. However, it is not entirely mechanical because the Earth’s radius varies with latitude. The Earth’s radius is greater at the equator than it is at the poles. For this reason, the stable element uses the process of Schuler tuning. Schuler tuning torques the platform to a position normal to the gravity vector by signals received from a computing loop.

**Solving Navigational Problems**

The frame of reference of an inertial system will govern, to some degree, the uses of the system. The geographical coordinate system with north reference is the most common, but not the only system used. A north-oriented system requires that one accelerometer be mounted aligned to north and another mounted 90 degrees to the first to sense east-west accelerations. This arrangement allows for any movement to indicate distance traveled east-west and north-south. Distance north-south is converted to coordinates by dividing miles traveled by 60 to obtain degrees; east-west travel requires that distance be multiplied by the secant of latitude and divided by 60 to obtain degrees. These calculations due to the convergence of meridians and is performed by computers.

Although convenient, latitude and longitude reference has the distinct disadvantage of not being adaptable to use in the polar regions because of convergence of longitudes. It is possible to offset the pole to a point on the equator. This offset would result in the polar areas being covered by a square
grid. There is no specific reason to use a north-oriented system because no external reference, such as magnetic north, is used in the inertial system. As a matter of fact, some inertial systems use a principle known as “wander angle,” which does not require the gyros to be oriented to true north. A wander angle inertial system has the advantage of being able to operate in polar regions.

The Earth is not a perfect sphere, but instead an ellipsoid, with the equator diameter 27 miles longer than the polar diameter. The INS maintains a continuous local vertical reference and measures distance traveled over a reference spheroid, which is perpendicular to the local vertical. This reference spheroid is mechanized by the INS computer. On this spheroid, the latitude and longitude of the present position are continuously measured by the integration of velocity. In Figure 4-64, phi (Ф) represents latitude north-south (N-S) and lambda (λ) represents longitude east-west (E-W).

The axes are arbitrarily designated X, Y, and Z, which correspond to east, north, and local vertical, respectively. This designation defines their positive directions. From now on, reference to velocities, attitude angles, and rotation rates will be about the X, Y, and Z axes. The local vertical (Z) is established by platform leveling. This value is the most fundamental reference direction. To complete platform alignment, north (Y) must be known; this value is accurately established by gyrocompassing. However, prior to gyrocompassing, the platform is course aligned, which means rotating the platform about the vertical (Z) axis through an angle equal to magnetic heading, plus local variation, to an accuracy of 0.5 degree or less. It should be pointed out here that gyrocompassing established platform alignment to the Earth’s axis of revolution, or North Pole. The INS is capable of doing this to an accuracy of 10 minutes of arc or less. After the platform is aligned, it remembers its alignment and always stays pointing to true north and the local vertical, regardless of the maneuvers of the aircraft.

Ground speed components of velocity in track (V) are measured by the system along the X- and Y-axes, as shown in Figure 4-65. These components, VX and VY, include all effects on the aircraft, such as wind, thermals, engine accelerations, and speed brake decelerations. The ground speed (V) is usually displayed by some form of digital readout.

The angles between the aircraft attitude and the platform reference attitude are continuously measured by synchros. The aircraft yaws, rolls, and pitches about the platform in a set of gimbals, with each gimbal being rotated through some component of attitude. True heading is measured as the horizontal angle between the aircraft’s longitudinal axis and platform north, as shown in Figure 4-66. Roll and pitch angles are measured by synchro transmitters on the platform roll and pitch gimbals.
Computer

Three of the basic components in any INS—accelerometers, integrators, and the stable element with its gyros—have been discussed. The fourth component is the computer.

The principle of inertial navigation does not include fixing en route; thus, there is a need for much greater accuracy in the computers used with inertial navigation than in those used with other systems. Because the input from the integrators is already defined as distance, the operation requires only the solution of present position. The second function of the computer is to send a positioning signal to the stabilized platform. The computers perform additional operations, such as solution and display of true
headings, ground track ground speed, wind direction, and velocity. These additional operations are not required of inertial systems computers.

**DOPPLER NAVIGATION SYSTEM**

In this section, you will learn about a representative radar navigation set. However, before this set is introduced, the Doppler principle, as it applies to Doppler radar navigation, is presented.

**Doppler Radar Principles**

Doppler radar uses CW RF transmission along with the Doppler effect. Remember, pulse-type radar determines the distance to the target by measuring the period between transmission of a pulse and receipt of the reflected pulse. The CW Doppler radar, however, senses velocity by measuring a proportional shift in frequency of the reflected signal. This frequency shift is the Doppler effect.

In operation, the airborne CW Doppler radar transmits fixed-frequency RF signals as two or more narrow beams. The beams are transmitted earthward and displaced laterally and longitudinally at fixed and equal angles. The same airborne set receives a portion of the earth-reflected CW signals, each of which has undergone a Doppler frequency shift caused by the Doppler effect. Velocity proportional difference frequency signals are extracted by continuously mixing the received energy with samples of the transmitted energy, followed by electronic detection. These signals are Doppler signals, and they contain composite velocity information. Because they are of audio frequency, they may be amplified, electromechanically or electronically tracked, and compared with pitch, roll, and altitude rate information to derive the individual components of the aircraft’s velocity relative to the axes or the Earth’s surface.

**Doppler Effect**

Electronically, the Doppler effect is the apparent increase or decrease in frequency in a received signal that results from the following conditions:

- The movement of either the transmitter or receiver, or both relative to each other
- The simultaneous movement of a combined transmitter-receiver relative to each other, or relative to a fixed reflecting surface

Disregarding angular motion for the present, the magnitude of the frequency shift is directly proportional to the closing or receding velocity along a straight-line distance between the transmitter and receiver, or between the combined transmitter-receiver and fixed reflecting surface.

A representation of the Doppler effect is shown in *Figure 4-67*. Assume three conditions of flight relative to transmitter T, represented by aircraft A, B, and C.

**Aircraft A.** Aircraft A is heading on a straight-line course toward T. It is flying at a constant speed of approximately 11 wavelengths per second and covers the distance from point X to X¹ in 1 second.

**Aircraft B.** Aircraft B is heading on a straight-line course away from T. It is flying at the same constant speed as A, and covers the distance from Y to Y¹ in 1 second.

**Aircraft C.** Aircraft C is heading on a straight-line course toward T. It is flying at a constant speed approximately 1 1/2 times the speed of A. Aircraft C covers the distance from Z to Z¹ in 1 second.

During all three preceding conditions, transmitter T is transmitting a VHF, CW signal of \( f \) cycles per second. Therefore, each distance (from X to X¹, from Y to Y¹, and from Z to Z¹) is equal to a specific number of wavelengths at frequency.
Each aircraft (A, B, and C) is equipped with a relatively broadband receiver capable of accepting signals at frequencies higher or lower than transmitted frequency \( f \). During the 1-second interval in which A is flying from point X to X\(^1\), \( f \) number of cycles of the signal from T reach point X. Because A is advancing in a straight line toward the signal source, it receives the following signals:

- The \( f \) number of cycles it would receive if stationary for 1 second over point X
- It simultaneously receives additional wavelengths of the signal en route between point X\(^1\) and X

Therefore, aircraft A receives a signal that is of apparent higher frequency than that emitted by the transmitter.

The magnitude of the preceding frequency shift is proportional to the speed of the aircraft toward T, and inversely proportional to the frequency of the transmitted signal. The direction of frequency shift depends on the direction of flight relative to the signal source. The effect of flight direction and speed on the direction and magnitude of frequency shift is shown by aircraft A, B, and C.

Because aircraft B is flying away from the signal source at a speed equal to the speed of A, the apparent frequency is lower than the transmitted signal. However, it is equal in magnitude to the apparent frequency received by A.

Because aircraft C is flying in the same direction, but at approximately 1 1/2 times the speed of A, the frequency received by C is also apparently higher than the transmitted signal but greater than that received by aircraft A. The apparent frequency shift is the Doppler effect.

An aircraft sets its heading toward a fixed ground transmitter in Figure 4-68. However, it experiences drift, which if not corrected, results in the position shown by aircraft B. The Doppler frequency shift is proportional to the amount of drift.

Aircraft A. Aircraft A is flying with zero drift and headed straight toward transmitter T.

Aircraft B. Aircraft B is flying at the same speed as aircraft A but is drifting past the transmitter.

In the interval of 1 second, aircraft A has approached closer toward the transmitter than aircraft B. You can see this difference by comparing the arcs scribed at Y and Y\(^1\). Because of the faster rate of approach to the transmitter, aircraft A receives more cycles of the transmitted frequency per unit of time than aircraft B. This difference results in an apparent increase in frequency received by aircraft A.

Figure 4-67 — Doppler frequency shift, stationary transmitter, and airborne receiver.
over that received by aircraft B. The difference in the Doppler effect on received frequency of zero drift and drift conditions suggests a means of determining drift angle.

Two-Beam System

The Doppler frequency shift previously described also occurs when the transmitter and receiver are in motion together; for example, when they are carried in an aircraft, and received signals are signals reflected from a fixed point on the Earth’s surface. The receiver senses a Doppler frequency shift that is directly proportional to the speed of the aircraft. The ratio of frequency shift to ground speed is twice that shown in Figures 4-67 and 4-68 because a proportional shift occurs in the signal on its way to the Earth’s surface and occurs again, to an equal degree, during straight-line flight in the signal returning to the receiver. To obtain the largest possible frequency shift, you must focus the transmitted beam toward the Earth at the angle that yields the largest ratio of change in distance between the transmitter-receiver and the Earth’s surface. The desired rate of change is obtained when the transmitted beam is inclined toward or away from the direction of the aircraft’s heading. The Doppler shift sensed by an airborne transmitter-receiver in which the beam is focused obliquely downward and aft of the aircraft’s longitudinal axis is shown in Figure 4-69.
In *Figure 4-69*, aircraft A flies from point X to X¹ in 1 second. The signal $f_1$ Hz is reflected from the ground toward the receiver. For each second the receiver recedes from the reflected signal, a distance equal to 16 wavelengths of frequency $f_1$ is traveled. Because each wave must catch up with the receiver, the time between each of the reflected waves is increased and therefore delayed in arrival. In effect, the reflected signal frequency $f_1$ decreases to $f$ Hz.

To sense drift and heading velocities simultaneously, two transmitter beams are used. They are directed laterally relative to aircraft heading as well as earthward and aft. In a basic two-beam radar navigation set, two beams are directed symmetrically—one to port and one to starboard of the aircraft’s longitudinal axis. The orientation of the transmitter beams relative to the horizontal and vertical planes is shown in *Figure 4-70*.

### Effect of Drift on Frequency

The Doppler effect in a dual-beam system is shown in *Figure 4-71*. Assuming the aircraft is not drifting, simultaneous radiations of each beam are reflected back to the aircraft from separate points on the Earth’s surface. The time in transit of the microwave energy in each beam is a direct function of the aircraft velocity. If they could be seen, the continuous waves of transmitted energy would form dual traces across the Earth’s surface; these traces comprise successive instantaneous points of reflection.

In *Figure 4-71*, the port transmitted beam P has a rate of travel equal to its corresponding starboard transmitted beam S. Therefore, points RP and RS and RP¹ and RS¹ are the instantaneous points of reference for determining the rate of travel by the received beams of aircraft A and B, respectively. In the zero drift condition, aircraft A maintains heading H from X to X¹ for 1 second. The rate at which A recedes from reflecting points RP and RS is equal; therefore, the effective wavelength of the RF energy in beams P¹ and S¹ is equal. Because Doppler frequency shift is proportional to the relative velocity between the reflector (Earth) and the receiver, the Doppler frequency shift in beams P¹ and S¹ of A is equal.

In the drift to port condition, aircraft B encounters drift forces and covers ground track (GT) in 1 second. The rate at which aircraft B recedes from reflecting point RS¹ is greater than the rate at which it recedes from point RP¹. Therefore, the distance that beam S¹ of aircraft B travels in 1 second is greater than its associated beam P¹ in equal time by the distance from point Z to RS¹. Because the rate of travel of effective wavelength for beam S¹ is greater than beam P¹ in a port drift condition, the Doppler frequency shift is greater in S¹ than in P¹. If the drift were to starboard instead of port, the largest Doppler frequency shift would occur in the port beam.
You can see that by using dual oblique beams, the direction of drift can be derived from the received beam that registers the least frequency shift. The velocity of drift can be computed from the difference between the magnitude of frequency shift in each beam, and ground speed can be computed from the sum of the magnitudes of frequency shift in each beam. A similar method is used for deriving direction, velocity of drift, and ground speed in radar navigation sets.

Functional Theory of the Radar Navigation Set

Two narrow beams of continuous microwave energy are transmitted by the transmitter-receiver and focused obliquely toward the Earth. The beams are displaced laterally, one to port and one to starboard, both forward and aft (Figure 4-70). A portion of the transmitted energy from each beam is reflected from the Earth’s surface at an angle sufficient to be intercepted by the receiving portion of the transmitter-receiver antenna. Each received CW signal is mixed with continuous samplings of the transmitted signal within the waveguide assembly of the antenna, and then coupled to its respective port or starboard crystal detectors. The resultant difference frequency output signal \( f_{dp} \) and \( f_{ds} \) of each detector is proportional to the aircraft’s velocity along the port and starboard beam axes, respectively. These Doppler signals are of equal frequency as long as the aircraft maintains a straight-line heading with no pitch or roll. As the aircraft drifts to port or starboard, the following conditions occur:

- Its drift is sensed as a decrease in Doppler frequency derived from the beam that is focused in the direction of drift.
- An increase in Doppler frequency is derived from the beam focused opposite to the direction of drift.

Because of the lobe pattern of the transmitted beams, the reflected energy of each beam comprises a narrow band of frequencies rather than a single frequency. The result is narrow-band Doppler difference signals (port Doppler frequency and starboard Doppler frequency), which are fed from the port and starboard crystal detectors, respectively, to the dual-channel amplifier assembly. At this point, each signal is amplified under AGC and then fed to the signal data converter.

Using what are initially only noise inputs, the signal data converter initiates a search function to acquire well-defined Doppler signals in both port and starboard channels. Simultaneously, this converter supplies gain-increasing AGC feedback voltages to the amplifier assembly and a memory

Figure 4-71 — Effect of drift on frequency shift in dual beams.
signal used in the ballistics computer. This memory signal also causes an indicator lamp to come on, indicating that the signal data converter is operating in the search mode. When a satisfactory Doppler signal is acquired, the signal data converter locks on and tracks the center of each Doppler energy spectrum, and converts these signal frequencies to rate-proportional pulse outputs. The memory signal is cut off, and the indicator or lamp goes out. These rate-proportional pulse outputs, which are representative of aircraft velocity data, are then routed to the ballistics computer.

**Four-Beam System**

A typical four-beam Doppler navigation system is a lightweight, miniaturized ground speed and drift angle measuring system. It is designed to satisfy the navigational requirements of modern military aircraft. It uses Doppler pulsed radar techniques to measure ground speed and drift angle directly, continuously, and accurately. It is easily installed in most fixed-wing aircraft because of its small size and light weight.

These units emit short pulses of microwave energy, so the transmitter is not operative while an echo is being received. Therefore, in a single-beam radiation pattern, there is no second frequency with which to compare the echo. However, two beams—one projected dead ahead and the other directly behind—would experience equal but opposite Doppler shifts. In this case, one-half the difference between the two echo frequencies is the Doppler shift of either beam, and this shift is proportional to ground speed. This condition assumes no drift. If drift is present, the two-beam system described above does not detect it when used with pulsed beams. Antennas radiating to the left and right detect sideways motion, but not fore and aft motion.

To make simultaneous measurement of both ground speed and drift angle, a modification of the two-beam pattern is used. The vicinity of the aircraft is divided into four quadrants—left forward, left rearward, right rearward, and right forward (Figure 4-72, view A). Simultaneous beams are radiated into diagonal quadrants with switching of the quadrants at regular intervals.

![Figure 4-72 — Four-beam pattern, using two-beam transmission.](image)
When there is no drift, the ground track and aircraft heading coincide. In this condition (Figure 4-72, view B), the radiation pattern is symmetrical about the axes of the aircraft, and the left and right beams are at the same angle from ground track. The Doppler shift is equal in the beams.

When the antenna is not aligned with ground track (Figure 4-72, view C), an angle exists between the antenna axis and ground track. The beams experience unequal shifts. The difference frequency resulting from one pair of beams is higher than that from the other. As the switching action occurs, this difference is processed as an error signal, which, through servo action, drives the antenna into alignment with the ground track.

When the antenna is aligned with ground track (Figure 4-72, view C), the angle between the antenna axis and the aircraft heading represents the drift angle. Through a synchro system, this information, along with the ground speed data, is supplied to the computer.

**Eight-Beam System**

The typical eight-beam Doppler navigation system provides airborne ground speed and drift information using the Doppler principle to extract data from reflected signals. A lightweight system, operating on a frequency of 13.325 (0.05) GHz, it precisely measures, processes, and indicates ground speed and drift angle information aboard aircraft. It is used with a navigation/weapon delivery computer, an inertial measurement system, and a heads-up display set.

In measuring the ground speed and drift angle of an aircraft, the system transmits narrow beams of electromagnetic energy downward from an antenna stabilized in pitch, roll, and azimuth to illuminate small areas on the Earth’s surface. A portion of the transmitted energy is reflected from the surface, received, and processed by the system to determine the Doppler frequency shift.

A typical system radiates a four-beam pattern that consists of two-beam pairs alternately switched from left to right of the aircraft’s fore-aft axis. Frequency shifts occurring in each beam are proportional to the components of the aircraft’s forward and lateral velocity along the respective antenna beam. The frequency shifts are detected by mixing a portion of the transmitted signal with the received signal and detecting the audio beat frequency.

After detection, the Doppler signals are fed to ground speed and azimuth tracking circuits. These circuits convert the signals into voltages proportional to ground speed and azimuth. Outputs proportional to these voltages are provided in proper electrical form to drive the appropriate auxiliary equipment.

The magnetron in the radar transmitter generates 200-volt pulses of RF energy at a PRF of 80 to 120 kHz, with an average power of 10 watts. The magnetron output is applied to a crystal switch that passes the magnetron pulses to a duplexer, which routes the microwave energy to a waveguide assembly. During the transmit cycle, the receiver crystal switch is closed, minimizing coupling of transmitted energy into the receiver. The duplexer permits the use of the same antenna for both transmitting and receiving, and it isolates the receiver from the transmitter. The duplexer also couples the transmitted signal to the waveguide assembly, and, during the receive cycle, couples the return signal from the waveguide to the receiver switch. The waveguide couples transmitter RF energy to the antenna. Four radiating elements composed of a J-band waveguide, four reflectors, and a waveguide flange complete the antenna array.

When the set is transmitting, the generated RF energy is applied through the crystal switch to the duplexer and waveguide assembly, coupling the energy to the antenna so that the switching and array combination generates eight beams of energy (Figure 4-73). The beams are radiated two at a time in the following order:

1. Front right (A) and aft left outer (A¹)
2. Front right (B) and aft left inner (B¹)
3. Front left (C) and aft left outer (C¹)
4. Front left (D) and aft right inner (D¹)

Left-right switching and fore-aft beam lobing are caused by coded signals supplied by the receiver-transmitter to the switching modules in the antenna assembly.

The antenna is stabilized in pitch and roll to compensate for changes in aircraft attitude. Pitch and roll stabilization is achieved by means of servo loops that receive pitch and roll attitude signals from a pitch and roll reference input. Servomotors drive the antenna array pitch and roll gimbals through their respective gear trains. The array is also driven in azimuth by a servo loop, aligning it with the aircraft ground track to compensate for aircraft drift conditions up to 30 degrees. During receive, the return signal is coupled with the antenna through switching modules, through the waveguide assembly, and to the duplexer, where it is then routed to a receiver switch.

The receiver accepts the Doppler return and processes it to provide output frequencies falling within a 1 to 36 kHz band, which contains both ground speed and azimuth drift information. These output frequencies are applied to frequency tracking circuits, which consist of ground speed tracking and azimuth tracking loops. The ground tracking circuits measure Doppler frequency and provide an analog ground speed output. The azimuth tracking loops compare Doppler shift of two transversely switched beam-pair returns and drive the antenna in azimuth until it is aligned with the ground track. At this time, the Doppler shifts from both beams are equal. A potentiometer positioned by an antenna azimuth drive shaft provides an electrical analog output of drift angle to analog-to-frequency conversion circuits. Frequency-to-digital conversion circuits use input frequencies to represent ground speed and drift angle to provide a 60-bit word. This word represents ground speed, drift angle, and system status for use by digital navigation computers and in inertial system correction.

GLOBAL POSITIONING SYSTEM

GPS is funded by and controlled by the U. S. Department of Defense (DoD). While there are many thousands of civilian users of GPS worldwide, the system was designed for and is operated by the U. S. military. GPS provides specially coded satellite signals that can be processed in a GPS receiver, enabling the receiver to compute position, velocity, and time. Four GPS satellite signals are used to compute positions in three dimensions (Figure 4-74, frames 1 and 2) and the time offset in the receiver clock.

GPS is a one-way (listen only) system, in which the satellites transmit signals but are unaware who is using the signal (no receiving function). The user (or listener) does not transmit a signal, and therefore cannot be detected by the enemy (military concern), and cannot be charged for using the system (civilian concern).

As GPS is a multi-satellite system, a number of satellites are always visible simultaneously anywhere on the globe and at any time. The Satellite Constellation is made up of 24 operational satellites in
10,898-mile-high, semisynchronous orbits. A minimum of five satellites are observable from anywhere on Earth, with four satellites required to produce the most accurate position solution.

GPS can support a number of positioning and measurement modes in order to satisfy simultaneously a variety of users, from those requiring only navigation (decameter) accuracies to those demanding very high (millimeter/centimeter) accuracies for military use, which are dependent on cryptographic codes.

**GPS Today**

The evolution of airborne navigation from compasses and inertial gyros of the 1950s to the GPS receivers of today has produced a dramatic increase in the speed and accuracy with which an aircraft’s position on the Earth can be determined.

GPS was rapidly adapted for aviation because it can give a position (latitude, longitude, and height) directly, without the need to measure angles and distances between intermediate points. Position can now be established almost anywhere because it is only necessary to have a clear view of the sky so the signal from the GPS satellites can be received clearly.

Today’s GPS satellites transmit two carrier frequencies that are commonly referred to as L1 and L2, both of which contain codes that provide positioning, timing, and navigation information. Utilizing
these frequencies and codes allows GPS receivers to track several satellite signals at the same time so that precise positioning can be calculated anywhere on Earth.

L1 carrier contains coarse/acquisition (CA) code, which is commercially available. The L2 carrier contains only the precise (P) and classified (Y), which is an encrypted code reserved for military use (Table 4-2).

Crypto keys enable GPS to receive highly accurate P code and Y navigation signals.

<table>
<thead>
<tr>
<th>Carrier</th>
<th>Frequency</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>1,575.42 MHz</td>
<td>C/A and P/Y</td>
</tr>
<tr>
<td>L2</td>
<td>1,227.6 MHz</td>
<td>L2C and P/Y</td>
</tr>
</tbody>
</table>

Each satellite transmits two RF signals. Each signal is modulated with a unique code sequence and navigation data message. The code sequence allows the GPS to identify each satellite. The navigation data message provides the GPS with ephemeris and almanac data. Almanac data represents current satellite positions, while ephemeris data represents satellite clock and position errors calculated by dedicated ground stations.

GPS receives, tracks, and processes L1 and L2 frequency band RF GPS signals from the antenna and provides position, velocity, and time (PVT) information to aircraft interfaces. GPS is made up of hardware and software to do the GPS signal navigation tasks and to do a BIT on the GPS receiver and the batteries installed. Signal processing involves reception and amplification of the satellite signal, sequential code and carrier tracking to measure pseudo-range and delta range, and data demodulation to verify correct reception.

GPS aircraft position data is not susceptible to local atmospheric pressure variations or other environmental effects, but it is affected by two types of atmospheric delays that can affect the accuracy of satellite signal measurements.

Tropospheric delay can be predicted and included in the satellite almanac data. After collecting the almanac data, the GPS removes the predicted delay from the satellite signal measurements.

Ionospheric delay occurs because the ionosphere is thicker in some areas than in others (Figure 4-75). This delay causes a greater phase shift of the L2 RF signal than in the L1 RF signal. The delay is measured by the difference in phase shift between the two signals.

**GPS in Naval Aircraft**

The typical GPS you will encounter on naval aircraft comprises the components described below.

**Receiver**

The receiver receives modulated navigation signals from satellites to determine aircraft PVT and then provides PVT information to aircraft interfaces for use by other navigation and sensor systems. The receivers have batteries to maintain nonvolatile memory when aircraft power is removed.

The GPS receiver determines distance to a satellite by measuring the time difference between when the satellite transmits the signal and the time GPS receives the signal. The time the GPS receives the signal is determined by the GPS clock. When the GPS clock is not perfectly synchronized with the satellite clock, the time measurement is inaccurate.

The inaccurate time measurement used in the distance calculations prevents accurate GPS position to be found. The satellite clock error is measured by a dedicated ground station, and the correct data is included in the data sent to the GPS receiver. The sole purpose of one of the four satellites is to provide additional measurement data needed for GPS to calculate the clock error common to all
distance measurements. Once the clock error is found, it is removed from the distance measurements.

Antenna

The antenna is usually flush mounted on the aircraft’s upper fuselage surface (Figure 4-76) and provides RF navigation signals to the GPS receiver in L1 and L2 range.

RF Cable Assembly

A coaxial cable carries the RF signals from the antenna to the GPS receiver. The cable has a frequency range of 1 to 1.6 GHz and usually has maximum attenuation values over this frequency range that must be periodically verified.

Key Fill Panel

The key fill panel can be located in the nose landing gear wheel well, avionics bays, cockpit, or crew section of the aircraft and contains the following components: data fill connector, data fill indicator, and data fill switch.
NAVIGATIONAL COMPUTER SYSTEM

A navigation computer system relieves the aircrew of many manual operations required to direct the aircraft in flight. When automatic sensing devices are tied into a navigation computer system, the pilot or aircrew is automatically provided current readings of present latitude and longitude, ground speed, and heading. The navigation computer system eases the in-flight workload and frees aircrew to make decisions that are beyond the capability of computers.

Aircraft are capable of speeds and ranges that require extensive navigation calculations rapidly and accurately. For example, on a flight from the United States to a foreign country, the route could pass over land, water, and ice caps. Many challenges face pilots or tactical coordinators. They must contend with overcast or undercast conditions, day and night flight, altitude changes, turning points, and mandatory estimated time of arrival (ETA) requirements. To handle all of these conditions at the speed of sound or faster, they use automatic navigation computers. These systems vary by aircraft type, model, and series. A general overview of system integration will be discussed in this chapter.

A typical navigational computer system consists of the following components:

- Data-gathering units (sensors) such as radar, Doppler, INS, TACAN, and GPS
- Computer units where the computations and comparisons are made
- Information display system to give aircrew monitoring and control capability

Sensors

Sensors are data-gathering units such as conventional radar, Doppler radar, INS, TACAN, and GPS.

Conventional Radar

When radar is incorporated into the computer system, movable electronic crosshairs (Figure 4-77) or target designators (Figure 4-78) are indicated on some display types so that range and direction of radar returns are measured and inserted into the computer. The crosshairs consist of a variable range mark and a variable azimuth mark. They may be automatically assigned or maneuvered by aircrew with a control device, such as a trackball or light pen. On the display, they resemble a single fixed-range mark and a heading mark. By moving the control device, the aircrew simultaneously changes the position of the crosshairs and the corresponding coordinate measurements (east-west and north-south) being fed to the navigation computers.

When the aircrew positions the crosshairs on a given return, the computers determine the distance between the aircraft and the return. After the coordinates of the return have been set in the computer, the computer can maintain a running account of the aircraft latitude and longitude.
Doppler Radar
In aircraft equipped with Doppler radar, its contribution to the computer system is ground speed and drift angle. These two outputs are put to several uses in the computer system. Doppler ground speed is used to drive the present position latitude and longitude counters. Doppler outputs are used in platform leveling and checking inertial ground speed in an inertial system. When present, Doppler radar is an essential part of navigation computer systems.

Inertial Navigation System
The INS is used to feed velocity information into the computers. Once the inertial sensor is leveled and in operation, it is used to continually update the present position counters.

Tactical Air Navigation
TACAN is an integral part of most navigation computers. Because the TACAN output is given in the form of a range and bearing, the computers only need the coordinates of the TACAN station being used. This data is set into the computer before the mission begins. Some variables must be applied to TACAN outputs to increase accuracy. The bearings received from TACAN are magnetic; therefore, the computer must have an accurate magnetic variation value at all times. This variation data is usually built into the computer. TACAN range output is expressed in slant range. The computer applies absolute altitude above the station to the slant range to produce exact ground range.

Global Positioning System
GPS enables navigation computers to nearly instantaneous PVT information.

Computer Unit
The computer combines inputs from all sensors to provide the aircrew with integrated situational information on position, velocity, attitude, and heading to the desired destination. Information is also provided to electronic warfare and weapons systems.

Units incorporating GPS are known as Embedded Global Positioning System/Inertial Navigation Systems (EGIs). EGIs provide primary navigation and directional information to aircrew, as well as high-precision attitude, heading, velocity and flight data to the aircraft fire control computer or integrated system processor.
Determining Position

Regardless of computer type, the problems to be solved by a navigation computer remain the same. The ever-present problem facing aircrew is determination of aircraft position. With a computer system, it is not necessary to estimate a position based on a track and ground speed derived from the last known position. The computer always displays the current position for convenient reading.

The INS sends a true heading to the computer, and the Doppler registers ground speed and drift information. The true heading and drift are combined in the computer to produce a value of track.

The ground speed can be resolved around the direction of track to produce values of ground speed to drive the latitude and longitude counters. Though this process seems basically simple, a few corrections must be applied to the ground speed components before they are sufficiently accurate for present position drive. These corrections, done within the computer, include such things as compensation for convergence of meridians, gravitational variances (Figure 4-79), and the Earth’s imperfect shape causing other factors, such as deflection of vertical (Figure 4-80).

Determining Heading to Destination

Another question the aircrew often faces is, “What is the destination’s heading?” This question is also answered by many navigation computer systems. The computer first computes the required track, either rhumb line or great circle. To do this calculation, it computes the direction and

Figure 4-79 — Gravity map.

Figure 4-80 — Deflection of vertical.
distance from the present latitude and longitude to the destination latitude and longitude. The present track taken from the inertial system, in this instance, is then compared to the required course to destination; the difference is a heading correction. Ground speed may be applied to the distance to destination, and a time-to-go may be computed to provide a continuously updated ETA.

**Navigation Panels**

The navigation panels make up the greatest part of the computer system visible to the aircrew. Panel appearance and operation vary with each computer system. The multitude of counters, dials, switches, buttons, control knobs, and selectors gives the aircrew maximum use and control of the system. DDIs contain selectors that determine which sensors will be used and which readouts will be displayed, allowing the aircrew to switch from one mode of operation to another, as shown in Figure 4-81.

The computer system aids the aircrew in other ways. Most computers have limits built into them so they will not accept unreasonable information. For instance, if the coordinates of a fix point are set 1 degree of latitude in error, the computer rejects the fix because the information is totally incompatible with information already in the computer. A rapid change in ground speed from a sensor might be rejected, and that sensor output would no longer be used because it would be considered unreliable.

So far in this discussion, only basic navigation has been considered. Computer systems can solve ballistic problems, automatically releasing bombs and missiles. If the system is installed on a transport-type aircraft, cargo drops and notification of bailout time to parachutists can be controlled by the navigation computer. The mission requirements of the aircraft dictate what capabilities a computer system should include.

**ELECTRONIC ALTIMETER SYSTEM**

Airborne electronic altimeters (commonly called radar altimeters or radalt) are absolute altimeters because they measure and indicate the height (altitude) of the aircraft above the terrain, rather than with respect to sea level, as do barometric altimeters. They may operate on FM, pulse modulation principles, or a combination of both. Most modern radar altimeters use pulse-modulation principles.

Because they operate by transmitting and receiving RF energy, they are accurate over all types of terrain and under all types of weather conditions.
**Basic System Principles**

A typical radar altimeter system operates on the accurate timing of the interval required for an RF pulse to travel from the aircraft’s transmitting antenna to the terrain below and return to the aircraft’s receiving antenna. The system converts the time interval to a range signal that is used as the input to various readout circuits. Basic elements of a radar altimeter system are shown in Figure 4-82. When the transmitter fires, it transmits a pulse of RF energy out the transmitting antenna, and at the same time, generates a time-zero (T-zero) pulse that is used to start the measurement of the transmission-reception time interval. The time-measuring circuit is commonly called the range computer or tracker. When the RF return (echo) pulse arrives at the receiver, a video return pulse is generated. A track gate (which is generated in the range computer by the T-zero pulse) is positioned on the leading edge of the video return pulse, which, in turn, causes the output of the range computer to be an analog signal that represents range or altitude. The output of the range computer may also be in the form of a bit digital word, which is used by some system readout indicators.

**Closed-Loop Tracking**

Typically, most radar altimeter receiver-transmitter units use a closed-loop tracking system (Figure 4-83) contained in the unit’s range computer. For explanation purposes, we will analyze the closed-loop tracking system used by a typical range computer. This representative altimeter has a maximum altitude readout of 5,000 feet.
Each time the transmitter fires, a T-zero pulse is generated. This pulse triggers the ramp generator, which generates a ramp voltage that varies linearly from 0 to 28 V in 10.17 μsec (Time required for RF energy to travel 10,000 feet; that is, to echo from a 5,000-foot altitude.).

At the same time, an internal range voltage is being swept from 0.5 to 32 V at a relatively slow rate (two to three times a second). When these two voltages coincide at the comparator, a track gate pulse is generated and appears at one input to the track gate. The level that the ramp voltages reach at the time the track gate pulse is generated is proportional to altitude or range. When a track gate pulse and a video return pulse occur simultaneously (in time) at the track gate inputs, a track gate output pulse is generated, which controls the value of the internal range voltage. The internal range voltage, at the instant the track gate output pulse is generated, represents the radar range (altitude). This output is applied to an indicator readout unit servo system, which drives the indicator needle.

When the track gate pulse is applied coincidently with the video return pulse, the track gate output consists of the overlapping portion of the track gate pulse and the video return pulse. Various time relationships of the two pulses are shown in Figure 4-84. When the altimeter system is properly tracking the RF echo, the track gate output (shaded area) will be as illustrated in Figure 4-84, view C. The track gate output will consist of pulses, at a rate of 8,500 pulses per second (transmitter firing rate), with individual values (amplitude) equal to the overlapping (shaded) portion of the two pulses. The track gate output pulses are then processed to maintain a constant overlap of the track gate and video pulses. If the RF transmission path distance should change (height above terrain), the track gate output pulse values would also change. This change in the track gate output pulse will change the internal range voltage, which, in turn, will change the position (time) of the track gate (the track gate pulse would occur at a different time because the ramp generator would have a different time to reach the new voltage value of the internal range voltage).
Leading-Edge Tracking

You will notice that the trailing edge of the track gate pulse intercepts the leading edge of the video return at the approximate midpoint. This characteristic is called “leading-edge tracking.” By controlling the amplitude of the video return pulse so that it has a constant amplitude under all conditions (altitude, attitude, terrain, etc.) and by controlling the position of the track gate with respect to the leading edge of the return video, the radar altimeter system is made essentially independent of all characteristics except the clearance of the aircraft over the terrain.

The basic functions of the leading-edge, closed-loop portion of the range computer are shown in Figure 4-85. As previously mentioned, a track gate pulse is generated whenever the ramp generator voltage and the internal range voltage are equal at the comparator. The internal range voltage can be changed from 0.5 to 32 volts only relatively slowly by track error current inputs, and will hold its value whenever the track error current becomes zero. The ramp generator voltage also changes from 0 to 28 volts. However, this voltage changes linearly in 10.17 μsec, as previously explained. This ramp is generated each time the altimeter’s transmitter fires (8,500 pulses per second [pps]). The sequence of events and the voltage relationships at the comparator during one transmission cycle are illustrated in Figure 4-86. A comparator output pulse is generated each time the ramp generator and internal range voltages are equal. When the comparator output pulse occurs, a track gate pulse is generated. Each time a track gate pulse is generated, a ramp reset signal is also fed back to the ramp generator, commanding the generator to return to zero.

To keep the trailing edge of the track gate pulse intercepting the midpoint of the video return pulse, the video leading-edge output pulses from the track gate are amplified, filtered, and summed with an offset current to produce an error current to control internal range voltage, as illustrated in Figure 4-86. When the track gate pulse overlaps the leading edge of the video return signal by the amount desired, the output of the amplifier and post detection integrator (PDI) will be 15 microamperes of current. The offset current is a negative 15 microamperes of current. Therefore, under ideal conditions, the track error current to the internal range voltage control will be zero. Consequently, the time delay used in generating the track gate value of the internal range voltage will not change.

Figure 4-85 — Radar altimeter system-tracking elements.
When the altitude of the aircraft increases gradually, the amount of overlap between the track gate pulse and video return pulse decreases (video arrives later) with each succeeding return video pulse applied to the track gate, as shown in Figure 4-87. Consequently, the output of the amplifier and PDI function decreases from 15 microamperes, and the track error current out of the summation network becomes negative (some negative portion of the negative offset current). This negative input to the internal range voltage control is phased to cause the internal range voltage to increase, and more time will be required for the ramp generator voltage to equal it. The result is that the track gate pulses follow the leading edge of the received signals at the track gate.

When the altitude of the aircraft decreases, the overlap of the track gate pulse with the video return pulse increases. The signal arrives sooner, so more of the video is in the gate. The output of the amplifier and PDI function then becomes greater than the 15 microamperes. The track error current becomes positive out of the summation network, causing the internal range voltage to decrease. The ramp generator voltage will reach this new value sooner. Therefore, the track gate pulse will be generated sooner and, with decreasing altitude, the echo signal will still be tracked.

Gain Control

The accuracy of the radar altimeter altitude measurement is dependent not only on the slope and linearity of the ramp generator voltage, but also on the consistency of the rise time of the video return pulse. The purpose of an altimeter’s gain control system is to keep the rise time of the video return pulse the same under all received signal strength conditions. The relationship of the gain control function and the tracking/search mode control function is shown in Figure 4-88. There are two system gain control functions: signal strength controlled and range controlled. The signal-controlled gain consists of noise automatic gain control (NAGC) and keyed automatic gain control (KAGC). Range-controlled gain consists of sensitivity range control (SRC) and sensitivity range control assist.

The receiver’s IF gain control system is phased so that the IF gain control system is the internal range voltage that is used to drive the SRC. Its gain schedule is a nonlinear function of altitude, decreasing the receiver’s sensitivity only at very low altitudes to prevent false tracking of the transmitter antenna leakage pulse (stray radiation). There are two gain controlling sources from the range computer: NAGC and KAGC. The NAGC is a wide band control used to sense all noise and video signals from the receiver’s IF amplifier. It will limit the IF gain to maintain a usable signal-to-noise ratio. The KAGC circuit is a fully keyed (gated) circuit. That is, it allows only those IF signals that occur during the KAGC pulse to control IF amplifier gain. The KAGC pulse is generated simultaneously with the track gate pulse. However, the KAGC pulse is wider than the track gate pulse; therefore, it overlaps much

![Figure 4-86 — Developing track gate output.](image-url)
more of the video return pulse than does the track gate pulse. It must include the video pulse peak. The function of the KAGC circuit is to control the receiver’s IF gain so that the peak of the video pulse remains constant under all conditions of signal strength. The SRC is assisted during the search mode of operation. Because the IF gain control circuit has a time constant of approximately 50 milliseconds (msec), it cannot react fast enough to reduce the IF gain during the rapid 20 msec retrace cycle of the internal range generator. If not compensated, the increased sensitivity would allow the system to begin tracking stray antenna radiation signals because the IF gain would be relatively high as the track/search control caused the internal range voltage to begin its outbound sweep. Therefore, during the retrace, the SRC (provided by an output from the track/search control) forces the IF gain control to reduce the IF gain; consequently, receiver sensitivity before the retrace ends, and the outbound sweep begins.

**Mode Control**
The previous discussion has assumed that the system was tracking an echo pulse. In actual operation, the system is either in an automatic mode or the self-test mode. The automatic mode contains three submodes: track, search, and memory, during which the system searches for an echo pulse or tracks that pulse. The self-test mode is manually commanded and fully exercises the automatic mode, causing the system to acquire and track a synthetic target and display a 100-foot
range. The automatic mode control system receives its input from the KAGC circuit and return pulse. If 8 to 10 consecutive video return pulses have sufficient amplitude, the mode control will not modify the tracking mode if the system is tracking, and will switch to track if it is searching. The mode control first switches to the tracking operation when 8 to 10 consecutive synchronous video pulses, of 6 V amplitude or greater, are applied to the KAGC gate. The time constant of the track/no-track detector of the track/search control circuit is selected so that it will require 8 to 10 pulses before its output will exceed the tracking threshold. This step prevents the system from being switched into the track mode by random pulses from other systems operating in the area.

The mode control has a 0.2-second hold condition to provide for momentary drops in signal strength. If the video return pulse does not return to sufficient strength within the 0.2-second interval, the mode control enables a memory mode of operation. The memory mode lasts for approximately 1 second, during which time the internal range circuits search for a new target, and the last valid external range output is maintained. If a new target is detected during the memory mode, the system reverts to the normal track mode. If a target is not detected, the system switches to the search mode. During the search mode, the track/search control overrides and controls the track loop. The track loop current is removed from the internal range control circuits, and the track/search control forces the internal range voltage through its limits of 0.5 to 32 V at about three times a second (the search-out rate is about 15,000 to 20,000 feet per second).

Figure 4-88 — Gain and track search mode control.
This condition causes the KAGC and track gate pulses to run through their full range of delays, seeking to find the video return pulse.

During the search retrace portion of the cycle, the track/search control is inhibited from switching to the track mode of operation assuring the system will not acquire a secondary target (one having greater range than the primary target) during the retrace cycle. The search and acquisition waveform relationships are shown in Figure 4-89. When video return pulses of adequate amplitude return, the KAGC gate pulses will overlap them. After successfully sampling several video pulses, the command to the track/search control causes it to remove all its overriding controls, enabling the normal track mode of operation.

**Altimeter Transmitter**

The altimeter transmitter module contains the circuitry necessary to generate and control the RF energy pulse, which is needed to detect that pulse and supply a corresponding time-zero pulse to the range computer. Basically, the circuits are those of a typical radar transmitter.
Figure 4-89 — Search and acquisition waveforms.
Altimeter Receiver

The altimeter receiver module contains the circuits necessary to produce a usable video signal for the range computer. It is typical of most superheterodyne receivers. The transmitter and receiver are normally integrated into a single unit, as shown in Figure 4-90.

Altimeter Height Indicator

The height indicator is both the control box and height readout for the radar altimeter system. The front view of a typical altimeter height indicator is shown in Figure 4-91. It is a null-balancing servo device, which operates from the radar range voltage (analog signal) from the RT range computer and a reference voltage, also supplied by the RT unit’s power supply. The indicator also contains a low-altitude warning circuit, which is energized whenever the height-indicating needle reads lower than the altitude selected on the low-altitude limit index. The warning circuit will illuminate the low-altitude warning light. In some indicators, a 400 Hz tone to the headset is also supplied in the event of low altitude.

Transmitting and Receiving Antennas

The transmitting and receiving antennas are identical (Figure 4-92) and are flush-mounted, dielectric-loaded, flared-horn type antennas shown in Figure 4-93. Operation is in the 4,250 to 4,350 MHz range (typical frequency range of radar altimeters).

Interference Blanker

An interference blanker is required by a radar altimeter system only if the receiving and transmitting antenna isolation is less than 85 decibels (dB). It consists of RF attenuators, RF isolators, and a
pulse-shaping network. Its sole purpose is to attenuate the RF signal, resulting from direct antenna leakage, to a level that is below the tracking capability of the altimeter system preventing a possible zero-altitude indication (zero-lock) above the altimeter’s maximum altitude.

**System Operation**

The control knob (Figure 4-91) is the system’s sole operating control. In the fully counterclockwise position (indented), the power is off. Turning the control clockwise past the indent turns the system on. After a short warmup period, the OFF flag will disappear, indicating the system is on. If you further adjust the control knob, it will adjust the low-altitude index needle. The altimeter should lock on at 0 to 6 feet of altitude, depending on the particular aircraft.

The self-test feature is initiated by pushing in on the control knob. Most self-test circuits will cause the altimeter to read 100 feet. (This could vary.) With the indicator needle reading the self-test altitude, adjust the low-altitude index to some altitude reading below it. The low-altitude warning light should light, and a low-altitude warning signal (if supplied) should be heard in the headset.

Once the aircraft is airborne, the aircrew need only to turn the system on and adjust the low-altitude index pointer to the desired low limit. The system will then automatically read out the aircraft’s height above the terrain and will give a low warning indication any time the aircraft drops below the preset low-altitude index needle.

**Figure 4-92 — Radalt antenna.**

**Figure 4-93 — Flush-mounted radalt antenna.**
End of Chapter 4

Navigation

Review Questions

4-1. An automatic direction finder (ADF) indicator pointer (needle) will indicate which of the following types of information?

A. Magnetic bearing to a station  
B. Relative bearing to a station  
C. Magnetic bearing from a station  
D. Relative bearing from a station

4-2. What type or types of antennas are used in the manual mode of operation?

A. Loop only  
B. Sense only  
C. Loop and sense  
D. Loop, sense, and rhombic

4-3. What type of antenna is the sense antenna of an automatic direction finder (ADF) system?

A. Helix  
B. Dipole  
C. Cosecant square  
D. Monopole

4-4. An automatic direction finder (ADF) system requires both a loop and a sense antenna to prevent the system from indicating what degree of error?

A. 90  
B. 120  
C. 180  
D. 270

4-5. Which of the following phrases best describes the purpose of a very-high-frequency (VHF) omnidirectional range (VOR) navigation system?

A. To let aircrew know when the aircraft is over a given station  
B. To give aircrew altitude information  
C. To allow aircrew to guide an aircraft over long distances  
D. To give aircrew bearing information to a given station

4-6. What is the frequency band, in megahertz, of a very-high-frequency (VHF) omnidirectional range (VOR) transmitter?

A. 9.96 to 117.95  
B. 108.00 to 117.95  
C. 116.00 to 151.95  
D. 118.00 to 225.00

4-92
4-7. What modulation frequency is induced in the airborne very high frequency (VHF) omnidirectional range (VOR) receiver by the VOR transmitting station?

A. 30 Hz
B. 30 kHz
C. 30 MHz
D. 30 GHz

4-8. What is the purpose of the course set knob on a typical very high frequency (VHF) omnidirectional range (VOR) indicator?

A. To center the vertical bar in order to obtain the correct bearing information to a station
B. To center the heading marker pointer to indicate true north
C. To center the vertical bar to indicate true north
D. To turn on the marker beacon light

4-9. The AN/ARA-63 all-weather aircraft approach guidance system receives what type of transmissions?

A. Standard microwave
B. Radiofrequency
C. Coded microwave
D. Pulsed

4-10. The radio receiver R-1379/ARA-63 provides input to the _______.

A. receiver control.
B. pulse decoder.
C. course deviation indicator.
D. course indicator.

4-11. What AN/ARA-63 module identifies the intrapair pulse spacing received?

A. Memory
B. Video-identity
C. Clock/BIT-flag
D. Error

4-12. The AN/ARA-63 logic module error board produces which signal?

A. Track quantizer
B. Write
C. Video initiation
D. Timing pulses
4-13. Typical tactical air navigation (TACAN) systems operate on one selected channel from how many available channels?

A. 126  
B. 146  
C. 252  
D. 292

4-14. In the receiver section of the tactical air navigation (TACAN) system, the radiofrequency (RF) driver multiplies and amplifies the fundamental frequency to produce a local oscillator frequency of what frequency, in megahertz?

A. 925 only  
B. 925 to 1,050  
C. 1,050 only  
D. 1,025 to 1,150

4-15. In a tactical air navigation (TACAN) system, the antenna switching takes place at what interval, in seconds, until a usable signal is located?

A. 0.5 sec  
B. 1.5 sec  
C. 3.0 sec  
D. 5.0 sec

4-16. If a tactical air navigation (TACAN) system’s transmitter power is low, what circuit output signal will produce a flag warning?

A. Power monitor  
B. Diplexer  
C. Monitor and flag  
D. Decoder

4-17. Which of the following qualities makes an inertial navigation system (INS) a desirable component of any aircraft navigation system?

A. The ability to easily interface with ground stations makes it easy to track.  
B. The ability to communicate with other aircraft increases accuracy of position information.  
C. Reliance on commercial satellites ensures low cost.  
D. Accuracy is only limited by technology and manufacturing precision.

4-18. If velocity is integrated with time in the accelerometer of the inertial navigation system (INS), what information is provided?

A. Acceleration of the aircraft  
B. Mass of the aircraft  
C. Distance the aircraft traveled  
D. Direction the aircraft is traveling
4-19. Which of the following is an advantage of the wander angle inertial system?

A. It is always true north oriented.
B. It provides latitude and longitude references.
C. It can be used for polar region operation.
D. It randomly provides position information.

4-20. What component or components mechanize the reference spheroid in the inertial navigation system (INS)?

A. Computer
B. Accelerometers
C. Integrators
D. Gyros

4-21. What type of information is supplied to the aircrew from a Doppler navigation radar system?

A. Ground only
B. Drift angle only
C. Ground and drift angle
D. Velocity

4-22. Continuous wave (CW) Doppler navigation radar senses velocity by measuring a reflected signal's change in_______.

A. pulse width.
B. frequency.
C. amplitude.
D. return time.

4-23. How does aircraft drift affect a typical Doppler navigation radar signal’s travel when track, heading, and antenna are in alignment?

A. Both port and starboard signals travel the same distance.
B. Port and starboard signals cancel each other out.
C. The port signal travels farther than the starboard signal.
D. The starboard signal travels farther than the port signal.

4-24. What component is used to cause switching and beam lobing in a typical eight-beam Doppler navigation radar?

A. Duplexer inputs
B. Waveguide outputs
C. Crystal switches
D. Coded signals
4-25. A global positioning system (GPS) provides specially coded satellite signals that can be processed in a GPS receiver, enabling the receiver to compute position, velocity, and ________.

A. size.
B. distance.
C. time.
D. frequency.

4-26. What type of signal is transmitted from each satellite?

A. Acquisition carrier (AC)
B. Coarse/acquisition (CA)
C. Direct carrier (DC)
D. Radiofrequency (RF)

4-27. What are the two transmitting frequencies of global positioning system (GPS) satellites?

A. (a) 1,575.42 kHz  (b) 1,227.6 kHz
B. (a) 1,575.42 kHz   (b) 1,227.6 MHz
C. (a) 1,575.42 MHz  (b) 1,227.6 kHz
D. (a) 1,575.42 MHz   (b) 1,227.6 MHz

4-28. What types of atmospheric interferences affect global positioning systems (GPS)?

A. Ionospheric and supersonic
B. Ionospheric and tropospheric
C. Ionospheric and stratospheric
D. Tropospheric and stratospheric

4-29. Which of the following systems is a sensor for the navigational computer system?

A. Leading-edge flap (LEF) assembly
B. On-board oxygen generation system (OBOGS)
C. Auxiliary power unit (APU)
D. Global positioning system (GPS)

4-30. What is the purpose of designating a target with a conventional radar’s crosshairs?

A. To track the designated aircraft
B. To mark the designated aircraft for destruction
C. To speak with the aircraft’s aircrew
D. To take an electronic photo of the aircraft
4-31. The tactical air navigation (TACAN) system provides what type of information to the navigation computer?

A. Altitude
B. Bearing
C. Velocity
D. Temperature

4-32. Which of the following factors of an aircraft dictates the capabilities and requirements of the type of computer system and sensors used for navigation in naval aircraft?

A. Speed
B. Mission
C. Range
D. Generator type

4-33. How does an aircraft electronic altimeter measure in order to indicate altitude?

A. Measures received signal power
B. Measures transmitter signal power minus received signal power
C. Measures the time from the moment the transmitter fires until the signal returns from the terrain below
D. The time between received signals

4-34. The pulse repetition frequency (PRF) on the typical electronic altimeter transmitter is how many pulses per second (pps)?

A. 7,000
B. 7,500
C. 8,000
D. 8,500

4-35. After it stops receiving a signal, the typical electronic altimeter will indicate an altitude reading for what maximum amount of time, in seconds?

A. 0.2
B. 1.2
C. 2.0
D. 5.0

4-36. In the self-test mode, the low-altitude warning lamp will come on under which of the following conditions?

A. When the control knob is pushed
B. When the control knob is fully clockwise
C. When the low-altitude limit index is adjusted above 100 feet
D. When the low-altitude limit index is adjusted below 100 feet
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CHAPTER 5

ANTISUBMARINE WARFARE

Antisubmarine Warfare (ASW) is a core mission area for the United States Navy. Execution of that vital mission is critical to protecting the strategic speed and operational agility of joint and coalition forces across the largest maneuver space in the world – the sea. ASW includes the detection, localization, and identification of potentially hostile forces or objects below the surface of the sea.

This chapter will introduce you to fundamental concepts of ASW and familiarize you with the characteristics, uses, and peculiarities of typical equipment and systems currently employed by naval aircraft. It is beyond the scope of this manual to train you on the complete repair of any system. Appropriate maintenance instruction manuals will guide you through effective testing, troubleshooting, and repair procedures.

LEARNING OBJECTIVES

When you have completed this chapter, you will be able to do the following:

1. Identify ASW airborne platforms.
2. Explain sonar principles and behavior of a sound wave in water.
3. Explain functional relationships of ASW system components.
4. Describe ASW system principles of operation and characteristics.
5. Recognize operating features and modes of operation of the sonar system.
6. Describe a typical ASW acoustic system.
7. Discuss sonobuoy characteristics and capabilities.
8. Describe the theories behind magnetometers, nuclear resonance, and Larmor frequency.
9. Describe operating principles of magnetic anomaly detection (MAD) and submarine anomaly detecting (SAD) systems.
10. Recognize the components and operating features of a typical magnetic compensator group and terms associated with the compensation process.

OVERVIEW

The 21st century environment is one of increasing challenges, due to the littoral environment in which we operate and advanced technologies that are proliferating around the world. Operations in the future will be centered on dominating near-land combat, rapidly achieving area control despite difficult sound propagation profiles and dense surface traffic. The operating environment will be cluttered and chaotic, and defeating stealthy enemies will be an exceptional challenge.

Detect-to-engage strategies demand that our ASW systems operate at optimal levels to deny enemy submarines any offensive capability while maintaining the ability to destroy them, if and when required, at a time and place of our choosing. Battlespace superiority (Figure 5-1) will depend on our ability to prosecute this mission, allowing friendly forces to “climb into the ring” and stay there.
Airborne Platforms

Airborne platforms supporting the ASW mission include both rotary-wing and fixed-wing aircraft. The two primary airborne platforms are the Multi-Mission Helicopter (MH)-60R Seahawk (Figure 5-2, view A) and P-8A Poseidon (Figure 5-2, view B).

MH-60R Seahawk
The Navy’s shipboard submarine hunter, the MH-60R Seahawk, is the cornerstone of the Navy’s helicopter concept of operations. Using both acoustic and nonacoustic systems (magnetic anomaly detection [MAD]), ASW and surface warfare are the MH-60R’s primary missions. The Seahawk is based aboard cruisers, destroyers, and frigates and deploys sonobuoys (sonic detectors), dipping-sonar, and torpedoes in an antisubmarine role. One of the system’s primary functions is to provide a data link to shipboard sonar receiving sets.

P-8A Poseidon
The P-8A Poseidon provides long-range ASW, antisurface warfare (ASuW), and intelligence, surveillance, and reconnaissance (ISR) aircraft capabilities for broad-area, maritime, and littoral operations. The Poseidon is designed to use high altitude antisubmarine warfare (HAASW) techniques. These techniques integrate modified sonobuoy sensors to enhance the Poseidon’s capability to conduct its mission at higher than traditional fixed-wing airborne ASW altitudes. The HAASW capability for the P-8A includes the following technologies:

- Receive, process, and store in-buoy global positioning satellite (GPS) data received from AN/SSQ-53, AN/SSQ-62, and AN/SSQ-101B sonobuoys

Figure 5-1 — ASW battlespace.
Integrate the GPS drop vector algorithm (GDVA) to enhance sonobuoy splash point prediction and accuracy in real time.

Receive, command, and process the AN/SSQ-101B sonobuoy with the digital uplink/downlink format for radiofrequency interference (RFI) mitigation and increased bandwidth, while retaining legacy uplink/downlink capability.

The Poseidon’s AN/APY-10 radar provides high-resolution imaging synthetic aperture radar (ISAR) capabilities for detection, classification, and tracking of surfaced submarines. It is also capable of detecting submarine periscopes using high scan speeds and high pulse repetition frequencies in high-resolution mode with advanced sea clutter rejection. The Poseidon globally operates from shore-based airfields.

SONAR PRINCIPLES

The term “sonar” is derived from the initial letters of SOund, NAvigation, and Ranging is a method that uses sound propagation for acoustic location. Over the years, sonar became less of an acronym and more of a stand-alone term the Navy uses to describe equipment that locates targets by transmitting and receiving sound energy propagated through water. Each sound heard is the result of an object that vibrates. The vibrations are transmitted through a medium (for example, air, water molecules) and detected by the sensor (by ear). For ASW purposes, sound originates from either natural (for example, whales, rain) or manmade sources (for example, submarines, shipping, drilling, sonar transducers). The sound travels through the complex ocean medium and arrives at the hydrophone sensor (an underwater microphone). The particular sound waves of interest to the sonar operator are the waves that leave the sonar transducer (an underwater speaker) and go out into the water in search of a submarine. If the sound wave finds a target, it will return (reflect) as an echo. Depending upon the vibration frequency and the signal strength (or volume), some sounds can be transmitted long distances underwater.

Airborne sonar equipment, commonly known as dipping-sonar, is carried aboard MH-60R Seahawk helicopters. Sonobuoys, which are sound-activated devices, are dropped into the ocean from helicopters and from fixed-wing ASW aircraft, such as the P-8A Poseidon and formerly the P-3C Orion, and monitored by radio.

Active and Passive Sonar

Sonar systems have two modes of operation: active and passive. When conducting active sonar operations, the equipment sends out a signal and listens for the return echo to gather information. In passive operations, system operators are listening for unusual undersea noise to gather information. Active sonar operations create noise that can be used to locate the emitter while passive sonar does not.

Transducers

A transducer is a two-way device used in sonar operations. In an active mode, the transducer converts the electrical signal into acoustic energy that is transmitted through the water. The signal is known as a “ping.” After transmitting the ping, the transducer listens for a return echo. The acoustic echo is then converted into an electrical signal for analysis. Transducers use a diaphragm to create pressure differences underwater to transmit the ping similarly to the way a stereo speaker creates sound. The process is reversed when the transducer is in receive mode.
Figure 5-2 — MH-60R Seahawk and P-8A Poseidon.
In the case of airborne sonar, the transducer is lowered into the water by a helicopter in a process commonly known as dipping-sonar, as shown in Figure 5-2, view A.

**Factors Affecting Sound Waves**

To understand the principles on which sonar systems operate, maintenance technicians and sonar operators should know what factors can weaken sound waves as they travel through water, what factors in the seawater determine the path and speed of the sound wave, and what factors affect the strength and character of the echo.

Signal strength lost during the wave’s travel through the water is known as transmission loss. As sound travels underwater, the ocean absorbs the sound and reduces its loudness. Additionally, sound waves can be bent or scattered in different directions and sound velocity can be affected by water temperature and salinity. Some of the factors determining transmission loss are discussed in the following paragraphs.

**Absorption and Scattering**

Some of the sound energy emitted by the source will be absorbed while passing through the water. The amount absorbed this way depends on the sea state. Absorption is high when winds are great enough to produce whitecaps and cause a concentration of bubbles in the surface layer of the water. In these circumstances, part of any sound striking the surface is lost in the air, and part is reflected in scattering directions in the sea. In areas of wakes and strong currents, such as riptides, the loss of sound energy is greater. Therefore, echo ranging through wakes and riptides is difficult because of the combined effect of false echoes, high reverberations, and increased absorption. Absorption is greater at higher frequencies than at lower frequencies. As a result, lower frequencies tend to travel farthest.

Sound waves are weakened when they reach a region of seawater that contains foreign matter, such as seaweed, silt, animal life, or air bubbles. This foreign matter scatters the sound wave and causes loss of sound energy. The practical result of scattering is to reduce echo strength, especially at long range.

**Reflection**

An echo or reflection occurs when a sound wave hits an object (Figure 5-3) or a boundary region between transmission mediums in such a manner as to reflect the sound or to throw it back to its origin. Reflection of sound waves sometimes happens when a wave strikes a medium of different density from that through which it has been traveling. This situation will occur in cases where the two mediums are of sufficiently different densities, and the wave strikes at a large angle. This phenomena happens because the sound wave travels at different speeds through the two different densities. For example, a sound wave traveling through seawater is almost entirely reflected at the boundary of the water and air. The speed of sound in seawater is about four times greater than the speed of sound in air, and the density of water is more than 800 times greater than that of air. Therefore, practically all of the sound wave will be reflected downward from the sea surface.

Sound waves bounce off the ocean bottom and reflect upward. If the ocean bottom is a smooth, hard surface, there is little signal loss. In deep waters of 600 feet or more, the sound may never strike the bottom because the water pressure is so great that the sound velocity actually begins to speed up and forces the sound waves to refract, or bend, back toward the surface.
When a sound wave traveling through the seawater strikes a solid object such as a submarine, the difference in the density and the sound velocity in the two mediums is such that all but a small amount of the sound wave will be reflected. That portion of the wave that strikes surfaces of the submarine perpendicular to the wave will be reflected directly back to the origin as an echo.

Reverberation

When sound waves echo and re-echo in a large hall, the sound reverberates. Reverberations are multiple reflections. Lightning is an example of this from nature. When lightning discharges, it causes a quick, sharp sound; but by the time the sound of the thunder is heard, it is usually drawn out into a prolonged roar by reverberations.

A similar case often arises in connection with sonar. Sound waves often strike small objects in the sea, such as fish or air bubbles. These small objects cause the waves to scatter. Each object produces a small echo, which may return to the transducer. The reflections of sound waves from the sea surface and the sea bottom also create echoes. The combined echoes from all these disturbances are called reverberations. Since they are reflected from various ranges, they seem to be a continuous sound. Reverberations from nearby points may be so loud that they interfere with the returning echo from a target.

There are three main types of reverberation or backward scattering of the sound wave. Each is described below:

- Mass of water. Causes of this type of reverberation are not completely known, although fish and other objects contribute to it.
- Sea surface. This is most intense immediately after the sonar transmission; then it decreases rapidly. The intensity of the reverberation increases markedly with increased roughness of the sea surface.
- Sea bottom. In shallow water this type of reverberation is the most intense of the three, especially over rocky and rough bottoms.
**Divergence**

Just as the beam from a lighthouse spreads out and becomes weaker with distance, so does sound. The farther the target is from the sonar transducer, the weaker the sound waves will be when they reach it. This effect is known as spreading or divergence.

**Refraction**

If there were no temperature differences in the water, the sound wave would travel in a straight line. This phenomenon would happen because the speed of sound would be roughly the same at all depths. The sound wave would spread and become weaker at a relatively constant rate.

Unfortunately, the speed of sound is not constant at all depths. The speed of sound in seawater increases from 4,700 feet per second to 5,300 feet per second as the temperature increases from 30 to 85 degrees Fahrenheit (°F). Because of the varying temperature differences in the sea, the sound wave does not travel in a straight line, but follows curved paths. This results in the bending, splitting, and distorting of the sound wave.

When the sound wave is bent, it is said to be refracted. A sound wave is refracted when it passes from a medium of a given temperature into a medium with a different temperature. An example of this is a sound wave traveling from an area of warm water into a layer of cold water. The sound wave will bend away from the area of higher temperature (higher sound velocity) toward the lower temperature (lower sound velocity).

As a result of refraction, the range at which a submarine can be detected by sound may be reduced to less than 1,000 yards, and this range may change sharply with changing submarine depth.

**Factors Affecting Speed of Sound Waves**

The three main characteristics of seawater that affect the speed of the sound wave traveling through the water are temperature, salinity, and pressure.

**Temperature**

Temperature is the most important factor affecting the speed of the sound wave in seawater. The speed will increase with increasing temperature at the rate of 4 to 8 feet per second per degree of change, depending on the temperature.

The temperature of the sea varies from freezing in the polar seas to more than 85 °F in the tropics. The temperature can also decrease by more than 30 °F from the surface to a depth of 450 feet. Thus, the temperature is the most important factor because of the extreme differences and variations. Remember, the speed of sound in water increases as the temperature increases. Except at the mouths of great rivers, where salinity may be a factor, the path of the sound wave will be determined by temperature.

When the surface of the sea is cooler than the layers beneath it, as shown in Figure 5-4, the temperature increases with depth, and the water has a positive thermal gradient. This is an unusual condition, but when it does happen, it causes the sound wave to be...
refracted sharply upward. When the sea gets colder as the depth increases, the water has a negative thermal gradient. In this situation, the effect of temperature far outweighs the effect of depth, and the sound wave is refracted downward.

If the temperature remains the same throughout the water, the temperature gradient is isothermal (constant temperature). The surface layer of water in Figure 5-5 is isothermal, but beneath this layer the temperature decreases with depth, causing the sound wave to split and bend upward in the isothermal layer and downward below it.

Figure 5-5 — Isothermal conditions.

When the temperature changes with depth, the sound wave bends away from the warmer water.

Under normal conditions the temperature structure of the sea is similar to that shown in Figure 5-6. This structure consists of three layers:

1. A surface layer of varying thickness with uniform temperature (isothermal) or a relatively slight temperature gradient
2. The thermocline, which is a region of relatively rapid decrease in temperature
3. The rest of the ocean, with slowly decreasing temperature down to the sea floor

If this arrangement changes, the path of the sound wave through the water will change.

Layer depth is the depth from the surface to the top of a sharp negative gradient. Under a positive thermal gradient condition, the layer depth is the depth of maximum temperature. Above layer depth, the temperature may be uniform, or a weak positive or negative gradient may be present.

Sea Surface

<table>
<thead>
<tr>
<th>Temperature Uniform or Changing Slightly with Depth</th>
<th>Surface Layer Isothermal or &quot;Mixed Layer&quot; when Temperature Uniform</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature Decreasing Rapidly</td>
<td>Thermocline</td>
</tr>
<tr>
<td>Temperature Decreasing Slowly</td>
<td>Region Below the Thermocline</td>
</tr>
</tbody>
</table>

Sea Bottom

Figure 5-6 — Normal sea temperature structure.
Layer effect is the partial protection from echo ranging and listening detection, which a submarine gains when it submerges below layer depth. Reports from surface vessels indicate that effective ranges on submarines are greatly reduced when the submarine dives below a thermocline, and that the echoes received are often weak and sound "mushy."

Salinity
Salinity refers to the salt content in seawater. Compared to temperature, salinity has a much smaller effect on sound speed in the sea.

Higher salinity equates to more dense water. The overall effect of increased salinity is an increase in the speed of the sound wave in the water. This means that as the sound travels through water of varying salinity, it travels faster through the water with more salt content. Such a change in salinity is considerable at the mouth of a river emptying into the sea. Elsewhere, the difference in salinity is too small to change the rate of travel of the sound wave significantly and may be ignored.

Pressure
Pressure is always present and always acts in the same manner, bending the sound wave upward away from the high pressure with equal temperature present. Even though the temperature does not change, the speed of the sound increases with depth. The speed increase is due entirely to the effect of pressure.

Doppler Effect
When there is relative motion between the source of a sound wave and its receiver, the received frequency differs from the transmitted frequency. When the source’s motion is moving toward the receiver, more waves per second are received than when the source remains stationary. The effect at the receiver is an apparent decrease in wavelength and, therefore, an increase in frequency. On the other hand, when the source’s motion is moving away from the receiver, fewer waves per second are received, which gives the effect of a longer wavelength and an apparent decrease in frequency. This change in wavelength is called the Doppler effect. The amount of change in wavelength depends on the relative velocity between the receiver and the source. Relative velocity is the resultant speed between two objects when one or both are moving.

An example of this is what is heard at a railroad crossing. As a train approaches, the pitch of the whistle is high. As the train (sound emitter referred to as emitter) passes by, the pitch seems to drop. Then, as the train goes off in the distance, the pitch of the whistle is low. The Doppler effect causes the changes in the pitch.

Sound waves generated by the whistle were compressed ahead of the train. As the waves approached, they were heard as a high-pitched sound because of the shorter distance between waves. When the train went by, the sound waves were drawn out, resulting in the lower pitch. Refer to Figure 5-7 relating to the following explanation of Doppler effect.

If 1 second of the audio signal radiated by the train whistle is examined, the signal is composed of many cycles of acoustical energy. Each cycle occupies a definite period of time and has a definite physical wavelength. (Every 10th wave is illustrated in Figure 5-7, view A.) When the energy is transmitted from a stationary source (stopped train), the leading edge will move out in space the distance of one wavelength by the time the trailing edge leaves the source. The cycle will then occupy its exact wavelength in space. If that cycle is emitted while the source is moving, the source will move a small distance while the complete cycle is being radiated. The trailing edge of the cycle radiated will be closer to the leading edge.
The effect of relative motion on a radiated audio signal is shown in Figure 5-7, view B. The wavelength of the sound from the stationary emitter changes, as illustrated in Figure 5-7, view B, condition (1).

The emitter is moving toward the listener (closing) in Figure 5-7, view B, condition (2). When the cycle is compressed, it occupies less distance in space. Thus, the wavelength of the audio signal has been decreased, and the frequency has been proportionately increased (shifted) upward.

The opposite is true in Figure 5-7, view B, condition (3). The emitter is moving away from the listener (opening). The wavelength occupies more distance in space, and the frequency has been proportionately decreased. The factors that determine the amount of Doppler shift are the velocity of the sound emitter, the velocity of the receiver, and the angle between the direction of motion of the receiver and the direction of motion of the sound emitter.

The Doppler shift works both ways. Stationary crossing bells from the train would appear as a higher frequency as the train approaches (or closes) and then as a lower frequency as the train moves farther away (or opens).

**Doppler Effect on Sonar**

Sonar equipment deals with three basic sounds:

- The sound or ping sent out from the equipment
- The reverberations returning from the generated sound wave reflecting off particles in the water—seaweed, fish, and so forth
- The useful echo returning from the target

The sound sent into the water by sonar equipment, the ping, is not heard by the operator. Generally, sonar systems blank out this signal so that it does not distract the operator, who is discerning target echoes from other reverberation noise. Reverberations return to the emitter with little change in frequency, making them irrelevant noise or clutter. It can be a difficult task to distinguish reverberations from target echoes. Separating the noise from useful target echoes is where the Doppler effect comes into play, as shown in the following examples.
If the sonar transducer is stationary in the water and sends out a ping of 10 kilohertz (kHz), the particles all send back a sound that has the same 10 kHz pitch. If the submarine were also stationary or moving at a right angle to the transducer, the echo would also be 10 kHz, as shown in Figure 5-8.

If the submarine is moving toward or closing on the transducer, as shown in Figure 5-9, it is as though the submarine is the train heading toward the crossing bells. The pitch of the crossing bells sounds higher as the train approaches the crossing. In a similar manner, the submarine reflects an echo of higher pitch than that caused by the particles in the water, which are not moving. The opposite form of Doppler shift will occur when the submarine is heading away from the transducer. In this case, the pitch of the echo is lower than the pitch of the reverberations (Figure 5-10).

**SYSTEM DESCRIPTION**

As previously discussed, the ASW mission includes long-range search, detection, localization, and classification of submarines. This mission involves leveraging the use of all avionics equipment aboard ASW aircraft. Supporting systems include radar, navigation, communication, and detection equipment. This chapter will concentrate on the two ASW-specific systems: acoustic and nonacoustic.
Acoustic

ASW acoustic equipment includes all the systems that relate to sound. Navy ASW aircraft are equipped with an acoustic ASW system suite. The acoustic system suite consists of active and passive types of sonobuoys deployed from the aircraft and electronic components installed in the aircraft. Sonobuoys are used to detect sound from submerged submarines and to transmit the sound(s), via very high frequency (VHF) radio signals, to an aircraft.

The acoustic system components in the aircraft receive and process the sound-modulated VHF signals for use by ASW operators. These operators include the tactical coordinator (TACCO) and/or a sensor operator (SENSO) and are considered part of the acoustic ASW system. In this chapter, we will discuss ASW acoustic platforms, their components, and the functions of each. A typical acoustic system is composed of components that detect, process, and display sonobuoy-detected data for analysis as shown in the functional block diagram Figure 5-11. This diagram is a representation of a typical acoustic suite with generic names for components. The deployed sonobuoy’s acoustic data is received by a sonobuoy receiver system (SRX) and is input into an acoustic data processor (ADP) and a digital data recorder. The ADP-processed data goes to an auxiliary readout unit (ARU) or multipurpose display (MPD) through the controls of the SENSO or TACCO. Most platforms and acoustic suites contain similar equipment. Specific SRXs such as AN/ARR-78 and 84 may vary, but they function to receive sonobuoy acoustic data.

Fixed-Wing Acoustic Data System Overview

This system, shown in Figure 5-11, is representative of basic acoustic systems used in fixed-wing ASW aircraft. Figure 5-11 shows that five data and control signal paths interface with the ADP unit, and five paths interface with the general purpose digital computer (GPDC).

Sawtooth-shaped arrows represent radiofrequency (RF) signals transmitted from the ultra-high frequency (UHF) transmitter (TX) to active-type sonobuoys and RF signals transmitted from active, passive, and range only (RO) types of sonobuoys to the SRX in the aircraft. Sound-data output of the SRX is fed to three other components: the digital data recorder, the ADP, and the GPDC.

In the ADP (a 16-channel input, frequency analyzing group), the analog acoustic signals detected by the SRX are converted to digital form. The ADP processes the digital signals for frequency, bearing, and range for display and for audio monitoring and recording.
Acoustic Data Processor

The ADP consists of the two half systems, as shown by the dashed line in Figure 5-12. The figure shows that half system number 1 and half system number 2 contain almost identical components. These components are known as weapons replaceable assemblies (WRAs). The two half systems are capable of simultaneously analyzing acoustic signals detected by a total of 16 sonobuoys. The SRX provides eight audio signals to a signal data converter in half system number 1 and eight audio signals to a signal data converter in system number 2, for a total of 16 signals. The functions of the signal data converter and each of the other components are given below.

Signal Data Converter

This unit accepts audio signals from the SRX. Processing the audio signals in the converter involves de-multiplexing, heterodyning, translation, and filtering. The processed data is routed to the sonobuoy monitor (SONO MON) panel, the spectrum analyzer-signal generator of the signal data computer, and the digital data storage unit. The signal data converter also generates built-in test equipment (BITE) signals.

Sonobuoy Monitor Panel

The SONO MON panels provide the SENSO and TACCO with manual controls to detect sonobuoy target bearing and to monitor sonobuoy audio. By monitoring this panel and adjusting controls, the SENSO or TACCO is able to control the gain of the system audio outputs, the direction of steerable nulls, and the selection of sonobuoy audio.

Spectrum Analyzer-Signal Generator

This unit provides the active sonobuoy commands that are transmitted by the UHF TX to displayed sonobuoys. The unit also performs narrow-band analysis, directional processing, bathythermograph (BT) processing, and frequency standardization of data received from the signal data converter unit. This unit also functions as a computer interface.

Spectrum Analyzer Converter

This unit provides interfacing with the tactical display ARU. It also performs narrow-band ARU analysis, directional processing, and frequency standardization of data received from the spectrum analyzer (SA) converter and the spectrum analyzer-signal generator units.

Digital Data Storage Unit

This unit has memory provisions for time compression, gram storage, automatic line integration (ALI) storage, computer auxiliary program storage, and ARU and MPD refresh.

Power Supply

This unit supplies electrical power for the data handling and storage unit.

Sonar Data Computer

This unit provides MPD format and interfacing, computer interfacing, digital data flow control, directional frequency analysis and recording (DIFAR) bearing calculations, and ARU refreshing.
Tactical Coordinator Power Control Panel

The power switch on this panel activates the acoustic group system. When the power switch is in the ON position, 28-volt direct current (dc) and 115-volt, three-phase, 400-hertz alternating current (ac) are applied through the power relays to the two half systems.

Radio Receiving Set

This unit is the SRX. It is capable of receiving and demodulating up to 99 sonobuoy signals. Any 16 audio outputs can be selected, eight of which can be routed to the signal data converter in each half system. The 16 audio signals may be live signals or signals played back from the acoustic signal data recorder/reproducer set.

Signal Data Recorder/Reproducer Set

This unit records sonobuoy audio data for later use. For example, personnel may remove the tape from an aircraft following a mission for data analysis at an antisubmarine warfare operations center (ASWOC).
General-Purpose Digital Computer
This unit provides overall control for the ADP system. It also processes information for display on the SENSO and TACCO display units.

Tactical Indicator Display Group Multipurpose Displays
These units display sonobuoy signal characteristics and locations. Appropriate alphanumeric characters, symbols, vectors, and conics are also displayed.

Tactical Indicator Display Group Auxiliary Readout Unit
This unit is an auxiliary display unit. It provides a master display of sonobuoy acoustic characteristics.

Rotary-Wing Acoustic Data System Overview
Helicopter ASW acoustic data platforms are similar to those used in fixed-wing aircraft. The main difference is that this sonobuoy system is designed primarily for detection and classification of submarines by providing an airborne data link between acquisition sonobuoys and a shipboard installed telemetric data receiving set. In addition, this system is capable of processing onboard range only (RO) sonobuoy signals to provide a permanent recording and a means for converting scalar distances of these recordings into direct reading range indications.

The MH-60R acoustic sensor subsystem receives sonobuoy data from deployed sonobuoys. The raw acoustic data is sent to the ship, via a radio terminal set (data link), for shipboard processing, and to a spectrum analyzer for use aboard the helicopter. The subsystem then processes the sonobuoy data for display and aural monitoring aboard the helicopter. Major components of the helicopter acoustic system include a radio receiving set and a spectrum analyzer. Functions of these units are discussed in the following text.

Radio Receiving Set
The SRX receives, demodulates, and amplifies sonobuoy data. The SRX consists of four VHF radio receivers. Each of the four receivers can operate on a separate channel, independent of the others. The RF signals received by the sonobuoy antennas are applied to each of the four receiver modules, where tuned filters select the signals for each module. The signals then pass through a series of amplifiers, filters, and mixers to produce the output audio signals. The output signals are applied to the spectrum analyzer and the data link. The spectrum analyzer produces the audio signal for the communications (COMM) group to allow monitoring by the aircrew. In SHIP CONTROL, ASW mode, the sonobuoy receivers are tuned by the shipboard operator through the data link.

Spectrum Analyzer
The spectrum analyzer is a high-speed signal processor designed to extract acoustic target information from both active and passive sonobuoy data. It determines frequency, amplitude, bearing, Doppler range, and other signal characteristics for acoustic targets. In addition to narrow-band processing, the spectrum analyzer performs the following functions:

- Filtering, analog-to-digital conversion, and de-multiplexing of directional sonic data
- Band separations by octaves
- Generation of low-power audio signals and of command-activated sonobuoy control signals
- Passing of sonic gauge tones coincident with or with the start and stop of sonobuoy commands for downlink to a ship, or when ping signals are received
Nonacoustic

Although the nonacoustic system's purpose and use aboard other platforms may be different from the acoustic system's, the circuitry and theory are basically the same. Examples of nonacoustic systems are radar, navigation, electronic countermeasures (ECM), electronic support measures (ESM), infrared detecting sets (IRDS), and MAD. The discussion in this chapter will be limited to the MAD system theory, which will be discussed later in the chapter.

ACOUSTIC SYSTEM CHARACTERISTICS

This discussion of the ASW acoustic system addresses sonobuoy characteristics, receiver characteristics, and general maintenance procedures.

Sonobuoy Characteristics

Sonobuoys are air-launched, expendable, electro-mechanical sensors, as shown in Figure 5-13. Sonobuoys provide both a deployable acoustical signal source and reception capability for underwater signals of interest. These received signals are transmitted to monitoring units that process the signal for target analysis, classification, and recording for replay and post-event analysis. Established sonobuoy tactics allow for short- and long-range detection of surface ships and submarines resulting in the prosecution of identified hostile targets. They contain VHF radio transmitters to relay acoustic information to the monitoring units including aircraft.

The sonobuoy is aircraft deployable by any of four methods: spring, pneumatic, free-fall, or cartridge. Because descent velocities can exceed 120 feet per second, a descent-retarding device is used to increase aerodynamic stability and to reduce water-entry shock. Parachutes or rotochutes are used as descent-retarding devices.

The force of water impact or battery activation initiates the deployment of various sonobuoy components. Jettisoning of the bottom plate allows the hydrophone and other internal components to descend to the preselected depth (Figure 5-14). Upon the release of the parachute or rotochute, the antenna is erected. In some sonobuoys, a seawater-activated battery fires a squib, which deploys a float containing the antenna. A termination

Figure 5-13 — Typical sonobuoy.

Figure 5-14 — Typical deployed sonobuoy.
mass and/or drogue stabilizes the hydrophone at the selected depth, while the buoyant sonobuoy section or float follows the motion of the waves. A section of elastic suspension cable isolates the hydrophone from wave action on the buoyant section. Most of the sonobuoys in the fleet today are equipped with seawater-activated batteries, which provide the power required for the sonobuoy electronics. Data transmission from the buoys usually begins within 3 minutes after the buoy enters the water. In cold water and/or water with low salinity, the activation time might be increased. Some sonobuoys have lithium batteries.

At the end of the preselected time, the sonobuoy transmitter is deactivated. Either the sonobuoy has an electronic RF OFF timer, or, as is most common, the transmitter is deactivated when the buoy is scuttled. At the end of the sonobuoy life, or for some types of sonobuoys upon RF command, a mechanism allows seawater to flood the flotation section in the buoy. In some cases, the flotation balloon is deflated to scuttle the unit. Either way, the unit fills with seawater and sinks.

Description
Sonobuoys used in ASW may be grouped into three categories:

- **Passive**
  - Air Deployable Active Receiver (ADAR)
  - DIFAR
  - Vertical line array directional frequency and recording (VLAD)

- **Active**
  - RO
  - Command active sonobuoy system (CASS)
  - Directional command active sonobuoy system (DICASS)

- **Special purpose**
  - BT

Because sonobuoys are expendable, they do not require periodic inspections, preventive maintenance, repair, alignment, disassembly, or testing at the intermediate maintenance level. However, operators should be familiar with sonobuoy characteristics if repair of the associated processing and recording systems becomes necessary.

**Passive Sonobuoys**
Passive sonobuoys operate in a listen-only mode of operation. The basic acoustic sensing system that uses the passive sonobuoy for detection and classification is known as the DIFAR system.

**Air Deployable Active Receiver Sonobuoy**
The ADAR sonobuoy is an expendable unit capable of receiving UHF downlink commands and sending real-time beamformed acoustic data via a VHF digital uplink to the monitoring unit. The ADAR is a free-floating, acoustic data receiver that operates in conjunction with an acoustic source. The buoy scuttles automatically upon detection of a low voltage state or completion of its six-hour life. The ADAR sonobuoy is expended by all compatible ASW aircraft and over-the-side (OTS) by shipboard personnel. The electronic function select (EFS) selector will be used to select one of three available depths and the default acoustic beamform band. Once in the water, the acoustic frequency band can be changed, the RF channel can be changed, and the RF can be turned on or off via a downlink command function. Once activated, the sonobuoy receives, beamforms, and transmits real-
time acoustic data in the selected frequency band to the monitoring unit. The separately deployed acoustic source will be commanded to "ping," ensonifying the water and any target present, generating an acoustic "return" that is received and transmitted by the ADAR receiver. Aboard the monitoring unit, the data will be processed and displayed (visual and aural), providing the operator a means of determining range, bearing, amplitude, and possibly Doppler (coherent acoustic sources only) on submarine targets.

**Directional Frequency Analysis Recording**

DIFAR sonobuoys self-activate upon water entry and operate in a passive mode at the preset life and depth. Upon reception of acoustic signals, the subsurface unit converts the pressure waves into amplified electronic signals and provides a magnetic reference for each signal through utilization of the flux gate compass. These signals are sent to the surface unit via the cable assembly. The surface unit applies these signals to a preset frequency-modulated (FM) carrier for VHF transmission. The monitoring platform receives the signals for recording, processing, and analysis.

The DIFAR (*Figure 5-15*) sonobuoy incorporates the EFS capability which provides the operator with the capability to electronically select one of the available 99 RF channels, sonobuoy life of one-half, one, two, four, or eight hours, and hydrophone depth of 90, 200, 400, or 1,000 feet. Newer units also have improved suspension, wider sonic response curve, and electronic upgrades compared to previous DIFAR sonobuoys.

Additionally, DIFAR sonobuoys also incorporate command function select (CFS). Through CFS, a suitably equipped ASW aircraft can transmit UHF radio commands to the sonobuoy. These commands select VHF operation (on-off), hydrophone reception constant shallow omni (CSO)/normal, automatic gain control (AGC) operation (on-off), and change RF channel frequency. The CSO is an omnidirectional hydrophone positioned at a depth setting of 45 feet. It is less sensitive than the normal DIFAR hydrophone, but is useful against an evasive submarine. AGC selection provides the operator additional flexibility when operating in a noisy environment. The ability to select VHF operation and change RF channels enhances operations in the littoral environment.

**Vertical Line Array Directional Frequency and Recording**

The VLAD sonobuoy is an expendable, omnidirectional, passive sonar unit. The VLAD sonobuoy uses a multi-element, omnidirectional hydrophone array and a beamforming filter assembly to enhance acoustic sensitivity. The VLAD has a selectable configuration incorporated into the EFS. This allows the operator to select either bottom bounce or convergence zone sound reception. The EFS will also allow selection of one of 99 RF channels, two operating depths of 500 and 1,000 feet, and selectable life settings of one, four, or eight hours. In all other respects, the VLAD is comparable to the DIFAR. The VLAD sonobuoy, upon self-activation, operates in a passive mode for the preset life, depth, and sound reception pattern. Upon reception of acoustic signals, the subsurface unit converts the pressure waves to amplified electronic signals. These signals are then transferred to the beamforming assembly where the signal is amplified and filtered and a magnetic bearing reference is
applied. The amplified signal is then routed through the cable assembly to the surface unit and applied to an FM carrier for VHF transmission. The monitoring platform receives the signal for recording, processing, and analysis.

**Active Sonobuoy**

Active sonobuoys are either self-timed (the sonar pulse generated by the sonobuoy at a fixed pulse length and interval) or commandable, as determined by a UHF command signal from the controlling aircraft. An active sonobuoy uses a transducer assembly (TA) to radiate a ping that is reflected from the hull of a submarine. The time interval between the ping and the echo return to the sonobuoy is measured. Taking into account the Doppler effect on the pulse frequency, this time-measurement data is used to calculate both range and speed of the submarine relative to the sonobuoy.

**Range-Only**

Self-timed active sonobuoys, known as RO sonobuoys, are set to ping for a limited period, starting from the time they are deployed.

**Command Active Sonobuoy System**

The CASS allows the aircraft to deploy the sonobuoy, but the sonobuoy remains silent until it receives a command signal from the aircraft to radiate a sound pulse. This technique allows the aircraft to surprise a submarine.

**Directional Command Active Sonobuoy System**

A DICASS sonobuoy allows the aircraft acoustic analysis equipment to determine both range and bearing to a target with a single sonobuoy. DICASS sonobuoys replaced the older RO and CASS sonobuoys.

The DICASS sonobuoy is an expendable, active sonar unit. Via an RF UHF downlink, the monitoring unit controls the DICASS sonobuoy. The DICASS sonobuoy, upon self-activation, is able to process UHF command signals transmitted by the monitoring unit. This command-activated, active sonobuoy provides range, bearing, and Doppler information on active sonar contacts. The monitoring platform is capable of commanding the transducer to deeper depths, activating sonar transmission, including pulse mode and pulse duration changes, and sonobuoy scuttle. Upon receiving a UHF command signal from the monitoring unit and decoding the signal for the proper address codes, the DICASS sonobuoy emits, as selected, either a continuous wave or FM ping. The transducer array emits pulses, which are omnidirectional on the horizontal plane and beamformed on the vertical plane. The received signal is amplified and filtered prior to transfer to the compass and multiplexer subassembly where a magnetic bearing reference is provided. This signal is then routed through the cable assembly to the surface unit where it is applied to an FM carrier for VHF transmission. The monitoring platform receives the signal for recording, processing, and analysis.

The DICASS sonobuoy is powered by a thermal battery and includes the EFS and CFS capabilities. Extremely versatile, the sonobuoys may operate at depths of 50, 90, 150, 300, 400, and 1,500 feet. The range of depth options provides sufficient flexibility for both littoral and open ocean ASW operations. Additionally, the sonobuoy includes four available sonar channel frequencies into a single sonobuoy which provides significant logistics savings.

**Multi-static Coherent Source**

Multi-static coherent sonobuoys generate a variety of waveforms, and are designed to work with the DIFAR, VLAD, and ADAR sonobuoys. The sonobuoy’s RF channel can be programmed to any of the
standard sonobuoy operating channels. At any time after deployment, they can be commanded to change their operating parameters or depth (deeper only), generate a ping, or scuttle.

**Multi-static Non-Coherent Source**

The multi-static non-coherent extended echo ranging (EER) sonobuoy operates on one of 31 selectable RF channels. Its upper section performs control functions and is similar to the DICASS sonobuoy while its lower section has two signal underwater sound (SUS) explosive payloads.

**Special Purpose Sonobuoys**

Special purpose sonobuoys in use include the BT, search and rescue (SAR), and air transportable communication (ATAC) types. These sonobuoys are not designed for use in submarine detection or localization. Only the BT is used in support of ASW operations and will be discussed.

**Bathythermograph**

The BT sonobuoy is used to measure water temperature versus depth. The water depth is determined by timing the descent of a temperature probe. Once the BT enters the water, the probe (Figure 5-16) descends automatically at a constant 5 feet per second to a maximum depth in excess of 2,600 feet. The operating life of a BT sonobuoy is approximately 12 minutes.

The probe uses a thermistor, a temperature-dependent electronic component, to measure the temperature to an accuracy of ±1 °F. The electrical output of the probe is applied to a voltage-controlled oscillator, whose output signal frequency modulates the sonobuoy transmitter. The frequency of the transmitted signal, which is recovered at the sonobuoy receiver in the aircraft, is linearly proportional to the water temperature. The water temperature and depth are recorded for use by the ASW operator.

While the capability still exists for the system to process the RO and CASS modes, these sonobuoys have been phased out and are not in use.

**Receiver Characteristics**

The function of the SRX is to receive the RF signals from deployed sonobuoys and detect the intelligence on the signals. The SRX also gives the intelligence to various onboard equipment for acoustic analysis and recording, and for navigation purposes. A typical SRX functional flow diagram is shown in Figure 5-17. The sonobuoy data is amplified in the preamplifiers and input to the receiver assembly.

**Sonobuoy Receiver Set**

One commonly used SRX comprises 31 radio receivers that receive FM signals in the VHF range of 162.25 to 173.5 megahertz (MHz). Thus, simultaneous reception, demodulation (detection), and audio output of up to 31 RF channels are possible. These channels may each be any 1 of 31 preselected channels within the 162.25 to 173.5 MHz VHF range. Each audio output is provided in
two levels—high audio and standard audio. These names refer only to the voltage level they provide for a given peak sinusoidal FM deviation of ±75 kHz.

The equipment is primarily intended for (but not limited to) installation in either fixed- or rotary-wing aircraft. Although capable of being used as an independent unit, the equipment is normally used in conjunction with some combination of several types of sonobuoys, a signal processor, and an ADP.

The radio set control contains channel selector switches for each of the 31 receivers in the receiver assembly, output level meters for each selected receiver, and a digital display of the selected channels. The receiver assembly contains 31 separate but identical receiver modules, a common power supply, and a main electrical equipment chassis.

The radio set control is a small unit consisting of parts and hardware assembled together, and is a single module in itself. The receiver assembly is modularly constructed so that the 31 receiver modules and the power-supply module plug into the chassis. Each of the modules and chassis are further modularized so that printed-circuit assemblies and other small assemblies plug in or easily connect to the modules and chassis. Few parts are discretely assembled to the module chassis or main chassis.

The SRX set is controlled during operational use by the radio set control or dual channel control indicator (DCCI). This unit is mounted so it is accessible to the operator for carrying out the various operational functions. The receiver assembly unit is normally mounted in a remote area away from the radio set control because there are no operational controls on the receiver assembly.

Newer sonobuoy receiver groups provide the capability of simultaneously receiving 20 sonobuoy signals. This is accomplished through use of 20 subassemblies, each of which may be independently and automatically tuned to any 1 of 99 sonobuoy RF channels now in use, and those that are in development for future deployment.

**Generator-Transmitter Group**

A typical generator-transmitter group provides simultaneous processing and display of four channels of omnidirectional range information. Processing control can be accomplished by either the generator-transmitter group or the digital data computer. Four channels of range information are supplied to the generator-transmitter group from the sonobuoy receivers through the SONO interconnection box. Range data is preprocessed by the generator-transmitter group, and is routed to the DIFAR system for processing and display. Command functions and sonic tones are developed within and transmitted by the generator-transmitter group to the DICASS sonobuoy.
On-Top-Position Indicator

The on-top-position indicator (OTPI) receiver provides reception of any 1 of the 31 sonobuoy frequencies. Operating in conjunction with the aircraft’s UHF-direction finder (DF) group, the OTPI provides relative bearing to the sonobuoy. The relative bearing is displayed on the No. 1 needle of the aircraft’s horizontal situation indicator (HSI) or equivalent indicator.

Sonobuoy signals received on the UHF-DF loop antenna are lobe switched and routed to the OTPI receiver. Receiver audio is routed to an electronic control amplifier that provides drive signals to the antenna. When the received lobes are equal, the drive signals are reduced to zero and the antenna stops. A synchro generator, geared to the antenna drive motor, provides relative bearing to the selected sonobuoy.

Sonobuoy Reference System

The sonobuoy reference system (SRS) is used to determine the positions of deployed sonobuoys relative to aircraft position. Through the use of angle-measuring equipment (AME), the SRS provides direction data to the aircraft’s central computer to determine the positions of sonobuoys that are within line-of-sight of the aircraft. The information is used to update the sonobuoy positions on the tactical plot without the aircraft having to fly directly over the sonobuoys. The SRS consists of the components illustrated in Figure 5-18. Once an eligible sonobuoy has been selected, the SRS receiver is then commanded to measure and send to the computer.

![Figure 5-18 — SRS functional diagram.](image-url)
bearing data for the selected channel. For each antenna pair, the SRS receiver measures the difference in time-of-arrival for the selected RF signal between one antenna and the other.

In general, the on-aircraft antenna array is positioned so that the signal from the sonobuoy will reach one antenna before the other, and thus provide the SRS receiver-converter a signal phase difference that it can measure, as shown in Figure 5-19. If the incoming signal reaches both antennas at the same time, as shown in Figure 5-20, the signals at the antenna outputs will be in phase with one another. Hence, there will be no phase difference for the SRS to measure. The signal phase difference at any given moment establishes the angular relationship between the antenna array baseline and the line-of-sight direction to the sonobuoy.

Before proceeding, certain terms that will be used in this SRS discussion will be defined, along with their relationship to SRS. The imaginary line between the two antennas of the array is known as a baseline. The length of this baseline is expressed in wavelengths (A). Thus, the baseline value of an antenna array (expressed as a number of wavelengths or complete cycles) depends upon the frequency of the sonobuoy radio signal.

General Maintenance

A typical sonobuoy receiver group sonar system (Figure 5-21) includes an acoustic sensor signal generator (ASSG), which simulates sonobuoy signals aboard the aircraft. O-level maintenance personnel use the ASSG as a piece of BITE for the miniature SRX. The ASSG provides the necessary modulated signals for verifying proper system operation. The ASSG aids in troubleshooting by sending RF output signals to three points in the aircraft system. In the external mode, a signal is routed to the antenna via the preamp and provides end-to-end testing. The preamp mode routes a signal directly to the preamp and eliminates the antenna from the system. The receiver mode bypasses the antenna and preamp and sends a signal directly to the receiver input. The
organizational technician troubleshoots the system to a repairable component or faulty ASSG and orders it through supply. It is important that the I-level technician understands the critical necessity for proper ASSG operation.

**Acoustic Sensor Signal Generator**

The maintenance plan for a typical ASSG includes I-level repair and alignment. The ASSG is a signal generator that uses voltage-controlled oscillators (VCOs), summing amplifiers, and modulator circuitry for signal generation. A basic functional diagram is shown in Figure 5-22. The specific mode of operation determines which circuits are enabled to provide the desired output from the ASSG. If an ASSG cannot be properly aligned to provide the required output signals within the tolerances, the system will need further troubleshooting. The maintenance instruction manual (MIM) provides information for alignment and troubleshooting.

**Miniature Sonobuoy Receiver System**

Normally the Fleet Readiness Center (FRC) will receive a module from a receiver stick. The automatic test equipment (ATE) shop will conduct troubleshooting and repair. Receivers use typical circuitry found in heterodyned receivers, as explained in Chapter 3 of this manual. The modules are interchangeable with the exception of the RF oscillator. The system can be troubleshooting with basic electronics circuitry knowledge, the MIM, and appropriate test equipment.

*Figure 5-21 — Sonobuoy receiver group.*
Signal Processing

A signal processor, spectrum analyzer, or ADP provides basically the same functions when considered as part of an acoustic system. Signal processors are specific to the platform on which they are deployed. All of these systems have basically the same mission and perform some of the same functions.

A typical SA processes sonobuoy signals from CASS, RO, DIFAR, and DICASS sonobuoys through the receiver. After processing, the signals are either displayed, recorded, or further analyzed, depending on the aircraft platform and acoustic suites. The SA consists of functional subunits, which contain all the major items needed for unit performance. Each functional subunit contains replaceable electronic modules. The functional subunits include:

- Control processor
- Input signal processor
- Storage controller
- Bulk store
- Arithmetic processor
- Power supply
- Input/Output (I/O)
- Proteus digital channel
- Diagnostics and power control panel

The SA is a high-speed signal processor especially designed for extracting target information from both active and passive sonar inputs. In most platforms the job assigned to the SA is determining source signal frequency, amplitude, bearing, Doppler, range, and similar parameters.

Acoustic Data Sound Recorder-Reproducer

The acoustic data sound recorder-reproducer-hard drive (ADR-HD) variant provides expanded recording capabilities with digital signal processing to simultaneously record and play back (reproduce) sonobuoy receiver audio, DICASS signals, intercommunication system (ICS) audio, and time code signals digitally on a hard drive, and also provides distribution of signals. The sound recorder-reproducer loads from the front. It records digital data using the Digital Tape Format (DTF) for physical recording.
To record data, the sound recorder-reproducer has both digital and analog acoustic signal interfaces, capable of recording 32 analog channels of acoustic data, 16 digital channels of acoustic data, and 5 additional channels of auxiliary data, dependent on the channel specified. Operator-selectable channel modes determine the combinations available. Unlike tape track formats on analog tape recorders, the ADR-HD references recording and recorded data by channels stored in a digital format on the hard drive. For example, to select data to be monitored using the remote control panel (RCP) or local control panel (LCP), the operator selects a channel, not a track.

For record/monitor, the sound recorder-reproducer monitors up to four operator-selected digital acoustic data channels (excluding digital annotation) as it is being recorded, as well as three fixed acoustic data channels.

For control of the sound recorder-reproducer operation, the front or LCP provides selection of power, mode, speed, output channel, and BITE. RCP provides duplicate control of the same functions. The time code generator-decoder (TCG) provides (time) search operation from the time code signals recorded and reproduced on the sound recorder-reproducer. At end of media (EOM), the END OF TAPE indicator at Sensor Station 1 indicates when the EOM condition occurs.

The sound recorder-reproducer’s LCP contains a digital 4-line by 20-character display, 11 switch/indicators, and 2 indicators. The sound recorder-reproducer has extensive built-in test (BIT) capability for diagnosis of system operation. The LCP utilizes some of the indicators and switch/indicators to display operational data for the modes of operation: READY, REC (including Record/Monitor), PLAY, FORWARD, REWIND, FAST REWIND (REW2), and BIT. As discussed earlier, the sound recorder-reproducer is a hard drive-based system that records data on a hard drive so that when the FORWARD control is pressed, the hard drive moves forward toward the end of data.

Transducer and Hydrophone Principles

As discussed, a transducer functions as an underwater loudspeaker during sound transmission and an underwater microphone during sound reception. The hydrophone is used only to receive sound.

Transducers used in sonar operate on either the magnetostriction principle, the piezoelectric principle, or the electrostrictive principle. The construction of two transducers is shown in Figure 5-23. A piezoelectric transducer is shown in view A and has crystals mounted on the diaphragm, while view B shows the magnetostrictive transducer, which has many nickel laminations. The nickel laminations of the magnetostrictive transducer and the crystals of the piezoelectric transducer are placed so close together that they cause the backing plate to act as one large vibrating surface. This arrangement is a contributing factor in producing the sound energy needed for sonar operation.

The magnetostrictive transducer can be filled with a moisture-free gas to ensure long trouble-free operation. The piezoelectric transducer uses a watertight case that has a rubber dome for the diaphragm. The case is filled with special moisture-free oil. This oil, which has nearly the same sound transmission characteristics as seawater, acts as a medium between the crystals’ vibrations and the diaphragm. Both types of transducers must be made watertight to prevent corrosive action.

The hydrophone operates on the magnetostriction principle or the piezoelectric principle, but not the electrostrictive principle.

Magnetostriction Transducer

The property that causes certain metals to change shape or dimensions when placed in a magnetic field is called “magnetostriction.” The stronger the magnetic field, the greater the contraction. Magnetostriction is most pronounced in nickel and nickel alloys. For this reason, nickel tubes are used exclusively in magnetostriction transducers.
As previously discussed, a transducer is similar to a radio loudspeaker. A loudspeaker has a diaphragm that is caused to vibrate. These vibrations produce sound waves. Since the diaphragm of a transducer is operated under the surface of the water, it must be much heavier in construction than a diaphragm operating in air. Therefore, it needs a large driving power.

One type of magnetostriction transducer contains nickel tubes that are rigidly attached to a heavy diaphragm. These tubes are placed in an alternating magnetic field. This alternating field causes the nickel tubes to contract and expand, which causes the diaphragm to vibrate and produce sound waves in the water. The frequency of the sound waves depends upon the frequency of the alternating magnetic field around the nickel tubes.

Another type of magnetostriction transducer does not employ nickel tubes. Instead, the elements of the transducer have nickel laminations pressed into a thermoplastic material. Permanent magnets are so mounted that they provide a magnetic field for polarizing the nickel. The transducer illustrated in Figure 5-23, view B, is of this type, and it is normally used with scanning sonar equipment.

The directivity of the transducer determines the accuracy of the bearing information. The sound wave for a given frequency can be made narrower in azimuth by increasing the width of the transducer diaphragm. If a higher operating frequency is used, the transducer can be made smaller and still have the desired directivity. However, there are limitations. If the frequency is increased too much, propagation losses caused by absorption become objectionable.

**Piezoelectric Transducer**

The piezoelectric transducer operates in the same manner as the magnetostriction type except that crystals are used instead of nickel tubes. If a mechanical stress is applied to certain crystalline substances, an electrostatic voltage is produced. Conversely, an electric field applied to a crystalline substance causes a mechanical stress (expansion or contraction of the crystal). This property of a crystal is called piezoelectric effect. There are various types of crystals, such as quartz, Rochelle salts, and tourmaline, that have this property. Quartz crystals are not used in sonar transducers because the frequency response of a quartz crystal is too narrow.

Crystals can be damaged by either moisture, shock, or high temperature. Since high power produces high temperatures, the crystal transducer has a disadvantage in that it cannot handle as much power as the magnetostriction transducer. One advantage of the crystal transducer is that it can operate over a much wider frequency range than can the magnetostriction transducer. Additionally, the crystal type is sensitive and very efficient.

**Figure 5-23 — Construction details of two types of sonar transducers.**
Electrostrictive Transducer

When an electric field is applied across a dielectric, the dielectric is deformed. This phenomenon of change in dimensions is called "electrostriction," and is independent of the direction (sign) of the electric field and proportional to the square of the field intensity. In the crystal transducer, the electrostrictive effect is present, but it is much smaller than the piezoelectric effect and so is ignored. However, with barium titanate, a ceramic, the electrostrictive effect is large in comparison with the piezoelectric effect.

Ceramic for transducers has the advantage over crystals in that ceramic can be molded to any desired shape. This property is particularly desirable for making cylindrical scanning or omnidirectional transducers. The converse of electrostriction, the change in electric potentials when the material is stressed, takes place only when a constant polarization potential is present. The ac sonar signal is thus superimposed on the larger dc polarization, and the material dimension will vary directly with the magnitude of the resultant potential. The polarization of electrostrictive materials is thus analogous to the magnetic polarization required for magnetostrictive materials. Without the polarization, mechanical stresses will not produce an electric potential.

Nearly all transducers now being built are of the ceramic type. Ceramic compounds have high sensitivity, high stability with changing temperature and pressure, and relatively low costs.

Hydrophone

The hydrophone is a microphone especially constructed to pick up sounds while submerged. It is used only as a receiving device. The transducer is used for both transmitting and receiving sound waves. (The transducer acts as a hydrophone when it is receiving an underwater signal.) The hydrophone can be designed so that its receiving characteristics are highly directional. This enables the hydrophone to provide accurate target bearing information. The hydrophone is also designed to operate over a wide frequency range.

TYPICAL AIRBORNE ACOUSTIC SONAR SYSTEM

A modern airborne sonar system has many of the operating characteristics and features of its predecessors. Use of solid-state components and digital computer techniques, however, has improved the sensitivity, accuracy, and reliability of the typical airborne sonar system. The operating features, major components, and modes of operation of a typical airborne dipping-sonar set (Figure 5-24) will be presented in the following paragraphs.

Operating Features

The typical sonar detecting-ranging set is a lightweight, airborne, sonar set for use in an ASW helicopter as either a variable depth dipped passive/active sonar or an acoustic processor for real-time display of passive/active sonobuoy sensors. Dipping-sonar operation provides detection, tracking, and classification of underwater targets by a sonar TA lowered into the water from the hovering helicopter. The dipping sonar may be operated with adaptive processor sonar (APS) to increase detection capability in shallow water and reverberation limited conditions. Data transmitted to onboard VHF receivers from DIFAR, VLAD, or DICASS sonobuoy sensors are digitally processed by the sonar set 1 for display on the sonar set cathode ray tube (CRT). Also, the sonar set provides voice communications (WQC) and BT profile.

Active/Passive Dipping Sonar

In the active mode, the sonar set obtains bearing, range, and Doppler information by pinging and receiving target echoes on selectable range scales of 1, 3, 5, 8, 12, and 20 kiloyards. The transmitter
produces one of 3 selectable sonic frequencies of 9.230, 10.000, and 10.770 kHz at a selectable pulse width of 3.5 or 35 milliseconds. The shorter pulse is used for close ranges and better target echo resolution. The transmitter output is 500 watts at any transducer depth with the range scale set to 1 kiloyard. In 3-, 5-, 8-, 12-, or 20-kiloyard ranges where transducer depth exceeds 27 feet, the transmitter produces an output of 7,500 watts; however, low power (500 watts) can be selected at any range scale setting or at any transducer depth greater than 27 feet by setting the indicator TEST switch 6 to 0-9.

The returning echoes are received by the transducer, processed by the multiplexer, and applied to the receiver. To allow for ±45 knots of Doppler, a bandpass of ±315 hertz (Hz) about the ping frequency is provided by the receiver front end. The echo is converted to appropriate video and bearing signals which are presented to the indicator. The indicator provides a plan position indicator (PPI) display on a single gun CRT which employs spiral scan deflection, beginning at the CRT center and sweeping outward to the CRT edge at a rate governed by the selected range scale. The spiral scan permits 360 degrees of azimuth to be continuously viewed and the top of the CRT is slaved to magnetic north by means of a fluxgate compass located in the transducer and COMPASS VARIATION switches located on the multiplexer. The 360 degrees of azimuth are divided into 45-degree sectors, numbered clockwise 1 through 8 with sector 1 between 270 and 315 degrees. An approximate 3/16-inch circular cursor that time shares deflection with the spiral scan appears on the CRT and is manually positioned by the sonar operator's CURSOR POSITION controls.

**Adaptive Processor Sonar**

In either shallow water reverberation limited or deep water wideband noise limited conditions, the detection capability of the active dipping sonar may be increased by 20 and 13 decibels respectively, by utilizing APS. The APS is an integral part of the sonar data computer (SDC), a digital programmable processor which uses fast Fourier transform (FFT) techniques to provide narrow-band analysis of the uniquely shaped pulse transmitted in the APS mode. The display remains the familiar PPI readout of target range and bearing, with the exception of the square cursor.
The 3.5 and 35-millisecond rectangular pulse generated by the active dipping sonar without APS, results in a frequency spectrum having considerable energy in the sidebands away from center frequency. The APS transmission utilizes one of two types of pulses; a 200-millisecond or a 700-millisecond pulse. Both pulses have a contoured envelope which results in a spectrum with a narrower center lobe and very low sideband levels. Also, the longer pulse length will enhance target strength by more nearly matching the acoustic length of the transmission to that of a typical submarine. Transmitter output is 7,500 watts unless the indicator TEST switches are set to 0-9, the receiver RANGE SCALE-KYDS (kiloyards) switch is set to 1 or the transducer depth is less than 66 feet.

Echoes received by the transducer pass through the AGC circuits and 630 hertz bandpass filters in the sonar receiver. A multiplexer in the receiver sequentially samples the intermediate frequency (IF) signals in each sector and applies the samples to the SDC, where an FFT is performed on each sector. The FFT process, which is essentially a comb filter, produces a 630-Hz wide frequency spectrum at small range intervals throughout the range sweep. Recognized reverberation components are not presented on the display. Wideband sea noise is reduced to small amounts of noise energy at the output of each narrow-band filter in the comb. A target echo at a discrete frequency will appear at the output of a narrow-band filter. In a background of little noise energy at the filter output, the signal may be easily detected. The same target echo received by the sonar receiver without APS, appears at the input to the conventional detector amid high noise energy level contained in the 630-Hz bandpass and may be completely undetectable.

In the APS mode, targets (brightened squares) are placed at precise points on the CRT in accordance with computed range and bearing of the detected signal in the spectrum analysis. The SDC also refreshes the display to prevent fading. A digital readout of bearing, range rate in knots, and range is alphanumerically displayed at the top of the CRT. Sonar audio is treated in the same manner as the dipping-sonar without APS. Range and bearing information can be transferred to the aircraft computer system.

Voice Communication

When the sonar set is operated in the communications mode, underwater voice communications may be conducted between other dipping-sonar, submarines, or surface ships equipped with similar equipment. The receiver converts the normal voice frequencies to a single sideband transmission format within the band of 6 to 11 kHz. In the communications mode, the transmitter produces 500 watts peak envelope power (PEP), single sideband signals detected by the transducer are converted to normal voice frequencies by the receiver and are also displayed on the CRT as a directional noise spoke. The voice signals are routed through the audio ALL/ONE function into the ICS.

Bathythermograph

Search, tracking, or target classification operations are normally not initiated until a BT has been obtained of existing water conditions. The transducer or BT sonobuoy sensor is lowered to maximum depth while temperature is plotted against depth on the CRT. The CRT display is compared with range prediction charts to determine optimum operating depth.

Sonobuoy Acoustic Processing

The SDC provides a means of processing passive/active sonobuoy signals received by the VHF receiver. The processed data is converted to real-time display formats suited to the indicator deflection system and CRT. Processed data is also made available for transfer to the aircraft computer system. The sonobuoy signals are filtered in the SDC and presented to the ICS as
sonobuoy audio. Additionally, downlink command tones are generated by the SDC to modulate a UHF transmitter which transmits the tones to command-activated sonobuoys.

The SDC processes three types of sonobuoys including:

- **Passive:**
  - DIFAR
  - DIFAR (VLAD): similar to DIFAR.

- **Active:**
  - Directional Command Activated Sonobuoy System (DICASS)

The passive sonobuoys detect omnidirectional target noise in a band of interest between 10 and 2,010 Hz. In addition to omni-directional, DIFAR/VLAD detect target noise on 2 directional hydrophones for bearing (magnetic) calculations in the computer. Active sonobuoys ping and the detected echoes are processed by the SDC to obtain target range and range rate in addition to bearing provided by DICASS. Ping command tones to the SDC must be sent to DICASS. Other DICASS command tones include transducer payout intermediate (IM); deep (DP), and scuttle commands.

Sonobuoys transmit target data on VHF radio to the aircraft for processing by the SDC. One onboard sonobuoy receiver provides the capability of simultaneously receiving from 4 sonobuoys. Each of the 4 receiver channels, designated A through D, is set to one of 99 selectable sonobuoy RF channels.

The SDC is a programmable digital processor which uses an FFT technique to provide a spectral analysis of passive/active sonobuoy signals. The FFT process is essentially a comb fitter created by digital means. The SDC can simultaneously process up to four sonobuoys, depending on type. Mixed sets cannot be simultaneously processed. The maximum number of sonobuoys that can be processed is indicated in the following list of sensor sets:

- **Passive:**
  - Two DIFAR/VLAD (high resolution)
  - Three DIFAR/VLAD (minimized processing due to additional memory load results in reduced resolution)

- **Active:**
  - Two DICASS

The resulting frequency spectrum from processed passive sonobuoys is displayed on one of 4 selectable display formats. By narrowing the discrete filters in the FFT process, a higher frequency resolution is achieved; however, an overall reduction in the analysis bandwidth is then apparent. Four frequency resolutions are available by selecting analysis bandwidths. The operator may position each analysis band in any area of the incoming spectrum. The displayed frequency spectrum is periodically updated but the update interval is due to a slower FFT rate required to resolve greater resolution. Between updates, the display is refreshed to prevent fading. The operator may select and control up to ten harmonic cursors on the (2) ALI or BRG/ALI displays. The operator may select multiple verniers MV1 or MV2 on the (2) ALI or BRG/ALI displays. Utilizing the cardioid null option, the operator can steer the cardioid beam null on the DIFAR sonobuoy to direct maximum attenuation on the BRG/ALI displays. Harmonic cursors, multiple verniers, and cardioid null functions can all be active at the same time in DIFAR mode.

To increase detectability of weak stable frequencies within the displayed sea noise, an ALI function may be selected. The ALI function places individual integrators between each discrete output from
the FFT processor and the display. Random sea noise, which normally exhibits up and down fluctuations with each display update, is averaged out by the integrators. Therefore, the perception of weak stable frequency lines in the display becomes more pronounced. The ALI function provides 3 selectable time constants of 0.5, 1.5, and 5.0 minutes. The longer integration time further minimizes the display sea noise amplitude.

Twenty lines of consecutive spectrums can be viewed in a waterfall display mode, which provides the operator with frequency trends and history. To minimize the effects of detected fleet noise on bearing calculations for target frequencies, a bearing null function can be selected to reduce bearing pull (error) in the bearing display.

The SDC simultaneously displays data from the processed passive sonobuoys in the following display mode:

- **DIFAR/VLAD mode:**
  - Two-Amplitude vs. Frequency
  - One-Bearing vs. Frequency with Amplitude vs. Frequency
  - One-Waterfall (high resolution)
  - Two-Waterfalls (reduced resolution)

A vertical cursor is provided for each passive display mode except two-waterfalls which has a cursor in each fall. By positioning the cursor over the frequency line of interest, the precise frequency (ALI, ‘FALL, ‘FALLS), frequency and bearing (BRG/ALI) is displayed in alphanumerics at the top of the CRT. An analysis band frequency scale is displayed along the bottom of the CRT. The cursor intersect point along the frequency scale coincides with the digital frequency readout except in 2-waterfalls display mode where a hollow arrow rides the scale to provide an analog indication. In the 1-bearing vs. frequency plus amplitude vs. frequency display mode, a movable horizontal reference line is provided in the bearing vs. frequency field. The reference line does not affect the readouts.

Bearing data from a DIFAR sonobuoy in the bearing vs. frequency plus amplitude vs. frequency display mode can be transferred to the aircraft computer system. Additionally, the sonobuoy signals from the sonobuoy receivers are filtered but not digitally processed in the SDC. One of the sonobuoy audio signals is selected by the operator for routing through the indicator to the ICS.

For active DICASS sonobuoys, the SDC provides 3 selectable ping pulse widths of 0.1, 0.5, and 1 second which are interlocked with 3 selectable range scales of 5, 8, and 12 kiloyards as indicated in Table 5-1.

### Table 5-1 — Selectable Ping Pulse Widths

<table>
<thead>
<tr>
<th>Pulse Length</th>
<th>Range Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short</td>
<td>5 yards (yds) (automatically selected if short pulse width is selected)</td>
</tr>
<tr>
<td>Medium</td>
<td>5, 8, and 12 yds</td>
</tr>
<tr>
<td>Long</td>
<td>8 and 12 yds (If 5 is present when long pulse is selected, range jumps to 8)</td>
</tr>
</tbody>
</table>

For DICASS sonobuoys the address of the sonobuoy to be pinged is automatically determined by the SDC from RF channel information received on the data bus from the tactical data processor (TDP).

The frequencies of DICASS echoes are down converted to center-frequencies (0 Doppler) of 800 and 850 Hz, respectively, prior to transmission. In the FFT process, a fixed bandwidth wide enough to accommodate Doppler is centered around the down converted frequency. Frequency spectrums are produced at short intervals from the time of ping to the end of range sweep.
Four different display modes are available for active sonobuoys. One active display mode reveals the entire content of each processed spectrum and the other display modes select only one frequency in each spectrum (automatic target candidate selection). In relation to the non-target candidate selected display mode, each active spectrum appearing during the range sweep is essentially stood on end and rotated 90 degrees so that the top of each spectrum is viewed as a column of dots along a plus and minus Doppler scale. The dot intensity varies with the amplitude of the discrete frequency. Consecutive spectrums (vertical) are placed side by side across the range scale during the sweep period. The entire field of spectrums is refreshed to prevent fading. During the next sweep, each new spectrum is displayed while the old one at the same range is erased.

In the automatic target candidate selected display modes, the process is similar to that just described, except (1) the SDC analyzes each spectrum reverberation components which are then kept from display and (2) the strongest of the remaining discrete frequencies is selected for display. The target candidate selected appears as a single brightened dot along the vertical Doppler scale. The automatic target candidate selection process is repeated for each spectrum produced during the sweep interval. If a DICASS is being processed, the bearing of the selected target candidate in each processed spectrum is calculated and in BRG/DOP mode is presented to display as a dot along a vertical bearing scale between 0 and 360 degrees. The FFT rate is high enough that two or more spectrums will be processed during the time span of an echo; thus, target returns displayed on any active display mode appear as several brightened dots in a row.

The SDC simultaneously displays data from 1 to 4 of the processed active sonobuoys in the following display modes:

- DICASS mode:
  - Two-Bearing vs. Range (automatic target candidate select)
  - Two-Doppler vs. Range (non-automatic target candidate select)
  - One-Bearing vs. Range plus Doppler vs. Range (automatic target candidate select)

Auto-track cursors may be simultaneously utilized on all four scales. Range rate and range information from each sonobuoy is sequentially transferred one at a time.

IM, DP, and scuttle command tones are generated by the computer and if initiated, modulate a UHF transmitter which sends the command tones to DICASS sonobuoys. An IM command causes the sonobuoy to drop to the intermediate depth. A DP command causes the sonobuoy to drop to a maximum depth. A scuttle command causes the sonobuoy to sink. A command can be sent to only one sonobuoy at a time and the sonobuoy does not have to be one that is being processed or displayed. Sonobuoy addressing is accomplished by setting SDC switches to the active RF channels (1 to 31) of the sonobuoy for which the command is directed.

**Built-In Test Equipment**

BITE includes both fault monitoring and test signal generating functions. During normal operation of the sonar set, various areas of the equipment circuitry are monitored for failures including: indicator, multiplexer and SDC power supplies, receiver clocks, dome control, and transducer. All power failures are indicated by a fault indicator on the indicator panel.

In the dip sonar configuration, simulated signals are injected into the transducer to provide an end-to-end test which assures mission readiness. In the sonobuoy processing configuration, mission readiness is assured by SDC BITE, which generates a test signal for each type of sonobuoy. Downlink commands are routed to SDC BITE from either the SDC output or the VHF transmitter output for observation on the CRT. The VHF receiver interface is also verified by a test signal generated within the VHF receiver. To localize a faulty weapons replaceable assembly, an individual
receiver, indicator, dome control, multiplexer, transducer and SDC test can be performed by sonar set BITE.

**Major Components**

A typical dipping-sonar set illustrated in *Figure 5-24*, consists of the azimuth and range indicator, multiplexer, dome control, sonar receiver, sonar data computer, sonar transducer, reeling machine assembly, and cable and reel assembly, hereafter referred to as indicator, multiplexer, dome control, receiver, SDC, transducer; and reeling machine, cable, and reel assembly.

**Azimuth and Range Indicator**

The indicator chassis is fitted with access panels on both sides and top. These panels are secured with quarter-turn fasteners. The indicator is attached to the top of the receiver with four quick-release pins, two on each side. The assembled indicator and receiver are secured to the shock mount base with four additional quick-release pins.

The function of the indicator (*Figure 5-25*) is to display the target echoes on a planned position indicator and to provide direct readout of bearing and range information. The indicator has various selector and screen controls to optimize viewing for the operator.

**Multiplexer**

The multiplexer provides the electrical interface between the sonar set units mounted in the helicopter and the sonar transducer submerged in the water. The multiplexer is located in the cabin area, parallel to the reeling machine.

**Dome Control**

The dome control provides controls for raising and lowering the sonar transducer and indicators for monitoring the sonar transducer and reeling machine. The dome control is located at the sensor station.
Receiver
The sonar receiver generates the transmit signal and receives and processes sonic signals from the transducer for display on the indicator. The receiver also provides audio to the ICS for aural monitoring of acoustic signals. The receiver should not be confused with the sonobuoy receiver, which detects RF signals from deployed sonobuoys.

Sonar Data Computer
The SDC revolutionized sonar capabilities and functionality. This computer is integrated with the sonar set to provide processing and display of DIFAR sonobuoy signals on the sonar set’s indicator. The SDC is also used to provide an accurate fix on the target by providing a digital readout of target range, speed, and bearing.

Transducer
The sonar transducer generates and transmits sonar pulsed (ping) energy or voice signals into the water. The sonar transducer also acts as a listening device, converting sound energy received in the water into electrical signals. In the Airborne Low-Frequency Sonar (ALFS) system, power is supplied by the helicopter eliminating the need for expensive in-unit sonar batteries.

Reeling Machine, Cable, and Reel Assembly
The transducer is lowered or raised by the reeling machine unwinding or winding the cable on the reel assembly (Figure 5-26). Lower and raise operations of the reeling machine are controlled by the dome control. The dome control also monitors a number of parameters during the lower and raise operation and transducer conditions, to either alert the operator to a minor malfunction, or to stop the reeling machine where a serious problem may cause damage to the equipment or injury to personnel.

The transducer, attached to a cable 1,575 feet long, is lowered and raised by the reeling machine. It is lowered at an average rate of 18 feet per second in the water, and 15 feet per second in the air. Raise speed is approximately 22 feet per second until a depth of 193 feet or cable payout of 233 feet is reached; then the raise speed is reduced to 5 feet per second until cable payout is approximately 9 feet. The transducer is then raised to the seated position at a rate of 1 foot per second.

Emergency raising of the transducer is provided in the event that the helicopter or reeling machine hydraulic system malfunctions. An auxiliary raise relay that applies ac voltage to the reeling machine may be activated by depressing the dome control AUX RAISE switch at which time an ac electric motor is utilized to raise the transducer at an average rate of 6 feet per second.

Modes of Operation
The sonar set operates in a number of different modes, as mentioned earlier in the chapter. The echo-ranging, passive, COMM, SDC sonar, sonobuoy, and test modes are discussed in more detail in the following paragraphs.
Echo-Ranging Mode

In the active mode, the sonar set obtains bearing, range, and Doppler information by transmitting sound energy and receiving target echoes on selectable range scales of 1, 3, 5, 8, 12, and 20 kiloyards. The transmitter assembly, located in the transducer, provides one of three selectable sonic frequencies of 9,230, 10,000, and 10,770 kHz at a selectable pulse width of 3.5 or 35 milliseconds. The shorter pulse width is used for close ranges and better target echo resolution. The transmitter assembly power output is 500 watts in the sonar mode at any transducer depth with the receiver RANGE SCALE-KYDS switch set to 1 kiloyard or MODE switch set to COMM. In the 3, 5, 8, 12, or 20 kiloyard range where transducer depth exceeds 27 feet, the transmitter assembly produces a power output of 7,500 watts; however, a high-power defeat function is available to the operator (BITE 0-9).

Returning echoes are received by the hydrophone, located in the transducer, and are applied through the multiplexer to the receiver. To allow for 42 knots of Doppler, a bandpass of ±315 Hz (7 Hz per knot) about the transmit frequency is provided by the receiver front end. The echo is convened to appropriate video and bearing signals, which are presented to the indicator. The indicator provides a PPI display on a single-gun at which employs spiral scan deflection, beginning at the CRT center and sweeping outward to the CRT edge at a rate governed by the selected range scale and temperature of the water. The spiral scan permits 360 degrees of azimuth to be continuously viewed and the top of the CRT is slaved to true north by means of a reference north magnetic compass located in the transducer and COMPASS VARIATION switches located on the multiplexer. The 360 degrees of azimuth are divided into 45-degree sectors, numbered clockwise 1 through 8, with sector 1 between 270 and 315 degrees. A small circular cursor that time shares deflection with the spiral scan appears on the CRT, and is manually positioned by the sonar operator.

The transducer transmits at the beginning of a spiral scan (CRT center) and a returning echo appears as a brightened spot on the CRT. Precise target bearing and range information is displayed on the receiver by digital readouts that follow the manually positioned cursor. Bearing, range, and range rate (Doppler) information can be transferred to an aircraft computer system in the form of serial data. Additionally, the echo signal from the target under the cursor is also directed to the range rate detector circuitry. Opening/closing range rate information up to 42 knots is directly indicated on the indicator RANGE RATE-KNOTS meter.

A moving target indicator (MTI) function that removes brightened reverberation clutter is available for use by the sonar operator. During reverberation blanking, echoes from stationary targets will not be displayed, but targets exceeding selected thresholds of 1, 2, or 3 knots will be displayed. If the MTI THRESHOLD switch is set to OFF, the MTI is automatically disabled and the echoes from both stationary and moving targets are displayed.

In addition to the visual indications presented on the CRT, echoes are converted to lower audible frequencies which are made available to the sonar operator’s headset. The sonar operator may elect to listen to audio which is collectively derived from echoes in all sectors, or only from echoes received from the sector in which the cursor is placed. In the audio ALL mode, echoes received in left sectors 1, 2, 7, and 8 are applied to the left earphone; and echoes received in the right sectors 3, 4, 5, and 6 are applied to the right earphone. A different nonharmonic tone is generated with one tone being unique to left/right sector pairs 2/3, 1/4, 8/5, and 7/6 to aid in identifying a target by aural means. In the audio ONE mode, audio from echoes appearing only in the sector containing the cursor is presented in both earphones. The resulting tone is the same for echoes monitored in any sector.

Depth and temperature sensing devices are installed in the transducer to provide depth and temperature information. Automatic sound velocity correction is provided utilizing the water temperature correction information.
Passive Mode
In the passive mode of operation, the sonar set does not transmit. Information concerning a distant object is obtained by evaluating the sound generated by the object. Since the sonar set is primarily an active sonar, operating in the region of 10 kHz, the listening capability is limited to a bandpass of 630 Hz centered about the selected sonic frequency of 9.230, 10.000, or 10.770 kHz. Sound received from an object appears on the CRT as outward sweeping brightening (noise spoke) along the bearing axis of the object, relative to true north. The noise spoke may be monitored in the sonar operator’s headset, using the audio ALL or ONE functions.

Communication Mode
When the sonar set is operated in the communication mode, underwater voice communications may be conducted between other dip sonar and submarines, or surface ships equipped with similar equipment. The receiver converts the normal voice frequencies from the microphone to a single sideband transmission format within the band of 8 to 11 kHz. In this mode, the transmitter assembly produces 500 watts PEP, single sideband signals detected by the transducer hydrophone are converted to normal voice frequencies by the receiver, and are routed through the audio ALL ONE function into the helicopter intercommunication system. The voice signals are also displayed on the indicator CRT as a directional noise spoke.

Sonar Data Computer Mode
When the sonar set employs the SDC, input data signals are supplied by the receiver, or sonobuoy receiver. Signals supplied by the receiver are acoustic data from which bearing, range, and Doppler are derived. Signals supplied by the sonobuoy receiver are also acoustic data signals. Switches on the indicator and SDC determine which input signal source will be selected for processing and display. The SENSOR switch on the SDC must be in the Q13 (PPI) and the DISPLAY switch on the indicator must be depressed to the BUOY position. In this configuration, the APS mode of operation is selected. The receiver applies 16 half-beam time-shared multiplexed signals to the SDC audio select circuits. In this mode of operation, the transmitter assembly output will be a 200-millisecond cosine squared or a 700-millisecond extended cosine signal, depending on the position of receiver switches. If the receiver MODE switch is set to SHORT, the transmitter assembly output will be a 200-millisecond cosine squared pulse when the RANGE SCALE-KYDS switch is set to 3, 5, 6, 12, or 20. If the receiver MODE switch is set to LONG, the transmitter assembly output will be a 200-millisecond cosine squared pulse when the RANGE SCALE-KYDS switch is set to 3 or 5, and a 700-millisecond extended cosine pulse when the RANGE SCALE-KYDS switch is set to 6, 12, or 20. The transmitter assembly power output will be 500 watts, if transducer’s depth is less than 60 feet in SHORT, less than 120 feet in LONG, indicator TEST switches set to O-Q, or the receiver RANGE SCALE-KYDS switch is set to 1. When the transducer depth is greater than 60 feet in SHORT or greater than 126 feet in LONG, the receiver RANGE SCALE-KYDS switch set to a position other then 1, and the indicator TEST switches set to O-O, the transmitter power output will be 7,500 watts. The video signals are digitized by an analog-to-digital (A-to-D) converter.

The SDC analyzes the acoustic data from the receiver and applies the resultant video information to the indicator. Target echoes picked up by the transducer hydrophone are uplinked to the receiver in the same manner as for the active normal mode. The receiver contains a multiplexer that sequentially samples the IF signals in each sector and applies the samples to the SDC, where FFT analysis is performed for each sector. The FFT process, which is essentially a comb filter, produces a 630-Hz wide frequency spectrum at small range (time) intervals throughout the range sweep.

The digital bearing and range data applied to the indicator is converted to horizontal and vertical deflection signals and an intensity signal that controls the display on the CRT. The bearing and range
Data is displayed on the CRT in a two-dimensional format. Through reverberation whitening and automatic target selection, target information can be resolved from excessive background noise. The usual spiral scan sweep during active/normal operations is not employed on the CRT when the SDC is monitoring active or passive sonar or sonobuoys. During the BUOY mode of operation, the CRT is blanked, except for the major targets which are to be displayed. Targets (brightened spots) are displayed at precise points on the indicator CRT in accordance with the computed bearing and range of the detected echo during spectrum analysis. The SDC refreshes the target display at regular intervals to prevent fading. The target Doppler is displayed alphanumerically at the top of the CRT. The indicator RANGE RATE-KNOTS meter is inoperative in the BUOY mode. The bearing and range digital readouts on the receiver are slaved to the cursor controls, and operate in the same manner as for the active normal mode. However, the cursor displayed on the CRT consists of a small square instead of the circle used in the active normal mode. Sonar audio is not processed by the SDC, and is treated in the same manner as for the active normal mode. Bearing, range, and Doppler (range rate) can be transferred to the TDP via the data bus.

**Sonobuoy Mode**

Sonobuoy operation is selected by setting the SDC SENSOR switch to the type of sonobuoy from which signals are to be received, processed, and displayed. Signals from up to four identical type sonobuoys can be received simultaneously by the sonobuoy receiver, and then applied to the SDC. The actual number of sonobuoy signals processed by the SDC depends on the setting of the SDC SENSOR switch. The number and type of sonobuoys that can be selected are placarded on the SDC front panel.

Sonobuoy RF channel codes are provided to the SDC from the TDP through the data bus and the CDU. The sonobuoy input signals are then processed and converted to the appropriate output format for display on the CRT. The four computer PROCESS MODE switches, A through D, select the signals for processing (PRCS position) or display on the CRT (DSPL position) or PING for DICASS buoys. The SDC AUDIO stepping switch selects any one of the four signals from the input signal conditioner, and applies it through the audio select circuit to the sonar set audio system for presentation to the headphones. This audio is used for analysis of sonobuoy received acoustic data.

Sonobuoy signals are processed and analyzed in the same manner described for the dip sonar operation. Information (such as acoustic emission spectrum analysis, bearing, range, and Doppler) is acquired from the sonobuoy signals. The data is processed by the SDC and is converted to deflection and Intensity signals to be applied to the CRT. The SDC generates alphanumeric data in accordance with the SDC control settings to produce numeric readouts for the vertical and horizontal scale values displayed on the CRT. The alphanumeric data is applied to the display/MPR interface where it is converted to deflection and intensity signals for presentation on the CRT.

The DICASS sonobuoy, from which signals originate, is controlled by a command function generator in the SDC. When an active sonobuoy is selected for transmission (or pinging), the SDC causes the command function generator to generate ping command signals to the aircraft uhf radio for transmission to the sonobuoy. The proper sonobuoy address command frequency is automatically selected. The length and repetition rate of the ping command pulses to the selected sonobuoy are controlled by the PULSE LG and RANGE-KYD switch on the SDC.

The command function generator then generates the correct address frequency signal. The intermediate deep or scuttle command signals are selected by the CMD SEL IM/DP/SCUTTLE switch on the SDC and executed by pressing the front panel COMMAND/ARMED/EXEC switch. This command is generated by the function generator and applied to the aircraft UHF radio for transmission to the sonobuoy.
Test Modes

The test modes check the operational status of the system as a whole and the various components of the system as individual units. These test modes use internally generated stimuli.

During normal operation, the test circuits sample major system functions and voltages. If a sampled function exceeds preset limits, the FAULT indicator illuminates for the length of time that the fault exists.

The indicator contains the BITE function control which includes two TEST digital switches that select the BITE mode, and the BITE control logic signal generators that set up the test conditions and provide the simulated input signals. BITE signals are applied to the indicator, receiver, dome control, multiplexer, and transducer for tests. The indicator TEST switches set the BITE mode, governing the unit to be tested and the type of BITE signals to be generated. BITE control signals are routed to the receiver for receiver BITE, to the multiplexer for multiplexer BITE, and to the transducer for end-to-end mission readiness BITE and for transmitter assembly and battery BITE tests. For downlink BITE, the indicator applies BITE control and enables BITE modulated signals to the multiplexer. The BITE signals are transmitted to the transducer as a part of the multiplexed downlink-data to cause the sonar transducer to generate a simulated signal that can be displayed and evaluated.

Airborne Low Frequency Sonar

The Navy currently uses ALFS installed in MH-60R Seahawk helicopters. The ALFS provides longer detection ranges and improved detection capabilities over previous sonar dipping sets. The improvements are provided by the use of lower frequencies, less signal attenuation, longer pulse lengths, and increased transmission power. The system also uses an enhanced modular signal processor for improved sonobuoy processing capabilities.

The dipping-sonar provides a low frequency sonar to locate and track submerged contacts in the aircraft operating environment. The system also provides underwater communications (WQC) and environmental collection capabilities.

The system interfaces with the following systems: data handling (DH), navigation (NAV), air vehicle segment (AVS), COMM, and signal processor set.

Functional Description

The dipping-sonar system consists of a submersible sonar transducer, sonar receiver/transmitter (R/T), and supporting equipment to detect underwater target and ocean environments. Additional WRAs include the reeling machine interface unit (RMIU), cable/reel assembly, reeling machine, reeling machine control, cable angle panel, and the cable angle control panel. The dipping-sonar serves as the aircraft’s primary acoustic sensor. Secondary acoustic sensors are the various sonobuoys used in conjunction with the sonobuoy receiver set.

The system uses the sonar transducer as the sensor to locate underwater targets. Received acoustic sensor signals are sent to the signal processor for extraction of target information and forwarding of contact data to the aircrew audio/visual interfaces. Detection is based on the sound wave echoes received in response to selected acoustic signal transmissions generated by the sonar R/T. The transducer projects and receives these acoustic signals in active or passive modes, to allow detection and tracking of submarine platforms in the mission area.

Sensor data is first sent to the acoustic processor for signal conditioning and advanced processing functions to extract target information. The target information is then sent to the DH for correlation and formatting prior to aircrew viewing the mission display subsystem.
The dipping-sonar system is primarily controlled by the signal processor subsystem. The dipping-sonar system reports performance monitoring to the acoustic processor, but also communicates with the DH system to provide BIT status and cable angle information. The reeling machine and sonar cable provide the physical interface between the aircraft and the transducer. The RMIU controls the reeling machine operations and provides the electrical interface between the reeling machine, sonar R/T, and the reeling machine control. The reeling machine control provides centralized control and display for the reeling machine and monitoring of the dipping-sonar system status.

The dipping-sonar system also interfaces with the NAV system to provide CABLE ANGLE LAT/LONG (latitude/longitude) status and LAT/LONG DRIFT control signals for use by the automatic flight control system in determining aircraft hover position over the transducer.

The ALFS system is extremely complex at the intermediate maintenance level and a brief system overview follows.

**Sonar Transducer**

The transducer provides the aircraft primary acoustic sensor capabilities and in-water operations. The transducer provides the acoustic signal transmit/receive functions for the sound wave signals generated by the sonar R/T. It also provides the WQC capability and environmental sensor functions. The transducer’s transmit array is a vertical line array. The receive array consists of a multi-stave, multi-arm volumetric array.

It transmits high-power and WQC active waveforms, receives acoustic energy, performs cardioid beamforming, and collects environmental data. Received acoustic analog signal data is converted to digital format and encoded to high density bipolar order of 3 (HDB3) data prior to sending it to the sonar R/T. The transmitter is installed on the end of the cable/reel assembly and when seated, is located inside the aircraft funnel and transducer housing.

The transducer performs the following functions:

- Receives high-power acoustic pulse and WQC transmit signals from the sonar R/T and projects them into the water
- Receives in-water active sonar echo returns, WQC signals, and passive acoustic signals; provides front-end processing, converts the signals to digital uplink data, and sends it back to the sonar R/T
- Processes downlink control signals from the sonar R/T to unfold/fold the receiver array, initiate front-end attenuation, initiate BIT, and set sonar mode

**Sonar Receiver/Transmitter**

The sonar R/T provides sound wave generation and power control of the transducer transmission/reception functions. It performs acoustic and WQC audio signal generation functions, signal conditioning, and command/status interface communications with the signal processor. Operating command, status reporting, and sonar sensor signal interfaces with the acoustic processor are handled via an Ethernet interface. The sonar R/T also interfaces with the RMIU for control/status functions.

The sonar R/T power control and signal interfaces with the transducer via the transducer bus and cable/reel assembly. The sonar R/T generates the transmit acoustic pulse signals (high-power active waveforms) and provides the return interfaces for uplink sensor data and received underwater voice audio, which is sent to the signal processor. The downlink control and WQC underwater voice transmissions are routed to the transducer via the slip ring on the cable/reel assembly.

Additionally, the sonar R/T performs the following functions:
Receives/executes sonar and BIT commands from the acoustic processor including active waveform selection, power level, output mode, and initiate BIT

Provides status to the acoustic processor including mode, BIT, fault codes, and ping synchronization

Receives WQC audio and transmit key from the COMM system and generates single sideband, suppressed carrier signal for WQC transmission

Generates downlink tone commands for the transducer, including the commands to unfold/fold the transducer array, initialize front-end attenuation, and select transducer mode

Processes uplink data from the transducer, including transducer temperature, depth, bottom proximity, and vertical inclination

Provides an interface for real-time recording of transducer data and reeling machine status

Reeling Machine Interface Unit

The RMIU provides the reeling machine interface function for controlling reeling machine operations. The RMIU provides the electrical interface between the reeling machine, R/T, reeling machine control, and the aircraft platform. The RMIU transfers the reeling machine control processing/logic signals for control of the reeling machine and cable/reel assembly mechanical, electrical, and hydraulic elements.

The RMIU regulates smooth transitions of sonar transducer dipping activities, and performs local control/status of the reeling machine BIT and safety circuits. The RMIU performs numerous functions including; snag sense and response, position sensing, and ensuring the array is folded prior to raising.

Cable/Reel Assembly

The cable/reel assembly provides a means to support, raise, and lower the transducer in the water. The assembly provides 2,550 feet of cable that is stored on a reel frame assembly. The reel frame assembly has a slip ring assembly, which provides the electrical interface between the sonar cable and the R/T. The cable/reel assembly is installed within the reeling machine.

Reeling Machine

The reeling machine supplies drive power to the cable/reel assembly. The reeling machine is a hydraulic winch that deploys and retrieves the sonar transducer. It uses 3,000 pounds per square inch (psi) hydraulic pressure from the aircraft’s hydraulic system to drive the cable/reel assembly rotational speed when raising/lowering the transducer. The reeling machine has an electric auxiliary motor that can raise the transducer in the event of hydraulic power loss. A hand crank is also available for maintenance purposes.

A hydraulic motor drives a gear train assembly, which in turn drives the cable/reel assembly. As the cable/reel assembly rotates, the cable is rolled out, or retrieved, passing over a level wind mechanism, cable stress sensor, and through the cable angle sensor.

Reeling Machine Control

The reeling machine control provides manual operator command of reeling machine operations. It provides centralized interface/display functions for local operator control of the reeling machine and monitoring of the transducer deployment status. The reeling machine control command signals are interfaced to the reeling machine via the RMIU.
In addition to operating controls for the reeling machine, the reeling machine control provides for lowering/raising the sensor and has indicators for visual detection of normal or faulty cable/transducer operations. Fail-safe functions in the reeling machine control will automatically place the reeling machine in a stop (safe) state when certain conditions exist including: cable limit reached, the transducer is 50 feet from the ocean floor, and when the data uplink is lost.

The reeling machine control also provides all necessary controls for operating the reeling machine in manual mode and initiating BIT. Self-test results are shown on a front panel display.

**Cable Angle Panel**

The sonar cable angle panel display function provides the latitude/longitude signal inputs for generation of cable angle displays shown on the mission and flight display subsystems. The cable angle panel displays assist the aircrew in maintaining the aircraft hover position over the transducer during dipping operations.

The dipping-sonar system communicates cable display data to the DH system via a digital interface. This provides the reeling machine cable angle valid and delay, latitude/longitude, water entry, and submerged data to the primary mission/flight computer and backup flight computers.

The cable angle panel display function is active during all modes of operation.

**Cable Angle Control Panel**

The cable angle control function provides for local sonar operator (SO) console control and adjustment of cable angle to assist maintaining proper aircraft hover position during dipping operations. The cable angle control panel contains LAT DRIFT and LONG DRIFT controls to allow the operator to make limited aircraft position corrections relative to the sonar angle cable. The LAT/LONG DRIFT interface signals are used by the automatic flight control system in determining aircraft hover position over the transducer. The cable angle control panel also provides a TEST discrete interface with the cable angle panel. An ENGAGED indicator on the cable angle control panel illuminates to confirm the aircraft is in cable angle hover mode.

It also contains the switches required for pilot/copilot control of cable angle HOVER mode during dipping operations. Additionally, it contains a FAIL ADVISORY indicator that illuminates to advise the pilot/copilot when hover adjustments are necessary.

**Operational Modes**

The dipping-sonar system, in conjunction with the acoustic processor, operates in the following modes:

- Active acoustic detection
- Acoustic signal analysis (ASA)
- Environmental data acquisition
- Underwater communications (WQC)
- Preventative maintenance (PM)

**Active Acoustic Detection**

In the active acoustic detection mode, the dipping-sonar R/T generates an active pulse and sends it to the transducer over the cable/reel assembly sonar transducer bus. The transducer transmits the active pulse and listens for the return echo to complete the ping event. When the transducer receives a return echo, it converts it to uplink data and sends it to the sonar R/T.
The sonar R/T reformats the uplink sensor data, separates the acoustic and non-acoustic data, and sends the reformatted data to the acoustic processor. The acoustic processor uses the acoustic data to generate active range, bearing, range Doppler, range intensity, threshold crossing, and aspect display data that is sent to the DH system. The acoustic processor also generates an audio representation of the acoustic data and forwards it to the COMM system for relay to the aircrew headsets.

This mode does not use non-acoustic data. The overall sonar waveform parameter/characteristic selections are sent to the sonar R/T by the acoustic processor to optimize sonar mission success. The data selections include:

- Operating frequency
- Source level
- Pulse length
- Waveform
- Range scale
- Display data type
- Receive sensitivity
- Audio binaural/beam
- Doppler gate
- Spatial nulls parameters

**Acoustic Signal Analysis**

The dipping-sonar provides an ASA mode to detect and analyze remotely generated underwater communications, navigation, and sonar transmissions. The ASA mode is active during all normal sonar operating modes except active acoustic detection and WQC. In the ASA mode, the acoustic processor filters the acoustic data and compares it against a selectable threshold. When the acoustic data exceeds the threshold, the acoustic processor sends a message to the primary mission/flight computer indicating a target of interest (TOI) or acoustic energy is detected.

The TOI messages to the DH system include frequency of transmission, signal strength, transmission bearing, and pulse length. The ASA mode allows the acoustic processor to generate an audio representation of the acoustic data that is sent to the COMM system for relay to the aircrew headsets. This mode receives frequency, sensitivity, and ASA threshold parameters, which are sent to the sonar R/T by the acoustic processor to optimize sonar mission success. The ASA function is a passive mode.

**Environmental Data Acquisition Mode**

The environmental data acquisition mode is used to collect environmental data for the generation of in-water sound velocity profiles (SVPs). This mode is available in the normal sonar operating and training modes, and is automatically activated when the transducer is in the water. This mode is automatically disabled whenever the transducer is out of the water.

The transducer sensor collects temperature and depth data BT, converts it to HDB3 uplink data and sends it to the sonar R/T. The sonar R/T reformats the uplink sensor data to a digital format, separates the acoustic and non-acoustic data, and sends it to the acoustic processor. The acoustic processor stores the non-acoustic environmental data in memory and makes it available to the
primary mission/flight computer. The acoustic processor generates data for the SVP display information, which it sends to the DH system. The acoustic processor can retrieve stored SVPs and use them to identify the best sonar transducer in-water depth and area of coverage for mission success.

The environmental data acquisition mode does not use acoustic data.

**Underwater Communications**

In the WQC mode of operation, the dipping-sonar set provides underwater voice communication capability that is compatible with the AN/WQC sonar communications set. In this mode, the sonar R/T receives WQC audio from the aircrew headsets and converts it to a high-power transmission signal. The sonar R/T sends the high-power signal to the transducer which then transmits the signal into the water and listens for return communications. The transmission signal is a single sideband, suppressed carrier sound wave with a carrier frequency of 8.0875 kHz (WQC high) or 3.6kHz (WQC low).

When the transducer receives the return analog communications signals, it converts them to digital format, encodes the HDB3 format and sends the uplink data to the sonar R/T. The acoustic processor separates the acoustic data and generates an audio representation of the received transmission to be relayed to the aircrew headsets.

This mode does not use the non-acoustic data and receives WQC high/low and sensitivity parameters, which are sent to the sonar R/T by the acoustic processor to optimize sonar mission success. Transmit/Receive control discretes are sent directly to the sonar R/T from the COMM system via PUSH-TO-TALK switches on the aircrew headsets.

**Preventative Maintenance Mode**

The PM mode, while not involved in actual process of detecting submarines, operates in a continuous, non-invasive manner to monitor mission-critical functions of the dipping-sonar system. Dipping-sonar system health/performance monitoring is reported to the signal processor set. Overall status of both the signal processor and dipping-sonar subsystems is provided to the primary mission/flight computer by the acoustic processor.

Status messages indicate either no failures detected, or identification of the failed WRAs. This mode is automatically enabled during normal operations and runs in the background as part of the BIT capability. Continued degraded mode of the acoustics system may be available if the failure is not critical.

**Sonobuoy Receiver Set**

The typical sonobuoy receiver set works in conjunction with independent sonobuoys placed in the water by the sonobuoy launcher set. The sonobuoy receiver set also provides the automatic identification system (AIS) function.

The sonobuoy receiver set consists of the following WRAs:

- Sonobuoy Receiver Antenna
- Software defined sonobuoy receiver (SDSR)
- Preamplifier unit (PAU)
Sonobuoy Receiver Set Functional Description

The sonobuoy receiver set is an antenna, preamplifier, and SDSR equipment set that provides receiver capability for the aircraft's sonobuoys. Acoustic signal reception allows detection and tracking of underwater targets in the aircraft operating environment. Received acoustic sensor signals are sent to the signal processor set for processing of target information and forwarding of contact data to the aircrew audio/visual interfaces. The sonobuoy receiver set provides the aircraft secondary acoustic sensors and receives signals from both active and passive sonobuoys. The aircraft primary acoustic sensor is the dipping-sonar.

The operation is similar to the fixed-wing sonobuoy receiver system and a brief overview follows. The sonobuoy receiver set antenna receives VHF signals from expendable in-water sonobuoys and provides antenna RF signals to the SDSR. The sonobuoy receiver set antenna also receives a BIT RF (test signal) input from the SDSR for operational monitoring of the antenna and receiver group circuits. The SDSR provides the capability for monitoring eight separate sensor channels. All eight channels of sonobuoy acoustic sensor data are sent to the acoustic processor for onboard processing and to the radio terminal set and COMM system to enable remote parent ship processing of the acoustic sensor data.

Sonobuoy Receiver Set Operational Modes

The sonobuoy receiver set, in conjunction with acoustic processor support, operates in the following modes:

- Sonobuoy active acoustic detection
- Sonobuoy passive narrow-band detection
- Sonobuoy environmental data acquisition

Sonobuoy Active Acoustic Detection

The sonobuoy receiver set provides active acoustic detection mode processing to support DICASS sonobuoy operations. The acoustic processor generates downlink data consisting of sonobuoy depth and scuttle commands sent over UHF downlink via the COMM system. The acoustic processor receives uplink data from DICASS omni sonobuoys via the SDSR. This information is used to generate range, Doppler, and bearing data for range bearing/range Doppler displays.

Sonobuoy Passive Narrow-band Acoustic Detection Mode

The sonobuoy receiver set provides for passive narrow-band acoustic detection in the following modes:

- Low Frequency Analysis and Recording (LOFAR)
- Demodulation of broadband noise (DEMON)
- DIFAR
- Tracker

The LOFAR, DEMON, and DIFAR functions process sonobuoy data and use it to generate narrow-band spectral data to support the detection, localization, and tracking of submerged contacts. The tracker function uses the narrow-band spectral data to generate frequency and bearing data.
Light, radar, and sound energy cannot pass from air into water and return to the air in any degree that is usable for airborne detection. On the other hand, lines of force in a magnetic field are able to make this transition almost undisturbed because the magnetic permeability of water and air are practically the same. Specifically, the lines of force in the Earth’s magnetic field pass through the surface of the ocean without deviation by the change of medium (from water to air or vice versa) and undiminished in strength. Consequently, an object under the water can be detected from a position in the air above if the object has magnetic properties that distort the Earth’s magnetic field. A submarine has sufficient ferrous mass and electrical equipment to cause a detectable distortion (anomaly) in the Earth’s field. Detection of this anomaly is the function of MAD equipment.

**Magnetic Anomaly**

The lines comprising the Earth’s natural magnetic field do not always run straight north and south. If traced along a typical 100-mile path, the field twists at places to east or west, and assumes different angles with the horizontal. Angles of change in the east-west direction are known as angles of variation, while angles between the lines of force and the horizontal are known as angles of dip (Figure 5-27). At any given point between the equator and the magnetic poles, the relationship of the angle between the Earth’s surface and the magnetic lines of force is between 0 and 90 degrees. This angle is determined by drawing an imaginary line tangent to the Earth’s surface and to the line of force where it enters the Earth’s surface. The angle thus formed is called the dip angle.

If the same lines are traced only a short distance, 300 feet for instance, their natural changes in variation and dip over such a short distance (short-trace) are almost impossible to measure. However, short-trace variation and dip in the area of a large mass of ferrous material, though still extremely minute, are measurable with a sensitive anomaly detector. This is illustrated in Figure 5-28. The dashed lines represent lines of force in the Earth’s magnetic field.

The angular direction at which natural lines of magnetic force enter and leave the surface of the Earth are shown in Figure 5-28, view A. This view shows that the angles of dip are considerably steeper in extreme northern and southern latitudes than they are near the equator. An area of undisturbed natural magnetic strength is shown in Figure 5-28, view B. When a submarine’s magnetic field distorts the Earth’s natural field, a disturbance results, as shown in Figure 5-28, views C and D. The density of the natural field is decreased in view C and increased in view D. The natural angle of dip is also affected, but only very slightly.

The maximum range at which a submarine may be detected is a function of both the intensity of its magnetic anomaly and the sensitivity of the detector. A magnetometer is used as the detector in MAD equipment. Magnetometer theory is discussed later in this chapter.

A submarine’s magnetic moment (magnetic intensity) (Figure 5-29), which determines the intensity of the anomaly, is dependent mainly on the submarine’s alignment in the Earth’s field, its size, the latitude at which it is detected, and the degree of its permanent magnetization.
MAD equipment, in proper operating condition, is very sensitive, but the submarine’s anomaly, even at a short distance, is normally very weak. The strength of a complex magnetic field (such as that associated with a submarine) varies as the inverse cube of the distance from the field’s source. That is, if the detectable strength of a field source has a given value at a given distance and the distance is doubled, the detectable strength of the source at the increased distance will then be one-eighth of its former value.

Two things should be clear. First, MAD equipment must be operated at a very low altitude to gain the greatest proximity possible to enemy submarines. Second, the searching aircraft should fly at a predetermined speed and strictly follow a planned search pattern to thoroughly search the prescribed area so that no existing anomalies are missed.
Anomaly Strength

Up to this point, the inferred strength of a submarine’s anomaly has been exaggerated for purposes of explanation. Its actual value is usually so small that MAD equipment must be capable of detecting a distortion of approximately one part in 60,000. This fact is made apparent by pointing out that the direction of alignment of the Earth’s magnetic lines of force is rarely changed more than one-half of 1 degree in a submarine anomaly.

A contour map showing the degree of anomaly caused by a submarine is shown in *Figure 5-30, view A*. The straight line is approximately 800 feet in length and represents the flight path of a searching aircraft through the area of the submarine anomaly. If the submarine were not present, the undisturbed magnetic intensity in the area due to its assumed natural characteristics would be 60,000 gammas. (The gamma, symbolized by the Greek letter, \( \gamma \), is a measure of magnetic intensity.) All variations in the field, when the submarine is present, would then be above or below this natural intensity. The 60,000 gamma zero reference drawn (*Figure 5-30, view B*) on the moving paper tape is shown in *Figure 5-30, view C*.

![Contour map and anomaly indications.](image)

With the aircraft starting at point A, where the anomaly is undetectable, the Earth’s field concentration decreases to an intensity of –2 (59,998) at point B. Its intensity then increases until a peak value of +45 is reached at point C. From that point it decreases to zero at point D. Beyond point D, another zone of what amounts to magnetic rarefaction is encountered. The Earth’s field is less intense than its normal value. Consequently, anomalous values in this zone are considered as minus quantities. A peak minus intensity is reached at point E, and thereafter, the signal rises back to its normal, or undetectable, intensity at point F.

In the illustration just given, the search aircraft’s altitude was 200 feet. At a lower altitude, the anomaly would have been stronger, and at a higher altitude, it would have been weaker.
Magnetic Noise

Any noise or disturbance in the aircraft or its equipment that could produce a signal on the recorder is classified as magnetic noise.

Noise Sources

In an aircraft there are many sources of magnetic fields, such as engines, struts, control cables, equipment, and ordnance. Many of these fields are of sufficient strength to seriously impair the operation of MAD equipment. Consequently, some means must be employed to compensate for “magnetic noise” fields. Noise sources fall into two major categories: maneuver noises and dc circuit noises.

Maneuver Noises

When the aircraft maneuvers, the magnetic field of the aircraft is changed, causing a change in the total magnetic field at the detecting element. The aircraft maneuver rates are such that the signals generated have their major frequency components within the bandpass of the MAD equipment.

Maneuver noises may be caused by induced magnetic fields, eddy current fields, or the permanent field.

The variations in the induced magnetic field detected by the magnetometer are caused by changes in the aircraft’s heading. This causes the aircraft to present a varying size to the Earth’s magnetic field, and only the portion of the aircraft parallel to the field is available for magnetic induction.

Eddy current fields produce maneuver noise because of currents that flow in the aircraft’s skin and structural members. When an aircraft’s maneuver causes an eddy current flow, a magnetic field is generated. The eddy current field is a function of the rate of the maneuver. If the maneuver is executed slowly, the effect of the eddy current field is negligible.

The structural parts of the aircraft exhibit permanent magnetic fields, and, as the aircraft maneuvers, its composite permanent field remains aligned with it. The angular displacement between the permanent field and the detector magnetometer during a maneuver produces a changing magnetic field, which the detector magnetometer is designed to detect.

Direct Current Circuit Noises

The dc circuit noise in an aircraft comes from the standard practice in aircraft design of using a single-wire dc system with the aircraft skin and structure as the ground return. The resulting current loop from the generator to load to generator serves as a large electromagnet that generates a magnetic field similar to a permanent magnetic field. Whenever the dc electrical load of the aircraft is abruptly changed, there is an abrupt change in the magnetic field at the detector.

Compensation

Regardless of its source, strength, or direction, any magnetic field may be defined in terms of three axial coordinates. It must act through any or all of three possible directions—longitudinal, lateral, or vertical—in relation to the magnetometer detector.

Compensation for magnetic noises is necessary to provide a magnetically clean environment so that the detecting system will not be limited to the magnetic signal associated with the aircraft itself.

Experience has shown that the induced fields and eddy current fields for a given type of aircraft are constant, meaning that from one MH-60R to another, the difference in fields is negligible. These fields may be expected to remain constant throughout the life of the aircraft, provided significant structural
changes are not made. In view of these factors, the aircraft manufacturer compensates for induced fields and eddy current fields.

Eddy current field compensation is usually achieved by placing the detector magnetometer in a relatively quiet magnetic area. Helicopters tow the detector head on a cable. The detector head Figure 5-31 is shown in the stowed position.

Induced magnetic field compensation is accomplished by using Permalloy strips. The aircraft is rotated to different compass headings, and the magnetic moment is measured. The polarity and the variation of the magnetic moment are noted for each heading, and Permalloy strips are oriented near the detector magnetometer to compensate for field changes due to aircraft rotation. Additional compensation is needed for the longitudinal axis, and is provided for by the development of outrigger compensators of Permalloy near the detecting element.

Permanent field compensation must be done in three dimensions rather than in two, and it is accomplished by three compensating coils mounted mutually perpendicular to each other (Figure 5-32). The aircraft is rotated in 5- and 10-degree steps around its three axes. Adjustment of the field strength is accomplished by controlling the amount of direct current that flows through a particular coil.

Compensation for the dc magnetic field is accomplished by using electromagnetic compensating loops. The loops are arranged to provide horizontal, vertical, and longitudinal fields, and are adjusted to be equal and opposite to the dc magnetic field caused by the load current. The compensating loops are connected across a variable resistor for a particular distribution center, and are adjusted to allow current flow proportional to the load current for correct compensation.

The procedure for adjustment of the dc compensation system makes use of straight and level flight on the four cardinal headings (north, south, east, and west). For example, actuation of a cowl flap motor will cause dc field changes representative of those caused by any nacelle load. The load is energized, the size and polarity of the signal are noted, and the compensation control is adjusted. The process is repeated until the resulting signals from dc fields are minimized.
Under ideal conditions, all magnetic fields tending to act on the magnetometer head would be completely counterbalanced. In this state, the effect on the magnetometer is the same as if there were no magnetic fields at all. This state exists only when the following ideal conditions exist:

- The aircraft is flying a steady course (no maneuvers) through a magnetically quiet geographic area.
- Electric or electronic circuits are not turned on or off during compensation.
- Direct current of the proper intensity and direction has been set to flow through the compensation coils, so that all stray fields are balanced.

Compensation of MAD equipment is usually performed in flight, well at sea, under operating conditions that closely resemble those of actual ASW search flights.

The objective of compensation is to gain a state of total magnetic force balance around the magnetometer. Any sudden shift in one of the balanced forces (such as an anomaly in the Earth's field force) upsets the total balance. Any shift is indicated on the recorder and, if not a shift in the Earth's natural magnetic field, is considered noise.

**Magnetic Nuclear Resonance**

Magnetic nuclear resonance is based on the theory of atomic structure, which states that “the atom is considered to be a nucleus around which one or more electrons are orbiting.” The nucleus has a positive charge because protons are part of it. The electrons have a negative charge that causes the atom to be neutral. The electrons and the nucleus have a spin and, because of the spin and the charge, a magnetic moment results.

The electron also is spinning about its own axis (much like the Earth orbits around the sun once a year and spins about its axis once a day). This spin causes the electron to have a magnetic moment, much like a small magnet, and to exhibit the characteristics of a tiny gyro. As is the case with a mechanical gyro, a force applied to the electron causes it to precess, resulting in the wobble motion of the electron’s spin axis, as shown in Figure 5-33, view A. The magnetic characteristics of an electron make it possible to substitute a magnetic field force (Earth’s magnetic field) for the mechanical force normally used to precess a conventional gyro. Additionally, if a rotating magnetic field at a radiofrequency is applied perpendicularly to the main magnetic field, the electron precesses further. This condition is depicted by the dash lines in Figure 5-33, view B, as an increased wobble motion of the electron’s spin axis.

When the frequency of rotation of the magnetic field is adjusted until it is the same as the natural frequency of the particular material in use (helium in this case), the deviation of the spin axis of the electrons tends to increase and paramagnetic resonance is achieved. Electron paramagnetic resonance is resonance in which the electron is the only particle shifting energy states. Resonance occurs when the angular velocity of the rotating magnetic field is approximately the natural spin axis wobble rate, or precession rate, of helium electrons. This wobble rate is also called the Larmor frequency. As the electrons are caused to precess more by the external RF magnetic field, the amplitude of the precession becomes so great that the electrons jump to a higher energy level, at which time light energy is absorbed by the helium. Light is used initially to increase the energy level of the electrons to a metastable energy state, which is a higher energy level with a much longer lasting duration than any other excited level. Helium gas is one of the elements or materials that can assume a metastable energy level.

Some MAD systems use a beam of low-frequency light to periodically increase the energy level of the electrons and orient the magnetic moments of the atoms and their electrons on a plane in the direction of the light beam. This procedure is known as “optical pumping.” The pumping action of the
light energy causes the electrons to jump two energy levels; that is, from ground energy level (E₀) to excited energy level (E₂). Excited energy state 2 (E₂) has a very short lifetime without external excitation. Since the light is pumping, the electrons tend to fall back toward the stationary state (E₀), but must pass through the metastable excited state—energy state 1 (E₁).

If the pumping action is made continuous, the majority of electrons at any one time will congregate at the E₁ or metastable excited state. This is necessary because if resonance of unaligned ground state helium were attempted with an external rotating magnetic field, only a small percent of the gas would change state and absorb light energy. This would make detection of resonance difficult. However, with the helium’s atomic system aligned and excited when resonance occurs, a great majority of the atoms change state and an easily monitored amount of light is absorbed. The metastable state in the gas is necessary to have a relatively stable higher energy level in a much larger number of atoms. This produces a much greater change when resonance occurs.

During optical pumping, energy is absorbed and released by the electron during these energy level transitions. It should be noted here that resonance can apparently be achieved only in certain solids and liquids with loosely knit atomic structures and in gases such as helium.

This discussion so far has concerned the energy level change of the helium atom electrons by the use of an external magnetic field (supplied through coils) oriented 90 degrees to the Earth’s field. The external field rotates at the Larmor frequency of the electron, which was determined by the Earth’s magnetic field strength. Since the precession or Larmor frequency of electrons varies with magnetic field intensity at the rate of 28 Hz per gamma, monitoring the Larmor frequency changes is a convenient method for detecting and measuring changes in the Earth’s magnetic field.

However, a small change in the Larmor frequency of electrons is difficult to measure directly. It is more convenient and accurate to make an indirect measurement by monitoring the definite increase in light energy absorption that occurs at resonance. The atoms then radiate some of this light energy as the Larmor frequency shifts away from the externally applied field’s frequency, and resonance is lost. Thus, variations in the Earth’s magnetic field strength are reflected by the changes in the quantity of light passing through the helium gas. Helium gas is contained in a transparent container called an absorption cell.

Figure 5-33 — Electron precession.
Energy is absorbed in forcing electrons to jump from one orbit to another orbit at a greater distance from the nucleus, as shown in Figure 5-34, view A. The depiction of an atom giving up energy as the electrons move back to their original orbit is shown in Figure 5-34, view B.

When the oscillator supplying the coils (resonance oscillator) reaches the Larmor frequency, light is absorbed. When the resonance oscillator comes off the Larmor frequency, light is emitted. Thus, the Larmor frequency (which represents the Earth’s magnetic field strength) can be tracked by knowing the resonant oscillator frequency when the absorption cell is absorbing energy.

The light energy source shown in Figure 5-35 for the magnetic resonance magnetometer is a helium lamp. The infrared (IR) detector is used to track the light energy level changes.

**Helium Magnetometer Operation**

The necessary components for a magnetic resonance magnetometer are shown in Figure 5-35. The external energy source, the helium discharge lamp, applies light energy to the transparent helium-filled absorption cell. Light energy is absorbed or given up by the helium atoms as the cell goes in and out of resonance, caused by slight changes in the Earth’s field. The IR detector, mounted on the other side of the absorption cell from the light source, picks up these energy level changes and produces an electrical output. The energy level is low when the cell is resonant and high when it is not resonant. The IR detector output signal can then be used to keep the resonance oscillator on or about the Larmor frequency of the helium in the cell, regardless of changes in the Earth’s magnetic field. A magnetic anomaly can then be detected when the resonance oscillator center frequency makes atypical swing within the bandpass relative to the flight envelope of the MAD-equipped type of aircraft.

If the resonance oscillator frequency were always maintained precisely at resonance, the IR output would simply be a very low dc level. This low dc level would be difficult to monitor and would not provide a phase change above and below resonance. For this reason the RF energy applied to the resonance coils is frequency modulated by 430 Hz. The resultant variation in the magnetic field forces the helium atoms in and out of resonance around the null and provides a phase reference signal to a phase detection circuit. The phase reversal above and below resonance is shown in Figure 5-36. It is important to note that at resonance, which is the normal operating point, the IR detector acts much like a full wave rectifier. As a result of rectifying action, the IR output at resonance is a pulsating 860-Hz signal. The detector also acts like a discriminator, in that the FM swing of the resonance oscillator is converted to an amplitude modulated (AM) output when near the resonant frequency of the helium.
atoms in the absorption cell. This is true because its output goes positive with each increase in light energy given off by the absorption cell.

**MAGNETIC ANOMALY DETECTION SYSTEM CHARACTERISTICS**

The representative MAD system includes a SAD system, selector control group, magnetic compensator, and associated system components involved in the localization and detection of submarines. SAD and the selector control group recognize submarine signals and mark them automatically in the presence of geologic, maneuver, geomagnetic, and equipment noise as detected by the MAD system. The magnetic compensator group compensates for magnetic fields generated by the aircraft in flight. It should be noted that United States Navy P-8A Poseidon aircraft do not have MAD systems. References to the MAD boom are for theoretical training purposes only.

The typical MAD system includes a magnetic detector, amplifier-power supply, and detecting set control. The magnetic detecting set is a sensitive metastable helium magnetometer used to locate and classify submarines by detecting a disturbance or change in the normal Earth’s magnetic field.

**Submarine Anomaly Detector**

SAD works in conjunction with MAD and increases the capability to detect submarines through evaluating MAD signals and separating submarine anomaly from magnetic noise. SAD also provides audio and visual indications that a submarine type of contact has been made. The system separates the submarine anomaly by selective filtering, full-wave rectification, short-term integration, and correlation of aircraft maneuvers through recognition and maneuver circuits.

The MAD/SAD system interface is accomplished by the selector control group. The group includes a selector control panel and the selector control subassembly. The selector control panel provides controls for operating the selector control subassembly, which receives, processes, and distributes signals between the MAD/SAD system and the central repeater system, ICS, and ADP system. The selector control panel selects the signal to be routed through the subassembly, which is either the auxiliary (AUX), SAD, or MAD signal.
Magnetic Detector

The description of a helium magnetometer given in preceding paragraphs is for the basic sensing element. The actual arrangement of the magnetometer is shown in Figure 5-37.

The detection element includes six separate helium absorption cells and six IR detectors, arranged in pairs, with the pairs oriented at 90 degrees to each other. This configuration ensures that one or more of the pairs is at least partially in line with the Earth’s field regardless of aircraft attitude or direction of flight. The signals from all three detector pairs are combined in a summing amplifier; thus, the final output to the amplifier power supply is not affected by aircraft maneuvers.

Two helium discharge lamps provide light energy to the three absorption cell pairs in the magnetic detector. The lamps are ignited by a 52 kHz, 1,500-volt supply (Figure 5-38). After ignition the lamps are maintained in an ionized state by the 49.6 MHz output of the exciter regulator.

In addition, the magnetic detector unit includes a pressure transducer and an altitude compensator circuit. The output of the pressure transducer varies the frequency of a 5.4 kHz oscillator in the altitude compensator at the rate of 1 Hz/ft of altitude change. The total swing of the oscillator is 5.0 to 5.8 kHz, which can compensate for a maximum of 400-foot rapid altitude variations. Additional circuitry in the amplifier power supply converts the altitude-induced frequency change to a varying dc level. This dc level may, at the operator’s discretion, be used to correct the final signal output.

**CAUTION**

When maintenance is performed on or near the magnetometer head, special nonferrous tools MUST be used. Additionally, any parts (nuts, bolts, or screws) that are replaced MUST be made of a special non-ferrous metal. Always consult the MIM for the system being worked on before attempting repairs.

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Figure 5-37 — Magnetometer axis orientation.
Amplifier Power Supply

A single coaxial cable carries all signals between the magnetic detector and the amplifier power supply. The signals on the coaxial cable include the 5.4-kHz altitude signal, the 430/860-Hz IR signal, the 0.6- to 2.2-MHz resonance coil excitation, and the 52-kHz ignition signal. The 52-kHz ignition signal is monitored first by system BITE for its presence and, with the latest configuration, is checked approximately 5 minutes later (maximum warmup time) for its absence. If the signal is not initially present, the system timer stops and shows a detector head failure. Approximately 5 minutes later, the absence of the signal is checked. The absence of the signal indicates that the intensity of both helium lamps was sufficient to cause the system to switch from ignition to the normal 49.6-MHz exciter signal. If this switchover did not occur, the system removes power to the detector head and illuminates the detector failure indicator. Bandpass filters at both ends of the coaxial cable route the frequencies to their respective circuits. The IR detector error signal is phase-detected in the phase demodulator to produce a variable positive or negative dc voltage. (Any time 430 Hz is present, the IR detector error signal represents an error between the Larmor frequency and the resonance oscillator center frequency; 860 Hz indicates matched frequencies.) The variable dc is, in turn, used to change the resonance oscillator frequency. This closed loop action keeps the oscillator always at resonance as the Earth’s field strength changes or as an anomaly is detected. When neither 430 Hz nor 860 Hz is coming back from the magnetic detector, the system senses this and causes the resonance oscillator to sweep its entire range (0.6 to 2.2 MHz). During the down sweep of the resonance oscillator, when 430/860 Hz is detected, the sweep is stopped and the loop is closed. The resonance oscillator output is routed to the resonance coils via the line driver and the preamplifier/summing amplifier. It is also applied to the phase lock oscillator assembly.

The purpose of the phase lock oscillator is to reproduce the resonance oscillator frequency, retain the magnetic anomaly, and eliminate the 430-Hz modulation signal. The oscillator is voltage-controlled by a dc signal from the acquisition circuit until it locks on to the resonant frequency. After lock-on, the phase detector provides the control necessary for tracking the resonant frequency. This tracking is similar to the way the resonant oscillator tracks the Larmor frequency.

Figure 5-38 — Simplified block diagram of a MAD system.
The frequency converter develops a variable dc signal proportional to the frequency shift of the phase
lock oscillator. The frequency converter also generates a variable dc voltage proportional to the
frequency shift of the 5.4-kHz altitude compensation signal input supplied by the magnetic detector
unit. If the operator selects ALT COMP on the control unit, the two dc signals are combined by a
summing network to compensate for magnetometer altitude change effects. Two driver-amplifiers
provide a primary output to the detecting set control unit and an auxiliary output for test purposes.
The primary output is passed through a series of high- and low-pass filters in the control unit. The
filters remove all extraneous frequencies and noise from the variable dc except the anomaly signal.
The filtered dc output drives the pen of a recorder to produce a permanent record of the submarine
anomaly.

**Magnetic Compensator Group**

A magnetic compensator group is used in conjunction with a MAD system to reduce the effects of
unwanted magnetic disturbances (anomalies) during MAD subsystem operation. As previously
discussed, the MAD compensator generates magnetic fields to nullify noise interference from
unrelated sources.

**Magnetic Field Terms**

Relative to MAD compensation theory, the word “term” refers to a magnetic field component.
Permanent field terms are designated by a single capital letter such as \( T \), \( L \), or \( V \), which stand for
transverse, longitudinal, and vertical, respectively. These three axes are references to the three
aircraft axes and remain fixed regardless of aircraft orientation with respect to the Earth. Induced
terms are designated by two capital letters, which may be any combination of \( L \), \( T \), or \( V \), such as \( LL \),
\( VL \), or \( TT \). The first capital letter designates the inducing aircraft structure axis, and the second capital
letter designates the resulting field axis as seen at the detector head. The inducing axis may be
different from the resulting field axis at the detector head. Eddy current terms are designated by two
lowercase letters, which may be any combination of the three basic components in the same manner
as induced terms, such as \( lt \), \( vl \), or \( tt \).

The total interfering field at the sensor can be resolved theoretically into 16 terms comprising three
permanent, five induced, and eight eddy current terms. The interference could be eliminated by
generating an opposing field at the detector containing 16 terms, which cancel their interfering
counterparts. In practice, not more than nine are required to compensate any aircraft satisfactorily
because not all the induced and eddy current terms are significant.

**Magnetic Compensator Components**

The basic magnetic compensator system contains a control-indicator unit, an electronic control
amplifier (ECA), a magnetometer assembly, and compensation coils. Refer to Figure 5-39 and
observe the relationship between the various signals and components involved.

**Control-Indicator Unit**

The control-indicator unit contains all the controls and indicators required for system operation and all
the elements necessary for term adjustment. The control unit provides the operator with a numeric
indication of compensation potentiometer position.

**Electronic Control Amplifier**

The ECA processes standard MAD signals from the MAD subsystem, operator compensation
adjustments, and maneuver signals from the magnetometer. The ECA provides compensation
currents, which are sent to the MAD boom compensation coils. The ECA provides all necessary

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interconnections and receives all inputs to the system. It converts nine separate term adjustment outputs from the control-indicator to three current outputs, which energize coils of the output coil assembly.

**Magnetometer Assembly**

The magnetometer contains three coils oriented to sense magnetic strength in each of the basic longitudinal, transverse, and vertical aircraft axes. This arrangement results in three output signals, which are sent to the ECA as operating voltages for induced and eddy current compensation.

- **Transverse Magnetic Compensation Coil.** The transverse coil generates a transverse magnetic field that opposes the aircraft-generated noise field for compensation. This field cancels or minimizes magnetic fields interfering with MAD operation. The transverse coil is located in the MAD boom.

- **Vertical Magnetic Compensation Coil.** The vertical coil generates a vertical magnetic field that opposes the aircraft-generated noise field for compensation. This field cancels or minimizes magnetic fields interfering with MAD operation. The vertical coil is located in the MAD boom.

- **Longitudinal Magnetic Compensation Coil.** The longitudinal coil generates a longitudinal magnetic field that opposes the aircraft-generated noise field for compensation. This field cancels or minimizes magnetic fields interfering with MAD operation. The longitudinal coil is located in the MAD boom.

**Magnetic Field Computer**

The addition of the compensator group adapter (CGA) completely computerizes the compensation calculation. Compensation is performed simultaneously on all nine terms by performing a maneuver pattern requiring only a few minutes. The computer provides the necessary interconnection between primary components of the CGA and receives 28 analog maneuver signals. These maneuver signals are digitized for data processing to provide light emitting diode (LED) drive voltages to the magnetic field indicator.

Figure 5-39 — Magnetic compensator group interface diagram.
Magnetic Field Indicator

The indicator contains the controls and indicators necessary to operate the CGA to perform semiautomatic compensation. The unit also displays term difference figures, calibration voltages, and BITE codes. The MODE control selects the various operating conditions of the computer.

GENERAL MAINTENANCE CONCEPTS

The maintenance concept for ASW acoustic and nonacoustic systems is the same as other avionics systems and is divided into organizational-, intermediate-, and depot-maintenance support. Intermediate maintenance includes ATE and actual specialized bench testing and repair. Many WRAs undergo troubleshooting at an organizational or intermediate activity, down to a shop replaceable assembly (SRA) or subshop replaceable assembly (SSRA). An FRC usually receives the SRA and either runs ATE or bench checks the components, or, in many cases, performs both.

The majority of testing and troubleshooting at the intermediate and depot levels is done on the Consolidated Automated Support System (CASS) family of test equipment. Advanced technology is increasing the speed and accuracy of repairs, and is responsible for providing highly reliable and sophisticated equipment. The increasingly sophisticated equipment and test equipment requires even more experienced technicians.

All ASW acoustic system equipment repairables are routed through the local supply department and FRC. The activity individual component repair list (ICRL) will indicate the repair capability and specific work center responsible for repair. All repairables will be sent to the applicable work centers for diagnostic testing, adjustment, or repair as needed.

After diagnostic testing, specifically identified work centers will troubleshoot the repairable down to another repairable SRA or SSRA, depending on the work center’s capability and the source, maintenance, and recoverability (SM&R) codes. If the capability exists, including maintenance instructions, test equipment, and technical skills, the units will be troubleshooted to the next lower repairable, then the faulty repairable will be removed, ordered, and routed through supply. The repairable may come back to the original work center for discrete component-level troubleshooting or be sent to another specialized work center for repair. In-depth FRC procedures can be found in COMNAVAIRFORINST 4790.2(series).
End of Chapter 5

Antisubmarine Warfare

Review Questions

5-1. What aircraft conducts high altitude antisubmarine warfare?

A. E-2 Hawkeye  
B. P-8A Poseidon  
C. MH-60R Seahawk  
D. F/A-18 Hornet

5-2. What antisubmarine platform uses magnetic anomaly detection?

A. P-8A Poseidon  
B. C-130 Hercules  
C. MH-60R Seahawk  
D. F/A-18 Hornet

5-3. What antisubmarine platform possesses both an acoustic and non-acoustic system?

A. F-15 Strike Eagle  
B. E-2 Hawkeye  
C. CH-53 Sea King  
D. MH-60R Seahawk

5-4. What antisubmarine platform is designed to operate with large area sonobuoy fields?

A. P-8A Poseidon  
B. MH-60R Seahawk  
C. E-2 Hawkeye  
D. F/A-18 Hornet

5-5. What is the name of the warfare system that relies on the properties of sound under water?

A. Radar  
B. Forward looking infrared  
C. Sonar  
D. Identification friend or foe

5-6. What mode of sonar sends out a ping and listens for a return echo?

A. Passive  
B. Active  
C. Temperature  
D. Refractive
5-7. Which of the following characteristics of sound best describes an echo?

A. Divergence  
B. Refraction  
C. Reflection  
D. Reverberation

5-8. Which of the following characteristics of sound best describes why a weak signal is found the further one gets from a point source of sound?

A. Divergence  
B. Refraction  
C. Reflection  
D. Reverberation

5-9. What is the name of the apparent decrease in wavelength when a sound’s source is moving toward the receiver?

A. Parabolic shift  
B. Doppler effect  
C. Radar shift  
D. Larmor effect

5-10. In a typical acoustic antisubmarine warfare system, the ultra-high frequency transmitter transmits signals to which of the following types of sonobuoys?

A. Active  
B. Overt  
C. Inactive  
D. Passive

5-11. What acoustic data processor component is used to provide the active sonobuoy commands that are transmitted by the ultra-high frequency transmitter to displayed sonobuoys?

A. Signal data converter  
B. Data storage magnetic drum  
C. Spectrum analyzer converter  
D. Spectrum analyzer-signal generator

5-12. What acoustic antisubmarine warfare system component contains the power switch that activates the acoustic group system?

A. General-purpose digital computer  
B. Tactical coordinator power control panel  
C. Sonobuoy monitor panel  
D. Power supply
5-13. What acoustic antisubmarine warfare system component provides a master display of sonobuoy signal characteristics?

A. Tactical coordinator control panel  
B. General-purpose digital computer  
C. Sonobuoy monitor panel  
D. Tactical indicator display group auxiliary readout unit

5-14. What is the primary function of a transducer?

A. Receive underwater sound only  
B. Transmit underwater sound only  
C. Receive and transmit underwater sound  
D. Store underwater sound only

5-15. Which of the following types of information is sent via very-high frequency radio signals from the sonobuoy to the deploying aircraft?

A. Visual  
B. Tactile  
C. Acoustic  
D. Sonic

5-16. Which of the following sonobuoys is considered a listen-only antisubmarine warfare sonobuoy?

A. Range-only  
B. Directional frequency analysis and recording  
C. Search and rescue  
D. Command active sonobuoy system

5-17. Both range and bearing to a target with a single sonobuoy is provided by which of the following types of sonobuoys?

A. Directional command active sonobuoy system  
B. Search and rescue  
C. Directional frequency analysis and recording  
D. Bathythermograph

5-18. Which of the following sonobuoys provides distance to the target only?

A. Low frequency analysis  
B. Search and rescue  
C. Active distance  
D. Range-only
5-19. What is the basic function of the sonobuoy receiver?

A. To provide a means of voice communication between aircraft and submarines.
B. To determine the positions of deployed sonobuoys relative to aircraft position.
C. To receive the radiofrequency signals from deployed sonobuoys and detect the intelligence on the signals.
D. To provide a permanent record of audio data for analysis of contacts.

5-20. What component of a typical sonobuoy receiver group simulates sonobuoy signals for onboard troubleshooting purposes?

A. The dual radiofrequency preamplifier
B. The channel audio switching assembly
C. The dual channel control indicator
D. The acoustical sensor signal generator

5-21. What is the maximum operating range of the typical dipping-sonar detection system?

A. 10,000 yards
B. 15,000 yards
C. 20,000 yards
D. 30,000 yards

5-22. How does a sonar operator determine target range and bearing when operating in passive mode?

A. Command that a ping be sent to gather precise bearing information.
B. Place cursor over target for precise range and bearing display.
C. Check radar multipurpose display panel.
D. Contact pilot or copilot for visual range and bearing confirmation.

5-23. What mode of operation is used to determine ocean water temperatures at specific depths?

A. Active
B. Passive
C. Communication
D. Bathythermograph

5-24. How many feet per second is the dipping-sonar’s dome lowered in the air?

A. 5
B. 8
C. 11
D. 20
5-25. What component of an acoustic sonar set displays target echoes on a planned position indicator for the operator?

A. Multipurpose display panel  
B. Azimuth and range indicator  
C. Bearing and range indicator  
D. Recorder scope panel  

5-26. How does an operator know how much cable is paid out when observing the cable and reel assembly?

A. Record lowering time and multiply by descent rate.  
B. Observe color bands marked on the cable.  
C. Use the intercom to ask the pilot.  
D. Observe the radar altimeter to determine aircraft altitude.  

5-27. What is the purpose of a dipping-sonar’s stave?

A. Convert received acoustic pulses to low-level alternating current signals.  
B. Pry the cable loose when it gets jammed.  
C. Convert electrical pulses into high power acoustic energy for transmission.  
D. Provide strength to delicate hydrophone components when out of water.  

5-28. What is the maximum depth ocean temperatures will be recorded in bathythermograph mode?

A. 25 feet  
B. 75 feet  
C. 200 feet  
D. 450 feet  

5-29. Which of the following is a non-acoustic antisubmarine warfare system?

A. Dipping-sonar set  
B. Sonobuoy receiver set  
C. Magnetic anomaly detection  
D. Airborne low frequency sonar  

5-30. Which of the following types of energy is least disturbed when passing from air into water and returning?

A. Sound  
B. Magnetic  
C. Light  
D. Electromagnetic
5-31. Which of the following terms best describes angles between the magnetic lines of force and the horizontal?
A. Angles of force  
B. Angles of variation  
C. Angles of deviation  
D. Angles of dip

5-32. Which of the following terms best describes how a state of total balance of magnetic forces around a magnetometer is achieved?
A. Deviation  
B. Variation  
C. Isolation  
D. Compensation

5-33. The Larmor frequency is the measurement of the precession or “wobble rate” of what element?
A. Carbon  
B. Oxygen  
C. Helium  
D. Nitrogen

5-34. What piece of antisubmarine warfare equipment operates on the principle of variations in magnetic field strength caused by changes in the quantity of light passing through helium gas?
A. Magnetometer  
B. Sonar dome  
C. Magnetostriction transducer  
D. Bathythermograph sonobuoy

5-35. Which of the following antisubmarine warfare systems is used to increase the capability to detect submarines by evaluating magnetic anomaly detection signals and separating them from magnetic noise?
A. Radar  
B. Sonar  
C. Submarine anomaly detection  
D. Magnetic anomaly detection compensator

5-36. Which of the following antisubmarine warfare system equipment is used to reduce the effects of unwanted magnetic disturbances?
A. Radar compensator  
B. Sonar detector  
C. Submarine anomaly detector  
D. Magnetic anomaly detector compensator
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CHAPTER 6
RADAR CIRCUITS

Radar is an essential weapons platform in today's military. It is a primary active sensor used in operational warfighting units, and is incorporated in most tactical aircraft. Proper understanding and interpretation of radar is a vital component in successfully prosecuting and engaging hostile/enemy contacts. Radars vary considerably in size, composition, and performance depending upon their intended function and location. This chapter is designed to discuss basic circuits and their functions and is not considered all-encompassing. Detailed information on particular systems and their capabilities is not provided.

LEARNING OBJECTIVES

When you have completed this chapter, you will be able to do the following:

1. Identify the operating requirements for radar synchronizers, to include timers and markers.
2. Recall the purpose of radar transmitters, to include modulators and switching devices.
3. Recall the purpose of radar receivers, to include mixers, oscillators, preamplifiers, amplifiers, and automatic frequency control.
4. Recognize types of radar indicators to include A-scope, B-scope, and C-scope, E-scan/range height indicator, detections and sweeps, and miscellaneous presentations.
5. Identify the operating principles and characteristics of an identification friend or foe system, to include interrogation modes.

Radar systems consist of a transmitter that sends out radiofrequency (RF) signals, a receiver that is located at the same site, and an indicator that gives a visual indication of echoes returned by the target. To accomplish this, many circuits are required. The circuits described in this chapter are those of typical pulsed-type radar. The major functional components are synchronizers, transmitters, receivers, and indicators. Technology has made great advances in weapons systems radar capabilities, much of which cannot be discussed in this presentation. Although modern weapons systems may not incorporate every circuit discussed or identify components in the same manner, they are presented to establish a basic understanding of principles before receiving training on more advanced versions.

SYNCHRONIZERS

The purpose of a radar timer is to synchronize the sweep voltage or current for the indicator with the transmitter pulse. In modern radar systems, synchronizers are normally an integrated component of the radars' data processor. The specific function of the synchronizer is to produce the trigger pulse that starts the transmitter, the sweep circuits, range mark generators, blanking circuits, and gating circuits.

Either timing or control is the function of the majority of the circuits in radar. Circuits in a radar set accomplish one of these functions by producing a variety of voltage waveforms, such as square waves, sawtooth waves, trapezoidal waves, rectangular waves, brief rectangular pulses, and sharp peaks.

In sound systems and in radio, electronic circuits operate within the limits for which they are designed. In radar timing circuits, electronic circuits are often severely overdriven, frequently operating at points that range from well into the base current region to far beyond cutoff. Although all
of these circuits are broadly classified as timing circuits, the specific function of any individual circuit might be timing, wave shaping, or wave generating.

Radar systems may be classified as either self-synchronized systems or externally synchronized systems. Today’s radar systems are self-synchronized. In a self-synchronized system, the timing trigger pulses are obtained from the transmitter. In an externally synchronized system, the timing trigger pulses are obtained from a master oscillator, which is usually external to the transmitter. The master oscillator may be a stable (free-running) multivibrator or a blocking oscillator.

When a blocking oscillator is used as a master oscillator, the timing trigger pulses are usually obtained directly from the oscillator. When an astable multivibrator is used as a master oscillator, pulse-shaping circuits are required to form the necessary timing trigger pulses.

In a self-synchronized radar system, the repetition rate of the timing trigger pulses is determined by the repetition rate of the modulator (or transmitter) pulses. In
an externally synchronized radar system, the repetition rate of the timing trigger pulses from the master oscillator determines the pulse repetition rate of the transmitter.

An indicator, such as a cathode-ray tube (CRT) or digital display indicator (DDI) (*Figure 6-3*), is associated with every radar system. CRTs have largely been replaced by high resolution liquid crystal displays (LCD) with legacy capabilities. The functions of CRTs or DDIs are unique to their design and the input they receive. However, the information they display is similar based on capabilities of the radar system. They present target data (range, bearing, and elevation) in visual form so that the target may be located. For simplicity reasons, CRT operation will be discussed in this chapter. Trigger pulses from the timer (synchronizer) are frequently used to produce gate pulses. When applied to the indicator, these gate pulses perform the following functions:

- Initiate and time the duration of the indicator sweep voltage
- Intensify the CRT electron beam during the sweep period so that the echo pulses may be displayed
- Gate a range mark or range marker generator so that range marker signals may be superimposed on the indicator presentation. (The terms marks and markers are normally interchangeable)

The time relationship of waveforms in a typical radar set is shown in *Figure 6-4*. The timing trigger pulses are applied to both the transmitter and the indicator. When a trigger pulse is applied to the transmitter, a short burst, or pulse, of RF energy is generated. This energy is conducted along a transmission line to the radar antenna, from which it is radiated into space. If the transmitter energy strikes one or more reflecting targets in its path, some of the transmitted energy is reflected back to the antenna. Echo pulses from three reflecting targets at different ranges are illustrated in the part of *Figure 6-4* labeled “echo pulses.” The corresponding receiver output signal is also shown.

The initial and final pulses in the receiver output signal are caused by the energy that leaks through the transmit-receive (TR) device when a pulse is being transmitted.

The indicator sweep voltage (*Figure 6-4*) is initiated at the same time that the transmitter is triggered. By delaying the timing trigger pulse fed to the indicator sweep circuit, it is possible to initiate the indicator sweep after a pulse is transmitted while it is also possible to initiate the indicator sweep before a pulse is transmitted.

Note that the positive indicator intensity gate pulse (applied to the CRT control grid) occurs during the indicator sweep time (*Figure 6-4*). As a result, the CRT trace occurs only during the sweep time and is eliminated during the flyback (retrace) time. The negative range marker gate pulse also occurs
during the indicator sweep time. This negative gate pulse is applied to a range marker generator, which produces a series of range marks.

The range marks are equally spaced and last only for the duration of the range marker gate pulse. When the range marks are combined (mixed) with the receiver output signal, the resulting video signal applied to the indicator may appear as shown in Figure 6-4.

**Basic Requirements**

The basic timing circuit should meet three requirements:

- Must be free running (astable); since the timer is the heart of the radar, it must establish the zero time reference and the pulse-repetition frequency (PRF).
- Must be stable in frequency; the PRF, or its reciprocal, the pulse-repetition time (PRT), must not change between pulses for accurate ranging.
- The frequency must be variable in steps for the radar to operate on different ranges.

There are two basic circuits that can meet the above three requirements; the master-trigger multivibrator and the single-swing blocking oscillator.

Block diagrams and waveforms of these two timers used in externally synchronized radar systems are shown in Figure 6-5. Note that in each case equally spaced timing trigger pulses are produced. The repetition rate of each series of timing trigger pulses is determined by the operating frequency of the associated master oscillator.

**Multivibrator Timer**

In a multivibrator timer, the master oscillator generally consists of an astable multivibrator. If the multivibrator is asymmetrical, as in Figure 6-5, view A, it generates rectangular waves. If the multivibrator is symmetrical, it generates square waves. In either case, the timing trigger pulses are equally spaced after the limiter removes undesired positive or negative lobes.

The output of the astable multivibrator consists of two rectangular waves. There are two transistors in an astable multivibrator. The two collector output voltages are equal in amplitude, but 180 degrees out of phase. One set of rectangular pulses is applied to the resistive-capacitive (RC) differentiator and converted into positive and negative trigger pulses.
The negative trigger pulses can be removed by means of a negative lobe limiter. Both sets of rectangular pulses from the astable multivibrator are applied to the indicator for the following purposes:

- One set of pulses is used to intensify the CRT electron beam for the duration of the sweep.
- The other set of pulses is used to gate the range marker generator. As will be shown later, rectangular pulses can also be used to produce range steps.

**Blocking-Oscillator Timer**

In the blocking-oscillator timer (*Figure 6-5, view B*), a free-running, single-swing blocking oscillator is generally used as the master oscillator. The advantage of the single-swing, blocking oscillator is that it generates sharp trigger pulses directly. Timing trigger pulses of only one polarity are obtained by use of a limiter.

Gate pulses for the indicator circuits are produced by applying the output of the blocking oscillator to a one-shot multivibrator. Crystal-controlled oscillators may be used when very stable operation is required at a particular frequency.

**Range Markers**

The accuracy of target-range data provided by radar varies with the designated use of the radar. For example, fire control radar operating in its search mode needs to be accurate only within a few percent of its maximum range. However, a radar tracking in air-to-air velocity search mode must supply range data that is accurate within a few yards.

Range markers allow aircrew to estimate and track the range of targets under surveillance or geographic features. In air-to-surface modes and other applications, electronic range arcs (*Figure 6-3*) are supplied to the indicator. They appear as arcs on radiating azimuth grid arcs on a DDI and as concentric circles on a planned-position indicator (PPI) scope. The distance between range marks is generally determined by the type of equipment and its mode of operation.

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*Figure 6-5 — External timer block diagrams.*
In weapons systems radar that requires extremely accurate target-range data, a movable range marker may be used. The range marker is obtained from a range marker generator and may be a movable range gate or range step. When a PPI scope is used, a range circle of adjustable diameter is used to measure range accurately. In some cases, movement of the range marker is done by turning a calibrated control, light pen, or by push-button from which you can obtain range readings. In other cases, the range marker may be used as a range gate for automatic range tracking. In this case there may be no direct range readout.

This discussion describes the operation of three types of range markers (generators): the range gate generator, the range marker generator, and the range step generator. The range gate generator, used in conjunction with a blocking oscillator, generates a movable range gate. The range marker generator and the range step generator, used in conjunction with an astable multivibrator, generate fixed range marks and a movable range step, respectively.

**Range Gate Generator**

A simplified block diagram of a typical radar synchronizer that includes a range gate generator is shown in *Figure 6-6*. The indicator is a B-scope with the range deflection voltages applied to the vertical plates. Scopes are discussed later in this chapter.

![Figure 6-6 — Synchronizer with range gate generator.](image-url)
The PRF is controlled by a master oscillator, or multivibrator, whose output is coupled to a solid-state trigger. The output of the trigger is used to trigger the radar modulator and the B-scope sweep circuits, thus starting the transmitting pulse and the range sweep at the same instant.

The multivibrator in the sweep circuits is a timing circuit that supplies a sweep sawtooth to the sweep amplifier. The width of the gate and sawtooth is dependent on the range selected by the operator.

The range gate circuit receives its input pulse from the trigger and generates a delayed range gate pulse. The delay of this pulse is dependent on the position of the target in range when tracking, or on the manual positioning of the range volts potentiometer by the operator when in the search mode. The range gate triggers the range strobe multivibrator, whose output is amplified and sent to the blocking oscillator. This oscillator sharpens the pulses, as shown in Figure 6-6.

The range gate selects the target to be tracked and, when in track mode, brightens the trace or brackets the target (depending on the system) to indicate which target is being tracked.

Range Marker Generator

A block diagram of a typical range marker generator is shown in Figure 6-7. This generator consists of a ringing oscillator Q1611-Q1612, an emitter follower Q1613, a countdown multivibrator Q1616-Q1617, and a pulse-forming amplifier Q1614. Generation of the marks starts at the ringing oscillator, which is excited into operation by incoming trigger pulses. Once in operation, it produces a sinusoidal output, which is synchronized to the trigger pulses. This sinusoidal output is then applied to the emitter follower, which provides inter-stage buffering by isolating the ringing oscillator from the countdown multivibrator. The output coupling circuit of the emitter follower shifts the average output level to zero (ground) and clips the negative-going portions of the signal allowing only the positive half of each sine wave to reach the countdown multivibrator. The countdown multivibrator receives a high-frequency positive trigger corresponding to a fixed interval driving the countdown multivibrator to develop a negative pulse train. The period of the pulse train is controlled by the range marks selector switch. This negative output is applied to the pulse-forming amplifier, where it is reshaped and passed on to a marker mixer.

The output of a range marker generator can be applied directly to one of the deflection plates on an A-scope. In this case, range marker pulses appear simultaneously with the radar echo signals, and permit estimation of target range. In B-scope and PPI-scope applications, the output of the range marker generator is applied to a video mixer. In this case, radar echo signals are combined with marker signals before being applied to the grid of the CRT.

Range Step Generator

A schematic diagram and waveforms of a typical range step generator are shown in Figure 6-8. The range step generator consists of a sawtooth voltage generator Q1, a negative clipper CR1, and a limiting amplifier. Diode CR1 is frequently referred to as a pickoff diode. The position of the range step along the indicator time base is controlled by potentiometer R3. When the range step coincides
with the leading edge of a target echo pulse, the target range can be read directly from a calibrated range dial associated with R3.

Between times $t_0$ and $t_1$ (Figure 6-8 view B), the base of transistor Q1 is at ground potential (zero volts). As a result, Q1 conducts and the Q1 collection voltage ($E_1$) equals Q1 collector-supply voltage ($V_{cc}$) minus the voltage drop across the load resistor R1. The horizontal dashed line across the $E_1$ waveform indicates the $E_{R3}$ voltage (Figure 6-5, view A) at the adjustable tap of potentiometer R3. Since $E_1$ is less than $E_{R3}$ between times $t_0$ and $t_1$, the anode of the negative clipper CR1 is less positive than the CR1 cathode, and CR1 does not conduct. Hence the CR1 cathode voltage ($E_2$) equals $E_{R3}$, the voltage at the R3 tap.

Between times $t_1$ and $t_3$ the base of transistor Q1 is driven below cutoff. As a result, Q1 ceases to draw collector current. When no collector current flows in Q1, the capacitor C1 changes through the Q1 load resistor R1, and the collector voltage of Q1 rises exponentially toward the Q1 $V_{cc}$. At time $t_2$, $E_1$ exceeds $E_{R3}$, and diode CR1 conducts. If the CR1 anode resistance is small, the CR1 cathode voltage ($E_2$) practically equals $E_1$ between times $t_2$ and $t_3$.

Following time $t_3$ the base of Q1 returns to ground potential, and Q1 again conducts. As a result, capacitor C1 discharges through Q1, and the Q1 collector voltage decays exponentially toward its initial value. As soon as $E_1$ becomes less than $E_{R3}$, CR1 no longer conducts, and the CR1 cathode voltage again equals $E_{R3}$.

When the $E_2$ waveform is amplified and limited by the limiting amplifier, the amplifier output-voltage ($e_{out}$) waveform appears, as shown in Figure 6-8, view B. Note that a nearly vertical edge (step) appears in the $e_{out}$ waveform the instant CR1 begins to conduct (time $t_2$).

By varying the setting of the R3 tap, you can vary the instant at which CR1 conducts. You can therefore control the position of the range step by adjusting the setting of R3. If a linear relationship is
to be established between the delay of the step \((t)\) and the voltage at the R3 tap \(E_{R3}\), the Q1 sawtooth collector voltage must be linear.

The \(e_{out}\) waveform is applied to the vertical deflection plates of a CRT. Only the portion of the \(e_{out}\) waveform that occurs between times \(t_1\) and \(t_3\) is displayed on the CRT screen. Remember, the indicator trace is blanked out during the flyback (retrace) time.

**TRANSMITTERS**

The purpose of a radar transmitter is to develop high-power, high-frequency pulses of RF energy to be radiated into space by the antenna system. Our discussion will be limited to transmitting devices that are used in fire control radar. In most cases, older magnetrons and klystrons have given way to solid-state variants of gridded traveling wave tubes and other similar devices. The construction, operating characteristics, and limitations of these transmitters are covered in Navy Electricity and Electronics Training Series (NEETS), Module 11, Microwave Principles, NAVEDTRA 14183A.

Basically, a transmitter is an RF oscillator, which is turned on and off by a signal received from a modulator. The oscillator is not normally controlled directly by the signal from the timer. Instead, the timer triggers the modulator, which, in turn, switches the transmitter on and off.

**Radar Modulators**

Radar modulators control the pulsewidth using a rectangular direct current (dc) pulse of the required duration and amplitude. The peak power of the transmitted (RF) pulse depends on the amplitude of the modulator pulse.

Waveforms of the trigger pulse (Figure 6-9) applied by the timer to the modulator, the modulator pulse applied to the radar transmitter, and the transmitted RF pulse. Note the following:

- The modulator pulse is applied to the transmitter the instant the modulator receives the trigger pulse from the timer.
- The modulator pulse is flat on top.
- The modulator pulse has very steep leading and trailing edges.

For accurate determination of target range, the timing circuit must be triggered the instant the leading edge of the transmitted RF pulse leaves the transmitter. Thus, the trigger pulse that controls the operation of the modulator also synchronizes the sweep circuits and target range.
The line-pulsed modulator replaced the drive-hard-tube modulator for most radar uses. The line-pulsing modulator stores energy and forms pulses in the same circuit element. This element is usually the pulse-forming network (PFN). The drive-hard-tube modulator forms the pulse in the driver. The pulse is then amplified and applied to the modulator. The reasons for the replacement are that the drive-hard-tube modulator had lower efficiency, its circuits were more complex, higher power supply voltage was required, and it was more sensitive to voltage changes. The line-pulsed modulator is easier to maintain because of its less complex circuitry and, for a given amount of power output, it is more compact and light. Because it is the modulator used most in aviation radar, it is the one we will discuss.

The components of a basic radar modulator are shown in Figure 6-10. The components of the radar modulator are as follows:

- A power supply
- A storage element (a circuit element or network for storing energy)
- A charging impedance (to control the charge time of the storage element and to prevent short-circuiting of the power supply during the modulator pulse)
- A modulator switch (to discharge the energy stored by the storage element through the transmitter oscillator during the modulator pulse)

A basic modulator switch open and the storage element charging is shown in Figure 6-10, view A. With the modulator switch open, the transmitter produces no power output, but the storage element stores a large amount of energy. Upon closing the switch (Figure 6-10, view B), the modulator’s storage element discharges through the transmitter. The energy stored by the storage element is released in the form of a high-power, dc modulator pulse. The transmitter converts the dc modulator pulse to an RF pulse, which is radiated into space by the radar antenna. Thus, the modulator switch is closed for the duration of a transmitted RF pulse, but is open between pulses.

Many different kinds of components are used in radar modulators. The power supply generally produces a high-voltage output, either alternating or direct current. The charging impedance may be a resistor or an inductor. The storage element is

![Figure 6-10 — Basic radar modulator block diagram.](image)
generally a capacitor, an artificial transmission line, or a PFN. The modulator switch is usually an electron tube.

**Modulator Storage Elements**

Capacitor storage elements are used only in modulators that have a dc power supply and an electron-tube modulator switch. The capacitor storage element is charged to a high voltage by the dc power supply, and releases only a small part of its stored energy to the transmitter. The electron-tube modulator switch controls the charge and discharge of the capacitor storage element.

The artificial transmission line storage element (*Figure 6-11*) consists of identical capacitors (C) and inductors (L), arranged to simulate sections of a transmission line. The purposes of the artificial transmission line are to store energy when the modulator switch is open (between transmitted RF pulses) and to discharge and form a rectangular dc pulse (modulator pulse) of the required duration when the modulator switch is closed.

The duration of the modulator pulse depends on the values of each inductive and capacitive (LC) section of the artificial transmission line (*Figure 6-11*) and the number of LC sections used. Other arrangements of capacitors and inductors (PFNs) are very similar in operation to artificial transmission lines.

**Capacitor**

The schematic diagram of a modulator that uses a single capacitor (C1) as its storage element is shown in *Figure 6-12, view A*. The charge and discharge of C1 is controlled by transistor Q1, which is a switching transistor normally held below cutoff by a negative dc bias applied to its base.

When a positive trigger pulse (from the radar timer) is applied to the base of Q1, Q1 conducts for the duration of the trigger pulse. When Q1 is cut off, storage capacitor C1 charges through the series circuit consisting of the dc power supply, charging impedance Z1, and charging diode CR1. The low voltage across CR1 effectively prevents the RF oscillator from operating.

When a positive trigger pulse is applied to the base of Q1, Q1 suddenly conducts, and C1 discharges. The discharge path is a series circuit consisting of switching transistor Q1 and the RF oscillator. Note that discharge current I2 is opposite in direction to charge current I1. Since charging diodes can conduct in only one direction (from cathode to anode), CR2 remains cut off during the modulator pulse. Thus, discharge current I2 flows through the RF oscillator and an RF pulse is generated by the oscillator.

During the modulator pulse, storage capacitor C1 discharges, and the C1 voltage decreases. Since the C1 voltage (modulator pulse) is applied to the RF oscillator, the frequency of the oscillator changes if there is any significant change in the C1 voltage. To keep the C1 voltage practically
constant, C1 must have a large capacitance. Thus, only a small fraction of the charge is removed from C1 during the modulator pulse, and the C1 voltage remains practically constant.

The switching transistor starts and stops the modulator pulse. Thus, the width (duration) of the modulator pulse depends on the width of the trigger pulse applied to the base of Q1. The pulse repetition rate depends on the rate at which trigger pulses are applied to the base of Q1. To obtain a modulator pulse with nearly vertical sides (a dc rectangular pulse), the trigger pulse must also have nearly vertical sides. Modulators that use capacitor storage elements and switching transistors as switches have the following advantages:

- The pulse repetition rates can be varied over relatively wide limits.
- The pulsewidth can also be varied over relatively wide limits.

Figure 6-12 — Applications of basic modulator elements.

The switching transistor starts and stops the modulator pulse. Thus, the width (duration) of the modulator pulse depends on the width of the trigger pulse applied to the base of Q1. The pulse repetition rate depends on the rate at which trigger pulses are applied to the base of Q1. To obtain a modulator pulse with nearly vertical sides (a dc rectangular pulse), the trigger pulse must also have nearly vertical sides. Modulators that use capacitor storage elements and switching transistors as switches have the following advantages:
Artificial Transmission Line

A radar modulator that uses an artificial transmission line as its storage element is illustrated in Figure 6-12, view B. A switch (modulator switch) controls the pulse repetition rate. When the modulator switch is open (between modulator pulses), the transmission line charges.

The charge path includes the primary of pulse transformer T1, the dc power supply, and charging impedance Z1. When the modulator switch is closed, the transmission line discharges through the series circuit, consisting of the modulator switch and the primary of pulse transformer T1.

The artificial transmission line is effectively an open circuit at its output end. Thus, when the voltage wave reaches the output end of the line, it is reflected. As the reflected wave propagates from the output end toward the input end of the line, it completely discharges each section of the line. When the reflected wave reaches the input end of the line, the line is completely discharged, and the modulator pulse ceases abruptly. If the oscillator and pulse transformer circuit impedance is properly matched to the line impedance, then the voltage pulse that appears across the T1 primary is one-half the voltage to which the line was charged initially.

The width of the pulse generated by an artificial transmission line depends on the time required for a voltage wave to travel from the input end to the output end of the line and back. Thus, the pulsewidth depends on the velocity of propagation along the line (determined by the inductance and capacitance of each section of the line) and the number of line sections (the length of the line).

Pulse-Forming Networks

A PFN is similar to an artificial transmission line because it stores energy between pulses and produces an almost rectangular pulse. The PFN (Figure 6-13, view A) consists of inductors and capacitors arranged so they approximate the behavior of an artificial transmission line.

Each capacitor in the artificial transmission line (Figure 6-13, view B) must carry the high voltage required for the modulator pulse. Since each capacitor must be insulated for this high voltage, an artificial transmission line consisting of many sections is bulky and cumbersome.
The PFN (Figure 6-13, view C) can carry high voltage, but it does not require bulky insulation on all of its capacitors. Only series capacitor C1 must be insulated for high voltage. Since the other capacitors are in parallel with the corresponding inductors, the modulator pulse voltage divides nearly equally among them. Thus, except for C1, the elements of the PFN are relatively small.

PFN may be insulated by immersing each circuit element in oil. The network is usually enclosed in a metal box on which the pulse length, characteristic impedance, and safe operating voltage of the network are marked. If one element in such a network fails, the entire network must be replaced.

**Switching Devices**

The voltage stored in a storage-element capacitor, artificial transmission line, or PFN must be discharged through a switching device. The switching device conducts for the duration of the modulator pulse, and is open-circuited between pulses. Thus, the modulator switch must perform the following functions:

- Close suddenly and reach full conduction in a fraction of a microsecond
- Conduct large currents (tens or hundreds of amperes) and withstand large voltages (thousands of volts)
- Cease conducting (become an open circuit) with the same speed that it starts to conduct
- Consume only a fraction of the power that passes through it

Highly reliable solid-state switches have replaced thyratrons in radar transmitters. These devices have the ability to switch short, large amplitude currents required by high voltage circuits in today’s radar systems. For simplicity of explanation, we will discuss the operation of a basic thyratron.

The thyratron, normally held below cutoff by a negative grid voltage, conducts when a positive trigger pulse is applied to its grid. Once fired, the thyratron continues to conduct as long as the storage element (artificial transmission line or PFN) is discharging.

During discharge of the storage element, the gas in the thyratron is highly ionized. While the storage element discharges, the plate-to-cathode resistance of the thyratron is practically zero. When the storage element is completely discharged, current ceases to flow through the thyratron and the gases become deionized. Thus, the negative grid bias regains control, and the thyratron is cut off (the modulator switch opens).

Most radar modulators use a high-voltage, dc power supply. Typical dc power supplies for radar modulators use a half-wave rectifier, a full-wave rectifier, or a bridge rectifier.

The modulator charging impedance (Figure 6-14, view A) prevents the dc power supply from becoming short-circuited when the modulator switch closes. When the modulator switch is open, the charging impedance also controls the rate at which the storage element charges. When the charging impedance is large, the storage element charges slowly. When the charging impedance is small, the storage element charges rapidly.

Many different kinds of charging impedance and charging circuits are used in radar modulators. The type of charging impedance and charging circuit used depends on the following:

- The type of power supply alternating current (ac) or dc.
- The type of storage element
- The modulator pulse voltage required
- The pulse repetition rate
• The frequency of the available ac supply voltage

Most radar modulators charge very slowly compared with the rate at which they discharge. The interval between modulator pulses is much longer than the pulsewidth. Because the charging current is relatively small and changes very slowly, inductances in a modulator storage element have negligible effect on charging. Thus, all modulator storage elements can be represented as a capacitor during their charging interval, as in Figure 6-14, view B.

**Resistance Charging**

In Figure 6-14, view B (the equivalent charging circuit of the radar modulator), note that a capacitor (C) represents the storage element (artificial transmission line) of the modulator. A resistor (R) represents the charging impedance. When the modulator switch is open, the storage element charges, along a typical RC charge curve, to a maximum voltage $-E$ (time interval $t_0 - t_1$, Figure 6-14, view C).

When the modulator switch is closed (time $t_1$), the storage-element voltage ($E_{st}$) decreases to $E/2$. (Remember, if an artificial transmission line or PFN is charged to a maximum voltage, $E$, and a matching impedance load is suddenly connected across the line, the line voltage decreases instantly to $E/2$). Voltage $E_{st}$ remains at $E/2$ for the duration of the modulator pulse (time interval $t_1 - t_2$). At the end of the modulator pulse (time $t_2$), voltage $E_{st}$ suddenly decreases to zero. Shortly afterwards, the modulator switch opens, and a new charging cycle begins.

With the storage element charging (time interval $t_0 - t_1$), the change in current through T1 pulse-transformer primary (Figure 6-14, view A) is too slow to produce an output voltage. Thus, the T1 secondary voltage $E_{out}$ (Figure 6-14, view D) is zero. When the modulator switch closes (time $t_1$), the rapid decrease in storage-element voltage ($E_{st}$, Figure 6-14, view C) appears across the T1 primary and induces a high voltage in the T1 secondary.

During the modulator pulse (time interval $t_1 - t_2$), voltage $E_{out}$ remains constant. At the end of the pulse (time $t_2$), T1 secondary voltage decreases suddenly to zero. Thus, pulse transformer T1 converts the rapidly changing storage-element voltage to a steep, high-voltage pulse.
Resonance Charging

If the charging resistor is replaced by an inductor, the charging circuit becomes series resonant. When a dc voltage is applied to a series resonant circuit (Figure 6-15, view A), capacitor C begins charging through inductance L. When $E_c$ approaches the applied dc voltage $E$, the magnetic lines of force due to current flow through L begin collapsing and sustain the charging current. In this way capacitor voltage $E_c$ rises to its maximum value, which is twice the applied dc voltage, $E$. Due to circuit losses in actual practice, this voltage is approximately $1.9E$. The capacitor voltage then oscillates at the resonant frequency of the LC circuit. These oscillations gradually decay until $E_c$ becomes constant, and equals $E$, the applied dc voltage and is called dc resonance charging. Dc resonance charging is used only when the pulse repetition period corresponds to the resonant frequency of the LC circuit. For example, with dc resonance charging, the modulator switch closes at the instant the capacitor voltage reaches its maximum value (time $t_1$) (Figure 6-15, view A). The advantage of dc resonance charging is that it permits the storage element to be charged to a voltage twice the dc power-supply voltage. Its disadvantage is that the pulse repetition rate is fixed by the resonant frequency of the LC charging circuit.

Addition of a diode to the resonant charging circuit permits the storage element to charge to a dc voltage twice the applied dc voltage. As a result, $E_c$ increases to its maximum value ($2E$), and then remains constant. Notice the schematic diagram (Figure 6-15, view B) and the capacitor voltage ($E_c$) waveform of a resonant charging circuit that uses a diode. Note that diode CR1 is connected in series with the charging impedance (inductor L) and the storage element (represented by capacitor C). Since CR1 can conduct in only one direction, capacitor C is charged through the dc power supply. The storage element (C) can be discharged at any time after $E_c$ reaches its maximum value. Thus, the pulse repetition rate can be varied over a wide range.
RECEIVERS

Because the received RF echo pulses are very small, the radar receiver must have high-gain and low-noise capabilities. Because of the noise produced by RF amplifier stages at microwave frequencies, radar receivers are modified slightly. Instead of RF amplifier stages, the typical radar receiver uses a waveguide balanced mixer (microwave mixer) and an intermediate frequency (IF) preamplifier to produce the gain normally achieved by RF amplifier stages with much less inherent noise.

Microwave Mixer

The typical radar receiver microwave mixer is a waveguide balanced mixer (Figure 6-16). This section of waveguide forms a hybrid junction (also referred to as “hybrid T” or “magic T”). It is a waveguide arrangement with four branches. The branches are constructed so that energy (signals) entering one of the four branches is coupled to only two of the three remaining branches. The four branches are labeled arm A, arm B, arm C, and arm D in Figure 6-16, view A. The receiver crystals (CR1 and CR2) are inserted directly into the waveguide, and coaxial probes are used to couple the output signals. The crystals are located one-quarter wavelength from their respective short circuited waveguide ends. This is the point of maximum voltage along a tuned line. The crystals are also connected to an impedance network located in the IF preamplifier. This network can be adjusted for optimum coupling and best noise figure.

The local oscillator signal is injected into arm B (Figure 6-16, view A) by a coaxial probe. The signal is distributed as shown in Figure 6-17. Notice that the local oscillator signal is in phase across the crystals. The received signal is injected into arm D (Figure 6-16, view A) by waveguide connection from the antenna. The signal is distributed as shown in Figure 6-17, view B. Note the signal is out of phase across the crystals. The resulting fields are illustrated in Figure 6-17, view C.

Because there is a difference in phase between the received signals applied across the two crystals, and because the local oscillator signal is in phase across both crystals, there will be a condition when both

![Figure 6-16 — Microwave mixer.](image-url)
signals applied to CR1 will be in phase and the signals applied to CR2 will be out of phase. This results in an IF (difference between local oscillator and received signal frequencies) of one polarity across CR1 and of the opposite polarity across CR2. When these two signals are applied to the input circuit of an IF preamplifier, they will add. Outputs of the same polarity will cancel each other. This action helps to eliminate inherent local oscillator noise. The IF preamplifier will be discussed later in this chapter.

**Local Oscillator**

For many years, the local oscillator used in practically all microwave radar systems was the reflex klystron. With the advent of solid-state devices and particularly the varactor, it became possible to design more efficient oscillator circuits. Most modern radars today use solid-state, variable-frequency, voltage-controlled, varactor oscillators.

The varactor diode is a semiconductor device that is employed as a variable reactance circuit element. The variable reactance is provided by the positive-negative (PN) junction capacitance, which varies as a function of the voltage applied to it. The varactor operates principally between a very small positive bias and the reverse breakdown voltage. Under these conditions, the varactor shown in Figure 6-18, view A, can be represented electrically by the equivalent circuit shown in Figure 6-18, view B. The applied voltage can vary the junction capacitance sufficiently to provide a useful capacitance change. This variance enables the varactor diode to be used for tuning oscillator tank circuits over a wide frequency range.

A diagram of a typical varactor, voltage-controlled, variable-frequency oscillator circuit (VCO) used in some present-day radars is shown in Figure 6-19. The input sawtooth voltage is applied across R7 to varactor diode CR1. CR1 is essentially a voltage-sensitive variable capacitor in series with a semiconductor diode. The diode portion of CR1 is effectively at RF ground because it is connected to the 12V bias line and bypassed to ground by capacitor C5. The incoming sawtooth voltage changes
the capacity of CR1 PN junction, which is in parallel with coil L4, forming a resonant tank circuit in the collector circuit of Q1. Coil L4 is effectively connected from the collector to the base of Q1, due to bypass capacitor C4. The feedback necessary to sustain oscillations is provided by adjustable capacitor C9. The RF effects of bypass capacitors C4 and C5 effectively place the base of Q1, L4, and CR1 to ground or a common tie. This causes Q1, CR1, and L4 to form a transistor Colpitts oscillator circuit.

The sine wave output signal of Q1 (whose frequency is dependent upon the capacitance of CR1) is applied to the base of Q2. Q2 is a buffer amplifier, whose output is coupled by capacitor C1 to the microwave balanced mixer local oscillator input probe.

Figure 6-18 — Equivalent circuit for a varactor diode at microwave frequencies.

Figure 6-19 — Typical radar varactor, voltage-controlled oscillator circuit.
IF Preamplifier

The typical radar IF preamplifier is a low-noise, high-gain amplifier, which is tuned to the receiver's IF (normally in the range of 60 megahertz [MHz]). Signal flow diagram of a typical IF preamplifier is shown in Figure 6-20. The diagram shows the preamplifier connected to a microwave balanced mixer. For illustration purposes, Figure 6-21 shows a simplified schematic of the IF preamplifier with only those components labeled that appear in Figure 6-20. Refer to these figures during the following discussion.

The input from the balanced mixer (received IF) is coupled across C1 and C2, through L1 to the base of Q1. The bias of the balanced mixer crystals is adjusted by R1 and R2 for the best noise figure. Impedance matching network L1 and C4 is also adjusted for the best noise figure. Q1 and Q2 are high gain, cascode amplifiers. The output of Q2 is taken off the collector and coupled across C3 to the bases of Q3 and Q4. Parallel amplifiers Q3 and Q4 provide the necessary signal power without gain compression. The center frequency of the amplifier is tuned by L2 and T1 adjusts the amplifier's bandwidth and gain. The output signal is coupled across T1 and is the input to the receiver's IF amplifier stages. The rest of the unlabeled components establish biasing, etc., for the amplifier. The sensitivity time control (STC) input controls the gain of the preamplifier to prevent saturation of the display indicator by large nearby ground clutter targets. This input is a negative ramp voltage from an STC circuit. It consists of a monostable multivibrator, a charging RC network, and a driver amplifier. The resistance of the RC network is controlled by an adjustable pot located on the radar's control panel. The operator adjusts the pot for best picture. By adjusting the RC time, both the ramp duration and amplitude can be set lowering the gain of the preamplifier for a period of the receive time. This period is usually from 0 to 20 miles on the indicator. This voltage is applied to the emitters of Q1, Q3, and Q4 and controls the gain of these stages by controlling the emitter-base bias. The more STC adjusted in by the operator, the less negative voltage is applied to the emitters during STC time, thus decreasing the amplification factor.
IF Amplifiers

At this point you might want to review NEETS, Module 18, Radar Principles, NAVEDTRA 14190A as an aid to your understanding of IF amplifier operation. Radar receiver IF amplifiers require high gain to amplify the input signal to the level required to operate the detector. Many different circuit arrangements are used to achieve this required gain. One circuit arrangement, which is increasing in use, is the logarithmic amplifier. This type of amplifier stage produces high gain while maintaining the resonant frequency and bandpass of the tuned coupling circuits fairly constant over the dynamic range of the input signal. The output of a logarithmic amplifier is a logarithmic (as opposed to linear) function of its input signal, meaning the output is a logarithmic curve versus a linear or straight line.

The functional signal flow of a typical logarithmic IF amplifier is shown in Figure 6-22. A schematic diagram is shown in Figure 6-23 of the first IF amplifier stage in Figure 6-22. All of the IF amplifier stages (1st through 5th) are identical. The following discussion refers to Figures 6-22 and 6-23.

The IF input signal (from the IF preamplifier) is coupled across C1 to the bases of the A and B amplifiers. These amplifiers are in parallel across the output coupling transformers. The A amplifier consists of Q1 and Q2 and the B amplifier consists of Q3 and Q4. Both A and B amplifiers are single-ended differential amplifiers.

The A amplifier (Q1 and Q2) has a constant gain of approximate unity as determined by R3 and R4. Because there is no load resistor for Q1, the collector bias supply filter capacitor, C4, (located in the +7 Vdc power supply) effectively grounds the collector for ac signals to pass. The output of Q1 is taken off its emitter and applied through R3 and R4 to the emitter of Q2. The output of Q2 is taken off its collector and applied to T1, the inter-stage transformer coupler. T1 and C8 form a tuned tank, which is tuned to the IF.
The B amplifier (parallel with the A amplifier) has a high gain for weak signals. It is quickly limited as the input signal strength increases. When Q3 conducts (in the same manner as Q1), the output signal is taken off its emitter at the top of R6. The signal is coupled across C6 to the emitter of Q4. Q4 is so biased that it will cut off before Q3 reaches saturation. The weaker the input signal, the more Q4 will conduct and aid the output of Q2. The output of Q4 is taken off its collector and is applied to T1 along with the output of Q2. Since Q2 and Q4 are in parallel, feeding a common load, as the input signal increases, the high-gain stage quickly decreases toward unity, closely approximating a logarithmic response. By cascading amplifiers (1st through 5th), a large dynamic input range is attained. The output is detected after the last (5th) stage and goes to the video amplifier stages.

**Automatic Frequency Control Circuits**

The purpose of the radar receiver’s automatic frequency control (AFC) circuits is to tune the receiver local oscillator to the correct operating frequency. For the receiver to process the received signal, the local oscillator must be tuned to the proper frequency so that the IF output of the receiver’s balanced mixer (difference frequency of the local oscillator and received signal) is correct. The local oscillator must be tuned during transmit time (prior to the reception of a return pulse). To accomplish this tuning, the AFC circuits use another microwave balanced mixer similar to the receiver’s balanced mixer shown in Figure 6-16, view B. The inputs to this mixer are the receiver local oscillator and an attenuated sampled transmitted pulse. The output IF would be the same as the receiver balanced mixer. The received signal is the transmitter pulse reflected off a target. The output of the AFC microwave balanced mixer goes to the receiver’s AFC circuits. A simplified block diagram of a typical AFC circuit is illustrated Figure 6-24.

There are three basic steps or modes of operation used by the AFC circuits to tune the local oscillator to the correct frequency. They are the search, acquisition, and loop control modes.
Search Mode

AFC circuits go into a search mode any time the local oscillator is so far off frequency that the IF produced by the balanced mixer (difference frequency of local oscillator and transmitter frequency) is outside the limits of the receiver’s IF tuned circuits and cannot be processed. An IF preamplifier contained in the AFC discriminator is tuned to the receiver’s IF. Therefore, if the IF input to the discriminator is beyond the receiver’s bandpass limits (usually ±10 MHz), the signal will not be processed by the AFC discriminator and there are no output signals from the discriminator to either the AFC logic circuits or the AFC controller circuits. Instead, a comparator (Figure 6-25) (AR2), part of the AFC logic circuit, gets an input (search feedback) from an integrator (Figure 6-26) (AR2), which is part of the AFC controller circuit and may be either positive or negative, depending on the output state of the integrator. The output of the comparator (Figure 6-25) is coupled through R1, bypasses switch Q22 (which is cut off as there is no wideband video signal input from the discriminator), and goes to CR1 and CR3 (Figure 6-26) of the AFC controller. Depending on the polarity of the comparator output, the output goes through either CR1 and CR2, or CR3 and R1, to the integrator AR2. The gain of the integrator is different for the different polarities of the comparator output resulting in a sawtooth output voltage from the integrator AR2. The sawtooth voltage goes through the summing amplifier AR3 and is also fed back to the comparator AR2 (Figure 6-25), causing it to change states when a certain voltage level is reached. The output of the summing amplifier AR3 is applied to the sample gate Q2 (N-channel Junction Field-Effect Transistor [JFET]). The gate Q2 is open at this time. This operation will be explained in the sample gate control section which is part of the AFC logic circuit. The sawtooth runs through Q2, across a hold charging circuit consisting of R7, 8, 9, and 10 and C5, 6, 7, and 8, and through gate Q3. It is amplified by drivers Q4 through Q6, and is applied to the receiver local oscillator varactor. The amplitude of the sawtooth will cause the local oscillator to sweep through its entire operating range. It is also large enough to overcome the hold circuit.
Figure 6-24 — AFC circuit simplified block diagram.

Figure 6-25 — AFC logic circuit functional signal flow diagram.
When the local oscillator reaches a certain frequency, it is mixed with the sampled transmitted pulse in the microwave mixer. When an IF is produced within the IF bandpass of the receiver (±10 MHz), the IF signal will be processed by the AFC discriminator circuits signifying that acquisition has occurred.

**Acquisition Mode**

The AFC mixer’s IF output must be within the ±10 MHz bandpass of the AFC discriminator’s preamplifier. The input to the discriminator (Figure 6-27) will then be amplified/limited (depending on signal amplitude) by Q1 through Q3. The output of Q3 is fed via Q4 to the discriminator circuit, consisting of T1, R4, R5, R6, C1, C2, R7, R8, R9, CR1, CR2, C3, and C4. The output of Q3 is also fed to Q6. The circuitry of Q6 phase shifts the output (delays the signal) by 270 degrees. The output of Q6 is applied between CR1 and CR2, and is the reference signal for the discriminator. The output of Q6 is also applied to wideband filter Q12 and Q13.

The operation of the discriminator is similar to the Foster-Seeley discriminator explained in NEETS Module 12, Modulation Principles, NAEDTRA 14184A. It is basically a phase detector with the output rectified and filtered. The output of the discriminator is a pulse, the width of the transmitter pulse, that has an amplitude and polarity that is determined by the frequency difference between the local oscillator and the sampled transmit pulse. This output is amplified by Q7 through Q11 and is the video error signal, which is applied to C1 and C3 (Figure 6-26) of the AFC controller.

The output of the wideband filter Q12 and Q13 (Figure 6-27) is detected by Q14, amplified by Q15 through Q18, and is the wideband video signal, which is applied to Q15 (Figure 6-25) of the AFC logic circuit.

The wideband video signal causes Q15 and Q16 to conduct, which charges C4. When the charge on C4 reaches a predetermined value, the signal is coupled by Q17 and Q18 to amplifiers Q19 and Q20, and turns on switch Q22. Q22 clamps the output of the comparator AR2, and it also clamps the feedback circuit (Figure 6-26) of the integrator AR2, which is part of the AFC controller. The integrator will no longer generate the (search) sawtooth voltage to the local oscillator. At this point, the search mode is terminated, acquisition is complete, and tracking (loop-control mode) begins.

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**Figure 6-26 — AFC controller functional signal flow diagram.**
Loop-Control Mode

There are actually two paths or loops comprising the loop-control mode. One is commonly referred to as “slow loop,” which corrects the oscillator frequency from ±10 MHz to within ±5 MHz of the desired center IF. The second path is referred to as the “fast loop,” and it will correct the oscillator frequency from ±5 MHz to the correct frequency.

Slow-Loop Operation

The video error signal (Figure 6-26), which was the output of the discriminator (beginning at acquisition), is applied to C1 and C3. The fast-loop circuit, C1, is ineffective when the local oscillator frequency error exceeds ±5 MHz. The video error signal is coupled across C3 and C4 to sample gate Q1. Q1, like Q2 in search mode, is open at this time. The signal passes through gate Q1 to Q4. Q4 and AR1 operate as a voltage follower circuit. The output of AR1 is integrated by AR2, amplified by AR3, and applied across the opened sample gate Q2 to the hold circuit. Slow-loop operation can be summarized as follows: So long as the oscillator frequency error exceeds ±5 MHz, the slow-loop circuit takes a series of video error signal samples. The slow-loop circuit integrates them until a sufficient voltage level is reached to charge the hold circuit to open gate Q3 and drive the local oscillator frequency to within ±5 MHz of the desired frequency, signaling the beginning of the fast-loop operation.

Fast-Loop Operation

The video error-signal output of the discriminator will now be coupled across C1 and C2 to the sample gate Q2. The sample gate at this time will open periodically as determined by the sample gate control circuits, which are part of the AFC logic circuit. When gate Q2 opens, the video error signal goes to the hold circuit of Q3. The hold circuit, charged by the slow-loop circuits, is at the threshold voltage level to turn on Q3. The error signal amplitude is sufficient to turn on Q3 and send a short voltage burst to the local oscillator varactor to tune the oscillator to the desired frequency. Once the desired frequency is reached, there will no longer be a video error-signal output from the discriminator and no further tuning of the local oscillator.

Figure 6-27 — AFC discriminator and video amplifier functional signal flow diagram.
frequency drift slightly, a video error-signal output from the discriminator would again go through the fast loop circuits and retune the local oscillator. In this manner, the AFC circuits maintain the desired IF output of the receiver’s balanced mixer.

Sample Gating Operation
The sample gates, Q1 and Q2 (Figure 6-26), are initially opened by a Schmitt trigger oscillator (STO) trigger (Figure 6-25) being applied to the sample gate control circuits Q7 through Q14. Prior to receiving the STO trigger, the output of Q14 is a highly negative (approximately -15 Vdc) voltage, which applied across (Figure 6-26) CR5 and CR6 causes the N-channel gate to be closed. The STO trigger is a pulse from the radar synchronizer and occurs a few microseconds prior to the basic timing pulse which fires the transmitter and the scope sweep circuits, etc. This condition ensures the sample gate is opened prior to any possible output from the receiver or AFC balanced mixers. The output of the balanced mixers is the difference frequency of the local oscillator and sampled transmitter pulse. The gates Q1 and Q2 (Figure 6-26) will close (Figure 6-25) with the detected transmit pulse being applied to Q5. This pulse triggers a monostable multivibrator, AR1. The negative pulse output of AR1 causes the sample gate control Q7 through Q14 to turn off (close) the sample gates Q1 and Q2 (Figure 6-26). The multivibrator will generate different negative output pulses depending on the PRF of the radar. Since typical radar is normally capable of operating at two different PRFs and pulsewidths for long- and short-range operation, the basic timing pulse (Figure 6-25) is applied to switch drivers Q1 through Q3. The output of the switch drivers opens and closes gate Q4, which changes (determines) the time constant of AR1. Therefore, sample gates Q1 and Q2 (Figure 6-26) will be open for different periods of time, depending on the PRF of the radar. However, the overall time the sample gates are opened is from the STO trigger time to the time of the detected transmitter pulse. The time constant of the monostable multivibrator is such that gates Q1 and Q2 (Figure 6-26) will close just prior to the trailing edge of the transmitted pulse ensuring that the AFC circuits will not inadvertently tune the receiver local oscillator during the receive cycle of the radar operation.

Special Receiver Circuits
Gain control of radar IF amplifiers takes many different forms. The simplest type is manual gain control. More complex forms of gain control are automatic gain control (AGC), instantaneous automatic gain control (IAGC), and STC. Gain control is necessary to adjust the radar receiver sensitivity for signals of widely varying amplitude. Some gain-control circuits are used to overcome unintentional or intentional interference (jamming).

Although it is possible to control IF gain with only one IF amplifier stage, the amount of control is usually insufficient. Because a stage has capacitance between its input and output ends, a signal is coupled to the output end even when the stage is cut off. The maximum variation in gain by the control of a single stage is approximately 20 dB. With two-stage gain control, approximately 40 dB of gain variation can be obtained.

Automatic Gain Control
Many radar sets are provided with AGC and manual gain control. Provision is usually made for switching between automatic and manual gain control. In this way, manual gain control can be used, if necessary, to adjust for best reception of a particular signal.

The various types of gain control differ in the following ways:

- Circuits used
- Speed of response
- Type of response

6-27
The simplest type of AGC adjusts the IF amplifier bias (and gain) according to the average level of the receiver signal. AGC is not used as frequently as other types of gain control because of the widely varying amplitudes of radar return signals.

With AGC, gain is controlled by the largest received signals. When several radar signals are being received simultaneously, the weakest signal may be of greatest interest. IAGC is used more frequently because it adjusts receiver gain for each signal.

**Instantaneous Automatic Gain Control**

A typical IAGC circuit is essentially a wideband dc amplifier that instantaneously controls the gain of the IF amplifier as the radar return signal changes in amplitude by using an output of the second detector of the receiver as bias for the amplifier. The effect of IAGC is to decrease the amplification of strong signals and allow full amplification of weak signals. The range of IAGC is limited by the number of IF stages in which gain is controlled and is the reason most modern receivers use sensitivity time control circuits.

**Sensitivity Time Control**

In radar receivers, the wide variations in return signal amplitude make adjustment of the radar receiver gain difficult. You should adjust receiver gain for best visibility of nearby target return signals. Circuits used to adjust amplifier gain with time, during a single pulse repetition period, are called STC circuits.

A schematic diagram and output-voltage waveform of an STC circuit is illustrated in *Figure 6-28*. The input signal to the STC circuit (*Figure 6-28, view A*) is a pulse obtained from the radar modulator. When the modulator pulse is applied to the base of emitter follower Q1, a large voltage appears across capacitor C1. At the same time, a negative voltage appears across capacitor C2. The amount of negative bias developed across capacitor C2 is determined by the setting of potentiometer R5. A large voltage across C2 drives Q2 beyond cutoff. Thus, $E_{out}$ (curve D, *Figure 6-28, view B*) remains constant while the voltage across C2 decays toward zero. When the voltage across C2 becomes equal to the Q2 cutoff voltage, Q2 begins to conduct and $E_{out}$ rises toward zero.

Output voltage $E_{out}$ (*Figure 6-28, view A*) is applied to the base of an IF amplifier (not shown), and thus places a constant bias on the IF amplifier for a short time after the modulator pulse. During this period, the IF amplifier gain is held

![Figure 6-28 — Sensitivity time control circuit.](image-url)
constant. When the Q2 output voltage begins to decrease, less bias is applied to the IF amplifier, and the receiver sensitivity increases with time. As a result, weak signals from distant targets are amplified more than signals from nearby targets.

When potentiometer R5 is set so that Q1 is not driven beyond cutoff, the bias on Q2 begins to decrease as soon as the modulator pulse ends. In this case, output voltage \( E_{\text{out}} \) rises toward zero, as shown by curve C (Figure 6-28, view B). As a result, a large negative bias is applied to the IF amplifier at the time of the modulator pulse, thereby decreasing IF amplifier gain.

As soon as the modulator pulse ends, the bias applied to the IF amplifier begins to decrease, and IF amplification begins to increase. Thus, the IF amplifier gain is minimal directly after a modulator pulse. The gain increases at a later time when weak signals from distant targets are expected.

The combination of STC and IAGC circuits results in better overall performance than with either type of gain control alone. STC decreases the amplitude of nearby target return signals, while IAGC decreases the amplitude of larger-than-average return signals. Thus, normal changes of signal amplitudes are adequately compensated by the combination of IAGC and STC.

In some cases very large changes of signal amplitude are encountered. For example, enemy jamming may produce large amplitude interfering signals. The interfering signals may be either continuous or pulsed. The interfering signal amplitudes may be large enough to block the receiver, and thus cover up signal return from enemy aircraft. To overcome jamming, special receiver circuits, called anti-jamming circuits, are used.

**Anti-Jamming Circuits**

Among the many different circuits used to overcome the effects of jamming, two important ones are gated AGC circuits and short-time-constant circuits. A gated AGC circuit permits signals that occur only in a very short time interval to develop AGC. If large amplitude pulses from a jamming transmitter arrive at the radar receiver at any time other than during the gating period, the AGC does not respond to these jamming pulses.

Without gated AGC, a large received signal from a jamming transmitter would cause the automatic gain control to follow the interfering signal and to decrease the desired signal amplitude to an unusable value. Because gated AGC produces an output signal for only short times, the AGC output voltage must be averaged over several cycles to keep the automatic gain control from becoming unstable.

Although gated AGC does not respond to signals that arrive at times other than during the desired target return signals, AGC can do nothing with interference that occurs during the gating period. Neither can gating the AGC prevent the receiver from overloading due to jamming signal amplitudes far in excess of the desired target return signal of that particular amplitude. As an aid in preventing radar-receiver circuits from overloading during the reception of jamming signals, short-time-constant coupling circuits are used to connect the video-detector output to the video-amplifier input circuit.

A short-time-constant or a fast-time-constant (FTC) circuit is a differentiator circuit located at the input of the first video amplifier. When a large block of video is applied to the FTC circuit, only the leading edge will pass due to the short time constant of the differentiator. A small target will produce the same length of signal on the indicator as a large target, because only the leading edge is displayed. The FTC circuit has no effect on receiver gain. Although it does not eliminate jamming signals, it greatly reduces them.
Video Amplifiers

Video amplifiers are used to amplify the output signal from the video detector to a level high enough to be used by the radar presentation system. Because radar receivers are frequently far removed from the presentation circuits, some video amplification is provided in the radar receivers. Video amplifiers may also be located in the radar presentation circuits (scope).

Since the radar video signal may have frequency components up to several megahertz, coaxial cables are used to connect the video output circuit of the receiver to the video input circuit of the presentation system. When these coaxial cables are long, special video-amplifier circuits are generally used in the radar receiver. Among the video-amplifier problems that must be met in radar circuits are the following:

- Limitation of low-frequency response (This limitation occurs when cathode-bypass capacitors are used)
- Limitation of low-frequency response by screen-grid bypass capacitance (capacitance between the screen grid and ground)
- Limitation of high-frequency response by input interelectrode capacitance, distributed wiring capacitance, and output interelectrode capacitance

Some of the special video-amplifier circuits mentioned above, whose purpose is to compensate for these problems, are discussed in NEETS Module 8, Amplifiers, NAVEDTRA 14180A.

The high-frequency performance of solid-state circuits has been improved greatly since the early devices. These early circuits were generally limited to about 500 kilohertz (kHz). Transistors are capable of operating at frequencies far above the operating range of conventional vacuum tubes. Transistors do, however, have high-frequency limitations. The design of high-frequency transistor circuits must take into account factors that are not significant at low frequencies.

Basically, transistor high-frequency limitations arise because of transit time effects and the inherent junction capacitance. At high frequencies, these factors become significant and begin to affect the operation of the circuit. Stage gain is lowered and problems involving instability appear as the impedance and gain of the transistor become complex quantities.

When transistors having an upper frequency limit only slightly higher than, or equal to, the high frequency end of the desired video band are used, the attenuation and phase shift due to the transistor must be compensated for in the amplifier and may be done by the use of compensating networks and/or the use of negative feedback.

The high-frequency compensation of video amplifiers consists of attenuating the normal midrange gain of the amplifier to within a few dB of the maximum gain obtainable at the highest frequency of interest, so that the bandwidth is extended to this high frequency. This process is how negative feedback increases the bandwidth of an amplifier. It may be used around one or more stages, and it results in increased stability as well as bandwidth.

Two terminal high-frequency compensation circuits using two or more compensating elements are commonly used in vacuum tube circuits. These circuits can also be used for the high-frequency compensation of transistor amplifiers, although the design relationships are not quite as straightforward. This method of high-frequency compensation consists essentially of using RLC peaking circuits to maintain a nearly constant amplification factor over the required band.

The three-stage, 50 MHz wide-band amplifier shown in Figure 6-29, view A, uses negative feedback frequency compensation in conjunction with an RLC compensating network placed directly in the feedback path. This arrangement provides 34 dB of negative feedback from 50 kHz to 5 MHz.
The current amplification factor is virtually flat at 34 decible (dB) from dc to 10 MHz, and within 3 dB to 50 MHz. The feedback RLC network maintains the feedback loss flat to 10 MHz. The interstage RLC networks compensate the gain characteristic between 5 and 100 MHz, and the feedback around the first stage provides compensation in the vicinity of 7 MHz. The emitter bypass capacitors control the frequency response from dc up to approximately 50 kHz. The frequency characteristic of the amplifier is shown in Figure 6-29, view B.

Video signals are usually coupled to the presentation circuits through relatively long lengths of low-impedance, large-capacitance coaxial cables. Thus, video output stages generally have a low output impedance.

These coaxial cables may have a capacitance of 20 picofarad (μf) per foot. Thus, a 5-foot cable would have a capacitance of 100 μf. To prevent attenuation of high-frequency signals by the shunt capacitance, coaxial cables must be terminated in their characteristic impedance (usually 100 ohms or less).

For coaxial cables that are very short (less than a quarter-wavelength long), the termination resistance may be higher than the characteristic impedance without affecting high-frequency response. Higher values of terminating resistance result in higher output voltages.

**INDICATORS**

The various types of radar indicators (A-scope, B-scope, PPI-scope, etc.) and some of the fundamental principles of their operation are discussed in NEETS Module 18, Radar Principles, NAVEDTRA 14190A. You should review the basic radar principles before continuing with this...
A-Scope

A simplified block diagram and scan presentation of a typical A-scope is presented in Figure 6-30. In the operation of the A-scope, an initial trigger pulse from the timer is applied to both the radar transmitter and the one-shot (monostable) multivibrator in the A-scope. The one-shot multivibrator generates the following:

- A negative gate pulse that is fed to the range marker generator

![A-Scope Scan Presentation](image-url)
• A negative gate pulse that is fed to the range sweep generator
• A positive gate pulse that is fed to the control grid of the CRT

The gate pulse to the range marker generator causes a series of equally spaced range marks to be generated. These range marks are added to the receiver output signal in the video mixer. The output of the video mixer is applied between ground and one vertical-deflection plate of the CRT. The other vertical-deflection plate is connected to the vertical-centering control. In some cases, the receiver output signal is applied to one vertical-deflection plate, and the range marks are applied to the other vertical-deflection plate.

The negative gate pulse, fed to the range sweep generator, causes a nearly linear sawtooth sweep voltage to be generated. In general, the different timing capacitors in the one-shot multivibrator and in the range sweep generator are connected to a common range switch. In this way, the RC time constants of both circuits are changed simultaneously when the operating range is changed.

When the duration of the negative gate pulse is changed, the duration of the sawtooth sweep voltage is changed, but the amplitude of the sweep voltage is unchanged. Hence, for different operating ranges, the scanning spot travels approximately the same distance across the A-scope screen. However, the speed of the scanning spot increases as the range setting is decreased.

The sawtooth output of the range sweep generator is amplified by the range sweep amplifier, and then applied to the paraphase amplifier (phase splitter). The paraphase amplifier permits the sawtooth sweep voltage to be applied in a push-pull configuration to the horizontal-deflection plates of the CRT reducing the defocusing of the electron beam that results when sweep voltage is applied to only one horizontal-deflection plate.

The positive gate pulse applied to the control grid of the CRT intensifies the electron beam during the sweep time enabling the output of the video mixer to be displayed on the A-scope screen. When the positive gate pulse is removed, blanking results (the electron beam is cut off).

Clamping circuits are frequently used with A-scopes to keep the display properly positioned despite changes in the average (dc) value of the sweep or signal voltages. Remember, clampers hold one part of the signal waveform at a constant voltage level. In some A-scopes, expanded sweep circuits are used. These circuits enable a small section of the sweep to be expanded to cover the A-scope screen. Thus, more accurate range measurements can be made.

B-Scope

Often the situation in which a radar is used calls for simplicity of circuitry and construction; therefore, B-scope is often used.

In B-scope, three variables are possible. These are range (a function of time), azimuth (a function of antenna rotation), and the intelligence received by the radar or associated equipment.

From the operator’s standpoint, the ideal situation is for the presentation to be an exact replica of the area scanned and involves complicated construction and circuitry. The B-scope represents a compromise between the extremes of simple and complex circuitry. The B-scope involves the simplest circuitry and construction of any two-dimensional presentation, and yet presents information as a reasonably faithful replica of the area scanned by the antenna (Figure 6-31). It works best under conditions where the antenna scans a sector of less than 180 degrees. It can be employed in a situation where a 360-degree area is scanned.

Range is usually presented vertically by the use of a conventional sweep circuit (Figure 6-32). The scope presentation may be created by either magnetic or electrostatic deflection. Since electrostatic
deflection is usually employed in CRT technology, the final amplifiers are operated push-pull to gain the advantage of good sweep linearity.

Azimuth is presented horizontally by the use of a potentiometer that is mechanically connected to the antenna. The output of the potentiometer controls the horizontal push-pull amplifiers, which, in turn, controls the horizontal deflection.

The intelligence is presented on the indicator by intensity-modulating the sweep. The antenna scanning speed is approximately one scan per second, whereas the sweep speed is at the PRF rate; therefore, the intelligence will also have range and bearing.

**C-Scope**

C-scopes (Figure 6-33) are used primarily to present data on the bearing and elevation of targets. C-scopes may sometimes be used in aircraft interception. Like B-scopes, C-scopes provide a rectangular display on their screens. However, in C-scopes, the vertical axis represents elevation and the
horizontal axis represents bearing. Thus, in aviation fire control radar, targets may appear on either side of both the horizontal and vertical axes.

To obtain a rectangular display on the screen of a C-scope, both horizontal and vertical-sweep generators are used. Since the sweep frequencies are relatively low, potentiometers (like the azimuth sweep potentiometer of the B-scope) are generally used. These potentiometers are connected to the radar antenna.

When the antenna turns sideways, the scanning spot on the C-scope screen is deflected horizontally. When the antenna is tilted up or down, the scanning spot is deflected vertically. Echo signals, applied to the control grid (or cathode) of the CRT during the sweep period, cause the brightness of portions of the horizontal trace to be increased. The position of a bright spot indicates the elevation and bearing of a target.

Targets at different ranges, but with the same bearing and elevation, appear as a single spot on a C-scope. Targets of this kind cannot be distinguished individually on the C-scope. Indicators that present range data are generally used in conjunction with C-scope presentations. Once the range of a particular target has been determined, a range gate pulse (rectangular pulse) is applied to the C-scope intensifying the electron beam only for the duration of the range gate pulse. Thus, only the desired target echo appears on the C-scope. All other signals are blanked out and the bearing, range, and elevation of a particular target can be determined.

Plan-Position Indicators

Type-P indicators, also called PPI, or PPI-scopes, are used primarily to present data on the range and bearing of targets. Like the B- and C-scopes discussed, this PPI-scope uses a CRT with a long persistence screen. Liquid crystal or light emitting diode (LED) displays use synthetic digital signals to maintain target designators, range markers, and radial sweep lines as required by the operator. These types of displays may be seen in airborne early warning and control aircraft.

The PPI presentation (Figure 6-34) is practically an exact replica of the region scanned by the radar antenna.
Figure 6-34 — PPI presentation.
Distance along the radial sweep line represents target range. Rotation of the radial sweep line, synchronized with the antenna’s rotation, produces a circular display.

When echo signals are applied to the control grid (or cathode) of the PPI CRT during the sweep period, the brightness of portions of the radial sweep line is increased. As in B-scopes, increasing the brightness of some portions of the PPI radial sweep line results in a maplike picture. A typical series of PPI presentations are shown in Figure 6-34.

Normally, the center of the PPI screen represents the location of the radar. The range and bearing of the target can be determined by electronic range circles and azimuth (bearing) scale. Range circles are usually obtained by adding uniformly spaced pulses to the receiver output signal during the sweep period.

The pulses cause bright spots to appear at equal intervals along the radial sweep line. When the radial sweep line rotates, the spots produce concentric circles. The distance between the center of the PPI screen and a range circle indicates a specific distance.

A simplified block diagram of a typical PPI scope is shown in Figure 6-35. In the case illustrated, the CRT has a fixed deflection yoke. The sawtooth sweep currents required to produce the rotating radial sweep line are obtained from the trapezoidal-voltage sweep generator, a rotary transformer (synchro resolver), and two push-pull amplifiers.

Figure 6-35 — Typical PPI scope, block diagram.

The rotary transformer is a variable-ratio transformer with one primary winding (the rotor) and two secondary windings (the stator). The voltage ratio between the primary winding and each secondary winding changes when the rotor is turned.
The rotor is connected mechanically to the radar antenna. Thus, when the antenna turns, the rotor turns, and the voltage ratio changes. One secondary voltage varies as the sine of the angle of antenna rotation; the other secondary voltage varies as the cosine of the angle of antenna rotation.

The PPI operates as follows: Trigger pulses from the timer (synchronizer) are fed to both the transmitter and the one-shot monostable multivibrator. The one-shot multivibrator generates negative gate pulses that are applied to the trapezoidal-voltage sweep generator and the cathode of the CRT.

The output of the trapezoidal-voltage sweep generator is fed to a power amplifier. The output of the power amplifier is applied to the primary winding of the rotary transformer. The secondary voltages of the rotary transformer are trapezoidal and have amplitudes that depend on the antenna position.

To apply trapezoidal voltages to the two push-pull amplifiers, a center-tapped resistance network is connected across each of the two secondary windings of the rotary transformer. Network R1 produces two voltages (e₁ and e₂) of equal amplitude and opposite phase, which are applied to one push-pull amplifier. Likewise, network R2 produces two voltages (e₃ and e₄) of equal amplitude and opposite phase, which are applied to the other push-pull amplifier. For simplicity, only the waveforms of e₁ and e₃ are shown in Figure 6-35.

Trapezoidal voltages e₁ and e₂ produce sawtooth sweep currents i₁ and i₂, respectively. Trapezoidal voltages e₃ and e₄ produce sawtooth sweep currents i₃ and i₄, respectively. The angular position of the radial sweep line at any instant depends on the relative amplitudes and the phase relationship of the sawtooth sweep currents at that instant.

Sawtooth sweeps current i₁ and i₂ are equal in amplitude, but opposite in phase. Likewise, i₃ and i₄ are equal in amplitude, but opposite in phase. For simplicity, only the waveforms of i₁ and i₃ are shown in Figure 6-35. The relative amplitudes and polarities of i₁ and i₃ (also of i₂ and i₄) vary as the rotary transformer is rotated. This condition causes the radial sweep line to rotate in synchronism with the radar antenna (which is geared to the rotary transformer).

In general, plan-position indicators used in conjunction with rotary transformers also use clamping circuits (clamplers). The clamping circuits ensure that the scanning spot always starts from the same point on the PPI screen. The fundamentals of clamping circuits are discussed in NEETS Module 9, Introduction to Wave Generating and Wave-Shaping Circuits, NAVEDTRA 14181A.

Negative gate pulses are applied to the cathode of the PPI CRT to intensify the electron beam during each sweep period. The electron beam is intensified to the point where the radial sweep line is barely visible. When echo signals are applied to the control grid of the CRT during each sweep period, the brightness of portions of the radial sweep line is increased.

**E-Scan/Range Height Indicator**

The range height indicator (RHI) presentation (Figure 6-36) is another type of scan for presenting range and height information. The RHI is also known as the E-scan. E-scan is a modification of the B-scope, on which an echo appears as a bright spot with range indicated by the horizontal coordinate and the elevation (height) as the vertical coordinate. This type of scan is used in directing aircraft during ground- and carrier-controlled approaches, and in fire control systems.
An air-to-ground, terrain avoidance sub-mode display is shown in Figure 6-37. During terrain avoidance mode, the radar searches directly in front of the aircraft and displays detected terrain on the radar display. Terrain above the aircraft is displayed on the DDI at its brightest clearance intensity, terrain within 500 feet below the aircraft is at an intermediate intensity, and terrain more than 500 feet below the aircraft is not displayed. The brightness wedge serves as a reference for the two clearance intensities and helps the pilot recognize returns from rain or chaff.

IDENTIFICATION FRIEND OR SYSTEM

With the destructive power of modern weapon systems and the speed of modern weapon delivery systems, it was not practical to wait until a detected radar target is identified by visual means before preparing for combat. Therefore, a means of distinguishing friendly targets from hostile targets at long range was required. It was this need that brought about the advent of identification friend or foe (IFF) systems. The IFF system permits friendly forces to identify themselves automatically when interrogated by either a ground station or another craft. Both aircraft and surface forces maintain IFF systems with operating ranges in excess of 345 miles.

IFF is also used in commercial aviation due to the high density of air traffic. A special operating mode of IFF gives an aircraft the ability to identify itself (by special codes) to ground stations equipped with an Air Traffic Control Radar Beacon System (ATCRBS). Another IFF mode of operation enables an aircraft to automatically report its altitude to an ATCRBS ground station.

A typical IFF system is shown in Figure 6-38. It consists of an interrogator unit, a coder synchronizer unit, a search radar unit, and a transponder unit. The interrogator, synchronizer, and radar units comprise the challenging station, and the transponder unit is the responder station. It should be noted that the challenging station can be a ground station, ship, or another aircraft. The responder station is normally an aircraft.

**Interrogation (Challenge)**

The interrogator is a pulse-type transmitter, which is triggered by the coder synchronizer. The coder synchronizer is synchronized to the radar system (IFF challenges are transmitted 1 to 40 microsecond (μsec) after the radar transmitter pulse, depending on the particular system) so that reception of the IFF response and radar echo signals cannot occur simultaneously. The output (challenge signal) of the interrogator is different for different modes of IFF operation. As long as the aircraft transponder is operating in the correct mode, it will receive these interrogation signals and will transmit back to the interrogator the proper coded reply pulses. The IFF reply pulses (Figure 6-38) are sent via the coder synchronizer to the radar indicator. These reply pulses will appear as dashed lines just behind the aircraft target on the scope. Representations of these reply signals are shown in Figure 6-39.
Interrogation Modes and Codes

There are presently six modes of IFF operation used by ATCRBS and naval aircraft. The ATCRBS is capable of making interrogations in any four of the six different modes. Modes 1 and 2 are for exclusive use by the military as tactical modes for target identification. Mode A is the civil and military air traffic control mode. Because civil Mode A is the same as Mode 3 in military equipment, this common air traffic control mode is called mode 3/A. Modes 1, 2, 4, and 5 are military tactical modes. Mode 4 provides for positive secure friend identification. The operation of Mode 4 is classified. Mode 5 provides for enhanced secure friend identification. Mode B is a civil air traffic control mode but is not used in the United States. Mode C is used in conjunction with an external pressure altitude digitizer to report the aircraft’s altitude to an ATCRBS. Mode D has been established, but its use has not been specified. Only interrogators and transponders using the same encrypted codes can communicate with each other. We will discuss Modes 1, 2, 3/A, C and 4 in depth. Mode 5 is classified and will not be covered in this chapter. In addition, there is a test mode of operation used only by the aircraft transponder as a self-check of the transponder equipment.
Interrogation Pulse Characteristics

The interrogation pulse characteristics for the various modes of IFF operation are shown in Figure 6-40. These pulses are transmitted at a frequency of 1,030 MHz, and are recognized by the transponder through pulsewidth and spacing. Modes 1, 2, 3/A, C, and test each use two interrogation and one side-lobe suppression (SLS) pulse 0.8 μsec wide. The pulse spacing is different for each mode of operation. The pulse spacing for Modes 1, 2, 3/A, C, and test are 3, 5, 8, and 7 μsec, respectively. The side-lobe suppression pulse occurs 2 μsec after the leading edge of the first interrogation pulse in each case. The SLS pulse is used by the transponder receiver circuits to prevent jamming of the IFF system and to suppress the receiver during operation of tactical air navigation (TACAN) systems, radar, or other L-band (systems operating in the 1 to 2 gigahertz [GHz] frequency spectrum) equipment operating in the vicinity of the transponder.

Mode 4 interrogation pulses consist of four pulses 0.5 μsec wide referenced from the leading edge of the first pulse, in multiples of two determined by an external computer programming device. The four pulses may be followed by as many as 32 additional pulses spaced as close as 2 μsec apart. The SLS pulse for Mode 4 is spaced 8 μsec from the leading edge of the first interrogation pulse used.

Transponder (Reply)

In early IFF, the transponder of the aircraft being interrogated would receive the interrogation pulses (either 3, 5, or 8 μsec spacing depending on mode of operation), and would automatically respond with reply pulses of the same spacing. But with the increase of air traffic, a more positive means of identification was required, bringing about the advent of the selective identification feature (SIF). This

Figure 6-40 — IFF interrogator pulse characteristics.
feature has led to the common usage of the designation IFF/SIF system, instead of just the nomenclature IFF system. With the present IFF/SIF system, there are 32 separate reply codes that can be transmitted on Mode 1, and 4,096 separate reply codes that can be transmitted on Modes 2 and 3/A. Mode C has 1,024 separate reply codes available.

**Transponder Control Panel**

The operation of the interrogated aircraft’s transponder (mode of operation and specific codes, etc.) is controlled by a control panel similar to the one shown in *Figure 6-39, view A*, which is normally located on the pilot’s control panel.

**Master Control Switch**

The MASTER control switch is a five-position rotary switch placarded OFF, STBY, LOW, NORM, and EMER. In the STBY position, power is applied to the IFF coder, but interrogations are inhibited. In the LOW position, the IFF coder is operational, but the receiver sensitivity is reduced. In the NORM position, the IFF coder is fully operational at normal receiver sensitivity. In the EMER position, the IFF coder transmits emergency replies to interrogations in Modes 1, 2, or 3/A. The Mode 3/A emergency reply includes code 7700. With EMER selected, Mode 4 is enabled regardless of the position of the Mode 4 switch, and Mode C continues to function normally if selected. To select the EMER position, the control is pulled outward and rotated to the EMER position.

**IDENT/OUT/MIC Switch**

The IDENT/OUT/MIC switch is a three position toggle switch. Momentarily actuated (the switch has spring-loaded return) to the IDENT position, the IFF coder adds an identification of position response to Modes 1, 2, and 3/A, for 15 to 30 seconds. In the MIC position, the identification of position function is activated for 15 to 30 seconds whenever the microphone switch is actuated. In the OUT position, the IDENT reply is disabled.

**Mode 1-3A Code Selectors**

Six code-selector switches are provided for selection of Mode 1 and Mode 3 codes. Mode 1 has two thumbwheel selectors, which allow selection of 32 different codes. Mode 3 has four thumbwheel selectors that provide the capability to select 4,096 codes.

**Mode-Selector Test Switches and Light**

Four mode-selector/test-selector switches labeled M-1, M-2, M-3/A, and M-C have TEST, ON, and OUT positions. In the momentary TEST position with the MASTER switch at NORM, lighting of the TEST light indicates proper operation of the mode selected. The mode switches for the modes not being tested should be OUT when testing on the ground to prevent unnecessary interference with nearby ground stations.

The OUT position for each switch disables its respective mode. The ON position for each switch enables the transponder to reply to interrogations for the mode selected. The M-C switch provides automatic coded altitude reporting in response to a ground station’s interrogation for air traffic control identification.

**NOTE**

The TEST light may flash once as each mode switch is released from TEST, and as the RAD TEST/MON switch is moved. This flash has no significance.
RAD TEST/MON Switch

The RAD TEST/MON switch is a three-position toggle switch spring-loaded to the OUT (center) position. When MON is selected, the TEST light comes on for 3 seconds each time an acceptable response is made to an interrogation in Modes 1, 2, 3/A, and C. When RAD TEST is selected, Mode 3/A or Mode 4 responds to TEST mode interrogations from a ramp test set during ground maintenance testing.

Mode 4 Operation

The Mode 4 controls and indicator light are grouped on the left side of the control panel. The MASTER rotary switch controls transponder operation in Mode 4 as well as in the other modes of operation. Mode 4 will operate normally, when selected, in either the NORM or EMER position, and at reduced receiver sensitivity in the LOW position. The Mode 4 function will be inoperative in either the STBY or OFF position. With the transponder functioning, Mode 4 operation is selected by placing the Mode 4 ON-OUT toggle switch to ON. Placing the switch to OUT disables Mode 4 operation.

The Mode 4 CODE control selects either of the two (A or B) Mode 4 codes. It has two additional positions, HOLD and ZERO. The switch is spring loaded to return from HOLD to the A position. At a designated daily time and/or prior to the day’s mission, maintenance or operations personnel mechanically set the Mode 4 code for the present code period in position A, and the code for the succeeding code period in position B, with a single insertion of the KIK-18/TSEC code changer key. Both code settings will automatically zeroize when power is turned off or lost after the landing gear has been retracted (that is, after initial takeoff). The code settings can be retained by activating the HOLD function, normally done after the aircraft has landed (landing gear must be down and locked) and before power is removed from the transponder. Place the Mode 4 CODE control to HOLD, and release. Allow transponder power to remain on for at least 15 seconds, and then turn it off. The code setting is now mechanically latched and will be retained when aircraft power is turned off.

Mode 4 settings should be manually zeroized if the aircraft does not make an initial takeoff (that is, gear was never raised), or if the hold function has been engaged and a subsequent takeoff was not carried out.

NOTE

If power is removed from the transponder less than 15 seconds after selecting HOLD, either by turning the transponder off or by turning off aircraft electrical power, the code setting may not be mechanically latched and will zeroize.

With aircraft power on and the MASTER rotary switch in any position except OFF, both code settings can be zeroized at any time by placing the CODE switch to the ZERO position. Both code settings will also be zeroized if the HOLD function has not been properly actuated before the MASTER switch is turned to OFF. Inadvertent selection of OFF is prevented by switch design, which requires that the rotary knob be pulled out before it can be turned to OFF. When the CODE switch is placed in the A position, the aircraft transponder will respond to Mode 4 interrogations from an interrogator using the same code setting as that set into the aircraft’s code A position. In the B position, interrogations from an interrogator using the same code setting as that set into the aircraft’s code B position will be answered. The changeover time from code A to code B use is operationally directed.

The Mode 4 AUDIO-LIGHT switch selects the aircraft indication for Mode 4 replies. In the LIGHT position, the Mode 4 REPLY lamp (green) will light when Mode 4 replies are transmitted. In the AUDIO position, an audio signal in the pilot’s headset indicates Mode 4 interrogations are being
received, and lighting of the Mode 4 REPLY light indicates when replies are transmitted. Mode 4 audio volume can be adjusted by the appropriate aircraft intercom audio volume control. In the OUT position, both light and audio indications are inoperative.

Mode 2 Code Selectors

The code control thumbwheels for Mode 2 are located on the front of the IFF/SIF transponder, as illustrated in Figure 6-41, view B. The Mode 2 reply code setting is usually established and dialed in by the technician prior to flight. As with Mode 3/A, the four thumbwheels provide for 4,096 available codes. The Mode 2 reply code normally cannot be changed in flight due to the inaccessibility of the transponder unit.

Transponder Normal Reply Modes and Codes

During IFF/SIF interrogation, the interrogating station will notify the pilot (via ultra-high-frequency or very-high-frequency communications) to set the transponder to a specific mode (1, 2, 3/A, and/or C or 4) of operation, and to undergo interrogation (identification), and in the case of Modes 1 and 3/A, will direct the pilot to set a specific reply code. Mode C and Mode 4 codes are automatically controlled by external equipment, and Mode 2 is preset.

Normal reply pulse characteristics of the IFF/SIF transponder are shown in Figure 6-42. These reply pulses are transmitted at 1,090 MHz, between two framing pulses labeled F1 and F2. The interrogator transmits on 1,030 MHz and receives on 1,090 MHz; the transponder receives on 1,030 MHz and transmits (replies) on 1,090 MHz. The following discussion refers to Figures 6-41 and 6-42.

When the transponder processes a Mode 1 challenge, a reply pulse train is transmitted containing two framing pulses 20.3 μsec apart, plus 0 to 5 information pulses (dependent upon the Mode 1 control dial settings). The information pulses are spaced in multiples of 2.9 μsec starting from the initial framing pulse. The position where a sixth pulse (17.4 μsec) would appear is not used. The information pulses are designated by a letter, with a number subscript, to identify a specific reply.

Figure 6-41 — Typical IFF/SIF transponder control box and transponder front panel Mode 2 control dials.
pulse. The subscript numbers are constructed in binary form (1, 2, 4, and so on). In the case of Mode 1, a maximum of three A pulses are possible (A1, A2, and A4) and a maximum of two B pulses (B1 and B2) are available. These reply codes (pulses) are set by the two control dials (M-1) on the control box. The left dial is used for setting the A reply pulses and the right dial is for the B reply pulses. All five of the information pulses are present in the reply train, as illustrated in Figure 6-42, corresponding to the maximum dial setting of Mode 1, which is 73. The left (A) dial has 8 settings, 0 through 7, and the right (B) dial has 4 settings, 0 through 3, which gives a maximum of 32 possible codes available. The way to construct a specific reply pulse train is governed by the addition of the particular pulse (such as A) subscript numbers. As an example, if 0 were selected on the left M-1 (A) dial, no A pulses would be present in the reply train. If 1 were selected, only the A1 pulse would be present in the reply train. If 3 were selected, the A1 and A2 (by adding subscript numbers you get 3) would be present, and so on. Keep in mind that any number (0 through 7) selected on the A control dial would read out in binary form in the A pulses' subscript numbers. As shown in Figure 6-42, in the Mode 1 reply pulse train, with A1, A2, and A4 pulses present, the A dial setting is 7 (1 + 2 + 4 = 7) and with B1 and B2 pulses present, the B dial setting is 3 (1 + 2 = 3).

When the transponder processes either Mode 2, 3/A, or test challenges, a reply pulse train is transmitted containing two framing pulses 20.3 μsec apart, plus 0 to 12 information pulses (dependent upon the respective dial settings for each mode). The information pulses are spaced in multiples of 1.45 μsec apart, starting from the initial framing pulse. The position where the seventh pulse (10.15 μsec) would appear is normally not used. This position, called the X-pulse position, will be explained later in this chapter. As in Mode 1, the 12 information pulses are designated by a letter and subscript numbers. Since Modes 2 and 3/A have four code dials (labeled M-3 on the control box and M-2 on the front of the transponder), there are four possible reply pulses that can be set. They are labeled A, B, C, and D, and correspond to the four control dials from left to right. The four control dials (for Modes 2 and 3/A) have 8 settings each (0 through 7) for a total of 4,096 available codes (8 x 8 x 8 x 8 = 4,096). As in Mode 1, the various pulse subscript numbers are in binary form for a particular pulse dial setting. As shown in Figure 6-42, all 12 information pulses are present in the reply train, signifying a dial setting of 7777. Add A subscript numbers, B subscript numbers, etc., to obtain the dial reading. If the dial setting for Mode 3/A were 1, 2, 3, 4, then the pulses present in the reply train would be A1, B2, C1, C3, and D4. Remember, the dial setting will read out in binary form the reply pulse subscript numbers.

The Mode C function of the transponder (altitude reporting) is referred to as AIMS. When this function was first introduced, it was believed that AIMS was an acronym for Altitude Information Monitoring...
System. However, AIMS is actually an acronym made up of other acronyms; A from ATCRBS, I from IFF, M from MARK XII Identification System, and S from system.

When the transponder processes a Mode C challenge, a reply pulse train is transmitted containing two framing pulses 20.3 μsec apart, plus 10 information pulses (as determined by an external pressure altitude digitizer based on the aircraft’s pressure altimeter reading). The information pulses are spaced 1.45 μsec apart from the initial framing pulse. The positions where the 7th (10.15 μsec), 9th (13.05 μsec), and 11th (18.85 μsec) pulses would appear are not used. From the 10 information pulses, a total of 1,024 codes are available (8 x 8 x 8 x 2). Note that in Modes 2, 3/A and C (Figure 6-42), the pulse positions are not in sequence (A, B, C, etc.) as they are in Mode 1. However, reading the subscript numbers for A pulses will give you the A dial setting, B for the B dial setting, and so on.

As previously stated, Mode 4 reply pulse coding is accomplished by external crypto equipment and is classified information. This information can be found in technical manuals for the KIT-1A/TSEC equipment.

**Transponder Special Reply Functions**

The special reply pulse characteristics for Modes 1, 2, and 3/A are shown in Figure 6-43. Modes C and 4 are not affected by the special reply functions.

**Identification of Position**

The identification of position (I/P) function is controlled by the IDENT/OUT/MIC (Figure 6-41, view A) switch and affects the operation of Modes 1, 2, and 3/A. In Mode 1, the reply pulse train containing the code in use is transmitted twice, instead of once, for each interrogation pulse received. The second reply pulse train is spaced 24.65 μsec from the leading edge of the first framing pulse in the first train. In Modes 2 and 3/A, the reply pulse train containing the code in use is transmitted once, followed by a special position indicator (SPI) pulse for each interrogation pulse received. The SPI pulse is spaced 24.65 μsec from the leading edge of the first framing pulse of the first train. The result of the extra pulse train in Mode 1 and the SPI pulse in Modes 2 and 3 can be seen in Figure 6-40. Two rows of dashed lines appear behind the target, instead of just one row as in normal operation. This feature is normally used to distinguish between two aircraft operating in the same mode and SIF code.
Emergency Reply Mode

The emergency mode of operation of the transponder is controlled by the master switch. Also, most aircraft have emergency IFF override switches on either the crew seats or the canopy. These switches energize when a crew member or canopy is jettisoned. These switches bypass the master switch and will automatically turn on the IFF and transmit emergency replies when interrogated.

The emergency function affects the operation of Modes 1, 2, and 3/A. In Modes 1 and 2, the reply pulse train containing the code in use is transmitted once for each interrogation pulse received, followed by three sets of framing pulses and no information pulses. The framing pulses will appear at 24.65 μsec, 44.95 μsec, 49.3 μsec, 69.6 μsec, 73.95 μsec, and 94.25 μsec. For each interrogation pulse received in Mode 3/A, one reply pulse train containing the code 7700 (regardless of the Mode 3 control dial settings) is transmitted, followed by three sets of framing pulses and no information pulses. The framing pulses are spaced the same as Modes 1 and 2. The result of these extra pulses can be seen in Figure 6-40. Four rows of dashed lines appear behind the target, instead of just one in normal operation.

X-Pulse

The military uses the X-pulse to distinguish unmanned aeronautical vehicles (UAVs), targets, and other special platforms from manned aircraft. This process has been in place for more than four decades. The X-pulse, 10.15 μsec from the initial framing pulse, appears in a normally unused position of Modes 1, 2, and 3/A. When the control box is modified, all replies in Modes 1, 2, and 3/A will include this pulse along with the normally selected information reply pulses, between the two framing pulses.

As you can see, with the capabilities of the IFF/SIF system to respond with over 8,100 reply codes in Modes 1, 2, and 3/A, plus the encrypted Modes 4 and 5, and the ability to report altitude information, the system allows for positive identification at long range, and aids greatly in air traffic control.
Review Questions

6-1. What is the basic function of the radar timer?

A. Produce range markers
B. Synchronize the sweep voltage or current for the indicator with the transmitter pulse
C. Synchronize the current and sweep voltage to produce gating circuits
D. Produce sweep pulses

6-2. In an externally synchronized system, the timing trigger pulses are obtained from ________.

A. the transmitter.
B. a master oscillator usually configured internally.
C. a master oscillator, usually external to the transmitter.
D. the receiver.

6-3. Which of the following circuits typically determines the repetition rate of radar timing pulses?

A. Countdown multivibrator
B. Double-swing blocking oscillator
C. Harley-Colpitts oscillator
D. Astable multivibrator

6-4. What is the main advantage of the single-swing blocking oscillator?

A. It generates two signals, 180 degrees out of phase
B. It generates sharp pulses directly
C. It generates positive triggers
D. It generates negative triggers

6-5. Intercept radar operating in the track mode must provide range data that is accurate to within which of the following measurements?

A. Inches
B. Feet
C. Yards
D. Miles

6-6. In B-scope and plan-position indicator-scope applications, the output of the range marker generator is applied to the ________.

A. transmitted pulse.
B. deflection plates.
C. video mixer.
D. cathode-ray tube directly.
6-7. The transmitter develops what kind of pulses or radiofrequency energy, which are radiated into space by the antenna?

A. High-power, high-frequency pulses  
B. Low-power, high-frequency pulses  
C. High-power, low-frequency pulses  
D. Low-power, low-frequency pulses

6-8. What unit in the radar system controls the radar pulsewidth by means of a rectangular direct current pulse of the required duration and amplitude?

A. Modulator  
B. Synchronizer  
C. Transmitter  
D. Receiver

6-9. Which of the following are types of storage elements used in a modulator?

A. Capacitor, battery, and artificial transmission line  
B. Artificial transmission line, capacitor, and antenna pedestal  
C. Pulse-forming network, battery, and artificial transmission line  
D. Capacitor, pulse-forming network, and artificial transmission line

6-10. In the figure above, the charge and discharge of C1 is controlled by what component in the circuit?

A. Q1  
B. Direct current power supply  
C. CR1  
D. Radiofrequency oscillator
6-11. In the figure above question 6-10, what factor controls the modulator pulsewidth?

A. Frequency of the radiofrequency oscillator  
B. Width of the trigger pulse applied to the base of Q1  
C. Size of the charging diode  
D. Size of the storage capacitor

6-12. In the figure above, what component controls the pulse repetition rate of the circuit?

A. Direct current power supply  
B. Charging impedance Z1  
C. Modulator switch  
D. Pulse transformer

6-13. In the figure to the right, what type of circuit is formed if the charging resistor is replaced by an inductor?

A. Parallel-resonant  
B. Series-resonant  
C. Capacitive  
D. Reactive

6-14. What component do radar receivers use to eliminate noise generated by radiofrequency amplifiers?

A. High-gain detector  
B. Cascade inverter  
C. Microwave mixer  
D. Low-gain mixer

Basic modulator – artificial transmission line.
Typical radar varactor, voltage-controlled oscillator circuit.

6-15. In the figure above, what is the function of component CR1?

A. Resistor  
B. Capacitor  
C. Transistor  
D. Varactor

6-16. In a radar receiver, what is the purpose of the automatic frequency control circuit?

A. To tune the local oscillator to the correct frequency  
B. To tune the transmitter to the receiver’s usable frequency  
C. To ensure the local oscillator is turned on during receive  
D. To ensure the local oscillator is not tuned during transmit time

6-17. What types of variables are possible on a B-scope display?

A. Range, azimuth, and intelligence  
B. Range, elevation, and intelligence  
C. Azimuth, elevation, and intelligence  
D. Range, azimuth, and elevation
6-18. In a C-scope presentation, what is represented by the vertical axis?

A. Range only  
B. Azimuth only  
C. Range and azimuth  
D. Elevation

6-19. In a plan-position indicator-scope presentation, what is represented by the distance along the sweep line?

A. Target range only  
B. Target azimuth only  
C. Target range and azimuth  
D. Target elevation

6-20. The E-scan presentation displays which of the following information?

A. Range and bearing only  
B. Azimuth and bearing only  
C. Range and height only  
D. Azimuth and height only

6-21. Which of the following is a function of the identification friend or foe system in combat?

A. Identify friendly aircraft to hostile force air traffic controllers  
B. Permit friendly forces to identify themselves when properly interrogated  
C. Provide a means for hostile aircraft to notify friendly forces of their intent to strike  
D. Provide range and bearing data to friendly aircraft

6-22. How many identification friend or foe modes of operation do naval aircraft use?

A. 4  
B. 5  
C. 6  
D. 7

6-23. What unit in the identification friend or foe system allows the operator to challenge incoming aircraft?

A. Transponder  
B. Interrogator  
C. Coder synchronizer  
D. Modulator

6-24. Which of the following situations does the presence of the x-pulse signify?

A. Medical evacuation aircraft  
B. In-flight emergency declared  
C. Unmanned aeronautical vehicle  
D. Aircraft returning from space
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6-53
CHAPTER 7

OPTIC AND INFRARED SYSTEMS

The purpose of electro-optical and infrared (IR) systems is to display essential flight and mission information directly to the pilot and battlespace commanders. The electro-optical sight uses a light source to display information that is useful to the pilot (Figure 7-1). A cathode-ray tube (CRT) is used to produce the displayed information. This system is known as a head-up display (HUD). Forward looking infrared (FLIR) systems use thermal imaging to deliver precision guided ordnance and gather intelligence to maintain battlespace superiority. In this chapter, you will see how these systems display flight and mission information. You will learn about typical HUD and FLIR systems used in ground attack and multirole fighter attack aircraft.

LEARNING OBJECTIVES

When you have completed this chapter, you will be able to do the following:

1. Identify the components and operating principles of a HUD system.
2. Discuss the proper test setup of a HUD system.
3. Recognize functions, characteristics, components, and operating principles of thermal or IR imaging.
4. Recognize components and functionality of a typical FLIR system.

HEAD-UP DISPLAY

The HUD unit is a visual display device that shows flight information without impairing the pilot's field-of-view (FOV) (Figure 7-2). The HUD receives flight information data from a tactical computer set; aircraft performance data from aircraft flight sensors; and discrete signals from various aircraft systems. Information received from the various systems is displayed on a transparent mirror (combiner) located directly in front of the pilot at eye level. Symbology characters provide information to the pilot on weapons aiming, navigation, aircraft situation, and steering. The symbols are focused to infinity and are superimposed over real world objects in line with the aircraft flight path even though the real world objects may not be visible.

During conditions of poor visibility, video imaging, referred to as raster, is produced and projected into the pilot's FOV. Symbology, referred to as stroke, can be displayed by itself or with raster. The combining of stroke with raster produces imagery where symbols appear to be superimposed on objects located an infinite distance from the aircraft.

Figure 7-1 — Basic principles of a sight system.
DESCRIPTION

The HUD (Figure 7-3) comprises a combiner assembly, mounted on an irregular shaped cast box structure. The box structure comprises a lower housing enclosed by an upper housing and top cover assembly. HUD basic components include the following assemblies:

- Combiner
- Bracket and prism
- Solar cell
- Upper housing
- Lower housing
A further breakdown of internal assemblies is included in the following text. A simplified disassembled view is provided in Figure 7-4.

**Combiner Assembly**
Combiner assembly U1 is mounted on top and to the rear of the upper housing via bridge assembly U2. It comprises a metal frame holding two optically coated combiner glasses. When the HUD is installed, the glasses are accurately located in the forward field of view and require no further alignment.

**Bracket and Prism Assembly**
The bracket and prism assembly comprises video pickup prism bracket A4A1 and HUD video camera (HVC) prism A4A2. Video pickup prism bracket A4A1 is mounted on top of the upper housing between top cover assembly U3 and bridge assembly U2. It provides a mounting for HVC prism A4A2 and an external video camera, HVC prism A4A2, is mounted on the left hand side of video pickup prism bracket assembly A4A1. It optically combines and transmits HUD display symbology and the forward FOV to the external video camera. External video camera operation will not be discussed in this chapter.

**Deflection Amplifier Assembly**
Deflection amplifier assembly AR1 is mounted on the left, inside face of the upper housing. It comprises a plug-in printed circuit card clamped to a machined heat sink. The heat sink houses high power components and provides a rigid structure. The assembly shapes and amplifies analog deflection signals to drive the electron tube assembly V1 deflection coils.
**Low Voltage Power Supply Assembly**

The low voltage power supply (LVPS) PS2 is mounted on the right, inside face of the upper housing. It comprises a plug-in printed circuit card clamped to a machined heat sink. The heat sink houses high power components and provides a rigid structure. The LVPS receives unregulated direct current (dc) inputs and converts them to regulated dc outputs for use within the HUD.

**Solar Cell Assembly**

The solar cell assembly is mounted on top of the top cover assembly U3. The assembly comprises a light sensor which senses changes in ambient lighting. When selected, it varies the display brilliance to compensate for changes in background lighting. The assembly is connected to the remainder of the HUD via a terminal board and connector assembly in the top cover assembly U3.

**Upper Housing**

The upper housing comprises an upper housing assembly A1, housing an optical desiccant container U4. It forms the upper portion of the HUD. The upper housing is secured to the lower housing by special hinged screw assemblies.

**Upper Housing Assembly**

Upper housing assembly A1 consists of a large rigid casting, housing optical components and a wired harness assembly. The rear half comprises a sealed optical section housing the optical components. The front half of the assembly and the top cover assembly U3 enclose the electronic section of the HUD. It incorporates a heat exchanger, which with air channels in lower housing assembly A2, facilitates cooling.

Assembly A1 provides mounting facilities for a coordinate data control (CDC). The CDC is mounted to the rear of assembly A1 by brackets and to the rear of assembly A2.

**Optical Desiccant Container**

Optical desiccant container U4 is mounted in the left side of the optical section of assembly A1. It maintains a dry environment within the optical section of the HUD.

**Lower Housing**

The lower housing forms the lower portion of the HUD. It comprises a lower housing assembly A2, housing the following assemblies:

1. Control panel assembly A3  
2. Brightness control circuit card assembly A5  
3. Video electronics circuit card assembly A6  
4. Built-in test (BIT) electronics circuit card assembly A7  
5. Interface and burn protection circuit card assembly A8  
6. Rectifier assembly PS1  
7. High voltage power supply assembly PS3  
8. Electron tube assembly V1
Lower Housing Assembly
Lower housing assembly A2 comprises a large rigid casting, frame assembly, hinged top module assembly, and wiring harness assembly.

Wiring Harness Assembly
The wiring harness assembly provides the main electrical interface between the various assemblies of the HUD. It includes electrical receptacle connectors, A2J1 and A2J3, which provide external interface facilities. Receptacle connector A2J1 is located on the front face of assembly A2. Receptacle connector A2J3 is located on the rear face of assembly A2.

Control Panel Assembly
Control panel assembly A3 provides control of the HUD switch-on, symbology display, and video display functions. The HUD switch-on and symbology display controls comprise HUD symbology (HUD SYM NORM/REJ1/REJ2) mode switch A3S3, brightness (HUD SYM BRT) control A3S5/R2, and brightness level (HUD SYM DAY/NIGHT/AUTO) switch A3S1 and altitude (ALT BARO/RDR) switch A3S2. The video display controls comprise video brightness (VIDEO BRT) control A3S4/R1 and contrast (VIDEO CONT) control A3R3. The control panel assembly plugs into the rear face of assembly A2.

Brightness Control Circuit Card Assembly
Brightness control circuit card assembly (CCA) A5 plugs into the top module assembly. It comprises a plug-in printed circuit card with components on one side. The assembly controls the brightness of the electron tube assembly display.

Video Electronics Circuit Card Assembly
Video electronics CCA A6 plugs into the top module assembly. It comprises a plug-in printed circuit card assembly with components on one side. The assembly processes and shapes composite video for use by the electron tube assembly V1.

BiT Electronics Circuit Card Assembly
BiT electronics CCA A7 plugs into the frame assembly using guides to ease replacement. It comprises a plug-in printed circuit card with components on one side. The assembly interrogates the HUD circuit functions. It also controls the HUD ready and HUD go/no-go outputs to external sources.

Interface and Burn Protection Circuit Card Assembly
Interface and burn protection CCA A6 plugs into the frame assembly using guides to ease replacement. It comprises a plug-in printed circuit card with components on one side. The assembly selects the output from an external source to be used by the HUD. It also provides burn protection for the electron tube assembly V1.

Rectifier Assembly
Rectifier assembly PS1 is mounted in the bottom face of assembly A2. It comprises a baseplate upon which are mounted a three-phase transformer and printed circuit card, housing rectifying diodes. It also contains relays and interference suppression components. The assembly receives an external 115/200 Vac, 400 Hz, three-phase phase alternating current (ac) supply. It generates ac and unregulated dc voltages for use within the HUD.
High Voltage Power Supply Assembly
The high voltage power supply (HVPS) PS3 is essentially an encapsulated block mounted in the bottom face of assembly A2. The assembly converts unregulated dc inputs to highly stable high voltages for use by the electron tube assembly V1. It incorporates a dynamic focus system which varies the focus voltage according to the position of the electron tube assembly display point.

Electron Tube Assembly
Electron tube assembly V1 is mounted within assembly A2, with its display end adjacent to the optical section of assembly A1. It comprises a CRT assembly V1A1, CRT electronic circuit card assembly V1A2 and harness assembly V1WS. CRT assembly V1A1 comprises a CRT with deflection coils integrated into a metal envelope. CRT electronics circuit card assembly V1A2 houses presets for the electron tube assembly functions. Harness assembly V1WS provides electrical interconnections within the electron tube assembly and to the remainder of the HUD. The electron tube assembly displays symbology in response to external inputs.

PRINCIPLES OF OPERATION
The HUD comprises a completely integrated electronic optical system. The electronic section of the system converts electrical inputs from an external source to a visual display. The optical section of the system transmits the visual display to the wide forward FOV. It also transmits the visual display and the wide forward FOV to the external video camera.

Power Distribution
It is recommended that schematics in Figures 7-5 and 7-6 be printed out to observe the overall power distribution flow.

Three values, 28 Vdc, 115 volts ac (Vac), and ground, are supplied to the rectifier assembly through reference points B8, 9, and 14 (Figure 7-5). Power up is initiated by S5 on the HUD control panel. Initial rotation of S5 closes the contacts, enabling power up. 28 volts dc (Vdc) is applied to the coils of the power on relays, closing contacts PS1K1-A, PS1K1-B, PS1K2-A, and PS1K2-B, allowing 115 Vac to flow to the three-phase transformer rectifier circuit.

Energizing the 3 phase transformer rectifier circuit produces nine voltage outputs (reference points 1, 2, 3, 6, 9, and 13) and provides ground (reference points 10, 15, and 17).

NOTE
The following assemblies contain electrostatic sensitive devices, which can be damaged if special handling techniques are not used:
1. Deflection amplifier assembly, AR1
2. Brightness control CCA, A5
3. Video electronics CCA, A6
4. BIT electronics CCA, A7
5. Interface CCA, A8
6. LVPS, PS2
7. HVPS, PS3
8. Electron tube assembly, V1
Figure 7-5 — HUD power distribution 1 of 2.
Figure 7-6 — HUD power distribution 2 of 2.
Direct current voltages and ground are supplied to the low voltage power supply PS2 through reference point 1 (Figure 7-6). There is 6.3 Vac supplied to the BIT electronics circuit card and the electron tube assembly through reference points 3 and 9. Also, -140 Vdc is supplied to the video electronics circuit card and capacitor A1C1 on the low voltage power supply through reference point 6. There are three values, +30 Vdc (reference point 13), ground, and chassis ground (reference points 15, 16, 17), supplied to the high voltage power supply.

The low voltage power supply PS2 (Figure 7-6) produces regulated +15 Vdc, -15 Vdc, and +5 Vdc outputs. These regulated outputs are supplied to the brightness control card; the interface and burn protection card; the BIT electronic card; the video electronics card; the deflection amplifier; and the electron tube assembly. The low voltage power supply PS2 (Figure 7-6) provides +15 Vdc and -15 Vdc to the high voltage power supply. Positive 15 Vdc potential is felt at schematic reference point 14, and negative 15 Vdc potential is felt at schematic reference point 11 in Figure 7-5. Positive 15 Vdc is supplied to the control panel assembly to provide power for the switches. Negative 15 Vdc flows through the closed contacts of PS1 K2-B and down to schematic reference point 5 in Figure 7-6. Negative 15 Vdc flows to the power on relay of the electron tube assembly. On the high voltage power supply card (Figure 7-6), the internal dc power supplies produce multiple dc voltages that energize the shut-down switch, anode power supply, G2 power supply, and the focus power supply.

The electron tube assembly V1 (Figure 7-6), produces four focus outputs, focus H, W, L, and dynamic focus, which are sent to the focus power supply. The remote focus and dynamic focus inputs to the focus power supply cause the +3,500 Vdc output to vary, correcting for radial focus variation of the CRT. The electron tube assembly V1 incorporates an extra high tension (EHT) circuit. When V1 is triggered to shut down, it sends a dc voltage to the high voltage power supply shut-down switch. The shut-down switch interrupts high voltage dc output.

**Display System**

It is recommended that schematics in Figures 7-7 through 7-10 be printed out to observe overall operation and signal flow.

**Deflection Channels**

The HUD receives analog X and Y deflection inputs from the display computer on reference points B24, 28, 29, and 30 (Figure 7-7). The analog X and Y deflection signals are inputted to the interface and burn protection circuit card differential amplifiers. Signals are combined and amplified by the interface and burn protection card for output on reference points 5 and 6. Analog video deflection signals are received by X and Y deflection correction amplifiers on deflection amplifier assembly AR1 (Figure 7-8). The X and Y deflection correction (or pin-cushion) amplifiers shape the inputs to compensate for windshield curvature and CRT pin-cushion effect. The X and Y deflection correction amplifier outputs are sent to X and Y summing networks. The FXX and FXY outputs are combined and sent to the voltage follower. The pin-cushion and windshield corrected deflection outputs are further altered by the X and Y summing networks and amplified by the X and Y deflection amplifiers.

The X and Y deflection correction amplifier outputs, FXX and FXY, are buffered by the voltage follower to produce an FX2 output. The FX2 output is sent to the dynamic focus amplifier on the CRT electronics circuit card to produce 3,500 Vdc dynamic focus output.
The X and Y deflection amplifiers produce several outputs, dampening feedback, X and Y coil signals, and outputs to the respective differential amplifiers. Dampening feedback is used to correct outputs through the summing networks.

The X and Y deflection amplifier outputs are referenced to ground through low resistance current sense resistors RSX and RSY.

The RSX resistor produces three outputs—one output goes to the X differential amplifier; another is an X sensing resistor that goes to the energy recovery circuit; and the third is X deflection (X DEF) that goes to X gain preset on the CRT electronics card V1A2.

Resistor RSY produces three outputs—the Y differential amplifier; the Y deflection (Y DEF) output to the Y gain preset on the CRT electronics circuit card; and the Y coil – signal output. The Y coil – signal output from resistor RSY, along with Y coil + signal and X coil + signal outputs, are inputted to the CRT assembly V1A1.

The X monitor and Y monitor outputs (Figure 7-8) are produced by the respective differential amplifiers. The X and Y monitor signals are inputted to the interface and burn protection card and are monitored by an external circuit. On the CRT electronics card, six outputs—X Gain, Y Gain, X Align, Y Align, X BIT, and Y BIT, are produced and fed back to the X summing network on the deflection amplifier assembly. On the CRT electronics card, X DEF and Y DEF signals go through preset resistors to produce X Gain and Y Gain feedback signals for the summing networks on the deflection amplifier assembly. The purpose of the feedback signals is to control amplification of X and Y deflection signals to the CRT assembly. Four analog switches are controlled by sample cathode output from the brightness control card and BIT sample output from the BIT electronics card. The X BIT adjust and Y BIT adjust values are buffered and sent to the summing networks on the deflection amplifier assembly. The X and Y Align outputs are produced by +15 Vdc and -15 Vdc reference voltages sent through presets. The X and Y align values are buffered, and then sent to the deflection amplifier X and Y summing networks on the deflection amplifier card.

**Brighten Up Control**

The operation of the bright-up control varies with the display mode selected. The display modes are stroke, raster, and raster/stroke. Stroke is used to display symbology; raster is used to display a video picture of the outside world; and raster/stroke is used to display both simultaneously.

Inputs from the display computer to the brightness control card are test brightness, complex analog symbology, and complex analog raster/stroke. In stroke mode, the raster/stroke input provides a signal that enables stroke display. Symbology and raster/stroke signals are inputted to differential line receivers through reference points B-A1, B26, and B27 shown in Figure 7-7. Symbology signals are combined and sent to the differential comparator, then outputted as stroke bright-up (BU) to the BU gating logic. The stroke BU output is produced when symbology input is at stroke peak brightness. Raster/stroke signals through a differential line receiver are outputted as raster/stroke to the BU gating logic. The raster BU output is produced when symbology input is at either raster or stroke peak brightness. The Consolidated Automated Support System (CASS) sample signal, from the BIT card, is routed through the sample cathode timer and produces two outputs. One output is applied to the video electronics card and to external circuits while the second output is applied to the BU gating logic. The control panel provides night discrete input to the BU gating logic when night is selected. Bright-up gating logic produces three outputs to the BU summing amplifier that are used to produce output to the brightness control multiplier. The output of the bright-up summing amplifier produces BU demand with four output levels—stroke peak brightness for stroke display; stroke peak brightness for stroke in raster display; raster peak brightness for raster display; and occult for all other conditions.
Figure 7-7 — HUD functional diagram 1 of 4.
Figure 7-8 — HUD functional diagram 2 of 4.
The PG2 input from reference point 25, from the CRT electronics card, passes through the brightness gain transistor switch and is inputted to the brightness control multiplier. The brightness control multiplier amplifies the BU demand input with the brightness gain input PG2. The brightness control multiplier output is fed to a buffer amplifier. The symbology brightness demand output, from buffer amplifier, along with sample cathode, is applied to the video electronics card to drive the CRT grid. That concludes the stroke portion of the bright-up control. Next, you will learn about raster bright-up control.

Complex analog raster/stroke input from the display computer is applied to a differential line receiver. Output from the differential line receiver is fed to the bright-up gating logic, the field blanking monostable, the line blanking monostable, and the inverter. The inverter produces raster/stroke output. Raster/stroke signal is outputted to the interface and burn protection circuit card assembly mode select switch and is monitored by an external circuit through reference point A95. The field blanking monostable controls the beginning and end of the video blanking fields as the image is painted on the CRT screen.

The field blanking monostable (Figure 7-7) produces two outputs. Retrace inhibit is sent to the video electronics card through reference point A84. The second output triggers the bright-up gating logic and the field blanking transistor switch. Raster switch signal is produced by the field blanking transistor switch. The raster switch signal is not produced when the BU inhibit signal is felt on the field blanking transistor switch. The raster switch signal is sent to the video electronics card and is monitored by an external circuit. The line blanking monostable controls the beginning and ending of the line blanking period when the raster line is flying back to start painting another line. Line blanking monostable output is sent to the transistor drive to produce line blank output to the video electronics card through reference point A82.

Raster and raster in stroke modes of display are enabled when switch S1 is in the night position, applying night discrete ground potential to the bright-up gating logic. Raster/stroke input provides a string of pulses that control the field and line blanking periods through the monostables. When raster is selected, raster/stroke input, with raster switch output, and night discrete ground potential cause the bright-up gating logic to produce raster BU output to the bright-up summing network. This allows symbology information to be superimposed on raster display.

Display Brightness

Display brightness controls the grid of the electron tube assembly. Brightness control begins with test brightness signal from an external source on reference point A80 in Figure 7-7, or the solar cell, when HUD control panel switch S1 is in the auto position. The solar cell monitors cockpit lighting and produces an output, matched to the response of the human eye, to the solar cell amplifier. The shaping amplifier ensures the display is suitably bright under conditions of darkness and corrects for eye response. The HUD control panel switch S1 has three positions-day, auto, and night. The S1 switch gives the pilot control of display brightness. In auto position, a value from the solar cell circuit is used as a reference voltage. If day or night are selected +15 Vdc, as dropped by resistor ASA2R3, it is used as a reference voltage.

Reference voltage through switch S1 flows to resistor R2, allowing the pilot to manually adjust brightness control demand to the amplifier. The amplifier, which is on the brightness control circuit card, provides positive offset value for low brightness conditions. The amplifier produces PG1 output to analog switches on the BIT electronics card and to an external circuit for monitoring through reference point A89.

The PG1 reference voltage signal on reference point 19 shown in Figure 7-8 is applied to the analog switches on the brightness control card. The analog switches are controlled by BIT sample output from the BIT sample gating logic. Using either PG1 reference voltage or +3.3 Vdc if PG1 voltage is
lower or absent, the analog switches enable brightness gain output voltage. Brightness gain reference voltage is applied to the brightness gain preset potentiometer on the CRT electronics card and is monitored by an external circuit through reference point A88.

Brightness gain reference voltage crosses the brightness gain adjustment preset potentiometer on the CRT electronics card and is outputted as PG2 reference voltage through reference point 25. PG2 voltage is applied through the brightness gain transistor switch to the brightness control multiplier. The PG2 determines the magnitude of the BU demand pulses.

**Burn Protection**

The interface and burn protection card (Figure 7-7) employs two methods to protect the CRT from burning the phosphor screen, BU inhibit, and EHT shutdown. Inputs to the card are X and Y deflections; reference points B24/30 and B28/29; X monitor and Y monitor signals; reference points 13 and 12 from the deflection amplifier assembly (as explained in display system flow, bright-up control); and raster/stroke signal produced by the brightness control card.

The BU inhibit circuit is controlled by the X and Y monitor and raster/stroke signals. The X and Y monitor signals are inputted to differential comparators and raster/stroke signal is inputted to the mode selection switch on the interface and burn protection card. Raster/stroke signal is fed through the mode selection switch to the X monostable to control the time-out periods for raster and stroke modes of operation. Normally, X and Y deflections change constantly, and the monostables retrigger regularly. If either the X or the Y deflections become stable, then the corresponding X or Y monostable fails to retrigger.

When either X or Y monostable fails to retrigger, the BU gating logic senses the lack of change and produces the BU inhibit signal. BU inhibit signal is outputted to an external circuit through reference A83 and to the brightness control card, brightness gain transistor switch, and field blanking transistor. The BU inhibit signal to the brightness gain transistor switch interrupts brightness gain signal, PG2, from being inputted to the brightness control multiplier, interrupting symbology output to the video electronics card. The BU inhibit signal to the field blanking transistor switch interrupts raster switch signal output to the video electronics card and external circuits.

The EHT shutdown circuit on the interface and burn protection card is comprised of the differentiator, comparator, EHT monostable, buffer amplifier, and EHT gating logic. The EHT circuit monitors the BU demand through the grid monitor input from the video electronics card. The BU demand on the grid monitor line is inputted to the comparator and the differentiator. If the differentiator detects a stationary or interrupted BU demand, it sends output to the EHT monostable to inhibit retriggering. The EHT monostable retriggers regularly, which inhibits output to the EHT gating logic. Raster/stroke signal is fed through the mode selection switch to the EHT monostable to control the time-out periods for raster and stroke modes of operation. If the EHT monostable is not retriggered within its time-out period, it produces output to the EHT gating logic. The comparator compares the BU demand from the grid monitor signal with a cut-off voltage value from the brightness control card.

On the CRT electronics card (Figure 7-8), the cut-off adjustment variable resistor uses +15 Vdc and -15 Vdc values to produce the cut-off value. The cut-off output value is set to the brightness cut-off level of the CRT. The cut-off output value is inputted to the comparator through a buffer amplifier on the interface and burn protection card (Figure 7-7) through reference point 22. Cut-off output is also sent to the video electronics card. The comparator measures the grid monitor BU demand in comparison to the cut-off value. If the grid monitor BU demand exceeds the cut-off value, the comparator produces output to the EHT gating logic. The EHT shutdown signal is supplied to an external circuit and goes off the schematic at line reference points 14 (to the video electronics card) and 20 (to the CRT electronics card).
The EHT shutdown is fed to the video electronics card and the CRT electronics card. The EHT shutdown voltage is routed through the video electronics card (Figure 7-8) to the high voltage power supply shutdown lead. The high voltage power supply shutdown interrupts high voltage dc supplied to the CRT. The EHT shutdown voltage is present at schematic line reference point 20, and down the EHT shutdown line to the cathode supply on the CRT electronics card. Normally, the cathode supply receives -15 Vdc on the power on relay line. During normal shutdown, +250 Vdc from the high voltage power supply is used to apply a voltage that rises to +80 Vdc and then decays to 0 Vdc on the CRT cathode. The cathode supply also produces output to the cathode current monitor to produce auto reset signal for the video electronics card and is monitored by an external circuit through reference point A97. The gain of the cathode current monitor is set by the auto reset adjust variable resistor on the cathode supply. During EHT shutdown, cathode supply output is held positive instead of decaying down to 0 Vdc during normal shutdown. The purpose of applying positive voltage to the CRT cathode is to prevent damage to the phosphor at switch off.

Video Channel

The video channel is comprised of the video electronics card (Figure 7-9) and a portion of the control panel. The video electronics card processes and shapes the external composite (comp) video signal to provide a video signal. The comp video signal from the external source is inputted to the video electronics card differential amplifier through reference point B-A2. In addition to comp video signal, inputs from the brightness control card and the CRT electronics card are used to control display brightness on the CRT. Voltage values present from the CRT electronics card are cut-off, video gain, and auto reset. Signals present from the brightness control card are line blank, retrace inhibit, symbology, raster switch, and sample cathode.

Manual adjustments from the control panel produce video brightness (A3S4 potentiometer R1) and video contrast (potentiometer A3R5) voltage values. The comp video signal is processed by the differential amplifier. Output from the differential amplifier is fed to the sync separator and the black level clamp. The synchronization (sync) separator produces a comp sync trigger signal every time there is separation between the synchronization pulses and the video information signal is below the blanking level. Comp sync signal is outputted to the back porch monostable and to an external monitoring circuit via line 34. Comp sync signal triggers the back porch monostable to output pulses to the black level clamp sample hold circuit.

The black level clamp (Figure 7-9) sample hold circuit and the black level clamp form a feedback loop to set the black level value for the CRT display. The black level clamp sets the black level of the comp video input to 0 Vdc. Video signal from the black level clamp is sent to a multiplier. Video contrast voltage value is fed through the associated buffer amplifier and provides the second input to the multiplier. The multiplier, using video contrast signal as a gain factor, multiplies the black level video signal and outputs it to the summing amplifier.

Video brightness value is fed through the associated buffer amplifier to the summing amplifier. Video brightness voltage is used to offset the video signal. The summing amplifier produces video signal that is fed to a video limiter through reference point 33. There are more input signals to the video electronics card to discuss before moving on to the second half of the card. Video gain voltage is sent through two buffer amplifiers to produce two outputs that continue down the card through schematic line reference points 29 and 30. Retrace inhibit and raster switch video signals inputted to the fly back monostable produce a resonant retrace signal sent to the CRT electronics card through reference point 32. In raster mode, raster switch input turns off the resonant retrace pulse during line blanking periods. In stroke mode, retrace inhibit interrupts resonant retrace output.
Figure 7-9 — HUD functional diagram 3 of 4.
Video signal from the summing amplifier is fed to the video limiter from reference point 33 in Figure 7-9. The video limiter purpose is to limit video signal to prevent over driving the CRT. Video limiter output is fed to the analog switches and raster contacts. The analog switches are controlled by signals from the first half of the video electronics circuit card. The mode gating logic circuit uses raster switch and sample cathode input video signals to control the analog switches. On the 450SUM3, the outputs are routed to the raster and gamma analog switches. On the 450SUM5, the outputs are routed to the stroke and raster switch. The voltage follower uses a reference voltage to produce a BU signal at the sample cathode analog switch through reference point 39, Figure 7-9. The cathode current sample/hold circuit uses inputs from sample cathode and auto reset to produce a reset control signal at reference point 41.

Mode gating logic circuit analog output signals are applied at reference points 37 and 38, shown in Figure 7-10, to control the raster and gamma switches on the 450SUM3. Also applied is BU signal, from the voltage follower, reference point 39 to the sample cathode switch. Zero Vdc is supplied to the gamma analog switch. Raster switch video signal at reference point 36 is already in place to control the stroke analog switch. Sample cathode video signal at reference point 40 controls the sample cathode analog switch. The gamma analog switch is used on the 450SUM3 system only. The 0 Vdc output is used to reduce noise in the gamma correction circuit of the summing network.

Reset control signal, produced by sample cathode and auto reset signals through the cathode current sample hold circuit, comes on to this schematic at line reference point 41. The reset control signal maintains the black level of the CRT grid and is monitored by an external circuit. All the input signals to the summing network are in place. The summing network uses all nine inputs to produce a composite signal that controls the grid drive amplifier. The grid amplifier receives -140 Vdc from the rectifier, PS1, and composite signal from the summing network. Grid drive amplifier output drives the grid on the CRT, and is sent through a divider circuit for monitoring by an external circuit and the interface and burn protection card. Outputs from the video electronics card (Figure 7-8) are resonant retrace, grid, and grid monitor signals. Resonant retrace signal is routed off this schematic, and then returns at line reference point 27. From reference point 27, it is fed to the energy recovery circuit on the CRT electronics card. Resonant retrace pulse is produced by the fly back monostable, on the video electronics card, during line painting periods. During line blanking, the absence of the resonant retrace pulse enables the energy recover circuit to store residual current from the X coil.

**Built-In Test**

The BIT system checks the HUD for correct function and produces outputs that protect the HUD and provide information to external monitoring circuits. The CRT has a photodiode (Figure 7-8) that monitors a phosphor dot on the CRT screen for brightness. The photodiode output is sent to the level detector on the CRT electronics circuit card. The photodiode output is processed by the level detector and is referenced to the BIT level adjust preset. The resulting value is fed to the comparator. The comparator circuit uses the input from the level detector to produce BIT comp output. BIT comp is fed to the delay circuit on the BIT electronics card and is monitored by an external circuit through reference point A87.

The BIT card receives BIT/SYNC 1 signal from an external circuit through B15 and 16 to the differential line receiver. BIT/SYNC 1 signal is a 30 microsecond (µs) pulse transmitted at the end of each CRT framing period. BIT/SYNC 1 differential line receiver produces an output to the BIT sample gating logic. The BIT sample gating logic circuit generates digital BIT sample and digital BIT sample outputs. The BIT sample and BIT sample corresponds directly to the start of each BIT/SYNC 1 pulse. BIT sample and BIT sample signals initiate BIT interrogation. BIT sample output controls the analog switches, is monitored by an external circuit, and is sent to the sample cathode timer on the brightness control card. BIT sample closes the analog switches allowing PG1 voltage and +3.3 Vdc
reference voltage to produce the brightness gain output to the CRT electronics card. BIT sample signal flows off the schematic at line reference 15. The BIT sample signal at reference point 15 flows to the sample cathode timer on the brightness control card. The BIT sample input to the sample cathode timer produces sample cathode and a second output. The second output is sent to the bright-up gating logic enabling stroke BU during BIT interrogation. Sample cathode signal is monitored by an external circuit and flows to the CRT electronics card via schematic reference point 21.

Sample cathode signal comes on to the schematic (Figure 7-8) at reference point 21 and controls analog switches on the CRT electronics card. The analog switches when closed apply reference voltages to produce X BIT and Y BIT outputs toward the end of the BIT interrogation. On the BIT electronics card (Figure 7-8), the BIT sample gating logic produces BIT sample, which is applied to analog switches, controlling brightness gain, and to the delay circuit to latch the BIT comp signal. BIT sample signal controls analog switches on the CRT electronics card. BIT sample signal to the CRT electronic card analog switches connecting the X BIT and Y BIT outputs centralize the CRT electron beam to the phosphor dot target for approximately 1 µs. When the HUD is functioning correctly, the X BIT and Y BIT signals cause the CRT phosphor dot to illuminate. The CRT photodiode picks up the intensity of the phosphor dot and the CRT electronics card produces BIT comp signal, as previously shown in this lesson segment.

The BIT comp signal (Figure 7-8) to the delay circuit is fed to the HUD go/no-go logic to transmit a HUD ready and a HUD go/no-go signal. When the HUD is functioning correctly, the BIT comp signal is high and the go/no-go logic produces HUD go signal to the external monitoring circuit through B19. When a HUD fault is detected, BIT comp signal goes low (BIT fail), after a 192 millisecond (msec) delay, by the delay circuit, the HUD go/no-go logic transmits the no-go signal to the external monitoring circuit.

**Optical System**

The HUD optical system transmits the CRT display to the pilot’s FOV. It also transmits the CRT display together with the wide forward FOV to the external video camera. The system comprises the upper housing optical section, HVC prism A4A2, and combiner assembly U1.

The upper housing optical section collimates the CRT display. The section incorporates a field flattener lens, input lenses, a solar filter lens, a mirror, exit lenses, and windshield correction lens. The solar filter lens minimizes the damaging effects of direct sunlight on the CRT assembly V1A1 phosphor. The windshield correction lens provides the main compensation or windshield curvature distortion effects.

The collimated CRT display is transmitted to the combiner assembly U1. The twin glasses of the combiner assembly U1 superimpose the CRT display in the wide forward FOV.

The HVC prism A4A2 optically combines and transmits the CRT display and the forward FOV into the external video camera. It comprises semi-reflecting and combining beam splitters, a rectangular glass block, mirror and roof prisms, and relay and field lenses.

The semi reflecting beam splitter reflects the CRT display to the combining beam splitter through the rectangular glass block. It also transmits the CRT display to combiner assembly U1. The semi reflecting beam splitter is positioned above the left-hand side of the upper housing optical section exit lenses.

The FOV mirror prism reflects the forward FOV to the combining beam splitter. The CRT display is accurately superimposed onto the forward FOV image within the combining beam splitter. The resultant combined image is relayed to the external video camera via the relay and field lenses and the relay mirror and roof prisms.
Figure 7-10 — HUD functional diagram 4 of 4.
TEST SETUP

The HUD is tested electronically and optically using the CASS (Figure 7-11). This section explains how the HUD is connected to CASS for testing. The CASS runs both diagnostic and performance tests on the HUD. In both cases, operator intervention is required for several steps.

The test bench diagram for testing the HUD using CASS is shown in Figure 7-12. There are three major assemblies in the system used for testing the HUD. These assemblies are the CASS station AN/USM-636(V), the interface device (ID), and the HUD test fixture (mounted on the mobile maintenance cart).

The following instructions are generalized and are for training purposes only. These steps are to be completed in order:

1. Remove protective covers and mount the ID on the test station. The ID protective cover must be removed. The ID connectors must be visually inspected for damage prior to being installed on the CASS station. Remove the protective cover prior to mounting the ID. Inspect the connectors for damage prior to mounting the ID. The ID is then mounted on the CASS station as shown in Figure 7-13. After the ID is mounted properly, you are ready to move on to the next step.

2. Remove the CASS work surface and install the mobile maintenance cart. Move the mobile maintenance cart into position on the last CASS unit and secure in place.

3. Connect ground cables to the test fixture and mobile cart as shown in Figure 7-12. CASS provides the common ground (GND) point, GS1, to HUD test fixture at P1/J103 and the mobile maintenance cart.
cart at P1/GND for the test setup. In addition to the external ground, the ID also requires external ac power to P2/J101 from the CASS station, P1.

4. Connect the HUD test fixture to the ID. Connect the HUD as shown in Figure 7-12 to the ID using three cable assemblies, W201, W202, and W203:
   a. Cable assembly W201 connects the HUD test fixture and the CASS ID at the highlighted points.
   b. Cable assembly W202 connects the telescope, the HUD airflow sensor, and the CASS ID at the highlighted points.
   c. Cable assembly W203 connects the HUD solar cell and the CASS ID at the highlighted points. The HUD solar cell is not connected until after the HUD has been installed into the test fixture.

5. Install the HUD on the HUD test fixture. Proper mounting of the HUD in the test fixture is important to ensure correct electrical and optical performance. The lower rear section of the HUD features alignment holes, electrical connectors, and airflow cooling coupling. Once the HUD is positioned on the alignment pins (Figure 7-14), the center jack bolt is tightened to seat the HUD in the test fixture. Then, the two outer captive bolts are tightened to lock the HUD in place.

6. Cover the combiner lens and digital camera. Using the cover specified, cover the combiner lens and digital camera to keep ambient light and images out of the visual field during testing.

7. Insert the solar cell cable and adapter. The solar cell adapter slips over the outer circumference of the solar cell cylinder. The adapter allows CASS to control the level of ambient light the solar cell senses and can measure the effect on brightening and dimming the CRT display.

8. Connect the blower hose to the HUD test fixture. The HUD test fixture features a connection to provide cooling air to the HUD during testing (Figure 7-15). The airflow travels inward toward the HUD. The air flow sensor signals when cooling air is flowing into the HUD. The CASS will not operate the HUD testing program until it receives this signal.
The HUD is now properly installed and ready for diagnostic testing and troubleshooting. At this point, a systematic set of procedures is provided to maintenance personnel by the test program set index (TPSI). Instructions are specific to the type of equipment being tested and will not be discussed in this chapter.

**THERMAL IMAGING**

Humans can see only a small part of the entire electromagnetic spectrum; however, other parts of the spectrum contain useful information. The IR spectrum is a small portion of the entire electromagnetic spectrum.

IR radiation is also known as thermal or heat radiation. Most materials emit, absorb, and/or reflect radiation in the IR region of the electromagnetic spectrum. For example, an aircraft parked on a sunlit runway absorbs and radiates varying amounts of IR radiation. After sunset, the aircraft continues to radiate the absorbed heat, making detection at night possible. Even if the aircraft is moved, detection of the aircraft is possible because the runway surface, which was directly below the aircraft, will be cooler than the surrounding runway.

Thermal imaging is referenced in terms of temperature instead of reflectivity (radar) or color (visible light). Variations of the temperature in a scene tend to correspond to the details that can be visually detected. It is the function of the IR imaging system to process this information and convert it into information that the system operator can use. Currently, the types of imaging systems generally used are mechanical scanning, fast-framing devices. They use the frame rate (information update rate) that is similar to television. They are known as FLIR devices.

Before a target can be detected, it must exchange energy with its environment, be self-heating, have emissivity differences, and reflect other sources. An aviation warfare systems operator from an anti-submarine helicopter squadron scans for surface contacts using a FLIR pod in *Figure 7-16*. The FLIR operator aims the limited FOV FLIR to search the scene for targets, using a search pattern and clues, such as radar targets or laser designators.
Thermal sensitivity, image sharpness, spectral response, contrast, and magnification are used in the FLIR system to produce a visual image of the thermal scene. The operator uses training, experience, and image interpretation skills to detect and identify targets.

**Infrared Radiation**

The atmosphere is a poor transmitter of IR radiation because of the absorption properties of carbon dioxide (CO$_2$), water (H$_2$O), and ozone (O$_3$). Infrared radiation is broken into four regions by characteristics: near, middle, far, and extreme (Table 7-1). The transmission spectrum of the atmosphere is shown in Figure 7-17. The best transmission wavelength is between 3 to 5 micrometer (µm) and 8 to 14 µm. The range between these frequencies is known as a “window.” Infrared imaging devices are designed to operate in one of the two windows, usually the wider 8 to 14 µm.

<table>
<thead>
<tr>
<th>Name</th>
<th>Acronym</th>
<th>Wavelength</th>
</tr>
</thead>
<tbody>
<tr>
<td>Near Infrared</td>
<td>NIR</td>
<td>0.72 – 3 µm</td>
</tr>
<tr>
<td>Middle Infrared</td>
<td>MIR</td>
<td>3 – 6 µm</td>
</tr>
<tr>
<td>Far Infrared</td>
<td>FIR</td>
<td>6 – 15 µm</td>
</tr>
<tr>
<td>Extreme Infrared</td>
<td>XIR</td>
<td>15 – 1000 µm</td>
</tr>
</tbody>
</table>

**Table 7-1 — Characteristics of IR Radiation**

Infrared Radiation Sources

All matter with a temperature above -273 °C (absolute zero) emits IR radiation. The amount of the IR radiation emitted is a function of heat. Theoretically, a perfect emitter is a blackbody with an emissivity of 1. Realistically, the best emissivity is somewhere around .98. The emissivity of various objects is measured on a scale of 0 to 1.

The total energy emitted by an object at all wavelengths is directly dependent upon its temperature. If the temperature of a body is increased 10 times, the IR radiation emitted by the body is increased 10,000 times.

If the energy emitted by a blackbody and its wavelengths is plotted on a graph, a hill-shaped curve results (Figure 7-18). Notice that the energy emitted by short wavelengths is low. As the wavelengths get longer, the amount of energy increases up to a peak amount. After the peak is reached, the energy emitted by the body drops off sharply with a further increase in wavelength.

**Infrared Optics**

Many of the materials commonly used in visible light optics are opaque in the IR frequency range. Optical materials used in IR imaging systems should have a majority of the following qualities:

1. Be transparent at the wavelengths on which the system is operating.
2. Be opaque to other wavelengths.

3. Have a zero coefficient of thermal expansion to prevent deformation and stress problems in optical components.

4. Have high surface hardness to prevent scratching the optical surfaces.

5. Have high mechanical strength to allow the use of thin lenses (high-ratio diameter to thickness).

6. Have low volatility with water to prevent damage to optical components by atmospheric moisture.

7. Be compatible with antireflection coatings to prevent separation of the coating from the optical component.

None of the materials currently used for IR optics have all of these qualities; however, silicon, germanium, zinc selenide, and zinc sulfide have many of them.

Infrared Detectors

The detector is the most important component of the IR imaging system. There are many types of detectors, each having a distinct set of operating characteristics. Bolometers, Golay cells, mercury-doped germanium, lead sulfide, and phototubes are the most commonly used types of detectors. Detectors are characterized by their optical configuration or by the energy-matter interaction process. There are two types of optical configurations: elemental and imaging.

Elemental Detectors

Elemental detectors average the portion of the image of the outside scene falling on the detector into a single signal. To detect the existence of a signal in the FOV, the detector builds up the picture by sequentially scanning the scene. Consequently, the elemental detector requires time to develop the image because the entire scene must be scanned.

Imaging Detectors

Imaging detectors yield the image directly. Each of the detectors responds to a discrete point on the image. Therefore, the imaging detector produces the entire image instantaneously. A good example of an imaging detector is photographic film.

Energy-Matter Interaction

There are two basic types of energy-matter interaction: thermal and photon effect.

- Thermal Effect. Thermal effect type of energy-matter interaction involves the absorption of radiant energy in the detector resulting in a temperature increase in the detector element. Radiation is detected by monitoring the temperature increase in the detector. Both the elemental and imaging forms of detectors use the thermal effect.
• Photon Effect. In photon effect type of energy-matter interaction, photons of the radiant energy interact directly with the electrons in the detector material. Usually, photon effect detectors use semiconductor materials. There are three specific types of photon effect detection.
  
  o Photoconductivity is the most widely used. Radiant energy changes the electrical conductivity of the detector material. An electrical circuit is used to measure the change in the conductivity.
  
  o Photoelectric, or photovoltaic, uses a potential difference across a positive (P) material and negative material (N) junction caused by the radiant signal. The photocurrent (current generated by light) is added to the dark current (current that flows with no radiant input). The total current is proportional to the amount of light that falls on the detector.
  
  o Photoemissive effect is also known as external photo effect. The action of radiation causes the emission of an electron from the surface of the photocathode in the surrounding space. The electron is photoexcited from the Fermi level (top of the collection of electron energy levels) above the potential barrier at the surface of the metal.

Infrared Imaging Systems

Infrared imaging systems have the following components: detectors, scene dissection system, front-end optics, refrigeration system, and an image processing system.

Detectors

Detectors convert the IR radiation signal into electrical signals that are processed into information used by the operator. Many different configurations of detectors are used in IR imaging systems including single detectors and arrays.

• Single Detector. Single detectors require one set of supporting circuitry. In this arrangement, the image is scanned across the detector so the detector can see the whole image (Figure 7-19, view A). An optical system is required that can supply the scanning. This type of system is adequate if real-time information is not needed or if the object of interest is stationary or not moving quickly.

• Detector Array. Only a small portion of the image scene is taken by a detector (or detectors) to achieve maximum resolution. A large number of detector elements can be grouped together to form an array (Figure 7-19, view B). The elements of this array are packed closely together in a regular pattern. Thus, the image of the scene is spread across the array like a picture or a mosaic; each detector element views a small portion of the total scene. The disadvantage of this type of system is that each detector element requires a supporting electronic circuit to process the information that it provides. Additionally, each detector element requires a preamplifier to boost the signal to a usable level.

Figure 7-19 — IR detectors.
Scene Dissection System

The scene dissection system is used to scan the scene image. There are many types of scanning—one associated with each type of detector array. When a single detector with one axis of fast scan and one axis of slow scan is used, the scene is scanned rapidly in the horizontal direction and slowly in the vertical direction. As a result, the line is scanned horizontally; then, the next line is scanned horizontally, and so forth.

A vertical linear array is scanned rapidly in the horizontal direction. One detector element scans one line of the image. In the linear array, there is a space, one element wide, between each element. The scan is one axis with an interlace being used. A vertical linear array is scanned rapidly in the horizontal direction. After each horizontal scan, the mechanism shifts the image upward or downward one detector element width so that on the next scan, the lines that were missed are covered.

Each system has an optimum configuration of detector array and image dissection. As the number of elements in the detector are increased, the system becomes more complicated, the cost increases, and system reliability decreases. If the number of detectors is decreased, the amount of information that can be processed is reduced forcing a compromise between cost and reduced information. The linear array scans in one direction only. Each detector scans one line of the scene image. The complexity of the electronics is reduced, and the amount of information that is processed is increased. Therefore, the size of the scene viewed and detail increases.

Many types of mechanisms can be used to scan the scene. When scanning two axes, the two scanning motions must be synchronized. Electronic signals control the sampling of the detectors and must be synchronized with the scanning motions.

Front-End Optics

Front-end optics collect the incoming radiant energy and focus the image at the detectors. The optics may be reflective or refractive, or a combination of both. Systems offer a zoom capability, allowing a continuous change in magnification of the image without changing the focus. Spectral filters are used to prevent unwanted wavelengths of light from reaching the detector and interfering with the imaging process.

Refrigeration System

A refrigeration system is needed in imaging systems because many types of IR detectors require low temperatures to operate properly. The two types of detector cooling systems are the open- and closed-cycle.

Open-cycle cooling requires a reservoir of liquefied cryogenic gas. The liquid is forced to travel to the detector where it reverts to a gas. As it changes from a liquid to a gas, it absorbs a great deal of heat from the surrounding area and the detector.

In closed-cycle cooling, the gas is compressed and the heat generated by the compression is radiated away by the use of a heat exchanger. The gas is then returned to the compressor and the cycle repeats itself.

Image Processing Systems

Image processing systems are used to convert data collected by the detectors into a video display. Data from detectors is multiplexed, or combined into one signal, so that it can be handled by one set of electronics. The data is then processed so that the information coming from the detectors is in the correct order of serial transference to the video display. At this point, any other information that is to be displayed is added. In other image processing systems, the signals from the detectors are amplified and sent to a light emitting diode (LED) display.
FORWARD LOOKING INFRARED SYSTEM

The Advanced Targeting Forward Looking Infrared (ATFLIR) system provides the operator with real-time, passive thermal and visible imagery during day and night operations. The FLIR systems can be used to detect, classify, track, and designate both air-to-air and air-to-surface targets of interest that would be concealed from either visual observation or radar detection. The system was designed to give the operator the ability to deliver precision-guided ordnance at a standoff distance outside of anti-air weapon envelopes. FLIR systems scan an operator-selected portion of the terrain along the aircraft’s flight path and display a televised image of the IR and visible patterns of the terrain. In addition, FLIR systems do not emit transmissions that can be detected by enemy forces when operating passively. Although various types of FLIR systems are used in the Navy, the ATFLIR system shown in Figure 7-20 is a good representation of the components and operational capabilities of other systems currently in use.

FLIR Description

The typical FLIR system consists of weapons replaceable assemblies (WRAs). The WRAs are listed below and described in the following paragraphs:

1. Pod adapter unit (PAU)
2. Advanced Navigation Forward Looking Infrared (ANFLIR) sensor
3. Electro-optical sensor unit (EOSU)
4. Pod electronics housing (PEH)
   a. Roll drive motor (RDM)
   b. Roll drive amplifier (RDA)
   c. Laser transceiver unit (LTR)
   d. Laser electronic unit (LEU)
   e. Eurocard modules
5. Roll drive unit (RDU)
6. Environmental control valve (ECV)
7. Power interrupt protector

Pod Adapter Unit

The PAU (Figure 7-21) attaches to the aircraft fuselage at weapons station four and provides the mounting and interface for the PEH and ANFLIR sensor. When a pod is installed on the aircraft, the PAU provides the connection point for power, signal routing, and cooling air to the ECV.
Advanced Navigation Sensor
The ANFLIR (Figure 7-22) sensor unit is a single WRA mounted at the forward end of the PAU. The IR targeting sensor presents real-time passive thermal imagery that can be placed on the HUD to provide a 1:1 overlay with the real world view. The imagery provides video for day or night detection, tracking, and designation of land or sea targets while maneuvering and navigating safely at low altitudes and high air speeds. The imagery delivered by the ANFLIR sensor is comparable to flying during daylight operations while operating at night.

Electro-Optical Sensor Unit
The EOSU (Figure 7-23) is a self-contained component designed to protect and seal the optics and laser equipment from moisture, contaminants, and electromagnetic interference. The EOSU is mounted to and rotates in the RDU and is driven by the RDM. Housed within the EOSU are the ATFLIR midwave IR receiver, gimbal-mounted telescope, laser spot tracker, and visible electro-optical (EO) camera. All optical components are mounted on a one-piece, beryllium aluminum optical bench. The bench was designed to eliminate alignment errors when individual optical components are removed for maintenance. The outer structure of the EOSU is designed to withstand the wind loads of mach plus velocities associated with high-speed aircraft. The outer structure includes the windscreen, multispectral, and laser spot tracker windows. The optical bench is suspended in the outer structure on four vibration isolators and gimbals. The EOSU interfaces with many of the power supply and processor Eurocard modules.

Pod Electronics Housing
The PEH (Figure 7-24) provides mounting and interface for the PAU, laser transceiver, laser electronics unit, and ECV. In addition, the pod electronics housing provides interface and mounting for the RDU, RDM, and Eurocard module cooled card cage and backplane. The PEH contains a single-panel maintenance door for access to WRAs.
Roll Drive Motor
The roll drive motor (Figure 7-25) is mounted to the roll drive unit. The RDM provides 360-degree EOSU rotation when a roll command signal is received from the RDA. It is a brushless motor with an integral tachometer. Position readout is received with anti-backlash gearing and measuring pinion and ring gear position. The RDM electrical interface is provided by the PEH.

Roll Drive Amplifier
The RDA (Figure 7-26) attaches to the PEH and the RDM. The roll drive amplifier provides the drive power to the RDM.

Laser Transceiver Unit
The LTR (Figure 7-27) is located in the forward section of the PEH and provides the energy for laser generation enabling the operator to determine ranging information to a selected target. The LTR is purged with dry air and sealed to protect against contamination. The laser transceiver unit provides a boresight reference source in the form of a laser diode, which produces a low-power signal that is precisely aligned to be parallel with the main beam output wavelengths. The unit delivers laser energy at repetition rate of 20 hertz (Hz) at a wavelength of 1.064 µm. The actual power output level of the laser energy being generated by the transceiver unit is classified information.
Laser Electronics Unit

The LEU (Figure 7-28) is the primary interface between the LTR, the aircraft, and the pod. The LEU interfaces with the LTR by way of a serial bus to the ATFLIR laser target designator and rangefinder (LTD/R). The LTD/R provides the capability to automatically or manually laser designate a target and receive accurate target ranging data.

Eurocard Modules

The Eurocard modules (Figure 7-29) are located in the PEH card cage and are responsible for managing and processing a variety of signals to control the operational functions of the ATFLIR system. The processor group interfaces with the mission computer system to perform the following functions: sensor video processing, target processing, pod control functions including pointing, stabilization and alignment processing. The power supply group conditions and distributes primary ac and dc power to the ATFLIR. The Eurocard modules are mounted in a cooled card cage within the PEH.

Roll Drive Unit

The RDU (Figure 7-30) serves as the mechanical and electrical mounting attachment and electrical interface unit between the EOSU and the PEH. Mechanical aspects of the RDU include a cooling air path for the EOSU, ring gear drive and an optical path for the LTR. Roll axis rotation, and radial and axial alignment are also provided to the EOSU by the roll drive unit.
Environmental Control Valve

The ECV (Figure 7-31) is mounted aft of the PEH and regulates the aircraft cooling air for installed components. In addition, the ECV enables airflow for the pod when the pod is operated on the ground and receives a weight-on-wheels signal. The ECV is a vital component to the ATFLIR system, especially in warmer operating areas.

PRINCIPLES OF OPERATION

Specific principles of operation will not be discussed in this chapter due to the diverse nature of individual FLIR components and the complexity of their operation. Further information on principles of operation and maintenance procedures is available in the AN/USM-636 Electro-Optics Three (EO3) and ATFLIR intermediate maintenance course.

Upon completion of that course, aviation electronics technicians will have acquired sufficient skills and knowledge to operate, test, and perform scheduled/unscheduled maintenance on the AN/USM-636 CASS EO3 and ATFLIR under minimum supervision in a Fleet Readiness Center/Marine Aviation Logistics Squadron working environment.

Figure 7-31 — ECV.
Review Questions

7-1. What component changes unregulated direct current (dc) inputs to regulated dc outputs for use throughout the head-up display (HUD)?

A. High voltage power supply
B. Error signal generator
C. Low voltage power supply
D. Correction signal generator

7-2. What component changes the head-up display (HUD) brightness to compensate for changes in cockpit lighting?

A. High voltage power supply
B. Solar cell
C. Low voltage power supply
D. Rectifier assembly

7-3. What are the three head-up display (HUD) modes?

A. Day, night, and day/night
B. Stroke, day, and night
C. Stroke, raster, and day/night
D. Stroke, raster, and stroke/raster

7-4. What are the interface and burn protection card’s two methods for preventing burn damage to the head-up display’s (HUD’s) cathode ray tube (CRT) screen?

A. Bright-up (BU) inhibit and extra high tension shutdown
B. Bright-up (BU) shutdown and solar cell inhibit
C. Solar cell inhibit and extra high tension shutdown
D. Stroke intensity inhibit and solar cell shutdown

7-5. Which step is performed prior to attaching the interface device (ID) to the consolidated automated support system (CASS) bench?

A. Ensure head-up display (HUD) is power down
B. Power down the ID
C. Apply power to the mobile maintenance cart
D. Remove protective cover and inspect the ID connectors
7-6. Refer to the diagram above. What connector provides external ac power to the interface device (ID) from the consolidated automated support system (CASS)?

A. GS1  
B. P1/J103  
C. P2/J101  
D. P1/GND

7-7. What device ensures proper optical alignment and provides airflow coupling?

A. Blower hose assembly  
B. Test fixture  
C. Bracket and prism assembly  
D. Interface device

7-8. What device keeps ambient light and unwanted images out of the visual field?

A. Video electronics card  
B. Solar cell cable and adapter  
C. Cathode ray tube control card  
D. Combiner lens and camera cover
7-9. What reference is used in thermal imaging?
   A. Reflectivity
   B. Temperature
   C. Color
   D. Visible light

7-10. What type of device detects temperature variations and processes that data to produce an image?
   A. Forward looking infrared (FLIR)
   B. Side scan radar
   C. Pulse modulated reckoning
   D. Big look radar

7-11. What is the most important component of an infrared (IR) imaging system?
   A. Optics
   B. Detector
   C. Laser
   D. Amplifier

7-12. Which of the following is a type of energy-matter interaction?
   A. Optical conversion
   B. Phasar effect
   C. Photon effect
   D. Parallel conversion

7-13. What type of optical detector configuration in an infrared (IR) detector produces an entire image instantaneously?
   A. Thermal
   B. Elemental
   C. Imaging
   D. Photon

7-14. Which of the following is a type of photon effect detection?
   A. Photopermissive
   B. Photoposition
   C. Photomatriculation
   D. Photoelectric
7-15. What unit of a typical forward looking infrared (FLIR) system internally houses the infrared (IR) receiver, gimbal-mounted telescope, and visible camera?

A. Pod adapter unit  
B. Electro-optical sensor unit  
C. Eurocard module cage  
D. Pod electronics housing

7-16. What unit regulates aircraft cooling air and provides airflow when serving the forward looking infrared (FLIR) system during ground maintenance?

A. Environmental control valve (ECV)  
B. Roll drive cooling fan  
C. Eurocard modules  
D. Transceiver cooling fan
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CHAPTER 8

TELEVISION

Television (TV) is defined as the transmission and reception of visual images by means of electrical signals from one point to another.

As an aviation electronics technician (AT), you must be familiar with basic TV systems used in a variety of applications, including special weapons guidance, weapon prelaunch information, and the use of TV as an attack display.

LEARNING OBJECTIVES

When you have completed this chapter, you will be able to do the following:

1. Identify fundamental characteristics of a basic TV system.
2. Describe the different scanning methods.
3. Describe basic TV signals.
4. Identify TV pickup devices, characteristics, and the purpose of composite video.
5. Describe the basic function of the control unit and synchronization (sync) circuitry.
6. Describe the major sections of a TV receiver.
7. Describe basic TV receiver sound systems.
8. Describe the function of picture tube components.
9. Identify TV circuits and their components.

TELEVISION FUNDAMENTALS

Television transmission of a picture from one point to another involves a process in which light, reflected from a scene, is converted into electrical impulses of varying magnitude. This process is called “synchronized scanning.” In synchronized scanning, the picture is examined by the camera and reproduced by the viewing monitor. This is done point by point and in regular pattern. The process is carried out so rapidly that the entire picture is scanned many times each second, and the eye sees it as a single complete image. A digital TV (DTV) block diagram is shown in Figure 8-1, view A. For simplicity purposes, a basic monitor using a cathode ray tube (CRT) and an analog broadcast is discussed.

BASIC TELEVISION SYSTEM

The basic TV system is shown in Figure 8-1, view B. It consists of a transmitter and a monitor. An image of the scene is focused on the camera pickup device. An electron beam in the device scans the optical image and produces an electrical signal that varies in amplitude with the amount of light that falls on each point of the image. A synch signal is added to the electrical picture signal from the camera. The resultant composite video signal is transmitted to the display monitor.

Within the monitor, the sync signal causes the beam to scan the CRT (TV picture tube) faceplate in sync with the camera scanning beam. The intensity of the CRT beam is varied with the picture signal, and the image appears on the face of the CRT.
The time required for one vertical scan of the picture in broadcast TV systems in the United States is 1/60 of a second (60 hertz [Hz]) or a multiple or submultiple thereof. The frequency of 60 Hz was chosen because most commercial electrical power sources in the United States operate at a frequency of 60 Hz. Synchronization with the power frequency reduces the visible effects of hum and simplifies the problem of synchronizing film projectors with scanning.

Figure 8-1 — Basic TV system and digital TV block diagram.
Scanning

The number of scanning lines determines the maximum ability of the system to resolve fine detail in the vertical direction. Also, the number of scanning lines is related to the resolution ability in the horizontal direction. Resolution is determined by the number of scanning lines because, for a given video bandwidth and frame time, horizontal resolution is inversely proportional to the number of scanning lines. Therefore, as the number of scanning lines is increased, the bandwidth of the system must also be increased in the same ratio to maintain the same resolution in the horizontal direction.

Maintaining approximately equal values of horizontal and vertical resolution is ideal. The bandwidth requirements increase as the square of the number of scanning lines increases. Originally, a system of 525 lines was chosen for broadcast TV as the most suitable compromise between channel width and picture resolution. This number of lines has also been found satisfactory for, and used in, many closed-circuit TV (CCTV) systems.

Noninterlaced Scanning

The simplest scanning method is called “noninterlaced” or sequential scanning (sometimes called progressive). This scanning method uses an electron beam that moves very rapidly from left to right on an essentially horizontal line while it travels slowly from the top to the bottom of the picture. When the electron beam reaches the end of a line, a blanking voltage is applied that shuts off the beam. This period of time is known as the horizontal retrace period or “flyback” time. Similarly, when the beam reaches the bottom of the picture, the beam is blanked out and reappears at the top of the picture.

Interlaced Scanning

An important variation of the scanning method discussed above is called interlaced scanning. It is used in broadcast TV and in most CCTV equipment. With interlaced scanning, it is possible to reduce the video bandwidth by a factor of 2 without reducing resolution or seriously increasing flicker.

In the standard 2:1 method of interlacing, alternate lines are scanned consecutively from top to bottom. Then, the remaining alternate lines are scanned. This principle is illustrated in Figure 8-2, which shows interlaced scanning with 13 scanning lines. In this kind of scanning, each of the two groups of alternate lines is called a “field.” The complete set of lines, consisting of two consecutive fields, is called a “frame.” Interlacing is accomplished by making the total number of lines in a frame an odd integer. Thus, the number of lines in each of the two fields is an even number plus one-half line. This design results in consecutive fields that are displaced in space with respect to each other by one-half of a line, and interlacing of the lines is produced. In the actual method used for broadcast TV and most CCTV, the total number of lines is 525, the total per field is 262 1/2, the vertical scanning frequency is 60 Hz, the number of complete pictures (frames) per second is 30, and the horizontal scanning frequency is 15,750 Hz (60 × 262 1/2).
TELEVISION SIGNALS

The standard TV signal consists of four elements:

- The picture information generated during active scanning time
- The picture blanking pulses
- The picture average direct current (dc) component
- The picture sync pulses

Picture Information

The basic part of the signal, the picture information, is a series of waves and pulses generated during active line scanning of the pickup device. A scanning line traverses (travels back and forth) the face of the pickup tube. It is modulated in amplitude in proportion to the brightness variations in the scene it is scanning. The signal produced varies in amplitude proportionally with the brightness of the scene. For commercial broadcasting, the amplitude variations are such that the maximum video amplitude produces black and the minimum video amplitude produces white. Ordinarily the maximum and minimum video amplitude values represent 75 percent and 15 percent of the maximum carrier voltage, respectively.

Modern cameras do not use a pickup tube but rather a charge coupled device (CCD), briefly discussed later in the chapter.

Picture Blanking Pulses

To prevent undesirable signals from entering the picture during retrace time, blanking pulses are applied to the scanning beams in both the camera tube and the receiver CRT. Camera blanking pulses are used only in the pickup device. They serve only to close the scanning aperture on the camera tube during retrace periods and never actually appear in the final signal sent to the receiver. In some systems, the same pulse that triggers the scanning circuit and blanks the CRT also closes the camera scanning aperture.

The function of the CRT blanking pulses is to suppress the scanning beam in the CRT during both vertical and horizontal retrace time. They are simple rectangular pulses, somewhat wider than the corresponding camera blanking pulses. They have a duration slightly longer than the actual retrace periods in order to trim up the edges of the picture and provide a clean noise-free period during retrace. The complete video signal shown in Figure 8-3 contains pulses for the removal of visible lines during horizontal retrace periods only. The horizontal pulses recur at intervals of 1/15,750 of a second. At the bottom of the picture they are replaced by vertical blanking pulses, which are similar to the horizontal pulses, except they are of much longer duration (approximately 15 scanning lines) and have a periodic recurrence of 1/60 of a second.

The blanking pulses (and sync pulses) are added at a relatively high-level point in the transmitter and are, therefore, considered to be noise free. The importance of noise-free blanking and sync pulses should not be underestimated. They determine the stability of the viewed picture or the degree to which a picture will remain locked in on a CRT, even under the most adverse transmission conditions. This point is especially important when considering the use of TV for closed-circuit applications. Extreme environmental conditions can seriously degrade the picture signal, making it difficult to synchronize or lock in a picture unless the original blanking-to-picture and signal-to-noise ratios are high.
Picture Average Direct Current Component

If a TV picture is to be transmitted successfully with the necessary fidelity, it needs the dc component of the picture signal. This component is a result of slow changes in light intensity. The loss of the dc component occurs in alternating current (ac) or capacitive coupling circuits, and is evidenced by the picture signal tending to adjust itself about its own ac axis. The dc component is returned to the video signal by a dc restorer or inserter circuit.

Synchronizing

Synchronization of the scanning beams in the camera and the receiver must be exact at all times to provide a viewable picture. To keep the beams exact, synchronizing information is provided in the form of electrical pulses in the retrace intervals between successive lines and between successive pictures, as illustrated in Figure 8-3. The retrace periods (which are as short as circuit considerations permit) are in areas in which sync pulses may be inserted without interfering with the picture.

Synchronizing pulses are generated at the program origin end of the TV system in the equipment that controls the timing of the scanning beam in the pickup tube. These pulses become a part of the complete signal transmitted to the receiver or monitor. In this manner, scanning operations at both ends of the TV system are always in step with each other. In general, sync signals should provide positive synchronization of both horizontal and vertical sweep circuits. The signals should be separable by simple electronic circuits to recover the vertical and horizontal components of the composite sync signal. They should also be able to be combined simply with the picture and blanking signals to produce a standard composite TV signal.

Most TV systems produce sync information that conforms to generally accepted requirements of synchronization. An example of how the sync signal waveform is added to the picture information and blanking signals to form a complete composite picture signal ready to be transmitted is shown in Figure 8-3. Notice the duration of the horizontal sync pulses are considerably shorter than that of the blanking pulses. Vertical sync pulses are rectangular, but are a much shorter duration than horizontal pulses. Thus, vertical sync pulses provide the necessary means for frequency discrimination.

Synchronization presents a difficult problem because the largest number of failures occurs as a result of the loss of proper interlacing. Discrepancies in either timing or amplitude of the vertical scanning of
alternate fields cause displacement in the space of the interlaced fields. The result is nonuniform spacing of the scanning lines. This situation reduces the vertical resolution and makes the line structure of the picture visible at normal viewing distance. The effect is usually called “pairing.”

To prevent the pairing problem and maintain continuous horizontal sync information throughout the vertical synchronization and blanking interval, another series of pulses is added before and after the vertical sync pulses, called “equalizing” pulses (Figure 8-4). The time between the last horizontal sync pulse and the first equalizing pulse changes from a full horizontal line interval to one-half of a horizontal line interval every other field. This change is caused by the ratio between 15,750 Hz and 60 Hz. The ratio produces the necessary difference between fields to provide interlaced scanning. Because the horizontal oscillator is adjusted to the frequency of the horizontal sync pulses, it is triggered only by every other equalizing pulse or serration of the vertical sync pulse.

![Figure 8-4 — Vertical sync and equalizing pulses.](image)

CAMERA PICKUP DEVICES

Older cameras were developed with vacuum tube technology using a variety of tubes, including the vidicon. Most modern cameras do not have a tube but a CCD. For training purposes and circuit analysis, the vidicon camera tube will be discussed.

**Charge Coupled Device**

The CCD contains a grid of millions of tiny devices called photodiodes. When an image is focused on the CCD, the light causes the photodiodes to become charged, converting the light into electrons. This situation is called the “photoelectric effect.” The more intense the light is at each pixel in the grid, the more the charge will be held in that photodiode. The next step is to read the charge of each cell in the image. In a CCD device, the charge is actually transported (coupled without loss) across the chip and read at one corner of the array. An analog-to-digital converter turns each pixel's value into a digital value.

The type of camera tube used is determined by the intended use of the camera and the amount of available illumination. The amount of light required by a camera tube is rated in candelas. The minimum number of candelas required by a camera tube is a measure of the tube’s sensitivity.
**Vidicon Tube**

The vidicon camera tube (*Figure 8-5*) has a transparent conductive coating, called the signal electrode, on the inner surface of the faceplate; a layer of photoconductive material deposited on the signal electrode; an accelerating anode; a focusing coil; and a cathode emitter for producing a beam of electrons. Associated with the vidicon tube are the alignment coil, the focus coil, and the deflection coils.

![Vidicon structure](image)

*Figure 8-5 — Vidicon structure.*

The alignment coil produces a magnetic field that is variable in both magnitude and direction, and is used to adjust the direction of the electron beam so that it is parallel to the field of the focus coil. Control of the alignment coil current is accomplished in the control unit.

The focus coil surrounds the vidicon tube and establishes a magnetic field along the axis of the tube. It is connected between the +300- and the +150-volt power supplies through a resistor located in the rotatable section of the base unit.

The vertical and horizontal deflection coils are excited by linear sawtooth currents from the control unit. These currents produce the field that causes the beam to scan the photosensitive layer.

The beam of electrons is directed toward the layer of photoconductive material (on the cathode side of the signal electrode) at a medium velocity because of the relatively low accelerating potential between the cathode and the accelerating electrode. A sharp beam is formed by the electrostatic field of the focus electrode, the axial magnetic field of the focus electrode, and the axial magnetic field of the focus coil surrounding the tube. The electron beam is deflected by the deflection coil in such a way as to scan the photoconductive layer. When no light is permitted to reach this layer, its resistivity is extremely high. One side of the layer is maintained at a small positive potential of 0 to 70 volts by direct contact with the signal electrode.

When light from the scene being televised passes through the faceplate and is focused on the photoconductive layer, the resistivity of this material (which has been extremely high) is reduced in proportion to the amount of light reaching it. Because the potential gradient between adjacent elements in the photoconductive layer is much less than the potential gradient between opposite sides of the layer, electrons from the beam side of the layer leak by conduction to the other side between scans of the electron beam. Consequently, the potential of each element on the beam side
approaches the potential of the signal electrode side, and it reaches a value that varies with the amount of light falling on the element. On the next scan, the electron stream replaces a number of electrons on each element just sufficient to return it to the potential of the cathode. Because each element is effectively a small capacitor, a capacitve current is produced in the signal-electrode circuit that corresponds to the electrons deposited as the element is scanned. When these electrons flow through the load resistor in the signal-electrode circuit, a voltage, which becomes the video signal, is produced.

**CAMERA CIRCUITS**

The purpose of camera amplifier circuits is to amplify the extremely low output signal from the camera tube. The video signals must be increased in amplitude to overcome tube noise, random circuit noise, and hum that may be injected into the video output.

**Camera Video Amplifier**

Camera circuits are carefully designed to amplify high- and low-frequency signals equally. The output of the camera tube (*Figure 8-6*) must be as large as possible. The output circuit contains high resistance, providing good gain at low frequencies but low gain at high frequencies. Because a video signal contains both high- and low-frequency components, the video stages are designed to amplify more at some frequencies than at others.

Video preamplifier Q1/Q2 serves as a “peaker” circuit because it provides greater amplification to the higher video frequencies. Notice that the resultant frequency response curve at the output of Q1/Q2 is reasonably flat over a wide band of video frequencies.

The video signal from preamplifier Q1/Q2 is routed through emitter follower Q3 and developed across a resistor in the camera control unit. Emitter follower Q3 is used to match the output impedance of the camera unit to the input impedance of the control unit.

**Camera Circuit Analysis**

The circuits in a typical black-and-white camera unit are illustrated in *Figure 8-7*. The vidicon is represented schematically by V1. The elements in a vidicon tube have functions similar to those in an ordinary electron tube; however, the vidicon tube terminology differs somewhat because the control grid is called the beam control, and the plate the target control.

When the camera circuit is operating, the video signal leaves the vidicon through pin C and is developed across R3. A variable dc focusing voltage is applied to pin 6 of V1 via decoupling network R4 and C2. A fixed positive accelerating voltage is applied from pin 13 of J1, through the contacts of K1, to pin 5 of V1. K1 is normally energized while the camera is operating. (K1 is shown energized).
Vertical blanking pulses and a variable beam control bias are applied from pin 1 of J1 to pin 2 of V1. Pulses from the horizontal deflection yoke are coupled through S2 (shown in normal position), differentiated by C1 and R2, clipped by CR1 and R1, and applied as sharp positive horizontal blanking pulses to the cathode of V1.

Video output from V1 is coupled through C3 to the base of Q1. Q1 and Q2 comprise a compound-connected transistor circuit known as a Darlington amplifier. This type of circuit was selected for use as the preamplifier stage because it has high input impedance, very high current gain, and excellent frequency response. Forward bias for the stage is provided by voltage divider components R6 and R7. R9 and C5 are primarily intended for temperature compensation. The amplified video output from the collector of Q2 is developed across R8 and L1 (a shunt-peaking circuit), and coupled through R12 and L2 (a series-peaking circuit) to the base of emitter follower Q3. This stage provides an impedance match to allow coupling of the video via coaxial cable to emitter load resistor R26 in the camera control unit.

**Vidicon Protection Circuitry**

Transistors Q4, Q5, and Q6 are used in circuitry designed for vidicon tube protection. Recall from your knowledge of CRT that it is undesirable to allow the electron beam to remain too long on the
same spot. If this occurs or the beam retraces the same line too often, the phosphor coating on the screen will “burn.” A vidicon target is similar to a CRT screen in this regard because, if the vertical and horizontal sweep signals are not present, the vidicon target can “burn.”

Pulsed amplifier Q4 serves to amplify a sampling of the vertical sweep signal, which enters the camera on pin 14 of J1. This signal is attenuated by R26 and R25 and coupled through C8 to the base of Q4. After being amplified by Q4, the signal is coupled through C10, rectified by CR2, and filtered by R23 and C13. The resultant positive dc voltage is used as forward bias for Q6. Notice Q6 is connected in series with Q5, forming (in terms of digital computers) a logic AND gate. To allow current to flow through both Q5 and Q6, forward bias for Q5 must also be provided.

Forward bias for Q5 is developed, logically enough, by action of the horizontal sweep signal, which consists of pulses at 15,750 Hz. This signal enters the camera unit through pin 7 of J1. The pulses are attenuated by R11, coupled through C14 to the anode of CR3, and then rectified R29 and C16 filter the resultant dc, which is used as forward bias for Q5.

Remember that Q6 is forward biased only as long as a vertical deflection signal is present in the camera unit, and Q5 is forward biased only as long as a horizontal deflection signal is present. Therefore, both the vertical and horizontal deflection signals must be present for current to flow through Q5 and Q6.

Notice that the coil of current-sensitive relay K1 is in the collector circuit of Q5. If Q5 and Q6 are conducting, K1 is energized. Look at pin 13 of J1. A +285 volt dc (Vdc) is routed from pin 13 through R21 and the energized contacts of K1 to pin 5 of the vidicon. If the +285 Vdc is not present, the vidicon is cut off. If K1 de-energizes, a ground is applied through R24 to pin 5 of the vidicon tube, assuring that the tube is cut off.

To summarize, if either the horizontal or vertical deflection signal is not present, relay K1 will de-energize, causing the vidicon to cut off. This provision, of course, serves to protect the vidicon target from being "burned" if sweep signals are lost.

COLOR CAMERAS

The camera unit used for color pickup is similar to the black-and-white camera previously discussed. In the color camera, the camera unit (Figure 8-8) has three pickup tubes (one for each of the TV primary colors of red, green, and blue). Filters and mirrors are used to direct the right color of light to its respective pickup tube. The output of the camera unit provides a red, green, and blue video signal to the matrix system (a circuit that proportions the primary signals to produce the correct brightness and chrominance colors). Chrominance is the information

![Figure 8-8 — Color TV transmitter block diagram.](image)
that defines the color (hue and saturation) of a television image, but not the brightness. The three primary colors are identified as \( R \) for red, \( G \) for green, and \( B \) for blue.

The matrix section is essentially a resistive voltage-divider circuit that proportions the primary color signals, as required, to produce the brightness and chrominance signals. With red, green, and blue color video voltages as inputs, there are three video signal output combinations:

- **Luminance signal**, designated the \( Y \) signal, which contains the brightness variations of the picture information
- **Color video signal**, designated the \( Q \) signal, which corresponds to either green or purple picture information
- **Color video signal**, designated the \( I \) signal, which corresponds to either orange or cyan picture information

Together the \( Q \) and \( I \) signals contain the color information for the chrominance (hue and saturation) signal.

**Composite Video**

The composite video signal contains all the information needed to reproduce the picture. Its contents include the video from the camera unit, sync pulses to synchronize the transmitter signal with the receiver/monitor, and blanking pulses to obliterate the retrace signals from the picture tube. The video signal is combined with the blanking pulse, and the sync pulse is placed on top of the blanking pulse, as shown in Figure 8-9.

In the composite video signal, successive values of voltage and current amplitudes are shown against values of time during the scanning of three horizontal lines. During the time when blanking and sync pulses are being transmitted, no video appears. The overall signal amplitude is divided into two parts: the lower 75 percent is for video, and the upper 25 percent is devoted to sync pulses. Standardization is necessary to ensure the transmitted signal is suitable for all receiver monitors.

The lowest amplitudes correspond to the whitest parts of the picture. The picture becomes blacker as amplitude increases toward 75 percent. This standard of transmission is called “negative transmission,” which is defined as decreasing signal amplitude for decreasing light intensities. As the level reaches 75 percent, the grid becomes negative, cutting off the picture tube. The absence of light establishes the blackest level, which is the case when the blanking level occurs.

Details of the horizontal blanking and sync pulse are shown in Figure 8-10. The interval of the complete scan is 63.5 microseconds (\( \mu \)secs) because the horizontal frequently is 15,750 Hz. The horizontal blanking pulse is 10.16 \( \mu \)secs, or about 16 percent of total sweep. The sync pulse, superimposed on the pedestal, occupies 5.08 \( \mu \)secs or one-half the blanking time.
The part of the pedestal just before the 0.254 µsec sync pulse is called the “front porch”; the portion following the sync pulse (4.826 µsecs) is called the “back porch.” The front porch blanks the right side of the picture screen just before the sync pulse begins. Flyback occurs with the leading edge of the sync pulse and continues for 4.42 µsecs of the back porch. The next sweep starts, but the left side of the screen is blanked for 0.406 µsec of the starting sweep. This action strives to maintain a straight left edge.

The vertical blanking pulse blanks the picture during retrace time when the electron beam has completed one field and is returned to the top, ready to start the next field. Immediately following the last active line, the video signal is brought up to the black level by the vertical retrace.

The form and the timing of the sync pulses are such that the horizontal and vertical oscillators are triggered at exactly the right instant to keep the sweep in the camera tube and the sweep in the picture tube locked in step. Because the horizontal oscillator must be triggered during the vertical sync pulse (to prevent the horizontal oscillator from drifting out of control), the vertical pulse is serrated, as shown in Figure 8-11. As a result, the vertical pulse is chopped into six pieces. The fluctuations resulting from serrations do not affect the operation of the vertical oscillator, but only keep the horizontal oscillator properly triggered.

In addition to the serrations in the vertical pulse, equalizing pulses are necessary before and after each vertical pulse. The necessity for equalizing pulses \((E)\) as shown in Figure 8-11, view B, may be explained as follows:

First, assume that no equalizing pulses are used, as shown in Figure 8-11, view A. If the vertical pulse is inserted at the end of the field, which occurs simultaneously with the end of a full horizontal line, (part 1), the firing potential of the vertical oscillator is reached at the correct time to produce the desired interlaced scan. If the vertical pulse is inserted at the end of a field, which recurs simultaneously with the end of a half horizontal line, (part 2), the firing potential of the vertical oscillator is reached too early. This condition happens because the slight charge on the capacitor in the triggering circuit of the vertical oscillator (due to each horizontal pulse) does not have time to leak off before the vertical pulse arrives. The residual voltage across this capacitor, plus the voltage due to the vertical pulse, causes the vertical oscillator to fire too soon.

Second, the situation is corrected, as shown in Figure 8-11, view B, by the use of equalizing pulses. The buildup of the vertical pulse across the capacitor now begins at the same point, whether the vertical pulse arrives at the end of a full line or at the end of a half line. In other words, the equalizing pulses cause the potential on the capacitor to be at the same level (at the same time the vertical pulse arrives) whether the vertical pulse occurs at the end of a half line or at the end of a full line. Although not shown in the figure, equalizing pulses are also used after the vertical pulses.
CONTROL UNIT

Sync generators in the control unit provide reference signals to keep the scanning signals in the monitor in step with those in the camera. Another function of the control unit is to maintain a stable phase relationship between the vertical and horizontal scanning signals. If the phase relationship between these signals is allowed to vary, the 2:1 interlaced scan will not be stable. To obtain the required phase lock, both the horizontal and vertical sync signals are generated in a common master oscillator. Then, they are converted to signals having the required frequencies by the use of appropriate count-down circuits.

A typical pulse-counter sync generator is shown in Figure 8-12. Master oscillator Q1 generates the 31.5-kilohertz (kHz) signal from which both the horizontal and vertical drive signals (which will later become sync signals) are derived. The frequency and phase of the master oscillator signal are stabilized by phase detector Q9. This stage compares both the frequency and phase of the vertical drive signal with those of the 60 Hz power-line reference signal. Frequency divider Q2 serves to halve the master oscillator frequency to 15,750 Hz. This signal is used to trigger Q3, the horizontal-drive multivibrator.

Figure 8-11 — Synchronizing pulse forms without and with equalizing pulses.
Buffer amplifier Q4 is an isolation stage used to shield the master oscillator from the loading effects of Q5, a single-cycle blocking oscillator (SCBO). The first of four count-down circuits (Q4, Q6, Q7, and Q8), Q5 is used to produce the 60 Hz vertical drive signal. Notice that Q8 has two output signals, one of which is the vertical drive signal. The other output signal is routed back to phase detector Q9 where (as stated before) its frequency and phase are compared with those of the 60 Hz power-line reference voltage. The vertical and horizontal drive signals are then routed from the sync generator to sync insertion circuits in another section of the control unit.

Sync Generator Circuits

Sync generators usually consist of only a few basic circuits, with these circuits being repeated in different areas. Simplified versions of some of the more common sync generators are described in this section.

Master Oscillator

A simplified schematic of a 31.5 kHz master oscillator schematic is shown in Figure 8-13. Transistor Q3 is configured to form a modified Armstrong oscillator circuit. The frequency of this free-ruining master oscillator is determined by the values of C6 and T1. The inductance of T1 can be changed by adjusting the position of its movable core.

Transistor Q2 and associated circuitry comprise a reactance stage capable of changing the master oscillator frequency as a function of the dc control voltage applied to the base of Q2. The dc control voltage is the output of the phase detector previously discussed in the block diagram analysis.
In general, if the output signal of an amplifier can be made to lead or lag the input signal, that amplifier can function electrically as a variable capacitor. Refer again to Figure 8-13 and imagine Q2 and associated circuitry to be a variable capacitor in series with C6. C4 and varicap diodes CR1 and CR2 form a capacitive voltage divider in the feedback loop of Q2. Being capacitive, the feedback loop causes the correction signal voltage to lag the signal current in the loop. The degree of lag is proportional to the amplitude of the correction signal. The apparent change in capacitance tunes the master oscillator to the desired frequency.

**Phase Detector**

The phase detector shown in Figure 8-14 is used to provide a dc correction voltage to the reactance stage previously discussed and shown in Figure 8-13. Notice in Figure 8-13 that a vertical drive signal is fed to the base of Q1 and a 60 Hz ac reference signal is fed to the emitter. Q1, which is normally cut off, is brought into conduction by the vertical drive signal (consisting of negative pulses). The normal phase relationship between the vertical drive and the 60 Hz reference signal is shown in Figure 8-15. As long as a vertical drive pulse appears when the reference signal passes through zero, a normal control voltage will be produced. If, however, the normal phase relationship tends to drift, a larger or smaller correction voltage will be produced. C3 in the collector circuit (Figure 8-14) acts as a filter capacitor, ensuring that a smooth dc correction voltage is applied to the reactance stage.

**Frequency Divider**

An SCBO (Figure 8-16) circuit is often used as a frequency divider circuit (or count-down circuit) in sync generators. In this circuit, Q9 is normally cut off. Input pulses from a preceding stage gradually build up a charge across C17 until a forward bias condition is achieved. As Q9 begins to conduct, a regenerative signal is coupled through T2 to the base of Q9. This regenerative signal causes Q9 to reach saturation rapidly. As soon as Q9 saturates, C17 discharges through the transistor. When C17 discharges sufficiently, Q9 abruptly stops conducting. The
collapsing field around the secondary of T2 assists in driving Q9 into sharp cutoff. Diode X6 swamps T2, suppressing resonance oscillations. The values of C17, R31, and R30 have been specially chosen to allow the transistor to conduct when the appropriate number of input pulses has been applied. The circuitry shown in Figure 8-16 is appropriate for a 5:1 countdown oscillator.

**Sync and Blanking Insertion**

The earlier discussion of camera circuits revealed that the video signal is developed in the camera tube and routed through the video amplifier and peaking circuits to the control unit. After entering the control unit, the video signal is subjected to additional amplification and peaking. Video from the camera tube is referred to as "raw" video; that is, no sync or blanking signal is included. Therefore, it is necessary to insert the sync and blanking signals to produce a composite video signal. Sync and blanking insertion are often performed in the control unit. Typical insertion circuits are discussed in the following paragraphs.

**Blanking Insertion**

Blanking signal insertion is most often performed before sync signal insertion. Before the blanking signal can be inserted, the proper dc reference level must be established by clamping circuitry. Clamping is needed because a coupling capacitor cannot pass dc, and it also has difficulty in passing low-frequency ac signals. Notice in Figure 8-17 that the resistive-capacitive (RC)-coupled signal assumes an average level, varying about the bias voltage level of the preceding stage. Keyed clamper circuits are used in many CCTV systems. Consequently, no clamping occurs unless a keying pulse is present. Typically, the horizontal drive signal is used as a keying pulse.
In the blanking insertion circuit illustrated in *Figure 8-18*, Q8 is forward biased each time a clamping pulse (horizontal drive pulse) is applied to its base.

When Q8 conducts, the video signal is clamped at the blanking level established by R31. The clamped signal (video) is applied to the base of emitter follower Q9, amplified, and directly coupled to the base of Q10, the blanking mixer stage. Notice that the level of forward bias for Q10 is determined by the potential at the emitter of Q9, which is itself controlled by adjustment of R31. The blanking signal is therefore clipped (limited) by Q10 at a level established by R31. The output of this stage is routed to a sync insertion circuit.

**Sync Insertion**

The sync signal is normally inserted into the composite video signal after the blanking signal has been inserted. The sync insertion circuit used is generally a simple additive mixer similar to the sync-adding network shown in *Figure 8-19*. In this network, sync is added (via R5 and R6) to the video signal at the video output terminals.

Isolation amplifier Q4 prevents the coupling of video to the sync input terminals. Adjustment of potentiometer R4 sets the gain of Q4, thus controlling the sync signal amplitude. Transistor Q1 is the video-output stage.
A sectional block diagram of a TV receiver is shown in Figure 8-20. Each of the major sections is discussed in the following text.

**Tuners**

TV tuners, like those of communications receivers, consist essentially of three parts—the radiofrequency (RF) amplifier, the oscillator, and the mixer—and are preset according to industry standards. Some TVs today are not equipped with over-the-air (OTA) tuners and are designed for use with cable or satellite systems that use their monitor function. The function of the tuner, often called the front end, is to amplify the input signal, to produce a locally generated RF signal, and to mix these two signals in such a way to produce signals at the chosen audio and video intermediate frequencies.

A block diagram of an OTA tuner is shown in Figure 8-21.
Radiofrequency Amplifiers

Because the TV signal available at the input of the TV receiver is weak, it is desirable to amplify the signal in a stage of RF amplification before it is applied to the mixer. Various types of RF amplifiers employed in TV receivers include common emitter, pentode, and field-effect transistors (FETs), all of which are discussed in detail in Navy Electricity and Electronics Training Series (NEETS), Module 7.

A simplified circuit with a dual-gate FET used as an RF amplifier is shown in Figure 8-22. An automatic gain control (AGC) voltage is developed across a voltage divider comprising resistors R1, R2, and R3. Capacitors C1 and C2 filter the AGC voltage so that only a dc voltage is applied to the gates. The largest part of the AGC voltage is applied to gate G2.

The RF signal from the antenna is applied through C3 and developed across R3. This signal voltage appears on gate G15. The amount of current through the FET is controlled by two voltages: the AGC voltage and the RF input voltage. The source bias is supplied by R4, and C4 is used to prevent degeneration. The output signal is taken from the secondary of transformer T15 and fed to the mixer stage.

Local Oscillators

Local oscillators provide a signal that is heterodyned in the mixer with the RF signal. As in the case of superheterodyne radio receivers, the local oscillator frequency is normally above the incoming RF frequency by a frequency that is equal to the receiver intermediate frequency (IF).

The local oscillator frequency is changed whenever the channel selector is changed/tuned from station to station. The fine-tuning control varies the oscillator frequency over a narrow range. The setting of the fine-tuning control is very important if a satisfactory color picture is to be obtained. This example is provided assuming an analog signal is being received. Digital TV broadcast frequencies are exact: either they are present or they are not. You will not normally see a fuzzy picture due to IF tuning variances.

Mixers

The mixer receives a signal from both the RF amplifier and the oscillator circuits and converts them to a different frequency output, called the IF, as shown in Figure 8-21. This conversion is accomplished by applying both the RF and oscillator voltages to an amplifier. Heterodyning will take place and the
output signal will include both the sum and difference frequencies, as well as the two original frequencies. A selective network will only pass the desired IF.

The dual-gate metal-oxide-semiconductor field-effect transistor (MOSFET) makes an ideal mixer amplifier. This type of transistor is shown in Figure 8-22. Recall it had two gates for inputs, allowing for multiple configurations. In its most common configuration, one of the gates is used for the RF input and the other for the oscillator input.

**Video Intermediate Frequency Amplifiers**

Video IF amplifiers perform essentially the same functions that are performed by the IF amplifiers in superheterodyne radio receivers. However, bandpass considerations require trapping unwanted sound and video beat frequencies, making the design of video IF amplifiers somewhat complex.

**Traps**

Five types of traps are used in conjunction with video IF amplifiers. These types are series, parallel, absorption, degenerative, and bridged-T. The bridged-T trap is the most widely used circuit and is indispensable in color TV receivers.

The series trap is a parallel resonant circuit configuration (Figure 8-23). It is placed between two IF states and tuned to the frequency to be rejected. This type of trap circuit is a sharply tuned network designed to reject one frequency or, at most, a narrow band of frequencies. When a signal voltage at the trap frequency appears at the input of the circuit, the impedance offered by the LC network is very high, and almost all of the undesired voltage is dropped across the trap. A negligible amount of the voltage appears across the input circuit of the following IF amplifier. At all other frequencies, the resonant circuit offers negligible impedance, and the desired signals pass easily.

The parallel trap is a tuned circuit that is placed across, or in shunt with, the circuit. A series-resonant circuit used in this manner is shown in Figure 8-24. At the frequency for which it is set, the trap acts as a short circuit, bypassing the resonant frequency to ground and preventing further penetration into the circuit. At other frequencies, the trap circuit presents a relatively high impedance, permitting these signals to proceed to the following stage. It is important that the parallel trap have a very high degree of selectivity or Q so the circuit will bypass only a narrow range of frequencies.

The absorption trap (Figure 8-25) is a widely used type of rejection circuit. It consists of a coil and a fixed capacitor inductively coupled to the load inductor of an IF amplifier. When the IF amplifier receives a signal at the resonant frequency of the trap circuit, a high circulating current develops in the trap network as a result of the coupling between the trap and the load inductor. The voltage in the
load coil L1 becomes quite low at the trap frequency. Consequently, very little of this interference voltage is permitted to reach the following stage. It is convenient to think of this kind of trap as being able to absorb all of the energy of the frequency to which it is tuned; therefore, no energy at that frequency is left available to pass on into the next stage.

Degenerative traps (Figure 8-26, views A and B) are designed to reduce the gain of an amplifier for frequencies to which the trap is tuned. These traps are used in the emitter circuit of a solid-state amplifier or in the cathode leg of a vacuum-tube circuit. In the latter application, the traps are often called “cathode traps.” The two types of traps normally used to provide the degeneration are the absorption type and the series type. An absorption type in which L1 in series with C1 forms a broadly tuned series-resonant circuit at the frequency to which the amplifier is tuned is shown in Figure 8-23, view A. This configuration permits the amplifier to function normally for all signals within its frequency range. At the resonant frequency of the trap, however, a high impedance is reflected into the emitter or cathode circuit by the trap, and the gain of the stage is reduced by degeneration.

The series type of degenerative trap (Figure 8-26, view B) places a parallel circuit directly into the emitter or cathode leg. At the resonant frequency of the trap, the impedance in this part of the amplifier circuit will be high, producing a large degenerative voltage and reducing the gain of the amplifier. At all other frequencies, the impedance of this parallel network is low. Only a small degenerative voltage appears, and only a slight loss in gain occurs except at the undesired frequency.

A trap that is more complex than any of the foregoing circuits, but also more effective, is the bridged-T trap, shown in Figure 8-27. In this circuit, L1, C1, and C2 are resonated at the frequency of the signal to be rejected. If the resistance of R is properly chosen, the attenuation imposed upon a signal to which L1, C1, and C2 are resonated will be great. Ratios of 50 and 60 to 1 are easily attainable using standard components which mean the strength of the desired signal at the output of the trap will be 50 to 60 times greater than the strength of the undesired signal.
Signal Flow

While reading this section, you should keep the IF response curve (Figure 8-28) in mind. A schematic diagram of a typical video IF system found in many color TV sets is shown in Figure 8-29. This system has three negative-positive-negative (NPN) transistor stages that are impedance coupled and pass a band of frequencies centered at 43.8 megahertz (MHz). Input to the IF system is through a plug-in link from the mixer stage in the tuner. The mixer output coil is tuned to position 42.17 MHz at the 50-percent point on the IF response curve, and the impedance of the coil is tapped to match the impedance of the coax link. Transistor Q1, the first IF amplifier, is coupled to the input coax link through L2 and C1. L2 is tuned to position 45.75 MHz at the 50-percent point on the opposite side of the response curve from the 42.17 MHz point. Both 50 percent points on the IF response curve are shown in Figure 8-29. The mutual coupling of L2 and the mixer output coil provide a wide bandpass through the coax link.

Two sound traps are at the input to Q1—one tuned to reject the adjacent channel sound frequency at 47.25 MHz and the other tuned to suppress the 41.25 MHz associated sound carrier. The 47.25 MHz trap consists of R6, C3, C4, and L55. This trap is a bridged-T configuration and delivers, to the base of Q415, two 47.25 MHz voltages that are equal but 180 degrees out of phase. One of these voltages is developed across R6, while the other is developed across C3, C4, and L5. At the base of Q1 the voltages cancel each other, eliminating the adjacent channel sound carrier from the IF band. The 41.25 MHz trap is a series-resonant network consisting of C7, C73, and L9. This trap, loosely coupled to the input circuit, improves selectivity and provides fine tuning.

In this system, AGC is applied only to the first IF amplifier stage. As the AGC voltage increases, forward bias is developed at the base of Q1. This bias increases the current flow through the transistor and, consequently, causes a greater voltage drop across R16, reducing the stage gain.

In the collector circuit of Q1, C21, and C22, divide the voltage developed across L20 and couple it to the base of Q25. The junction of the two capacitors matches the impedance of the coil to the base of Q2. L20 is tuned to 43.8 MHz, which is the center of the IF system bandpass. Coupling between Q2 and Q3 is identical to that between Q1 and Q2, with L28 also tuned to 43.8 MHz. The associated sound carrier is tapped off at the collector of Q3, the third IF amplifier.

The output circuit of the IF system is, in effect, very similar to the input circuit. Here, L395 is tuned to position 42.17 MHz at the 50-percent point on the IF response curve, as was indicated in Figure 8-28, and L54 positions 47.75 MHz at the same point but on the opposite slope. A bridged-T trap, consisting of R48, C42, C50, and L49, rejects the 41.25 MHz associated sound carrier, preventing it from reaching the video detector. The three sound traps in this system, two at 41.25 MHz and one at 47.25 MHz, suppress interference and account for most of the selectivity in the IF system.
Figure 8-29 — Solid-state color IF amplifier.
Video Detectors

The video detector in a TV receiver performs essentially the same function as the second detector in a superheterodyne amplitude-modulated radio receiver. It rectifies the signal (video and sync pulses) fed to it by the video IF system, removes the IF components, and feeds the remaining signal and sync information to the video amplifier. Various circuit arrangements, employing diodes, electron tubes, or crystals, are used.

One type of diode detector is shown in Figure 8-30. Two methods of connecting the diodes are shown. The output of CR1 has a negative picture phase, and CR2 has a positive picture phase. In Figure 8-30, view A, the low-amplitude positive-going picture signals correspond to the brighter portions of the picture. The higher amplitudes correspond to progressively darker portions of the picture and to the negative picture phase.

The low-amplitude negative-going picture signals of CR2 correspond to the brighter portions of the picture. The higher amplitudes correspond to progressively darker portions of the picture and to the positive picture phase, shown in Figure 8-30, view B.

The following paragraph will help clarify the concept of the negative picture phase. A video signal having a negative picture phase causes the cathode of the picture tube to be driven in a positive direction beyond cutoff during the blanking pulses. During the darker portions of the picture, the cathode is biased in the positive direction but not to cutoff. As a result, few electrons reach the picture tube screen, and the screen is relatively dark. During the brighter portions of the picture, the cathode is driven only slightly in the positive direction, and many electrons reach the picture tube screen. Therefore, the screen is relatively bright.

A video signal having a positive picture phase causes the grid of the picture tube to be driven negative below cutoff during the blanking pulses. During darker portions of the picture, the grid is driven considerably negative but not to cutoff. Consequently, fewer electrons reach the picture tube screen, and the screen is relatively dark. During brighter portions of the picture, the grid is driven only...
slightly negative, and many electrons reach the picture tube screen making the screen relatively bright.

The output of the detector in the receiver may have a positive or a negative picture phase, as indicated in Figure 8-30, irrespective of the type of transmission used. In either case, video amplifiers must supply a signal having a positive picture phase to the grid of the picture tube. If the signal is applied to the cathode of the picture tube, it must have a negative phase.

Refer to Figure 8-20 for a review of signal processing. Up to this point, you have seen that the TV signal has been received and amplified by an RF stage, converted to another frequency (IF) by means of a mixer, further amplified by the IF stages, and rectified by the diode detector. The strength of the signal at the output of the detector is not sufficient to drive the picture tube; therefore, one or more stages of video amplification are necessary.

**Video Amplifiers**

After the video signal (containing the video information and the blanking and sync pulses) has been rectified in the second detector, it must be amplified in one or more video amplifiers before it is applied to the picture tube. Because a wide band of frequencies must be passed without discrimination by the video amplifiers, they must be carefully designed. Special high- and low-frequency compensating circuits must be used to extend the approximate range of frequencies passed from 30 hertz to 4 MHz while reducing frequency distortion as much as possible.

The low-frequency video components include low-frequency ac variations (represented on the picture screen as portions of the image that does not contain fine detail), blanking pulses, and sync pulses (vertical and horizontal). The high-frequency video components are high-frequency ac variations that produce the fine detail on the picture screen. In addition to the low- and the high-frequency components in the transmitted signal, there is a zero frequency, or dc component present.

If all of the frequency components are not properly amplified in the video amplifier section, a distorted image is produced. The distortion may appear as a lack of fine detail, a lack of image sharpness in the larger objects, or a lack of contrast.

In addition to frequency distortion, phase distortion must also be reduced as much as possible. Phase distortion means that certain components (frequencies) that make up complex waveforms are not passed by the amplifier in the same length of time that other frequencies are passed. For example, in resistance-coupled amplifiers, the coupling capacitor and the grid resistor, acting together, cause a phase shift that varies with the frequency. Phase distortion may alter the background of the picture shown on the TV screen; portions that should be white may be gray or even black. At the lower frequencies, excessive phase shift may cause larger objects to be blurred on the screen. At the higher frequencies, excessive phase shift causes the fine detail to be blurred.

The average resistance-coupled amplifier has a flat response of only a few thousand hertz; therefore, it is not suitable for amplifying video frequencies. In order to amplify the higher frequencies as much as the middle range of frequencies, it is necessary to use some form of high-frequency compensation. This type of compensation commonly takes the form of shunt compensation, series compensation, or a combination of both. An example of the combination type of compensation is shown in Figure 8-31.

In a resistance-coupled amplifier, the output capacitance of the first amplifier stage, the distributed capacitance of the wiring, and the input capacitance of the second amplifier stage tend to shunt the high frequencies of the first stage to ground. Therefore, there is less output voltage at these frequencies available to the second stage, and the high frequencies are not amplified as much as the middle range of frequencies.
The shunting effect is compensated for (or the frequency range extended) by the use of a small inductor (L1), shown in Figure 8-31, inserted in series with the load. The value of this inductor is chosen so that it will neutralize the distributed (output and input) capacitance of the circuit. That is, this inductor, together with the distributed capacitance, forms a parallel-resonant (Cf and Rf) circuit that is resonant at a frequency where the response curve begins to fall appreciably. The frequency range is thereby extended. This type of compensation is called shunt compensation, and the coils are called peaking coils.

Series compensation is also used. In this case, a small inductor (L2), shown in Figure 8-31, is added in series with the coupling capacitor and forms a series-resonant circuit (resonant at a frequency where the response curve begins to drop) with the distributed capacitances. At resonance, increased current flows through these capacitors and larger voltages are available at the input of Q2. To prevent a sharp peak in the response curve, a resistor is shunted across the series inductor.

To amplify the lower frequencies as much as the middle or high range of frequencies, it is necessary to use some form of low-frequency compensation. At low frequencies, the reactance of the coupling capacitor is large, and much of the signal voltage is dropped there and not available at the base input. If a large coupling capacitor could be used, the stray capacitance and leakage current would be increased. Of course, a coupling capacitor introduces some phase shift at low frequencies.

It is possible to compensate for the loss in gain and the increase in phase shift at the lower frequencies by dividing the load resistor (RL) into two parts and bypassing one part with a capacitor. In Figure 8-31, the load resistance is divided into two parts by using RL and Rf. One part is bypassed by using Cf. At lower frequencies, the load includes both resistors; therefore, the output voltage is higher. At the higher frequencies, a portion of the load is effectively bypassed by the capacitor, and the output is proportionately lower.

**Direct Current Restorers**

The dc restorer (or clamper) restores the dc component of a pulse waveform after this component has been removed by the passage of the waveform through the coupling capacitor in the video amplifier stage. It is necessary to reinsert the correct dc component at the input of the TV picture tube if the correct level of background illumination is to be maintained. Also, if the correct dc component is not reinserted, the blanking level will vary (instead of remaining constant as it should), and retrace lines will appear on the screen during the time the blanking voltage is insufficient to cut off the picture tube during retrace.

The average brightness of one seamed line may differ widely from the average brightness of another scanned line, as shown in Figure 8-32, view A. The average dc component depends on the average brightness of a scanned line. A low dc component in the negative direction means a high level of brightness exists during that line. A high dc component in the negative direction means a low level of brightness exists during that line. Therefore, the average dc component establishes the blanking level.
An illustration of what happens when the dc component is removed by the passage of the video signal through a coupling capacitor is shown in Figure 8-32, view B. Although the picture tube may be biased so that it is not driven in a positive direction beyond a certain value, nevertheless the blanking level varies and the retrace is often visible. The background brightness level also differs from that at the transmitter.

A simplified dc restorer circuit is shown in Figure 8-33. The function of the circuit is to restore the dc component that was lost when the video signal passed through the coupling capacitor of the video amplifier. To accomplish dc restoration, enough dc voltage is added to the instantaneous ac signal to bring the blanking voltage to the cutoff point.

The dc diode restorer acts in the following manner. Without the diode, the input signal voltage appears as shown in Figure 8-32, view B. During the negative portion of the cycle (when the blanking and sync pulses are active), the diode

Figure 8-33 — Diode dc restorer.
(Figure 8-33) conducts because its cathode is negative and its plate is positive. Capacitor C charges rapidly through the diode and has the polarity indicated. The amount of the charge (voltage across C) depends on the strength of the input signal.

During the positive portion of the signal, shown above the 0 line in Figure 8-32, view B, the diode cannot conduct, and C (as shown in Figure 8-33) discharges slowly through R. A positive potential, which reduces the bias on the picture tube, is applied between grid and cathode during the scan interval between the blanking pulses. During this interval, the diode is effectively an open circuit, and the video signal appears across R in series with the dc voltage supplied by C. The greater the input voltage, the less the net bias remaining on the grid of the picture tube and the higher the average brightness. Thus, the condition existing in Figure 8-32, view A, is reestablished.

When direct coupling is employed between all stages in the video amplifier section, including the coupling stage between the video detector and the first video amplifier and picture tube, dc restoration is not required. An example of this direct coupling is shown in Figure 8-34. Detector D1 is direct coupled to first video amplifier Q1 through peaking coil L12. This emitter-follower stage develops a signal across R48. The base of second video amplifier Q2 receives its signal directly from the emitter of Q1. The second amplifier is a conventional (common emitter) amplifier stage direct coupled to the picture tube through the contrast control, diode D2, and peaking coil L18. Diode D2 is used to compensate for nonlinearity in transistor amplifier Q2 on high-amplitude signals.

**Figure 8-34 — Direct-coupled video amplifier stages.**

**SOUND SYSTEMS**

The sound system of a TV receiver is essentially the same as that of a frequency-modulated (FM) receiver. An important difference, however, is the system used for IF amplification. A wide variety of high-performance sound systems is in use today. Two basic configurations exist: the split-carrier sound system and the intercarrier sound system.
Split-Carrier Sound System

A block diagram of a split-carrier sound system is shown in Figure 8-35. In the split-sound system, the sound IF is removed, or split, at the output of the converter (or from the first video IF) and amplified in a series of sound IF amplifiers.

![Figure 8-35 — Split-carrier sound system.](image)

Intercarrier Sound System

A block diagram of an intercarrier sound system is shown in Figure 8-36. Its advantage is that the sound is amplified along with the video, which means fewer audio stages are necessary.

The carrier IF in the output of the RF unit is the same as those in the output of the RF unit in the split-sound system. Because the IF stages in the intercarrier system must pass both the picture and the sound IF carrier, the bandpass must be wide enough to pass both of these frequencies.

![Figure 8-36 — Intercarrier sound system.](image)
Integrated-Circuit Sound System

The advantage of an integrated-circuit (IC) sound system for a TV sound section is that it incorporates the functions previously discussed in a low-power solid-state configuration. In a very simple circuit there would be five terminals: one for ground, one for power, a 4.5 MHz input, a lead for the volume control, and a connection that goes directly to the speaker. A representative TV FM sound circuit containing an IC and other components is shown in Figure 8-37. It would incorporate automatic frequency, impedance, and tuning controls to optimize the output audio. The power transistor and output transformer are required because ICs are usually small devices with low-power dissipation. Some additional gain is therefore required to change to the power and impedance requirements of a 4-ohm, 35-watt speaker.

The two IF amplifiers are not transformer or resonant-circuit coupled. Instead, adequate selectivity is obtained with just the resonance of L1 and C2. A gain of 2,000 at 4.5 MHz is typical. This large gain saturates the last IF amplifier and produces the square-wave signal required for the quadrature detector.

The quadrature detector is an FM detector circuit that acts as both a discriminator and a limiter in one stage. This type of FM detector is easily produced as part of an integrated circuit. Tuning merely requires making L2 and C2 resonant at 4.5 MHz.

The audio-voltage amplifier is a three-stage, four-transistor, de-coupled amplifier. Direct coupling allows a good bass response and also avoids the use of capacitors. Notice that, except for the speaker transformer and the two capacitors associated with the volume control, this system would have a bass response down to dc.

Advances in technology have greatly enhanced the TV audio experience, especially when watching movies. Audio/video processing has enabled advanced features, such as customized audio modes for movies, music, and news. Additionally, digital processing has made virtual surround-sound commonplace in the home.

PICTURE TUBES

A monochrome picture tube is a specialized form of the CRT. An electron gun in the tube directs a beam of electrons toward a fluorescent material on the screen, which glows when struck by the electrons. Between the gun and the screen are deflection coils that deflect the beam horizontally and vertically to form a raster. The brightness of the screen at any point depends upon the number and velocity of electrons striking that point. The brightness of the picture is controlled by varying the grid-
bias voltage with respect to the cathode voltage. This bias can be changed by varying either the cathode voltage or the grid voltage. The AV-8 and some F/A-18 head-up display (HUD) systems are examples of a monochrome CRTs in use today. A typical HUD and CRT are shown in Figure 8-38.

Color picture tubes operate on the same basic principle as monochrome picture tubes. The difference between the two systems is the types of phosphors that coat the screen. The different types of phosphors produce colors when struck by electron beams. Three basic or primary colors are used in combination to produce all the other desired colors. These TV primary colors are red, green, and blue. In the three-gun color picture tube illustrated in Figure 8-39, there is a separate gun for each of the color phosphors. The tube’s screen consists of small, closely spaced phosphor dots of red, green, and blue. They are arranged so the red, green, and blue dots form a small triangle. The shadow mask provides a centering hole in the middle of the triangle of dots. The convergence electrode causes the three separate electron beams to meet and cross at the hole in the shadow mask.

Each electron gun is electrostatically focused by a common grid voltage. In other words, each gun has its own electrode, but all three are connected together, requiring only one grid voltage. The three electron beams scan the screen as controlled by the deflection yoke, which is mounted externally around the neck of the tube. As the three beams scan the phosphor screen horizontally and vertically in the standard scanning pattern, the dot triads will light according to the video input signals (Figure 8-40).

The purifying coil produces a magnetic field within the tube, which aligns the electron beams parallel to the neck of the tube. Rotating the purifying coil adjusts the electron beams so they strike their respective color dots without striking neighboring dots. When this adjustment is made for the red dots, the other two electron beams are aligned as well.
The high-voltage anode is a metallic ring around the tube. The field-neutralizing coil aids color purity at the outer edges of the picture tube. A metal shield, called a mu-metal shield, is placed around the bell of the tube to prevent stray magnetic fields from affecting the electron beams.

**Color Circuits**

A simplified color TV receiver (Figure 8-41) contains many circuits that are markedly different from the circuits used in monochrome receivers. The differences are outlined in the following paragraphs.

The tuner and amplifier stages in color receivers are designed to pass a wider band of frequencies than do conventional monochrome receivers. Wideband characteristics in these stages are necessary to assure uniform amplification of the high-frequency color subcarrier sidebands that carry the chrominance (color) information.

The video amplifier stage in monochrome receivers may only consist of one stage of amplification, while color receivers usually contain three stages of amplification. Additional stages of amplification are made necessary because the luminance signal in color receivers is used to drive the cathodes of all three electron guns in the CRT, as compared to the single-gun monochrome CRT.

A video delay line, usually located between the video output stage and the CRT, is used to delay the luminance signal for a fixed period of time so the luminance and chrominance information arrive at the CRT simultaneously. As shown in the block diagram (Figure 8-41), this fixed delay is necessary because the chrominance signals pass through additional stages before being applied to the control grids of the CRT. Were it not for the delay of luminance information, the two signals would not arrive in coincidence, and a distorted video presentation would result.

Because of the use of an aperture mask type picture tube, the brightness of a color receiver is characteristically low, meaning a higher voltage is necessary to maintain adequate brightness. The output voltage of the high-voltage supply is nominally 20 to 25 kilovolts (kV), as compared with 15 to 18 kV for monochrome receivers. All three electron guns must be sharply focused onto the screen to obtain good monochrome and color reproduction. The focus rectifier in color receivers provides a variable focus voltage (4 to 5 kV) that is applied to electrostatic focus elements of the CRT. The load of the high-voltage rectifier must be held fairly constant in color receivers, or severe blooming or shrinking of picture size will occur during reception of signals having a varying brightness level. Voltage regulator circuits provide a fairly constant anode voltage, regardless of the brightness level of incoming signals.

The color demodulator section is the heart of the color TV receiver. In this section, the 3.58 MHz subcarrier sidebands are demodulated to produce color information signals. The color information signals are then applied to a matrix, where color difference signals are produced by matrixing proportionate amounts of the demodulated signals. The color difference signals are, in turn, amplified and applied to the control grids of the CRT in the proper proportions to reproduce the televised scene.
Figure 8-41 — Color TV receiver, block diagram.
The color convergence circuits provide a secondary control over the electron beam of each gun. Convergence of the three electron beams to exact locations on the face of the CRT is necessary to produce good monochrome and color images on the three-gun CRT.

Other differences in color receiver circuits, such as automatic color control, tuning indicators, and color reception indicators, serve to simplify the operation of front-panel controls.

**Bandpass Amplifier**

The chrominance 3.58 MHz subcarrier signal and the color-sync burst signal are coupled from the first video amplifier to a bandpass amplifier (*Figure 8-41*). The bandpass amplifier is tuned to amplify the subcarrier frequency and reject the lower frequency video signals. The 3.58 MHz subcarrier sideband signal must now be demodulated to recover the color information. Consequently, a locally generated 3.58 MHz oscillator signal must be mixed with the subcarrier sideband to produce the chrominance signals. The frequency and phase of the locally generated signal is critical. It must be nearly identical to that of the station transmitter in order to recover exact color information. Therefore, the local oscillator is constantly synchronized by the burst reference signal. At the output of the bandpass amplifier, the burst signal, which is composed of approximately 10 cycles of the 3.58 MHz signal generated by the transmitting station’s oscillator (*Figure 8-42*), is selected by a burst separator. The burst separator in this instance is a time-gated amplifier that is gated, or keyed on, by a horizontal pulse from the flyback transformer during the horizontal retrace time. The burst signal is then applied to the automatic frequency and phase control (AFPC) circuits, which control the 3.58 MHz local oscillator.

**Automatic Frequency and Phase Control Circuit**

The burst signal is coupled to the AFPC circuit, as shown in *Figure 8-41*. The reference circuit is usually one of two types: the stable oscillator-phase detection type or the frequency-phase detection supplemented type. Only the former will be discussed. The stable oscillator-phase detection type of AFPC, shown in *Figure 8-43*, accepts the keyed signal from the burst gate and applies it to a phase detector. In
the phase detector, the locally generated oscillator signal is compared with the incoming burst signal, and an error or corrective voltage is developed. The error voltage is applied to a reactance modulator, which is connected in parallel across the 3.58 MHz oscillator tank. The reactance modulator acts as a variable capacitor, with its capacitance either increasing or decreasing, depending upon the polarity of the voltage applied. When the phase of the local oscillator changes appreciably, the voltage developed by the phase detector changes the capacitance of the reactance modulator, and the oscillator output signal shifts in phase to correspond to the burst signal.

The frequency of the local oscillator is primarily controlled by an input crystal tank circuit. However, when the local oscillator does drift off frequency, the phase detector error or correction voltage causes the oscillator to swing through its frequency range until the phase and frequency error voltages equal zero, and the oscillator locks in.

**Color-Killer Circuit**

The purpose of the color-killer circuit is to disable the color circuits when a monochrome signal is being received. Disabling is usually accomplished by biasing the bandpass amplifier below cutoff. No signal passes until the burst is applied to the color-killer circuit. In order to demonstrate the effectiveness of a color-killer circuit, assume that a signal of high noise characteristics is present at the input of the bandpass amplifier. The transistor goes into conduction, which enables the color circuits and results in a colored noise presentation on the CRT. The color-killer circuit prevents this noise presentation on the CRT by sensing the absence of the color burst signal. If the burst is absent, the color-killer circuit conducts and applies bias to the bandpass amplifier, thereby cutting off the color circuits. When the color-killer circuit senses the presence of the burst signal, such as by sensing a negative voltage at the output of the phase detector, as shown in Figure 8-43, the color-killer circuit ceases to conduct, and thereby permits the bandpass amplifier to admit the chrominance information.

Various circuits have been devised to eliminate this undesirable color during monochrome transmission. One simple method involves merely biasing off the bandpass amplifier by adjusting the familiar color control on the front of the receiver. However, a second and more sophisticated method of color-killer circuit operation is shown in Figure 8-44. This diode phase detector circuit uses the 3.58 MHz burst signal and the 3.58 MHz signal from the crystal oscillator as inputs. It compares the phase of these two signals and generates a dc output proportional to their phase difference.

Notice the location of the color-killer potentiometer (R1). It is adjusted so the Q1 is biased up to a point just slightly below cutoff. If the bursts are not present in the video signal, then a large phase error is detected causing a positive bias to add to the bias mentioned above, and Q1 turns on. This sends a negative bias to the chroma amplifiers, turning them completely off. If color bursts are...
present, the color-killer detector does not turn Q1 on, thereby allowing the chroma amplifiers to operate normally.

Chroma Detectors

The purpose of the chroma detector circuit is to recover the chrominance components from the 3.58 MHz subcarrier sideband. These components are transmitted by the station transmitter. The chrominance components are then used by the receiver circuits to reproduce a replica of the televised scene of the face of the CRT.

Matrix and Color Difference Amplifier Circuits

Matrix circuits are designed to reassemble the chrominance signals to form the original camera output signals. The signals corresponding to the camera video signals are combined with the luminance signal to produce a replica of the televised scene on the face of the CRT. Matrix circuits take on many forms, and the particular circuit used in any one individual receiver depends upon the receiver design. At the transmitter, the luminance signal (EY) and chrominance signals (EI and EQ) were formed by combining proportionate parts of the red, green, and blue camera tube outputs. It would seem, then, that to reverse the process a similar matrix should be used at the receiver. At the receiver, however, the chrominance signals are demodulated to form color difference signals of R-Y and B-Y, rather than the transmitted chrominance signals of EI and EQ. (The reason is based on the economic advantages of using equiband circuits). As a general rule, the EY signal is combined with the color difference signals in the color CRT; however, this again is determined by receiver design.

Synchronizing Circuits

The previous discussion on TV was focused primarily on delivering the video signal to the picture tube. Equally important, from the point of view of overall receiver operation, is the system by which the various circuits are synchronized with those at the transmitter and made to function together to produce the desired picture. Refer to Figure 8-41 for an overview of the system. As previously stated, the blanking pulses and the horizontal and vertical sync pulses are amplified in the various stages along with the video information. The sync separator, automatic gun control, and sweep circuits are virtually the same in color receivers as in monochrome receivers.

The detected composite video signal (containing sync pulses, blanking pulses, and video) is applied to the control grid or cathode (depending on phase) of the picture tube. The video information intensity modulates the scanning electron beam, producing varying degrees of black through white information on the screen. The blanking pulses cut the picture tube off to prevent a visual indication of retrace. The sync pulses are present but have no effect because they are present during the time the picture tube is cut off and only drive the tube beyond cutoff.

After detection and amplification, the composite video signal is also fed to a sync separation or clipper stage. The vertical and horizontal sync signals are removed from the composite video signal and filtered then the pulses are amplified and reshaped according to the needs of the synchronization and sweep systems. A block diagram of the synchronization circuits is shown in Figure 8-45 with the associated pulse waveforms.

The horizontal sync signal fires the horizontal oscillator at exactly the right instant to maintain the proper synchronization between the horizontal sweep in the receiver picture tube and the horizontal sweep in the transmitter camera tube. The output of the horizontal oscillator is formed into a sawtooth waveform. It is then amplified and applied to the horizontal deflection coils.

The vertical sync signal fires the vertical oscillator at the right instant to maintain the proper synchronization between the vertical sweep in the receiver picture tube and the vertical sweep in the transmitter camera tube. As in the case of the horizontal oscillator output, the vertical oscillator output
is formed into a sawtooth wave (modified into a trapezoidal form). It is then amplified and applied to the vertical deflection coil.

Sync Separators

Sync separation, or sync clipping, may be accomplished by the use of circuits employing tubes or transistors. A simplified circuit of a diode sync separator is shown in Figure 8-46. During the time the sync voltage is applied to the input, the diode plate is positive with respect to the cathode, and capacitor C is charged through the low resistance of the conducting diode. Between pulses, capacitor C discharges through R, and thus maintains a negative bias between plate and ground cutting off all signals up to the blanking level. The bias is maintained at approximately the blanking level, and only the sync signal causes pulses of current to flow through R1, across which the output is taken.

The output pulses consist of the horizontal sync pulses, the equalizing pulses, and the serrated vertical sync pulses. These pulses are fed to filter circuits that separate the vertical sync pulses from the horizontal sync pulses.
The simple diode separator is easily converted into a transistor sync separator because the transistor’s input terminals (base-emitter terminals) are actually a diode. The transistor merely adds gain to the basic diode sync separator. A simplified transistor sync separator is shown in Figure 8-47.

The problems involved in removing (sync clipping) the sync signals from the composite signal and in amplifying, separating, and using those signals to control the horizontal and vertical oscillators are treated only in a general way in this section. Because there are many methods of solving these problems, a detailed treatment of each method is not possible in this training manual.

Because the repetition rate of the vertical sync pulses is 60 Hz and that of the horizontal sync pulses is 15,750 Hz, they are easily separated by filters. One filter, the high-pass filter, is used to pass and shape the trigger voltages for the horizontal oscillator (multivibrator or blocking oscillator), as shown in Figure 8-48. The circuit in this figure has a short time constant with respect to the period (width) of the horizontal pulse. The output signal is developed across R.
The leading edge of the square-wave input pulse causes a rapid charge of C through R. The trailing edge causes an equally rapid discharge of C through R. The flow of charge and discharge currents through R causes the sharp spikes of output voltage, as shown in Figure 8-48. Only one spike in each pair (for example, the positive spike) is needed to trigger the horizontal oscillator. The other spike of the pair occurs at a time when the oscillator is insensitive to triggering pulses.

The low-pass filter used to pass and shape the trigger voltages for the vertical oscillator (a multivibrator or blocking oscillator) is shown in Figure 8-49. The RC time constant is long with respect to the width of each serration in the vertical pulse. Because of the long time constant in the integrator circuit, C does not have time to discharge during the interval between serrations. However, the RC time constant is short compared to the period of the combined vertical serrated pulses. Thus, C charges up to the peak value during the time the vertical serrated pulse is applied (190.44 µsec in the figure) and discharges to zero before the next horizontal pulse arrives.

The circuit is relatively insensitive to the longer, low-repetition-rate pulses that control the vertical oscillator. The reason is clear when you notice that the time constant (with respect to the width of each horizontal pulse) of the differentiator circuit is short and the output is taken across the resistor. Because of the long time constant (with respect to the width of each horizontal pulse) of the integrator circuit, the horizontal pulses have very little effect, and the equalizing pulses have even less effect. The only pulse that produces a useful output is the serrated vertical pulse. Sixty of these pulses occur each second, 30 for each of the two fields. The vertical pulses are serrated to provide the triggering action for the horizontal oscillator during the vertical retrace period.

**Sweep Circuits**

After being separated and shaped, the horizontal and vertical sync pulses are applied to the vertical sweep oscillators so they may be triggered at the correct instant to synchronize the receiver with the transmitter. Both the vertical and horizontal sweep oscillators, when fed into the correct circuits, produce current sawtooth waveforms.
The sawtooth waveforms produced by the horizontal sweep oscillator are amplified and applied to the picture tube in a manner that will cause the electron beam to be deflected (swept) horizontally across the face of the tube. Likewise, the waveforms produced by the vertical sweep oscillator cause the electron beam to be deflected from the top to the bottom of the picture tube. Multivibrators and blocking oscillators are two types of RC oscillators commonly used in the sweep circuits (vertical and horizontal) of TV receivers.

In electromagnetic deflection systems, the driving force in the picture tube is a magnetic field. To develop such a field, a sawtooth deflection current is required. Because of the inductive action in the output state of a tube-type vertical-output amplifier, a trapezoidal waveform is required to produce this sawtooth of current, as illustrated in Figure 8-50. To produce a sawtooth of current through a resistive circuit, a sawtooth of voltage must be applied (Figure 8-50, view A). To produce a sawtooth of current through an inductive circuit, a square wave of voltage must be applied (Figure 8-50, view B). To produce a sawtooth of current through an inductive-resistive circuit, both a sawtooth and square wave (trapezoidal wave) must be applied (Figure 8-50, view C).

Vertical Sweep

The vertical sweep circuit (Figure 8-51) produces a current that moves the electron beam of the picture tube from the top to the bottom. Notice that when transistors are used for the vertical and horizontal output amplifiers, the input wave to the output transistor is generally not trapezoidal but is close to a sawtooth.

The vertical oscillator (Q1) shown in Figure 8-51 is a conventional blocking oscillator. The signal from this oscillator is fed to the vertical output stage (Q2) and on to the series-connected vertical yoke coils. Oscillator frequency is determined by the RC time of C2, R4, and R5. The height control (R8) varies the collector bias voltage, thus changing the amplitude of the output signal. Without compensation, this amplitude change could change the oscillator frequency because it affects the charging capacitor by changing the amount of charge. Hence, a compensating network is included to prevent this from occurring. R1 is connected from the negative 6-volt supply to the secondary of winding T1, shunting both R8 and R2. The effect of this network is to change the forward bias on the oscillator so that the frequency is shifted in the opposite direction to compensate for any shift caused by the height adjustment.

The oscillator signal is coupled to the base of the output stage through C4. Forward bias for Q2 is provided by the voltage divider network (R10, R11, and R12) in the base circuit. Both emitter and collector currents normally flow. The positive pulse from the vertical oscillator opposes this forward bias and abruptly reduces the emitter-collector current. This period of abrupt current drop is the vertical retrace time and lasts for the duration of the oscillator pulse. C5, C6, and C8 combine to form the sawtooth wave for the vertical trace period. R15, in series with C8, forms a wave shaping feedback circuit between the emitter and collector of Q2. C5 and R13 perform the same function between the output and the base.
Vertical output transformer T2 is a voltage step-up device, with the secondary providing sufficient voltage for vertical retrace blanking. C9 is connected from the secondary to ground to prevent any horizontal pulses from distorting the vertical output. The vertical yoke coils, which are actually the collector ac load, are returned to the emitter of Q2 through C11 to isolate the yoke from dc. C10, connected from the collector to ground, provides further filtering.

**Automatic Frequency Control**

The use of incoming sync pulses to trigger and control the vertical and horizontal sweep oscillators is the simplest, most economical, and most direct method of controlling the motion of the electron beam in a TV. This simple, direct system would be satisfactory if it were not for the presence of noise pulses that may cause the oscillators to fire at the wrong time. When the vertical oscillator fires at the wrong time, the picture is not properly synchronized vertically and the picture bounces, or moves in jumps upward or downward across the screen. When the horizontal oscillator fires at the wrong time, the picture is not properly synchronized horizontally and the picture tears or becomes streaked, giving the appearance that the picture is jumbled.

Although noise pulses may affect the operation of both the vertical and the horizontal oscillators, a far worse effect is felt by the horizontal oscillator. The long time constant of the vertical filter makes it insensitive to the short bursts of noise energy, and the effect on the vertical oscillator is not generally objectionable. In CCTV, noise from electrical machinery can be just as destructive as atmospheric noise in a conventional home TV system.

The short time constant of the filter that feeds the sync pulses to the horizontal oscillator permits the passage of short bursts of noise energy. Consequently, it is necessary to employ a control circuit that effectively isolates the horizontal oscillator from the effects of noise pulses, and at the same time permits the sync pulses to assume control.

Two systems that isolate the horizontal sweep oscillator from the effects of noise bursts are shown in the block diagrams of Figure 8-52. In the system shown in Figure 8-52, view A, two signals are applied to the frequency discriminator. They are horizontal sync signals and horizontal sweep oscillator signals. The frequency discriminator compares the frequency (or phase) of these signals and produces an output dc voltage that depends on the difference between the frequencies (or phase) of the two signals. The output voltage, normally varying at a relatively slow rate, is fed via a low-pass filter to the grid of the reactance tube. This tube functions in such a manner that its output
changes the frequency of the horizontal sweep oscillator to maintain its frequency exactly the same as that of the incoming horizontal sync pulses.

The second method of isolating the horizontal sweep oscillator from noise bursts is shown in Figure 8-52, view B. As in the previous system, a frequency (or phase) discriminator is used. It compares the sync signal input from the filter or sync amplifier with the input feedback from the horizontal sweep amplifier and produces a dc output that is proportional to that difference. The reamer in which this dc output is amplified and used causes the frequency of the horizontal sweep oscillator to lock in step with the incoming sync signals.

**Horizontal Sweep**

In general, the same basic types of deflection oscillators found in the vertical deflection system are also used in the horizontal system: the blocking oscillator and the multivibrator types that employ both tubes and transistors.

A simplified schematic diagram of the phase detector and oscillator portion of the TV receiver’s horizontal sweep section is illustrated in Figure 8-53. The phase detector samples a feedback signal from the horizontal output stage and compares its phase with the incoming horizontal sync pulses. Any phase difference results in an appropriate dc voltage from the phase detector being applied to the oscillator. This signal then causes the oscillator to change its frequency.

Figure 8-52 — Horizontal sync control systems.

Figure 8-53 — Horizontal sweep (A).
When the pulses are in phase, the outputs from D1 and D2 are equal and opposite; thus, no dc control voltage is produced for the base of the oscillator. When the oscillator frequency is low or lagging the sync, D1 conducts more heavily than D2, producing a positive control voltage at the output. This positive voltage, applied to the base of Q1, increases the frequency of oscillations. When the frequency of the oscillator is high or leading the sync, D2 conducts more heavily, producing a negative control voltage that lowers the frequency of the oscillator.

The horizontal oscillator, Q1, is a blocking oscillator that operates similar to the one in the vertical section. Transformer T1 is the blocking-oscillator transformer, and L1 is a stabilizer coil.

Stabilizing coil L1 is in series with the secondary of T1 and is shunted by C6. When an abrupt current change through the coil occurs due to oscillator action, C6 discharges through the coil. The resulting magnetic field around the coil induces a voltage that recharges the capacitor, but to a lower level than previously charged, dampening the oscillations. The timing of this ringing action is adjustable to the point where it helps fire the oscillator at a constant rate, thus providing a degree of stability.

Horizontal hold control R6 establishes the bias on the base of Q1 to bring the oscillator within control range of the phase detector. Because the setting of R6 can affect the balance of the phase detector, isolating and compensating resistors R4, R7, R8, and R10 are incorporated to minimize this effect. The horizontal output pulse that is fed back to the phase detector is shaped into a sawtooth wave by C4, C10, and R16.

The balance of the horizontal sweep circuits (buffer, horizontal output, and high voltage) are shown in Figure 8-54. The positive output pulse of the oscillator is inverted by inter-stage transformer T2 and applied to the base of Q1 as a negative pulse. The buffer is normally cut off because there is no forward bias from the base to emitter.

The negative pulse at the base of the buffer amplifier drives the stage into conduction. A base bias is developed from the signal current by RC network C9 and R15, which permits conduction only on the peaks of the pulses. Because a common emitter circuit is used, a positive pulse appears at the collector. The positive signal from the buffer is transformer-coupled through T1 to the base of the horizontal output transistor Q2.

The output transistor is a special power-type transistor capable of handling the relatively high-power requirements of the stage. At the collector, a positive horizontal sweep pulse appears and is directly coupled to the horizontal yoke coils connected in parallel. The horizontal pulse causes a relatively linear sawtooth current in the yoke coils. Yoke damping action is provided by diode D1, which dampens any self-resonant oscillations of the yoke.

A tap on the primary of horizontal output transformer T3 is used to develop a 12-volt supply through diode D2. Two taps on the secondary of the same transformer provide +12- and +300-volt power supplies through their respective diode rectifiers and filters.

Figure 8-54 — Horizontal sweep (B) and high voltage.
When the horizontal output transistor is conducting, collector current is drawn through the primary of T3, and the collector voltage declines from -6 volts in a positive direction, producing a positive horizontal sweep pulse. The heavy current flow through the transformer primary causes high peak-voltage pulses to be developed across the high-impedance secondary winding. These pulses are applied to the plate of the first high-voltage rectifier, V1. The rectifier current charges C5 to approximately 5,000 volts. This voltage is applied to the plate of the second rectifier, V2, through R5. Capacitor C4 also couples the high-voltage pulse from the transformer secondary to the plate of V2, thus adding to the high dc voltage applied through R5. As a result, approximately 10,000 volts appear at the filament of V2 and is the high voltage that is applied to the second anode of the CRT. Voltages up to 30 kV are found in color TV high-voltage systems.

**LIQUID CRYSTAL DISPLAY**

Liquid crystal display (LCD) panels are fairly simple to understand. The signal comes in and, as with a CRT, the signal from the video controller is decoded and understood by a display controller on the monitor itself. The controller has two things to control: the electrics of the pixels and the light source.

The actual image on a panel is made up of a matrix of pixels. Each pixel is made up of three sub-pixels, which have red, green, and blue filters in front of them, just as each pixel on a CRT has red, green, and blue (RGB) phosphors. The sub-pixels are made up of a group of liquid crystal molecules. These molecules are suspended between transparent electrodes and are mashed between two polarizing filters.

The two filters are exact opposites of each other. As the light from the light source behind the first filter comes in, the filter effectively whites it out, which means that if it were to pass through the liquid crystals with no interaction, the filter on the other side would polarize it back to black, with no color being emitted. In fact, alternating current—leaving the crystals dark—is how black is created on a panel. The backlight itself is a cold cathode.

These cathodes are diffused through a layer of plastic and then through multiple layers of diffusing material of the kind you might find on a flashgun diffuser for photography.

**POWER SUPPLIES**

Because of the high-voltage requirements of the CRT, TV receivers usually employ two power supplies: high and low voltage (HVPS and LVPS). The HVPS was discussed in the previous section. A typical LVPS will now be discussed.

TV receivers use both high- and low-voltage transistors. This requires a large assortment of voltages. Because transistors are low-impedance devices, they work best when driven by voltages from low-impedance supplies.

A LVPS that provides multiple low-impedance output voltages is shown in Figure 8-55. The -20 and +24-volt output voltages drive most of the low-level stages in the set. A Zener regulator is used for the +24-volt supply, and an active filter is employed in the -20-volt circuit.

![Figure 8-55 — Black-and-white, solid-state power supply.](image-url)
supply. The +100-volt output services the output stages of the following sections: video, vertical, horizontal, and audio. Notice the wiring arrangement of the two full-wave rectifiers. This arrangement is done in some receivers so that part of the diode can be physically connected to ground. The ground is then used as a heat sink, eliminating the need for an insulator between ground and the rectifier body.

Generally speaking, color TV power supplies are slightly larger and more complex than those found in old black-and-white sets due to the power required by the extra circuits in the color sets and the automatic degaussers.

A typical power supply used in a color TV receiver is shown in Figure 8-56. This type of power supply, with its numerous output voltages, feeds both transistors and tubes. Most of the transistors receive their power from the +20 volts developed by the active filter. After a little extra filtering, this same +20 volts is sent to the tuner. R7 is used to adjust this output. All of the tube heater filaments, except the picture tube, receive their power from the same output winding that provides the +20-volt outputs. The picture tube heater is on a separate winding that is biased to +140 volts to prevent cathode-to-heater shorts.

The +290-volt B+ supply has a degaussing circuit in series with it. A thermistor and varistor control the current in the degaussing coil. As the circuit warms up, the thermistor decreases in resistance and the varistor increases in resistance. The net result is a surge of current through the degaussing coil for a few seconds before the set warms up. Very little current then flows through the coil during normal receiver operation. The +290-volt supply uses a half-wave voltage doubler. Capacitors C2 and C4 are across the diodes for transient protection. This feature gives the diodes a much longer life.

**DIGITAL TELEVISION**

In 1987, the Federal Communications Commission (FCC) began a process to select and implement a new television standard that is in place today. The FCC set up an advisory committee on advanced television service, and on November 28, 1995, the advisory committee voted to recommend the FCC's adoption of the Advanced Television Systems Committee Digital Television (ATSC DTV) standard.

The ATSC DTV standard adopted capabilities such as the 16:9 wide-screen aspect ratio, compact disc (CD) quality audio, and multicasting of several programs simultaneously while maintaining the 60 Hz frame rate and 6 MHz bandwidth. The standard also allows for future expansion, improvement, and integration of enhanced features.

In 2006, the United States Congress established February 17, 2009 as the last date of analog TV transmissions beginning the new era of fully digital broadcasting.
End of Chapter 8
Television

Review Questions

8-1. A basic television has how many elements?

A. One
B. Two
C. Three
D. Four

8-2. In a television system, what device reproduces a received synchronized scanned image?

A. Vidicon
B. Orthicon
C. Monitor
D. Reverberator

8-3. Television transmission uses what type of scanning?

A. Synchronized
B. Nonsynchronized
C. Horizontal
D. Vertical

8-4. How long is one vertical scan of a picture broadcast in the United States?

A. 1/60 of a second
B. 1/120 per second
C. 60 per minute
D. 600 per minute

8-5. What factor determines a television’s maximum ability to resolve fine detail?

A. Transmission frequency
B. Number of heterodyned receivers
C. Number of scanning lines
D. Broadcaster signal strength

8-6. What are two types of television scanning?

A. Interlaced and optical
B. Interlaced and noninterlaced
C. Intermodal and intramodal
D. Rapid action and interlaced
8-7. What type of scanning is used in most closed-circuit television systems?
A. Nonintralaced
B. Interlaced
C. Transverse
D. Intermodulated

8-8. What is the horizontal scanning frequency, in hertz, of commercial broadcasts and most closed-circuit televisions?
A. 30
B. 60
C. 525
D. 15,750

8-9. The standard analog television signal consists of what total number of elements?
A. One
B. Two
C. Three
D. Four

8-10. In commercial television broadcasting, what qualities do (a) the maximum video amplitude voltage and (b) the minimum video amplitude voltage correspond to on a television monitor?
A. (a) Clear picture (b) snowy picture
B. (a) Snowy picture (b) clear picture
C. (a) Black (b) white
D. (a) White (b) black

The complete video signal for three scanned lines.
8-11. Refer to the figure above. What is the maximum length of time, in seconds, for a horizontal blanking pulse?

A. 1/30  
B. 1/60  
C. 1/120  
D. 1/15,750

8-12. At what point in the broadcast are the synchronization pulses generated in a television system?

A. At origination  
B. At destination  
C. During demodulation  
D. During amplification

8-13. What television pickup device contains a grid of millions of photodiodes?

A. Accelerating anode  
B. Focusing coil  
C. Charge coupled device  
D. Signal electrode

8-14. Which of the following statements describes the output circuit of a camera tube?

A. It must reduce its signal strength to minimum.  
B. It must amplify all frequencies equally.  
C. It must be as small as possible.  
D. It must be as large as possible.

8-15. What information is contained in a television receiver’s composite video signal?

A. Video blanking pulses  
B. All information needed to reproduce the picture  
C. Frequency modulation and audio  
D. Synchronization pulse

8-16. What portion of the horizontal blanking and synchronization process blanks the right side of the screen?

A. Back porch  
B. Front porch  
C. Equalization pulse  
D. Sweep pulse
8-17. A monitor's control unit provides which of the following functions?

A. Synchronize the camera's scanning signals
B. Provide channel selection capabilities
C. Synchronize the monitor with the camera
D. Control the camera's broadcast frequency

8-18. At what ratio are the horizontal and vertical scanning signals maintained by the monitor's control unit?

A. 1:1
B. 1:2
C. 2:1
D. 2:2

8-19. At what frequency, in hertz, does the synchronization generator's master oscillator operate?

A. 15,750
B. 22,500
C. 31,500
D. 62,000

8-20. In a television monitor's synchronization generator, what is the countdown of the frequency divider?

A. 2:1
B. 3:1
C. 4:1
D. 5:1

8-21. In addition to the mixer, what other two basic parts make up a television tuner?

A. Video amplifier and oscillator
B. Video amplifier and radiofrequency amplifier
C. Video detector and oscillator
D. Radiofrequency amplifier and oscillator

8-22. In a television receiver, what type of circuit is used to remove unwanted sound and video beat frequencies?

A. Crystal filter
B. Trap
C. Detector
D. Attenuator
8-23. Which of the following statements describes a television video detector’s output?

A. A positive picture phase
B. A negative picture phase
C. A constant deflection coil reference phase
D. A positive or negative phase, depending upon where the signal is applied

8-24. When used between all stages in the video-amplifier section, what type of coupling, if any, eliminates the need of a dc restorer?

A. Direct
B. Resistive-capacitive
C. Resistive-inductive
D. None

8-25. What are the two basic configurations of television sound systems?

A. Intracarrier and split
B. Intercarrier and split
C. High fidelity and monaural
D. Intercarrier and mono

8-26. Which of the following characteristics is a requirement of a television’s intercarrier sound system?

A. A wide enough bandpass to allow the audio and video signal to pass
B. A narrow bandpass to allow only the audio frequencies to pass
C. A varying bandpass to allow monaural audio
D. A dual-channel amplifier to allow passage of stereo audio

8-27. What characteristic of a split-carrier sound system makes it different from an intercarrier sound system?

A. It requires fewer audio amplifier stages.
B. It amplifies both audio and video signals in the same circuits.
C. The audio and video are separated and processed individually.
D. The audio is split into two stereo channels.

8-28. The construction of integrated-circuit sound systems has of the following advantages?

A. High-power, solid-state construction
B. Low-power, solid-state construction
C. High-power, individualized circuit construction
D. Low-power, individualized circuit construction
8-29. How is a picture displayed on a cathode ray tube display?

A. Liquid crystal on silicon projects image with cold cathode backlight.
B. Liquid crystal display projects image with cold cathode backlight.
C. Light-emitting diodes project image through shadow mask.
D. An electron gun fires electron at a fluorescent material on the screen.

8-30. What two voltages control the brightness on a cathode ray tube screen?

A. Grid and cathode
B. Composite and cathode
C. Intermediate and cathode
D. Grid and composite

8-31. What is the basic difference between color and monochrome picture tubes?

A. The type of biasing used
B. The phosphors coating the screen
C. The cathode circuit
D. The grid circuit

8-32. What shape is formed by the red, green, and blue dots on the screen of a color picture tube?

A. Circle
B. Square
C. Triangle
D. Rectangle

8-33. What is the difference, if any, between the tuner and amplifier stages of color television (TV) receivers as compared to black-and-white receivers?

A. Color TV components have a wider bandpass
B. Black-and-white TVs use one-stage amplifiers
C. Color TV Components have a narrower bandpass
D. None

8-34. How many video amplifier stages are typically contained in a color television system?

A. One
B. Two
C. Three
D. Four

8-35. The 3.58-megahertz chrominance subcarrier signal originates (a) at what location and contains (b) what information?

A. (a) Transmitting station (b) color information
B. (a) Transmitting station (b) synchronization pulses
C. (a) Receiver oscillator (b) color information
D. (a) Receiver oscillator (b) synchronization pulses
8-36. What characteristic of the vertical sweep oscillator’s filter circuitry overcomes the system’s sensitivity to noise pulses (spikes)?

A. Wide bandpass
B. Narrow bandpass
C. Short time constant
D. Long time constant
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CHAPTER 9

COMPUTERS AND PROGRAMMING

The phrase “kick the tires and light the fires” is frequently heard when preparing to launch an aircraft sortie. That figure of speech from days long past meant that as long as there was an airframe with nothing falling off, an engine that would start and achieve takeoff speed, and air in the tires, the aircraft would be launched so pilots could get flight time. Those days are long gone and the term “mission” has become the prime objective of the aircraft. The performance of these missions is dependent upon the status of the various avionics packages. If one or more of these packages are degraded or do not work at all, the aircraft may be considered partial mission capable (PMC) or not mission capable (NMC). This lack of mission capability has thrust many avionics work center supervisors into the spotlight.

Newer and more sophisticated aircraft are being designed and built. The avionics systems are becoming more complex, thus allowing the aircraft to perform more complex missions. The increased complexity forces the problems to have solutions in microseconds. Only computers are capable of performing these solutions. Each associated avionics system will act as a sensor that feeds continuously updated information to one or more computers. The computer assimilates the data and sends out information where it is needed. Today’s aircraft receive data from virtually every system including battlespace information and awareness, engines, weapons systems, flight controls, fuel systems, and hydraulic systems to be processed by computers and disseminated as required.

Because computers are used extensively in naval aircraft, today’s avionics electronic technician must have a basic understanding and working knowledge of computers. The depth of knowledge will continue to grow at a rapid pace with current and future aircraft.

This chapter will provide the basic operating principles of computers including programming fundamentals and an overview of the Abbreviated Test Language for All Systems (ATLAS) programming language.

LEARNING OBJECTIVES

When you have completed this chapter, you will be able to do the following:

1. Identify electronic components of a computer.
2. Identify computer programming languages and applications.
3. Recognize operating principles of analog and digital computers.
4. Referring to various schematic and block diagrams, recognize the components of a central processing unit and the function(s) of each.
5. Recognize concepts and procedures used in construction of a computer program.
6. Describe how digital computers communicate with external peripheral devices.
7. Identify peripheral avionics systems and describe their interaction with the computer.
8. Identify components of the ATLAS program to include a test program.
BASIC COMPUTER
Computers process large amounts of data, images, signals, and graphics to solve complicated problems quickly and accurately without human interaction. Computers are selected based on the task at hand.

COMPUTER MAKEUP
All computers operate on the same basic principles but vary in computing power and capability driven by the mission requirements. Computers can be broken down into two sections: hardware and software.

Hardware
The physical parts of the computer such as displays or monitors, microprocessors, printers, and printed circuit cards are commonly called hardware. The basic components (Figure 9-1) of all computer systems are a central processing unit, primary memory, secondary (auxiliary) memory, and input/output (I/O) or peripheral devices.

Central Processing Unit
The main processing unit in a computer is the central processing unit or CPU. CPUs contain circuitry that executes instructions contained in a program to process or manipulate data. The key component of a CPU is the microprocessor. Actual function of the microprocessor is based upon the manufacturer’s design. Of all the processes that take place within a computer, the most important is the manipulation of data, which takes place within the red box of Figure 9-1. The data processor block diagram does not represent physical characteristics or location. The CPU is composed of two units, the control unit (CU) and arithmetic logic unit (ALU). In most cases, the CU and ALU are a single silicon chip, while the memory is separate. The CU and ALU have the following functions:

- CU. Directs the overall operation of the computer in accordance with a prescribed program (plan).
- ALU. Executes the arithmetic and logical operations after receiving instructions from the CU.

Although technically not actually part of the CPU, the memory unit is an integral part of data manipulation. Many variations and configurations of memory exist. One or more of these units store the program and the data to be processed.

Figure 9-1 — Basic computer functional diagram.
Primary Memory

Primary or internal memory is the computer circuitry that holds program instructions and data for immediate use. There are several types of memory including random access memory (RAM), read only memory (ROM), and virtual memory.

- RAM (*Figure 9-2*) holds data about to be processed and the program instructions when the computer is on. Similar to a chalkboard, data is written there until no longer needed and then erased. It also temporarily stores the processed data prior to transferring to permanent storage.
- ROM stores often-used instructions such as those the computer uses during the bootstrap or start-up process. It is normally permanent and installed by the manufacturer.
- Virtual memory is a programming option that allows the computer’s CPU to access mass storage for use as RAM when processing large amounts of data or running large programs.

Secondary Memory

Computers process large amounts of data that must be stored for future use. Secondary or auxiliary memory stores this data and is accomplished by a number of devices or methods. Data storage requirements are determined by the computer’s mission requirements and operational environment. Secondary storage is normally non-volatile, meaning it will not be lost if power is removed from the system. The following is a list of the most common storage devices or methods:

- Hard disk drive (HDD). HDDs use one or more rotating platters or disks coated with magnetic material to store and retrieve large amounts of data. The platters contain non-volatile memory in sectors similar to RAM, meaning it can be accessed out of sequence. Storage capacity ranges from 500 gigabytes (GB), where 1 GB = 1 billion bytes, to several terabytes (TB), where 1TB = 1,000 GB. A HDD uses magnetic heads on a moving arm to read and write data to the disks.
- Solid state drive (SSD). SSDs use solid state logic gates to store non-volatile information. This type of storage is particularly attractive for military applications due to its lack of moving parts and ability to operate under harsh conditions. However, SSDs are expensive and capacity is less than a standard HDD.
- Optical disk drive (ODD). ODDs (*Figure 9-3*), more commonly known as compact discs (CDs) or digital versatile discs (DVDs), use laser light in the spectrum near visible light to read and write data. CDs store approximately 650 megabytes (MB) of data while a DVD may have a capacity greater than 9 GB.
Magnetic tape is used as a storage medium for large amounts of data, normally as a main storage backup. It is used as a backup because of its long access time. Data is magnetically encoded on the tape and must be located, sequentially, before it can be retrieved. The two main advantages of using magnetic tape are its large storage capacity and low cost.

**Peripheral Devices**

Peripheral devices include all the I/O devices used with a computer system. Devices under the control of the CPU are considered online while a device operating independently is considered offline. Common peripheral devices include:

- Keyboard
- Monitor
- Printer
- Mouse
- Scanner

**Software**

Software is a term that is applied to a set of computer programs, procedures, and associated documentation concerned with the operation of a data processing system. Software includes compilers, assemblers, executional routines, and I/O libraries.

The advances in computer software provide the industry with the greatest realm of application possibilities. The problem of attempting to communicate with a computer has led to the development of symbolic languages that approach human language. The fact that a person can tell a computer what to do, just as one directs the actions of another person, has been made possible through software.

Programming in a universal language has led to the development and refinement of a number of computer languages. Many of these languages are for a special area or purpose; for example, in the 1950s FORTRAN (FORmula TRANslator) was developed for business and scientific programs, COBOL (COmmon Business Oriented Language) for business, and Jovial was adapted for military command and control applications and later, the APG-73 all-weather, coherent, multimode airborne radar used by some models of the F/A-18 Hornet and other military aircraft. Each of the languages fulfills a specific need for a specific problem but lacks the universal ideal application.

As computer use expanded, so did the number of programming languages until it became a financial burden on the Department of Defense’s (DoD’s) budget. Costing an estimated $13 billion annually in today’s dollars, the DoD High Order Language Commonality program began in 1975. The programming language Ada was developed as a DoD-wide standard. However, that never came to fruition and by 1997 the standard was rescinded. Computers in use today use a variety of languages but are generally moving towards commercial off-the-shelf (COTS) software with adequate security considerations. For example, the F-35 Lightning II Joint Strike Fighter air vehicle’s programming is written using widely available C++ language.

Software is also used to overcome environmental and operating arena challenges. Programming around these challenges is a common practice in the computer industry. Software is, in fact, often used to determine design feasibility.

Perhaps the most critical application has been in the area of real-time processing. Real-time processing is a situation in which data that is submitted to a computer requires an immediate
response. The capability of a computer to perform real-time processing could determine the success or failure of an aircraft’s mission.

COMPUTER CATEGORIES

In general, there are two basic categories of computers: analog and digital.

Analog Computers

The term analog (sometimes called mechanical), as applied to computers, pertains to representation by means of continuously variable physical quantities. For example, an analog computer can be a device that solves problems by setting up electrical circuits that represent the physical equivalents of certain phenomena and by taking measurements of them. These electrical circuits vary with changes in the phenomena. However, the analog computer is by no means restricted to electrical circuits as equivalents. The physical equivalents may be gear trains, gases, fluids, and so on. A digital computer, on the other hand, is a device that solves problems by manipulating the numerical equivalents of phenomena in accordance with mathematical and logical processes. These numerical equivalents may be expressed as binary numbers, octal numbers, decimal equivalents, and so forth. In an electronic digital computer, the numerical equivalents are generally expressed as binary numbers: 1’s and 0’s. Values of voltage and current are used to represent the 1’s and 0’s of the binary numbers.

Analog computers, because of their nature, have some inherent limitations. The use of physical equivalents limits their versatility. They are limited to performing only the tasks for which they were designed or, in certain instances, closely related tasks.

The Norden bombsight (Figure 9-4) is an example of a special purpose analog computer used by the Navy in World War II. The Norden, essentially an analog calculator, could adjust for air density, wind drift, and the bomber’s airspeed and groundspeed while controlling the bomber’s final run on the target. Notice the small anchor on the unit’s lower right chassis.

Digital Computers

The versatility of digital computers is based on the fact that they use numerical equivalents to represent not only the data to be processed, but also the instructions for processing the data. In other words, digital computers are generally provided with a wide variety of instructions. They are designed to respond in certain ways to the numerical equivalent of these instructions. Programming is merely a matter of modifying and/or arranging these instructions so that the computers will respond in a predictable manner to a given situation. Digital computers are limited to the variety of tasks they can perform by such factors as follows:

- Quality of the I/O devices
- Design of their central processors
- Memory type, speed, and quantity
• Programmer’s capability to develop a numerical method for representing and solving the problem

There are two basic types of digital computers: special-purpose and general-purpose.

**Special-Purpose Computers**

Special-purpose digital computers are designed to follow a specific set of instruction sequences that are fixed at the time they are manufactured. For example, the digital stores (weapons) management system in *Figure 9-5* is specifically designed to provide the operator individual weapons status of up to 18 weapons stations, selection, arming, release, and post launch control of precision guided munitions. To change the operation of this type of computer, the actual construction and programming of the machine may have to be altered.

*Figure 9-5 — Stores management system.*
General-Purpose Computers

General-purpose digital computers follow instruction sequences that are read into and stored in memory prior to the calculation performance. This type of computer operation can be altered by programming a different set of instructions. Since the operation of general-purpose digital computers can be changed with relative ease, as compared to special-purpose computers, they provide far greater usage flexibility. For example, the Consolidated Automated Support System (CASS) uses a computer that is able to test a wide variety of systems from aircraft communication equipment to shipboard systems depending on the operational test program set employed. While specifically configured to test avionic equipment, the computer section could easily be reconfigured with new software to perform other general-purpose functions.

DIGITAL COMPUTER OPERATIONS

All computers operate in a similar manner. They fetch or gather data from an input source, process the information, store the results, and produce an output in a usable media.

Each major section of a computer is comprised of various electrical circuits, such as flip-flops (bistable devices), amplifiers, logic circuits, and passive memory elements. These elements are, in turn, organized into registers (a series of electronic devices for temporary storage of a binary word), counters (a series of electronic devices that progress through a specific binary sequence), and logic gates (logic functions to set a flip-flop or generate a times condition signal). The computer manipulates binary numbers (1’s and 0’s) representing numerical values or conditions. Devices to retain these binary figures comprise the majority of the computer registers, and each register has a distinct purpose or function. Operations require the binary word or data be transferred from one register to another. Several different words may be transferred simultaneously.

Gates are used to control the transfer of data words from one register to another. These gates consist of microscopic diode and resistor networks. The gate circuit generates a signal to transfer the contents of one register to another at a particular time if certain conditions are met, such as if the instruction being executed is an add, and if one of the numbers being added is a negative number. If these conditions are met, a command signal is generated; if they are not met, the signal is not generated.

Gates in computers are active only during specific instructions, such as divide, and, then possibly, only during that instruction while other gates generate signals that are common to several instructions. In the design of a computer, each instruction that the computer is to perform is very methodically analyzed, and, for each signal required, a gate is designated to generate the signal.

The size of the registers determines the general size of the computer. Not all registers in the computer have the same word length. Some are determined by the accuracy required, while others are determined by the instruction word, number of addresses in the memory, and various other parameters.

Control Unit

Depending on the details of the computer, the CU of a typical digital computer includes the instruction register, P register, general register(s), and shift count (SC) register. A basic explanation of these registers follows:

- Instruction register. This register holds the instruction code during execution. The size of the register is dependent upon the instruction word and makeup of the computer. The instruction code usually has more than one part or field.

9-7
• P register. The P register contains the memory address of the next sequential instruction to be executed. The contents of the P register are automatically advanced by one by the P + 1 adder.

• General register. This register stores the quantity used for address modification. In addition, it usually has the properties of automatic increment or decrement. Most computers have more than one general register.

• SC register. The SC register consists of one or two registers to hold a shift count. Its size is dependent on the maximum number of places that a word can be shifted.

An easy way to comprehend the operation of the CU is to compare it to a telephone exchange. The act of dialing a phone number energizes certain switches and control lines in a telephone exchange. In a similar manner, each program instruction, when executed, causes the control section to energize certain “switches” and “control lines.” This enables the computer to perform the function or operation indicated by the instruction.

Computer instructions or programs are generally stored in a section of the computer’s internal memory. In certain applications, they may be read instruction-by-instruction from an external operational test program medium.

In addition to telling the computer what to do, CUs also contain an operating system that dictates how and when each specific operation is to be performed. Operating systems are designed to support computer’s basic functions, such as running applications or controlling I/O devices. They are also active in initiating circuits that locate information stored in the computer and in moving this information to the point where the actual manipulation or modification is to be accomplished.

The CU reads an instruction from the primary memory section (as instructed by the program). The information read into the CU from memory is in the form of varying voltage levels that make up a “binary word,” and represents a specific operation that is to be performed. The location of the data to be operated on is generally a part of the instruction and energizes circuitry that causes the specified operation (add, subtract, compare, and so on) to be executed. Subsequently, the CU “reads” the next instruction or jumps as directed to find the next instruction to execute.

Computer instructions are broken down into four general categories. These categories are transfer, arithmetic, logic, and control.

• Transfer commands transfer data from one location to another. One of the instructions is usually an address in memory, and the other is either a register or an I/O device.

• Arithmetic instructions combine two pieces of data to form a single piece of data, using one of the arithmetic operations. In some computer types, one of the pieces of data is in a location specified by an address contained in an instruction, and the other is already in a register (usually the accumulator). The results are usually left in the accumulator.

• Logic instructions enable programmers to construct programs capable of multi-tasking. These instructions enable the CPU to compare sets of data and follow a specific routine depending on the result. For example, an inventory maintenance program may follow one routine if an inventory is low and another if the item count is too large. The choice of which set of procedures to use is made by the CU under the influence of the logic instructions. Logic instructions provide the computer with the ability to make decisions based on the results of previously generated data.

• Control instructions send commands to devices not under direct control of the CU, such as I/O units. The address portion of the control instruction does not specify a location in memory, but is usually a coded group specifying an action required of a particular piece of equipment.
Every computer provides circuitry for a variety of logic instructions, thus providing the capability of selecting alternate instruction sequences if certain desirable or undesirable conditions exist. The ability to “branch” at these key decision points makes the computer able to perform such tasks as missile control, navigation, and tactical air plotting.

**Arithmetic Logic Unit**

The ALU is the section in which arithmetic and logic operations are performed on the input or stored data. The operations performed in this unit include adding, subtracting, multiplying, dividing, counting, shifting, complementing, and comparing.

Generally, information delivered to the CU represents instructions, while information routed to the ALU represents data. Frequently, it is necessary to modify an instruction. This instruction may have been used in one form in one step of the program but must be altered for a subsequent step. In such cases, the instruction is delivered to the ALU, where it is altered by addition to or subtraction from another number in the accumulator. The resultant modified instruction is again stored in the memory unit for use later in the program.

All arithmetic operations can be reduced to any one of four arithmetic processes: addition, subtraction, multiplication, or division. In most computers, multiplication involves a series of additions; and division, a series of subtractions.

The ALU contains several registers-units that can store one “word” of computer data. This group of registers generally includes D, X, and Q registers (so named for identification purposes only), and a unit called an accumulator (A register). During an arithmetic process, the D, X, and Q registers temporarily hold or store the numbers being used in the operation, called operands. The accumulator stores the result of the operation. The CU instructs the ALU to perform the specified arithmetic operation (as requested in the instruction). The CU then transfers the necessary information into the D, X, and Q registers from memory and controls the storage of the results in the accumulator or in some specific location in memory.

The ALU also makes comparisons and produces yes-no or go-no-go outputs as a result. The computer can be programmed so that a yes or go result causes the computer to perform the next step in the program, while a no or no-go instruction may cause the computer to jump several programmed steps. A computer can also be programmed so that a no result at a certain point in the program will cause the computer to stop and await instructions sent from a keyboard or other input device.

**Primary Memory Function**

All computers must contain facilities to store computer words or instructions (which are intelligible to the computer) until they are needed in the performance of the computer calculations. Before the computer can begin to operate on its input data, it is first necessary to store, in primary memory, a sequence of instructions and all figures, numbers, and any other data that is to be used in the calculations. The process by which these instructions and data are read into the computer is called loading.

The first step in loading instructions and data into a computer is to manually place enough instructions into memory by using some sort of peripheral, such as a keyboard, so that these instructions can be used to bring in more instructions as desired. Primary ROM contains the instructions used to bootstrap or start a routine set of instructions upon initial system load during power-up.

The memory (or storage) section of a computer is essentially an electronically operated file cabinet. It is actually a large number of storage locations; each location is referred to as a storage address or memory location.
register. Every computer word that is read into the computer during the loading process is stored or filed in a specific storage address, and is almost instantly accessible.

**Input/Output Section**

The I/O section is that portion of the digital computer through which the CPU communicates with the external peripheral devices. Data is read or entered into the computer, processed, and then transferred to the output. The peripheral units handle the data input and output display functions. The I/O section controls the transfer of data between the computer and the peripherals.

The I/O section is the interface between the computer and any external devices. An interface is an assembly of electronic circuits that make the computer compatible with the peripheral units. This compatibility permits the computer and peripheral units to interact and interpret one another intelligently. The compatibility involves logic levels, timing or speed, and control.

When digital data is transmitted between two units, the binary voltage or current levels must be compatible. Logic-level conversion is often required to properly interface different types of logic circuits. For example, logic-level shifting is often required to properly interface bipolar and metal-oxide-semiconductor (MOS) circuits. The speed of the data transmission must also be compatible. Some type of temporary storage between the two units may be required as a buffer to match the high-speed CPU to a low-speed peripheral unit.

Control is another function of the interface. Status lines tell when the computer or peripheral unit is ready or busy, and strobe lines actually initiate the data transfers. This process is often referred to as “handshaking.”

The type of information exchanged between the I/O unit and the peripheral devices includes data, addressing, and control signals. Since multiple I/O units can usually be connected to a computer, some coding scheme is required to select the desired unit. This is usually done with a binary word used as an address. The address is transmitted to all the peripheral devices. The unit recognizing the address is connected to the I/O section. Data can then be transmitted to or from the device over the interconnecting data lines. The actual data transfers are controlled by control signals between the two devices.

Programmed data transfers that take place as the result of executing an I/O instruction usually cause data to be transferred between the peripheral unit and the accumulator register in the CPU. Other CPU registers may also be used, depending upon the computer architecture and the instruction. In some computers, peripheral units are treated as memory locations. The peripheral units are addressed as storage locations, and all memory reference instructions can be used in performing I/O operations. No special I/O instructions are used.

**Data Transmission**

There are two methods of transmitting digital data: parallel and serial (Figure 9-6). In parallel data transmission, all bits of the binary data are transmitted simultaneously. For example, to transmit 6-bit binary numbers in parallel from one unit to another, six interconnecting data transmission lines are required. Each bit requires its own separate data path. All bits of a word are transmitted at the same time. Therefore, a significant amount of data can be moved in a given period of time.

The disadvantage of the parallel method is the large number of interconnecting cables between the two units. For large binary words, cabling becomes complex and expensive. This is particularly true if there is a significant distance between the two units. Long multi-wire cables are not only expensive, but also require special interfacing to minimize noise and distortion problems.
Serial data transmission is the process of transmitting binary words a bit at a time. Since the bits time-share the transmission medium, only one interconnecting lead is required.

While serial data transmission is much simpler and less expensive because of the use of a single interconnecting line, it is technically a slower method of data transmission. Nevertheless, simplicity and greatly reduced cost make it attractive for systems where extremely high speed is not a requirement. Serial data transmission techniques are widely used to transmit data between a computer and its peripheral units. For example, many printers physically attached to a computer use a universal serial bus (USB). While the computer operates at very high speeds, most peripheral units are slow because of their electromechanical nature. Slower serial data transmission is more compatible with such devices. Since the speed of serial transmission is more than adequate in such units, the advantages of low cost and simplicity of the single interconnecting line can be realized.

Parallel Data Transmission

There are a variety of ways to implement this data path. The two basic classifications of transmission line circuits are single-ended and balanced. Single-ended transmission systems use a single wire data path for each bit. When combined with a ground or return reference, the electrical circuit between the sending circuit and the receiving circuit is complete. In a balanced-transmission line system, two conductor cables are used to send the data. The data on the dual-transmission line is complementary. The dual-transmission lines also use a ground return reference. While a single-ended transmission line is simpler and less expensive, it is subject to more noise problems than the dual- or balanced-transmission line system.

Serial Data Transmission

The simplest, most economical, and easiest to use method of transferring digital information from one point to another is serial data transmission. In a serial system, the digital data is sent one bit at a time; therefore, only a single pair of transmission wires is required. The serial transmission of data is far slower than parallel transmission. However, in most computer systems, the low-speed penalty is no disadvantage. Data rates of 400 megabits per second (Mbps) or greater are achievable in serial data systems.
Serial data transmission is preferred because it is inexpensive. It is especially beneficial in transferring data over long distances. For long distances, you can see that multiple parallel lines are far more expensive than a single cable.

Serial data transmission also permits transmission of data by radio. A radio communications path represents only a single interconnecting link similar to a transmission line pair. Therefore, for data to be transmitted by radio, it must be in serial format. Serial digital data is used to modulate a radio carrier in various ways.

In digital computer systems, you will find that both serial and parallel data transmission methods are used. Parallel methods are used where high speed and short distances prevail. Serial data transmission is used where low cost, simplicity, low speed, long distances, and minimum cost are necessary.

Fiber Optics

Both serial and parallel data transmission methods can also be applied with a fiber optic system with the addition of specialized optical transceivers. For parallel transmission, the same theory applies, in that a 6-bit data word requires 6 fibers in a parallel system. The data transmission speeds of fiber optics far exceed those of traditional serial and parallel buses. Fiber optic transmission lines are able to achieve speeds of 40 gigabits per second (Gbps) or greater. Fiber optic lines will not be discussed in detail in this chapter.

Input/Output Devices

I/O devices are similar in operation but perform opposite functions. It is through the use of these devices that the computer can communicate with devices external to the computer itself (peripheral devices).

Input Devices

Input data may be in one of three forms:

- Manual inputs from a man-machine interface (MMI) such as a keyboard or console
- Analog and/or digital inputs from instruments or sensors
- Inputs from a source on or in which data has previously been stored in a form intelligible to the computer

Computers can process hundreds of thousands of computer words per second. Thus, a study of the first method (manual input) reflects the inability of human-operated keyboards to supply data at a speed that matches the speed of digital computers. A high average speed for keyboard operation is two or three characters per second, which, when coded to form computer words, reduces the data input rate to the computer to less than a word per second. Since the computer can read several thousand times this amount of information per second, it is clear that manual input reduces the efficient use of computer time.

Instruments used as input sensors are capable of supplying several thousand samples regarding pressure, temperature, speed, and other measurements per second. This is equivalent to 10,000 to 20,000 bits or binary digits per second. Digital computers that use these devices must be equipped with analog-to-digital (A-to-D) encoders (assuming the input is in an analog format) to convert physical change to specific increments.

Another method of entering data into a computer is to link two or more computers together and program them to communicate with each other. This is perhaps the fastest method of entering or
extracting data from a computer. An example of this is the interaction between computers and various I/O sources in a stores management system in Figure 9-5.

Output Devices

Output information is also made available in three forms:

- Displayed information, such as that on a digital display indicator (DDI) in the crew station of an aircraft, which is used by the operator to make decisions
- Control signals that operate a control device such as a lever, aileron, or actuator in a flight control system
- Recordings, which are items of information stored in a machine language or human language on discs or printed media

Devices that store or read output information include HDDs, SSDs, magnetic tapes, monitors, and printers.

The main advantage of computers is their ability to process large amounts of highly complex data quickly. In most cases, the processing speed far exceeds the ability of input devices to supply information. One limitation of input devices is that their operation may include some form of mechanical operation; for example, the movement of a scanner’s feeder. Because a mechanical movement of some part of these devices cannot take place fast enough to match electronic speeds with the computer, these input devices limit the speed of operation of the associated computer. This is particularly evident in cases where successive operations are dependent upon the receipt of new data from the input medium.

The I/O section of a computer provides the necessary lines of communication and generates such signals as are necessary for the computer to establish communications with and, where necessary, to control the operation of the I/O devices. The I/O section, once it has been initiated by the control unit, usually operates independently of the control section except when it must time-share memory with the control section.

Regardless of the type of I/O device or sensor being used, the purpose of the I/O section is to provide the computer or user with access to the data these devices or sensors provide.

PROGRAMMING FUNDAMENTALS

Computer programming is the process of planning a solution to a problem. You can derive a general outline for calculating total resistance of a parallel resistance circuit by using the following steps.

1. Take the reciprocal of the resistance in ohms of all resistors in a circuit.
2. Calculate the sum of the values from step 1.
3. Compute the reciprocal of the value from step 2.

The process of preparing a program from this explanation is not difficult. One basic characteristic of the computer must be considered: it cannot think. It can only follow certain commands, which must be correctly expressed and must cover all possibilities. If a program is to be useful, it must be broken down into specifically defined operations or steps. These operations or steps, along with other data, must be communicated to the computer in a language that it can understand.
Generally, the steps that a computer follows in the execution of a program are as follows:

1. Locates parameters (constants) and such data as necessary for problem solution.
2. Transfers the parameter and data to the point of manipulation.
3. Performs the manipulation according to certain rules of logic.
4. Stores the results of manipulation in a specific location.
5. Provides the user with a useful output.

Even with a simple program, such as the resistance program, each step must be broken down into a series of machine operations. These instructions, along with the parameters and data necessary for problem solution, must be translated into a language or code that the computer can understand.

Programming is a complex problem that may involve writing a large number of instructions. It may also involve keeping track of a great many memory cells that are used for instruction and data storage, which is time-consuming and can lead to errors.

To reduce time and the possibility of errors for complex program preparation, the compiler has been developed. The compiler is a program that takes certain commands and then writes, in a form the machine understands, the instructions necessary for a computer to execute these commands. Compilers can bring many instructions into the final program when called upon or signaled by a single source statement. The compiler is problem oriented because the operations produced are those needed to work the problem as set out by the problem statement. Compilers are built at various levels or degrees of complexity. The simplest form of compiler takes one mnemonic phrase and writes one machine instruction. A mnemonic code is an abbreviated term describing something to assist the human memory. For example, to shift the contents of the A-register right nine places, the mnemonic code RSH.A9 is used. This causes the compiler to write an instruction that shifts the contents of the A-register right 118 places. A compiler written on this level is commonly called an assembler. Note the advantages: (1) no opportunity to use the wrong function code; and (2) no necessity to convert the shift count to octal.

**Subroutines**

As a program grows larger, certain functions must be repeated. If the instructions necessary to perform each of these repeated functions are grouped together to form subroutines, these subroutines may then be referenced by a relatively few instructions in the main program. This eliminates repeating certain groups of instructions throughout the program.

Housekeeping is a term used frequently with subroutines. At the time of entry into a subroutine, the contents of the various addressable registers may or may not be of value. An addressable register is defined as any register whose contents can be altered under program control. The programmer must take steps to preserve the contents of these registers unless they are of no value. This process is termed housekeeping.
**Executive Routines**

The instructions that control access to the various subroutines are called the executive routines of the main program. Depending upon the complexity of the program there may be more than one executive routine and there may be executive subroutines within the executive routines.

**Jump and Return Jump Instructions**

The jump and return jump instructions are used in the construction of executive routines. These instructions provide the computer with the ability to leave the sequential execution of the main program or executive routine, execute any of the subroutines stored in its memory, and then return to the execution of the main program.

Execution of a return jump instruction causes the address of the next instruction to be executed in the main program to be stored (usually in the entry cell of the subroutine). It then causes the instruction of the second cell of the subroutine to be executed. The last instruction to be executed will usually be a straight jump to the address contained in the entry cell. Since a jump instruction specifies the address of the next instruction to be executed, the computer is provided with a means of returning to the main program once the subroutine has been executed.

**Program Construction**

The process of writing a program is broken down into six basic steps:

1. **Statement.** A statement forms a clear, comprehensive statement of the problem.
2. **Analysis.** Analysis consists of laying out the problem in a form that will lend itself to arithmetical and/or logical analysis, determining what logical decisions must be made, and determining if data manipulation is required.
3. **Flow diagram.** A flow diagram, or chart, is an expansion of steps in which special symbols are used to represent the various operations to be performed and the sequence in which they are to fall.
4. **Encoding.** This is the process of converting the operations listed in the flow chart into language the computer will use; either machine instructions, words, or compiler statements.
5. **Debugging.** This is the process of locating errors in the program. Various techniques are available for this purpose. A program may be written to include some aids for itself, or a separate debugging program may be run to test the operation of a malfunctioning program. For a simple program, a trial solution may be done on paper, and the computed results compared with those actually obtained at each step.
6. **Documentation.** Documentation is very important because later changes may be warranted in a program or it may be desirable to use subroutines from another program. Proper documentation will ensure that this can be accomplished. Documentation should include the following:
   - Program title
   - Problem statement
   - Programmer’s name
   - Date
   - Memory area used and/or number of cells used
• Registers used
• I/O devices required
• Flow diagram(s)
• Hard copy (program listings, especially a listing of the coded instructions)
• Program disks

**Flow Charting**

The programmer constructs a program “map” in determining a solution to a problem. This map is commonly called a flow chart or flow diagram and serves a multitude of important functions. The flow chart “maps” the logical steps required for decisions to be reached, and paths to be followed as a result of those decisions. When properly annotated, it defines I/O requirements, address allocations, data accuracy considerations, and register usage. A flow chart is valuable to a programmer when “debugging” a program and when making future changes.

Flow charting can be constructed at various levels of complexity. A high-level flow chart consists of a few symbols and presents a broad overview of the problem. A low-level flow chart may approach a one-to-one correspondence between flow chart symbols and program instructions. Usually, there will be several flow charts for a program area. These may be compared to the prints found in a maintenance manual. Maintenance manual prints include a block diagram to show the relationship of the major units (high level), functional block diagrams showing the major circuits in a unit (intermediate level), and the schematics of the circuits (low level). Flow charts should be at such a level that they will implement all the uses previously discussed.

**Maintenance Programs**

As we have previously stated, a routine or program is a series of instructions that control the operations of a computer. Each instruction is used to cause some action that is part of the overall task the computer must perform. Therefore, an instruction may be considered as the basic building block of a computer program.

An overall check of a computer can be done by the use of a maintenance program. The maintenance program provides a thorough and rapid method for the detection of failures in a specific portion of a computer. This type of overall maintenance check is flexible and efficient. The programs may use the same type of disk, memory, computing, and external storage media as operational programs. The maintenance program can be altered when the computer or auxiliary components are changed. The program can also be constantly improved. Generally, no extra test equipment is required since the computer circuits are used to perform the test. Testing by means of maintenance programs results in the computer circuits being used in a more comprehensive manner than during normal program execution. When a program has been checked and accepted as a good maintenance tool, it is not subject to deterioration. In contrast, test equipment may be checked and accepted only to become unreliable shortly after being placed in use.

Maintenance programs are divided into three main classes: reliability, diagnostic, and utility programs. Maintenance programs that are used to detect the existence of errors are called reliability programs. Reliability programs should be arranged to check as many computer circuits as possible.

Maintenance programs that are used to locate the circuits in which computer malfunctions originate are called diagnostic programs. An effective diagnostic program should locate the source of trouble as closely as possible. Actually, in many cases, reliability programs have diagnostic features, and diagnostic programs have reliability features. For convenience, a program is called either a reliability
or diagnostic program, depending on its intended emphasis. In general, programs that check rather than diagnose are shorter and simpler.

Utility programs work with the operating system to increase speed, efficiency, or capabilities of existing hardware, software and peripherals.

**PERIPHERAL AVIONICS SYSTEMS**

The aircraft's mission computer (*Figure 9-7*) is considered the most important avionics system in achieving the mission of the aircraft. However, the success of the computer depends upon its external sensors or other avionics systems. The quality of the input data is a prime factor in determining the quality of a computer's output data. The following avionics systems provide inputs to and receive outputs from the computer: navigation, radar, ordnance/weapons, and digital data link. These are only a few of the major aircraft avionics systems that interface with the mission computer; each system is discussed briefly below.

**Navigation**

Navigation systems are designed to tell pilots where they are, where they have been, and where they are going. The tactical air navigation/distance measuring equipment (TACAN/DME) system provides known station reference points, while an embedded global positioning/inertial navigation system (EGI) provides continuous updating of such information as latitude and longitude. This information is fed to the computer where it is compared, updated, and sent out to other systems.

**Search/Fire Control Radar**

A search radar system is designed to give visual indications of what is around the aircraft. Present-day aircraft have a 150-mile or greater range. Depending upon the size and/or speed of the radar indications, a computer can determine whether the target is stationary or moving, a landmass or an aircraft, friendly or unfriendly, and many other items of information. If a target is determined to be unfriendly, fire control radar can be used by the pilot to eliminate the unfriendly target.

**Ordnance/Weapons**

The design characteristics and ballistics of the many types of ordnance, weapons, and missiles require the use of a computer to store the information. The airborne computer aids the pilot in stores management and weapons release. The computer greatly increases the pilot's chances of destroying designated targets.

**Digital Data Link**

Combat aircraft must have the most up-to-date information available to successfully complete combat missions. On an aircraft carrier, the combat information center maintains constant contact with airborne early warning aircraft. These two command and control operations exchange their tactical
pictures with the use of a digital data link system. Digital data link uses radiofrequency and satellite capabilities to pass near real-time information. This information is sent to various ships and combat aircraft in the battlespace to ensure their success.

**ATLAS SYSTEM**

ATLAS was developed by Aeronautical Radio Incorporated as a structured language to provide greater uniformity between test specifications as provided by automatic test equipment (ATE) suppliers. ATLAS defines the requirements of the test in terms of the unit under test (UUT). ATLAS is designed to be easily read and understood by both people and computers. The Navy uses ATLAS programs in the CASS family of test equipment.

The ATE is provided with an ATLAS compiler/interpreter that translates ATLAS program statements into an intermediate language, which allows high-speed interpretation and reduces the amount of memory required. Characteristics of this interpreter permit the source language to be reconstructed online so that program changes can be inserted easily.

To use ATLAS with ATE, a compiler or interpreter is required to analyze the ATLAS statements and perform the requested actions. A compiler is a program that translates the ATLAS statements into machine language instructions suitable for execution by a computer. A compiler has the advantage of fast execution and reduced computer memory size, but it has the disadvantage of tedious program preparation because of the difficulty in introducing changes. An interpreter is a program that translates and executes ATLAS programs on a statement-by-statement basis. The original ATLAS statements are retained with the interpreter so that programs may be modified online. This means that the programmer may generate and verify a program using a keyboard and display conversationally to correct mistakes as they are found. The disadvantages of an interpreter are slower execution and a need for a relatively large computer memory.

**Sample Test Program**

A schematic diagram for a simple electronic UUT is shown in Figure 9-8. The corresponding ATLAS functional test program for the UUT is shown in Table 9-1. The UUT is a simple inverting operational amplifier circuit having a nominal gain of 10 and requiring ±15 volts direct current (Vdc) power. After a few of the program characteristics are mentioned, a statement-by-statement examination is given.
Table 9-1 — UUT Corresponding ATLAS Program

000005 BEGIN, ATLAS PROGRAM$
C000010 ATLAS DEMONSTRATION TEST PROGRAM$
C 30 DEFINE CONNECTIONS BETWEEN UUT ATE AND ANTICIPATED RESPONSES$
40 DEFINE, CONNECTIONS, PIN 100= P1-1, PIN 101= P1-2, PIN 102= P1-3, PIN 103= P1-4, PIN 104= P1-5$
50 DECLARE, ‘GOOD OUTPUT’ (10)$
60 FILL, ‘GOOD OUTPUT’ (1), .9, .9, .9, .9, .9, .9, .9, .9, .9, .8$
C000100 HOOKUP UUT POWER TO ATE POWER SUPPLIES$
05 APPLY, EARTH, CNX H1 P1-3$
10 APPLY, DC SIGNAL, VOLTAGE 15V, CNX H1 P1-1$
20 APPLY, DC SIGNAL, VOLTAGE -15V, CNX H1 P1-2$
C000200 TEST FOR OSCILLATION OR OFFSET$
10 APPLY, EARTH, CNX H1 P1-4$
20 VERIFY, (VOLTAGE-TRMS), AC SIGNAL, LT 1MV, CNX H1 P1-5 LO P1-3$
30 GO TO, STEP 350 IF NOGO$
40 REMOVE, EARTH, CNX H1 P1-4$
50 TEST GAIN AT 10 DIFFERENT FREQUENCIES$
60 LOOP, THRU STEP 290 WITH ‘F’=1 TO 10$
70 APPLY, AC SIGNAL, VOLTAGE .1V, FREQ ’F’KHZ, CNX H1 P1-4$
80 VERIFY, (VOLTAGE, AC SIGNAL, UL 2-’GOOD OUTPUT’ (’F’) LL ’GOOD OUTPUT’ (’F’), CNX H1 P1-5 LO P1-3$
90 GO TO, STEP 300 IF NOGO$
94 DISPLAY, RESULT, “TEST COMPLETE, UNIT GOOD”$
98 REMOVE, ALL$
99 FINISH$
C000300 FAILURE MESSAGES$
10 DISPLAY, RESULT, “UNIT FAILED GAIN TEST AT”; ’F’; “KHZ”$
20 REMOVE, ALL$
30 FINISH$
50 DISPLAY, RESULT, “UNIT FAILED OFFSET/OSCILLATION TEST”$
60 REMOVE, ALL$
70 FINISH$
000900 TERMINATE, ATLAS PROGRAM$

Program Characteristics

The test program starts when dc power is applied to the UUT. The amplifier input is then grounded, and a check is made at the amplifier output to determine that the output signal is less than 1 millivolt. Any signal in excess of this would have to be due to amplifier oscillations or offset voltage.

The program then begins a loop that checks the amplifier gain at 10 different frequencies, ranging from 1 to 10 kilohertz (kHz). The test is terminated if a failure is detected at any point. Test results are displayed at the end.

Note that the program uses only capital letters. These are used because the I/O devices (such as the keyboard, monitor, or printer) use only capital letters.

Note that each statement of the program begins with a number. These numbers are called statement numbers and serve to identify the statement. A program is made up of statements, most of which are instructions to the computer. Statement numbers specify the order in which the statements are to be performed by the computer. Program statements may be typed in any order. Before the program is
run, the computer sorts and edits the program, putting the statements into the order specified by their statement numbers.

Note that the format used in printing step numbers does not print the most significant four digits of the step number unless they differ from those of the preceding step. This implies that the second occurrence of step 10 is really statement 110, and the third occurrence of step 10 is really statement 210. This distinction is extremely important in retrieving program steps to be modified.

After its statement number, each statement starts with an English word. This word is the statement verb. The verbs for statements in ATLAS provide for testing UUTs, performing calculations, controlling the flow of the program, and communicating with the station operator.

**Program Examination**

The following is a step-by-step examination of the sample test program shown in Table 9-1.

Statements 10 and 30 are simply comment statements that have been included to make it easier for a reader to determine the function of the program. Statement 40 defines the connections between the UUT and the ATE. Each pin on the ATE has been assigned an integer number, and each pin on the UUT is identified by its normal name presented as a string of characters. This statement tells the test program that P1-1 on the UUT is connected to pin 100 on the ATE; P1-2 on the UUT is connected to pin 101 on the ATE; and so forth.

Statement 50 is used to define the anticipated response in an array variable form. It defines the array name as ‘GOOD OUTPUT’ and specifies that it has 10 elements. Statement 60 specifies that the first nine of the elements have a value of .9, and the tenth element has a value of .8. These values are then used for limit checking in statement 280 as 10 values of gain expected for 10 frequencies.

Statement 100 is a comment statement explaining the function performed by steps 105, 110, and 120. Statement 105 grounds pin P1-3. Statement 110 applies 15 volts dc to pin P1-1 on the UUT with the 15 volts return connected to ground. Statement number 120 applies minus 15 volts dc to pin P1-2 on the UUT with the return connected to ground.

Statement 200 begins the test for oscillations or offset. Statement 210 applies signal ground to pin P1-4 on the UUT. Statement 220 ascertains that the root-mean-square voltage level on pin P1-5 of the UUT is less than 1 millivolt. Statement 230 directs the program to statement 350 if the test performed in statement 220 results in a NOGO condition. Statement 240 removes the ground on pin P1-4 of the UUT at the completion of the test.

Statement 250 begins a test of alternating current (ac) signal gain with frequencies ranging from 1 to 10 kHz. Statement 260 initializes a program loop extending through statement 290, and specifies that the loop is to be performed with variable ‘F’ equal to 1 during the first iteration, 2 during the second iteration, 3 during the third iteration, . . . through 10 during the tenth iteration. Statement 270 causes the ATE to apply an ac signal having a voltage of 0.1 volt and a frequency of ‘F’ kHz to pin P1-4 on the UUT and to apply return to pin P1-8. Statement 280 directs the ATE to measure the root mean square (rms) voltage level on pin P1-5 of the UUT and to ascertain whether or not it is greater than the value of the array variable ‘GOOD OUTPUT’ (‘F’). Statement 290 directs the program to proceed to statement 300 if the preceding test resulted in a NOGO condition. Since statement 290 is within the range of the loops set up by statement 260, control will return to statement 270 unless ‘F’ is greater than or equal to 10.

If the loop has been completed, program execution continues with statement 294, which displays the message TEST COMPLETE, UNIT GOOD on the ATE monitor. Statement 298 then removes all connections to the UUT, and statement 299 returns control to the test station operator.
In the event that any of the tests resulted in a failure, the program would branch as directed in statements 230 or 290 to the appropriate error message statement. The branch to statement 310 results in a displaying of UNIT FAILED GAIN TEST AT, the value of ‘F’, kHz on the monitor. Statement 320 removes all connections to the UUT, and statement 330 returns control to the test station operator. The branch to statement 350 results in a display of OFFSET/OSCILLATION TEST on the monitor. Statement 360 removes all connections to the UUT, and statement 370 returns control to the test station operator.

Each of the statements is important to the proper operation of the test. For example, what would have happened if statements 110 and 120 had been omitted? The UUT would have had no power applied so that it would pass the test for oscillations or offset, but it would fail the gain test. Failing to include statement 240 would have resulted in an error when step 270 was executed since this would represent an attempt to apply an ac signal to a pin on the UUT that previously had been grounded. This error would be detected by the ATE, and would result in an error message being displayed and the test being terminated. If statement 294 was omitted, the operator would have no assurance that the test program completed all the tests.

The particular choice of statement numbers is arbitrary, as long as the statements are numbered in the order in which they are to be executed in stepping through the program. The statements could have been numbered 1, 2, 3, . . . , 31, although consecutive numbering is not recommended. Gaps are left between statement numbers so that it will be possible later to insert additional statements to make corrections to the test program. If it becomes necessary to add two statements between those numbered 210 and 220, they can be given any two numbers between 210 and 220; for example, 214 and 216. In the editing and sorting process, the computer will put them in their proper place in the program. If it is desirable to segregate independent tests, it can be done easily by starting each test with a statement ending in 00. This makes it easier to examine the program and determine which steps are used in any single test. A comment statement describing the test to be performed is considered good form.

**ATLAS Statement Components**

ATLAS statements contain various components, including characters, numbers, labels, variables, and arrays. These components are discussed below.

**Authorized Characters**

The only authorized characters for use in ATLAS statements are uppercase letters A through Z, numbers 0 through 9, and miscellaneous symbols listed in Table 9-2.

<table>
<thead>
<tr>
<th>Asterisk</th>
<th>*</th>
<th>Greater than</th>
<th>&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comma</td>
<td>,</td>
<td>Not equal (pound sign)</td>
<td>#</td>
</tr>
<tr>
<td>Period</td>
<td>.</td>
<td>Currency symbol</td>
<td>$</td>
</tr>
<tr>
<td>Equal</td>
<td>=</td>
<td>Slash</td>
<td>/</td>
</tr>
<tr>
<td>Plus</td>
<td>+</td>
<td>Right parenthesis</td>
<td>)</td>
</tr>
<tr>
<td>Minus</td>
<td>-</td>
<td>Left parenthesis</td>
<td>(</td>
</tr>
<tr>
<td>Hyphen</td>
<td>-</td>
<td>Apostrophe</td>
<td>’</td>
</tr>
<tr>
<td>“At” symbol</td>
<td>@</td>
<td>Double quote</td>
<td>“</td>
</tr>
<tr>
<td>Less than</td>
<td>&lt;</td>
<td>Blank space</td>
<td></td>
</tr>
<tr>
<td>Semicolon</td>
<td>;</td>
<td>Percent</td>
<td>%</td>
</tr>
</tbody>
</table>

9-21
When it is necessary to identify an alpha character literally as lowercase, such as in a manufacturer’s pin designation, a slash (/) is written preceding each affected character. The minus sign and hyphen are represented by the same character and will be interpreted according to the context of the statement. In this document, the apostrophe (’) is frequently referred to as a single quote mark in connection with its usage with labels.

**Numeric Representation of Constants**

The ATLAS interpreter uses two basic types of internal numeric representations for numbers. Numbers are classified as being either real or bit pattern. Real numbers are usable for all types of arithmetic computations. Bit pattern numbers are used for stimulating and checking the responses of digital UUTs. The rules for expressing numbers in ATLAS program are listed below.

1. Real numbers may be written as decimal numbers, with or without a decimal point, or they may be expressed in exponential notation for convenience in representing very large or very small numbers. Real numbers in decimal form may be written with a plus or minus followed by the string of characters 0 through 9, with the decimal point placed in the conventional reamer. Numbers written without the prefix plus or minus are accepted as positive (examples: -5268, 28.00, +55). Real numbers may also be written in the exponential form ±n.m E ±p where n, m, and p are numeric strings of up to six digits (examples: 1E6, 3E + 8, 1.72E - 19). If m is zero, the decimal point may be omitted. Real number accuracy is limited to six significant digits with a range of ±10 to the 38th power.

2. Bit patterns may be expressed in binary, octal, hexadecimal, or character string forms. A sign preceding the number has no meaning for bit patterns. Conversion from the decimal number form and several bit pattern representations are shown in Table 9-3.

3. Binary numbers are written with the letter B followed by the appropriate string of the numbers 0 and 1 enclosed in single quotes (example: B’0110010’). Up to 528 binary bits are permitted.

4. Octal numbers are written with the letter O followed by the appropriate string of numbers 0 through 7 enclosed in single quotes (example: O’701340’). Up to 176 digits are permitted.

5. Hexadecimal numbers are written with the letter X followed by the character string using 0 through 9 and A through F, which represents the hexadecimal value enclosed in single quotes (example: X’53A5D2’). Up to 132 hexadecimal digits are permitted.

6. The character string configuration is written with the letter C followed by any string of characters enclosed in single quotes, except the apostrophe and currency symbol characters, which may NOT be used. A character string is limited to 66 characters maximum (example: C’2A/=’).

**Table 9-3 — Number Conversions**

<table>
<thead>
<tr>
<th>Decimal</th>
<th>Binary</th>
<th>Octal</th>
<th>Hexadecimal</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0000</td>
<td>00</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>0001</td>
<td>01</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>0010</td>
<td>02</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>0011</td>
<td>03</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>0100</td>
<td>04</td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td>0101</td>
<td>05</td>
<td>5</td>
</tr>
<tr>
<td>6</td>
<td>0110</td>
<td>06</td>
<td>6</td>
</tr>
</tbody>
</table>
Table 9-3 — Number Conversions (continued)

<table>
<thead>
<tr>
<th>Decimal</th>
<th>Binary</th>
<th>Octal</th>
<th>Hexadecimal</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>0111</td>
<td>07</td>
<td>7</td>
</tr>
<tr>
<td>8</td>
<td>1000</td>
<td>10</td>
<td>8</td>
</tr>
<tr>
<td>9</td>
<td>1001</td>
<td>11</td>
<td>9</td>
</tr>
<tr>
<td>10</td>
<td>1010</td>
<td>12</td>
<td>A</td>
</tr>
<tr>
<td>11</td>
<td>1011</td>
<td>13</td>
<td>B</td>
</tr>
<tr>
<td>12</td>
<td>1100</td>
<td>14</td>
<td>C</td>
</tr>
<tr>
<td>13</td>
<td>1101</td>
<td>15</td>
<td>D</td>
</tr>
<tr>
<td>14</td>
<td>1110</td>
<td>16</td>
<td>E</td>
</tr>
<tr>
<td>15</td>
<td>1111</td>
<td>17</td>
<td>F</td>
</tr>
</tbody>
</table>

Labels

Unique character strings enclosed in single quotes are called labels. They are required in certain statements to provide unique identifiers within the program. A label may contain up to 62 characters. Blanks are significant in a label. Labels may be selected at the writer's convenience, and if properly selected, they will improve the readability of the program. Labels may be formed by any combination of the authorized characters except the apostrophe ('), currency symbol ($), at symbol (@), and double quote (").

Variables

Computer memory locations are made available to the ATLAS test programmer for storage of measured values, anticipated values, and intermediate results of arithmetic computations. These locations are designated as variables, and are identified by variable names, which may consist of up to 62 alphanumeric characters. These names are enclosed in single quotes and may be assigned uniquely by the programmer. Each variable may be used by the programmer to store real, octal, binary, hexadecimal, or character string forms of data. Variable locations that are to receive more than 32 bits of data must be declared larger in a DECLARE statement. Non-declared variables larger than 32 bits have the most significant bits truncated to 32 bits.

Two forms of variables are provided: simple variables and array variables. A simple variable is a single memory location designated by a single name such as 'NAME', whereas an array variable is a group of memory locations assigned a common name. All variables are set undefined at the start of execution of an ATLAS test program. The variable must be defined or assigned a value somewhere within the test program. Use of an undefined variable will result in a terminating error message when the program is executed. The value of a program variable is assigned by the program as it is executed, and it may change as new values are obtained. The value of a program constant is assigned by the test programmer. It remains fixed as a number during the program execution.

The variable, known as 'MEASUREMENT' (abbreviated 'ME'), is a permanent, preassigned identifier with special significance to the ATLAS interpreter. This variable will have its value set to the value of the measured characteristic by all READ, MEASURE, monitor, and VERIFY statements. The value contained in 'MEASUREMENT' may then be used in any subsequent statements. 'MEASUREMENT' may be used anywhere in the program where a real valued variable may appear. It may be assigned a value through a CALCULATE statement, although the user must be aware that its value will be reassigned by subsequent execution of any statement that returns a measured value. The value of 'MEASUREMENT' may be retained beyond the time it would otherwise be lost through execution of
another sensor statement by assigning its value to another variable through the use of a CALCULATE statement. The inclusion in a statement of a RESULT modifier followed by a variable name causes the value of ‘MEASUREMENT’ to be stored as the value of the variable upon completion of statement execution. This eliminates the need for a separate CALCULATE statement to perform this assignment. An example would be as follows:

```
30 MEASURE, (RE), IMPEDANCE, RESULT ‘IN-Z’, CNX HI J1-40 LO J1-45 $
```

Arrays

In addition to the simple variables used by ATLAS, there are variables that can be used to designate the elements of an array. These are used where a subscript would ordinarily be used; for example, the coefficients of a polynomial (A0, A1, A2, . . .) or to designate the elements of a vector.

The array variables used in ATLAS consist of the array name enclosed in single quotes followed by the subscript enclosed in parentheses. The subscript may of course be a formula. Thus, the programmer might write ‘A’ (0), ‘A’ (1), ‘A’ (2), and so forth, for the coefficients of the polynomial mentioned above. Individual elements of the array may be accessed by referring to the array name followed by a value enclosed in parentheses, such as ‘A’(4). The value in parentheses may range from 0 to the maximum number of elements that the array may contain. The number of elements in the array must be specified at the start of the ATLAS test procedure through a DECLARE statement.

The array ‘A’ (0), ‘A’ (1), ‘A’ (2), . . . ‘A’ (10) can be entered into the program by writing the following:

```
000010 DECLARE ‘A’(10)$
```

This statement identifies the variable ‘A’ as an array having 11 elements, which may be referred to as ‘A’ (0), ‘A’ (1), . . . ‘A’ (10). A subsequent FILL statement may then be used to load the array, such as the following:

```
000020 FILL ‘A’(0),2,4,6,8,10,9,8,7,6,5,5 $
```

This statement loads the array with the values shown so that ‘A’ (0) = 2, ‘A’ (1) = 4, . . . and ‘A’ (10) = 5. If the array is not to be preloaded with data, the FILL statement can be omitted. Note that the variable ‘A’ may no longer be referred to as a simple, unsubscripted variable.

Arithmetic Calculations

The ATLAS interpreter provides a powerful facility for performing arithmetic calculations and storing the results in variable locations through use of the CALCULATE verb. A single CALCULATE statement may be used to set a number of variables equal to a single value, a number of variables equal to a number of values, or any combination of these. Some examples of permissible CALCULATE statements are as follows:

```
000010 CALCULATE, ‘A’=4, ‘B’=‘C’=3$
   20 CALCULATE, ‘A’=4, ‘B’=7, ‘C’=7=19$
   30 CALCULATE, ‘A’=‘B’=4, ‘C’=17, ‘O’=5*(17.2+TAN(‘P’)))**4$
```

In a CALCULATE statement, the value on the right side of the equal sign is stored in the memory location specified by the variable on the left side of the equal sign. This variable then retains that value until it is changed by execution of some subsequent statement. In statements involving multiple-equivalence operations separated by commas or semicolons, the operations are performed in left to right order. Parentheses are used to indicate the order of reduction of the arithmetic operations and establish priorities for the calculation. If there is any question about the priority, add
more parentheses to eliminate possible ambiguities. The order of priorities is summarized in the following rules:

1. The formula inside the parentheses is computed before the parenthesized quantity is used in further computations.

2. In the absence of parentheses in a formula involving addition, multiplication, and exponentiation, the computer first performs the exponentiation, then performs the multiplication, and then addition comes last. Division has the same priority as multiplication, and subtraction the same as addition.

3. In the absence of parentheses in a formula involving operations of the same priority, the operations are performed from left to right.

4. The computer performs arithmetic calculations by evaluating formulas that are supplied in the program. These formulas are very similar to those used in standard mathematical calculations. Five arithmetic operations can be used to write a formula. These are listed in Table 9-4.

Table 9-4 — ATLAS Arithmetic Functions

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Example</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>+</td>
<td>'A' + 'B'</td>
<td>Addition (Add 'A' TO 'B')</td>
</tr>
<tr>
<td>-</td>
<td>'A' - 'B'</td>
<td>Subtraction (Subtract 'B' from 'A')</td>
</tr>
<tr>
<td>*</td>
<td>'A' * 'B'</td>
<td>Multiplication (Multiply 'B' by 'A')</td>
</tr>
<tr>
<td>/</td>
<td>'A' / 'B'</td>
<td>Division (Divide 'A' by 'B')</td>
</tr>
<tr>
<td>**</td>
<td>'A' ** 2</td>
<td>Exponentiation (find 'A'^2)</td>
</tr>
</tbody>
</table>

Logical operators may be used to operate on bit string numbers in a CALCULATE statement. The logical operators available are AND, OR, EXOR (exclusive OR), and NOT. For example:

```
CALCULATE, 'D'='A' AND 'B', 'C' (3)='D' (1) OR 'D' (2), 'E' ('X')=NOT 'G' ('X'), 'Z'='M' EXOR 'N' $
```

Three rules pertaining to a CALCULATE statement are given below.

1. Mixed mode calculations (calculations involving both real and bit string numbers) are not allowed.

2. CALCULATE is the system default verb and is assumed if no verb is present in the statement.

3. UUT pin numbers may be assigned or reassigned to ATE pins with a CALCULATE statement of the following form:

```
000100 CALCULATE,@PI-A@=5$
```

In the above example, UUT pin PI-A has been reassigned to ATE pin 5. Any subsequent statements involving PI-A in the CNX list will operate on ATE pin 5. The UUT pin identifier in the CALCULATE statement is always bracketed with two @ symbols. Pins defined in CALCULATE statements should not be included in DEFINE, CONNECTIONS statements.

**Mathematical Functions**

In addition to the five arithmetic operations and logical operators, the computer can evaluate a number of mathematical functions. These functions are given the special names shown in Table 9-5.
Table 9-5 — ATLAS Language Mathematical Functions

<table>
<thead>
<tr>
<th>Functions</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIN('X')</td>
<td>Find the sine of 'X' (in degrees)</td>
</tr>
<tr>
<td>COS('X')</td>
<td>Find the cosine of 'X' (in degrees)</td>
</tr>
<tr>
<td>TAN('X')</td>
<td>Find the tangent of 'X' (in degrees)</td>
</tr>
<tr>
<td>ATAN('X')</td>
<td>Find the arc tangent of 'X' (result in degrees)</td>
</tr>
<tr>
<td>EXP('X')</td>
<td>Find $E^X$</td>
</tr>
</tbody>
</table>

ATLAS Test Program Statement Construction

An ATLAS program contains one statement for each action to be performed. The actions are specified by ATLAS verbs, such as BEGIN, APPLY, MEASURE, DISPLAY, CALCULATE, REPEAT, and TERMINATE. If the verb corresponds to a UUT stimulus or measurement, nouns and modifiers are used to define the signal. AC SIGNAL and DC SIGNAL are examples of ATLAS nouns. Modifiers are used to specify parameters or qualities of a signal. VOLTAGE, DISTORTION, FREQ, and RISE-TIME are typical noun modifiers. Each stimulus or measurement statement also contains a connection field specifying the points on the UUT to which a signal is to be applied or measured.

An ATLAS test program consists of a series of valid ATLAS statements. These statements are ordered by statement number, and execution proceeds in the sequence of ascending statement numbers. Each statement has three fixed fields, which are followed by a set of statement peculiar fields. The first three fields of every statement are the flag, statement number, and verb. The flag and statement number fields may be null. The remaining fields are variable in composition, length, and location, depending upon the type of statement being written. The general construction of ATLAS statements, including fields, is given below in Table 9-6.

Table 9-6 — Example of Test-Oriented ATLAS Statements

<table>
<thead>
<tr>
<th>C000050</th>
<th>THESE ARE SAMPLE ATLAS STATEMENTS $</th>
</tr>
</thead>
<tbody>
<tr>
<td>000100</td>
<td>APPLY, DC SIGNAL, VOLTAGE 5V, CNX HI J1-2 LO J1-3 $</td>
</tr>
<tr>
<td></td>
<td>10 APPLY, AC SIGNAL, VOLTAGE 9V, FREQ 1 KHZ, CNX HI J2-3 LO J2-4 $</td>
</tr>
<tr>
<td></td>
<td>30 APPLY, SHORT, CNX HI J1-5 J1-6 J1-7 $</td>
</tr>
<tr>
<td>000200</td>
<td>MEASURE, (VOLTAGE), AC SIGNAL, CNX HI J1-2 LO J1-3 $</td>
</tr>
<tr>
<td></td>
<td>10 MEASURE, (FREQ), AC SIGNAL, CNX HI J1-2 LO J1-3 $</td>
</tr>
<tr>
<td></td>
<td>20 VERIFY, (VOLTAGE), DC SIGNAL, GT 19V, GO-TO-STEP 700, CNX HI J1-19 LO J1-20 $</td>
</tr>
<tr>
<td></td>
<td>30 MEASURE, (RES), IMPEDANCE, RESULT ‘IN-Z’, CNX HI J1-40 LO J1-45 $</td>
</tr>
<tr>
<td>000300</td>
<td>REMOVE, SHORT, CNX HI J1-5 J1-6 J1-7 $</td>
</tr>
<tr>
<td></td>
<td>10 REMOVE, ALL $</td>
</tr>
</tbody>
</table>

ATLAS Statements

Test-oriented statements in ATLAS have the following general construction:

fstatno <verb> (<measured characteristic>), <noun>, <statement characteristics> <CNX field> $
As can be seen in Table 9-6, each statement starts out with a flag field, f, which is followed by the statement number field, statno. A verb following the statement number identifies the function performed by the statement.

There is a 1,022-character limit to the length of an ATLAS statement. Completing the statement on one line is not necessary. By inserting spaces between statement elements, the writer can begin a new line at any point in the statement, with subsequent lines indented if desired. Extra spaces cannot be inserted in the middle of the ATLAS language syntax elements, as defined in Table 9-6. The fixed fields (flag, statement number, and verb) must be written on the first line, as required by the format.

**ATLAS Statement Fields**

These fields include flag field, statement number field, verb field, measured characteristic field, noun field, statement characteristic field, and CNX field as defined below:

- **Flag field.** The first field of each statement is the flag field. It is one character in length and is located in the first column of the first row of each statement. The field must be used for a B, C, or E entry or left blank.
  - B entry. B in the flag field indicates the destination statement of a GO TO statement from elsewhere in the procedure. Characters following the statement number and preceding the $ are commentary and are ignored during translation.
  - C entry. C in the flag field indicates that information in that statement is a comment to be ignored during translation. Characters following the statement number and preceding the $ are treated as commentary and are ignored during translation.
  - E entry. E in the flag field indicates entry points where the test conditions are completely stated and are not dependent on previous tests in any way. Characters following the statement number and preceding the $ are treated as commentary and are ignored during translation.

- **Statement number field.** The second field is the statement number. It is six digits long and provides a reference designator for each program statement. The first four digits of the number are called “test numbers,” and the remaining two digits are called “step numbers.” Each succeeding program step is assigned a higher number than the preceding one, but it is neither necessary nor advisable to use the next higher number. If the test number of a statement is the same as the previous statement, the first four characters of the statement number may be left blank. If no statement number is provided, the interpreter will execute the statement immediately upon successful completion of the syntax check. The statement will not be included in the memory resident program. The largest statement number is 32767.

- **Verb field.** The third field is the verb field. Its length is variable depending on the entry to be made. The verbs that can be used on the ATE are listed in Table 9-7. Every ATLAS statement must have an entry in this field; if no entry is present, CALCULATE is assumed. The statement number and verb fields are separated by one space. A verb may include a mandatory space as an integral character of the word, such as in WAIT FOR.
### Table 9-7 — ATLAS Statement Elements

<table>
<thead>
<tr>
<th>VERBS</th>
<th>NOUNS (CONTD)</th>
<th>MODIFIERS (CONTD)</th>
<th>LOC (CONTD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>APPLY (AP)</td>
<td>SYNCHRO</td>
<td>NOM</td>
<td>2-CRT, J-T.P.</td>
</tr>
<tr>
<td>ASSIGN</td>
<td>TIME INTERVAL</td>
<td>OVERSHOOT</td>
<td>4-D.P., 5-VOUGE</td>
</tr>
<tr>
<td>BEGIN</td>
<td>TRIANGULAR WAVE SIGNAL (TWS)</td>
<td>PERIOD</td>
<td>0300 NEGATIVE FOR</td>
</tr>
<tr>
<td>CALCULATE</td>
<td>POS-SLOPE</td>
<td>2/CRT, 3/T.P.</td>
<td>SHORT TEST DATA</td>
</tr>
<tr>
<td>COMMON (CO)</td>
<td>FLAG MODIFIERS</td>
<td>PRF</td>
<td>0301 ADDRESSES</td>
</tr>
<tr>
<td>COMPARE (CP)</td>
<td>AC-COUPLED</td>
<td>PULSE-WIDTH (PW)</td>
<td>0302 -1 FOR EXC’S OAR’S</td>
</tr>
<tr>
<td>CONNECT (CT)</td>
<td>+CLOCK</td>
<td>RATE</td>
<td>0303 FIRST SUB ADDR.</td>
</tr>
<tr>
<td>DECLARE (DEC)</td>
<td>-CLOCK</td>
<td>REF-LEVEL (RLV)</td>
<td>0304 LAST SUB ADDR.</td>
</tr>
<tr>
<td>DEFINE (DEF)</td>
<td>CONTINUOUS (CONT)</td>
<td>RES-VOLTAGE-MAX (RVM)</td>
<td>CNX DESIGNATIONS</td>
</tr>
<tr>
<td>DELAY</td>
<td>HIGH-ACCURACY (HIAC)</td>
<td>RES-DELAY (RSD)</td>
<td>A</td>
</tr>
<tr>
<td>DELETE</td>
<td>HIGH-FREQUENCY (HFREQ)</td>
<td>RESULT</td>
<td>B</td>
</tr>
<tr>
<td>DISCONNECT (DT)</td>
<td>IF-GO</td>
<td>RISE-TIME (RT)</td>
<td>C</td>
</tr>
<tr>
<td>DISPLAY (DI)</td>
<td>REF-POS-SLOPE (RPS)</td>
<td>SAMPLES</td>
<td>CNX</td>
</tr>
<tr>
<td>DO</td>
<td>REF-NEG-SLOPE (RNS)</td>
<td>SYNC-LVL</td>
<td>CNX-RESP</td>
</tr>
<tr>
<td>ED</td>
<td>REPETITIVE</td>
<td>TIME</td>
<td>CNX-STIM</td>
</tr>
<tr>
<td>END</td>
<td>RESP-COMP (RSC)</td>
<td>UNDERSHOOT</td>
<td>COMPL</td>
</tr>
<tr>
<td>EXECUTE</td>
<td>SINGLE</td>
<td>VOLTAGE (VOL)</td>
<td>HI</td>
</tr>
<tr>
<td>EXTERNAL</td>
<td>+SLOPE</td>
<td>VOLTAGE-AV (VV)</td>
<td>LO</td>
</tr>
<tr>
<td>FETCH (F)</td>
<td>-SLOPE</td>
<td>VOLTAGE-COMP (VOP)</td>
<td>N</td>
</tr>
<tr>
<td>FILL</td>
<td>STIM-ONLY (STO)</td>
<td>VOLTAGE-MAX (VX)</td>
<td>REF-A</td>
</tr>
<tr>
<td>FINISH (FI)</td>
<td>STIM-RESP-COMP (STRC)</td>
<td>VOLTAGE-ONE (VONE)</td>
<td>REF-B</td>
</tr>
<tr>
<td>GO TO (GOTO)</td>
<td>STIM-RESP-SAVE (STRG)</td>
<td>VOLTAGE-F (VF)</td>
<td>REF-C</td>
</tr>
<tr>
<td>INDICATE</td>
<td>+SYNC</td>
<td>VOLTAGE-PP (VPP)</td>
<td>REF-HI</td>
</tr>
<tr>
<td>LIST (L)</td>
<td>-SYNC</td>
<td>VOLTAGE-TRMS (VT)</td>
<td>REF-LO</td>
</tr>
<tr>
<td>LOOP</td>
<td>TYPE-PARALLEL (TYP)</td>
<td>VOLTAGE-ZERO (VZER)</td>
<td>REF-N</td>
</tr>
<tr>
<td>MEASURE (ME)</td>
<td>TYPE-SERIAL-LSB-FIRST (TYSL)</td>
<td>WORD-LENGTH (WORL)</td>
<td>SYNC</td>
</tr>
<tr>
<td>MONITOR (MO)</td>
<td>TYPE-SERIAL-MSB-FIRST (TYSM)</td>
<td>WORD-RATE (WOR)</td>
<td>TRUE</td>
</tr>
<tr>
<td>PRINT (PR)</td>
<td>LIST MODIFIERS</td>
<td>LASAR</td>
<td>Y</td>
</tr>
<tr>
<td>PTAPE</td>
<td>ERROR (ERR)</td>
<td>DATA-FILE (DF)</td>
<td>Z</td>
</tr>
<tr>
<td>READ</td>
<td>ERROR-INDEX (ERRI)</td>
<td>FAULT-MESSAGE (FTM)</td>
<td></td>
</tr>
<tr>
<td>REMOVE (RE)</td>
<td>GO-TO-STEP (GTS)</td>
<td>FAULT-SET (FS)</td>
<td>DIMENSIONAL UNITS</td>
</tr>
<tr>
<td>REPEAT (REP)</td>
<td>MASK-ONE (MAO)</td>
<td>IF-FAULT (IFS)</td>
<td>A</td>
</tr>
<tr>
<td>REPLACE</td>
<td>REF</td>
<td>LASAR-CHECK (LC)</td>
<td>BITS</td>
</tr>
<tr>
<td>RUN (R)</td>
<td>RESP</td>
<td>LASAR-TEST (LAT)</td>
<td>DEG</td>
</tr>
<tr>
<td>SAVE</td>
<td>STIM</td>
<td>MISMATCH (MM)</td>
<td>GHZ</td>
</tr>
<tr>
<td>SCRATCH (SCX)</td>
<td></td>
<td></td>
<td>kHz</td>
</tr>
<tr>
<td>SETUP (SE)</td>
<td>MODIFIERS</td>
<td>MISC</td>
<td></td>
</tr>
<tr>
<td>STEP AT (ST)</td>
<td>ANGLE</td>
<td>AND</td>
<td>KOHM</td>
</tr>
<tr>
<td>TERMINATE (TE)</td>
<td>APERATURE</td>
<td>CONNECTIONS (CON)</td>
<td>KPPS</td>
</tr>
<tr>
<td>TLIST</td>
<td>AVERAGE</td>
<td>ELEMENTS</td>
<td>KV</td>
</tr>
<tr>
<td>TRAP</td>
<td>BIT-RATE (BIR)</td>
<td>EXOR</td>
<td>MA</td>
</tr>
<tr>
<td>VERIFY (VE)</td>
<td>CAL</td>
<td>GO-NO-GO</td>
<td>MHZ</td>
</tr>
<tr>
<td>WAIT FOR (WF)</td>
<td>CLOCK-DELAY</td>
<td>MANUAL DATA</td>
<td>MIN</td>
</tr>
<tr>
<td>COUNT</td>
<td></td>
<td>MESSAGE (MES)</td>
<td>MOHM</td>
</tr>
<tr>
<td>TIME (T)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NOUNS</td>
<td>CURRENT (CU)</td>
<td>NOT</td>
<td>MRAD</td>
</tr>
<tr>
<td>AC SIGNAL (AC)</td>
<td>DC-OFFSET (DCO)</td>
<td>OR</td>
<td>MSEC</td>
</tr>
<tr>
<td>ALL</td>
<td>DISTORTION (DIST)</td>
<td>PIN</td>
<td>MV</td>
</tr>
<tr>
<td>DC SIGNAL (DC)</td>
<td>FALL-TIME (FT)</td>
<td>PROCEDURE</td>
<td>OHM</td>
</tr>
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<td>DIGITAL TEST (DIG)</td>
<td>FAULT-COUNT (FC)</td>
<td>PPS</td>
<td></td>
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<tr>
<td>EVENTS</td>
<td>FILTER</td>
<td>QUERY (Q)</td>
<td>PSEC</td>
</tr>
<tr>
<td>IMPEDANCE</td>
<td>FREQ (FR)</td>
<td>SEC</td>
<td></td>
</tr>
<tr>
<td>PULSEDC (P)</td>
<td>LEVEL</td>
<td>DEBUG FLAGS</td>
<td></td>
</tr>
<tr>
<td>RAMP SIGNAL</td>
<td>MAX-TIME (MT)</td>
<td>LOC</td>
<td>USEC</td>
</tr>
<tr>
<td>SHORT (SH)</td>
<td>NAME</td>
<td>0277 OUTPUT DEVICE</td>
<td>UV</td>
</tr>
</tbody>
</table>

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Measured characteristic field. A measured characteristic field is included in sensor-type statements to specify which of the available characteristics is to be evaluated by the sensor function. The field is positioned between the verb and noun in the statement and consists of one of the modifier mnemonics from the list associated with the noun. The characteristic to be measured is always enclosed in parentheses. Typical statements are as follows:

\[
\begin{align*}
000200 & \text{ MEASURE, (VOLTAGE), AC SIGNAL, CNX HI J1-2 LO J1-3} \\
10 & \text{ MEASURE, (FREQ), AC SIGNAL, CNX HI J1-2 LO J1-3} \\
000650 & \text{ VERIFY, (VOLTAGE), DC SIGNAL, UL 10V LL 8V, CNX HI J1 LO J2} \\
000690 & \text{ MEASURE, (VOLTAGE), DC SIGNAL, CNX HI J1-4 LO J1-6}
\end{align*}
\]

Notice that evaluation data such as upper and lower limits may be needed in statements that contain the measured characteristic field.

- **Noun field.** The noun is a word or words that define(s) the electrical or physical element upon which the verb is to act. The available electrical or physical elements are dependent upon the station hardware configuration. The nouns that can be used on an ATE are listed in Table 9-7.

- **Statement characteristic field.** The statement characteristic field follows immediately after the noun field. The information in this field identifies additional modifiers required by the interpreter to further define a signal that is to be applied or a measurement that is to be taken. Entries in the statement characteristic field consist of the name of a modifier such as FREQUENCY or VOLTAGE followed by a value that specifies the magnitude of the modifier. Some types of modifiers (such as +SLOPE) do not require a value to be specified. The value of the modifier may be indicated by a ‘label’, which refers to a variable established by another statement in the program. A dimensional unit, such as hertz (Hz) or kHz, may be appended to the modifier if desired. It has the effect of multiplying the value of the quantities by the required factor to convert the value into basic units, as all modifiers are handled internally in basic units (such as volts, Hz, and ohms). Modifiers may be entered in any order. Lists of modifiers and dimensional units that are legal are provided with the ATE hardware.

- **CNX field.** The last field of a test program identifies the UUT pins to which a stimulus or load is to be applied or from which a measurement is to be taken. The field is separated from preceding fields by a comma and the word CNX. The field contains a series of assignments of ATE functions to UUT pins. Each ATE function, such as a stimulus output or measurement input, has associated designators, which must be used within the CNX field. These are listed in Table 9-7. Examples are HI, LO, X, Y, Z, N. An assignment of a function is accomplished by entering one of these designators followed by one or more UUT pin designators. The UUT pin designators used are generally identical to those used by the SRA manufacturer, such as J1-2 or P2-AA. The UUT pin designator may be as long as 62 characters using an arbitrary sequence of ATLAS characters excluding blanks, apostrophes, currency symbols, commas, @ symbols, and quotation marks. To prevent ambiguities in the statement, UUT pin designators may not be identical to ATE function designators, such as HI, LO, A, B, and C. For example:

\[
001000 \text{ APPLY, DC SIGNAL, VOLTAGE 5V, CNX HI J1-2 LO J1-3}
\]

The physical connection between the UUT pins and the station interface connector pins is defined during program execution by a DEFINE CONNECTIONS statement in the preamble to the program or in a CALCULATE statement. The slash character (/) indicates that the next character, which must be alphabetic, is lowercase; for example, J/A-2 = Ja-2.
Other ATLAS Statement Characteristics and Requirements

These include terminators, separators, and blank space requirements as defined below:

- **Statement terminators ($)**. The last character of every ATLAS statement must be the currency symbol ($).

- **Field separators**. Since the fields following the verb are variable, a separator is used to identify the start of each new major field. A comma preceded and/or followed by optional spaces is designated for this purpose.

- **Blank space requirements**. Generally, blank spaces are not significant in the language, and their presence or absence in a statement will not affect the correctness of the ATLAS program. However, blanks are required to separate UUT pin designators within a CNX field. It is permissible to include any number of blank characters between any two language elements. Any number is a language element. Within language elements, the characters are fixed as defined. WAIT FOR, for instance, can only be written as an eight-character word, including the one blank space. LT may only be written as two characters with no space, but any number of spaces may follow WAIT FOR or LT.

ATLAS Program Construction

A complete ATLAS test program is a series of ATLAS language statements divided into two distinct sections referred to as the preamble and the procedure. The preamble section contains all the DEFINE, DECLARE, and COMMON statements and procedure definitions. The procedure section then uses the elements defined in the preamble section in performing its assigned tasks. Note that there is no statement that separates the preamble and procedure sections.

**Preamble Section**

The preamble section of an ATLAS program precedes the procedure section, and it contains the BEGIN statement, all of the COMMON, DECLARE, and DEFINE statements, and the procedure (subroutine) definitions. FILL statements may also be included in the preamble. Preamble statements do not cause any tests to be executed, but the information described in the preamble may be repeatedly referenced in the procedure section.

- **BEGIN statement**. This statement designates the first statement of a complete ATLAS program. For example:

  00100 BEGIN, ATLAS PROGRAM$

The BEGIN statement does not cause any action and is used only to designate the beginning of a program. It is not mandatory, but is considered good programming practice.

- **DEFINE, ‘PROCEDURE NAME’, procedure statement**. This type of DEFINE statement assigns a name to one or more complete ATLAS statements, which form an executable subroutine. The defined series of statements is then executed when the ‘procedure name’ is cited in a PERFORM statement in the procedure section of the program. If any input data or results of the subroutine execution must be passed between the programs, a parameter list must be provided. The word RESULT is used to identify the parameters that will return data from the subroutine. Parameter lists are not required to name a subroutine, but there is no facility for adding to a parameter list when the subroutine is performed. If used, parameters declared in the DEFINE statement will refer to the corresponding actual parameter in the PERFORM statement. The following are sample statements:
DEFINE, ‘GENERATOR START’, PROCEDURE

DEFINE, ‘RELAY TEST’, PROCEDURE (‘INPUT’, ‘VOLTAGE’)
RESULT (‘GOOD’)

- DEFINE, ‘CONNECTIONS’, statement. This type of DEFINE statement defines the physical connections between the ATE and the UUT at the interface adapter. Each entry in the pin definition list identifies a UUT pin using the name supplied by the equipment manufacturer and specifies the pin to which the UUT pin is mated or connected. For example, if UUT pin J1-4 is connected to ATE pin 17, write DEFINE, CONNECTIONS, PIN 17 = J1-4. A typical statement is as follows:

  DEFINE, CONNECTIONS, PIN 5=J1-1, PIN 12=J1-2, PIN 19=J1-3

All ATE interface pins and many ATE internal points are assigned pin codes from 0 to 32767. All UUT pins are identified with the pin designation supplied by the UUT manufacturer with these limitations:

- A pin name may be represented by an arbitrary sequence of ATLAS characters excluding blanks, apostrophes, currency symbols, @ symbols, commas, and quotation marks. The slash character (/) indicates that the next character is lowercase. For example, J/A-2=Ja-2.
- No more than 62 characters, including any slashes (/), are allowed in a pin name.
- A pin name may not duplicate an ATE function designator such as HI or LO.

Each UUT pin used in the ATLAS program is defined in a DEFINE, CONNECTIONS, OR CALCULATE statement. Use of undefined pins will result in a terminating error, as the interpreter is unable to determine the signal routing required for the statement.

- DECLARE statement– This statement specifies the memory allocation to be used in storing array variables and those simple variables that must contain more than 32 bits of information. The first element of each array is element zero. The last element of the array is designated by a number in parenthesis in the DECLARE statement. A typical DECLARE statement is as follows:


This statement declares that array ‘A’ consists of 11 elements, and array ‘B’ consists of 6 elements. It further specifies that all elements in arrays ‘A’ and ‘B’ may contain up to 61 bits of information; additionally, the simple variable ‘C’ may contain up to 61 bits of information. Any number of arrays or simple variables may be declared in a single DECLARE statement as long as they must all contain the same number of bits of information. If the number of bits is not explicitly stated in the DECLARE statement, a default of 32 bits is assumed. It is unnecessary to declare simple variables for which 32 bits or less of storage will suffice. It is wasteful of computer storage to declare arrays larger than necessary or to specify more bits than are actually required by the variable.

- COMMON statement– This statement designates variables that are to be used in common by several ATLAS programs. The format is identical to the format used in DECLARE statements except that storage is allocated for variables specified in COMMON statements in a special area of memory. Array and variable size declarations specified in COMMON statements are processed exactly as they are in DECLARE statements. Arrays of variables that are specified in COMMON statements are processed exactly as they are in DECLARE statements. Arrays of
variables that are specified in COMMON statements should not be specified in DECLARE statements. All COMMON statements must precede all DECLARE statements in any given ATLAS program. Specifying variables as common variables permits their values to be transferred between ATLAS program overlays. The names of the variables have no significance, and values are passed strictly in the order in which they appear in the COMMON statement. As a rule, however, all related program segments will have identical COMMON statements.

An example of a parameter passing through COMMON is shown in the below programs:

```
000010 COMMON, 'A', 'B'(3), 'C'$
20 FILL, 'B'(1), 1, 2, 3$
30 CALCULATE, 'A' = 5, 'C' = 7$
40 EXECUTE, 'NXT-PROG'$
50 FINISH$

PROGRAM 'NXT-PROG'

000010 COMMON, 'A', 'B'(3), 'D'$
20 PRIN, RESULT, 'A', 'B'(1), 'B'(2), 'B'(3), 'D'$
30 FINISH$
```

The printed result appears as follows:

```
5 1 2 3 7
```

Note that in this case, the executing program defines the three variables 'A', 'B', and 'C' in common. 'B' is an array defined in statement 20. Statement 30 sets 'A' equal to 5, and 'C' equal to 7. Statement 40 executes the program named 'NXT-PROG'.

A listing of program 'NXT-PROG' shows three variables, 'A', 'B', 'D', in common. 'B' is defined as a list of three elements whose values are specified. The program prints the value of the three variables it receives (actually five values because of the array) and terminates. From the printed result, it can be seen that the program received the correct variable values from the EXECUTING program. The use of variable name 'D' in the second program shows that the names of the variables have no significance. Such redefinition of names through COMMON statements is not recommended because it may be confusing to a person attempting to understand the program.

- **FILL statement**– This statement can be used to load an array with data specified in the FILL statement. FILL statements may be included in either the preamble or procedure section of the ATLAS program. FILL statements located in the preamble section of the ATLAS program will be executed before execution of the program is started. Any FILL statement encountered in the normal flow of the program will also be executed at the time it is encountered. This allows array elements to be modified through use of FILL statements during program execution.

Each FILL statement may be used to load the elements of a single array only. The FILL statement specifies the initial array element that is to be loaded. Data values following the first value go into subsequent array elements. Data values may be of type real, binary, octal, hexadecimal, or character string. Some typical FILL statements are as follows:

```
000010 FILL 'A'(1), 5, 6.3, B'101', 7$
000020 FILL 'B'(7), 3, 2, 1$
```
In these examples, statement 10 fills elements 1 through 4 or array ‘A’ with the four data values specified in the statement; statement 20 fills elements 7 through 9 of array ‘B’ with the three data values specified in the statement.

Procedure Section

The procedure section is the main body of an ATLAS test program. It consists of a series of statements that are executed in sequence. All statement types are legal in the procedure section except those using the verbs DEFINE, COMMON, and DECLARE. Statements in the procedure section may refer to lists, UUT pins, or procedures, which are defined in the preamble section. Each statement describes a portion of the required test that must be completed before the next statement.

As stated above, execution of an ATLAS test program normally proceeds by executing statements in strict numerical order. However, this sequence may be altered through execution of a statement containing a GO TO verb or a GO-TO-STEP modifier. The sequence may also be changed by the programming technique known as a loop. (Loops will be discussed in detail later.) Such statements are used to branch the test program to some statement other than the one next in sequence. The program branch may be taken on either an unconditional or a conditional basis, depending on the structure of the statement.

- **Unconditional branching.** In the following sample statement, line 10 is an example of the unconditional branch, the simplest type of GO TO statement. The test sequence is diverted as indicated every time the statement is executed. For example:

  000010 GO TO, STEP 210$

- **Conditional branch on arithmetic comparison.** The following examples illustrate the use of an arithmetic comparison as a condition on a GO TO statement. Formulas of any complexity may appear on either side of the arithmetic comparison symbol. Only the symbols = and # may be used for bit string comparisons. The branch will be taken only if the specified condition is true. In statement 110, the branch will be taken only if ‘B’ is greater than or equal to 93. For example:

  000100 GO TO, STEP 330 IF ‘A’>27$
  10 GO TO, STEP 340 IF ‘B’>=93$
  20 GO TO, STEP 350 IF ‘C’<=18$
  30 GO TO, STEP 360 IF ‘D’<=84$
  40 GO TO, STEP 370 IF ‘E’=16$
  50 GO TO, STEP 380 IF ‘F’#14$
  60 GO TO, STEP 390 IF ‘G’=B’101$
  70 GO TO, STEP 400 IF ‘H’#B’101$

- **Conditional branch after COMPARE or VERIFY verb.** A field for an evaluation characteristic is included in COMPARE and VERIFY statements. Limits for the value of a labeled variable or a measured signal are expressed in this field. For example:

  fstatno COMPARE,‘LABEL’,<evaluation characteristic>$
  000620 COMPARE,‘RESULT’,UL 9V LL 3V$
  000690 VERIFY(VOLTAGE),DC SIGNAL,UL10V LL8V, CNX HIJ1-1 LOJ1-2$

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The specification of limits in the COMPARE or VERIFY statement allows either single-ended comparisons (greater than, less than, equal, not equal, greater than or equal, less than or equal) or double-ended comparisons that specify upper and lower bounds. Limit specification abbreviations are listed in Table 9-8.

### Table 9-8 — ATLAS Limit Specification Abbreviations

<table>
<thead>
<tr>
<th>UL</th>
<th>Upper limit</th>
<th>GT</th>
<th>Greater than</th>
</tr>
</thead>
<tbody>
<tr>
<td>LL</td>
<td>Lower limit</td>
<td>LT</td>
<td>Less than</td>
</tr>
<tr>
<td>LE</td>
<td>Less than or equal to</td>
<td>EQ</td>
<td>Equal to</td>
</tr>
<tr>
<td>GE</td>
<td>Greater than or equal to</td>
<td>NE</td>
<td>Not equal to</td>
</tr>
</tbody>
</table>

As the words imply, algebraic magnitude determines which limit is identified as UL and which is LL. (Example: UL -4V LL -6V.)

The relationship between the value and the limits is preserved in a set of software flags, which may be examined by subsequent statements that contain a GO TO verb and an IF TEST such as the following:

```
20 GO TO, STEP 250 IF HI$
30 GO TO, STEP 260 IF LO$
40 GO TO, STEP 270 IF GO$
50 GO TO, STEP 280 IF NO GO$
60 GO TO, STEP 290 IF LE$
70 GO TO, STEP 300 IF GE$
80 GO TO, STEP 310 IF NE$
90 GO TO, STEP 320 IF EQ$
100 GO TO, STEP 250 IF HI, STEP 210 IF LO$
```

The software flags are HIGH, LOW, EQUAL, GO, and NOGO. GO TO statements may specify several conditions to be evaluated as shown in step 100. In this step, the branch is made to statement 250 if the condition is high, to step 210 if the condition is low, or to the step following 100 if neither of these is true. A single GO TO statement may contain any number of destination steps and conditions. Evaluation proceeds from left to right, and the first condition, which is identified as true, will have its branch selected. Execution will proceed with the next step in sequence if all conditions are evaluated as false.

- **Condition branch with GO-TO-STEP or IF-GO modifier.** The inclusion of a GO-TO-STEP modifier in the statement, as shown in the example below, will cause transfer to the statement number specified if the system NOGO is set upon completion of statement execution. This modifier eliminates the need for a separate COMPARE statement as it allows a measurement to be taken, a comparison to be made, and a NOGO branch to be taken in a single statement, eliminating the need for most GO TO . . . IF-NOGO statements in the test program.

```
20 VERIFY, (VOLTAGE), DC SIGNAL, GT 19V, GO-TO-STEP 700, CNX HI J1-19 LO J1-20$
```

The inclusion of an IF-GO modifier in the ATLAS interpreter provides a companion to GO-TO-STEP to allow the branch to be taken on the GO condition rather than the NOGO condition. The GO-TO-STEP modifier must be used with the IF-GO modifier. For example:
Loops. When a program is being written in which one or more portions are performed not just once but a number of times, the portion to be repeated may be written just once through the use of a programming device known as a loop.

The use of loops is illustrated by a comparison of the following programs used to print a table of the first 100 positive integers together with the square root of each. Without a loop, the program would be 101 lines long as follows:

```
000010 PRINT, RESULT,1, SQRT(1)$
000020 PRINT, RESULT,2, SQRT(2)$
000030 PRINT, RESULT,1, SQRT(3)$
...  # Repeated 99 times
000990 PRINT, RESULT,99, SQRT(99)$
001000 PRINT, RESULT,100, SQRT(100)$
001010 FINISH$
```

The following program uses a loop to obtain the same table with six instructions instead of 101.

```
000010 CALCULATE, 'X'=1$
000020 PRINT, RESULT,'X',SQRT('X')$
000030 CALCULATE, 'X'='X'+1$
000040 COMPARE, 'X'LE 100$
000050 GO TO, STEP 20 IF GO$
000060 FINISH$
```

Step 10 gives the value of 1 to 'X' and "initializes" the loop. In step 20, both 1 and its square root are printed. In step 30, the value of 'X' is increased by 1. Step 40 compares 'X' to 100 and sets the condition flags. Step 50 directs the program back to step 20 if the GO condition flag was set by step 40. This process is repeated until the loop has been traversed 100 times. After 100 and its square root have been printed, the value of 'X' becomes 101. The comparison in step 40 results in setting the NOGO flag, and step 50 will not direct the program back to step 20. This causes the next step, step 60, to be executed. Execution of step 60 terminates the program. All loops contain four characteristics: initialization (step 10), the body (step 20), modification (step 30), and an exit test (steps 40 and 50). Because loops are so important and because many of the type just illustrated arise so often, ATLAS provides LOOP and REPEAT verbs to specify a loop even more simply. ATLAS also provides loops within loops.

**LOOP verb.** This verb is illustrated in the following example:

```
000010 LOOP, THRU STEP 20 with 'X'=1 TO 100$
000020 PRINT, RESULT, 'X'SQRT('X')$
000030 FINISH$
```

Only three steps are required to perform the entire program. In line 10, 'X' is set equal to 1 and a test is set up. After this, each time step 20 has been completed, 'X' is incremented by 1, and a test is made to determine whether the loop should be repeated or the next statement should
be executed. The loop will be repeated as long as the incrementation results in ‘X’ being less
than or equal to 100. Thus, step 10 replaces steps 10, 40, and 50 in the preceding example.

Note that the value of ‘X’ is increased by 1 each time through the loop. If an increase of 5 were
wanted, it could be specified by writing:

```
000010 LOOP, THRU STEP 20 WITH ‘X’=1 TO 100 BY 5$
```

The computer would assign 1 to ‘X’ on the first time through the loop, 6 to ‘X’ on the second
time through, 11 on the third time, and 96 on the last time. Another step of 5 would take ‘X’
beyond 100, so the program would proceed to step 30 after printing 96 and its square root.
The increment value following the BY may be positive or negative. The same table printed in
reverse order could be obtained by writing step 10 as follows:

```
000010 LOOP, THRU STEP 20 WITH ‘X’=100 TO 1 BY -1$
```

For a positive incrementation value, the loop continues as long as the control variable is
algebraically less than or equal to the final value. For a negative incrementation value, the loop
continues as long as the control variable is greater than or equal to the final value. In the
absence of a BY value, an incrementation of +1 is assumed. More complicated LOOP
statements are allowed. The initial value, the final value, and the incrementation value may all
be formulas of any complexity. If the initial value is greater than the final value (less than for a
negative incrementation value), then the body of the loop will not be performed at all, and the
computer will automatically pass to the step following the end of the loop.

- Nested loops– It is often useful to have loops within loops. These are known as nested loops
  (Figure 9-9), and can be expressed by LOOP statements written in any order. However, the
  LOOP statements must actually be nested and must not cross.

Any number of loops may be nested to any level, and transfers out of the bounds of loops are
permitted. If such a transfer occurs on nested loops, only the loop whose range was
transferred out of will be disabled. Consider the example shown in Figure 9-10. Both loops A
and B are initialized and execution proceeds until the GO TO C statement is executed.
Because C is outside the range of loop B, loop B will be disabled at this time. This means that
subsequent transfers back into the range of loop B, which do not pass through the LOOP
statement, will not result in reactivation of loop B. The transfer does not, however, affect loop
A, and this execution will continue normally. If C had been outside the range of both A and B,
both loops would have been deactivated.

- REPEAT verbs– This verb provides additional loop capability. The REPEAT statement differs
  from the LOOP statement in that it appears at the end of the loop and is used to repeat a
  series of steps directly preceding the REPEAT statement. For example, to execute five cycles
  of power cycling, the following program could be used:

```
000010 APPLY, DC SIGNAL, VOLTAGE 5V CNX HI J1-1 LO J1-2$
000020 DELAY, 20 SEC$
000030 REMOVE, DC SIGNAL, CNX HI J1-1 LO J1-2$
000040 DELAY, 20 SEC$
000050 REPEAT, STEP 10 THRU STEP 40, 4 TIMES$
000060 FINISH$
```
Nested LOOP statements. Note that the REPEAT statement in step 50 only specifies 4 repetitions, as the sequence is performed once before the REPEAT statement is reached. REPEAT statements may be nested in any manner, although unusual results may occur if the REPEAT range is overlapped. Transfers out of the range of the REPEAT statement do not disable the repetition cycle, and a subsequent transfer back within the range will continue the repetition where it was left off. The REPEAT count is reinitialized only if the statement is being encountered for the first time, that it was never initialized previously, or if the previous repetition was successfully completed. Note that the last statement in a REPEAT loop must always be the statement immediately preceding the REPEAT statement.

Procedure

When a particular part of a program is to be performed more than one time or at several different places in the test program, it may be separated so that it need only be written once as a procedure. A procedure is performed by executing a PERFORM statement specifying the procedure name. The following example illustrates the creation and use of a simple procedure to apply POWER to the UUT.

```
000010 DEFINE, 'POWER UP', PROCEDURE('VOLTS')$
000020 APPLY, DC SIGNAL, VOLTAGE 'VOLTS', CNX HI J1-1 LO J1-2$
000030 APPLY, DC SIGNAL, VOLTAGE 'VOLTS', CNX HI J1-3 LO J1-2$
000040 END, 'POWER UP' $
...
001000 PERFORM, 'POWER UP', 5V$
...
002000 PERFORM, 'POWER UP', 10V$
...
003000 PERFORM, 'POWER UP', -15V$
```

Figure 9-9 — Nested loops.

Figure 9-10 — Nested loops transfers.
In this example, step 10 defines ‘POWER UP’ as a procedure having ‘VOLTS’ as a single variable whose value is to be specified by the PERFORM statement. Steps 20 and 30 are the body of the procedure, and step 40 is the end of the procedure. All procedure definitions must be contained in the preamble of the ATLAS test program. When called upon to RUN, the ATLAS test program scans the preamble, sets up linkages, and begins execution with the first step following the last END statement. END statements are used only in procedures. Execution of the example test program will proceed until step 1000 is encountered. Execution of step 1000 causes the ‘POWER UP’ procedure to be performed with ‘VOLTS’ = 5. This has the effect of applying +5 Vdc to J1-1 and ground to J1-3 of the UUT. When the END statement of the procedure is encountered, execution of the test program proceeds with the step following 1000. When step 2000 is executed, the ‘POWER UP’ procedure is performed again with the value of ‘VOLTS’ equal to 10 V. This results in applying +10 Vdc to J1-1 and ground to J1-3. The test program then resumes execution following step 2000. Step 3000 executes the ‘POWER UP’ procedure again, this time with the value of ‘VOLTS’ equal to -15. This has the effect of applying -15 Vdc to J1-1 and ground to J1-3.

When a procedure is performed, execution commences with the statement immediately following the procedure definition statement and continues until the first END statement is encountered. A procedure may, of course, have more than one END statement if branching is involved. There is no limit to the length of a procedure, and any statement except DEFINE, COMMON, and DECLARE may be used. A procedure may perform other procedures or may even perform itself if such usage makes sense. The level of procedure nesting is limited only by the amount of temporary core storage available during program execution.

Values transmitted to the procedure by the PERFORM statement are known as actual parameters and may be numbers, constants, variables, or formulas of any complexity. The corresponding values in the procedure definition (‘VOLTS’ in the example above) are known as formal parameters. They can only be variables. Any formal parameters specified by the DEFINE PROCEDURE statement may have a label identical to a variable used in the copy of the test program. However, this can cause confusing results and is, therefore, not recommended. The correspondence between the values of actual parameters and formal parameters is determined by position in the PERFORM statements and the DEFINE PROCEDURE statements, not by similarity in the label. No matter what value a formal parameter variable might achieve during execution of a procedure, its value will not be transferred through the parameters to the variable with the same name in the test program unless they occupy the same position in the specification of actual parameters and formal parameters.

Results or values may be passed from the procedure to the test program in two ways.

1. Set a formal parameter equal to the value to be passed. The value will be passed to the actual parameter in the corresponding location so that a value assigned to the formal parameter ‘VOLTS’ in the test procedure may appear as the value of the actual parameter ‘CURRENT’ in the body of the test program if the variables are labeled that way. If the corresponding actual value is a constant, an attempt to pass a new value to it will cause a terminating error to be generated.

2. Within the test procedure, place the value to be transferred in any variable used in the main body of the test program. All variables within an ATLAS test program are treated as global variables (similar to FORTRAN Common) except those that are defined as formal parameter procedure. This means the procedure can use and operate upon all the variables available to the entire ATLAS test program.
External Statement

A facility is provided to allow an ATLAS program to PERFORM a procedure that is not defined in its preamble but has been saved on the system disk. For such operation, the system disk must operate in the non-file-protected mode, as it is used for temporary storage during program execution. Procedures saved on a disk may be nested to any level permitted by the availability of disk storage. Arguments may be transferred to and from disk procedures only through the actual parameter list of the PERFORM statement or through variables declared as COMMON.

Non-COMMON arrays will not transfer as actual parameters. The usual global variable characteristic is not available with disk procedures. Disk procedures need not use COMMON at all, but if they do, the COMMON declaration should be identical in both the PERFORMING program and the disk procedure. The EXTERNAL statement is used by the test programmer to define all disk resident ATLAS programs and ATLAS procedures that are referenced by an ATLAS in EXECUTE or PERFORM statements. Any number of ATLAS programs or procedures may be declared as external in a single EXTERNAL statement. A typical EXTERNAL statement might be as follows:

```plaintext
000010 EXTERNAL, ‘SUB1’, ‘SUB2’, ‘PROG4’$
```

All EXTERNAL statements should appear in the preamble section of the ATLAS program. A good programming practice is to use only a single EXTERNAL statement in a given program. This provides a quick cross-reference to all programs and procedures referred to by that particular program.

ATLAS Output

ATLAS provides a facility for presenting messages and variables to the test operator with the DISPLAY, PRINT, and INDICATE verbs. These three statements have identical structure and differ only in the equipment on which the message appears. The DISPLAY statement directs messages to the monitor, the PRINT statement directs messages to the printer, and the INDICATE statement directs messages to the system indicator. In the discussion that follows, only the PRINT statement is considered, but all comments apply with equal validity to DISPLAY and INDICATE. The most common uses of the PRINT statement are as follows: to print the results of a test, to print a message for the test operator, to print a combination of the two, and to skip a line. There are two basic forms of the PRINT statement. These types are identified by the first two words of the statement, which may be either PRINT, RESULT or PRINT, MESSAGE.

The PRINT statement using MESSAGE is useful only for printing verbatim messages to the test station operator. It will print all characters between the comma and the dollar sign, and it will return the carriage at the end of the line. It may not be used to print the value of variables.

The format using RESULT is considerably more flexible. It may be used to type out verbatim messages to the operator, the values of internal program variables, constants, formulas, or any combination of these. A single print statement may intermix character strings and variables. This intermixing may be done in any order, and the variables may be replaced by formulas. Character strings must be enclosed in double quotes, and the character strings and variables must be separated from each other by commas or semicolons.

Character strings are printed as they are entered including all embedded spaces and adding none. All numeric values are printed left, justified in their fields, with leading zeros suppressed. No trailing spaces are appended to numeric values. For positive real numbers, the first character will be printed as a space. For negative real numbers, the first character will be printed as a minus sign.
Output Line Formats

The output line produced by DISPLAY, PRINT, and INDICATE statements is divided into five printing zones, starting at positions 0, 15, 30, 45, and 60. A terminator (comma or semicolon) controls the use of these zones. A comma (,) moves printing to the next zone, or if the fifth printing zone has been filled, to the first printing zone on the next line. A semicolon (;) produces more compact output by inhibiting spacing between printing zones, acting only to separate quantities to be printed or to suppress the usual carriage return at the end of a DISPLAY, PRINT, or INDICATE statement. Output format can be further controlled by use of the TAB function. Insertion of TAB (17) causes the printer to move to print column 17. For this purpose, output columns are numbered 0 through 79. TAB can contain any expression as its argument. The value of the expression is computed, truncated, and its integer partaken. The output device then moves forward to this position. If the position has already been passed, the TAB is ignored. If the result is greater than 71, the output device moves to position zero of the next line. The statement PRINT $ will cause a line to be skipped. Printing the character string “%%” will cause the output device to start a new page. Some sample PRINT statements and resultant printouts are shown below.

```
000010 PRINT, MESSAGE, THIS UUT IS A BASKET CASE$
20 CALCULATE, ‘A’=3, ‘B’=4$
   (‘B’**2+‘A’**2)$
   (‘B’**2+‘A’**2)$
```

The resultant printouts are as follows:

```
THIS UUT IS A BASKET CASE
A=3   B=4   SQRT=5
A=3   B=4   SQRT=5
A=3B=4SQRT=5
```

Number Formats

For printing all numbers, ATLAS provides a default format that automatically allocates a field large enough to contain the number and its sign. No leading or trailing spaces are included in the default format. A floating decimal point is used when required. The decimal point is omitted for integers. Exponential notation is used for real numbers outside the absolute range .1 to 999999. The form in which a number is printed is the same as the form in which it was entered or created. An octal number will be printed in octal format. A real number will be printed in the form of a real number.

Format Function for Number Control

Additional format control is provided for printed numbers by the format (FMT) function. The argument for the FMT function has two meanings, depending on the number to be printed. At run time, the interpreter determines if the number to be printed is a real number or a bit string number. The meaning attached to the argument is selected according to this determination. In either case, the argument is a five-digit integer. For example:

```
100PRINT, RESULT, FMT(20805), ‘B’$
```
ATLAS Input

There are times when it is desirable to have data entered by the test station operator during the running of a test program. Examples of this are entries of meter readings, the frequency at which a receiver is to be tested, or an indication of the state of illumination of an indicator on the UUT. With the WAIT FOR statement, the ATLAS interpreter provides three separate facilities for operator input. Examples of the use of this statement are as follows:

```
000100 WAIT FOR, MANUAL DATA, QUERY$
10 WAIT FOR, MANUAL DATA, GO-NOGO$
20 WAIT FOR, MANUAL DATA, ‘A’, ‘B’$
```

Statement 100 is an example of the flying look option. Upon executing this statement, the test program interrogates the console to see whether the GO key has been depressed. If it has, the GO software flag is set, and if not, the NOGO software flag is set. Execution then proceeds with the next statement.

Statement 110 causes the computer to wait until the operator depresses either the GO or NOGO keys on the console keyboard. Execution of the program will not proceed until one or the other of these keys is depressed. When this has occurred, the appropriate software flag is set and execution of the program continues.

Statement 120 is an example of how numeric data is obtained from the test station operator. Execution of this statement causes the program to type a question mark on the system control device and to await the operator’s entry of two real numbers. These are entered as two real numbers separated by a comma, and the line is terminated by a $. The values of these real numbers are then entered into variables ‘A’ and ‘B’ and execution continues with the next program step. Any number of variables may be requested. The program will not continue until the operator has entered the required number of variables.

Frequently, a WAIT FOR statement is combined with the DISPLAY statement to make sure that the operator knows what the question mark is asking for. An example might be the following:

```
000200 DISPLAY, RESULT, “TEST FREQUENCY”;$
10 WAIT FOR, MANUAL DATA, ‘FREQ’$
```

On the monitor display, the operator would see the following:

```
TEST FREQUENCY
```

Data entered with a WAIT FOR statement is not saved with the program. Furthermore, it may take a long time to enter a large amount of data using WAIT FOR. Therefore, WAIT FOR should be used only when the need for entering data during the running of the program is unavoidable.

Program Linking

A program linking feature has been built into the ATLAS interpreter that permits test programs to be written that are larger than the available computer core memory. To use this feature, the user stores the program on the disk file in segments as individual programs. Segment names are usually assigned in an orderly fashion, often by appending a letter suffix to the program name. Any ATLAS program may cause the loading and execution of any other ATLAS program that is resident on the disk through the use of the EXECUTE verb. When under ATLAS control, program segmentation is not required, since the program may be as large as the available space on the applications disk. But sometimes it can be useful to overcome limitations existing on the number of variables allowed under
ATLAS control. It is possible to pass variables between programs through the use of the COMMON statement.

- EXECUTE verb. This verb is used in a statement that specifies the name of the program to be executed and, if desired, the entry point to be used. It will cause the specified program to be loaded on top of the program in memory and the execution of the program to begin. Note that the original program will be lost from computer memory. If no entry point is specified, the program is executed from its beginning. Two examples follow:

001000 EXECUTE, ‘ALIGN TEST’$
001000 EXECUTE, ‘ALIGN TEST’, 3020$

An EXECUTE verb can be used with a statement number in a test program to link the program to another part of the test. When the EXECUTE verb is used in the Immediate Mode (that is, with no statement number), the program referenced is loaded from disk memory and executed.

- DELAY statement. This statement is used to postpone execution of the following statement until a specified interval has passed. If a time dimension is not specified, seconds is assumed. Two examples follow:

0630 DELAY, 5SEC$
0690 DELAY, ‘X’-3MSEC$

Delay times may range from zero to $3.2 \times 10^7$ milliseconds. Resolution is 1 millisecond or 0.001% of the delay time, whichever is greater.

- FINISH statement. This statement is required at the end of every ATLAS program to terminate testing, to reset test equipment to the quiescent state, and to return control to the operator. One example follows:

009990 FINISH$

- TERMINATE statement. This statement designates the last statement of a complete ATLAS program, and like the BEGIN statement, it has no function other than to improve readability of the program. If used, it is always the last statement in a program. One example follows:

009999 TERMINATE, ATLAS PROGRAM$
End of Chapter 9
Computers and Programming

Review Questions

9-1. Which of the following items is considered to be computer hardware?
   A. Microchip
   B. Compiler
   C. Assembler
   D. Execution routine

9-2. A set of computer procedures, programs, and associated documentation is known as ________.
   A. instructions.
   B. software.
   C. hardware.
   D. shareware.

9-3. What component controls the computer’s operations?
   A. Analog display unit
   B. Optical disk drive
   C. Central processing unit
   D. Digital interface

9-4. Which piece of hardware is a device for storing large amounts of processed data?
   A. Read only memory
   B. Short term memory
   C. Assembler drive
   D. Hard disc drive

9-5. Which early programming language was developed for business and scientific uses?
   A. C++
   B. Jovial
   C. Formula Translator
   D. Java

9-6. Which of the following is a common use for the Jovial programming language?
   A. Command and control
   B. Personal home computers
   C. Business and science
   D. Medical administration
9-7. Which computer language was developed for real-time applications?

A. Datamax  
B. Syntax  
C. Talstar  
D. PL/1

9-8. Which of the following was a purpose of the Department of Defense (DoD) High Order Language Commonality program?

A. Increase the variety of computer languages  
B. Reduce financial burden on the DoD  
C. Apply military programming languages to civilian uses  
D. Reduce commercial off-the-shelf programming languages in military use

9-9. What are the two basic types of computers?

A. Linear and digital  
B. Analog and digital  
C. Binary and logic  
D. Linear and octal

9-10. What type of computer computes data from gear trains, fluid, or mechanical inputs?

A. Analog  
B. Digital  
C. Logic  
D. General

9-11. What method is used to represent the instructions used by digital computers?

A. Analog input  
B. Delayed transmission  
C. Numerical equivalents  
D. Direct translation

9-12. What type of computer is designed and built to accomplish a specific task?

A. General purpose  
B. Adaptable  
C. Task purpose  
D. Special purpose

9-13. What are the main components of a central processing unit?

A. Hard disk drive and random access memory  
B. Control unit and arithmetic logic unit  
C. Control unit and random access memory  
D. Arithmetic logic unit and register
9-14. What part of the central processing unit directs the overall operation of the computer?

A. Control unit
B. Arithmetic logic unit
C. Register
D. Interconnecting bus

9-15. In a typical digital computer’s control unit, what register holds the next instruction?

A. General
B. P
C. Instruction
D. Shift count

9-16. What is the purpose of the central processing unit’s the general register?

A. Contain the memory address of the next sequential instruction
B. Stores the quantity used for address modification
C. Holds the shift count
D. Holds the address of the next instruction

9-17. What are instructions that provide the computer with the ability to make decisions based on the results of previously generated data?

A. Logic
B. Control
C. Division
D. Arithmetic

9-18. Arithmetic and logic operations are performed in what section of a digital computer?

A. Random access memory
B. Input/Output
C. Central processing unit
D. Arithmetic logic unit

9-19. What is the purpose of “bootstrap” instructions?

A. To cause the program to “branch,” depending on whether a certain condition is met
B. To place enough instructions into a computer memory so that these instructions can be used to bring in more instructions
C. To cause the program to terminate if a “bad-data” input is sensed
D. To perform multiplication of certain numbers

9-20. What is the purpose of a subroutine?

A. To store the entire program at various places
B. To enter administrative data relative to program construction
C. To eliminate repeating certain groups of instruction throughout the program
D. To delay a program
9-21. Which of the following actions is a function of the Input/Output section of a digital computer?

A. Perform arithmetic operations
B. Sort data to be processed
C. Act as an interface between the computer and any external devices
D. Store mass quantities of data

9-22. What two methods should be used to transmit digital data?

A. Slow and fast
B. In series and out of series
C. Serial and parallel
D. Linear and non-linear

9-23. Each bit of a binary word to be transmitted must have its own data path in what type of digital data transmission system?

A. Serial
B. Heterodyne
C. Parallel
D. Horizontal

9-24. What method of digital data transmission is considered to be the simplest, most economical, and easiest to use?

A. Parallel
B. Serial
C. End around
D. Direct

9-25. What aircraft avionics system is considered critical to achieving operational success?

A. Mission computer
B. Navigation
C. Distance measuring equipment
D. Tactical communications

9-26. Which of the following systems allows near real-time digital information to be transmitted to combat information centers?

A. Tactical air navigation
B. Global positioning system
C. Inertial navigation
D. Data link
9-27. What is a prime factor in determining the quality of a computer’s output data?

A. The type of computer language used
B. The quality of the peripheral input data
C. The number of systems providing input
D. The age of the aircraft

9-28. What type of information is provided to the aircraft’s computer by the search radar system?

A. Target direction and speed
B. Weapons status
C. Current weather conditions
D. Command and control status

9-29. What verb should be used in the Abbreviated Test Language for All Systems (ATLAS) program to perform arithmetic calculations?

A. MEASURE
B. DECLARE
C. FILL
D. CALCULATE

9-30. What Abbreviated Test Language for All Systems (ATLAS) statement should be used to specify the number of elements in an array?

A. COMMON
B. CALCULATE
C. DECLARE
D. VERIFY

9-31. In Abbreviated Test Language for All Systems (ATLAS) programs, logical operators may be used to operate on what category of numbers in a CALCULATE statement?

A. Bit string numbers
B. Standard numbers
C. Hexadecimal numbers
D. Redundant numbers

9-32. If an Abbreviated Test Language for All Systems (ATLAS) verb corresponds to a UUT stimulus or measurement, which of the following term(s) should be used to define the signal?

A. DISPLAY and CALCULATE
B. APPLY and CALCULATE
C. Modifiers only
D. Modifiers and nouns
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CHAPTER 10

WAVEFORM INTERPRETATION

A waveform may be considered a pictorial representation of a varying signal as it is related to time. An unknown waveform can be graphically plotted by using a system of coordinates where the amplitude of the unknown signal is plotted linearly against time. An analysis of the resultant waveform provides valuable information in determining the characteristics of many electronic devices. The waveform of a signal may indicate the presence of harmonics or parasitic oscillations, or it may indicate how closely a device is following a desired cycle of operation. Distortion of a waveform is the undesired change or deviation in the shape of the observed signal with respect to some reference waveform.

One of the most important steps in waveform analysis—the one which usually proves the most difficult for maintenance personnel—is the interpretation of patterns as viewed on the oscilloscope. For this reason, the following section of this chapter is designed to help you accomplish this task.

LEARNING OBJECTIVES

When you have completed this chapter, you will be able to do the following:

1. Identify and interpret the information regarding complex waveforms and phase development to illustrate and explain normal waveforms, abnormal waveforms, and their causes.
2. Discuss response and discriminator waveforms including single-, double-, and triple-peaked response curves, as well as discriminator type “S” curves.
3. Define waveform distortion and its various types.
4. Explain the basic operation of the spectrum analyzer including analyzing a spectrum pattern.
5. Discuss Lissajous figures and their use in illustrating phase relationships.
6. Explain transient response measurements to include measurement technique, transients, and the measuring equipment.

WAVEFORM AND PHASE DEVELOPMENT

A complete understanding of the appearance and reason for a normal waveform will help you to recognize an abnormal waveform, and may help you to understand the reason for the abnormality. Terms such as “loss of high frequencies” and “loss of response” will have special meanings when referring to a particular waveform. In this section, the causes of deteriorated voltage and current waveforms will be discussed. The information regarding complex waveforms and phase development given in this section will illustrate and explain normal waveforms, abnormal waveforms, and their causes. This material does not include a mathematical analysis of waveforms; it is presented only as an introduction to those individuals having a vital interest in waveforms and their development. It is not meant for those who desire to interpret mathematical explanations. A voltage or current waveform, as encountered in the electronics field, may be graphically represented in both height and width. The height of a graphically displayed waveform represents the quantity or amplitude of voltage or current. The width of the displayed waveform represents the elapsed time or waveform duration. A voltage or current waveform is normally represented in a two-dimensional (horizontal and vertical) plane without depth. The horizontal (X) axis on a graph will represent time measured in either whole seconds or parts of a second; the vertical (Y) axis will represent amplitude, quantity, or intensity of the subject waveform measured, in either whole or parts of volts or amperes. Any portion of the waveform
extending above the horizontal (zero amplitude) reference line is considered positive, and any portion of the waveform extending below the horizontal reference line is considered negative.

Sinusoidal Waveforms

The sine wave is the basis of all other waveforms. It represents the simple action of a swinging pendulum, a bouncing or vibrating spring, a free-running self-excited oscillator output, etc. When any outside source changes the shape of the sine wave, the wave is said to be distorted. However, you will find that the original sine wave is still present in combination with other sine waves introduced by the distorting entity to produce a single resultant waveform. Therefore, any waveform, no matter how complex, may be reduced to its individual sine wave components. The original sine wave components cannot be reduced further because they are the final remaining single-frequency basic components. No waveform that is composed of more than one frequency is a true sine wave.

The basic structure of a sine wave is graphically presented in Figure 10-1. A 60-cycle or hertz (Hz) wave is represented by one complete cycle; the total time duration for this cycle is 1/60 of 1 second. In other words, a perfect 60 Hz sine wave will complete 60 complete cycles in 1 second. Half of this cycle time is above the horizontal reference (zero amplitude) line and is considered positive, while the other half is below the horizontal reference line and is considered negative. The two halves of the sine wave do not cancel out or nullify each other because each half-cycle occurs during a different time. During the positive half-cycle, the negative half-cycle has not occurred; therefore, it does not exist. During the time that the negative half-cycle is present, the positive half-cycle does not exist. The single cycle illustrated in Figure 10-1 must not have any bumps or kinks on either its increasing or decreasing side. The top (positive peak) and the bottom (negative peak) must be smoothly curved with no appearance of either a point or a flat spot in this region. The positive and negative half-cycles of the sine wave must be exactly equal in both amplitude and time duration. In Figure 10-1, the maximum positive peak amplitude is represented by positive 1 volt, while the maximum negative peak amplitude is represented by negative 1 volt. The time duration illustrated is exactly 1/120 of a second for each half wave.

Considering that a sine wave represents a complete mechanical revolution or circle, it requires 90 degrees to traverse one-fourth of the circle; 180 degrees to traverse one-half of the circle, 270 degrees to traverse three-fourths of the circle; and 360 degrees (or back to 0 degrees) to complete the entire circle. There are an infinite number of points represented on a sine wave. For example, there are 360 different points, each representing an advance of 1 degree, on each sine wave. However, only four points (0 and 360 are similar to a start/finish line on an oval race track) are shown to illustrate the shape of a basic sine wave. This was done because it is only necessary to become familiar with the general features of the sine wave curve rather than to provide a point-by-point analysis.
Amplitude will not affect the general outline of a sine wave provided that the positive and negative portions of the waveform contain equal amplitudes. If the sine wave is viewed on an oscilloscope, the instrument controls must be set correctly for proper viewing. If the controls are incorrectly positioned, the resulting display may present the wave as either too narrow or too wide for its height.

The cosine wave is the same in all respects as the sine wave except for one difference: it leads, or begins 90 degrees (1/240 of a second in this case) before the sine wave time begins. The cosine wave is superimposed on the same graph as the sine wave to illustrate the cosine lead. These two waveforms are not used to provide a resultant waveform.

The half-sine waveform consists of a series of unidirectional pulses, each resembling a half-cycle of a sine waveform. The half-sine wave may exist either above (positive) or below (negative) the horizontal reference line. The half-sine waveform is produced by removing any amplitude variations from the complete sine wave in one direction for a period of one-half the time duration of the complete cycle. As shown in Figure 10-2, there are two types of half-sine waves. In Figure 10-2, view A, the negative portion of the sine waveform has been removed and its one-half cycle time interval remains as a zero direct current (dc) reference level. In this type of half-waveform, the frequency remains the same as the original full sine wave frequency. In Figure 10-2, view B, the negative half of the original full sine wave has been inverted over the horizontal reference line; consequently, the average dc voltage level is increased. Since each alternation occurs in one-half the time interval of the original full sine waveform, inverting the negative alternations to occupy the empty spaces between the positive alternations causes the frequency to double. Half-sine waveforms are composed of the original fundamental frequency in conjunction with a dc component and an infinite series of even numbered harmonics of progressively decreasing amplitude.

**Nonsinusoidal Waveforms**

The sine wave is the basic or standard alternating current (ac) voltage waveform used in combinations with phase or time differences and amplitudes to algebraically form all other waveforms. The sine wave is the wave most commonly used as an input to circuits under test because it does not introduce distortions commonly associated with nonsinusoidal waveforms.

All nonsinusoidal waveforms can be reduced to their individual component sine waves. A nonsinusoidal waveform is composed of more than one sine wave; other frequencies, usually harmonically related, are algebraically added to the fundamental frequencies to produce the resultant nonsinusoidal waveform. In this case, the sine wave of lowest frequency is normally considered to be the fundamental frequency, and higher frequencies that are exact multiples of the fundamental frequency are considered as harmonics of the fundamental. However, in some cases, the nonsinusoidal waveform being considered may be composed of only harmonic frequencies because the fundamental sine wave may have been intentionally removed. The algebraic addition of the fundamental sine wave (F), and the second harmonic of the fundamental (H = 2F) will provide a resultant nonsinusoidal waveform (R), as shown in Figures 10-3, 10-4, and 10-5. However, only the resultant would be shown on an oscilloscope or equivalent test instrument. The second harmonic of
Figure 10-3 is shown in phase with the fundamental because its amplitude increases in the same direction as the fundamental from the horizontal and vertical zero reference level. The second harmonic of Figure 10-4 is shown 180 degrees out of phase with the fundamental because it proceeds from the horizontal and vertical zero reference level in a direction exactly opposite (negative direction) from the fundamental. The second harmonic shown in Figure 10-5 is shifted 90 degrees behind (lagging) the fundamental. The resultant waveforms contained in Figures 10-3, 10-4, and 10-5 are the only waves you will see on an oscilloscope or other equivalent test instrument.

The amplitude of the second harmonic, relative to the fundamental sine wave, will either increase or decrease the amount of dip at points (A) and (B) of Figure 10-4, represented by two heavy arrows. However, if the phase of the second harmonic is changed with respect to the fundamental sine wave, the appearance of the resultant waveform will change completely. The positive half of the resultant waveform, shown in Figure 10-5, looks like part of a sine wave, but the negative half does not. Therefore, this resultant is definitely not a true sine wave. At any point along the horizontal zero reference line, the vertical amplitude of the fundamental can be added directly to the vertical amplitude of the harmonic to obtain the final amplitude of the resultant waveform at that particular point (that is, if $F = 3$ units and $H = -1$ unit, then $R = 2$ units; and, if $F = -6$ units and $H = -3$ units, then $R = -9$ units). The resultant waveforms (Figures 10-3, 10-4, and 10-5) show that the algebraic addition of a harmonic waveform to the original fundamental sine wave produces a new waveform that is no longer a sine wave. In many cases these new waveforms are created deliberately to perform functions beyond the capabilities of the original signal. For example, the new waveforms resulting from the addition of a fundamental and its harmonics may be used as timing pulses.
Phase Distortion

The results of feeding the fundamental and its second harmonic through a network that delays the second harmonic by 90 degrees is shown in Figure 10-5. This normal resultant waveform obtained by the algebraic addition of the second harmonic (without phase shift) to the fundamental sine wave is known as “phase distortion.” This type of time delay can be recognized only by becoming familiar with the proper waveforms. If the phase of a fundamental sine wave is shifted, its shape will not change. Therefore, special methods must be employed to recognize any change in phase. These methods are described in the following text.

Harmonic Distortion

The addition of harmonics to the fundamental wave shape creates a new resultant waveform. The resultant is a distortion of the original waveform and, if undesirable, is termed “harmonic distortion.” The resultant waveform created by the addition of only one harmonic to the original waveform can probably be recognized. However, the addition of several harmonics to the fundamental sine wave, in and out of phase, will create a resultant waveform of pure confusion. As mentioned previously, any waveform can be separated or removed from its resultant with the aid of suitable filters. Therefore, by removing all except one frequency component, you can extract a pure sine wave of some specific frequency that was not evident in the original wave or its harmonics. This newly extracted sine wave can then become the fundamental sine wave input to a circuit under test.

COMPLEX WAVEFORMS

The resultant waveforms discussed in this section are created either by adding harmonics to the fundamental waveform, by changing the phase of the harmonic with respect to the fundamental frequency, or by a combination of harmonic addition and phase change. Therefore, all resultants are termed “complex waveforms” no matter how simply or easily they are recognized. Complex waveforms are divided into two groups—periodic waves, and nonperiodic waves. Periodic waves contain the fundamental frequency and its related harmonics. Nonperiodic waves contain a continuous band of frequencies, resulting from the repetition period of the fundamental frequency approaching infinity, and thereby creating a continuous frequency spectrum. Actually, other effects are realized in the resultant waveform, depending on the addition of even (2nd, 4th, 6th, 8th, etc.) harmonics or odd (3rd, 5th, 7th, 9th, etc.) harmonics; on the percentage of harmonic waveform amplitude injected; and on the phase of the introduced harmonic with respect to the fundamental sine wave. All “distorted waveforms” are classified as complex waveforms. These complex waveforms are grouped into types of complex waveforms. The nonsinusoidal waveform results of adding a single harmonic to fundamental waveforms are shown in Figures 10-6 and 10-7.
Mirror symmetry means that when the positive part of the resultant wave is inverted over the horizontal reference line, it will exactly match the negative part of the resultant waveform; or conversely, if the negative part of the resultant wave is inverted over the horizontal reference line, it will have the same shape, outline, and appearance of the positive part of the resultant waveform. By viewing the resultant waveform, you can definitely determine whether even harmonics (2\textsuperscript{nd}, 4\textsuperscript{th}, 6\textsuperscript{th}, etc.) were added to the fundamental sine wave to create the resultant, or whether odd harmonics were used for this purpose. If even harmonics were algebraically combined with the fundamental sine wave, there will be a lack of mirror symmetry, as shown in Figure 10-8, view A. If odd harmonics (3\textsuperscript{rd}, 5\textsuperscript{th}, 7\textsuperscript{th}, 9\textsuperscript{th}, etc.) were algebraically combined with the fundamental sine wave, there may be mirror symmetry, as shown in Figure 10-8, view B, but only when there is an adequate percentage of the odd order harmonics amplitude.

**Figure 10-6** — Resultant waveforms created by algebraic addition of 2\textsuperscript{nd} harmonic to fundamental sine wave when 2\textsuperscript{nd} harmonic amplitude is 30 percent of fundamental.

**Figure 10-7** — Resultant waveforms created by algebraic addition of 3\textsuperscript{rd} harmonic to fundamental sine wave when 3\textsuperscript{rd} harmonic amplitude is 30 percent of fundamental.
Square Waveforms

The square waveform is a resultant waveform type composed of a sine waveform in conjunction with odd harmonics. Unlike the original sine waveform, the application of a square waveform to either a capacitive or inductive circuit will result in an output of a completely different waveform shape. As shown in Figure 10-9, the leading edge of a square wave rises from zero reference value to its maximum value, where it remains as a constant-amplitude wave over a set period of time. It then drops back toward its original zero reference level, or beyond, until it reaches a minimum value, where it remains as a constant-amplitude wave over an exact period of time that matches its positive excursion. The rise and fall times are negligible in an ideal square wave. Figure 10-9, view A, shows the ac square waveform; it is so called because the waveform extends in a negative direction below the horizontal reference line as well as above. Figure 10-9, views B and C, show the pulsating dc square waveforms; they are so called because they contain a dc component that prevents the waveforms from crossing the horizontal zero dc reference level. However, all three forms are identical except for amplitude. All corners must be square, the sides perpendicular, and the extremities flat.

Unfortunately, this idealized square waveform cannot be attained because the wave forming equipment is not perfect. The square wave is formed by the algebraic addition of the fundamental sine wave and an infinite number of odd harmonics of the fundamental sine wave. However, as shown in Figure 10-10, as few as three added odd harmonics will produce a reasonable facsimile of a square wave even though a minimum of 10 added harmonics are required to produce a usable square wave. The fundamental sine wave may start at any phase. For illustrative purposes, Figure 10-10 shows the

Figure 10-8 — Presence or absence of mirror symmetry due to harmonic addition to fundamental sine wave.

Figure 10-9 — Square waveforms.
sine wave as beginning at the horizontal and vertical zero reference level. Figure 10-10 shows the resultant waveforms as additional harmonics are progressively added to the fundamental sine wave. Although this illustration shows the algebraic addition of only three odd harmonics, it conveys the true impression that as each additional harmonic is added, the leading and trailing edges of the resultant waveform become flatter. The frequency \( f \) of any order odd harmonic can be determined by calculating the value with the aid of the formula:

\[
f_N = (2N + 1)f_1
\]

where \( f \) is the fundamental frequency and \( N \) is the order of the harmonic. For example, if the fundamental frequency is 100 Hz, the frequency of the 6th odd harmonic can be determined as follows:

\[
f_6 = [(2 \times 6) + 1] \times 100
\]
\[
= [(12) + 1] \times 100
\]
\[
= (13) \times 100
\]
\[
= 1,300 \text{ Hz}
\]

It also follows that each odd harmonic shown in Figure 10-10 has been added in phase (zero phase difference) with the original fundamental sine wave. Particular attention should be paid to the amplitude of each harmonic. Each is in direct proportion to the harmonic order; that is, the third harmonic contains one-third the amplitude of the fundamental, the fifth harmonic contains one-fifth the amplitude of the fundamental, etc. If the harmonic is not in phase, or has incorrect amplitude, etc., the resultant square wave is said to be distorted. However, the type of distortion observed may indicate the kind of trouble, and even the source of trouble, within a circuit.

**Rectangular Waveforms**

The rectangular waveform contains all but one feature of the square waveform discussed in Figures 10-9 and 10-10. This one feature is that while the square wave has identical periods of positive and negative pulsations, the rectangular wave has unequal periods (time duration) of the positive pulse with respect to the negative pulse. The rectangular pulse can be either bidirectional or unidirectional in that the waveform may be entirely above or entirely below the horizontal zero reference level, as shown in Figure 10-11. The period of the rectangular waveform, like that of the square waveform, is the total time required to complete both half-cycles together as one unit. For example, in Figure 10-11, view A, if the positive half-cycle duration is 50 microseconds (\( \mu \text{s} \)) and the negative half-cycle duration is 150 \( \mu \text{s} \), the total period for one cycle of this frequency is 200 \( \mu \text{s} \). Considering that the frequency of a cycle is the reciprocal of the time required for that cycle, \( 1/200 \mu \text{s} \), the frequency of this example waveform is 5,000 Hz. This means that this particular cycle will repeat itself 5,000 times every second; it is said to have a frequency repetition of 5,000 Hz. The shorter pulse durations require the presence of higher frequency components, whereas longer pulse durations require the presence of lower frequency components. The rectangular waveform is rarely used as a test voltage. However, it may be used in many special applications to perform a specific function (Figure 10-12).
In this case, the first rectangular wave has another rectangular wave riding atop it. This is a practical situation in the transmission and reception of a television signal cycle. The video information is shown riding on the minimum amplitude portion of the first rectangular wave between the blanking pulses that represents the positive excursions of this rectangular pulse. However, rectangular synchronization pulses are shown riding atop the blanking pulse. This rectangular pulse represents the so-called “front porch,” the synchronizing pulse proper, and the so-called “back porch.”

**Sawtooth Waveforms**

The sawtooth waveform, like all other waveforms except the fundamental sine wave, is composed of sine-wave components. The wave consists of a gradual linear change from a maximum negative-going peak to its maximum positive-going peak, as shown in *Figure 10-13*. It then follows a rapid drop to its original amplitude. Considering that this waveform is composed of many sine-wave components that may differ in both frequency and phase, you cannot apply the sawtooth waveform to any inductive or capacitive device to cause different lead or lag times between the sine-wave components that compose the sawtooth waveform. Therefore, the output from any reactive device, other than a pure resistance, will not be the same as the original sawtooth input. For illustration purposes, in the ideal waveform, shown in *Figure 10-13*, view A, the retrace time is shown as zero seconds. This is not possible in practice because any action or reaction requires a definite time for accomplishment. A practical case where the retrace time is some finite time rather than zero is shown in *Figure 10-13*, views B and C. However, the retrace time is normally assigned the smallest practical duration consistent with the design of the equipment with which it is to be used. If the voltage amplitude increases at a constant rate during the forward trace, the waveform is called a “linear sawtooth.”

The fact that half of the waveform shown in *Figure 10-13* is above the horizontal zero reference level and the other half is below this reference level will normally not be seen on an oscilloscope because

![Figure 10-11 — Square waveform.](image)

![Figure 10-12 — Rectangular waves used in television.](image)
the reference level line (time base line) is absent from the display. Unlike the square waveforms that were produced by the algebraic addition of odd frequency, or in-phase harmonic waves with the fundamental sine wave, the sawtooth waveform is the resultant wave produced by the algebraic addition of both even and odd frequency harmonics to the fundamental sine waveform.

A positive-going sawtooth waveform is produced by the algebraic addition of all harmonics to the fundamental sine wave, but the fundamental harmonic components must begin in-phase and start in a negative direction, as shown in Figure 10-14, views A, B, and C. A negative-going sawtooth is the resultant of the same sine-wave components, but the fundamental and the in-phase harmonics must start in a positive direction. The method of progressive algebraic addition of each higher frequency harmonic to the fundamental sine wave to gradually obtain the ultimate sawtooth waveform is shown in Figure 10-14. However, only the first two harmonics (2nd and 3rd) have been combined with the fundamental sine wave to form the resultant shown in Figure 10-14, view D. As more harmonics are progressively added, the resultant wave will approach more and more closely the required sawtooth form.

Figure 10-14 — Formation of sawtooth waveform.
Trapezoidal Waveforms

The trapezoidal waveform is the resultant of the algebraic addition of sine waves, but it is more easily understood in terms of a sawtooth rectangular waveform since both are composed of basic sine waves. As previously stated, a sawtooth of voltage applied to the input of either an inductive or capacitive device will not appear at the output of the reactive component or device as a sawtooth waveform. Therefore, those applications that require a sawtooth current waveform must obtain the sawtooth current from a device that has a sawtooth current output produced from a trapezoidal voltage input. The trapezoidal waveform has the necessary characteristics to cause a linear change in the amplitude of the current with respect to time as it passes through the resistive and inductive components of a coil.

The resultant output of a resistor versus a coil with an applied input sawtooth waveform is shown in Figure 10-15. The sawtooth wave passing through the pure resistive element produces no change in output waveform. However, the output from the coil with an applied sawtooth waveform is essentially a rectangular waveform.

The process of algebraically adding a sawtooth waveform to a rectangular waveform in order to produce a resultant trapezoidal waveform for application to a series resistive-inductive circuit is illustrated in Figure 10-16, the output of which is a sawtooth current waveform.

The trapezoidal waveform occurs in numerous varieties because of the amplitude differences of the sawtooth voltages and rectangular voltages prior to algebraic addition. A comparison of two varieties of trapezoidal waveforms
is shown in Figure 10-17. The resultant waveform in Figure 10-17, view C, is not the same as the resultant waveform in Figure 10-17, view F. The resultant trapezoidal waveform (view C) is commonly used in electronic technology. Sawtooth current waveforms are generated by deflection circuits for legacy cathode-ray-tube deflection coils. When a deflection coil has a small internal resistance as compared with its inductive reactance, the sawtooth current waveform is produced by a sweep voltage that is a combination of a small sawtooth waveform and a large rectangular waveform.

Figure 10-17 — Trapezoidal voltage waveform varieties.

Differentiated Voltage Waveforms

Various complex waves can be resolved into their component sine-wave frequencies, and any group of frequencies can be extracted from a complex wave by means of a falter. In the case of differentiation, the differentiated waveform extracts the high-frequency sine-wave components, while the integrator extracts the low-frequency sine-wave components. A differentiated waveform is obtained by the process of differentiation. This process is simply the procedure whereby a waveform is passed through inductive or capacitive components to provide a voltage output proportional to the rate of change of the input voltage waveform.

The most popular method of differentiation employs a capacitive-resistance (RC) network. The time-constant of the circuit, in microseconds, is the product of the resistance and capacitance in ohms and farads, respectively. A rapid change occurring in the input voltage waveform will produce a narrow sharp-peak (spike) in the output. The peak amplitude of the output pulse is directly proportional to the rate of change in the input waveform. An example of a square-wave input to the two most common differentiating circuits and their outputs is illustrated in Figure 10-18.

Figure 10-18 — Input to and output from differentiating circuits.
A square wave was used because of its rapid amplitude change and high harmonic frequency content on both the leading and trailing edges of the applied pulse. The flat horizontal portions of the square wave will produce zero output because they contain zero slope (change), and because the time-constant of the differentiator will not pass the lower frequencies contained in the square wave.

A sine wave is not used as an input voltage to a differentiation circuit because these circuits accomplish their function by shifting the phase of the input waveform. In the case of a sine wave, the output will be shifted in phase and will have a smaller amplitude, but will still be a sine wave. This output may be particularly useful as a phase-shifted wave formed from a continuously variable time-constant function.

Rectangular Voltage Waveforms

The rectangular waveform has the same characteristics as the square waveform with respect to differentiation. It is important to note that the output voltage has a sharp peak only when the differentiating circuit contains a short time-constant. Also, it should be realized that the sharp peak is produced only during the rapid rise or rapid fall of the input voltage. Therefore, the differentiator circuit is known as a “peaker” circuit. In a circuit containing a time-constant of less than one-tenth the time required for one cycle of input voltage, the time-constant is said to be “short”; it is said to be “long” if the circuit components permit a time of 10 times the duration of one cycle of input voltage.

A square waveform produces an output differentiated wave with evenly spaced positive and negative excursions, whereas a rectangular waveform produces a positive and negative peak spaced close together (paired), with a distance separation from the next pair of peaks as shown in Figure 10-19.

Sawtooth Voltages

When a sawtooth voltage is applied to a differentiating circuit containing a short time-constant, the output from that circuit will be a rectangular waveform. If the applied sawtooth is positive-going, the negative spike of the output rectangular waveform will increase in amplitude as the retrace duration time is made smaller. This condition is shown in Figure 10-20. However, as the time-constant of the differentiated circuit is increased, the output progressively takes on the appearance of the input sawtooth waveform, shown in Figure 10-21.

Resistor-Inductor Differentiation

The resistor inductor (RL) differentiator consists of a resistor and an inductor in series and serves the same purpose as the RC differentiator. The output of the RC circuit is taken from across the resistor, whereas the output of the RL circuit is taken from across the inductive element. However, using either form of differentiator, the time-constant of the circuit represents the actual time required for the voltage to charge the capacitor in the RC network or for the current to charge the coil in the RL network. The actual time-constant of a differentiator (in microseconds) can be obtained by use of the applicable formula: \( T = RC \) or \( T = L / R \), where \( R \) is in ohms, \( C \) is in microfarads, and \( L \) is in microhenries. The shape of the voltage waveform across the capacitor and the waveform of the
current through the coil are identical. Therefore, technical data pertaining to the output voltage waveform of the RC network is the same for the output current waveform of the RL network.

**Integrated Voltage Waveforms**

In contrast to the differentiator circuit, which is actually a high-pass filter, the integrator sums up the applied voltages and discriminates against high frequencies, which makes it a low-pass filter. The two common forms of integrator circuits are shown in Figure 10-22. The integrator can use exactly the same components as the differentiator circuit. However, in the case of an RC integrator circuit, the output is taken from across the capacitor, whereas in the differentiator circuit, the output is taken from...
across the resistor. The reverse is also true of the RL integrator circuit. The output is taken from across the resistor, whereas in the differentiator circuit, the output is taken from across the coil.

When a square wave is applied to an integrator circuit and the integrator circuit time-constant is increased, the output waveform will gradually take on the appearance of a sawtooth waveform and will decrease in amplitude. However, the shorter the circuit time-constant, the more closely the shape of the output will resemble the shape of the input. Various forms and representative amplitudes for input square or rectangular waveforms are illustrated in Figure 10-23.

![Figure 10-22 — Typical integrator circuits.](image)

![Figure 10-23 — Integrated output waveforms progressively illustrating an RC or RL circuit time-constant.](image)

When a square waveform is applied to the input of an integrating network having a long time-constant, the output waveform will approximate a sawtooth wave with the charge or trace portion equal to the discharge or retrace portion. However, if a rectangular waveform is used as the input to the same integrating circuit, the output will not have equal charge and discharge times; therefore, the resultant waveform will build up in either a positive or negative direction. A positive buildup of the output waveform as a result of an input rectangular waveform with longer positive pulse durations than negative pulse durations is illustrated in Figure 10-24.

The shorter time duration provided by the negative portion of the input rectangular pulse will provide less time for the output discharge, and, as a consequence, the output waveform will charge more rapidly to its maximum value.

**MODULATED WAVEFORMS**

The ability to superimpose on, combine with, or change the original carrier frequency by the addition of intelligence in the form of electrical energy is termed “modulation.” The three primary types of modulation are amplitude modulation, frequency (or phase) modulation, and pulse modulation.
Amplitude Modulation

The radiofrequency (RF) carrier is normally generated with the characteristics of a constant frequency and amplitude. However, the amplitude of this carrier can be varied in direct proportion with the intelligence to be transferred (the spoken word, music, etc.) by simply algebraically adding the amplitude of the intelligence to the amplitude of the RF carrier. This addition is accomplished by means of a mixing circuit. The components of a hypothetical amplitude modulation (AM) waveform and its basic spectral display obtained through mixing the two signals are shown in Figure 10-25. This resultant amplitude-modulated waveform is transmitted and received, detected (separated from the carrier), and converted back to a facsimile of the original intelligence information.

The AM carrier illustrated in Figure 10-26, view C, is actually a composite of one carrier frequency component (view B) in addition to the modulating frequency (view A). An imaginary line connecting the positive and negative peaks of the carrier waveform forms the identical shape of the modulating signal (intelligence). This imaginary line on the carrier waveform is known as the envelope. The two frequency displacements from the carrier, as shown in view D, are the sidebands, upper and lower, generated from linear mixing of the carrier and the modulation voltages. For example, if the carrier frequency shown in view B is 1,000 kilohertz (kHz) and the modulation voltage shown in view A is 10 kHz, the resultant modulated RF carrier shown in views C and D will contain the original carrier frequency component of 1,000 kHz, plus a lower sideband component obtained by algebraically subtracting the modulating frequency from the carrier frequency (1,000 kHz - 10 kHz = 990 kHz) and an upper sideband component obtained by algebraically...
adding the modulating frequency to the carrier frequency (1,000 kHz + 10 kHz = 1,010 kHz). If the same carrier is modulated with two modulating frequencies, such as 10 kHz and 20 kHz, the resultant modulated carrier will be composed of five frequency components (that is, 1,000 kHz, 990 kHz, 1,010 kHz, 980 kHz, and 1,020 kHz). After the carrier frequency is modulated, the intelligence is now contained within the parameters of the sidebands created.

The modulating voltage can increase the amplitude of the carrier any amount above and below the horizontal zero reference level of the carrier frequency without creating any operational difficulty. An example of distortion caused by modulation is shown in Figure 10-26, view A. The modulating frequency and carrier frequency are algebraically added; therefore, if the modulating signal’s amplitude causes the carrier frequency’s amplitude to decrease to the zero reference level, it will result in the loss of the existing carrier frequency and thus create distortion. This type of distortion is termed “overmodulation.” The pattern at 100 percent and 50 percent modulation is shown in Figure 10-26.

**Figure 10-26 — Overmodulated, 100 percent and 50 percent AM waveforms.**

**Frequency Modulation**

This method of modulating the constant-frequency, constant-amplitude carrier will also permit the transference of intelligence. An advantage of frequency modulation (FM) is that the majority of man-made or natural noise interference is AM, and FM systems are relatively free from noise or other interference during the process of intelligence transference. In the FM process, the modulation signal represents the intelligence by frequency changes, rather than by amplitude changes. Therefore, when the modulation signal is used to modulate the constant-frequency carrier signal, no amplitude change
occurs. The resultant RF-modulated carrier signal will contain no amplitude variation, but its frequency will vary in accordance with the frequency and amplitude of the modulating voltage, as shown in Figure 10-27. Increasing the modulation voltage causes the carrier frequency to decrease proportionally, while decreasing the modulation voltage has the reverse effect. Increasing the frequency of the modulation voltage will increase the rate at which the carrier frequency changes and decreasing the frequency of the modulating voltage will decrease the rate at which the carrier frequency changes. The percentage of modulation is not a consideration in FM since FM is measured in terms of deviation and modulation index.

Deviation is defined as the amount of shift to either side of the carrier frequency, and is directly proportional to the amplitude of the modulating signal. For example, if a 1-megahertz (MHz) carrier were to be shifted 10 kHz to either side of its center frequency for each cycle of the modulation frequency, the resulting deviation would be 10 kHz. Modulation index, on the other hand, is defined as the ratio of deviation frequency to modulation frequency. Thus, if the same 1 MHz signal were to be modulated by 2 kHz at the same amplitude as in the foregoing example, the modulation index would then be 5 (10 kHz deviation/2 kHz modulation). The spectral display of Figure 10-28 shows that the power within the FM spectrum is distributed throughout the sideband in an amount proportional to the amplitude of the modulation voltage. Figure 10-29 illustrates variations in carrier and sideband amplitude as the modulation index increases. In the AM spectrum, only one-fourth of the rated output power can be attained in each of the sidebands, and then only with 100-percent modulation. Furthermore, the sideband frequencies in the FM spectrum are separated from the carrier and from each other by an amount equal to the frequency of the modulation voltage. Theoretically, each modulating frequency creates an infinite number of sideband frequencies, but, in actuality, these are limited by the response of the transmitter circuitry.
Phase Modulation

Phase modulation (PM) of a constant-amplitude, constant-frequency carrier will result in basically the same type of transference characteristics as FM. PM involves changing the carrier phase in direct proportion to the intelligence. The primary difference between FM and PM is that in FM the deviation frequency of the carrier is a function of the modulation signal’s voltage, whereas in PM, it is a function of the modulation signal’s frequency and voltage.

Pulse Modulation

Pulse modulation is accomplished by periodically interrupting the carrier frequency. Either the amplitude or the width of the pulse can be varied as a means of transferring intelligence. In some applications, both width and amplitude are varied. The most common applications of pulse modulation are found in CW (continuous-wave) keying and in radar circuitry.

RESPONSE AND DISCRIMINATOR WAVEFORMS

A response curve is a form of graph showing the relationship between output voltage and frequency. The response curve can indicate the degree of acceptance, amplification, or rejection by either a component or a circuit as the signal frequency is varied over a desired range. There are three primary types of response curves: single-peaked, double-peaked, and triple-peaked, as shown in Figure 10-30. The frequency is plotted along the horizontal axis, while amplitude of the output current or voltage is plotted along the vertical axis. The circuit response for a given input frequency is the measured amplitude separation between that point on the response curve representing the frequency and the horizontal zero reference line. The amplitude of the response curve may be shown either above or below the horizontal zero reference line, as illustrated in Figure 10-31. Half-power points are 3 decibels (dB) down or 70.7 percent of the peak or maximum amplitude point on the curve. To determine the half-power points, multiply the amplitude peak value by 0.707. The value of 0.707 is an amplitude value above or below the horizontal zero reference level, and is obtained from the reciprocal of the square root of 2 (or \(1/\sqrt{2}\)). An example is provided in Figure 10-31.

A single-peaked response curve indicates the circuit is tuned to a single frequency, and will naturally provide a very narrow frequency pass band.

A double-peaked waveform is the result of the deliberate design of transformer-type circuits. A transformer-type circuit, when tuned to a single frequency, will provide a voltage maximum peak above the resonant frequency and a voltage maximum peak below the resonant frequency. The resonant frequency will be represented by the dip between the two peaks, as shown by Figure 10-30, view B. The purpose of this type of waveform is to increase the frequency pass band by increasing the amplitude of a greater number of frequencies adjacent to the center frequency. The greater the dip between the two peaks, the greater the coupling between the primary and secondary windings of the transformer. However, too great a dip is undesirable.
A triple-peaked waveform is shown in Figure 10-30, view C, as it forms a crude flat-top.

A flat-topped curve is ideal because all frequencies within the pass band will then be the same amplitude. Several response curves may be algebraically added through a mixing circuit to produce a flat-topped, broad resultant response curve, as shown in Figure 10-32.

The terms overcoupled (close coupling) and undercoupled (loose coupling) refer to the spacing between the primary and secondary windings of the transformer. For example, if the primary is brought closer to the secondary (overcoupled), all frequencies within the bandwidth will be transferred from the primary to the secondary with approximately the same amplitude; this provides a wider pass band, less frequency selectivity, and greater overall amplitude. However, if the primary and secondary windings are moved farther apart, more impedance is effectively placed between the two windings, and only the frequencies containing the greatest amplitude will have sufficient energy to bridge the gap. This will create a sharply peaked waveform in the output, representing a very narrow bandwidth, high-frequency selectivity, and less overall amplitude, even though the waveform peak is more pronounced. These effects are shown in Figure 10-33.
Broadbanding, or the technique of increasing the bandwidth to permit a greater number of frequencies to pass, is accomplished by two primary methods: overcoupling, as was just discussed; and stagger tuning. The term stagger tuning refers to the tuning of a series of circuit stages to slightly different frequencies. For example, three stages could be tuned 1,000 cycles apart from one another, as shown in Figure 10-34, to combine as a resultant waveform. This resultant waveform is considered a triple-peaked response curve.
Discriminator Curves

The output from a discriminator circuit is sometimes referred to as an “S” curve. The ideal form of an “S” curve is shown in Figure 10-35. Any deviation from this shape represents incorrect tuning of the primary or secondary transformer windings, or other improper circuit adjustment.

The “S” curve is linear and always crosses the horizontal zero reference axis at the point on the curve representing the center frequency. Many times, a marker pulse is electronically added so that it appears at some point on the curve. However, this marker will disappear at the center frequency because this point occurs at zero voltage amplitude. The positive amplitude and low-frequency components on one side of the center frequency should equal the negative amplitude and high-frequency components, respectively, on the opposite side of the center frequency.

Shown in Figure 10-35, \( A = A \) (amplitude) and \( B = B \) (frequency separation). The audio frequency response curve shown in Figure 10-36 is ideal. The constant height of this response curve proves that the circuit under test has a flat response from its lowest to its highest frequency. The horizontal zero reference baseline is useful for measuring relative amplitudes. Considering that the portion of the wave below the reference or baseline is exactly the same as the wave above the baseline, only the top half of any “S” curve may be observed for full information. Any peaks extending above the average amplitude of the waveform represent accentuation of the frequencies within that region of the pass band, and valleys or dips reflect attenuation of the frequencies at those points. Therefore, this waveform as an input not only shows the circuit behavior as a whole, but also instantly reflects any unusual frequency characteristic of any recently added components, filters, or circuits.

Video and other high-frequency response curves are similar to low-frequency (audio) response curves. However, in high-frequency curves, the frequency band pass is wider (broader), with an extremely low-frequency limit (60 Hz) and an extremely high-frequency limit (in the megacycle range). Two different types of markers may be used to designate exact frequencies. Both types of markers are shown on the typical high-frequency response curve in Figure 10-37. The first marker is a disturbance along the response curve at a particular frequency, whereas the second is produced by a tuned circuit that removes or absorbs energy from the response curve at a particular frequency.
Intensity Modulated Presentations

Information on oscilloscopes and spectrum analyzers is presented in generic terms for explanation purposes. For specific settings and capabilities, refer to the operator’s and manufacturer’s technical manuals.

The most common usage of intensity (relative brightness) modulation occurs in television. However, intensity modulation is also used to display signals on a raster (continuous display) or to brighten the mark-to-space transition when taking end-distortion measurements of teletype signals with a digital data distortion test set.

Intensity modulation is also employed in comparing frequencies in excess of 10:1, provided the frequency ratio involved is an integer such as 10:1, 20:1 and 30:1. In all instances, the information is obtained from the display by noting the degree of intensity of the display. This intensity can vary from zero magnitude to a very bright illumination.

Intensity modulation is accomplished by modulating the Z-axis—the electron beam—of the display scope. In television, the video signal modulates the beam. In a raster display, intensity modulation could result from a received signal at a specific frequency and in a given spectrum. On oscilloscopes, intensity variation is accomplished by the signal input to the Z-axis. Shaping circuits are incorporated in the Z-axis circuitry of an oscilloscope to ensure a definitive presentation, regardless of the type of signal being applied.

Comparing Two Frequencies

As the ratio of two frequencies being compared increases, the Lissajous pattern becomes more difficult to retain in a stationary position, and counting multiple loops becomes a more difficult task. For these reasons, the intensity modulation method of obtaining frequency ratios can be used to advantage. A circular pattern, obtained from the low-frequency signals, is passed through an appropriate phase-shifting network and applied to the vertical and horizontal inputs of the oscilloscope, as shown in Figure 10-38. The high-frequency signal is connected to the intensity modulation terminal of the oscilloscope, and the low-frequency signal then serves as the reference signal. In Figure 10-39, view A, the frequency ratio is 10:1. There are, therefore, 10 blanked-out segments of the original circular display. In Figure 39, view B, the frequency ratio is 20:1; therefore, there are 20 blanked-out segments in the pattern. The number of blanks in the pattern is equivalent to the ratio of frequencies. Because of this appearance, such displays are often called “spot-wheel” patterns.
Circular Sweep Presentations

A typical circuit connection for employing the circular sweep method of obtaining frequency ratios greater than 10:1 is shown in Figure 10-40. The circular sweep is developed by the low-frequency signal. The high-frequency signal is then applied to either input terminal of the oscilloscope. This configuration is only for one situation—the case where the high-frequency signal variations are superimposed on the circular sweep through the action of the vertical deflecting plates in the circuit. The resultant patterns of Figure 10-40 are 10:1 and 12:1, as shown in Figure 10-41, views A and view B respectively. Fractional sweeps in ratios of 11:3 and 12:5 are shown in Figure 10-42, views A and B, respectively.

Figure 10-39 — Spot-wheel patterns.

Figure 10-40 — Circular sweep comparison circuit, using deflection systems only.

Figure 10-41 — Integral frequency ratios in circular sweeps.
WAVEFORM DISTORTION

Distortion is normally considered as a deviation from the desired waveform. However, the undesirable waveform in one application may be the desired waveform in some other applications. Therefore, the term distortion refers to a particular waveform application, and is meaningless if no application is being considered.

A normal high-frequency current is characterized by its amplitude, frequency, and phase relationships, and can be altered by changing any one of these characteristics. Actually, any two (or possibly all three) characteristics may be altered by a circuit change. If the circuit change produces the desired signal, this new signal is termed an “undistorted” or “pure” waveform; if the circuit change produces an undesired signal, it is termed a “distorted” waveform. The factors contributing to waveform distortion in one application may be the same factors required to produce a desired waveform in some other application. The following paragraphs discuss only those undesirable factors that contribute to distortion.

The primary cause of distortion created within an actual circuit can normally be traced to overloading of the active component in that particular circuit. For example, overloading an active component will cause it to operate on a nonlinear portion of its characteristic curve, and the output waveform will not retain the same shape as that of the input. The same overloading effect can occur if the active component is defective or if one or more of the applied operating inputs is incorrect.

For other than active components or circuit defects and incorrect operating inputs, distortion can be eliminated by simply decreasing the input amplitude (volume control) or intensity. The placement of components, wires, or leads may create undesirable feedback voltages in a phase relationship that results in distortion. Distortion-removing circuits designed to eliminate feedback may be defective. Neutralization circuits may be used to remove or balance out distortion resulting from undesirable feedback. The elimination or overemphasis of the amplitude of particular frequencies, within a desired band or range of input signal frequencies, will create distortion. The primary and secondary windings of frequency-sensitive transformers may be incorrectly tuned or be spaced an incorrect distance from each other. Therefore, the sideband frequencies, which form an important part of the resultant desirable signal, may be missing from the output signal. Finally, defective input or output components may blank out certain pass-band frequencies or permit undesirable voltages to pass, thereby causing distortion.

Amplitude Distortion

Amplitude distortion may be caused by a limitation of bandwidth or by irregularities within the bandwidth. In either event, amplitude distortion is normally expressed in terms of attenuation because it is a logarithmic quantity that is algebraically added for cumulative stages. Amplitude distortion, free of phase distortion, cannot change the symmetry of a symmetrical input pulse. The response of a

Figure 10-42 — Fractional frequency ratios in circular sweeps.
circuit should be the same for all frequencies present in the input signal voltage. However, if the circuit response is not the same for all input frequencies, suppression or exaggeration of the amplitude of some frequencies will create distortion. The fundamental plus harmonics will be seen or heard in the output waveform when amplitude distortion exists. In the case of an amplifier stage, it can be determined whether amplitude distortion is present by applying a signal voltage of known characteristics to the amplifier input and then viewing or measuring the output signal. The output waveform should be a replica of the input waveform.

Amplitude distortion caused by an amplifier is the result of the generation, by the amplifier, of frequencies that were not contained in the input. The result of generating additional frequency components is seen by the change in waveform amplitude.

**Frequency Distortion**

Frequency distortion occurs when different frequency inputs are not all amplified equally. The distortion may be audible or inaudible, depending on the circuit frequency response limits. In addition, if the circuit output load is composed of reactive components, the low-frequency resonance and the increase in inductive resistance at high frequencies will increase the nonlinear (amplitude) distortion and modify the response. If a feedback network contains reactive elements, then the overall gain of an associated stage is a function of frequency, and frequency distortion due to feedback will be obtained. However, negative feedback, even when reactive elements are present, will decrease the total circuit distortion at the expense of maximum gain.

The distortion in linear amplifiers as a result of the relationship between the input voltage and output voltage is a type of frequency distortion as well as of amplitude distortion. With a square waveform applied to the input of a linear circuit, the output should also be a square waveform. However, if the circuit response is not the same for all frequencies, the output waveform will not be the same shape as the input waveform. Output waveforms for nonlinear circuit responses are shown in Figure 10-43.

FM distortion is often termed “flutter distortion.” This type of frequency distortion is generally the result of speed fluctuations as a recording is driven by the recorder or reproducer motor. The flutter effect may also be caused by a loudspeaker when it is reproducing two frequencies simultaneously. This is true because the sound pitch is a function of the relative velocities and sources with respect to the listener. Both linear and nonlinear loudspeakers produce this type of distortion.

**Interference Distortion**

The two signals in Figure 10-44 are separated slightly in frequency and differing in amplitude. The third waveform is the resultant obtained when the desired and undesired signals are combined algebraically at every point. The amplitude of the signal.
resultant varies at a rate equal to the difference in frequency between the two original signals. If both signals differ in frequency by 100 Hz, the resultant waveform amplitude will change 100 times per second.

In an AM receiver, this amplitude would be separated by the detector and be heard as a whistle from the speaker. The resultant waveform may at times lead, lag, or be in phase with the desired signal; therefore, the resultant is phase-modulated. This PM (and, indirectly, FM) is directly proportional to the amplitude difference between the two signal carriers. When the amplitude ratio between the two signals is 2 to 1, the phase angle shift is slightly less than 30 degrees. The rate of phase shift change is in direct proportion to the frequency difference between the two original signals.

Static is primarily a form of amplitude distortion caused by uncontrolled electrical waves associated with thunderstorms and other natural phenomena. The strength of these waves is sometimes great enough to drown out the desired station or prevent clarity of reception. Limiter stages will limit incoming bursts of static amplitude, and, by selecting a narrow bandwidth, much of the continuous crackling variety of static can be removed through frequency selectivity. For FM reception, transmission allocations are in the higher frequency bands, where static amplitude changes are not very noticeable; most of the outburst energy is limited to lower frequencies. Even if no external natural disturbances or other station interference is present, internal active component and circuit noises exist that will limit the weakest received signal to some minimum amplitude. Any signal lower than this minimum amplitude will not be amplified with clarity.

Thermal agitation is the term applied to the noise created by the random motion of electrons in any conductor. The thermal noise produced is proportional to the amplifier bandwidth.

Transistors generate noise by the shot effect caused by charge carriers (electrons and holes) randomly diffusing across the semiconductor junctions in the bias current, and their thermal noise is caused by inherent resistance in the base region. Surface recombination of electrons may also be a source of semiconductor noise that only becomes significant at very low frequencies.

Impulse noise, as distinguished from random noise, consists of external sharp bursts of energy. Normally, this noise is associated with automobile ignition systems and sparking gaps in electrical machines. A limiter stage is required to decrease the effects of this type of interference.

Hum interference is commonly caused by insufficient filtering in the power supply, poor or defective grounding, or defective coupling between circuits. This type of interference, as is true of other types of circuit noise, will combine with the desired signal and produce distortion.

**USE OF LISSAJOUS FIGURES**

Lissajous patterns are a useful method of determining the frequency ratio of one signal to another (sine wave). If one of the signals is known, the other can be determined from the displayed Lissajous
pattern. The known signal is applied to the horizontal axis input of the oscilloscope, and the unknown is applied to the vertical deflection input. Lissajous patterns with ratios of multiples of one are shown in Figure 10-45, examples A through E, with F showing that odd ratios can also be displayed. The accuracy of frequency measurements obtained by Lissajous patterns is limited by the accuracy of the reference frequency and the care exercised in obtaining a stationary display while counting the loops. The practical ratio limit in this type of measurement is 10:1; however, by using extreme care, it is possible to count frequency ratios as high as 30:1.

Lissajous figures can be used to measure the phase relationship existing between two voltages of the same frequency. The patterns involved appear as ellipses with different degrees of eccentricity. As shown in Figure 10-46, the pattern is formed when two sine waves of the same frequency are applied to the vertical and horizontal input terminals of the oscilloscope. Point-to-point plotting of like-numbered projections will verify the formation of the resultant pattern.

To measure the angle of phase displacement, it is necessary to use an oscilloscope with a cross-section screen, called a graticule, to provide a graph of the X- and Y-axis coordinates. If two sine waves of unequal amplitude are used, the resultant pattern will always be elliptical in form and often may not be used intelligently. In actual phase measurement, unequal amplitudes of the input to the scope are compensated for by adjusting the horizontal and vertical gain controls. The vertical gain is first reduced until a straight horizontal line is obtained. The horizontal gain control is then adjusted for some convenient length; for example, 2 inches.

Figure 10-45 — Lissajous patterns, showing frequency ratios.

Figure 10-46 — Formation of a Lissajous figure, illustrating 90 degrees of phase difference.
The next step is to place the horizontal function or selector switch in the horizontal input position. A small spot near the center of the oscilloscope will now be obtained, depending upon the relative adjustments of the vertical and horizontal positioning controls. Apply the signal to be measured to the vertical input terminals, and increase the vertical gain control to the same length of line as previously obtained; in this case, 2 inches. Since there is no horizontal deflection, the 2-inch trace will be only a thin vertical line. At this point the gain of both amplifiers is equalized, and you may apply the comparison signal to the horizontal input terminals and proceed with the phase measurement technique. However, it is to your advantage to make one further check for equalization.

Connect a jumper wire from the vertical input terminal of the scope to the horizontal input terminal so that the same signal is applied simultaneously to both amplifiers. The pattern should tilt over to a 45-degree line intersecting the corners of the 2-inch square, as shown for 0 degrees in Figure 10-47. The procedure just given is not the only method of equalizing the oscilloscope amplifiers, but it is applicable to any oscilloscope, and is not subject to any specials switching positions provided on a specific oscilloscope.

If the phase angle displacement between two input frequencies remains at a fixed angle, the phase angle may be calculated. Count the number of divisions along the vertical Y axis to the point where the ellipse intersects the Y axis. This number is known as the “Y-axis intercept,” or Y1. Next, count the number of divisions along the vertical Y axis to the point that indicates the maximum vertical amplitude of the ellipse. This number is known as the “Y-axis maximum,” or Y2. The angle of phase difference, \( \theta \), is found by performing the following calculation:

\[
\text{Sine } \theta = \frac{\text{Y-axis intercept}}{\text{Y-axis maximum}} = \frac{Y_1}{Y_2}
\]

A similar procedure, using the horizontal X axis in the same manner, will produce the same results. The direction in which these values are measured can be either positive or negative. The ratios obtained are independent of the direction taken when counting. Assume the calculated ratio of \( Y_1 \) and \( Y_2 \) is 0.5, which, when converted into angles will indicate a phase angle difference of 30 degrees as shown in Figure 10-48. Notice that the major axis of one of the ellipses lies in the first and third quadrants, and that the phase angle could therefore be 30 degrees or 330 degrees. Whether a signal is 30 or 330 degrees ahead of a second signal, the difference in phase is still 30 degrees. It is this difference that a Lissajous figure has the ability to illustrate and not which signal leads or lags the other.
Fortunately, it is not difficult to learn which is the leading signal when the information is not known from other sources.
Assume that a phase difference of 30 degrees is computed. If it happens that the signal applied to the vertical deflecting plates leads the horizontal signal by 30 degrees, an additional phase advancement of the vertical signal will reduce the eccentricity of the ellipse; that is, it will be made to resemble a circle. Conversely, if the vertical signal lags by 30 degrees (equivalent to leading by 330 degrees), an advancement in phase will bring the two signals more nearly into phase. Consequently, the ellipse will continue to until eventually it becomes a straight line.

There are a variety of circuits for shifting the phase of a signal, such as the one shown in Figure 10-49. One of the two signals under investigation, such as the signal applied to the vertical deflecting plates, can be impressed across a series circuit consisting of a potentiometer and a capacitor. At the frequency concerned, the resistance of the potentiometer should be about 10 times the reactance of the capacitor. An output from the network can be taken from either the resistance, as shown in Figure 10-49, or from the capacitor. If the signal developed across the capacitor is desired, the ground connection should be made to the input side of the capacitor. If the output signal is derived from the resistance, its phase will be advanced relative to the original signal; if taken from the capacitor, the phase will be retarded. It will be assumed in this case that the signal across the resistance is applied to the vertical terminals of the oscilloscope. If the vertical signal leads the horizontal signal, the ellipse will become broader as the resistance of the potentiometer is decreased. Most likely a circle will not be obtained since the amplitude of the signal also decreases as the resistance becomes less.

In those cases where one of the two applied frequencies is constantly changing phase with respect to the other, the resultant ellipse changes form, and the plane of the ellipse appears to rotate around either of two imaginary diagonal axes. As the phase difference increases from zero to 90 degrees, the plane of the ellipse appears to rotate around one of the imaginary diagonals; and as the phase difference increases from 90 to 180 degrees, the plane of the ellipse rotates around the opposite diagonal axis.

![Phase-shift network diagram](image)
When an oscilloscope is used to determine phase relationships, several precautions must be observed. It is imperative to know whether the circuits in the oscilloscope ahead of the deflecting plates have unequal phase-shift characteristics. If there is an inequality, the indicated phase relationship of the two signals undergoing investigation will be in error by the amount of the inequality. To determine the amount of phase error introduced by the oscilloscope circuits, apply a sine wave simultaneously to both the horizontal and vertical input terminals of the oscilloscope. If a straight line is displayed in the first and third quadrants, no phase shift is introduced by the oscilloscope amplifier. If the straight line appears in the second and fourth quadrants, a 180-degree phase shift is introduced by the amplifying stages of the oscilloscope, probably because the number of stages in the two sections are unequal. It is important to check this possibility, as the design requirements of the sections are not generally the same.

The appearance of an ellipse, however, discloses an inherent disparity in the phase characteristics of the two amplifiers, rather than a mere difference in design. This phase difference (in degrees) must be determined, and then added to or subtracted from the result of a phase measurement of the two signals according to which amplifier has the leading characteristic. This check of amplifier characteristics, which should be made over the entire frequency range of interest, is especially important in the low- and high-frequency portions of the band passed by the amplifiers.

Astigmatism in an oscilloscope may be so pronounced that accuracy in measuring Y-maximum and Y-intercept is difficult. In this case, the trace may be in focus over one region of the tube face, but out of focus in other regions. Wherever the trace is poorly defined, there will be uncertainty in a measurement of distance. For an accurate determination of the sine of the phase angle, it is necessary that Y1 and Y2 be measured accurately. This means that the intersection of the X and Y axes must be placed in the exact center of the ellipse.

2:1 Lissajous Patterns

The process of using Lissajous patterns was introduced on a limited basis with respect to multiple patterns and time-basis, and with respect to the phase-angle measurement in the preceding paragraphs. A detailed discussion of Lissajous figures is presented in the following text, with special attention given to frequency comparisons. There are many possible configurations for any ratio of applied frequencies.

One consideration is whether the higher or lower frequency is applied to the horizontal deflecting plates. The most significant consideration, however, is the “phase” of the high-frequency signal with respect to that of the low-frequency signal when the latter is beginning a cycle. Strictly speaking, “phase” in this sense is a misnomer, as the definition is normally in terms of a single frequency. Nevertheless, a cycle of the high-frequency signal is often well advanced at a time when a cycle of the low-frequency signal has just commenced; for convenience, this condition is usually referred to as a “difference in phase.”

When both applied signals start at the same time, the resulting pattern can be likened to a figure “8” resting on a side as shown in Figure 10-50.

A line drawn against the top edge of the pattern, called a “tangent,” would make contact with the pattern at two places as shown in Figure 10-51, views A and B. Similarly, a line drawn against a vertical side would be tangent at only one place. Notice that the horizontal tangents correspond to the vertical deflecting voltage, and that the vertical tangents correspond to the horizontal deflecting voltage. Hence, the ratio of the vertical deflecting frequency to the horizontal deflecting frequency is 2:1. If the two signals were applied to the opposite sets of deflecting plates, the resulting pattern would be rotated 90 degrees.
An interesting situation exists when the high-frequency signal is shifted ahead 90 degrees in phase. As shown in Figure 10-52, view B, the high-frequency signal may be at its maximum value when the low-frequency signal is just beginning a cycle. When this condition occurs, the two loops are closed into the form of a parabola, with its cup pointing downward. Similarly, if the high-frequency signal is at its most negative value when the low-frequency signal is commencing a cycle, the pattern is a parabola with its cup pointing upward, as shown in Figure 10-52, view D. This type of pattern is commonly referred to as a "double image" because the electron beam, after reversing its direction, traces out the same path. A double-image pattern is also called an "uncompleted loop" or "closed pattern."

Each type of 2:1 Lissajous pattern, except the parabola, is developed for two phase relationships. For example, the pattern of Figure 10-50 is also generated when the high-frequency signal is 180 degrees out of phase with the low-frequency signal. These alternative phases are shown in Figures 10-50 and 10-52 by the high-frequency signals that produce the vertical deflection. When a double image such as the parabola is developed, a somewhat different method of evaluating the frequency ratio must be employed.

If the contact of an open line against the side of a pattern is counted as one-half, the correct ratio can be determined as shown in Figure 10-51, view C. There is only one contact, against the vertical line, giving a figure of 1/2. There are two contacts against the top horizontal line, giving a total of 1. The ratio of the vertical deflection-plate signal frequency to the horizontal deflection-plate signal frequency is therefore 1:1/2, or still 2:1. Now assume the horizontal line had been drawn against the bottom edge of the pattern. Here, the rounded end, or closed loop, of the parabola clearly has a single point of tangency with the line, giving a total of 1. The ratio is now, therefore, 1:1/2, which is still 2:1.
3:1 Lissajous Patterns

Analogous conditions hold when the frequency ratio is 3:1. Representations of the various patterns that may be obtained are shown in Figure 10-53, view A. If the signals applied to the deflecting plates are interchanged, the resulting patterns are exactly the same except for an axis rotation of 90 degrees. In the case of the S-shaped curve, the frequency ratio is computed by the same procedure as described for closed patterns in the previous paragraph.

To illustrate, there would be a tangency and a contact with respect to a horizontal line drawn against the pattern shown in Figure 10-53, view B. This would be calculated at one loop (1) plus one free end (1/2) for a total of $\frac{3}{2}$. If a vertical line were drawn, there would be a single contact, a free end (1/2) for a total of $\frac{1}{2}$. The ratio of these two numbers is 3:1, which is consistent with the ratio of frequencies.

Examples of how the phase relationship of the signals affects the resultant Lissajous pattern are shown in Figures 10-54 and 10-55.

As the high-frequency signal starts from its maximum amplitude, a cycle of the low-frequency signal is ready to begin as illustrated in Figure 10-54. This results in a symmetrical pattern comprising three loops.

(This figure is also shown in Figure 10-53, view C, for ratio computation purposes.) As shown in Figure 10-53, view A, the same pattern is formed when the phase difference is 270 degrees instead of 90 degrees. An S-shaped pattern is formed when the two signals are in phase, as shown in Figure 10-55.

If the high-frequency signal began to swing negative as the low-frequency signal began, the pattern shown in Figure 10-53, view C, would result.
Other Lissajous Patterns

There are two restrictions on the frequencies of the signals applied to the deflecting plates. One was mentioned previously; namely, the frequency must lie within the useful pass band of the oscilloscope. Second, the relationship between the applied frequencies must not result in a pattern too involved for an accurate evaluation of the frequency ratio. As a rule, ratios as high as 10:1 and as low as 10:9 can be readily determined.

Patterns in which the ratios are 6:1, and 10:1, including the corresponding double images, are shown in Figures 10-56 and 10-57. The discussion thus far has been limited to integral ratios, such as 1:1, 2:1, 8:1, and 10:1. In addition to these patterns, there are many patterns for which, even though the numerator and denominator of the ratio are whole numbers (or integers), the ratio is not an integer. For example, there are the 3:2 patterns of Figure 10-58, the 5:4 patterns of Figure 10-59, the 7:2 patterns of Figure 10-60, etc. In every case, however, the methods for determining the ratio of the applied frequencies are the same as those previously described.

TRANSIENT RESPONSE MEASUREMENT

The ability of a linear device to cope with intermittent pulses is determined by the degree of transient response of the device. The quiescent state must be considered and calculated as being zero while the technician determines the transient response of the device. (The calculation of transient response by this method will apply to linear devices only.) When a linear constant parameter device is excited by an input pulse such as that shown in Figure 10-61, the quiescent component of the device remains

Figure 10-56 — 6:1 Lissajous patterns.
constant with respect to time (static-state current). When calculations are made, the total response shape can be considered as dependent only as the input pulse. The response of a linear constant-parameter device can be displayed and measured directly on an oscilloscope. The technician must be aware that if this method is applied to a device that does not have constant parameters, it will be extremely difficult to separate the quiescent response from the transient response. The quiescent component cannot be considered as being “zero” in a nonconstant parameters device. The response to a single pulse input, as shown in Figure 10-62, view A, is actually the time duration of the device’s response to a single pulse input, as shown in Figure 10-62, view B.

Figure 10-57 — 10:1 Lissajous patterns.

Figure 10-58 — 3:2 Lissajous patterns.

Figure 10-59 — 5:4 Lissajous patterns.

Figure 10-60 — 7:2 Lissajous patterns.
Measurement Technique

The input signal to the amplifier or other electronic device should be a rectangular pulse with the stage output being applied to an oscilloscope to provide a visual display. The half-period of the input rectangular pulse must require a longer time than the transient response duration. The oscilloscope should be adjusted to show the width of a single complete pulse or less. The result of applying a proper pulse versus a too narrow pulse is shown in Figure 10-63.

![Figure 10-61 — Input step function.](image)

The transient response of a stage, with an input square wave, is measured by viewing two separate response characteristics. The first of these is related to the leading edge of the output response curve and is composed of the rise time, time delay, and overshoot. The second response curve characteristic is related to the flat-top portion of the curve, called “sag.” Sag is possible in a circuit only if the circuit is not capable of passing dc currents. To examine the leading edge of the wave, as shown in Figure 10-64, view B, the technician should use a fast sweep rate on the oscilloscope, whereas to illustrate the flat-top, the technician should use a slow sweep rate, as shown Figure 10-64, view C. Wide-input pulses normally have long rise times. Therefore, narrow-input pulses with short rise times are used to obtain response pulse leading-edge measurements. Wide pulses should
be applied to the input for response pulse sag measurements. A pulsewidth of 5 μs is shown in Figure 10-64 as being adequate for leading-edge measurements, but 1,000 μs input pulses are required for the flat-top sag portions of the applied pulse. When an RF signal, rather than a rectangular pulse, is used as the input to a tuned stage or band-pass device undergoing transient response measurements, the parameters of the response are related only to the leading edge because there will be no flat-top characteristics. The response of a band-pass device or tuned stage is shown in Figure 10-65.

**Figure 10-64 — Transient response characteristics.**

**Figure 10-65 — Typical transient response of a tuned stage.**

### Transients

The total response in a linear circuit includes all of the individual transients due to the store of energy in each inductor, capacitor, and external energy source connected to the circuit, plus the steady state (forced response) of each external applied energy source. The response can be computed by starting at any arbitrary time \( T = 0 \) where all of the initial energy conditions of the proposed circuit are known.

### Reactive Elements

The discharge of a capacitive element through a resistor requires the time \( T_2 \) minus the original starting time \( T_1 \) for the voltage or current to decay to 37 percent of the original value. The same analogy applies if the capacitive or inductive component charges to 63 percent. This type of analysis may be used for any periodic applied voltage. The steady-state current and voltage for an applied voltage are determined, the periodic voltage is resolved into its individual harmonic components, and then the transient is determined. The transient waveform does not bear a relationship to the applied voltage, as the transient waveform depends only on the circuit constants and the initial current and voltage conditions.
Resistive Elements

Time is considered to be zero when no reactive elements are present. Pure resistance elements do not charge or discharge with time.

High-Frequency Elements

At ultra-high frequencies, the transit time of an electron traveling between the cathode and the plate of a diode constitutes an appreciable part of the input cycle. This causes the dynamic plate resistance of the diode to decrease. Therefore, the cathode-to-plate resistance must be represented by a series resistor capacitor. The curves of both the resistance and the capacitance are shown in Figure 10-66, each with respect to transit time, as the frequency increases. The resistance $R/R_p$ eventually oscillates about a zero reference level, and is sometimes negative.

Measuring Equipment

The device being tested contains a definite transit or rise time to be measured. However, the equipment used to test the device may affect the rise time. In fact, if the rise times of the pulse generator and oscilloscope are each less than 10 percent of the rise time of the device being measured, an accuracy within less than 1 percent can be obtained. To partially compensate for the sag on the rectangular pulse introduced by the testing equipment, the individual sags may be subtracted from the final measurement to obtain the correct value, assuming that the sag introduced by the equipment is small. A typical test setup for the measurement of transient response within linear equipment is shown in Figures 10-67 and 10-68.

The delay time measured with this test setup will be a larger delay time than is actually contained in the equipment itself because of the additional time introduced by the test equipment. However, the test equipment time can be directly subtracted from the final measured result, and the measuring equipment will also tend to reduce the leading edge overshoot of the waveform in the device being tested.

Figure 10-66 — Series resistive and reactive diode components represented as a function of frequency and transit times.

Figure 10-67 — Typical test setup for measurement of transient response in low-pass equipment.

Figure 10-68 — Typical test setup for measurement of transient response in band pass of FM equipment.
The requirements of test equipment used to measure transient response are extremely rigid, as shown by several special features of the oscilloscope. A triggered oscilloscope, referred to as a “synchroscope,” requires a variety of sweep speeds. The sweep circuit may be triggered by the trigger pulse that starts the pulse generator; the response being measured may be used to trigger the sweep so that later transient responses may be measured; or the applied signal may be used to trigger the sweep circuits of the synchroscope, and then be passed through a delay line to the circuit under test. The pulse or square wave generator must contain a wide range of available pulsewidths and frequencies; the leading and trailing edges of the output pulse must be short as compared with the pulsewidth; and the sag should be flat and contain no ringing or oscillation. Finally, the carrier frequency pulses must be relatively free from FM during the active pulse.

Test Equipment Connection

The connection of test equipment to the device being tested for transient response is extremely critical because the internal impedance of the test equipment can load down the equipment under test, and thus cause response distortion. An emitter-follower stage or other isolating device should be employed between the test equipment and the device under test to minimize the loading effect. All connecting leads should be maintained as short as possible, and the connecting lines must be matched to prevent feedback reflection along the line at high frequencies, which would cause spurious ripples or ringing.

Transistor Considerations

The transient response of a transistor used as a switch is important because of the time required to turn the transistor switch from the “off” to the “on” position, and vice versa. Normally, either a step or a pulse of current applied to the input is required to turn the transistor from “off” to “on.” Referring to Figure 10-69, which is the high-frequency equivalent circuit, some assumptions and simple calculations can be made that will provide an approximate rise time within a transistor circuit operating in an active region.

First, assume that load resistor $R_L$ is small enough to represent a short circuit; therefore, $R_3$ (the collector resistance) and $C_c$ (the barrier capacitance) are effectively in parallel with $R_2$ (the barrier resistance), as shown in Figure 10-69. Now, since $R_2$ is much smaller than $R_3$ in this parallel circuit, the value of $R_3$ can be disregarded. Furthermore, as $C_c$ (the barrier capacitance) is much larger in reactance than $R_2$ at the assigned frequency, $2\pi F_1 C_c$ also can be neglected. Thus, for a grounded base configuration, the equivalent circuit of Figure 10-69 can be reduced to the more practical equivalent circuit shown in Figure 10-70. The value of $C_d$ (the diffusion capacitance) is equal to the reciprocal of the assigned frequency, $2\pi F_1$, and the emitter resistance, $R_1$: 

$$\frac{1}{2\pi F_1 R_1}$$
Next, include a subsidiary circuit \((R \text{ and } C)\), as shown in Figure 10-71. The time of \(RC\) equals the reciprocal of \(2\pi F_1\). When the time \(T\) equals zero, output \(I_R\) equals zero, and when \(T\) equals infinity, output \(I_R\) equals the input \((I_{in})\). The time-constant is the reciprocal of the assigned frequency, \(\frac{1}{2\pi F_1 R}\), and the rise time is \(\frac{1}{2\pi F_1}\).

This is the time required for the output current to rise from 0.1 to 0.9 percent of its final value. The effect on the transient response of \(C_C\) (the collector capacitor) was not taken into account in the previous calculations because load resistor \(R_2\) was considered small enough to be an effective short circuit. A simplified equivalent circuit is shown in Figure 10-72, which recognizes that \(R_L\) does not affect the response when the input is from an infinite series-impedance current and \(R_L C_C\) is much larger than the time-constant \(\frac{1}{2\pi F_1}\).

In fact, if \(\frac{R_2}{R_3}\) is much smaller than 1 and \(2\pi F_1 R_3 C_C 2\) is much larger than 1, then the time-constant, calculated for the response with a very small or shorted value of \(R_L\), would be increased by the amount, \(2\pi F_1 R_L C_C + 1\). Therefore, the rise times and turn-on times would be increased by this same factor.

**Transistor Delay Time**

In the previous calculations of transistor response, the finite time required for the impulse signal to diffuse across the base region was neglected. Under this condition, if a current pulse is applied to the transistor emitter, a response will appear at the collector only after some delay in time. The value of \(I_R\) may be obtained for use in the equivalent circuits shown in Figures 10-70 and 10-72 by representing this delay time with an equivalent circuit, as indicated in Figure 10-73. The line attenuation will increase in direct proportion to the frequency. The resistive-capacitive delay line indicates a time interval before a response is indicated at the output.

**Transistor Storage Time**

Up to this point, the discussion has concerned the turn-on transistor process. If the transistor is in the active region, the turn-off process consists simply of applying a pulse of reverse polarity, and the required time-constant is calculated in the same manner, using the equation for the turn-on process. Unfortunately, if the transistor is in the “on” condition and is operating in the saturation region, an
abnormally large time-delay will occur before the transistor responds to the turn-off signal. This peculiar delay, termed “storage-time delay,” is shown in *Figure 10-74*, which shows the minority carrier density in the base region for three situations. The first situation shown is the cutoff condition, with both the emitter and collector junctions reverse biased. The minority carrier density is therefore zero at both junctions, and very small throughout the base region.

The second situation is shown by the active curve in *Figure 10-74*, where the minority carrier density is high at the emitter junction and zero at the collector junction. The change in density between the two junctions is the result of the diffusion process, which accounts for current flow across the base of the transistor. However, if an input signal drives the emitter junction to reverse bias condition, the diffusion process will not continue until the minority carriers in the base region have been removed.

The third situation is shown by the saturation curve in *Figure 10-74*. Unlike the cutoff and active conditions, the previously discussed equivalent circuits used to determine time delays, response, etc., do not apply in this case because both the emitter and the collector are emitting carriers into the base region. In addition, as both junctions are forward-biased, the junction voltages will be small and the collection process at the junctions will be slow. This, in turn, causes the density of minority carriers in the base region to build up to a relatively large value. This high-density level in the base region must be permitted to decrease before the turn-off process begins to take effect. This long-storage time delay may represent two or three times the normal rise or fall time in the active region. Therefore, it is evident that when a transistor switch is used in an application requiring high switching speeds, it must be restrained from entering the saturation region.

**Transistor Response**

*Figure 10-75* shows approximate waveforms that are required to represent the response from a transistor driven from cutoff to saturation and back again. A grounded-emitter switch is used because this type of configuration is the most useful and its response can represent other configurations.

The delay time is represented by the symbol $T_D$, the rise time by $T_0$, the storage time by $T_s$, and the decay or fall time by $T_1$. The input current reverses at the end of the pulse rather than falling only to zero. As a result, the output current response falls toward a negative value rather than toward zero. The fall time of the pulse is thereby reduced. The voltage input waveform of *Figure 10-75* was terminated in a minus $E_2$ voltage because the storage of minority carriers in the base region does not permit the transistor input impedance to immediately attain a large value. In fact, the input impedance remains small until the minority carriers at the transistor junctions are swept away. At this point, the input impedance increases and causes the input current to decrease in direct proportion to the speed with which the minority carriers throughout the base region drift to the junctions.
SPECTRUM WAVEFORM ANALYSIS AND MEASUREMENTS

The analysis of a complex waveform, prepared in terms of a graphical plot of the amplitude versus frequency, is known as spectrum analysis. Spectrum analysis recognizes the fact that any waveform is composed of the summation of a group of sinusoidal waves, each of an exact frequency and all existing together simultaneously.

Electromagnetic Frequency Spectrum

A chart showing the electromagnetic frequency spectrum is given in Figure 10-76. This chart indicates the frequency and wavelength of the various frequency bands and provides general categories and typical uses for each range.

Wavelength Frequency Conversion

The speed of electromagnetic energy or light in a vacuum is 299,792,458 meters per second. For simplification, 300,000,000 meters per second is used in the following discussions and calculations. Wavelength (λ) is equal to velocity (v) divided by frequency (f) \( \lambda = \frac{v}{f} \). For example, a 25 MHz radio wave has a wavelength of 12 meters.

\[
\lambda = \frac{v}{f} = \frac{300 \times 10^6 \text{meters per second}}{25 \times 10^6 \text{MHz}} = 12 \text{meters}
\]

Spectrum Analysis

In the realm of varying frequency, three axes of degree exist: amplitude, time, and frequency. The time domain (amplitude vs time) plot is used to recover phase relationships and basic timing of the signal, and is normally observed with the aid of an oscilloscope. The frequency domain (amplitude vs frequency) plot is used to observe frequency response, employing the spectrum analyzer for this purpose.

Spectrum analyzers are used to measure spectral purity of multiplex signals, percentage of modulation of AM signals, and modulation characteristics of FM and PM signals, and to interpret the displayed spectra of pulsed RF emitted from a radar transmitter.

The difference between frequency and time domain plots is shown in Figure 10-77, view A. The figure illustrates a three-dimensional coordinate of a fundamental frequency and its second harmonic with respect to time frequency and amplitude. The time domain display in Figure 10-77, view B, is as it would be seen on an oscilloscope. The solid line, \( f_1 + 2f_1 \), is the actual display. The dashed lines, \( f \) and \( 2f_1 \), are drawn to illustrate the fundamental and second harmonic frequency relationship used to
formulate the composite signal \( f_1 + 2f_1 \). Figure 10-77, view C, shows the frequency domain display of Figure 10-77, view B, as it would be seen on a spectrum analyzer. Note that in Figure 10-77, view C, the components, \( f_1 \) and \( 2f_1 \), of the composite signal are clearly seen.

**Frequency Domain Display Capabilities**

The frequency domain contains information not found in the time domain. The spectrum analyzer can display signals composed of more than one frequency (complex signals), and it can discriminate between its components while measuring the power level at each one. It is more sensitive to low-level distortion than an oscilloscope, and its sensitivity and wide dynamic range are also useful for measuring low-level modulation, as shown in Figure 10-78, views A and B. What appears to be a distortion-free signal on an oscilloscope is actually, when displayed on a spectrum analyzer, a signal with harmonic distortion, as shown in Figure 10-78, view A1. The waveform in Figure 10-78, view B1, appears unmodulated when, in fact, it presents low-level modulation when analyzed. The spectrum analyzer is useful in the measurement of long- and short-term stability such as noise sidebands on an oscillator, residual FM of a signal generator, or frequency drift of a device during warm-up, as illustrated in Figure 10-79. The swept frequency response of a filter or amplifier and the swept distortion measurement of a tuned oscillator are also measurable with the aid of a spectrum analyzer. In the course of these measurements, a variable persistence display should be employed for transient spikes and simplification of readability.
Examples of tuned oscillator harmonics and filter response are shown in Figure 10-80. Frequency conversion devices such as mixers and harmonic generators are easily characterized by such parameters as conversion loss, isolation, and distortion. These parameters can be displayed, as shown in Figure 10-81, with the aid of a spectrum analyzer. Present-day spectrum analyzers can measure segments of the frequency spectra from 0 Hz to 67 gigahertz (GHz) and higher with a wide range of end user defined capabilities to consider.

**Modulation Measurements**

In all types of modulation, the carrier is varied in proportion to the instantaneous variations of the modulating waveform. The two basic properties of the carrier available for modulation are the amplitude characteristic and the angular (frequency or phase) characteristic.
Amplitude Modulation Analysis

The modulation energy in an amplitude-modulated wave is contained entirely within the sidebands. AM of a sinusoidal carrier by another sinusoid would be displayed as shown in Figure 10-82. For 100-percent modulation, total sideband power would be one-half of the carrier power; therefore, each sideband will be 6 dB less than the carrier, or one-fourth of the power of the carrier. Since the carrier component is not changed with AM transmission, the total power in the 100-percent modulated wave is 50 percent higher than in the unmodulated carrier.

The primary advantage of the log display of the spectrum analyzer over the linear display provided by the oscilloscopes for percentage of modulation measurements is that the high dynamic range of the spectrum

\[
\text{fc} = \text{Carrier Frequency} \\
\text{fm} = \text{Modulation Frequency}
\]
The analyzer (up to 70 dB) allows accurate measurements of values as low as 0.06 percent. It also allows the measurement of low-level distortion of AM signals. Both capabilities are shown in Figure 10-83.

The chart in Figure 10-84 provides an easy conversion of dB down from carrier into percent of modulation. Anything greater than -6 dB is over 100-percent modulation, therefore, producing distortion as shown in Figure 10-83, view C.

In modern long-range high-frequency communication, the most important form of AM is single sideband. Either the upper or lower sideband is transmitted and the carrier is suppressed. Single sideband requires only one-sixth of the output power required by AM to transmit an equal amount of intelligence power and less than half the bandwidth. The effects of balancing out the carrier of an AM signal are shown in Figure 10-85. The most common distortion experienced in single sideband (SSB) is intermodulation distortion, which is caused by nonlinear mixing of intelligence signals. The two-tone test is used to determine if any
intermodulation distortion exists. An example of the spectrum analyzer display of the two-tone test is shown in Figure 10-86.

**Frequency Modulation Analysis**

AM contains the intelligence in the sideband current pairs spaced symmetrically about the carrier by an amount equal to each modulation frequency. Theoretically, FM can contain an infinite number of sideband current pairs per modulating frequency with the intelligence spread throughout them as well as along the carrier.

The amplitude of a particular pair of side currents may be larger than the center frequency component. This fact also holds true for PM, in that, with the same modulation index ($\beta$), the same spectrum distribution is obtained. The number of important side currents is larger for low frequencies in the signal band than it is for high frequencies.

To find the amplitude value of an individual side current pair in the frequency spectrum, use Table 10-1 to determine the amplitude factors used to multiply the maximum unmodulated carrier current level ($I_m$). For example, use a maximum center frequency ($F$) swing ($\Delta F$) = ±60 kHz and a 30 kHz signal frequency ($f$) to find the value of $\beta$:

$$\beta = \frac{\Delta F}{f} = \frac{60}{30} = 2$$

Using Table 10-1, $J_0 (\beta) = J_0 (2) = 0.2239$, and this is the value multiplied times the maximum unmodulated current ($I_m$) to obtain the magnitude of $F$. The value of $J_1 (\beta) = J_1 (2) = 0.5767$ multiplied times $I_m$ gives the amplitude of both the first upper side current at the frequency of ($F + 30$ kHz) and the first lower side current at the frequency of ($F - 30$ kHz).

### Table 10-1 — Abbreviated Bessel Factor Table

<table>
<thead>
<tr>
<th>$\beta$</th>
<th>$J_0(\beta)$</th>
<th>$J_1(\beta)$</th>
<th>$J_2(\beta)$</th>
<th>$J_3(\beta)$</th>
<th>$J_4(\beta)$</th>
<th>$J_{14}(\beta)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>1.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>0.5</td>
<td>0.9385</td>
<td>0.2423</td>
<td>0.0306</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.0</td>
<td>0.7652</td>
<td>0.4401</td>
<td>0.1449</td>
<td>0.0196</td>
<td>0.0025</td>
<td></td>
</tr>
<tr>
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<td>0.2239</td>
<td>0.5767</td>
<td>0.3528</td>
<td>0.1289</td>
<td>0.0340</td>
<td></td>
</tr>
<tr>
<td>5.0</td>
<td>-0.1776</td>
<td>-0.3276</td>
<td>0.0466</td>
<td>0.3648</td>
<td>0.3912</td>
<td></td>
</tr>
<tr>
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<td>0.0435</td>
<td>0.2546</td>
<td>0.0584</td>
<td>-0.2196</td>
<td>0.0120</td>
</tr>
</tbody>
</table>

10-47
The spectrum distribution for a modulation index of $\beta = 2$ is shown in Figure 10-87 using the variable $l_m = 1$. This graph was prepared from data obtained from Table 10-1. As all amplitudes are obtained by multiplying the Bessel factors obtained from Table 10-1 times $l_m$, the magnitude of the Bessel factors directly determines the intensity of the sideband current pairs in the useful frequency spectrum. The sideband current pairs that are too far down in amplitude from $F$ are not significant; they are less than 1 percent of the unmodulated carrier. Thus, the bandwidth is determined by the number of significant sideband current pairs.

![Figure 10-87 — Spectrum distribution for a modulation index of $\beta = 2$.](image)

The bandwidth may also be calculated from Table 10-1 for a specific frequency swing. For example, let $\beta = 10$ and read the Bessel function values across the chart, from left to right. As you can see, the 14th sideband pair is 0.012 times $l_m$, which is significant. Therefore, the maximum bandwidth for $\beta = 10$ is 2 (both side currents) times 14 sidebands times the signal frequency deviation. For a 30 kHz signal deviation, the bandwidth would be $2 \times 14(30) = 840$ kHz, and for 2 kHz it would be 56 kHz. This example shows why a higher modulation signal requires more frequency space (greater bandwidth) than does a lower modulation signal.

The effects of changing the amplitude or frequency of the modulating signal while holding the other constant is shown in Figure 10-88. The Bessel factors given in Table 10-1 and Figure 10-89 also show that the greater the modulation index $\beta$, the greater the number of significant sidebands. As the modulation energy spreads out from the carrier frequency, it can be determined at what point to establish the bandwidth. For example, in Figure 10-89, which was prepared for an index of $8 = 24$, the largest side currents occurred at the edges of the

![Figure 10-88 — Modulation frequency and amplitude effects on an FM carrier.](image)
pass band; thereafter, continue to read off the Bessel factors until the side current pairs are less than 1 percent of the unmodulated carrier current level. Sideband currents beyond this point do not have significant amplitudes for practical consideration.

FM, for modulation index values smaller than 0.2, is similar to AM in that both types of modulation contain only one significant side-current pair. Therefore, for a value of \( \frac{\Delta F}{f} = \beta = 0.2 \) or less, FM behaves exactly like AM with respect to spectrum distribution. However, unlike AM, no primary oscillator can be used in the FM transmitter because the carrier frequency must be varied during the modulation cycle to produce FM. The desired intelligence in FM or PM will create more energy distribution, and thus a larger response in a receiver demodulator than will noise energy. This is the outstanding desirable feature of FM over AM spectrum distribution.

**Phase Modulation Analysis**

In PM, unlike FM or AM, the carrier current level, as well as the center carrier frequency (\( F \)), remains constant. Only the relative phase (\( \theta \)) changes. The actual value of \( \theta \) is not important. The deviation from this value is important, and it produces the desired PM. For example, if \( \theta \) equals 30 degrees and the phase deviation is \( \pm 40 \) degrees, this will produce a certain modulation of the carrier. However, if \( \theta \) had originally been 80 degrees rather than 30 degrees and was subjected to a \( \pm 40 \) degree deviation, the same output PM waveform, containing the same intelligence, would have been produced. The original value of \( \theta \) indicates only the original amplitude at the start of the phase swing. Actually, the effect of a \( \pm 40 \) degree deviation would be to give the appearance of wobbling about the carrier frequency (\( F \)) as \( F \) goes through an angular distance of \( \pm 360 \) degrees, regardless of its beginning phase, \( \theta \). However, the equivalent instantaneous frequency of the modulated carrier would remain the same. Thus, PM entails the important fact that it is created not only by the maximum phase deviation (\( \Delta \beta \)), but also by the applied signal frequency (\( f \)). Therefore, the frequency shift is greater for higher frequencies than it is for lower frequencies.

The sidebands for PM are similar to the sidebands for FM, and the same general formula for the modulation index holds true. That is, \( \beta = \left( \frac{\Delta \theta}{\theta} \right) \).

As with FM, the side currents contain a symmetrical frequency distribution around the carrier. In other words, the first upper sideband and the first lower sideband have the same numerical value, amplitude, and frequency difference from the carrier; the value of the modulation index (\( \beta \)) is proportioned to the phase deviation (\( \Delta \theta \)); and for a fixed maximum phase swing, it does not matter whether you use a 15 Hz or 15 kHz signal to modulate the phase of the carrier. In either case, you will obtain the same number of important side-current pairs. However, for the 10th upper and lower sideband in the 15 Hz modulation case, the side-current pair is 10 x 15 Hz or 150 Hz above and below the carrier. For the 15 kHz case, the 10th side-current pair is 10 x 15 kHz or 150 kHz above and below the carrier, and thus requires a much broader bandwidth. Therefore, PM and FM, unlike AM,
have a spectrum distribution of the modulation energy, which is proportional to the square of the spectrum amplitudes, and does affect the carrier frequency amplitude. However, it does not matter whether the technician is dealing with a modulation index of 10 for FM or maximum phase deviation of 10 radians (573 degrees) for PM. This is true for PM as long as the maximum phase swing \((\Delta \theta)\), which causes the PM, is fixed. The same spectrum distribution is equally true for FM if the maximum deviation \((\Delta F)\), which causes the FM, changes directly with the signal frequency \(f\).

As the bandwidth of PM remains the same regardless of signal frequency changes, the PM bandwidth can be calculated directly from the modulation index \((\beta)\). For small values of modulation index (0.3 or less), PM will contain only one pair of significant sidebands, the same as for FM. Actually, this permits you to amplitude-modulate a carrier, suppress the carrier, and shift the modulation product by 90 degrees to provide narrow-band FM or PM. The FM or PM effect can be obtained by applying a signal voltage having a magnitude that is inversely proportional to the signal frequency \(f\). The phase-shifted product is then combined with the unmodulated carrier.

Both FM and PM contain a true instantaneous and an equivalent instantaneous carrier frequency. Therefore, the number of Hz must remain constant to prevent the center or mean frequency \(F\) from drifting to some other nearby frequency not originally assigned to the carrier. If this occurred, the entire spectrum centered around the carrier would drift and infringe on the other nearby FM channels.

**Pulsed Waves**

An ideal pulsed radar signal is comprised of a train of RF with a constant repetition rate, pulsewidth, shape, and amplitude. To receive the energy reflected from a target, the radar receiver requires close to ideal pulse radar emission characteristics. By observing the spectra of a pulsed radar signal, you can easily and accurately measure such characteristics as pulsewidth, duty cycle, peak, and average power.

**Rectangular Pulse**

A rectangular wave is used to pulse-modulate the constant frequency RF carrier to produce the pulse radar output. The rectangular wave is comprised of a fundamental frequency and its combined odd and even harmonics. Both in and out of phase harmonics relationships are utilized, depending on the desired pulsewidth or pulse interval. The development of a rectangular wave and its spectral content is illustrated in Figure 10-90.

**Pulsed Wave Analysis**

In AM, the sidebands are produced above and below the carrier frequency. The principle also applies for a pulse, except that the pulse is
comprised of many tones. These tones produce multiple sidebands, which are commonly referred to as spectral lines or “rails” on the analyzer display. There will be twice as many rails in the pulse radar’s modulated output as there are harmonics contained in the modulating pulse (upper and lower sidebands) as shown in Figure 10-91.

The pulse repetition frequency (PRF) is equal to the pulse interval of $1/T$ as shown in Figure 10-92. The actual spectrum analyzer display would show the lower lobes (shown below the reference line) on top because the spectrum analyzer does not retain any phase information. Changing the pulse interval or pulsewidth of the modulation signal will change the amount of rails (PRF) or number of lobe minima, as shown in Figure 10-93.

Analyzing the Spectrum Pattern

The leading and trailing edges of the radiated pulse-modulated signal must be extremely steep, with a constant amplitude between them. Incorrect pulse shape will cause frequency spread and pulling, which results in less available energy at the frequency to which the receiver is tuned. The primary reason for analyzing the spectrum is to determine the exact amount of AM and FM present. The amount of AM determines the increase in the number of sidebands within the applied pulse spectrum, whereas an increase in FM increases the amplitude of the side lobe frequencies. In either case, the energy available to the main spectrum lobe is decreased.

Typical Spectrum Patterns

Several illustrations of commonly obtained patterns are contained in Figure 10-93. These spectra are the result of pulse-modulated waves, which are special types of RF carrier AM. As can be seen, AM alone does not seriously affect the frequency spectrum on an RF pulse. The type of modulation present can be easily determined because AM primarily affects the amplitude of the side lobes and
does not affect the shape of the main lobe. FM affects the main lobe bandwidth. Spectrum asymmetry, as shown in Figure 10-93, view F, occurs only when both AM and FM occur simultaneously.

Figure 10-93 — Spectrum patterns.
Spectrum Analyzer Interpretations

A pulsed RF signal has unique properties; therefore, you must be careful to correctly interpret the display on a spectrum analyzer. Spectrum analyzer response to a pulsed radar signal can be of two kinds, resulting in displays that seem similar but are of completely different significance. One response is called a “line spectrum,” and the other is called a “pulse spectrum.” Both are responses to the same pulsed radar signal, and the line and pulse spectrum terms refer solely to the response of the display on the spectrum analyzer.

**Line spectrum** - A line spectrum occurs when the spectrum analyzer’s 3 dB bandwidth ($\beta$) is narrow compared to the frequency spacing of the input signal components, as shown in Figure 10-94.

**Pulse Spectrum** - A pulse spectrum occurs when the spectrum analyzer's bandwidth ($\beta$) is equal to or greater than PRF. The spectrum analyzer, in this case, cannot resolve the actual individual frequency components because several rails are within its bandwidth. However, if the spectrum analyzer's bandwidth ($\beta$) is narrow, as compared to the spectrum envelope, the envelope can then be resolved, as shown in Figure 10-95. The effect of varying the scan width bandwidth of the spectrum analyzer in the line analysis interpretation is shown in Figure 10-96. The effect of the same variations in the pulse analysis interpretation is shown in Figure 10-97.
**Figure 10-96 — Line spectra of a pulse-modulated 50 MHz carrier.**

A. Line spectrum of the pulsed 50 MHz signal. LINEAR DISPLAY 100 µV/DIV, SCAN 10 kHz/DIV.

B. Same spectrum in logarithmic display. SCAN WIDTH 10 kHz/DIV, BANDWIDTH 100 Hz, LOG REF. —20dBm, 10 dB/DIV.

C. Same spectrum with 300 Hz ANALYSER BANDWIDTH. SCAN WIDTH 10 kHz/DIV. LOG REF. —20dBm, 10 dB/DIV.

D. Same signal but SCAN WIDTH changed to 5 kHz/DIV. BANDWIDTH 100 Hz, LOG REF. —20dBm, 10 dB/DIV.

E. Carrier now modulated with a PULSE WIDTH of 0.05 ms (PRF = 1 kHz) SCAN WIDTH 10 kHz/DIV, BANDWIDTH 100 Hz, LOG REF. —20dBm, 10 dB/DIV.
Figure 10-97 — Pulsed RF signal in "pulsed" spectrum display.

A  Signal (Peak Amplitude —30 dBm) pulsed with PRF = 100 Hz, $T_{\text{eff}} = 1/10$ kHz = μs. SCAN WIDTH 10kHz/DIV, B = 1 kHz SCAN TIME 0.5 s/DIV.

B  Same signal but SCAN TIME changed to 0.1 s/DIV.

C  Same signal but SCAN TIME of 20 ms/DIV.

D  Same signal, but B = 300 kHz and SCAN TIME 2ms/DIV. The PRF can be measured to $1/10$ ms = 100 Hz.

E  Same signal with SCAN WIDTH 5 kHz/DIV, B = 1 kHz, SCAN TIME 0.1 s/DIV.

F  Same signal with B = 300 kHz SCAN WIDTH 10 kHz/DIV, SCAN TIME 0.2 s/DIV.

G  Same signal with B = 3 kHz.

H  Same signal with B = 10 kHz.
SPECTRUM ANALYZER OPERATION

The information desired from the spectra to be analyzed determines the spectrum analyzer requirements. Real-time analysis is used if a particular point in the frequency spectrum is to be analyzed, such as line spectra displays. Continuous or swept frequency analysis, which is the most common mode of observation, is used to display a wider portion of the frequency spectrum or (in some cases) the entire range of the spectrum analyzer in use. Changing the spectrum analyzer setting from one mode to another is accomplished by varying the scan time and/or the spectrum analyzer's bandwidth.

Most real-time spectrum analyzers, however, are preceded by mechanical filters, which limit the input bandwidth of the spectrum analyzer to the desired spectra to be analyzed. Tunable or swept spectrum analyzers function basically the same as heterodyne receivers, the difference being that the local oscillator is not used but is replaced by a voltage control oscillator (VCO). The VCO is swept electronically by a ramp input from a sawtooth generator. The output of the receiver is applied to a cathode ray tube (CRT), which has its horizontal sweep in synchronization with the VCO. The lower frequency appears at the left of the display. As the trace sweeps to the right, the oscillator increases in frequency. A block diagram of a typical heterodyne spectrum analyzer is illustrated in Figure 10-98.

Resolution

Before the frequency of a signal can be measured on a spectrum analyzer, it must be resolved. Resolving a signal means distinguishing it from other signals near it. Resolution is limited by the narrowest bandwidth of the spectrum analyzer because the analyzer traces out its own intermediate frequency (IF) bandwidth shape as it sweeps through a signal. Thus, if the narrowest bandwidth is 1 kHz, then the nearest any two signals can be, yet still be resolved, is 1 kHz. Reducing the IF bandwidth indefinitely would obtain infinite resolution were it not that the usable IF bandwidth is limited by the stability (residual FM) of the spectrum analyzer. The smaller the shape factor of the IF bandwidth, the greater the analyzer's capability to resolve closely spaced signals of unequal amplitude. Signals of equal amplitude can be resolved only when they are separated by the 3 dB bandwidth. Unequal signals can be resolved if they are separated by greater than half the bandwidth at the amplitude difference between them.

Other Spectrum Analyzer Considerations

It is important that the spectrum analyzer be more stable in frequency than the signals being measured. The stability of the analyzer depends on the frequency stability of its VCO. Scan time of the spectrum analyzer must be long enough, with respect to the amplitude of the signal to be measured, to allow the spectrum analyzer's IF circuitry to charge and recover.
End of Chapter 10
Waveform Interpretation

Review Questions
10-1. The integrator circuit may be considered to be which of the following types of filter?

A. Low pass  
B. High pass  
C. Bypass  
D. Resonant

10-2. With a carrier frequency of 1,600 kHz and a modulation voltage with a frequency of 500 Hz, what is the frequency of the (a) lower sidebands and (b) upper sidebands?

A. (a) 500 Hz (b) 2,600 kHz  
B. (a) 1,600 Hz (b) 2,100 Hz  
C. (a) 1,100.5 kHz (b) 2,200.5 kHz  
D. (a) 1,599.5 kHz (b) 1,600.5 kHz

10-3. Which of the following terms best describes distortion caused by a modulating voltage that is greater than the carrier voltage?

A. Undermodulation  
B. Overmodulation  
C. Hum modulation  
D. Noise modulation

10-4. When frequency modulating a carrier wave, the carrier is changed to represent the ________.

A. Phase.  
B. Amplitude.  
C. Intelligence.  
D. Voltage.

10-5. How many dB down from the peak or maximum amplitude point on a frequency response curve are the half-power points calculated?

A. 1 dB  
B. 2 dB  
C. 3 dB  
D. 4 dB

10-6. What portion of a double-peaked response curve represents the resonant frequency?

A. The lowest in frequency of the two peaks  
B. The highest in frequency of the two peaks  
C. 0.707 times the frequency between the peaks  
D. The dip between the two peaks
10-7. Which of the following transformer coupling methods produces greatest bandwidth?

A. Multicoupling  
B. Overcoupling  
C. Lateral coupling  
D. Undercoupling

10-8. Which of the following transformer coupling methods results in better circuit frequency selectivity?

A. Split coupling  
B. Close coupling  
C. Side coupling  
D. Loose coupling

10-9. What is the term to describe an undesirable deviation from a known waveform?

A. Distortion  
B. Integration  
C. Modulation  
D. Discrimination

10-10. Which of the following terms describes the amplitude distortion of a signal caused by circuit limitation of bandwidth?

A. Attenuation  
B. Integration  
C. Modulation  
D. Discrimination

10-11. The unintended addition of fundamental frequency multiples to a fundamental wave shape creates a new resultant waveform. What is the name of this type of distortion?

A. Multiples  
B. Harmonic  
C. Amplitude  
D. Complex

10-12. Which of the following types of frequency distortions best describes high-speed fluctuations of audio reproduction equipment?

A. Harmonic  
B. Linear  
C. Intermodulating  
D. Flutter
In answering question 1-13, refer to the figure above.

10-13. What Lissajous display indicates a phase shift of 90° or 270° of two voltages of like amplitude and frequency?

A. An ellipse  
B. A line slanted to the left  
C. A circle  
D. A line slanted to the right
10-14. When Lissajous patterns are created, unequal amplitudes of scope inputs may be compensated by first adjusting which of the following controls on the oscilloscope?

A. Phase shift network function control  
B. Horizontal selector control  
C. Z-axis intensity control  
D. Horizontal and vertical gain control

10-15. Which of the following frequency characteristics best describes the information provided by a “spot-wheel” Lissajous pattern?

A. Phase shift  
B. Frequency ratio  
C. Cosine value  
D. Relative amplitude

10-16. Which of the following Lissajous patterns indicates a 180-degree phase shift in the amplifying stages of an oscilloscope when a sine wave is simultaneously applied to both the horizontal and vertical input terminals?

A. A straight line in the second and fourth quadrants  
B. A straight line in the first and third quadrants  
C. An ellipse rotating around a diagonal axis in the second and fourth quadrant  
D. An ellipse rotating around a diagonal axis in the first and third quadrants

10-17. What is the frequency of radio wave with a wavelength of 45 meters?

A. 60 kHz   
B. 60 MHz   
C. 600 kHz   
D. 600 MHz

10-18. What two basic characteristics of a signal are observed with a spectrum analyzer?

A. Amplitude versus time   
B. Time versus frequency   
C. Sensitivity versus time   
D. Amplitude versus frequency

10-19. Spectrum analyzers are useful for displaying the components of what type of signal?

A. Complex   
B. Trigonometric   
C. Linear   
D. X ray
10-20. For a 100-percent amplitude-modulated (AM) signal, the total sideband power would be what fraction of carrier power?

A. 1/4  
B. 1/2  
C. 3/4  
D. 4/4

In answering question 1-21, refer to the figure above.

10-21. What are the (a) minimum and (b) maximum percentage of a waveform leading edge used to measure rise time?

A. (a) 10% (b) 90%  
B. (a) 25% (b) 75%  
C. (a) 32% (b) 68%  
D. (a) 40% (b) 60%

10-22. You must select a pulse generator and an oscilloscope to measure transient response of an amplifier. The amplifier has a rated rise time of 1.3 microseconds. What is the maximum rise time allowed for your test equipment in order for you to get a rise time measurement accuracy of at least 1 percent?

A. 1.3 microseconds  
B. 0.13 microseconds  
C. 1.3 milliseconds  
D. 0.13 milliseconds
10-23. What is the most common distortion experienced in AM single-sideband communications?

A. Frequency hopping  
B. Demodulation  
C. Intermodulation  
D. Overmodulation

10-24. What type of spectrum is displayed when the spectrum analyzer’s 3 dB bandwidth is narrow compared to the pulse repetition frequency of the input signal?

A. Pulse  
B. Wide  
C. Line  
D. Optical
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CHAPTER 11

AUTOMATIC TEST EQUIPMENT

Aircraft avionic systems have become increasingly complex, increasing the demands for new testing methods. Today’s avionic packages are vital to all facets of aircraft operation, necessitating new, more powerful, and efficient test systems to keep them in a ready for use condition.

In order to limit the growing cost of development, procurement, and support of electronic systems, a universal automatic test system has long been a goal of the U.S. Navy. The Consolidated Automated Support System (CASS) is the latest generation of automatic test equipment developed in the pursuit of this goal. Used aboard U.S. Navy aircraft carriers and fleet readiness centers at shore installations, the Consolidated Automated Support System family of test equipment is designed to deal with the continually changing field of avionic testing. Computerized automatic test equipment significantly reduces the space required for testing as compared to space required when equivalent special- and manual-support test equipment is used.

LEARNING OBJECTIVES

When you have completed this chapter, you will be able to do the following:

1. Identify the versions of the Consolidated Automated Support System and their capabilities.
2. Describe the purpose of the Consolidated Automated Support System consoles and components.
3. Describe proper electrical safety procedures used during maintenance operations.

CONSOLIDATED AUTOMATED SUPPORT SYSTEM FAMILY

The CASS family of test equipment is a suite of general purpose automatic test equipment (ATE) designed to perform functional testing, fault detection, and isolation of avionic equipment. The system uses test program sets (TPSs) to automatically test weapons replaceable assemblies (WRAs) and shop replaceable assemblies (SRAs) assigned to CASS test sets or stations. CASS stations are capable of generating all complex digital and radio-frequency (RF) signals, alternating current (ac) and direct current (dc) voltages, and providing diagnostics to units under test (UUT). The CASS (Figure 11-1) family of test equipment is designed to be modular and is currently operating in three versions:

- CASS
- Reconfigurable-Transportable CASS (RTCASS)
- Electronic CASS (eCASS)

Figure 11-1 — CASS hybrid station.
Consolidated Automated Support System

Originally, the Navy just named the CASS standard automatic test equipment family CASS. The basic CASS station provides shore-based and afloat intermediate and depot level maintenance and repair capabilities for all naval aircraft, ship, and submarine electronics systems. Fielded since 1994, CASS has been modernized through the years to ensure maintenance support for the current fielded Navy inventory of systems. It is scheduled to be phased out when eCASS, the most recent version of the CASS family, begins fielding in 2017. Five hundred and fifty-three stations are used by naval aviation. It is also in use at Naval Sea Systems Command activities and in nine foreign countries. Designed to be modular, it currently consists in five configurations:

- Hybrid (HYB)
- Radiofrequency (RF)
- Communications, Navigation, and Identification (CNI)
- Electro-Optical (EO)
- High Power Device Test Set (HPDTS)

General descriptions of CASS configurations are discussed later in this chapter.

Reconfigurable-Transportable Consolidated Automated Support System

The RTCASS is the U.S. Marine Corps (USMC) specific test set within the CASS standard automatic test equipment family (Figure 11-2). RTCASS provides intermediate and depot level avionics support for the Marine Corps, Air Force Special Operations Command (AFSOC), Navy depots, and foreign allies. The RTCASS provides a man-portable CASS configuration using commercial off-the-shelf (COTS) hardware and software to meet USMC V-22 and H-1 support requirements as well as to replace legacy CASS stations at USMC fixed wing aircraft (EA-6B, F/A-18, and AV-8B) support sites. In the RTCASS version, there are three configurations; basic, high power, and depot.

Basic

Basic RTCASS stations provide test capability for general purpose electronics, computers, instruments, and flight controls. It also provides electronic countermeasures (ECM), electronic counter-countermeasures (ECCM), electronic warfare (EW) support measures, fire control, navigation, tracking, and surveillance radar and radar altimeter support and other RF capability.

High Power

The RTCASS High Power station provides basic RTCASS capability plus the capability to test high power radar systems such as the APG-65/73 and ALQ-99 systems.
Depot

The depot configuration of the RTCASS station provides basic RTCASS functionality plus advanced analog and digital capabilities specifically designed for depot SRA testing.

Electronic Consolidated Automated Support System

The Navy’s eCASS version (Figure 11-3) is the most recent addition to the CASS automatic test equipment family. eCASS provides shore-based and afloat intermediate and depot level maintenance and repair capabilities for all naval aircraft, ship, and submarine electronics systems. In low rate initial production (LRIP), eCASS is replacing the existing aging legacy CASS stations at Naval Air Systems Command and Naval Sea Systems Command activities. Three hundred and thirty-eight eCASS stations are planned to support U.S. naval weapons systems, and it is anticipated that additional quantities will be procured by foreign allies. eCASS is replacing the five mainframe CASS configurations (Hybrid, RF, CNI, HPDTS, and EO).

Anticipated to run 20 percent faster, eCASS will have greater reliability while maintaining legacy compatibility with current CASS stations. Additionally, eCASS is designed to operate with commercial automated testing system software. The open software and hardware architecture provides eCASS with long-range upgrade capabilities allowing avionics system manufacturers to develop maintenance, testing, and upkeep plans that will seamlessly transition from the factory floor to Fleet Readiness Centers (FRCs).

The Navy’s entire aircraft inventory, including the F-35 Lightning (Figure 11-4), E/A-18 Growler (Figure 11-5), and P-8 Poseidon (Figure 11-6), will be supported by eCASS.

SUITE DESCRIPTION

As previously discussed, the CASS family of test equipment is designed to test a wide range of equipment and comes in many versions and mission specific configurations. To avoid obsolescence and allow upgrades for testing future avionic and weapon technologies, CASS uses a flexible hardware and software architecture.
The CASS family’s basic equipment configuration is the CASS hybrid (CASS HYB) station (Figure 11-1), which is contained in five racks. An additional special function console, rack 6, accommodates the specialty equipment required for testing RF and CNI functions. Other ancillary equipment, such as the pneumatics console, inertial navigation system (INS) inertial navigation unit (INU) holding fixture, multiple analog capability (MAC) instrumentation kit, and printer, may also be connected to the CASS HYB, as required, to provide additional test capabilities.

**Hybrid CASS**

The CASS HYB station provides the core test capability for general purpose electronics, computers, instruments, and flight controls and is comprised of five electronic enclosures (racks) which house the CASS common core test equipment. These five racks, designated racks 1 through rack 5, are bolted together in left-to-right ascending numerical order. The racks are connected electrically via cabling. The CASS HYB station can be reconfigured to any of the other CASS station configurations with minimum effort. Basically, the configuration change requires making changes to rack 3, rack 4, and rack 5 as required to meet the new configuration; and installation and connection of the rack 6 or ancillary equipment having the required unique specialty resources. The five racks that comprise the basic core test equipment are:

- Rack 1 Power Distribution Console
- Rack 2 Power Console
- Rack 3 Control Console
- Rack 4 General Purpose Interface (GPI)/Digital Test Unit (DTU) Power Console
- Rack 5 DTU Console

**Radiofrequency CASS**

The CASS RF station provides HYB station test capability plus ECM, ECCM, EW support measures, fire control, navigation, tracking, and surveillance radar, and radar altimeter support capability. The CASS RF station configuration consists of the hybrid test set common core consoles with the addition of RF console rack 6 (Figure 11-7) and additions to consoles 3 and 5. Changes to the control console (rack 3) include the addition of an asset controller and three synchro generators. Changes to the DTU console (rack 5) include an asset controller, gateway circuit card assembly (CCA), two arbitrary waveform generators (AWFGs), and a modulation control assembly.
Communications, Navigation, and Identification CASS

The CASS CNI station provides RF station capability plus communication, navigation, interrogation, and spread spectrum system support capability and consists of the CASS RF station with additions to the racks 3, 5, and 6. An additional AWFG is added to the control console. An asset controller, tactical air navigation (TACAN) assembly, correlator assembly, generic code generator, timing and control assembly, global positioning system (GPS) code generator, and modulation control assembly is added to the DTU power console, and the addition of spread spectrum modulator demodulator (SSMD).

Electro-Optical CASS

The CASS EO station (Figure 11-8) provides HYB test capability plus support capability for forward looking infrared (FLIR), lasers/designators, laser range finders, and visual systems and consists of a CASS HYB with the addition of the EO console and additions to racks 2, 3, 4, and 5. The EO console contains a collimator housing assembly (CHA), an integrated photonics asset (IPA), an integrated electronics assembly (IEA), and a double rhomboid assembly (DRA). A switcher power supply is added to the power console (rack 2), an asset controller and three synchro generators are added to the control console (rack 3), a video processor is added to the GPI/DTU console (rack 4), and two low voltage system supply assemblies are added to the DTU power console (rack 5).
High Power Device Test Set CASS

The CASS HPDTS station provides RF station capability plus the capability to test high power radar systems such as the APG-65 and APG-73. The CASS HP configuration consists of the RF station with the addition of a high power/high voltage (HP/HV) console (rack 7), a liquid cooling unit (LCU) (rack 8), a chilled water supply, and additions to racks 4, 5, and 6 (Figure 11-9). The HP/HV console accommodates operational test program set (OTPS) unique test assets through a peculiar asset area (PAA) interface and a plug in unit (PIU) interface. An auxiliary display unit (ADU) is provided to display needed information to the technician during CASS HP operation. The HP/HV console also has an alternating current (ac) power unit (APU) that provides ac power to the UUT and an ac inverter unit (ACIU) that provides 115 volts to racks 7 and 8. The LCU provides cooling for the UUT. The UUT transfers heat to a polyalphaolefin (PAO) loop, which is then cooled by chilled water in the LCU. The PAO also acts as a dielectric and must be free of air and moisture. A signal connector module, a power connector module, and an Ethernet hub are added to the GPI/DTU console (rack 4). The additions to the DTU power console (rack 5) are an asset controller (VXICON), a digital-to-analog (D/A) converter, an analog-to-digital (A/D) converter, a relay module, a multifunction input/output (I/O) module (MIM), an interface test adapter power supply (ITAPS), and a wiring integration unit (WIU). The RF console (rack 6) is contains an interface panel.

Console General Description

This section covers the consoles individually from left to right in Figure 11-10.
Power Distribution Console

The primary purpose of the power distribution console (Figure 11-11) is power conditioning, power distribution, and power control for the test set. The console supplies the ac and dc power required throughout the test set. The console consists of two slide-out drawers, 1A1 and 1A2.

A control panel is mounted on the front of drawer 1A1. The control panel provides mounting for the controls and indicators that control and monitor the ac power applied to the test set. The circuit breaker CB1 is manually operated by raising or lowering the plunger. CB1 is then tripped electronically by the circuit breaker controller CCA which applies three-phase ac power to the power conditioner. The sequential power down switch is a momentary toggle switch, which when set to the activate position, initiates an ordered, sequential power down of the test set. The facility power indicators are light emitting diodes (LEDs) that illuminate when three-phase ac power is available at the input of CB1. The station power indicators are LEDs that illuminate when CB1 is turned on. The drawer power indicator is an LED that illuminates when 270 volts direct current (Vdc) is provided from the power conditioner to the power distribution console.

The fault indicator has two hexadecimal displays that indicate error/status code as monitored by power controllers A and B. The number 20 displayed on the fault indicator display indicates that the power controller and associated circuits are operational. An indication of 20 is not indicative of overall station operation. The 270 Vdc indicators illuminate to confirm the presence of 270 Vdc at the input to power controller A and B. The power supply indicators illuminate to confirm the presence of the low voltages developed by the power controllers.

The battery compartment (Figure 11-12) consists of 18 battery pack assemblies, three battery fuse tray assemblies, a battery temperature sensor assembly, and a battery charger assembly mounted behind the battery compartment. The 18 battery packs are arranged in three strings of six assemblies (Figure 11-13). Each battery pack is a removable assembly that contains 24 battery cells. The battery packs provide a nominal output of 288 Vdc that is used as backup power for the test set during power interruptions. Each battery string is protected by a fuse tray assembly (Figure 11-14).

The battery charger assembly charges the battery packs, routes power from the battery packs, and provides constant monitoring of the battery packs. The battery packs provide the test set with a constant status of the voltage level. When the status is low, the charger routes a charging voltage to the affected battery pack.
Power Console

The power console (Figure 11-15) generates the ac and dc voltages required by the UUT and controls and monitors the 400 hertz (Hz) power feed through to the UUT. The console contains the following circuitry: 400 Hz ac power feed through, ac and dc power monitoring and control, and UUT ac and dc power supplies. A control panel is mounted on the front of drawer 2A1. The control panel provides mounting for the controls and indicators that control and monitor the ac power applied to the UUT. The circuit breaker applies 400 Hz power to contactors that are under software control. The circuit breaker CB1 is manually controlled by the plunger on the front panel. The circuit breaker controller CCA mounted behind the panel electronically trips the circuit breaker when directed by the test set. The drawer power on indicator is an LED that illuminates when 270 Vdc is applied to the power console. The 400 Hz UUT power phase indicator contains two groups of three indicators, facility phase, and station phase. The facility phase LEDs illuminate when 400 Hz three-phase power is available at the input of CB1. The station phase LEDs illuminate when CB1 is set to the ON position. The ac power connectors provide front panel ac power interface connections between the power console and the UUT connector J2 provides 1 - 135 volts alternating current (Vac) single phase output. Connector J3 provides 400 Hz, 115/200 Vac three-phase output. The UUT power on indicator is an LED that illuminates when power is output from either of the two ac power output connectors.
Control Console

The primary function of the control console (Figure 11-16) is control of the test station. The console houses the computer, fixed disk drive, optical disk drive, operator control panel, mounting for the main display unit, and the operator interface connections for the keyboard and trackball. The optical disk drive functions as a random access rotating memory device that stores data. The optical disk contains TPSs and automated technical information (ATI). The optical disk is mounted and removed by the operator. The operator interface provides connections for the keyboard and trackball. The operator control panel provides the mechanical interface for the test set computer halt and reset switches, LEDs that indicate computer power status, and small computer system interface (SCSI) connector receptacles. A SCSI terminator is installed when no external SCSI components are connected to the test set.

The display unit presents graphics and text from the test set computer. An audio alert speaker, mounted on the display unit, notifies the operator of test set status and activity. Two emergency shut off pushbuttons are also mounted on the display: one for the test set (EMER OFF STA) and one for the UUT (EMER OFF UUT).

The keyboard provides interface for power, return, and transmitted and received signals. The keyboard allows the operator to issue commands directly to the computer by keying text, moving the cursor to select icons, or by use of special function keys.

The trackball also provides interface for power, return, and transmitted and received signals. The trackball allows the operator to interface with the test station computer and display by rotating the ball to position the cursor and then keying one of the three action keys.

Figure 11-15 — Power console.

Figure 11-16 — Control console.
General Purpose Interface/Digital Test Unit Power Console

The primary purpose of the GPI/DTU console (Figure 11-17) is to provide an interface for the UUT. The console houses the DTU, the pulse generator (PG), the frequency time interval counter (FTIC), a digital multimeter (DMM), and an interface device (ID) receiver. The console also has probe connections for the DTU and DMM. The DTU has two power supplies mounted in the rear that supply all the power required by the DTU. The GPI receiver provides mounting for power, coaxial, and low frequency feedthrough modules, switching connector assemblies, and DTU interface connector modules. An ancillary ID is inserted and locked into the receiver assembly to adapt UUT power and signal connections to appropriate test set circuits.

The GPI receiver (Figure 11-18) provides connections for UUT power, waveform digitizer, timing circuits, and other analog and digital input/output signals. It also contains switching assemblies and relays controlled by the asset controller in the backplane to and from the UUT to instruments within the test set. The DTU coaxial assembly is designed with connectors reserved for future expansion or configuration changes.

The DTU probe connector (Figure 11-17) connects directly to the probe controller. Calibration (CAL) of the probe is accomplished by inserting the probe into the CAL connector. The CAL indicator will light when calibration is complete. The DMM probe connection (Figure 11-17) is connected to the internal DMM, has an attenuation factor of 1,000, and can measure up to 1,000 Vdc or 700 volts root mean square (Vrms).
Digital Test Unit Power Console

The primary purpose of the DTU power console (Figure 11-19) is to house the DTU power supplies, SRAs associated with the communications bus interfaces, the system timing assembly (STA), a waveform digitizing oscilloscope (WFRD), SRAs associated with spread spectrum testing, and SRAs associated with the EO system.

The communications bus interface panel has a military, a commercial, three advanced communications bus interface (ACBI) ancillaries, and (if equipped with MAC instrumentation) a bus test instrument (BTI) bus interface. The bus interfaces allow data transfer between the test set and the UUT or calibration equipment.

The high power test configuration provides an interface for the RF radiation hazard monitor (RF RHM). The RF RHM is a programmable asset that can be invoked by the UUT TPS to provide continuous background monitoring. The RF RHM uses a movable isotropic probe attached to a 4 foot extension cable.

Connectors on the digitizer probe panel allow inputs to channels C and D of the waveform digitizer. Two other connectors on the panel are provided for dc voltage calibration and a probe compensation ac calibration output.

Radiofrequency Console

The primary purpose of the RF console (Figure 11-20) is to provide RF stimulus and measurement capabilities. Interface between the test set and the UUT is accomplished with the RF test adapter. Components in the console include RF synthesizers, a spectrum analyzer (SA), a microwave transition analyzer (MTA), and RF power meters.
The RF test adapter (Figure 11-21) uses test connectors on the front to provide switched input/output and direct, non-switched RF input/output to interfaces between the RF functions of the test set and the UUT.

The test port section of the RF test adapter is used for testing the channel 1 and 2 inputs to the MTA from synthesizer number 2. Test jacks A, B, and C are program selectable through the RF interface module.

Synthesizer No. 1 provides a single output over a range of 10 megahertz (MHz) to 18.4 gigahertz (GHz) at a level of +10 to -110 decibels (dBm) or frequency modulated (FM) that can be modulated internally or externally. The output is routed through the RF interface module to connectors A, B, or C in the Synth No. 1 section as specified by the test program.

Synthesizer No. 2 provides a single output over a range of 10 MHz to 40 GHz with a maximum output level of 0 to +10 dBm, depending on the frequency selected. The output is routed through the RF interface module to connectors A, B, or C in the Synth No. 2 section as specified by the test program.

Synthesizer No. 3 provides a single output over a range of 3 MHz to 20 GHz with a maximum output level of +15 to +18 dBm, depending on the frequency selected. The output is routed directly to the connector in the Synth No. 3 section on the RF test adapter.

The SA has a single RF input with a frequency range of 100 Hz to 22 GHz and a resolution bandwidth of 10Hz to 3 MHz. Inputs A and B from the RF test adapter are program selectable through the RF interface module. The SA also outputs a noise source drive signal directly to the RF test adapter. The SA also has an IF input for signals between 10 Hz and 3 MHz, a local oscillator (LO) output that produces an 800 MHz phase locking signal, a bias input to the external mixer interface for use with the local oscillator to analyze signals above 22 GHz, and an RF noise preamplifier to analyze very low level signals.

The MTA is a two channel, sampler based instrument used for measurements from dc to 26.5 GHz. The MTA can be used to measure phase setting, rise and fall times, on/off ratios, time delay, switching time, peak and average power, and group delay. Input is by test jacks on the RF test adapter.

Two programmable power meters measure power in dBm, dB relative, watts, and percent relative modes. The frequency range is 100 kHz to 50 GHz and the power range is -70 to +44 dBm. The power meter generates a power reference signal that is routed through the RF interface module, the power heads, and back for self-test.

Inputs to the power meters from external sources are made by two connectors on the RF test adapter through the RF interface board or the power heads may be removed to make remote measurements.

Large signals input to the SA can be routed through an attenuator prior to application to the SA. These signals can also be switched by the RF interface module to an output connector on the RF test adapter.

In a CNI configuration, the SSMD provides spread spectrum modulation capability to the test set through three test jacks (MOD) on the RF test adapter.
High Power/High Voltage Console

The HPDTS automatically tests high power RF, high voltage dc, and high current ac and dc avionics units. The HPDTS is comprised of two consoles: the HP/HV console and the LCU added to a CASS RF test station.

The UUT power circuit breaker CB1 applies 115 Vac, three-phase, 400 Hz power to the APU and the PAA. The phase AC power indicators illuminate when power is available from CB1 to the APU and PAA. The HPDTS drawer power indicator illuminates when 270 Vdc is applied from CASS.

The HP/HV console (Figure 11-22) accommodates OTPS unique test assets through two PAA interfaces (upper and lower). The areas are designed to allow OTPS peculiar assets to be added and removed as necessary.

The PIU allows the OTPS to tailor the HP/HV console for specific weapons systems testing applications. The PIU hosts OTPS unique components that are not included as part of CASS. The PIU interface provides electrical and mechanical interface between the HP/HV console and OTPS.

The UUT power connector provides programmable voltage, three-phase, 400 Hz isolated power to UUTs that require a variable voltage or isolation from the facility. The UUT power on indicator illuminates when power is applied to the UUT from the APU.

Liquid Cooling Unit Console

The majority of the HPDTS UUTs tested require PAO for cooling. Heat generated by the UUT is carried through a PAO circuit loop to the LCU (Figure 11-23). The LCU transfers the heat to a water circuit loop using a heat exchanger. The water circuit loop is then cooled by a water chilling system.

The LCU is designed to provide monitored and metered PAO through two test ports connected to the UUT and test packages. Each test port’s flow rate, temperature, and pressure are monitored by electronic sensors and controlled by electronically actuated regulating control valves. In addition to absorbing heat from the UUT, the PAO also acts as a dielectric and therefore must have any air or moisture periodically removed from it. The LCU incorporates a vacuum pump capable of providing a vacuum of 26 inches of mercury vacuum (inHg) in the PAO storage tank to remove air and moisture. The drawer lamp is illuminated when power is available from the HPDTS. The power switches apply power to the internal components of the illuminating the ac and dc power lamps when power is applied through the power switches. The pump lamp illuminates when oil pump is on. The oil no. 1 sample and oil no. 2 sample hand valves allow oil to flow through the sample tubes. The vacuum hand valve vents the internal vacuum subsystem to the front panel and provides a continuous vacuum source. The oil level raise and lower hand valves allow oil to be returned to or drawn from the reservoir. PAO enters the UUT through one of two identical systems. The LCU has four quick
disconnect (QD) fittings on the front panel. QD1 and QD3 are the supply and return for system 1 and QD2 and QD4 are the supply and return for system 2.

**Auxiliary Display Unit**

The ADU (*Figure 11-24*) is a flat panel display with a touch panel interface, which is controlled by a single board computer located inside the ADU. The ADU provides remote access to OTPS test execution control and an HPDTS specific control interface. The touch panel is a clear glass overlay on top of the liquid crystal display (LCD). The ADU software implements a moveable cursor which responds to the touch of a finger. The cursor is controlled by moving a finger around and left mouse clicks are accomplished by touching the glass surface. The emergency UUT and STA buttons work identically to the buttons on the display of the control console. The audible alarm provides a warning in case of potentially hazardous RF fields as detected by the radiation hazard monitor.

**Electro-Optical Console**

The EO console (*Figure 11-25*) is a highly accurate and integrated photonics module. The console contains radiant sources and radiation sensitive detectors. The console design provides structural rigidity to maintain optical alignment between the collimator assembly and integrated photonics assets.

![Figure 11-23 — LCU console.](image)

![Figure 11-24 — ADU.](image)

![Figure 11-25 — Electro-optical console.](image)
The automated gyro/gimbal control system (AGCS) (Figure 11-26) mounts under the work station of the DTU power console. The AGCS provides a stable platform instrument that allows closed loop testing and measurement by transmitting and measuring synchro and analog signals to and from the gimbal system.

SAFETY

It is often said that the Navy values people as its greatest asset. The equipment that the Navy operates with is inherently dangerous. Power requirements, hazardous chemicals, and the sheer size and weight of some of the modules and equipment make on-the-job safety paramount. Additionally, when underway, the hazards are amplified by an unsteady platform rocked by the power of the sea. Heavy loads shift and particular care must be taken to remain clear of energized equipment. The Japanese have a saying known well by Sailors in the 7th Fleet, “Anzen daiichi,” which translated means “Safety first.”

This section will cover general safety rules and warnings. It is not all-inclusive as every situation is different.

It is extremely important to comply with safety rules when working on electrical devices. Basic electrical safety rules include:

- Never work alone. When working on energized circuits, someone qualified in first aid for electrical shock is required to be standing by during the entire operation. Another person may save your life if you receive an electric shock.
- Know the location of main power switches or circuit breakers that supply the power to the bench and test equipment.
- Remove all rings, wristwatches, bracelets, and jewelry before working on the equipment to reduce the chance of electric shock.
- Ensure all personal protective equipment is properly used as required by the maintenance instruction manuals or other guidance.
- When working on electrical circuits, power must be secured and tagged out at the source, using approved tag out procedures.
- Never bypass an interlock unless you are authorized to do so by the commanding officer. Upon authorization, properly tag the bypass.
When making alignments or taking measurements on energized circuits, where practical, use only one hand. Keep the other hand behind you to prevent an entry and exit path for current through your body.

When making alignments or taking measurements on energized circuits, stand on an approved insulating material, such as a rubber mat.

Using a shorting probe, discharge to ground those components capable of retaining an electric charge before working on de-energized equipment.

For any safety issues not covered, personnel must assess risks using the five steps of Operational Risk Management (ORM):

1. Identify hazards
2. Assess hazards
3. Make risk decisions
4. Implement controls
5. Supervise

Warnings, cautions, or notes shall highlight procedures or practices that, if not correctly followed, could result in injury to personnel or damage or destruction to equipment.

**WARNING**
An operating procedure, practice, or condition, etc., that may result in injury or death if not carefully observed or followed.

**CAUTION**
An operating procedure, practice, or condition, etc., that may result in damage or destruction to equipment if not carefully observed or followed.

**NOTE**
An operating procedure, practice, or condition, etc., that is essential to emphasize.

**PREVENTATIVE MAINTENANCE**

Preventive maintenance can be defined as follows: Actions performed on a time- or machine-run-based schedule that detect, preclude, or mitigate degradation of a component or system with the aim of sustaining or extending its useful life through controlling degradation to an acceptable level.

The scheduled maintenance tasks discussed in this section (Table 11-1) are for the high power device test set and are for training purposes only. For guidance on specific maintenance tasks, refer to the appropriate maintenance instruction manuals.
Table 11-1 — Periodic Maintenance

<table>
<thead>
<tr>
<th>Item</th>
<th>Interval</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>PAO</td>
<td>30 Day</td>
<td>Take sample of PAO at front panel hand valve port with LCU operating. Use caution as oil may be hot. Process PAO per Naval Oil Analysis Program (NOAP) requirements.</td>
</tr>
<tr>
<td>Breather B1</td>
<td>30 Day</td>
<td>Visually inspect breather B1 desiccant color. Desiccant should be blue. If desiccant is pink, replace B1.</td>
</tr>
<tr>
<td>Air Filters</td>
<td>90 Day</td>
<td>Remove and replace filters.</td>
</tr>
<tr>
<td>Mesh Strainer MS1</td>
<td>180 Day</td>
<td>Visually inspect mesh strainer MS1 for debris. Remove all debris and clean filter. If LCU begins failing after passing PAO between WRA and LCU, check mesh strainer for debris.</td>
</tr>
</tbody>
</table>

As part of the preventive maintenance system discussed above, the air filters for each console must be changed once each quarter. The procedures for removing and replacing the air filters are the same for each console. The air filter is accessible by opening the access door at the base of each rack. The procedures for removing and replacing the air filters are the same for all consoles but the filters are not all the same size. Ensure the right filter is installed in each console.

SECURITY PROCEDURES

When classified test program instructions (TPIs) are run on HPDTS, the VXI Slot 0 asset controller and auxiliary display unit become classified assets. Classified assets shall be controlled and stored per applicable security specifications for their classification level.

Existing CASS downgrade procedures involve powering down the station in order to erase volatile memory. The HPDTS VXI digital/analog (D/A) module contains non-volatile memory that is used exclusively for the storage of D/A offset and gain calibration factors, which are created only by the High Power Device Digital Analog Calibration (HPDDACAL) program, and are not themselves classified. Replace classified asset controller and ADU per the maintenance instruction manual.

The VXI Slot 0 asset controller cannot be declassified at the intermediate maintenance level and should be controlled, stored, and transported as a classified asset at all times. The HPDTS auxiliary display unit is declassified by removing the flash memory card. The flash memory card is located behind the access panel on the right side of the ADU.
End of Chapter 11

Automatic Test Equipment

Review Questions

11-1. What configuration provides the core test capability for the Consolidated Automated Support Systems (CASS) family?

A. Reconfigurable-Transportable
B. Electro-Optical
C. Hybrid
D. Communication, Navigation, and Identification

11-2. Which of the following organizations use Reconfigurable-Transportable Consolidated Automated Support System (RTCASS)?

A. Shipboard aircraft intermediate maintenance departments (AIMD)
B. U. S. Marine Corps support sites
C. Fighter/Attack squadrons
D. Patrol squadrons

11-3. Which of the following Consolidated Automated Support Systems (CASS) configurations is used to test forward looking infrared (FLIR)?

A. Hybrid
B. Radiofrequency
C. Electro-Optical
D. High Power

11-4. What configuration of the Consolidated Automated Support Systems (CASS) family tests global positioning equipment?

A. Reconfigurable-Transportable
B. Electro-Optical
C. High Power
D. Communication, Navigation, and Identification

11-5. What is the purpose of the Consolidated Automated Support Systems (CASS) auxiliary display unit?

A. Display needed information during CASS High Power operation
B. Allow two technicians to troubleshoot simultaneously
C. Compare two radiofrequency waveforms
D. Display tutorial video during training evolutions
11-6. What capability is added to a Consolidated Automated Support System (CASS) by the addition of a liquid cooling unit (LCU)?

A. Test high power devices  
B. Operate in high temperature environments  
C. Operate without chill-water cooling  
D. Test aerodynamic thermometers

11-7. What does an indication of “20” on the Consolidated Automated Support System (CASS) power distribution console’s fault indicator signify?

A. Loss of facility power  
B. Loss of chill-water  
C. The power controllers are operational  
D. The overall station is operational

11-8. What console provides mounting for power, coaxial, and low frequency feedthrough modules in a Consolidated Automated Support System (CASS) station?

A. Radiofrequency  
B. Control  
C. General Purpose Interface/Digital Test Unit Power  
D. Electro-Optical

11-9. Why should rings, wristwatches, and jewelry be removed before working on electrical equipment?

A. Reduce the chance of electrical shock  
B. Reduce the chance of theft  
C. Prevent voiding the system’s calibration  
D. Prevent them from being damaged

11-10. When are you allowed to work on electrical equipment alone?

A. When you’re on duty  
B. When directed to by the maintenance instruction manual  
C. When it is too dangerous for two technicians  
D. Never

11-11. Which button do you press to remove bench power from a Consolidated Automated Support System (CASS) in an emergency?

A. EMER OFF UUT  
B. EMER OFF STA  
C. Sequential PWR Down  
D. Power Down icon
11-12. What is the first step in Operational Risk Management (ORM)?

A. Implement controls
B. Supervise
C. Make risk decisions
D. Identify hazards
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CHAPTER 12

ELECTROSTATIC DISCHARGE

A necessary part of avionic maintenance is the knowledge of electrostatic discharge (ESD) and its effect on solid state electronic components and equipment. Electrostatic Discharge Sensitive (ESDS) components are damaged as a result of improper inspection, handling, packaging, shipping, storage, testing, installation, and maintenance techniques throughout the equipment life cycle. This damage can be catastrophic, causing the equipment not to operate, or subtle, leading to a degradation of performance. Since this damage may not be recognizable until after the maintenance/supply cycle, ESD damage prevention and protection measures must be an integral part of maintenance and supply routine.

Organizational and intermediate maintenance and the supply chain are responsible for the proper handling, packaging, and storage of ESDS items. All solid state electronic components and subassemblies containing such components (e.g., printed circuit board assemblies, modules, and shop replaceable assemblies) are considered to be ESDS assemblies.

LEARNING OBJECTIVES

When you have completed this chapter, you will be able to do the following:

1. Identify the hazards to electrostatic discharge sensitive devices.
2. Identify materials used to package and protect electrostatic discharge sensitive devices.
3. Explain the proper handling techniques when packaging electrostatic discharge sensitive devices.

ELECTROSTATIC DISCHARGE

Electrostatic discharge is the transfer of charge between bodies at different electrical potentials. All static electricity hazards and damage are initiated by the sudden energy release, known as an ESD event. An ESD event can damage electronics and be a safety hazard to personnel and fuel. The level of charge is affected by material type, speed of contact and separation, humidity, and several other factors.

Construction and design features of current microtechnology have resulted in devices being destroyed or damaged by ESD voltages as low as 20 volts. An example of the type of damage caused by ESD is shown in Figure 12-1. Advances in technology are increasing complexity, packaging density, and thinner dielectrics between active elements resulting in devices becoming more sensitive to ESD. It is extremely important to learn the effects of ESD to limit its negative impact on naval aviation.

Various devices and components are susceptible to damage by electrostatic voltage levels commonly generated during production, testing, and operations by maintenance personnel. Sensitive devices and components include the following:

- All microelectronic and most semiconductor devices, except various power diodes and transistors
- Thick and thin film resistors, chips and hybrid devices, and crystals

All subassemblies, assemblies, and equipment containing these components and devices without adequate protective circuitry are ESDS. ESDS items can be protected by implementing simple, low-
cost ESD controls. Lack of implementation has resulted in high repair costs, excessive equipment downtime, and reduced equipment effectiveness. Normal operational characteristics of a system may not show these failures. However, under internal built-in test monitoring in a digital application, they become pronounced. For example, a system may function normally on the ground, but when placed in an operational environment, a damaged component might further degrade causing its failure. Normal examination of these components will not detect the damage unless a curve tracer is used to measure or map a component’s signal rise and fall times, or the component’s reverse leakage current is checked.

**Static Electricity**

Static electricity is electrical energy at rest. Some substances readily give up electrons while others accumulate excessive electrons. When two substances are rubbed together, are quickly separated, or flow relative to one another (such as gas or liquid over a solid), one substance becomes negatively charged while the other becomes positively charged. An electrostatic field or lines of force emanate between the charged object and the object at a different electrostatic potential or ground. Objects entering this field will receive a charge by induction.

The capacitance of the charged object relative to another object or ground also has an effect on the field. If the capacitance is reduced, there is an inverse linear increase in voltage since the charge must be conserved. As the capacitance decreases, the voltage increases until a discharge occurs via an arc.

**Causes of Static Electricity**

The buildup of a static charge when contact (rubbing) or separation of two materials occurs is known as the triboelectric effect. A list of substances in the triboelectric series is shown in Table 12-1. The list is arranged in such an order that when any two substances in the list contact one another and then separate, the substance higher on the list assumes a positive charge.

The size of an electrostatic charge on two different materials is proportional to the distance of separation between the two materials. Electrostatic voltage levels generated by nonconductors can be extremely high. However, air will slowly dissipate the charge to a nearby conductor or ground.

The more moisture in the air, the faster a charge will dissipate. The typical measured charges generated by personnel in a manufacturing facility are shown in Table 12-2. This table shows the decrease in generated voltage with the increase in humidity levels of the surrounding air.
Table 12-2 — Typical Measured Electrostatic Voltages

<table>
<thead>
<tr>
<th>Means of static generation</th>
<th>Voltage level at relative humidity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low 10-20%</td>
</tr>
<tr>
<td>Walking across carpet</td>
<td>35,000</td>
</tr>
<tr>
<td>Walking over vinyl floor</td>
<td>12,000</td>
</tr>
<tr>
<td>Worker at bench</td>
<td>6,000</td>
</tr>
<tr>
<td>Vinyl envelopes for work instructions</td>
<td>7,000</td>
</tr>
<tr>
<td>Common poly bag picked up from bench</td>
<td>20,000</td>
</tr>
<tr>
<td>Work chair padded with urethane foam</td>
<td>18,000</td>
</tr>
</tbody>
</table>

**Effects of Static Electricity**

The effects of ESD are not easily recognized. Failures due to ESD are often analyzed as being caused by electrical overstress due to transients other than static. Many failures, often classified as other, random, or unknown, are actually caused by ESD. Misclassification of the defect is often caused by maintenance personnel not being able to perform failure analysis to the required depth.

**Component Susceptibility**

Most solid state devices, with the exception of various power transistors and diodes, are susceptible to damage by discharging electrostatic voltages. The discharge may occur across their terminals or through subjection of these devices to electrostatic fields. It is impossible to determine the sensitivity of all electronic equipment; therefore, it is best to handle all avionic equipment as ESDS.

**Latent Failure Mechanisms**

ESD overstress can produce a dielectric breakdown of a self-healing nature when the current is unlimited. When this condition occurs, the device may retest good, but contain a hole in the gate oxide. With use, metal will eventually migrate through the puncture, resulting in a shorting of this oxide layer.

Another structure mechanism involves highly limited current dielectric breakdown from which no apparent damage is done. However, this situation reduces the voltage at which subsequent breakdown occurs to as low as one-third of the original breakdown value. ESD damage can result in a lowered damage threshold at which a subsequent lower voltage ESD will cause further degradation or a functional failure.

**Electrostatic Discharge Damage Elimination**

The heart of the ESD control program is the ESD protected work area and ESD grounded work station (*Figure 12-2*), especially when handling an ESDS device outside its ESD protective packaging. All efforts to reduce or eliminate generated electrostatic voltage must be attempted. The greater the margin between the levels at which the generated voltages are limited and the ESDS item sensitivity level, the greater the probability of protecting that item.
Prime Generators

Under no circumstances shall prime static generators (polyethylene, vinyl, polystyrene foam, etc.) be brought in ESD-protected areas or used to package ESD items. This rule especially applies to bulk polystyrene foam packaging, polystyrene foam "peanuts," white polystyrene foam (or other plastic) coffee cups, and plain plastic bubble wrap.

PERSONAL APPAREL AND GROUNDING

An essential part of the ESD program is grounding personnel and their apparel when handling ESDS material as described in this section.

Smocks

When necessary, personnel handling ESDS-deemed items should wear long sleeve, ESD protective smocks (*Figure 12-3*). If these items are not available, other antistatic material should be used (such as cotton) that will cover sections of the body that could contact an ESDS item during handling. Generally, Navy uniforms are manufactured with ESD acceptable materials.

Personnel Ground Straps

Personnel ground straps should have a minimum resistance of 250,000 ohms. Based upon limiting leakage currents to personnel to 5 milliamperes, this resistance will protect personnel from shock from voltages up to 125 volts root mean square. The wrist bracelet end of the ground strap should have some metal contact with the skin as illustrated in *Figure 12-4*. Bracelets made completely of carbon-impregnated plastic may burnish around the area in contact with the skin, resulting in the impedance to ground being too high.

ESD PROTECTIVE MATERIALS

There are two basic types of ESD protective material, conductive and antistatic. Conductive materials protect ESD devices from static discharges and electromagnetic fields. Antistatic materials are nothing more than a non-static-generating material. Therefore, antistatic materials do not offer any other protection to ESD devices other than not generating static.
Conductive ESD Protective Materials

Conductive ESD protective materials consist of metal, metal-coated, and metal-impregnated materials. The most common conductive materials used for ESD protection are steel, aluminum, and carbon-impregnated polyethylene and nylon. The latter two are opaque, black, flexible, heat sealable, electrically conductive plastics. These plastics are composed of carbon particles, impregnated in the plastic, that provide volume conductivity throughout the material.

Antistatic ESD Protective Materials

Antistatic materials are normally plastic-type materials (such as polyethylene, polyolefin, polyurethane, and nylon) that are impregnated with an antistatic substance. The antistatic substance migrates to the surface and combines with the humidity in the air to form a conductive sweat layer on the surface. This layer is invisible, and although highly resistive, it is amply conductive to prevent the buildup of electrostatic charges by triboelectric methods in normal handling. Simply stated, the primary asset of an antistatic material is that it will not generate a charge on its surface. However, this material will not protect an enclosed ESD device if it comes into contact with a charged surface. This material is tinted pink, which is a symbol of it being antistatic. Antistatic materials are designed to be used as the inner wrapping packaging. However, antistatic materials are not used unless components and/or assemblies are contained in conductive packaging.

Hybrid ESD Protective Bags

Lamination of different ESD protective material is available. This combination of conductive and antistatic materials provides the advantages of both types in a single bag shown in Figure 12-5.

ESDS DEVICE HANDLING

The following are general guidelines applicable to the handling of ESDS devices:

- Ensure all containers, tools, test equipment, and fixtures used in ESD protected areas are grounded before and during use.
- Personnel handling ESDS items must avoid physical activities that are friction-produing in the vicinity of ESDS items. Some examples are putting on or removing smocks, wiping feet, and sliding objects over surfaces.
- Personnel handling ESDS items must wear cotton smocks and/or other antistatically treated clothing.
- Eliminate the use or presence of prime generators where ESDS items are handled, especially where they are out of their ESD protective packaging.
• Place the ESD protective material containing the ESDS item on a grounded work bench surface to remove any charge before opening the packaging material.

• Personnel must ground themselves before removing ESDS items from their protective packing by attaching their personnel ground straps to an approved grounding location.

• Remove ESDS items from ESD protective packaging with fingers or metal grasping tools only after grounding, and place on the ESD grounded work bench surface.

• Make periodic electrostatic measurements in accordance with local procedures or applicable maintenance instructions at all ESD protected areas. This practice assures the ESD protective properties of the work area and all equipment contained within have not degraded.

• Perform periodic continuity checks of personnel ground straps, ESD grounded work station surfaces, conductive floor mats, and other connections to ground in accordance with local procedures or applicable maintenance instructions.

ESDS DEVICE PACKAGING

Before an ESDS item leaves an ESD protected area, the following steps must be taken:

• Ensure shorting bars, clips, or non-corrective conductive materials are correctly inserted in or on all terminals or connectors.

• Package ESDS items using only approved packaging materials and prepare the items for shipment as per MIL-HDBK-773.

• Mark the packaged unit with the ESD symbol and caution as shown in Figure 12-6 as required.

![Figure 12-6 — ESDS symbols.](image)
End of Chapter 12
Electrostatic Discharge

Review Questions
12-1. Sensitive electronic devices are susceptible to what type of hazard?
   A. Electrostatic absorption
   B. Electrostatic discharge
   C. Electrostatic induction
   D. Electrostatic repulsion

12-2. What type of field emanates from two charged objects that are rubbed together?
   A. Reactive
   B. Electrostatic
   C. Inductive
   D. Magnetic

12-3. Why is electrostatic discharge damage often misclassified as voltage overstress?
   A. Equipment design doesn’t allow diagnostics
   B. Catastrophic damage prevents analysis
   C. Improper depth of failure analysis
   D. Improper reporting procedures

12-4. Which common type of material is considered a prime generator of static electricity?
   A. Wood
   B. Glass
   C. Metal
   D. Plastic

12-5. Personnel grounding straps are designed to protect workers from exposure to what maximum voltage level?
   A. 25 volts root mean square
   B. 50 volts root mean square
   C. 75 volts root mean square
   D. 125 volts root mean square

12-6. What must occur for an electrostatic discharge grounding strap to be effective?
   A. Must have metal to skin contact
   B. Must be insulated from skin
   C. Must be insulated from electrostatic discharge safe mat
   D. Must be insulated from electrostatic discharge safe work area
12-7. The most common conductive materials are steel, aluminum, carbon-impregnated polyethylenes, and what other material?

A. Cotton  
B. Nylon  
C. Rayon  
D. Teflon®

12-8. What color material is identified as being antistatic?

A. Yellow  
B. Red  
C. Pink  
D. Orange

12-9. What type of electrostatic discharge protective material has both conductive and antistatic properties?

A. Hybrid protective bags  
B. Bubble wrap  
C. Plastic wrap  
D. Polystyrene foam peanuts

12-10. In regard to electrostatic discharge (ESD), what must be done to all tools and equipment before using them in an ESD protected area?

A. Inventory  
B. Inspection  
C. Grounding  
D. Replacement

12-11. What procedure must regularly be accomplished to electrostatic discharge safe work stations?

A. Replacement monthly  
B. Upgrade when new equipment is available  
C. Perform periodic continuity checks  
D. Protect station with plastic wrap

12-12. What must be done to the package before an electrostatic discharge sensitive (ESDS) device leaves an electrostatic discharge protected area?

A. Have supply personnel take custody  
B. Properly mark as ESDS  
C. Take a photo to prove condition  
D. Properly attach grounding strap
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<thead>
<tr>
<th>Rate____</th>
<th>Course Name_____________________________________________</th>
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<tr>
<td>Revision Date__________</td>
<td>Chapter Number____</td>
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APPENDIX I

GLOSSARY

A/A—Air-to-Air—Engagement between opposing aircraft or airborne weapons platforms.

ABSORPTION—Dissipation of radio or sound waves as they interact with matter. The absorbing of light waves without reflection or refraction.

AC—Alternating current—An electrical current that encompasses the constant change in amplitude and regular intervals of change in polarity.

ACCELERATION—The increase in the rate or speed of an object.

ACCELEROMETER—A device that is used to produce a voltage proportional to the aircraft acceleration input. Accelerometers provide output signals proportional to the total accelerations experienced along the three axes of the stable element.

ACCUMULATOR—A computer unit wherein numbers are accumulated, usually holding one number in storage; when a second number is entered, the accumulator adds the two numbers and retains the sum in storage.

ACLS—Automatic carrier landing system—A precision approach landing system that provides electronic guidance to carrier-based aircraft and allows them to land in all-weather conditions with no limitations due to low ceiling or restricted visibility.

ACOUSTICS—The science of sound.

ACTIVE SONAR—Equipment that depends on a transmitted sound wave and the return of an echo.

ADDER—An electronic circuit capable of providing the sum of numbers entered therein.

ADDRESS—An identifying number or numbers that identifies a unique storage location of a record or data.

ADF—Automatic direction finder—An automatic radio compass that automatically aims a directional antenna to show the direction of the location of a transmitter.

ADP—Acoustic data processor.

ALFS—Airborne low frequency sonar—A sonar dipping set that is installed in the MH-60R Seahawk helicopter.

ALPHA—α—The emitter-to-collector current gain in a common-base circuit.

ALTIMETER, BAROMETRIC—An aneroid barometer calibrated to indicate feet of altitude above mean sea level based on the measurement of atmospheric pressure.

ALTITUDE—The vertical distance of a level, a point, or an object measured from a given surface.

ALTITUDE, ABSOLUTE—The height above terrain that is computed by subtracting terrain elevation from true altitude.

AM—Amplitude modulation—A method of transmitting intelligence (modulating signal) by varying the amplitude of a radiofrequency signal from a fixed reference amplitude according to the modulating signal.

AMBIENT CONDITIONS—Physical conditions of the immediate environment; may pertain to temperature, humidity, pressure, etc.
**AMBIENT NOISE**—The naturally occurring noise in the sea and the noise resulting from man’s activity, but excluding self-noise and reverberation.

**AMPLIFICATION**—The process of enlarging a signal, such as voltage or current. Also, the ratio of output magnitude to input magnitude in a device that is intended to produce an output that is an enlarged reproduction to its input.

**AMPLITUDE**—The size of a signal as measured from a reference line to a maximum value above or below the line. Generally used to describe voltage, current, or power.

**ANALOG COMPUTER**—A type of computer that provides a continuous solution of a mathematical problem with continuously changing inputs.

**AND GATE**—A logic circuit in which all inputs must be HIGH to produce a HIGH output.

**ANODE**—A positive electrode of an electrochemical device (such as a primary or secondary electric cell) toward which the negative ions are drawn.

**ANOMALY**—In magnetic detection systems, a disturbance in the Earth’s natural magnetic field.

**ANTENNA**—A conductor or system of conductors that radiates or intercepts energy in the form of electromagnetic waves.

**ANTIJAMMING**—A function of a radar set to reduce or eliminate enemy jamming of electromagnetic waves, which hinders the usefulness of specific segments of the radio spectrum.

**APPARENT PRECESSION**—The effect of the Earth’s rotation on a gyro, which causes the spinning axis to appear to make one complete rotation in one day.

**ARITHMETIC LOGIC UNIT**—The section of a computer’s central processing unit that performs all arithmetic operations (addition, subtraction, multiplication, and division) and logic operations.

**A-SCAN (A-DISPLAY)**—In radar, a display in which targets appear as vertical displacements from a line representing the time base. Target distance is represented by the horizontal distance from one end of the time base. Amplitude of the vertical deflection is a function of the signal intensity.

**ASSEMBLER**—A computer program used to access, manage, and alter computer hardware architecture.

**ASUW**—Anti-surface warfare. Operations conducted against surface combatants, their supporting forces, and bases.

**ASW**—Antisubmarine warfare—Operations conducted against submarines, their supporting forces, and bases.

**ATFLIR**—Advanced targeting forward looking infrared—A weapons system designed to enable the accurate delivery of precision guided ordnance at a standoff distance outside of infrared surface-to-air missile, anti-aircraft armament, and point defense missile system ranges.

**ATTENUATION**—A general term used to describe the reduction in the strength of a signal. For example, used to describe the reduction of signal strength in a coax cable or the reduction of radio signal strength due to atmospheric or system loss conditions.

**AXIS**—A straight line, either real or imaginary, passing through a body around which the body revolves.

**AZIMUTH**—Angular position or bearing in a horizontal plane, usually measured clockwise from true north. Azimuth and bearing are often used synonymously.

**AZIMUTH-RANGE INDICATOR**—In airborne sonar systems, a display that provides a visual representation of target range and bearing information. In addition, azimuth-range indicators contain
controls that are used to adjust display settings, audio settings, and target range thresholds and to initiate operational tests.

**BALLISTICS**—The science of the motion of projectiles or bombs.

**BANDWIDTH**—The total frequency width of a channel or band of frequencies.

**BATHYTHERMOGRAPH SONOBUOY**—A recording thermometer for obtaining a permanent graphical record of water temperature in degrees Fahrenheit or Celsius at different water depths, in feet, as it is lowered or dropped into the ocean.

**BATTERY**—A device for converting chemical energy into electrical energy, with two or more primary or secondary cells connected together electrically. The term does not apply to a single cell.

**BEACON**—A radio or radar signal station that provides navigation and interrogation information for ships and aircraft.

**BEAMWIDTH**—The width of an electromagnetic beam, measured in degrees on an arc that lies in a plane along the axis of propagation, between points of equal field strength. It may be measured in the horizontal or vertical plane.

**BEARING**—The angular position of an object with respect to a reference point or line. If the reference point is true north, the bearing is the true bearing; if the reference is NOT true north, then the bearing is a relative bearing. If magnetic north (vice true north) is used as the reference, the bearing then becomes a magnetic bearing. Also, the direction of the line-of-sight, from a radar antenna to a target, measured in degrees.

**BETA**—$\beta$—The ratio of a change in collector current to a corresponding change in base current when the collector voltage is constant in a common-emitter circuit.

**BFO**—Beat-frequency oscillator—An additional oscillator used in a receiver when receiving a continuous wave signal. It provides an audible tone.

**BIAS**—A direct current voltage specifically applied to control a circuit. In transistors, normally the difference of potential between the base and emitter and between the base and collector.

**BIDIRECTIONAL COUPLER**—A waveguide device that samples and presents signals at two outputs; the signal at one output is largely a function of the wave traveling in one direction, while the signal at the other output is largely a function of the wave traveling in the opposite direction.

**BINARY CODE**—A method used to represent two possible conditions (on or off, high or low, one or zero, the presence of a signal or absence of a signal) in an electronic circuit where only two conditions are possible.

**BIT**—Built-in-test—A test function designed into the equipment to test for the proper operation of a circuit, particular function, or system.

**BLACKBODY**—An ideal object that absorbs all incident light and therefore appears perfectly black at all wavelengths.

**BLANKING**—The process of applying negative voltage to the control grid of the cathode-ray tube to cut off the electron beam during the retrace or flyback period.

**BOLOMETER**—A small resistive element used in the measurement of low and medium radiofrequency power. It is characterized by a large temperature coefficient of resistance that is capable of being properly matched to a transmission line.

**BOTTOM BOUNCE**—That form of sonar sound transmission in which sound waves strike the ocean bottom in deep water at steep angles and are reflected back to the surface and returned, which allows the obtaining of target information at long distances.
BREAKDOWN—The phenomenon occurring in a reverse-biased semiconductor diode. The start of the phenomenon is observed as a transition from a high dynamic resistance to one of substantially lower dynamic resistance. This is done to boost the reverse current.

BRIDGE CIRCUIT—The electrical bridge circuit is a term referring to any one of a variety of electric circuit networks, one branch of which, the "bridge" proper, connects two points of equal potential, and hence carries no current when the circuit is properly adjusted or balanced.

B-SCAN (B-DISPLAY)—In radar, a rectangular display in which targets appear as illuminated areas, with bearing indicated by the horizontal coordinate and distance by the vertical coordinate.

BUS—System that uses low voltage electrical signals to transfer data between components.

CAPACITANCE—The property of an electrical current that opposes changes in voltage.

CAPACITIVE REACTANCE—The opposition offered to the flow of an alternating current by capacitance, expressed in ohms.

CAPACITOR—An electrical device capable of storing electrical energy in an electrostatic field.

CASS—Consolidated Automated Support System—Standard automatic test equipment family providing shore-based and afloat intermediate and depot level maintenance and repair capabilities for all naval aircraft, ship, and submarine electronics systems.

CATCC—Carrier Air Traffic Control Center.

CATHODE—A term that is generally used to describe a negative electrode or negative terminal of a forward-biased semiconductor diode that is the source of the electrons.

CCA—Circuit card assembly—Also referred to as a printed circuit board, a CCA mechanically holds and electrically connects the components forming a circuit.

CCD—Charge coupled device—A light-sensitive integrated circuit that stores and displays the data for an image so that each picture element is converted into an electrical charge that relates to the intensity of a color in the color spectrum.

CCTV—Closed circuit television—The application of television where reception is limited by broadcasting on specific frequencies and/or by connecting the receivers directly to the television camera via coaxial cables.

CLADDING—Material used in fiber optics to reduce the loss of light from the core into the surrounding air, reduce scattering loss at the surface of the core, protect fiber from absorbing surface contaminants, and add mechanical strength.

COMPOSITE VIDEO—The total video signal that consists of picture information, blanking pulses, and sync pulses.

COMPRESSION—In sonar, the action that occurs when a transducer diaphragm moves outward creating a high-pressure wave.

CONTINUITY—An uninterrupted, complete path for current flow.

CORRECTIVE MAINTENANCE—In general, the location and repair of equipment failures.

COUNTERMEASURES—Devices and/or techniques intended to impair the operational effectiveness of enemy activity.

COURSE—The intended horizontal direction of travel.

CPU—Central processing unit—The main processing section of a computer; it contains circuitry that carries out instructions from the program or operator to manipulate data and directs the overall operation of the computer.
CRT—Cathode-ray tube—An electron tube that has an electron gun, a deflection system, and a screen used to display visual electronic signals.

CRYSTAL—A natural substance, such as quartz or tourmaline, that is capable of producing a voltage at a certain frequency when under physical stress or produces a physical movement when a voltage is applied due to the Piezoelectric effect.

CURRENT—The movement of electrons past a reference point. Also, the passage of electrons through a conductor that is measured in amperes.

CW—Continuous wave—Method of transmission that directs a continuously transmitted wave of radiofrequency energy at a target. A shift in the frequency when a target moves toward or away from the transmitted radiofrequency energy.

DAMPING—A mechanical or electrical technique used in synchro receivers to prevent the rotor from oscillating or spinning, to minimize overshoot of the load and any influence within a system that restricts oscillations resulting in the absorption of energy.

DATA LINK—A system that is used for the electronic exchange of secure data between two capable and participating units.

DATABASE—Application of a computer that can be used to index and retrieve information. When an operator enters a specific keyword or heading, the computer system calls up the data and displays the information.

DB (dB)—Decibel—Unit used to measure the intensity of sound or the power level of an electrical signal. One decibel is one tenth of one bel.

DC—Direct current—An electric current that flows in one direction only.

DC RESTORER—Direct current restorer—A circuit used to reinsert the direct current component of the video signal lost during amplification.

DDI—Digital data indicator—An indicator used to display tactical and situational information to the operator.

DEAD RECKONING—A method of determining the position of an aircraft by estimating the direction and the speed data in relation to a previous position.

DEFENSIVE COUNTERMEASURES—Devices used to protect the aircraft from anti-air threats by dispensing flares, chaff, or radiofrequency jammers in manual, semiautomatic, or automatic modes of operation.

DEGREES OF FREEDOM (GYRO)—A term applied to gyros to describe the number of variable angles required to specify the position of the rotor spin axis relative to the case.

DELTA—Δ—The change or difference in a changeable quantity.

DEPLETION REGION—The region in a semiconductor where essentially all free electrons and holes have been swept out by the existing electrostatic field.

DICASS—Directional command activated sonobuoy system—An active sonobuoy that provides active sonar ranging, bearing, and Doppler information on a submerged target.

DIELECTRIC—An electrical insulator.

DIFAR—Directional frequency analyzing and recording—An antisubmarine passive sonobuoy acoustic sensing system used in pinpointing submerged contacts.

DIFFERENTIAL—A mechanical computing device used to add or subtract two quantities.
**DIFFUSION**—The spread of energy or particles from high concentration to low concentration due to random velocity and scattering.

**DIODE**—A two element, solid-state device normally made of either germanium or silicon and primarily used as a switching device; it makes use of the rectifying properties of a positive/negative junction to convert alternating current into direct current by permitting current flow in only one direction.

**DIP ANGLE**—In magnetic anomaly detection, this angle is determined by drawing an imaginary line tangent to the Earth’s surface and to the point where the line of force intercepts the surface of the Earth.

**DIPPING-SONAR**—A system used by helicopters. It is lowered from the helicopter for searching and retracted for flight.

**DIRECTIONAL COUPLER**—A device used to extract a portion of the radiofrequency energy moving in a given direction in a transmission line or waveguide. Energy moving in the opposite direction is rejected.

**DISCRIMINATOR**—A dual-input circuit in which the output is dependent on the variation of one input from the other input or from an applied standard.

**DISTORTION**—The production of an output waveform that is not a true reproduction of the input waveform. Distortion may consist of irregularities in amplitude, frequency, phase, etc.

**DIVERGENCE**—Energy loss caused by the spreading of a sound wave in all directions.

**DME**—Distance measuring equipment—a transponder-based radio navigation technology used in TACAN that measures slant range distance by timing the propagation delay of a radiofrequency signal.

**DOME**—The hydrophone and projector combination used in a dipping sonar system.

**DOPPLER EFFECT**—An apparent change in the frequency of a sound wave or electromagnetic wave reaching a receiver when there is relative motion between the source and the receiver.

**DRIFT**—Net change in characteristics of electronic components or parameters, resulting from external or incidental conditions.

**DUAL-GATE MOSFET**—A two-gate MOSFET in which either gate can control the conductor independently, a fact which makes this MOSFET very versatile.

**DUPLEX**—Data transmission method that is capable of both sending and receiving information.

**DUPLEXER**—An electronic switch that allows a radar system to use the same antenna to alternate between transmitting and receiving radiofrequency energy.

**ECASS**—Electronic Consolidated Automatic Support System.

**ECCM**—Electronic counter-countermeasures—Electronic warfare that reduces or eliminates the effects of the adversary’s electronic countermeasures on friendly forces’ electronic sensors such as those aboard vehicles, ships, and aircraft and missiles. ECCM efforts are focused on efforts to resist jamming.

**ECHO**—That portion of the energy reflected to the receiver from the target.

**ECM**—Electronic countermeasures. The means by which enemy electronic devices are nullified and, at the same time, intelligence is gathered concerning the nature of the enemy radiations. ACTIVE ECM implies jamming/deceptive techniques to degrade enemy equipment or operator functions. PASSIVE ECM entails the use of receiving (only) equipment to detect, locate, analyze, and evaluate enemy radiations and radio emissions.
EDDY CURRENT—Induced circulating currents in a conducting material that are caused by a varying magnetic field.

EHF—Extremely high frequency—The band of frequencies from 30 to 300 gigahertz.

ELECTRICAL ZERO—A standard synchro position, with a definite set of stator voltages that is used as the reference point for alignment of all synchro units.

ELECTRODE—The terminal at which electricity passes for one medium into another, such as in an electrical cell where the current leaves or returns to the electrolyte.

ELECTROMAGNETIC—Of or relating to the interrelation of electric currents or fields or magnetic fields.

ELECTROMAGNETIC FIELD—The combination of an electric and a magnetic field.

ELECTROMAGNETIC RADIATION—The radiation of radio waves into space.

ELECTROMAGNETIC SPECTRUM—The range of wavelengths and frequencies over which electromagnetic radiation extends.

ELECTROSTRICTION—That property of certain ceramic materials that, after having a permanent operating bias established, causes these materials to vary slightly in length when they are placed in an electric field.

ELF—Extremely low frequency—The band of frequencies up to 300 Hz.

EMISSIVITY—The ratio of the energy radiated from a material’s surface to that radiated from a blackbody at the same temperature and wavelength under the same viewing conditions.

EO—Electro-optical—An electronic device that is used to emit, modulate, transmit, or sense light or other wavelengths.

ESD—Electrostatic discharge—A transfer of electrostatic charge between objects at different potentials caused by direct contact or induced by an electrostatic field.

ESDS—Electrostatic discharge sensitive—A term used to describe components or devices that are sensitive to electrostatic discharge.

ESM—Electronic warfare support measures—A wide ranging field, ESM provides capability to detect, intercept, identify, locate, record, and/or analyze sources of radiated electromagnetic energy for the purposes of immediate threat recognition.

ENSONIFY—To fill the ocean or any fluid medium with acoustic radiation, which is then observed and analyzed to study the medium or to locate or image objects within it.

E-TRANSFORMER—A magnetic device with an “E” configuration, used as an error detector.

EW—Electronic warfare—Tactical use of electronics to prevent or reduce the enemy’s effective use of radiated electromagnetic energy and the actions taken to assure the effective use of ours.

FEEDBACK—The return of a portion of the output of a circuit stage to the input of that stage or a preceding stage, such that there is either an increase (regeneration) or a reduction (degeneration) in amplification, depending on the relative phase of the returned signal with the input.

FEEDBACK NETWORK—A component of an oscillator that is used to route parts of the signal back to the frequency determining network to maintain oscillation.

FERRITE—A hard and brittle crystalline substance made from a mixture of powdered materials, including iron oxides; it has special magnetic properties of particular value in computers and in many other applications.

FERROUS—A term used to describe a material that is related to or contains the element iron.
FIBER OPTIC—System that transmits light photons through a specifically designed glass medium to send and receive digital information. The light photons in a fiber optic system are created by either a light emitting diode or a laser diode.

FIBER OPTIC CORE—Located in the center of the optical fiber along the longitudinal axis and bound by the cladding, the core is the region with the highest index of refraction and is the light photon conducting part of the fiber.

FIDELITY—The extent to which a system, or a portion of a system, accurately reproduces at its output the essential characteristics of the signal that is impressed upon its input.

FILTER—A selective network of resistors, capacitors, and inductors that offer little opposition to certain frequencies, while blocking or attenuating other frequencies.

FLIP-FLOP—A device with two stable states and two input terminals (or types of input signals), each of which corresponds with one of the two states. The circuit remains in either state until caused to change to the other state by application of a voltage pulse. A similar bistable device with an input that allows it.

FLUX DENSITY—The number of magnetic lines of force passing through a given area.

FM—Frequency modulation—A method of transmitting intelligence (modulating signal) by radiating a radiofrequency signal whose frequency increases and decreases from a fixed reference frequency according to the modulating signal. The amplitude of the modulating signal determines how far the frequency changes, and the frequency of the modulating signal determines how fast the frequency changes.

FOV—Field-of-view—The extent of the observable world able to be seen at any given moment.

FREE GYRO—A gyro so gimbaled that it can assume and maintain any attitude in space. A free gyro has two degrees of freedom; torque cannot be applied to the rotor of a truly free gyro.

FREQUENCY—The number of cycles per second or hertz of an alternating current.

FREQUENCY BAND—The radio frequencies existing between two definite limits and used for a definite purpose; for example, standard broadcast band extending from 550 to 1,600 kHz.

FREQUENCY DETERMINING NETWORK—A component of an oscillator that is an inductive or capacitive circuit that contains a natural or man-made crystal.

G—Gravitational force—A measurement of the type of acceleration that indirectly causes weight.

GAMMA—γ—The ratio of a change in emitter current to a corresponding change in base current, when the emitter voltage is constant in a common-collector circuit.

GATING CIRCUIT (GATE)—A circuit used to activate (or deactivate) another circuit by permitting (or prohibiting) operation during selected periods of time.

GEOMAGNETIC FIELD—The natural magnetic field that surrounds the entire Earth.

GHz—Gigahertz—1 billion hertz.

GIGA—A prefix meaning 1 billion.

GIMBAL—A frame in which the gyro wheel spins and that allows the gyro wheel to have certain freedom of movement. It permits the gyro rotor to incline freely and retain that position when the support is tipped or repositioned.

GPS—Global positioning system—A space-based radio navigation system that provides continuous, all-weather, passive operation anywhere in the world.
GRADIENT, NEGATIVE THERMAL—A condition where the water temperature decreases with the increase in the depth of water.

GRADIENT, POSITIVE THERMAL—A rare condition where the water temperature increases with the increase in the depth of water.

GRADIENT, THERMAL—A term that describes the direction and the rate of temperature changes of water in a particular location.

GREAT CIRCLE—The intersection of a sphere and a plane that passes through the center of the sphere.

GROUNDING STRAPS, PERSONNEL—A device used to ground personnel; should have a minimum resistance of 250,000 ohms and should protect personnel from shock voltages up to 125 volts root mean square.

GYRO—Gyroscope—Mechanical device that contains a spinning mass that is universally mounted allowing it to spin rapidly about one axis and be free to move about one or both of the axes mutually perpendicular to the axis of spin.

HAASW—High altitude antisubmarine warfare—Antisubmarine warfare conducted with modified sonobuoy sensors at higher than traditional fixed-wing airborne altitudes.

HARMONIC—An exact multiple of the fundamental frequency. Even harmonics are 2, 4, etc. times the fundamental. Odd are 3, 5, etc. times the fundamental frequency.

HEADING—Horizontal direction in which an aircraft is pointed.

HENRY—The electromagnetic unit of inductance or mutual inductance.

HETERODYNING—The process of mixing an incoming signal with the local oscillator frequency, producing the two fundamentals and the sum and difference frequencies.

HF—High frequency—The frequency bands from 3 to 30 megahertz.

HORIZONTAL PLANE—A plane that is tangent to the surface of the Earth. Every plane parallel to the horizontal plane is likewise a horizontal plane.

HUD—Head-up display—A system that displays flight and tactical information from various aircraft systems on a transparent mirror (combiner) located directly in front of the pilot at eye level.

HYDROPHONE—An acoustic device that receives and converts underwater sound energy into electrical energy.

Hz—Hertz—A unit of frequency equal to 1 cycle per second.

IF—Intermediate frequency—A lower frequency to which a radiofrequency echo is converted for ease of amplification.

IFF—Identification friend or foe—A system that provides a long range means for distinguishing friendly aircraft from hostile aircraft. Additionally, it is used to identify commercial aircraft by transmitting special codes to ground stations equipped with an Air Traffic Control Radar Beacon System.

IFF INTERROGATOR—A pulse-type transmitter that sends out challenges to determine whether the unknown target is friendly or hostile. The target could be another aircraft, ship, or ground force.

IFF TRANSPONDER—A unit that receives interrogation pulses from identification friend or foe equipped units or ground stations and automatically replies with a properly coded response. Also used in general aviation to provide air traffic control with altitude information.
ILS—Instrument Landing System—A system that provides the data for visual steering commands that assist the aircrew for the last 25 miles before touchdown onto the aircraft carrier. The ILS interacts with the instrument carrier landing system and decodes the azimuth and elevation signals.

IMPEDANCE—Measure of electrical opposition in a circuit when current of voltage is applied.

INDUCTANCE—The property of a circuit that tends to oppose a change in the existing current flow.

INDUCTIVE REACTANCE—The opposition to the flow of an alternating current caused by the inductance of a circuit, expressed in ohms.

INERTIA—The physical tendency of a body in motion to remain in motion and a body at rest to remain at rest unless acted upon an outside force.

INFRARED DETECTORS—Thermal devices for observing and measuring infrared radiation, such as the bolometer, thermopile, pneumatic cell, photocell, photographic plate, and photoconductive cell.

INS—Inertial navigation system—A system that detects the motion of an aircraft and provides acceleration, velocity, present position, pitch, roll, and true heading data to compute present position.

INTELLIGENCE—The message or information conveyed, as by a modulated radio wave.

INTERFACE—A concept involving the specification of the interconnection between equipment or systems. The specifications include the type, quantity, and function of signals to be interchanged via those circuits. A device that converts or translates any type of information from one given medium into signals of another given medium.

IONOSPHERE—A layer of electrically charged particles at the top of the Earth’s atmosphere that result from strong solar radiation.

IR—Infrared—Invisible waves in that portion of the electromagnetic spectrum lying between visible light and radio frequencies. The infrared frequency range is from about 300 GHz to 400 THz and between wavelengths of 0.72 and 1,000 micrometers.

ISOTHERMAL LAYER—A layer of water in which there is no appreciable change of temperature with depth.

JUNCTION TRANSISTOR—A bipolar transistor constructed from interacting positive/negative junctions. The term is used to distinguish junction transistors from other types, such as field-effect and point-contact.

KHz—Kilohertz—1,000 hertz.

KILO—A prefix meaning 1 thousand.

KIRCHHOFF’S LAWS—(1) The algebraic sum of the current flowing toward any point in a circuit and the current flowing away from it is zero. (2) The algebraic sum of the products of the current and resistance in each of the conductors in any closed path in a network is equal to the algebraic sum of the electromotive forces in the path.

KNOT—The unit of speed that is equivalent to 1 nautical mile (6,080 feet) per hour.

LAMBDA—λ—A descriptor or symbol used to indicate wavelength.

LASER—Light amplification by the stimulated emission of radiation.

LATITUDE—Angular distance measured north or south of the equator along a meridian, 0 degrees through 90 degrees.

LAYER DEPTH—The depth from the surface of the sea to the top of the first significant negative thermocline.
LAYER EFFECT—Partial protection from echo ranging and listening detection when below layer depth.

LCD—Liquid crystal display.

LED—Light emitting diode—a positive material and negative material-junction diode that emits visible light when it is forward biased.

LF—Low frequency—the band of frequencies from 30 to 300 kilohertz.

LINE OF FORCE—a line in electric or magnetic field that shows the direction of the force.

LISSAJOUS PATTERN—a combined, simultaneous display of the amplitude and phase relationships of two input signals on a cathode-ray tube.

LOGIC CIRCUITS—Digital computer circuits used to store information signals and/or to perform logical operations on those signals.

LONGITUDE—the angular distance east or west of the Greenwich meridian, measured in the plane of the equator or of a parallel from 0 degrees to 180 degrees.

LOOP ANTENNA—one or more complete turns of wire used with a radio receiver or with direction-finding equipment.

LOS—Line-of-sight—the straight-line distance from a reference point to the horizon. Line-of-sight represents the radio and radar very high frequency and ultrahigh frequency transmission range limits under normal conditions.

MAD—Magnetic anomaly detection—the detection of slight distortions in the Earth’s magnetic field.

MAGNETIC FIELD—the region in space in which a magnetic force exists, caused by a permanent magnet or as a result of current flowing in a conductor.

MAGNETOMETER—a device that is used to detect anomalies in the Earth’s geomagnetic field.

MAGNETOSTRICTION—that property of certain ferrous-type materials that causes them to vary slightly in length when they are in an alternating magnetic field.

MAGNETRON—a microwave oscillator that uses an electron tube (consisting of a cathode and an anode), a strong axial magnetic field, and resonant cavities.

MEGA—a prefix meaning 1 million.

MERIDIAN—a great circle drawn through the north and south poles.

MF—Medium frequency—the band of frequencies from 300 kilohertz to 3 megahertz.

MHz—Megahertz—1 million hertz.

MICRO—a prefix meaning one-millionth.

MICROWAVES—Electromagnetic waves of extremely high frequency (between 300 MHz and 300 GHz).

MILLI—a prefix meaning one-thousandth.

MODULATION—the process of varying the amplitude or frequency of a carrier wave in accordance with other signals to convey intelligence.

MODULATOR—a circuit used in servo systems to convert a direct current signal to an alternating current signal. The output signal is a sine wave at the frequency of the alternating current reference voltage. The amplitude of the output is directly related to the amplitude of the direct current input.
**MODULE**—In electronic terminology, a group or cluster of circuits/components usually mounted together on a circuit board.

**MOSFET**—Metal-oxide semiconductor field-effect transistor—a semiconductor device that contains diffused source and drain regions on either side of a positive (P)- or negative (N)-channel area.

**MPCD**—Multipurpose color display.

**MULTIPLEXING**—A method for simultaneous transmission of two or more signals over a common carrier.

**NATURAL INTERFERENCE**—Radio interference caused by natural electrical noise that is separated into atmospheric static, precipitation static, and cosmic noise.

**NAUTICAL MILE**—A unit of distance used principally in navigation equal to approximately 6,080 feet.

**NOISE**—Any undesired disturbance within the useful frequency band; also, that part of the modulation of a received signal (or an electrical or electronic signal within a circuit) representing an undesirable effect of transient conditions.

**NOISE, RANDOM**—Electrical impulses that are of irregular shape, amplitude, duration, and recurrence rate. Normally, the source of the random noise is a variable contact between brush and commutator bar or slip ring, or an imperfect contact or poor electrical isolation between surfaces.

**NOT CIRCUIT**—In computers, a circuit in which the output signal is the opposite polarity as the input signal. A phase inverter.

**NULL**—A point or position where a variable-strength signal is at its minimum value (or zero).

**OHM**—The unit of electrical resistance.

**OMNIDIRECTIONAL**—Transmitting or receiving a signal in all directions.

**OPAQUE**—In optics, a term that means not able to be seen through or not having the characteristic of being transparent.

**OPERATING SYSTEM**—In computers, software designed to support a computer’s basic functions, such as running applications or controlling input/output devices.

**OPTICAL FIBER**—A flexible, transparent fiber made of extruded glass (silica) or plastic used to send light energy for communication.

**OR GATE**—A logic circuit having multiple inputs and a single output, so designed that the output is energized when any one or more of the inputs are in the prescribed signal state.

**OSCILLATOR**—A component that provides a constant frequency for radio transmitters and receivers.

**OTPI**—On top position indicator—a navigation system that provides the operator with the bearing of a sonobuoy in relation to the aircraft.

**PARALLAX ERROR**—The error in meter readings that results when you look at a meter from some position other than directly in line with the pointer and meter face. A mirror mounted on the meter face aids in eliminating parallax error.

**PARALLEL MODE**—Digital transmission method that uses a single line for each bit of data that will be transmitted or received. The data is transmitted via the lines simultaneously.

**PARAMETER**—In electronics, the design or operating characteristic of a circuit or device.

**PASSIVE SONAR**—Equipment that uses a hydrophone to detect unusual undersea noise indicating the presence of a possible target.
PERMALLOY—A material used for compensation of magnetic field changes created by the magnetic rotation of an aircraft.

PHASE—The angular relationship between two alternating currents or voltages when the voltage or current is plotted as a function of time. When the two are in phase, the angle is zero; both reach their peak simultaneously. When the two are out of phase, one will lead or lag the other; that is, at the instant when one of the two is at its peak, the other will not be at peak value and (depending on the phase angle) may differ in polarity as well as magnitude.

PHOTOCONDUCTIVITY—The most widely used photon effect. Radiant energy changes the electrical conductivity of the detector element. An electrical circuit is used to measure the change in conductivity.

PHOTOCURRENT—a term used to describe electrical current generated by light.

PHOTOELECTRIC EFFECT—The electric potential difference across a semiconductor that is caused by a radiant signal. The total current is proportional to the amount of light that falls on a detector.

PHOTOEMISSIVE EFFECT—The action of radiation that causes the emission of an electron from the surface of the photocathode to the surrounding space.

PHOTON—A particle of electromagnetic energy or a quantum of light.

PHOTOEFFECT—A type of energy-matter interaction in which photons of radiant energy interact directly with the electrons of infrared detector material.

PHOTON EFFECT—A term used to describe electrical current generated by light.

PHOTOVOLTAICS—See PHOTOELECTRIC EFFECT.

PICKOFF—In gyros, a sensing device that measures the angle of the spin axis with respect to its reference, and provides an error signal that indicates the direction and (in most cases) the magnitude of the displacement.

PIEZOELECTRIC EFFECT—Effect of producing a voltage by placing stress, either by compression, expansion, or twisting, on a crystal and, conversely, producing a stress in a crystal by applying a voltage to it.

PING—The sound wave that is generated by sonar equipment.

POLARIZATION—in electronics, a term used in specifying the direction of the electric vector in a linearly polarized electromagnetic wave as radiated from a transmitting antenna, or as picked up by a receiving antenna.

POTENTIOMETER—an electromechanical device with a terminal connected to each end of a resistive element, and a third connected to a wiper contact. The output is a voltage that is variable depending upon the position of the wiper contact.

PPI SCAN—Planned position indicator scan—a presentation in which the signal appears on a rotating radial line. Distance is indicated radially, and bearing as an angle.

PRECESSION—the rotation of the spin axis of a gyro in response to an applied force. The direction of precession is always perpendicular to the direction of applied force.

PREVENTIVE MAINTENANCE—Visual, mechanical, electrical, and electronic checks that are made to determine whether or not equipment is functioning properly.

PRF—Pulse repetition frequency—the rate at which pulses are transmitted, given in Hz or pulses per second. PRF is expressed as the reciprocal of pulse repetition time.

PRIME GENERATOR—Common plastics and other materials that are prohibited in an electrostatic discharge protected work area.
PROGRAM—A complete plan for the solution of a problem, including the complete sequence of instructions and routines necessary to solve the problem by a computer.

PROGRAMMING LANGUAGE—A set of unique key words or symbols used by an operator to design and implement computer applications to solve problems or to meet a specific need.

PROPAGATION—Waves traveling through a medium. Extending the action of, transmitting, or carrying forward as in space or time or through a medium (as the propagation of sound, light, or radio waves).

PRT—Pulse repetition time—The interval between the start of one pulse and the start of the next pulse. PRT is expressed as the reciprocal of pulse repetition frequency.

PULSE DURATION—The time interval between the leading and trailing edges of each of a particular group of pulses; the instantaneous values of these are often used in a specific relation to the peak pulse amplitude to determine power output.

PULSE INTERVAL—The time interval between the leading edges of successive pulses in a sequence.

PULSE SEPARATION—The time interval between the trailing edge of one pulse and the leading edge of the next pulse.

PULSE TRAIN—A series of pulses passed through a circuit as control or information signals.

PULSE WIDTH—The duration of time between the leading and trailing edges of a pulse.

Q—Figure of merit, quality, or efficiency of a circuit or coil. The ratio of inductive reactance to resistance in servos or the relationship between stored energy (capacitance) and the rate of dissipation in certain types of electric elements, structures, or materials.

RADALT—Radar altimeter—A unit that uses pulse range-tracking radiofrequency energy to measure the surface of terrain clearance below the aircraft. Also called an absolute altimeter.

RADAR—Radio detection and ranging—A system that operates by transmitting and receiving a radiofrequency pulse to determine the range, bearing, and altitude of a target.

RADAR MILE—The time it takes for a radiofrequency pulse to travel from a radar antenna to a target approximately 6,080 feet away and back. A radar mile is normally expressed as the time interval of 12.36 microseconds.

RADIAN—A unit of plane angular measurement that is equal to the angle at the center of a circle subtended by an arc whose length equals the radius or approximately 57.3 degrees.

RAM—Random access memory.

RANGE—The distance of an object from an observer.

RASTER—The illuminated rectangular area scanned by the electron beam on a display.

RATE GYRO—A gyro with one-degree-of-freedom, which has an elastic restraint, with or without a damper, and whose output will be proportional to the rate of the applied torque.

RECEIVER SENSITIVITY—The ability of a receiver to reproduce a weak input signal into a useable output signal. In receivers, the greater the sensitivity, the weaker the signal can be reproduced.

RECTIFIER—A device used to convert alternating current to pulsating direct current.

REFLECTION—In the case of sound, this action occurs when a sound wave hits an object or a boundary region between transmission mediums in such a manner as to return it back to its origin.
REFRACTION—The deflection or bending from a straight path undergone by an energy wave in passing obliquely from one medium into another in which its velocity is different. For example, the bending of a sound wave caused by variations in water temperature.

REGISTER—A specific computer unit, usually in the central processing unit, that holds data. Registers may hold a computer instruction, storage address, or individual data bits.

RELATIVE BEARING—An object’s position measured in a clockwise direction using the centerline of the measuring device (antenna, aircraft, etc.) as a reference point.

RELATIVE MOTION—The apparent movement of an object in relation to another object.

RELAY—An electromagnetically operated remote control switch often used to switch high current, high voltage, or other critical circuits.

RESISTANCE—The opposition a device or material offers to the flow of current. The effect of resistance is to raise the temperature of the material or device carrying the current.

RESISTOR—An electrical component that offers resistance to the flow of current. It may be a coil of fine wire or a composition rod.

RESOLUTION—In radar, the ability of a radar system to distinguish between targets.

RESONANCE—The condition in a circuit containing inductance and capacitance and is resonant at one frequency.

REVERBERATION—Multiple reflections of a sound or energy wave. In the ocean, reverberations are caused by irregularities in the ocean bottom, surface, and suspended natural matter.

RF—Radiofrequency—Any frequency of electromagnetic energy capable of propagation into space. The frequencies that fall between 3 kilohertz and 300 gigahertz are used for radio communications.

RF SPECTRUM—Radiofrequency spectrum—The spectrum of electromagnetic frequencies that are used for communications. The radiofrequency spectrum also includes frequencies that are used in radar and other systems.

RIGIDITY—In gyros, the characteristics of a spinning body that cause it to oppose all attempts to tilt away from the axis in which it is spinning.

ROOT MEAN SQUARE—The most common method of defining the effective voltage or current of an alternating current wave.

ROTOCHUTE—A rotating blade assembly that slows the descent of an airborne deployed sonobuoy to reduce the water-entry shock to the device.

ROTOR—The rotating member of a synchro that consists of one or more coils of wire wound on a laminated core. Depending on the type of synchro, the rotor functions similar to the primary or secondary winding of a transformer. In a gyro, the rotating member is sometimes called a gyro wheel.

SALINITY—The amount of salt content in seawater. Salinity can affect the travel of a sound wave through a body of water. The higher the salt content, the faster the sound wave will travel through the body of water.

SAR—Search and rescue.

SCANNING SONAR—Sonar that transmits sound pulses in all directions simultaneously.

SCANNING, STATIONARY-LOBE—The simplest form of scanning system that uses a single beam that is stationary in reference to the antenna.

SCATTERING—Reflection losses from foreign matter that is suspended in the water. The practical result of scattering is the reduction of the echo strength, especially at long ranges.
SCHULER TUNING (LOOP)—A closed loop circuit between the accelerometer, velocity integrator, and stable element used to torque the platform to a position normal to the gravity vector by signals received from a computing loop in an inertial navigation unit.

SELECTIVITY—The degree of distinction that a receiver can make between the desired and unwanted signals.

SEMI-SYNCHRONOUS ORBIT—An orbit with a period equal to half the average rotational period of the body (Earth) being orbited, and in the same direction as that body’s rotation.

SENSO—Sensor operator—A crewmember that operates the antisubmarine warfare platform’s acoustic and nonacoustic sensor systems.

SENSOR—A component that senses variables and produces signals derived from those variables. Some examples of sensors are temperature, sound, heat, and light.

SERIAL MODE—Digital data transmission method that transmits data one bit at a time on a single transmission line.

SERVO AMPLIFIER—An alternating current or direct current amplifier used in servo systems to build up signal strength.

SHF—Superhigh-frequency—The band of frequencies from 3 to 30 gigahertz.

SHIFT REGISTER—In computers, a circuit that will shift a digit or a group of digits either to the left or to the right; it is of particular importance in some multiplication and division processes, and in sequential storage of pulse trains.

SHOT EFFECT—Noise voltages developed as a result of the random flow of either primary or secondary carriers in transistors.

SIMPLEX—Data transmission that occurs in one direction (transmit or receive) only.

SIMULATION—Application of a computer that is used to simulate the operation of any type of system being designed.

SINE WAVE—The basic synchronous alternating waveform for all complex waveforms. Also known as a sinusoidal wave.

SINS—Ship’s inertial navigation system—The system that provides ship’s velocity, position, and attitude data to aircraft via a cable assembly or by an aircraft datalink system.

SINUSOIDAL—Having a magnitude that varies as the sine of an independent variable.

SLEW—To change the position of an indicator mark on a display.

SOFTWARE—A set of programs and procedures used by a computer to perform a particular function. Software includes compilers, assemblers, operating systems, and so on.

SONAR—Sound navigation and ranging—A term used to describe equipment that transmits and receives sound energy propagated through water.

SONAR DATA COMPUTER—In airborne sonar systems, a programmed array processor that analyzes and processes signals from dipping-sonar and multiple passive and active sonobuoys.

SONAR RECEIVER—In airborne sonar systems, a unit that generates the transmit signal and receives and processes sonic signals from the transducer for display on the azimuth-range indicator. The sonar receiver also provides the audio output for aural monitoring of acoustic signals.

SONIC—Within the audible range of the human ear.

SONOBUOY RECEIVER—A device that uses radios to receive, demodulate, and amplify sonobuoy transmissions in the very high frequency spectrum bands. A typical sonobuoy receiver system relays
acoustic data to other units (ships or aircraft) via a datalink system. The data from a sonobuoy receiver is routed to a spectrum analyzer.

**SONOBUOY**—A free-floating electronic device used to detect, localize, and track submerged submarines.

**SOUND CHANNEL**—Condition when two layers of water with near equal temperatures produce a sound channel. Sound between the two layers is refracted by the layers, stays between them, and travels for great distances.

**SPECTRUM ANALYZER**—In sonar, a high-speed processor that extracts acoustic information from the received signals of active and passive sonobuoys. A spectrum analyzer determines the frequency, amplitude, bearing, Doppler, and range of an acoustic target.

**SPEED OF LIGHT**—Measured at approximately 186,000 statute miles per second.

**SQUELCH**—A circuit that cuts off the output of a receiver when there is no input.

**SRS**—Sonobuoy reference system—The system used to determine the position of deployed sonobuoys relative to aircraft position.

**SRX**—Sonobuoy receiver system—A frequency modulated radio receiver system used exclusively for sonobuoy radiofrequency signal reception and processing.

**SSB**—Single sideband.

**STABLE ELEMENT**—In inertial navigation systems, a component that mounts in the gimbal structure of an inertial navigation unit so that, regardless of aircraft maneuvers, the platform maintains the original orientation. Additionally, the stable element serves as a level mount for the accelerometers.

**STATIC ELECTRICITY**—Stationary electricity that is in the form of a charge. The accumulated electric charge on an object.

**STATOR**—The stationary member of a synchro that consists of a cylindrical structure of slotted laminations on which three Y-connected coils are wound with their axes 120 degrees apart. Depending on the type of synchro, the stator's functions are similar to the primary or secondary windings of a transformer.

**STATUTE MILE**—Measurement that is equivalent to 5,280 feet.

**STBY**—Standby.

**SUBHARMONICS**—An exact submultiple of the fundamental frequency. Even subharmonics are one-half, one-quarter, etc. of the fundamental frequency. Odd subharmonics are one-third, one-fifth, etc. of the fundamental frequency.

**SUPPRESSION**—The process of eliminating an undesired portion of a signal.

**SYNC**—Synchronize—To cause two elements of a system to coincide in speed, frequency, relative position, or time.

**SYNCHRO**—A small motor-like device that operates like a variable transformer and is used primarily for the rapid and accurate transmission of data among equipment and stations.

**TACAN**—Tactical Air Navigation—A polar coordinate type radio air-navigation system that provides distance information and bearing information to a compatible station.

**TACCO**—Tactical coordinator.

**TEMPERATURE**—The most important factor that can affect the speed of a sound wave traveling in seawater. One degree of temperature change can increase the speed of sound in seawater by 4 to 8 feet per second.
TERA—A prefix meaning 1 trillion.

THERMAL EFFECT—A type of energy-matter interaction that involves the absorption of radiant energy in an IR detector.

THERMAL IMAGING—The use of specialized heat-sensing equipment to detect targets.

THERMISTOR—A solid-state, semiconducting device whose resistance varies with temperature.

THERMOCLINE—The layer in a body of water where the temperature decreases continuously with depth.

THETA—θ—A descriptor or symbol used to indicate angular displacement.

THYRATRON—A gas-filled, grid-controlled, electronic switching tube used mainly in radar modulators. Since the time required to turn a thyatron on is only a few microseconds, the current waveform in a thyatron circuit always has a sharp leading edge. As a result, the waveform is rich in radio interference energy.

THz—Terahertz—1 trillion hertz.

TORQUE—A force tending to cause rotational motion; the product of the force applied times the distance from the force to the axis of rotation.

TRANSCEIVER, FIBER OPTIC—A system component that incorporates fiber optic transmission and reception capabilities into one unit.

TRANSUDER—A device that converts signals received in one medium into outputs in some other medium; for example, electrical inputs to fluidic outputs, or mechanical motion into electrical quantities.

TRANSMITTER, FIBER OPTIC—A system component that converts electrical signals into optical signals and sends them through optical fiber cabling.

TRANSMITTER, RADAR—Generates radiofrequency energy in the form of short and powerful pulses. Transmitters use oscillators to turn a low-power radiofrequency signal into a high-power output signal.

TRANSMITTER, RADIO—Equipment that is responsible for generating the proper amount of radiofrequency energy to transmit information from one point to another.

TRIBOELECTRIC EFFECT—The process of generating static electricity by rubbing an object.

TRIGGER—An external signal starting an action in another circuit, which then operates for a time under its own control.

TRUE BEARING—A bearing given in relation to true geographic north.

TUMBLE—To subject a gyro to a torque so that it presents a precession violent enough to cause the gyro rotor to spin end over end.

TUNED CIRCUIT—A circuit that acts as a filter in a radio communication system by allowing or rejecting specific frequency ranges.

UFCD—Upfront control display—A touch sensitive display that provides the keypad, option select, scratch pad, and option displays.

UHF—Ultrahigh frequency—The band of frequencies from 300 megahertz to 3 gigahertz.

VARACTOR—A special semiconductor diode whose capacitance is varied with the amount of applied voltage. Used to vary the frequency output of an oscillator.
VELOCITY—A vector quantity that includes both magnitude (speed) and direction in relation to a given frame of reference.

VERTICAL PLANE—A plane that is perpendicular to the horizontal plane, and is the reference from which bearings are measured.

VHF—Very high frequency—The band of frequencies from 30 to 300 megahertz.

VLF—Very low frequency—The band of frequencies from 3 to 30 kilohertz.

VOR—Very high frequency omnidirectional radio range—A type of short-range radio navigation system that uses a series of radio beacons.

WAVE PROPAGATION—The radiation from an antenna of radiofrequency energy into space, or of sound energy into a conducting medium.

WAVEGUIDE—Metal tubes or dielectric cylinders capable of propagating electromagnetic waves through their interiors. The dimensions of these devices are determined by the frequency to be propagated.

WAVELENGTH—Distance traveled by a wave during the time interval of one complete cycle. It is equal to the velocity divided by the frequency.

WORD—In computers, a particular number of characters handled as a unit by the computer and having a specific meaning with respect to the computation process.

WRA—Weapons replaceable assembly—Replaceable packages of an avionics component, pod, or system as installed in an aircraft weapon system.

ZEROING—The process of adjusting a synchro to its electrical zero position.
APPENDIX II
SYMBOLS, FORMULAS, AND TABLES

Resistors:
- General
- Tapped
- Continuously Variable
- Nonlinear

Inductive Components:
- General
- Tapped
- Adjustable or Continuously Adjustable
- Saturable Core Reactor

Capacitors:
- Fixed
- Variable
- Ganged
- Shielded
- Split-stator
- Feed-through
- Differential
- Phase Shift

Transformers:
- General
- Magnetic Core Transformer
- Autotransformer
- With Taps Single-phase

(When Capacitor Electrode Identification Is Necessary, the Curved Element Shall Represent the Outside Electrode Electrode In Fixed Paper-dielectric and Ceramic-dielectric; The Negative Electrode In Electrolytic Capacitors; The Moving Element In Variable and Adjustable Capacitors, and the Low Potential Element In Feed-through Capacitors.)

Note: For Further Information Concerning Symbols Refer to IEEE Standards and American National Standard Graphics Symbols For Electrical and Electronics Diagrams, ANSI Y32 2/IEEE No. 315, Which Has Been Adopted For Mandatory Use By the DoD.

Figure All-1 — Electrical symbols.
Figure AII-1 — Electrical symbols (continued).
Figure AI-1 — Electrical symbols (continued).
Contacts (Electrical) (Continued):

- **Closed Contact (Break)**
- **Open Contact (Make)**
- **Time Sequence Closing**

Disconnecting Devices:
- Male (Pin Contact)
- Female (Socket Contact)
- Engaged (Pin-to-Socket)

- Coaxial (Male)
- Coaxial Connectors Mated

Coaxial Connected To Single Connector

The Connector Symbol Is Not an Arrowhead, It Is Larger and the Lines Are Drawn At a 90° Angle

- **Splice**

Connector Assembly (General)

Electron Tubes:

- Component Tube Symbols
  - Directly-Heated (Filamentary) Cathode
  - Indirectly-Heated Cathode
  - Grid
  - Pool Cathode
  - Cold Cathode
  - Anode or Plate
  - Photocathode

- Or
- Envelope (Shell)
- Gas Filled Envelope
- Split Envelope

Semiconductor Devices:

- Diode
- Transistors

- Breakdown Diode Bidirectional
  - Breakdown Diode Undirectional (Also Backward Diode)
  - Photodiode

Figure All-1 — Electrical symbols (continued).
Figure AII-1 — Electrical symbols (continued).
Figure AII-1 — Electrical symbols (continued).
Logic Functions (Continued):

Single Shot

SS

Schmitt Trigger

ST

Oscillator

OSC

Synchos:

General

A Letter Combination From the Following List May Be Placed Adjacent to the Symbol to Indicate the Type of Synchro:

TX - Torque Transmitter
TDX - Torque Differential Transmitter
CX - Control Transmitter
CDX - Control Differential Transmitter
TR - Torque Receiver
CT - Control Transformer

Synchos (Continued):

Resolver (Synchro)

Transmitter, Receiver, or Control Transformer

Singly-Wound Rotor

Differential Transmitter or Receiver

Doubly-Wound Rotor

Resolver

Singly-Wound Rotor

Doubly-Wound Rotor

Figure All-1 — Electrical symbols (continued).
Figure AII-1 — Electrical symbols (continued).
Table All-1 — Common Electrical Formula Symbols

<table>
<thead>
<tr>
<th>Electrical Symbol</th>
<th>General Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Current is measured in amperes</td>
</tr>
<tr>
<td>E</td>
<td>Voltage is measured in volts</td>
</tr>
<tr>
<td>R</td>
<td>Resistance is measured in ohms</td>
</tr>
<tr>
<td>P</td>
<td>Power is measured in watts</td>
</tr>
<tr>
<td>L</td>
<td>Inductance is measured in henrys</td>
</tr>
<tr>
<td>X</td>
<td>Reactance is measured in ohms</td>
</tr>
<tr>
<td>t</td>
<td>Measure of time</td>
</tr>
<tr>
<td>E_P</td>
<td>Voltage in a transformer primary</td>
</tr>
<tr>
<td>E_S</td>
<td>Voltage in a transformer secondary</td>
</tr>
<tr>
<td>N_P</td>
<td>Number of turns in a transformer primary</td>
</tr>
<tr>
<td>N_S</td>
<td>Number of turns in a transformer secondary</td>
</tr>
<tr>
<td>E_ave</td>
<td>Value of average voltage</td>
</tr>
<tr>
<td>E_max</td>
<td>Value of maximum voltage</td>
</tr>
<tr>
<td>E_eff</td>
<td>Value of effective voltage</td>
</tr>
<tr>
<td>F</td>
<td>Measure of magnetomotive force</td>
</tr>
<tr>
<td>Ŧ (flux)</td>
<td>Measure of magnetic flow</td>
</tr>
<tr>
<td>( R ) (reluctance)</td>
<td>Measure of magnetic opposition</td>
</tr>
<tr>
<td>H</td>
<td>Measure of magnetic force intensity</td>
</tr>
<tr>
<td>dB</td>
<td>Measure of intensity (sound or electrical)</td>
</tr>
</tbody>
</table>
Figure All-2 — Common electrical calculations formula wheel.
Ohm’s Law for Direct Current Circuits

\[ I = \frac{E}{R} = \frac{P}{E} = \sqrt{\frac{P}{R}} \]

\[ R = \frac{E}{I} = \frac{P}{I^2} = \frac{E^2}{P} \]

\[ E = IR = \frac{P}{I} = \sqrt{PR} \]

\[ P = EI = \frac{E^2}{R} = I^2R \]

**Resistors in Series**

\[ R_T = R_1 + R_2 \ldots \]

**Resistors in Parallel**

**Two resistors:**

\[ \frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots \]

**More than two:**

\[ \frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots \]

**Resistive-Inductance (RL) Circuit Time Constant**

\[ \frac{L \text{ (in henrys)}}{R \text{ (in ohms)}} = t \text{ (in seconds)}, \text{ or} \]

\[ \frac{L \text{ (in microhenrys)}}{R \text{ (in ohms)}} = t \text{ (in microseconds)} \]

**Resistive-Capacitive (RC) Circuit Time Constant**

\[ R \text{ (ohms)} \times C \text{ (farads)} = t \text{ (seconds)} \]

\[ R \text{ (megohms)} \times C \text{ (microfarads)} = t \text{ (seconds)} \]

\[ R \text{ (ohms)} \times C \text{ (microfarads)} = t \text{ (microseconds)} \]
R (megohms) × C (picofarads) = t (microseconds)

**Capacitors in Series**

Two capacitors:

\[ C_T = \frac{C_1 C_2}{C_1 + C_2} \]

More than two:

\[ \frac{1}{C_T} = \frac{1}{C_1} + \frac{1}{C_2} + \cdots \]

**Capacitors in Parallel**

\[ C_T = C_1 + C_2 + \cdots \]

**Capacitive Reactance**

\[ X_C = \frac{1}{2\pi fC} \]

**Impedance in an RC Circuit (Series)**

\[ Z = \sqrt{R^2 + (X_C)^2} \]

**Inductor in Series**

\[ L_T = L_1 + L_2 + \cdots \ (\text{No coupling between coils}) \]

**Inductors in Parallel**

Two inductors:

\[ L_T = \frac{L_1 L_2}{L_1 + L_2} \ (\text{No coupling between coils}) \]

More than two:

\[ \frac{1}{L_T} = \frac{1}{L_1} + \frac{1}{L_2} + \cdots \ (\text{No coupling between coils}) \]
Inductive Reactance
\[ X_L = 2\pi fL \]

Q of a Coil
\[ Q = \frac{X_L}{R} \]

Impedance of an RL Circuit (Series)
\[ Z = \sqrt{R^2 + (X_L)^2} \]

Impedance with R, C, and L in Series
\[ Z = \sqrt{R^2 + (X_L - X_C)^2} \]

Parallel Circuit Impedance
\[ Z = \frac{Z_1Z_2}{Z_1 + Z_2} \]

Sine-Wave Voltage Relationships

Average value:
\[ E_{ave} = \frac{2}{\pi} \times E_{max} = 0.637E_{max} \]

Effective or rms value:
\[ E_{eff} = \frac{E_{max}}{\sqrt{2}} = \frac{E_{max}}{1.414} = 0.707E_{max} = 1.11E_{ave} \]

Maximum value:
\[ E_{max} = \sqrt{2 (E_{eff})} = 1.414E_{eff} = 1.57E_{ave} \]

Voltage in an alternating circuit:
\[ E = IZ = \frac{P}{I \times PF} \]
Current in an alternating circuit:

\[ I = \frac{E}{Z} = \frac{P}{E \times PF} \]

Power in Alternating Current Circuit

Apparent power: \( P = EI \)

True power: \( P = EI \cos \theta = EI \times PF \)

Power factor:

\[ PF = \frac{P}{EI} = \cos \theta \]

\[ \cos \theta = \frac{\text{true power}}{\text{apparent power}} \]

Transformers

Voltage relationship:

\[ \frac{E_p}{E_s} = \frac{N_p}{N_s} \text{ or } E_s = E_p \times \frac{N_s}{N_p} \]

Current relationship:

\[ \frac{I_p}{I_s} = \frac{N_s}{N_p} \]

Induced voltage:

\[ E_{eff} = 4.44 \times BAfN \times 10^{-8} \]

Turns ratio:

\[ \frac{N_p}{N_s} = \sqrt{\frac{Z_p}{Z_s}} \]

Secondary current:

\[ I_s = I_p \times \frac{N_p}{N_s} \]
Secondary voltage:
\[ E_s = E_p \times \frac{N_s}{N_p} \]

Three-phase Voltage and Current Relationships

With wye connected windings:
\[ E_{\text{line}} = \sqrt{3} (E_{\text{coil}}) = 1.732E_{\text{coil}} \]
\[ I_{\text{line}} = I_{\text{coil}} \]

With delta connected windings:
\[ E_{\text{line}} = E_{\text{coil}} \]
\[ I_{\text{line}} = 1.732I_{\text{coil}} \]

With wye or delta connected winding:
\[ P_{\text{coil}} = E_{\text{coil}}I_{\text{coil}} \]
\[ P_t = 3P_{\text{coil}} \]
\[ P_t = 1.732E_{\text{line}}I_{\text{line}} \]

(To convert to true power, multiply by \( \cos \theta \))

Resonance

At resonance:
\[ X_L = X_C \]

Resonant frequency:
\[ F_0 = \frac{1}{2\pi\sqrt{LC}} \]

Series resonance:
\[ Z (\text{at any frequency}) = R + j (X_L - X_C) \]
\[ Z (\text{at resonance}) = R \]
Parallel resonance:

\[ Z_{\text{max}} \text{ (at resonance)} = \frac{X_L X_C}{R} = \frac{X_L^2}{R} = Q X_L = \frac{L}{CR} \]

**Bandwidth:**

\[ \Delta = \frac{F_0}{Q} = \frac{R}{2\pi L} \]

**Tube Characteristics**

**Amplification factor:**

\[ \mu = \frac{\Delta e_p}{\Delta e_g} \text{ (i_p constant)} \]

\[ \mu = g_m r_p \]

**Alternating current plate resistance:**

\[ r_p = \frac{\Delta e_p}{\Delta i_p} \text{ (e_g constant)} \]

**Grid-plate transconductance:**

\[ g_m = \frac{\Delta i_p}{\Delta e_g} \text{ (e_p constant)} \]

**Decibels**

**NOTE**

Wherever the expression “log” appears without a subscript specifying the base, the logarithmic base is understood to be 10.

**Power ratio:**

\[ \text{dB} = 10 \log \frac{P_2}{P_1} \]

**Current and voltage ratio:**

\[ \text{dB} = 20 \log \frac{I_2 \sqrt{R_2}}{I_1 \sqrt{R_1}} \]
\[
\text{dB} = 20 \log \frac{E_2 \sqrt{R_1}}{E_1 \sqrt{R_2}}
\]

**NOTE**

When \( R_1 \) and \( R_2 \) are equal they may be omitted from the formula.

When reference level is 1 milliwatt:

\[
\text{dBm} = 10 \log \frac{P}{0.001} \quad \text{(when } P \text{ is in watts)}
\]

**Synchronous Speed of a Motor**

\[
\text{rpm} = \frac{120 \times \text{frequency}}{\text{number of poles}}
\]

**Wavelength**

\[
\text{wavelength (in meters)} = \frac{300}{\text{frequency (in megahertz)}}
\]

\[
\lambda = \frac{300}{f \text{MHz}}
\]
BRIDGE CIRCUIT CONVERSION FORMULAS

Pi to Tee

\[ R_{1'} = \frac{R_1 R_2}{R_1 + R_2 + R_3} \]
\[ R_{2'} = \frac{R_1 R_3}{R_1 + R_2 + R_3} \]
\[ R_{3'} = \frac{R_2 R_3}{R_1 + R_2 + R_3} \]

Tee to Pi

\[ R_1 = \frac{R_{1'} R_{2'} + R_{2'} R_{3'} + R_{1'} R_{3'}}{R_3} \]
\[ R_2 = \frac{R_{1'} R_{2'} + R_{2'} R_{3'} + R_{1'} R_{3'}}{R_2} \]
\[ R_3 = \frac{R_{1'} R_{2'} + R_{2'} R_{3'} + R_{1'} R_{3'}}{R_1} \]
Calculating $R_T$ for Bridge

1. Redraw.

2. Convert Pi network made up of resistors $R_3$, $R_4$, $R_5$ to Tee network made up of $R'_3$, $R'_4$, $R'_5$.

\[
R_{3, r} = \frac{R_3 R_5}{R_3 + R_4 + R_5}
\]

\[
R_{4, r} = \frac{R_4 R_5}{R_3 + R_4 + R_5}
\]

\[
R_{5, r} = \frac{R_3 R_4}{R_3 + R_4 + R_5}
\]
3. Redraw circuit.


\[
R_{1r} = R_1 + R_{3r}, \quad R_{2r} = R_2 + R_{4r}
\]

5. Simplify again.

\[
R_{6r} = \frac{R_{1r}R_{2r}}{R_{1r} + R_{2r}}
\]

6. Solve for \(R_T\).

\[
R_T = R_{6r} + R_{5r}
\]
Table All-2 — Law of Exponents

<table>
<thead>
<tr>
<th>Numbers</th>
<th>Powers of Ten</th>
<th>Prefixes</th>
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<td>10^{12}</td>
<td>tera</td>
<td>T</td>
</tr>
<tr>
<td>1,000,000,000</td>
<td>10^{9}</td>
<td>giga</td>
<td>G</td>
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<tr>
<td>1,000,000</td>
<td>10^{6}</td>
<td>mega</td>
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<td>1,000</td>
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<td>100</td>
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<td>0.00000000000000001</td>
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</table>

To multiply like (with same base) exponential quantities, add the exponents. In the language of algebra the rule is: \( a^m \times a^n = a^{m+n} \).

\[
10^4 \times 10^2 = 10^{4+2} = 10^6 \\
0.003 \times 825.2 = 3 \times 10^{-3} \times 8.252 \times 10^2 = 24.756 \times 10^{-1} = 2.4756
\]

To divide exponential quantities, subtract the exponents. In the language of algebra the rule is:

\[
\frac{a^m}{n} = a^{m-n} \text{ or } 10^8 \div 10^2 = 10^6
\]

\[
3,000 \div 0.015 = 0.015 = (3 \times 10^3) \div (1.5 \times 10^{-2}) = 2 \times 10^5 = 200,000
\]

To raise an exponential quantity to a power, multiply the exponents. In the language of algebra:

\[
(x^m)^n = x^{mn}
\]

\[
(10^3)^4 = 10^{3\times4} = 10^{12}
\]

\[
2,500^2 = (2.5 \times 10^3)^2 = 6.25 \times 10^6 = 6,250,000
\]

Any number (except zero) raised to the zero power is 1. In the language of algebra:

\[
x^0 = 1
\]

\[
x^3 \div x^3 = 1
\]

\[
10^4 \div 10^4 = 1
\]
Any base number with a negative exponent is equal to 1 divided by the base with an equal positive exponent. In the language of algebra:

\[ x^{-a} = \frac{1}{x^a} \]

\[ 10^{-2} = \frac{1}{10^2} = \frac{1}{100} \]

\[ 5a^{-3} = \frac{5}{a^3} \]

\[ (6a)^{-1} = \frac{1}{6a} \]

To raise a product to a power, raise each factor of the product to that power.

\[ (2 \times 10)^2 = 2^2 \times 10^2 \]

\[ 3,000^3 = (3 \times 10^3)^3 = 27 \times 10^9 \]

To find the nth root of an exponential quantity, divide the exponent by the index of the root. Therefore, the nth root of \( a^m = a^{m/n} \).

\[ \sqrt[3]{x^6} = x^{6/2} = x^3 \]

\[ \sqrt[3]{64 \times 10^3} = 4 \times 10 = 40 \]

**Joint Electronics Type Designation System**

The Joint Electronics Type Designation System (JETDS) was developed to standardize the identification of electronic material and equipment. There is a three letter designation assigned to complete sets of electronic equipment that describes where they are used, the type of equipment, and purpose of that equipment. For example, the designator APG would represent piloted aircraft (A), radar (P), fire control or searchlight directing (G), or an airborne fire control radar system. The three letter system is provided as a reference to explain aircraft electronics systems designations and is shown on the following page in **Table All-3**.
<table>
<thead>
<tr>
<th>Installation Class</th>
<th>Type of Equipment</th>
<th>Purpose</th>
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</thead>
<tbody>
<tr>
<td><strong>A</strong> Piloted aircraft</td>
<td><strong>A</strong> Invisible light, heat radiation</td>
<td><strong>A</strong> Auxiliary assembly</td>
</tr>
<tr>
<td><strong>B</strong> Underwater mobile, submarine</td>
<td><strong>B</strong> Communications security</td>
<td><strong>B</strong> Bombing</td>
</tr>
<tr>
<td><strong>C</strong> Cryptographic</td>
<td><strong>C</strong> Carrier (electronic wave/signal)</td>
<td><strong>C</strong> Communications (receiving and transmitting)</td>
</tr>
<tr>
<td><strong>D</strong> Pilotless carrier</td>
<td><strong>D</strong> Radiac</td>
<td><strong>D</strong> Direction finder, reconnaissance and surveillance</td>
</tr>
<tr>
<td><strong>E</strong> Fixed ground</td>
<td><strong>E</strong> Laser</td>
<td><strong>E</strong> Ejection and/or release</td>
</tr>
<tr>
<td><strong>F</strong> General ground use</td>
<td><strong>F</strong> Fiber optics</td>
<td><strong>G</strong> Fire control or searchlight directing</td>
</tr>
<tr>
<td><strong>G</strong> Mobile (ground)</td>
<td><strong>G</strong> Interphone and public address</td>
<td><strong>K</strong> Computing</td>
</tr>
<tr>
<td><strong>H</strong> Portable</td>
<td><strong>H</strong> Electromechanical or inertial wire covered</td>
<td><strong>M</strong> Maintenance/test assemblies</td>
</tr>
<tr>
<td><strong>I</strong> Water</td>
<td><strong>I</strong> Telemetering</td>
<td><strong>N</strong> Navigational aids</td>
</tr>
<tr>
<td><strong>J</strong> Transportable (ground)</td>
<td><strong>J</strong> Countermeasures</td>
<td><strong>Q</strong> Special or combination</td>
</tr>
<tr>
<td><strong>K</strong> General utility</td>
<td><strong>K</strong> Meteorological</td>
<td><strong>R</strong> Receiving/passable detection</td>
</tr>
<tr>
<td><strong>L</strong> Vehicular (ground)</td>
<td><strong>L</strong> Sound in air</td>
<td><strong>S</strong> Detecting/range and bearing, search</td>
</tr>
<tr>
<td><strong>M</strong> Water surface and underwater combined</td>
<td><strong>M</strong> Radar</td>
<td><strong>T</strong> Transmitting</td>
</tr>
<tr>
<td><strong>N</strong> Piloted-pilotless airborne vehicles combined</td>
<td><strong>N</strong> Sonar and underwater sound</td>
<td><strong>W</strong> Automatic flight or remote control</td>
</tr>
<tr>
<td><strong>O</strong> Radio</td>
<td><strong>O</strong> Identification and recognition</td>
<td></td>
</tr>
<tr>
<td><strong>P</strong> Special or combination</td>
<td><strong>P</strong> Surveillance (search, detect, and multiple target tracking) and control</td>
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<tr>
<td><strong>Q</strong> Telephone (wire)</td>
<td><strong>Q</strong> Secure</td>
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<tr>
<td><strong>R</strong> Visual and visible light</td>
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<td><strong>S</strong> Armament (peculiar not already covered)</td>
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<td><strong>T</strong> Facsimile or television</td>
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<td><strong>U</strong> Data processing or computer</td>
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<td><strong>V</strong> Communications</td>
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APPENDIX III
REFERENCES

NOTE

Although the following references were current when this NRTC was published, their continued currency cannot be assured. When consulting these references, keep in mind that they may have been revised to reflect new technology or revised methods, practices, or procedures; therefore, you need to ensure that you are studying the latest references.

If you find an incorrect or obsolete reference, please use the Rate Training Manual User Update Form provided at the end of each chapter to contact the CNATT Rate Training Manager.

Chapter 1


Chapter 2


_Navy Electricity and Electronics Training Series, Module 13—Number Systems and Logic Circuits_, NAVEDTRA 14185A, Center for Surface Combat Systems, Dahlgren, VA, January 2012.


Chapter 3

_Installation and Repair Practices, Aircraft Fiber Optic Cabling_, NAVAIR 01-1A-505-4, TO 1-1A-14-4, TM 1-1500-323-24-4, Commander, Naval Air Systems Command, Patuxent River, MD, 13 August 2012.


_Navy Electricity and Electronics Training Series, Module 24—Fiber Optics_, NAVEDTRA 14196A, Center for Surface Combat Systems, Dahlgren, VA, June 2014.

Chapter 4


Chapter 5

Aviation Electricity and Electronics—Undersea Warfare, NAVEDTRA 14340, Center for Naval Aviation Technical Training, Pensacola, FL, April 2003.

Integrated Sensor Station 1 and 2, Update III and Block Mod Upgrade Program, Navy Model P-3C Aircraft, NAVAIR 01-75PAC-2-15, Commander, Naval Air Systems Command, Patuxent River, MD, 1 May 1993, Change 16, 15 September 2013.

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Maintenance Instructions, Organizational, Integrated Flight Station Systems, Navy Model P-3C Aircraft, NAVAIR 01-75PAC-2-9, Commander, Naval Air Systems Command, Patuxent River, MD, 1 May 1993, Change 16, 1 September 2013.

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Chapter 6


Chapter 7


Chapter 8


Interior Communications Electrician, Volume 02, NA VedTRA 14121A, Center for Surface Combat Systems, Dahlgren, VA, January 2011.


Chapter 9


Installation and Repair Practices, Aircraft Fiber Optic Cabling, NAVAIR 01-1A-505-4, TO 1-1A-14-4, TM 1-1500-323-24-4, Commander, Naval Air Systems Command, Patuxent River, MD, 13 August 2012.

Navy Electricity and Electronics Training Series, Module 13—Number Systems and Logic Circuits, NA VedTRA 14185A, Center for Surface Combat Systems, Dahlgren, VA, January 2012.


Chapter 10


Chapter 11

Operator’s Instructions Numerical Index of Effective Work Packages Electrical Equipment Test Sets AN/USM636A(V)1 Part No. 2048AS775–01 thru AN/USM636(V)8 Part No. 2054AS400–04, NAVAIR 16-30USM636-1-1, Commander, Naval Air Systems Command, Patuxent River, MD, 1 March 2014.

Technical Manual Intermediate Maintenance With Illustrated Parts Breakdown Hybrid Electrical Equipment Test Sets AN/USM636A(V)1, NAVAIR 16-30USM636-2-1, Commander, Naval Air Systems Command, Patuxent River, MD, 1 September 2014.
Chapter 12


APPENDIX IV

Answers to End of Chapter Questions

Chapter 1 — Servo Systems

| 1-1. | C |
| 1-2. | A |
| 1-3. | D |
| 1-4. | D |
| 1-5. | A |
| 1-6. | A |
| 1-7. | C |
| 1-8. | A |
| 1-9. | C |
| 1-10. | B |
| 1-11. | C |
| 1-12. | D |
| 1-13. | B |
| 1-14. | A |
| 1-15. | B |
| 1-16. | C |

Chapter 2 — Logic Devices

| 2-1. | A |
| 2-2. | B |
| 2-3. | D |
| 2-4. | B |
| 2-5. | B |
| 2-6. | D |
| 2-7. | D |
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| 2-9. | A |
| 2-10. | C |
| 2-11. | B |
| 2-12. | B |
| 2-13. | C |
| 2-14. | D |
| 2-15. | A |
| 2-16. | C |
| 2-17. | A |
| 2-18. | B |
| 2-19. | C |
| 2-20. | B |
| 2-21. | A |
| 2-22. | C |
| 2-23. | A |
| 2-24. | D |

Chapter 3 — Communications

| 3-1. | D |
| 3-2. | A |
| 3-3. | B |
| 3-4. | A |
| 3-5. | B |
| 3-6. | C |
| 3-7. | B |
| 3-8. | C |
| 3-9. | A |
| 3-10. | D |
| 3-11. | C |
| 3-12. | B |
| 3-13. | A |
| 3-14. | D |
| 3-15. | B |
| 3-16. | C |
| AIV-1 |
### Chapter 4 — Navigation Systems

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### Chapter 5 — Antisubmarine Warfare

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End of Book Questions Chapter 1

Servo Systems

1-1. A servomechanism is normally composed of a data transmission system, a servo control amplifier, and a/an ________.

A. control transformer.
B. servomotor.
C. error signal generator.
D. correction signal generator.

1-2. What error detector device should be used to develop either an ac or dc output voltage?

A. E-transformer
B. Potentiometer
C. Flux gate
D. Control transformer

1-3. The stator of a synchro transmitter consists of three coils which are displaced from each other by ________.

A. 60° physically.
B. 90° physically.
C. 90° electrically.
D. 120° electrically.

1-4. To eliminate the possibility of false null positions in a multiple-speed data transmission system, the system should be designed to contain a high-speed synchro. To work correctly, the synchro speed is maintained at which of the following rates?

A. At an odd multiple of the system’s low-speed synchro
B. At least twice the speed of the system’s low-speed synchro
C. At 10 times the speed of the system’s low-speed synchro
D. At a constant speed set higher than the system’s low-speed synchro

1-5. What is the purpose of damping in any servomechanism?

A. To increase error transient time
B. To decrease the width of the null
C. To provide steady-rate errors
D. To reduce oscillations

1-6. What type of damper would absorb too much power from a servo system?

A. Eddy current
B. Dry friction clutch
C. Pure viscous
D. Heavy flywheel
1-7. Servo response error to a constant velocity input is known as _______.

A. constant error.
B. velocity error.
C. inherent error.
D. angle error.

1-8. Increasing the gain of the servo amplifier in a servo system has which of the following effects?

A. Increases velocity errors in the system
B. Increases steady-state errors caused by restraining torques on the servo load
C. Decreases the speed of response to transient input
D. Increases the speed of response to transient inputs

1-9. The most common method(s) of zeroing synchro transmitters and receivers is/are the _______.

A. right hand method.
B. ac voltmeter and electrical lock method.
C. automatic synchronizing mode.
D. flux gate tuning method.

1-10. What are indexing pins used for?

A. Holding a unit in its index or zero position
B. Marking your page in a publication
C. Adjusting the exciter voltage
D. Correcting gyro spin rate errors

1-11. Before zeroing a differential synchro transmitter, it is critically important to _______.

A. warm up and calibrate your oscilloscope.
B. zero the unit whose position is being transmitted.
C. disconnect the control transformer’s stator.
D. verify the load is positioned 90° from zero.

1-12. To have a zero output from a control transformer, in what manner must the rotor winding be positioned with reference to the magnetic field of the stator?

A. Displaced by 120°
B. Displaced by 240°
C. Perpendicular
D. Parallel

1-13. In a basic radar system, the antenna will begin a 7 degree conical sweeping pattern when which of the following actions occurs?

A. The target is bracketed with strobe lines only
B. The lock-on switch is depressed only
C. The target is bracketed with strobe line and the lock-on switch is depressed
D. The radar is placed in the search mode
1-14. In a basic radar system, after the operator has achieved target lock-on, which unit automatically positions the antenna?

A. Vertical scan generator  
B. Control handle  
C. Flux gate  
D. Receiver

1-15. In a basic radar system operating in search mode, what is the function of the vertical scan generator?

A. Automatically engage the 50 Hz spin generator for horizontal stabilization  
B. Position the antenna in a vertical geometric plane  
C. Position the automatic spin motor  
D. Automatically generate unmodulated target video

1-16. In track mode, a basic radar system’s spin generator operates at a frequency of ________.

A. 2 Hz.  
B. 50 Hz.  
C. 60 Hz.  
D. 400 Hz.
End of Book Questions Chapter 2

Logic Devices

2-1. In reference to a junction diode, what does the abbreviation CR stand for?

A. Current remover  
B. Crystal rectifier  
C. Crystal resistor  
D. Current resistor

2-2. What junction diode rating indicates the amount of current allowed to flow in the forward direction in nonrepetitive pulses?

A. Peak current  
B. Repetitive forward current  
C. Surge current  
D. Average forward current

2-3. What direction does current flow when a basic junction diode is forward biased?

A. With the arrow  
B. Against the arrow  
C. Both with and against the arrow  
D. None

2-4. What is the name of the area where the N-type material and P-type material meet in a diode?

A. Solid-state  
B. Cross road  
C. Border  
D. Junction

2-5. What is the (a) input and (b) output of a common-collector connected transistor?

A. (a) Base to collector (b) base to emitter  
B. (a) Base to emitter (b) collector to emitter  
C. (a) Emitter to base (b) collector to base  
D. (a) Base to collector (b) emitter to collector

2-6. Which of the following transistor configurations has the highest input resistance and lowest output resistance?

A. Common-collector  
B. Common-emitter  
C. Common-base  
D. Common-gate
2-7. What is the current gain designated in the common-base transistor configuration?

A. Alpha
B. Beta
C. Gamma
D. Lambda

2-8. What is the phase relationship between the input signal and the output signal in a transistor connected in a common-emitter configuration?

A. 90° in phase
B. 180° out of phase
C. 270° out of phase
D. 360° in phase

2-9. Metal-oxide-semiconductor field-effect transistors are commonly used in applications that require what (a) impedance output and (b) current gain?

A. (a) High (b) low
B. (a) Low (b) low
C. (a) Low (b) high
D. (a) High (b) high

2-10. The nature of a logic inverter is that ________.

A. it converts ac power to dc.
B. if an input signal is positive, the output will be negative and vice versa.
C. if an input signal is weak, it amplifies the output.
D. it decreases the gain to half the input.

2-11. What term refers to a transistor’s capability to amplify a given signal?

A. Resistance
B. Impedance
C. Gain
D. Capacitance

2-12. A microphone amplifier does not require a large current gain. Which of the following transistor configurations is the best match for such an application?

A. Common-emitter
B. Common-collector
C. Common-gate
D. Common-base
2-13. What is the specialized thyristor that is commonly used in lamp dimmer and heating control applications?

A. TRIAC  
B. Impedance dimmer  
C. Switch-back  
D. GTO

2-14. Which thyristor can be controlled without an auxiliary communication circuit?

A. JFET  
B. ASCR  
C. GTO  
D. SCR

2-15. What term is used to define the time difference that occurs between the change in output voltage caused by a change in input voltage of an integrated circuit?

A. Storage time  
B. Phase shift  
C. Charge time  
D. Propagation delay

2-16. What is the oscillator-based circuit that provides a general-purpose replacement for the inductor in integrated linear circuit high-frequency applications?

A. Phase-locked loop  
B. Cascaded invertor  
C. Stagger tuner  
D. Switched capacitor

2-17. What is the logic operation performed by the multi-emitter transistor?

A. NOR  
B. NAND  
C. OR  
D. AND

2-18. What is the designation for a commercial-grade, low-power Schottky Transistor-Transistor Logic device?

A. 5400  
B. 54S00  
C. 74S00  
D. 74LS00
2-19. What is an advantage of gallium arsenide integrated circuits over silicon integrated circuits?

A. Relatively insensitive to heat
B. Lower cost
C. Reduced fidelity
D. Greater availability of raw materials

2-20. A particular logic gate can accommodate four logic inputs. What logic gate term best describes this characteristic?

A. Flip-flop
B. Fan-in
C. Fan-out
D. Reset-set

2-21. Which circuit changes a binary code into an audio signal?

A. Comparator
B. Logic gate
C. Digital-to-analog converter
D. Analog-to-digital converter

2-22. Which of the following number systems is most commonly used to display analog information in numerical form?

A. Gray code
B. Hexadecimal
C. Tertiary
D. Binary-coded decimal

2-23. What analog-to-digital conversion method uses a series of trials starting with the most significant bit and ending with the least significant bit?

A. Dual-slope
B. Successive-approximation
C. Single-slope
D. Encoding

2-24. Which of the following circuit characteristics best indicates what determines the resolution of a digital-to-analog converter circuit?

A. Number of bytes
B. Number system used
C. Weight of each bit
D. Value of reference voltage
End of Book Questions Chapter 3

Communications

3-1. What internal program monitors system performance and fault isolation?

A. Self-check  
B. Integrated evaluation  
C. Consolidated test program  
D. Built-in test equipment

3-2. What piece of equipment provides the most accurate indication of transmission frequency?

A. Spectrum analyzer  
B. Oscilloscope  
C. Frequency counter  
D. Digital tracker

3-3. By what ratio is a frequency-modulated (FM) radio station’s modulation index calculated?

A. Amplitude to deviation frequency  
B. Frequency deviation to frequency of the modulating signal  
C. Amplitude to frequency of modulating signal  
D. Frequency swing to modulating signal amplitude

3-4. Which of the following types of transmitter is more sensitive to nonlinear amplification distortion?

A. Phase-modulated  
B. Amplitude-modulated  
C. Frequency-modulated  
D. Interpolar-modulated

3-5. In equipment employing crystals, the alignment procedure must center on the crystals for what reason?

A. The frequency of crystals is not variable.  
B. The crystal’s sensitivity is unstable.  
C. The wide variety of crystal circuits.  
D. The crystals are fragile and may be cracked.

3-6. What property enables a receiver to discriminate against transmissions other than the one to which it is tuned?

A. Sensitivity  
B. Selectivity  
C. Qualitative  
D. Quantitative
Due to the high degree of oscillator frequency stability, automatic frequency control circuits are found in frequency-modulated (FM) receivers in what frequency range?

A. High frequency
B. Low frequency
C. Very high frequency
D. Medium frequency

What characteristic makes a crystal filter useful in communication receivers?

A. Low order of selectivity
B. Low Q
C. Broad frequency-cutoff ability
D. High Q

What device is used in a fiber-optic system to convert an electrical signal into light?

A. Receiver
B. Transmitter
C. Detector
D. Core

Why are fiber optic cables able to be placed near fuel cells and lines in aircraft?

A. Data transmission speed is low enough not to produce heat.
B. Data transmission is by light, not electrical signals.
C. Cables burn so fast that heat does not build up.
D. High moisture content of aramid yarn prevents ignition.

What component has a low index of refraction to contain the light within the core?

A. Aramid yarn
B. Core
C. Low halogen jacket
D. Cladding

What angle, when surpassed, will NOT reflect light?

A. Cone of acceptance
B. Acceptance angle
C. Critical
D. Index of refraction

What type of optical fiber transfers data at a higher rate due to low dispersion?

A. Multimode step-index
B. Single mode step-index
C. Multimode graded-index
D. Index-refracted
3-14. What common fiber optic cable design meets the Navy’s stringent environmental requirements?

A. Loose-tube
B. Tight-buffered
C. Gel-filled
D. Flexible-transitory

3-15. Variations of the index of refraction in the core and cladding is a symptom of which of the following factors?

A. Attenuation
B. Intermodal dispersion
C. Intramodal dispersion
D. Bandwidth

3-16. What connection is formed between a negatively charged dust particle and the end face of an optic connector?

A. Ionic bond
B. Thermal bond
C. Intrinsic junction
D. Melded junction
End of Book Questions Chapter 4

Navigation Systems

4-1. Which of the following loop antenna types can operate without a sense antenna?
   A. Rhombic
   B. Monopole
   C. Dipole
   D. Helix

4-2. A typical automatic direction finder (ADF) system has what frequency range?
   A. 90 kHz to 1,800 kHz
   B. 1,800 kHz to 2,500 kHz
   C. 2,500 kHz to 90 MHz
   D. 90 MHz to 1,800 MHz

4-3. Which of the following signals can be received by an automatic direction finder (ADF)?
   A. Amplitude-modulated (AM) and frequency-modulated (FM)
   B. Continuous-wave (CW) and frequency-modulated (FM)
   C. Amplitude-modulated (AM) and continuous-wave (CW)
   D. Single-sideband (SSB) and frequency-modulated (FM)

4-4. What type of interference is eliminated by calibrating a newly installed automatic direction finder (ADF) loop antenna on an aircraft?
   A. Night effect
   B. Electrical disturbances
   C. Quadrantal error
   D. Precipitation static

4-5. What is the purpose of very high frequency (VHF) omnidirectional range (VOR) tracks?
   A. To let aircrew know when the aircraft is over a given station
   B. To give aircrew bearing and distance to a given station
   C. To allow aircrew to guide an aircraft over long distances
   D. To give aircrew bearing to a known station

4-6. What two signals are transmitted from a very high frequency (VHF) omnidirectional range (VOR) station?
   A. Reference phase and time phase
   B. Reference phase and variable phase
   C. Variable phase and time phase
   D. Variable phase and phase lock
4-7. In a very high frequency (VHF) omnidirectional range (VOR) station, how many revolutions per minute (rpm) does the variable phase signal rotate?

A. 30  
B. 300  
C. 1,800  
D. 18,000

4-8. The purpose of the vertical bar on a typical course deviation indicator (CDI) is to indicate _______.

A. magnetic north.  
B. the heading of the selected station.  
C. true north.  
D. the aircraft’s altitude.

4-9. What is the purpose of an AN/ARA-63 all-weather aircraft approach guidance system?

A. To allow aircraft to land after the pilot ejects  
B. To enable aircraft to launch in poor weather conditions  
C. To enable aircraft to land in low visibility  
D. To provide input to ship’s bridge during aircraft recovery

4-10. What AN/ARA-63 module receives the quantized video from the video-identity module?

A. Clock/BIT-flag  
B. Error  
C. Memory  
D. BIT

4-11. Timing pulses used throughout the decoder are derived from what module?

A. Clock/BIT-flag  
B. AGC  
C. Memory  
D. Error

4-12. If the beam circuit counts the read gate pulses, how many gate pulses must be received in one beam for the beam to be considered valid?

A. 12  
B. 16  
C. 47  
D. 52
4-13. A typical tactical air navigation (TACAN) system provides what type of bearing and range?

A. Magnetic and slant  
B. Magnetic and linear  
C. Relative and slant  
D. Relative and linear

4-14. In a typical tactical air navigation (TACAN) system, what circuit calculates the relative direction of an aircraft from a TACAN station?

A. Decoder  
B. Distance control  
C. Bearing measurement  
D. Distance measurement

4-15. How many bits of data does the tactical air navigation (TACAN) system shift register store?

A. 16  
B. 24  
C. 32  
D. 64

4-16. What is the maximum range of a typical tactical air navigation (TACAN) system’s distance circuit, in nautical miles (nmi)?

A. 300.0  
B. 368.0  
C. 389.9  
D. 395.5

4-17. In a tactical situation, which of the following statements best describes why the inertial navigation system (INS) is most desirable?

A. It quickly provides position to satellites.  
B. It is a fully active navigation system.  
C. It is a fully passive navigation system.  
D. It is easily tracked by commercial satellites.

4-18. What component of an inertial navigation system (INS) stabilizes the platform on which the accelerometers are mounted?

A. Servomotor  
B. Torque motor  
C. Gimbals  
D. Amplifier
4-19. What component or components in the inertial navigation system (INS) system send a positioning signal to the stabilized platform?

A. Accelerometers  
B. Integrators  
C. Gyros  
D. Computer

4-20. The three basic components of an inertial navigation system (INS) are the gyrostabilized element, ________.

A. accelerometers, and indicators.  
B. integrators, and indicators.  
C. integrators, and magnetrons.  
D. accelerometers, and integrators.

4-21. Along a straight-line distance between the transmitter and receiver, the amplitude of the Doppler shift is directly proportional to the closing or receding ________.

A. range.  
B. velocity.  
C. altitude.  
D. distance.

4-22. What indication will the operator receive to indicate that the Doppler system is operating in the search mode?

A. The memory light illuminates.  
B. The memory light extinguishes.  
C. The automatic gain control (AGC) light illuminates.  
D. The search light illuminates.

4-23. What range is the magnetron’s pulse repetition frequency (PRF) of a typical eight-beam Doppler navigation radar?

A. 30 to 50 kHz  
B. 60 to 70 kHz  
C. 80 to 120 kHz  
D. 80 to 120 MHz

4-24. A typical eight-beam Doppler navigation radar is able to compensate for drift up to what maximum number of degrees?

A. 30  
B. 60  
C. 180  
D. 360
4-25. What minimum number of observable satellites is required to produce the most accurate position solution?

A. Two  
B. Three  
C. Four  
D. Five

4-26. Global positioning systems (GPS) can give position directly without the need to ________.

A. transmit signals to the user, even when not using the signal.  
B. compute positions in three dimensions.  
C. measure angles and distances between intermediate points.  
D. be observable from anywhere on Earth.

4-27. What signals does a global positioning system (GPS) satellite transmit?

A. Coarse/acquisition (C/A) and precise/classified (P/Y)  
B. Direct/Indirect (DI) and alternating/current (AC)  
C. Radio/fundamental (RF) and coarse/acquisition (C/A)  
D. Direct/indirect (DI) and line of sight (LOS)

4-28. A basic military global positioning system (GPS) is composed of the receiver, the key fill panel, and what other two components?

A. Transmitter and antenna  
B. Antenna and modulator  
C. Transmitter and cable assembly  
D. Antenna and cable assembly

4-29. Which of the following statements is an advantage of having a navigational computer system?

A. Allows pilots to sleep on missions  
B. Requires less training on navigation  
C. Relieves aircrew of manual navigation operations  
D. Allows air traffic control facilities to pilot the aircraft

4-30. What information do global positioning systems (GPS) provide to the navigation computer?

A. Nearly instantaneous position  
B. Target information  
C. Temperature  
D. Magnetic bearing

4-31. What sensor provides range and bearing of a known location to the navigation computer?

A. Inertial navigation system (INS)  
B. Doppler radar  
C. Tactical air navigation (TACAN) system  
D. Electronic altimeter
4-32. What sensor requires the navigation computer to have an accurate magnetic variation value at all times?

A. Inertial navigation system (INS)
B. Doppler radar
C. Tactical air navigation (TACAN) system
D. Electronic altimeter

4-33. An airborne electronic altimeter system displays what type of altitude information?

A. Absolute height above sea level
B. Absolute height above the terrain below the aircraft
C. Absolute height above the terrain in front of the aircraft
D. Barometric height above terrain

4-34. A typical electronic altimeter has what maximum altitude readout, in feet?

A. 5,000
B. 10,000
C. 15,000
D. 20,000

4-35. In the self-test mode of a typical electronic altimeter, the indicator reading should be what measurement, in feet?

A. 100 feet
B. 200 feet
C. 500 feet
D. 700 feet

4-36. What is the typical operating frequency range of electronic (radar) altimeters?

A. 8,500
B. 9,000
C. 4,250 to 4,350 kHz
D. 4,250 to 4,350 MHz
End of Book Questions Chapter 5
Antisubmarine Warfare

5-1. Which of the following aircraft types has an antisubmarine warfare system designed primarily as an airborne data link between sonobuoys and a shipboard receiving set?

A. P-3 Orion  
B. MH-60R Seahawk  
C. S-3 Viking  
D. F/A-18 Hornet

5-2. What antisubmarine warfare aircraft uses global positioning system drop vector algorithm to enhance sonobuoy splash point prediction?

A. F/A-18 Hornet  
B. MH-60R Seahawk  
C. P-8 Poseidon  
D. F-15 Strike Eagle

5-3. What antisubmarine platform uses dipping-sonar?

A. P-8 Poseidon  
B. MH-60R Seahawk  
C. C-2 Greyhound  
D. SH-2 Blackhawk

5-4. What antisubmarine warfare platform uses the APY-10 synthetic aperture radar?

A. MH-60R Seahawk  
B. P-3 Orion  
C. S-3 Viking  
D. P-8 Poseidon

5-5. Which of the following detection equipment uses the principle of sound waves striking an object and reflecting a portion of that energy back to its source?

A. Radar  
B. Sonar  
C. Tactical navigation  
D. Identification friend or foe

5-6. What mode of sonar does NOT emit a signal but uses only a hydrophone to listen to underwater noise?

A. Active  
B. Refractive  
C. Reflective  
D. Passive
5-7. Which of the following sources cause reverberation in seawater?

A. Seawater, surface, geometric magnetism
B. Surface, tides, and bottom
C. Bottom, seawater, and surface
D. Seawater, sunlight, and air temperature

5-8. Which of the following seawater characteristics most often affects the speed of sound in water?

A. Color
B. Temperature
C. Salinity
D. Pressure

5-9. Which of the following signals does the sonobuoy receiver send to the signal data converter subunits of the acoustic data processor?

A. Super tactile
B. Aural roping
C. Sonobuoy audio
D. Ultra high radiofrequency

5-10. What acoustic data processor component is used to provide memory provisions for auxiliary readout unit and multipurpose display refresh?

A. Spectrum analyzer converter
B. Spectrum analyzer-signal generator
C. Digital data storage unit
D. Signal data converter

5-11. What acoustic antisubmarine warfare system component displays sonobuoy signal characteristics?

A. Tactical coordinator power control panel
B. General-purpose digital computer
C. Sonobuoy monitor panel
D. Tactical indicator display group multipurpose display

5-12. Which of the following acoustic data system components is typical of those found onboard helicopters?

A. Radio receiving set and spectrum analyzer
B. Acoustic data processor and radio receiving set
C. Data storage magnetic drum and radio receiving set
D. TACCO power control panel and spectrum analyzer
5-13. What device converts electrical energy into acoustic energy to transmit underwater?
   A. Hydrophone
   B. Transducer
   C. Sonobuoy
   D. Transceiver

5-14. Compared to a low frequency analysis and recording sonobuoy, what additional information does a directional frequency analysis and recording sonobuoy provide?
   A. Duration
   B. Intensity
   C. Frequency
   D. Direction

5-15. What type of sonobuoy is used to measure water temperature versus depth?
   A. Directional command active sonobuoy system
   B. Search and rescue
   C. Directional frequency analysis and recording
   D. Bathythermograph

5-16. Which of the following sonobuoys is used to surprise a submarine by remaining silent until instructed to operate?
   A. Low frequency analysis and recording
   B. Search and destroy
   C. Command active sonobuoy system
   D. Directional frequency analysis and recording

5-17. How many receivers does a typical sonobuoy receiver set have and what type of modulation do they use?
   A. 16, frequency
   B. 16, amplitude
   C. 31, frequency
   D. 31, amplitude

5-18. What component of the receiver group provides relative bearing to the sonobuoy?
   A. On-top-position indicator
   B. Intermediate frequency receiver
   C. Tactical navigation indicator
   D. Radar receiver
5-19. What system uses angle-measuring equipment to update sonobuoy position without the aircraft having to fly directly over it?

A. Sonobuoy reference  
B. Locator reference  
C. Acoustic reference  
D. Directional reference

5-20. What acoustic sensor signal generator mode should be used to eliminate the antenna as a possible source of trouble when maintenance is performed on the sonobuoy receiver group?

A. External  
B. Preamp  
C. Receiver  
D. Antenna

5-21. How many active mode ranges are selectable in a typical dipping-sonar set?

A. 4  
B. 6  
C. 16  
D. 31

5-22. What components are included in a dipping-sonar’s dome?

A. Sonar receiver set and transmitter  
B. Hydrophone and projector  
C. Sonar receiver set and projector  
D. Hydrophone and transmitter

5-23. What is the pulsewidth of a dipping-sonar operating in active, long-range mode?

A. 3.5 milliseconds  
B. 35 milliseconds  
C. 40 milliseconds  
D. 3.5 seconds

5-24. How long is the dipping-sonar’s hydrophone/projector cable?

A. 50 feet  
B. 150 feet  
C. 2,000 feet  
D. 2,550 feet

5-25. How is the dome jettisoned when required by an inflight emergency?

A. The operator throws it out of the helicopter.  
B. The operator cuts the cable with an axe.  
C. The pilot activates a guillotine that cuts the cable.  
D. The operator lowers the dome until the cable falls off the reel.
5-26. What remote component displays digital range and bearing information to the pilot?

A. Multipurpose display panel  
B. Azimuth and range indicator  
C. Bearing and range indicator  
D. Recorder scope panel

5-27. What are the three operational modes of a typical dipping-sonar set?

A. Echo-ranging, passive, and communication  
B. Built-in test, echo-ranging, and passive  
C. Recorder, active, and passive  
D. Communication, active, and built-in test

5-28. What component inside the projector provides an output to indicate the dome’s depth?

A. Depth gage  
B. Pressure potentiometer  
C. Stave cylinders  
D. Ceramic ring assembly

5-29. Magnetic anomaly detection systems fall into what category of antisubmarine warfare systems?

A. Acoustic  
B. Active  
C. Nonacoustic  
D. Thermographic

5-30. Which of the following terms best describes magnetic angles of change in an east-west direction?

A. Force  
B. Variation  
C. Deviation  
D. Dip

5-31. The strength of a submarine’s magnetic intensity is known as a magnetic _______.

A. characteristic  
B. response  
C. interruption  
D. moment

5-32. What container holds the helium in a magnetometer?

A. Helium containment unit  
B. Absorption cell  
C. Oscillator coil  
D. Larmor tank
5-33. What system integrates with magnetic anomaly detection systems to provide audio and visual indications that a submarine has been detected?

A. Dipping-sonar  
B. Submarine anomaly detection  
C. Radar  
D. Identification friend or foe  

5-34. You must use special nonferrous tools on which of the following units of the typical magnetic anomaly detection system?

A. Interconnection cables  
B. Detecting set control  
C. Magnetometer head  
D. Amplifier power supply  

5-35. How does the magnetic compensator group reduce the effects of unwanted magnetic interference?

A. Generates a magnetic field to nullify interfering noise  
B. Removes magnetic noise by drawing it away from the magnetometer  
C. Amplifies the magnetometer’s power to reduce impact of interfering noise  
D. Removes all magnetic forces from the magnetometer  

5-36. What unit displays term difference figures, calibration voltages, and built-in test codes for the magnetic compensator group?

A. Azimuth and range indicator  
B. Bearing and range indicator  
C. Magnetic field indicator  
D. Helium magnetometer indicator
End of Book Questions Chapter 6
Radar Circuits

6-1. What unit within the radar data processor functions as the overall system timer?

A. Transmitter
B. Synchronizer
C. Duplexer
D. Traveling wave tube

6-2. Which of the following circuits is well suited as a radar timer?

A. Pulse pair generator
B. Automatic gain control
C. Single-swing blocking oscillator
D. Range gate generator

6-3. In a B-scope application, the output of the thyatron is used for which of the following purposes?

A. Trigger the radar modulator
B. Amplify the receiver gain circuits
C. Inhibit the transmitter pulse
D. Intensify the framing pulses

6-4. What type of waveform does a ringing oscillator generate?

A. Positive going
B. Sinusoidal
C. Square wave
D. Negative going

6-5. A radar system operating in search mode must provide range data that is accurate to within which of the following measurements?

A. 50 percent of its minimum range
B. 50 percent of its maximum range
C. A few percent of its maximum range
D. A few percent of its minimum range

6-6. When can accurate target range be determined in a typical radar range step generator circuit?

A. When the range step sweep voltage is adjusted by the operator.
B. When the operator compares visual sighting with scope presentation.
C. When the range step coincides with the leading edge of the target echo pulse.
D. When the range step coincides with the trailing edge of the target echo pulse.
6-7. What result is achieved by the timing circuit being triggered the instant the leading edge of the transmitted radiofrequency pulse leaves the transmitter?

A. Maximum target range  
B. Minimum target range  
C. Good target resolution  
D. Accurate target range

6-8. Which type of circuit usually stores energy in a line-pulsing modulator?

A. Colpitts oscillator  
B. Pulse forming network  
C. Inverter network  
D. Artificial oscillating network

6-9. With the radar's modulator switch open, the storage element is affected in which of the following ways?

A. It stores no energy  
B. It produces maximum power  
C. It stores a large amount of power  
D. It discharges through the transmitter

6-10. Pulse-forming networks are often insulated by the use of _______.

A. glass.  
B. fiberglass.  
C. oil.  
D. a heat sink.

6-11. Which of the following is an essential function of a modulator switching device?

A. Open suddenly and reach minimum conduction in a fraction of a second  
B. Consume maximum amounts of the power traveling through it  
C. Store massive amounts of energy in its network  
D. Cease conduction at the same speed that it starts conduction

6-12. When will a radar's thyratron modulator switch conduct?

A. For the duration of the trigger pulse  
B. As long as the pulse-forming network is discharging  
C. For a 10 second recharge time  
D. From the moment the radar becomes operational
6-13. What is the effect on the storage element, in relation to the applied voltage, with the addition of a diode to a resonant charging circuit?

A. One-half capacity  
B. Twice the capacity  
C. Same capacity  
D. Four times the capacity

6-14. In a radar receiver microwave mixer, how far are the crystals located from their respective short-circuited waveguide end?

A. Two wavelengths  
B. One wavelength  
C. One-half wavelength  
D. One-quarter wavelength

6-15. What number of paths or loops makes up the loop-control mode of automatic frequency control circuits in a radar receiver?

A. One  
B. Two  
C. Three  
D. Four

6-16. What is the purpose of gated automatic frequency control circuits in radar amplifiers?

A. To gate unwanted signals through for presentation  
B. To compensate for instantaneous automatic gain control  
C. To gate any signal through, no matter how large  
D. To use in anti-jamming circuits

6-17. In a C-scope presentation, what is represented by the horizontal axis?

A. Range only  
B. Height only  
C. Range and bearing  
D. Bearing

6-18. What radar presentation displays an exact replica of the area scanned by the antenna?

A. A-scope  
B. B-scan  
C. Range height indicator  
D. Plan-position indicator
6-19. What does the center of an airborne plan-position indicator normally represent?

A. Location of the target  
B. Location of the radar  
C. Strongest echo return  
D. Location of the airfield

6-20. Which of the following systems use E-scan/range height indicator presentations?

A. Search radar  
B. Search and rescue  
C. Anti-submarine  
D. Carrier approach

6-21. Which of the following is a function of the identification friend or foe system used in commercial air traffic control?

A. Provides coded altitude information  
B. Assist in automatic landing systems  
C. Provides updated weather information  
D. Mask aircraft identity information

6-22. Which modes of identification friend or foe are used by the military for tactical target identification purposes?

A. 1 and 2  
B. 1 and 3/A  
C. 2 and 3/A  
D. 4 and 5

6-23. How many reply pulses are available in identification friend or foe mode 1 operation?

A. 16  
B. 32  
C. 4,096  
D. 8,100

6-24. What is the distance between the framing pulses in modes 1, 2, 3/A, and C in an identification friend or foe system?

A. 2.9 microseconds  
B. 17.4 microseconds  
C. 20.3 microseconds  
D. 20.3 seconds
End of Book Questions Chapter 7
Optic and Infrared Systems

7-1. What component holds the head-up display’s (HUD’s) two optically coated glasses?
   A. Bracket and prism assembly
   B. Combiner assembly
   C. Lower housing assembly
   D. Solar cell assembly

7-2. In what assembly is the desiccant container housed?
   A. Lower
   B. Upper
   C. Control panel
   D. Bracket and prism

7-3. What component produces the head-up display’s (HUD’s) HUD ready and HUD go/no-go
   signals to the display computer?
   A. Deflection control card
   B. Interface and burn protection card
   C. Brightness control card
   D. Built-in test electronics card

7-4. What component provides for main compensation to prevent distortion?
   A. Windshield correction lens
   B. Video electronics card
   C. Solar cell assembly
   D. Raster correction card

7-5. What physically holds the head-up display (HUD) in the correct position?
   A. Bracket and prism assembly
   B. Mobile maintenance cart
   C. Interface device
   D. HUD test fixture

7-6. What controls the amount of ambient light the head-up display (HUD) receives during testing?
   A. Solar cell assembly
   B. Video electronics card
   C. Consolidated Automated Support System (CASS)
   D. Screen interface and burn protection card
7-7. What device holds the head-up display (HUD) seated on the test fixture alignment pins?

A. Interface device (ID)
B. Center jack bolt
C. Cable assembly W201
D. Solar cell adapter

7-8. What device provides the Consolidated Automated Support System (CASS) a signal that the head-up display (HUD) is receiving proper ventilation?

A. Combiner and camera shroud
B. Interface coupling device
C. Solar cell adapter
D. Airflow sensor

7-9. Which of the following is a condition that a target must meet in order to be detected by a forward looking infrared (FLIR) device?

A. Be brightly colored
B. Must exchange energy with its environment
C. Be highly reflective
D. Must have large radar cross-section

7-10. Which of the following characteristics should material used in infrared (IR) optics possess?

A. Have a zero coefficient of thermal expansion
B. Have a soft surface hardness to absorb energy
C. Be opaque at the system’s operational wavelength
D. Be porous to allow moisture absorption

7-11. What type of energy-matter interaction is due to radiant energy changing the electrical conductivity of the detector material?

A. Photoelectric
B. Photoconductivity
C. Photoemissive
D. Thermal

7-12. Which of the following is a component of a typical infrared (IR) imaging system?

A. Traveling wave tube
B. Klystron system
C. Scene dissection system
D. Modulating system

7-13. Which of the following is an advantage of a forward looking infrared (FLIR) system?

A. Has a large radar signature
B. Requires the operator to be in close proximity of target
C. Has the ability to deliver precision guided ordnance at standoff ranges
D. Requires intense analysis prior to using received data
7-14. What unit is mounted to the aircraft and provides connections for power, signal routing, and cooling air to the environmental control unit (ECV)?

A. Electronics control unit  
B. Roll drive housing  
C. Pod electronics housing (PEH)  
D. Pod adapter unit (PAU)

7-15. What unit provides the motor the power to rotate the electro-optical sensor unit (EOSU) 360 degrees?

A. Environmental positioner  
B. Roll drive amplifier (RDA)  
C. Backlash gearing assembly  
D. Roll drive unit (RDU)

7-16. What unit interfaces with the mission computer to perform sensor and target processing?

A. Laser transceiver unit (LTR)  
B. Eurocard modules  
C. Laser electronics unit (LEU)  
D. Electro-optical sensor unit (EOSU)
End of Book Questions Chapter 8
Television

8-1. What is the process in which light from a scene is converted into electrical pulses of varying magnitude?

A. Intermodulated scanning  
B. Transmission scanning  
C. Synchronized scanning  
D. Reflectometry scanning

8-2. What type of video is transmitted to a television display monitor?

A. Blanking  
B. Composite  
C. High definition  
D. Intermediate

8-3. Which of the following devices is a pickup device?

A. Traveling wave tube  
B. Charge coupled director  
C. Vidicon tube  
D. Monochrome monitor

8-4. For which of the following reasons was 60 hertz chosen as television’s synchronization frequency?

A. Increased repetition  
B. Reduced power consumption  
C. Difficulty in heterodyning  
D. Reduced hum

8-5. In regard to a television signal, what method of scanning is the simplest?

A. Interlaced  
B. Monochrome  
C. Noninterlaced  
D. Trinitron

8-6. What term describes a television’s horizontal retrace period?

A. Recovery  
B. Repetitive  
C. Flyback  
D. Flyover
8-7. Interlaced scanning provides what advantage?
   A. Reduced video bandwidth without reducing resolution
   B. Increased video bandwidth without flicker
   C. Reduced video bandwidth with reduced resolution
   D. Increased video flyback time and flicker

8-8. What was the original total number of scanning lines for resolution of fine detail in the horizontal direction in commercial broadcast television?
   A. 100
   B. 200
   C. 300
   D. 525

8-9. The video amplitude values represent (a) what maximum and (b) what minimum of the maximum carrier voltage?
   A. (a) 75 (b) 5
   B. (a) 65 (b) 5
   C. (a) 75 (b) 15
   D. (a) 65 (b) 15

8-10. What is the purpose of a television picture blanking pulse?
   A. To conserve energy during horizontal retrace
   B. To prevent unwanted signals from being displayed on the monitor during retrace
   C. To open the scanning aperture on the pickup device during retrace
   D. To turn the monitor off after a period of inactivity

8-11. What component returns the average picture current to the received video signal?
   A. Direct current restorer
   B. Alternating current inserter
   C. Current compensator
   D. Scanning synchronizer

8-12. Why is synchronization between the camera and the receiver required?
   A. To match scanning beams in order to produce a viewable picture
   B. To conserve energy by coordinating broadcast times
   C. To eliminate unnecessary radiofrequency broadcast
   D. To reduce unwanted electromagnetic interference

8-13. What television pickup device consists of a vacuum tube with a phosphorus coating?
   A. Charge coupled device
   B. Vidicon
   C. Liquid crystal display
   D. Light-emitting diode
8-14. What effect is produced when light from an image is focused on a charge coupled device?

A. Piezoelectric  
B. Triboelectric  
C. Photoelectric  
D. Electrostrictive

8-15. Which of the following is a characteristic of a television camera video amplifier circuit?

A. To increase both low and high frequencies gain equally  
B. To increase low-frequency gain only  
C. To amplify all frequencies equally  
D. To amplify some frequencies more than others

8-16. What percent of the composite video is normally dedicated to synchronization pulses?

A. 15  
B. 25  
C. 50  
D. 75

8-17. What unit in a monitor maintains a stable phase relationship between the vertical and horizontal scanning signals?

A. Tuner  
B. Vidicon  
C. Control unit  
D. Gain control

8-18. Why does the monitor’s control unit maintain the horizontal and vertical scanning signals at a 2:1 ratio?

A. To maintain a stable interlaced scan  
B. To conserve energy by reducing scans  
C. To ensure the scan is not interlaced  
D. To equalized the synchronization pulses

8-19. In a television monitor, what circuit is used to maintain phase lock in the horizontal and vertical sync signals?

A. Cathode follower  
B. Sync generator  
C. Blocking oscillator  
D. Common master oscillator

8-20. What type of mixer combines the sync signal and the composite video signal?

A. Superheterodyne  
B. Simple additive  
C. Direct coupling  
D. Clamping level
8-21. What is the function of a television tuner?
   A. To amplify and mix the input signal and locally generated radiofrequency signal
   B. To amplify the composite video signal to receive a selected channel
   C. To insert synchronization pulse to select narrow intermediate frequency
   D. To amplify and insert composite video into synchronization pulse

8-22. Which of the following statements describes a characteristic of the output of a television receiver’s bridged-T trap?
   A. It is equal to the input.
   B. It is less than the input.
   C. It is 50 to 60 times greater than the undesired signal.
   D. It is 50 to 60 times greater than the desired signal.

8-23. What is the typical frequency range of a television receiver’s video amplifier?
   A. 30 hertz to 4 kilohertz
   B. 30 hertz to 4 megahertz
   C. 30 hertz to 15.750 megahertz
   D. 1 kilohertz to 4 megahertz

8-24. Why is a direct current (dc) restorer required in a television’s video processing circuitry?
   A. To allow the background brightness to differ from the transmitter
   B. To allow the blanking level to vary with the video input
   C. To insert the dc component removed in the tuning stage
   D. To insert the dc component removed in the video amplifier stage

8-25. What type of radio receiver operates in a similar manner as television sound systems?
   A. Frequency modulated
   B. Amplitude modulated
   C. Phase modulated
   D. Pulse modulated

8-26. Which of the following statements describes an advantage of an intercarrier sound system over a split-carrier sound system?
   A. A narrower bandwidth
   B. A greater number of audio stages
   C. Fewer audio stages
   D. A wider bandwidth

8-27. Why are power transistors required when an integrated-circuit (IC) sound system is used?
   A. ICs require external power supplies to operate correctly.
   B. ICs are normally high-gain amplifiers with high-power dissipation.
   C. ICs require large amounts of power to operate.
   D. ICs are normally low-power dissipation devices that cannot power speakers.
8-28. In an integrated-circuit (IC) sound system, the output transformer serves which of the following purposes?

A. To cancel excessive noise from the desired output  
B. To mix the audio with the intermediate frequency  
C. To dissipate excessive heat from the IC  
D. To match the output impedance of the IC to the speaker

8-29. What determines the brightness of the picture displayed by a cathode ray tube?

A. The number and velocity of electrons  
B. The number of neutrons striking the screen  
C. The chrominance of the screen  
D. The type of phosphorus on the screen

8-30. In addition to the color red, a television monitor has what primary colors?

A. Yellow, and blue  
B. Gray, and blue  
C. Green, and blue  
D. Green and black

8-31. How many electron guns are in a typical color cathode ray tube television?

A. One  
B. Two  
C. Three  
D. Four

8-32. In a color television, what device causes the three electron beams to meet at the shadow mask?

A. Restrictor plate  
B. Convergence electrode  
C. Cross-point focus control  
D. Target imager

8-33. Why is a wider bandwidth required in tuners and amplifier stages of color television receivers as compared to monochrome receivers?

A. To represent all colors of spectrum  
B. To uniformly amplify color subcarrier sidebands  
C. To pass only low frequency chrominance signals  
D. To uniformly amplify the brightness control signal
8-34. The purpose of additional video amplifier stages in a color television receiver is to amplify (a) what signal and for (b) what purpose?

A. (a) Composite video signal (b) to drive the focus coil
B. (a) Luminance signal (b) to drive the cathodes of three electron guns
C. (a) Brightness signal (b) to drive a single-electron gun
D. (a) Shadow mask cathode ray tube voltage (b) to drive convergence coil

8-35. What circuits are disabled by the color-killer circuit?

A. The color circuits when a monochrome signal is being received
B. The color signals in a transmitter when a monochrome signal desired
C. The red and blue electron guns ensuring a monochrome display
D. The automatic frequency control circuits allowing only a monochrome display

8-36. What is the function of a television receiver's matrix circuit?

A. To transmit luminance information to transmitting station
B. To provide feedback to the transmitting station synchronizer
C. To reassemble the original camera's chrominance signal
D. To display the vertical and horizontal test signal
End of Book Questions Chapter 9
Computers and Programming

9-1. Which of the following items is considered to be computer hardware?

A. Loops
B. Random access memory
C. Jump and jump returns
D. Termination instructions

9-2. Technical language that provides operational instructions to a computer is considered ________.

A. hardware.
B. clarification statements.
C. software.
D. arithmetic functions.

9-3. Which electrical component holds the data about to be processed?

A. Primary memory
B. Keyboard
C. Display
D. Scanner

9-4. What piece of hardware can be used as temporary random access memory when large programs are being run or large amounts of data are being processed?

A. Auxiliary display unit
B. Digital interface device
C. Read only memory
D. Hard disk drive

9-5. Formula Translator (FORTRAN) is designed for what types of applications?

A. Command and control
B. Graphics and image
C. Scientific and business
D. Entertainment and gaming

9-6. What programming language is used in the APG-73 radar system?

A. Common Business Oriented Language (COBOL)
B. Jovial
C. Java
D. Syntax
9-7. Which of the following types of computer language does the F-35 Lightning II use?

A. Jovial  
B. C++  
C. Formula Translator (FORTRAN)  
D. Tesla

9-8. What type of programming language is being used in many modern military applications?

A. Special purpose  
B. Commercial-off-the-shelf (COTS)  
C. Military centric  
D. Shareware

9-9. What does the term “analog” mean in computer applications?

A. Representation by means of continuously variable physical quantities  
B. Representation by the use of numerical equivalents  
C. Representation by the use of graphic analysis  
D. Representation by the SWAG

9-10. What action may have to be taken to change the operation of a special purpose digital computer?

A. Increase the data input frequency  
B. Update or modify the printer  
C. Change the setwave  
D. Alter the construction of the machine or programming

9-11. What type of computer uses numerical equivalents to represent both the instructions and the data being processed?

A. Analog  
B. Special  
C. Digital  
D. Generic

9-12. What type of computer is easily adapted to a variety of functions by changing the software?

A. Specific purpose  
B. Analog  
C. Special purpose  
D. General purpose

9-13. What section of a central processing unit actually processes the data?

A. Arithmetic logic unit  
B. Control unit  
C. Random access memory  
D. Read only memory
9-14. In the control unit of a typical digital computer, what does the P register contain?

A. The address of the instruction being executed  
B. The instruction word during execution  
C. The address of the next instruction to be executed  
D. The quantity used for address modification

9-15. What central processing unit register holds the instruction code during execution?

A. General  
B. P  
C. Shift count  
D. Instruction

9-16. Devices used to control the transfer of data words from one register to another are known as ________.

A. gates.  
B. processors.  
C. arithmetic units.  
D. read only memory.

9-17. What are the four general categories of computer instructions?

A. Transfer, arithmetic, logic, and control  
B. Bit, byte, digit, and literal  
C. Input, output, shift, and double  
D. Binary, octal, digital, and hexadecimal

9-18. What computer program takes certain commands and translates them into instructions necessary for a computer to execute them?

A. CONVERTOR  
B. INTERPRETER  
C. TRANSLATOR  
D. COMPILER

9-19. What type of instructions controls access to the various subroutines?

A. Operational routines  
B. Executive routines  
C. Selection routines  
D. Access routines
9-20. Which of the following types of instructions provide(s) the computer with the ability to leave the sequential execution of the main program, perform a subroutine, and then return to sequential execution?

A. Sequencing
B. Jump and return jump
C. Executive
D. Encoding

9-21. What data transmission method permits radio use?

A. Serial
B. Parallel
C. Fiber optic
D. Acoustic

9-22. What data transmission method is used when high speed over short distances is required?

A. Serial
B. Analog
C. Parallel
D. Magnetic

9-23. Output information from a computer generally takes which of the following forms?

A. Codes or symbols displayed on a digital display or other device
B. Manually generated control information
C. Information recorded in read only memory
D. Software documentation

9-24. Which of the following statements is a common limitation of manual input devices?

A. They involve some mechanical operation.
B. They are located a great distance from the computer.
C. They require single-phase power.
D. They are not compatible with the computer.

9-25. What is the purpose of an aircraft’s mission computer?

A. Collect data from the battlespace for analysis
B. Process data from peripheral sensors to achieve mission success
C. Provide backup in the event the pilot cannot fly the aircraft
D. Control environmental systems of the aircraft

9-26. Which of the following systems provides aircraft location to the mission computer?

A. Radiofrequency communication
B. Data link
C. Search radar
D. Global positioning/inertial navigation system
9-27. What system aids the pilot in locating unfriendly aircraft and destroying them?

A. Navigation  
B. Data link  
C. Search/track radar  
D. Ordnance

9-28. Airborne early warning aircraft receive tactical instructions from what system?

A. Data link  
B. Communications  
C. Tactical air navigation  
D. Weapons control

9-29. The MEASUREMENT variable has its value set by READ, MEASURE, VERIFY, and what other statement?

A. STORE  
B. MONITOR  
C. EXECUTE  
D. INTERNALIZE

9-30. In Abbreviated Test Language for All Systems (ATLAS) programming, when a DELAY statement is used without a time dimension, what delay-time units should be assumed?

A. Minutes  
B. Seconds  
C. Milliseconds  
D. Microseconds

9-31. What part of an Abbreviated Test Language for All Systems (ATLAS) program uses an END statement?

A. Procedure  
B. Define  
C. Declare  
D. Common

9-32. Which of the following instructions are the two basic forms of Abbreviated Test Language for All Systems (ATLAS) PRINT statements?

A. PRINT, CHARACTER, and PRINT, RESULT  
B. PRINT, MESSAGE, and, PRINT, $  
C. PRINT, MESSAGE, and PRINT, RESULT  
D. PRINT, CHARACTERS and PRINT
End of Book Questions Chapter 10
Waveform Interpretation

10-1. All waveforms can be reduced to their basic components. The basis for these components is the _______.

A. half wave.
B. frequency spectrum.
C. phase wave.
D. sine wave.

10-2. Deviation of a frequency-modulated signal is directly proportional to which of the following characteristics of the modulating signal?

A. Wavelength
B. Phase
C. Frequency
D. Amplitude

10-3. Which of the following statements best describes frequency modulation (FM) index?

A. The deviation voltage divided by the modulation voltage
B. The deviation frequency divided by the modulation frequency
C. The deviation frequency divided by the modulation voltage
D. The deviation voltage divided by the modulation frequency

10-4. What is the maximum output total sideband power attained by 100-percent amplitude modulation (AM) of a carrier?

A. 1/16
B. 1/8
C. 1/4
D. 1/2

10-5. The purpose of broadbanding is to increase the _______.

A. bandwidth.
B. sensitivity.
C. selectivity.
D. amplitude.

10-6. Which of the following methods should you use to stagger tune a circuit?

A. Tune a series of circuit stages to the same frequencies to improve fidelity
B. Tune a series of circuit stages to slightly different frequencies to increase bandwidth
C. Tune a single stage to uncouple a frequency to improve selectivity
D. Tune a single stage to overcouple a frequency to improve frequency response
10-7. A nonsymmetrical “S” curve output from a frequency modulation (FM) discriminator circuit under test most likely indicates which of the following circuit problems?

A. Shorted capacitor in input tank circuit
B. Open secondary transformer coil
C. Marker pulse occurring at zero-amplitude voltage
D. Incorrect primary or secondary transformer tuning

10-8. Which of the following markers in frequency response curves are used to designate exact frequencies?

A. S-curve and stagger-tuned markers
B. Normal and absorption markers
C. Dip and reference-level markers
D. Deviation and time-constant markers

10-9. What is the most common use of intensity (relative brightness) modulation?

A. Tactical air navigation
B. Stereo hi-fi
C. Frequency modulation radio
D. Television

10-10. What axis of the display scope is modulated to obtain intensity modulation?

A. W
B. X
C. Y
D. Z

10-11. Which of the following types of circuits is specifically used to decrease distortion (static) caused primarily by uncontrolled electrical waves associated with thunderstorms and other natural phenomena?

A. Differentiator circuit
B. Limiter circuit
C. Discriminator circuit
D. Integrator circuit

10-12. What form of modulation is particularly affected by static from thunderstorms and other natural phenomena?

A. Frequency
B. Triple
C. Amplitude
D. Variable tuned
10-13. Which of the following types of interference is caused by the random motion of electrons in a conductor?

A. Hum interference
B. Impulse noise
C. Transistor noise
D. Thermal agitation

10-14. The term attenuation describes the amplitude distortion of a signal caused by ________.

A. circuit limitation of bandwidth.
B. integration limitation.
C. discriminator limitation.
D. coupling limitations.

10-15. What is the practical ratio limit of measuring frequency ratios of one sine-wave signal to another?

A. 21:1
B. 10:1
C. 5:3
D. 3:1

10-16. What is the name of the grid on the oscilloscope screen that provides a graph of the X and Y axis?

A. Graticule
B. Beams
C. Phase indicators
D. Angle indicators

10-17. Which of the following formulas should be used to calculate phase difference of two signals of like amplitude and frequency?

A. Sine \( \theta = \frac{-Y\text{-axis intercept}}{X\text{-axis maximum}} \)
B. Sine \( \theta = \frac{-Y\text{-axis intercept}}{Y\text{-axis maximum}} \)
C. Sine \( \theta = \frac{-X\text{-axis maximum}}{Y\text{-axis intercept}} \)
D. Sine \( \theta = \frac{X\text{-axis maximum}}{-X\text{-axis intercept}} \)

10-18. Which of the following changes will occur in a Lissajous pattern if a 60-degree leading phase sine wave, applied to the vertical deflecting plates, is given an additional phase advancement?

A. The eccentricity of the ellipse is reduced.
B. The eccentricity of the ellipse is increased.
C. The ellipse rotates clockwise.
D. The ellipse rotates counterclockwise.
10-19. You are calculating the frequency ratio for various phase relationships using Lissajous patterns. What is the value assigned for (a) a tangent touching a free end of a parabola and (b) a tangent touching a closed loop?

A. (a) 1 (b) 1/2
B. (a) 1/2 (b) 1
C. (a) 1 (b) 1
D. (a) 1/2 (b) 1/2

10-20. When you are working with Lissajous patterns, what are the two main restrictions on the frequencies of signals applied to oscilloscope deflecting plates?

A. The frequencies must lie within the useful band pass of the oscilloscope, and the relationship between the applied frequencies must not result in a pattern too involved for an accurate evaluation of the frequency ratio.
B. The frequencies must lie within the useful band pass of the oscilloscope, and the relationship between the applied frequencies must result in a pattern that indicates ratios of integers.
C. The frequencies may only be in the high-frequency (HF) or very-high-frequency (VHF) range, and the relationship between the applied frequencies must not result in a pattern too involved for an accurate evaluation of the frequency ratio.
D. The frequencies may only be in the HF or VHF range, and the relationship between the applied frequencies must result in a pattern that indicates ratios of integers.

10-21. Which of the following characteristics of a circuit determines the ability of a linear device to cope with intermittent pulses?

A. The ratio of displayed Lissajous pattern
B. The angle of phase difference
C. The degree of transient response
D. The amount of spectrum distribution

10-22. Calculate the wavelength in meters of a 10 MHz frequency.

A. 10 meters
B. 20 meters
C. 30 meters
D. 40 meters

10-23. Which of the following characteristics of signals under test can be best observed using a spectrum analyzer?

A. The frequency drift between two signals
B. The phase relationship between two signals
C. The basic timing of complex signals
D. The wave shape of complex signals
10-24. In single sideband amplitude modulation (AM) long-range high frequency HF communication, which of the following portions of the developing radio frequency (RF) signals are transmitted?

A. The modulated carrier  
B. The carrier and upper sideband  
C. The upper and lower sideband  
D. Either the upper or lower sideband
End of Book Questions Chapter 11
Automatic Test Equipment

11-1. What configuration of Reconfigurable-Transportable Consolidated Automated Support System (RTCASS) tests electronic counter-countermeasure systems (ECCMs)?

A. Hybrid
B. Basic
C. Communication, Navigation, and Identification
D. Electro-Optical

11-2. What version of the Consolidated Automated Support System (CASS) is man-portable and used by expeditionary forces?

A. Hybrid-Mobile CASS
B. Radiofrequency- Mobile CASS
C. Reconfigurable-Transportable CASS
D. Integrated-Transportable CASS

11-3. What configuration of Consolidated Automated Support System (CASS) requires the use of an integrated photonic assets and the collimator housing assembly?

A. Communication, Navigation, and Identification
B. High Power
C. Hybrid
D. Electro-Optical

11-4. What version of Consolidated Automated Support System (CASS) requires an auxiliary display unit (ADU) to allow the technician to read necessary information and make adjustments?

A. High Power
B. Radiofrequency
C. Depot
D. Electro-Optical

11-5. Which Consolidated Automated Support System (CASS) console uses polyalphaolefin as a dielectric?

A. Radiofrequency
B. Power distribution
C. Power
D. Liquid cooling unit
11-6. What is the purpose of the isotropic probe attached to the digital test unit power console?

A. Monitor work space air temperature  
B. Monitor the temperature of the polyalphaolefin  
C. Monitor for hazardous radiation  
D. Monitor transmitter output power

11-7. The electro-optical console is designed to maintain optical alignment between the collimator assembly and the _______.

A. integrated photonic assets.  
B. radiation sensitive detectors.  
C. digital test unit.  
D. automated gyro/gimbal control system.

11-8. What system within the electro-optical console provides a stable platform instrument, transmits, and measures synchro and analog signals?

A. Collimator housing assembly  
B. Automated gyro/gimbal control system  
C. Double rhomboid assembly  
D. Integrated electronics system

11-9. When testing a radar transmitter on a Consolidated Automated Support System (CASS), which button do you press to remove power to the unit in an emergency?

A. EMER OFF UUT  
B. EMER OFF STA  
C. Sequential PWR Down  
D. Power Down icon

11-10. What is the purpose of standing on an approved insulated mat while working on low-voltage equipment?

A. Prevent your feet from getting cold  
B. Prevent electrical shock  
C. Allow easy path for current to ground  
D. Improve point of view

11-11. Who is authorized to allow the bypass of safety interlocks?

A. Quality assurance officer  
B. Maintenance master chief  
C. Electrical officer  
D. Commanding officer
11-12. What component, instrument, or tool is used to discharge voltage from components capable of holding a charge in deenergized equipment?

A. Heavy gage wire  
B. Screwdriver  
C. Shorting probe  
D. Isotropic probe
End of Book Questions Chapter 12

Electrostatic Discharge

12-1. What minimum voltage can result in an electrostatic discharge sensitive device being damaged?

A. 20 volts  
B. 50 volts  
C. 75 volts  
D. 100 volts

12-2. What term describes the generation of static electricity by two objects rubbing together?

A. Dielectric effect  
B. Prime charge  
C. Electrostatic charge  
D. Triboelectric effect

12-3. Under which of the following conditions is the generation of static electricity decreased?

A. Humid air  
B. Hot air  
C. Dry air  
D. Cold air

12-4. What is the best method for determining a piece of electronic equipment’s electrostatic sensitivity?

A. Test for statics potential by walking across carpet  
B. Assume all electronic equipment is sensitive  
C. Ask a senior technician  
D. Rub with a polystyrene foam cup to see if it sparks

12-5. What is the heart of an electrostatic discharge control program?

A. Ungrounded work stations  
B. Antistatic carpet in work centers  
C. Electrostatic discharge safe designed equipment  
D. Electrostatic discharge safe work area

12-6. Which of the following testing methods could be used to verify that equipment was damaged by electrostatic discharge?

A. Visually inspect  
B. Use equipment built-in test  
C. Verify output voltages  
D. Check for reverse current leakage
12-7. What type of electrostatic discharge protective material normally consists of metal and metal-coated materials?

A. Conductive
B. Reactive
C. Antistatic
D. Inductive

12-8. What type of electrostatic discharge protective material is tinted pink?

A. Reactive
B. Conductive
C. Inductive
D. Antistatic

12-9. What type of clothing material should be worn when electrostatic discharge protective smocks are unavailable?

A. Polyester
B. Cotton
C. Linen
D. Wool

12-10. What electrostatic discharge protective material does not generate electrical energy and is not conductive?

A. Antistatic
B. Conductive
C. Hybrid
D. Inductive

12-11. Which of the following type of activities should be avoided when handling electrostatic discharge sensitive devices?

A. Testing equipment with power applied
B. Removing smock
C. Wearing wrist grounding strap
D. Standing on grounded mat

12-12. Which of the following publications provides guidance on packaging electrostatic discharge sensitive materials?

A. NAVSEA OP 3565
B. OPNAVINST 3750.6R
C. MIL-HDBK-773
D. NAVSUP 723