CHAPTER 5

RADAR FUNDAMENTALS

LEARNING OBJECTIVES

After you finish this chapter, you should be able to do the following:

1. Discuss the principles of radar and, using a block diagram, describe the basic functions, principles of operation, and inter-relationships of the basic radar system.
2. Discuss basic radio wave characteristics, including amplitude, cycle, frequency, and wavelength.
3. Discuss what affect radio wave constants such as pulse repetition rate, pulse repetition time, rest time, pulse width, and power have on the minimum and maximum ranges of a radar.
4. Identify the basic types of radar antennas and antenna components and state their uses.
5. Describe the factors that contribute to and detract from the accuracy of a radar.

INTRODUCTION

When you finish this chapter, you should be able to explain the basic principles of radar, both with block diagrams and in terms of the interrelationships between the components of a radar system. Furthermore, you will be able to explain basic radio wave characteristics, constants that affect all radar systems, and common factors that affect the proper operation of radar systems. Finally, you will be able to describe basic radar antenna systems.

EARLY HISTORY OF RADAR

Studying the history of radar is something like learning a magician's tricks. You may not be able to see how the magician makes the rabbit appear, but your mind tells you it didn't come from thin air.

Visible Light

During the 18th century, scientists accepted the theory that visible light is made up of waves of energy. They concluded that light waves have different lengths and that humans can perceive these different wavelengths as different colors. By the early part of the 19th century, scientists had discovered that visible light represents only a small part of the total energy radiated by the Sun. Most of the Sun's energy waves are invisible to the eye because their wavelengths are either too long or too short for the eye to detect. In other words, radiant energy from the Sun covers a spectrum of wavelengths, both visible and invisible.

The characteristics of these invisible waves or rays of energy have since been discovered, and are being used to our benefit. Some of these rays, X rays for example, have wavelengths so short they can penetrate many solid materials, while others, such as the waves emitted by electric power lines, are measured in miles. For the purposes of radar, we are concerned with the type called *radio waves*.

Radio Waves

James C. Maxwell, a Scottish physicist, published his theory of electromagnetism in 1873. In this theory, Maxwell mathematically predicted the existence of radio waves. He theorized that radio waves were the result of changing electrical and magnetic fields and could be created by vibrating an electric charge. Maxwell theorized further that radio waves traveled at the speed of light and would reflect when they struck an object.

In 1888 Heinrich Hertz, a German physicist, performed laboratory experiments that proved that radio waves could be generated and that their characteristics were exactly as predicted by Maxwell.

In 1895 Guglielmo Marconi, an Italian electrical engineer, began a series of experiments aimed at transmitting radio waves over long distances. With equipment modeled after Hertz's apparatus, he succeeded in transmitting signals across the English Channel in 1899. Two years later, he transmitted a radio signal across the Atlantic.

The radio waves that Marconi used to transmit his radio signal happened to be very long waves. The shortest radio waves are called *microwaves*. Both microwaves and longer radio waves are used in the operation of radar. Look at the electromagnetic spectrum, shown in figure 5-1.

DEVELOPMENT OF RADAR

In 1922, Marconi announced that he had noticed the reflection of radio waves by objects many miles away. As a result, he predicted that radio waves could be used to detect objects at great distances.

During that same year, two American scientists working at the Naval Research Laboratory in Washington, D.C., A. Hoyt Taylor and Leo C. Young also recognized the principles of reflected radio waves. Between 1922 and 1930, they conducted further tests which proved the military value of these principles by detecting objects hidden by smoke, fog, or darkness. This was the beginning of radar (RAdio Detection And Ranging) as we know it today.

During the 1930s, alerted by the Taylor-Young experiments, the British developed their own radar. They called it a *radio locator*. By 1940, the British had developed radar to such a degree that they were very successful in detecting and shooting down many enemy aircraft during the Battle of Britain.

Recognizing the importance of radar, the U.S. Navy ordered it for its ships in 1936. The first vessel to use radar was the battleship USS *New York*, in 1938.

During the early days of World War II, people heard about the "magic eye." This mysterious new device could pierce the darkness, fog, and weather to give warning by providing visual presentations of approaching enemy ships and aircraft. It was rumored that distant shore lines, landmarks, and other aids to navigation could also be picked up by the "eye" and displayed on a viewing screen. These rumors were confirmed in 1943 when the United States announced that it had been using an operational radar system for several years.

Since World War II, radar development, both by military and commercial laboratories, has progressed so rapidly that today radar has unlimited uses. Commercially, radar is being used for safety and navigation in aircraft and large and small ships, for tracking aircraft and controlling aircraft landings, for detecting and tracking weather, and for tracking tiny satellites in the vast regions of outer space. Practically all Navy ships now have complex radar systems. We will discuss the principles and operational uses of these systems and their related equipment in this chapter and in others in this book.

PRINCIPLES OF RADAR

The principles upon which radar operates are very similar to the principles of sound-wave reflection. If you shout in the direction of a cliff or some other sound-reflecting surface, you will hear an echo. What actually happens is that the sound waves generated by the shout travel through the air until they strike the cliff. There they are reflected, returning to the originating spot, where you can hear them as weak echoes. A certain amount of time elapses between the instant the sound leaves your mouth and the instant you hear the echo. You notice this time interval because sound waves travel through air at a relatively slow rate (1,100 feet per second). The farther you are from the cliff, the longer this time interval will be. If you are 2,200 feet from the cliff when you shout, about 4 seconds will pass before you hear the echo. In other words, it takes 2 seconds for the sound waves to reach the cliff and 2 seconds for them to return to you.

Radar is an application of radio wave principles. It is possible to detect the presence of objects, to determine their direction and range, and to recognize their character. Detection involves directing a beam of radio-frequency waves over a region to be searched. When the beam strikes a reflecting object, some the beam's energy is reflected. A very small part of this reflected energy is returned to the radar system. A sensitive receiver, located near the transmitter, detects the echo signal and causes it to be presented visually on a viewing scope. The radar system can determine direction (bearing) and range because the receiving system can be made directional and can make extremely small time measurements. This process is illustrated in figure 5-2.

Radar systems may vary greatly in design. Depending on data requirements, they may be simple or complex. But, the principles of operation are essentially the same for all systems. Therefore, we can use a basic radar system to demonstrate the functional performance of any radar system. A basic pulse-modulated radar system consists of several

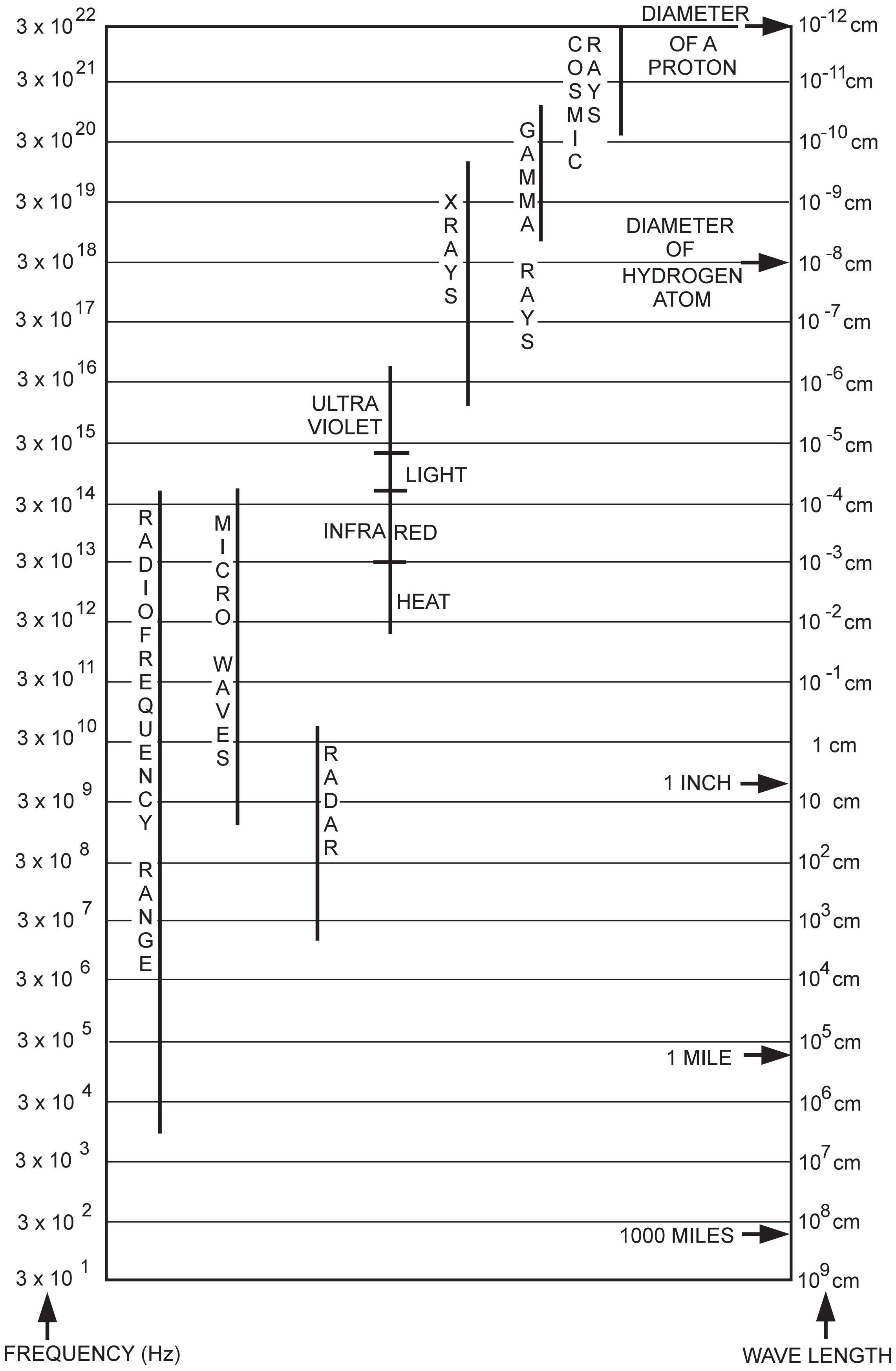

Figure 5-1.—Electromagnetic spectrum.

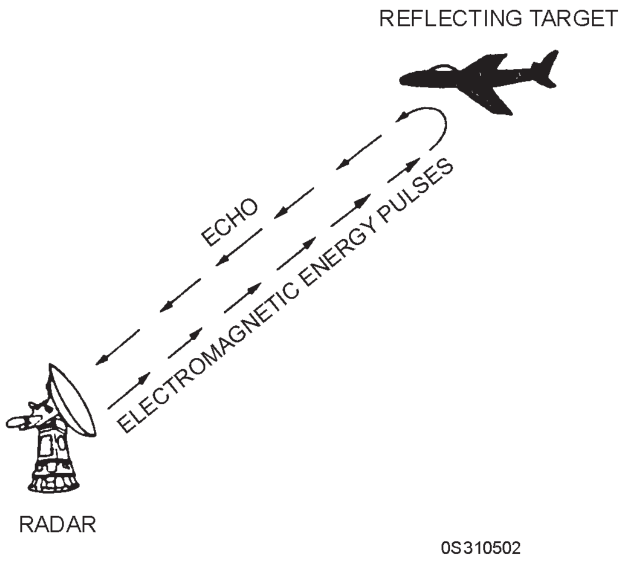

Figure 5-2.—Radar echo.

essential components. These components, shown in figure 5-3, are as follows:

- **Modulator**. The modulator produces the signals that trigger the transmitter the required number of times per second. The modulator also triggers the indicator sweep and coordinates the other associated circuits.
- **Transmitter**. The transmitter generates radio frequency (RF) energy in the form of short, powerful pulses.
- **Duplexer**. The duplexer permits the use of a common transmission line and a single antenna for both transmitting and receiving.
- **Antenna System**. The antenna system takes the RF energy from the transmitter and radiates it in a highly directional beam. The antenna system also receives any returning echoes and passes them to the receiver.
- **Receiver**. The receiver amplifies the weak returning echoes and produces them as video pulses to be applied to the indicator.
- **Indicator**. The indicator produces a visual trace of the area being searched by the radar and accurately displays the returning video echo on this trace.
- **Power Supply**. The power supply (not shown) furnishes all of the dc and ac voltages necessary for the operation of the system components.

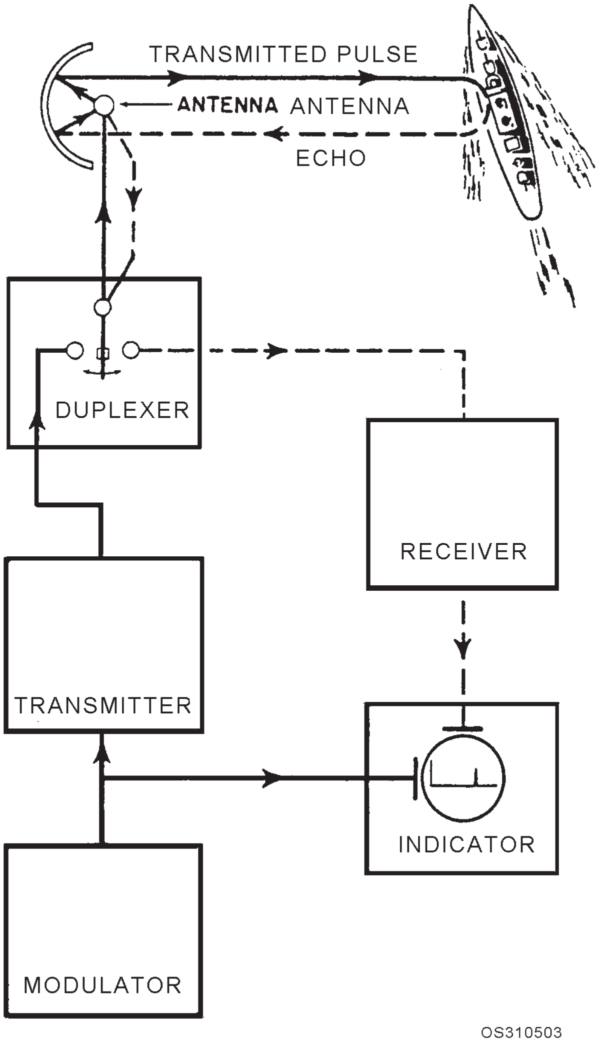

Figure 5-3.—Block diagram of a fundamental radar system.

Q1. What component of a radar system generates the radio frequency energy in the form of short, powerful pulses?

Q2. What component of a radar system amplifies weak returns and presents them as video pulses?

RADIO WAVE CHARACTERISTICS

Radio frequency (RF) waves travel through space at the speed of light—186,000 *statute* miles per second. You will see this speed used in most commercial publications on radar. In the Navy, however, all distances are expressed in terms of the *nautical* mile. The nautical mile is actually slightly longer than 6,000 feet, but the Navy uses 6,000 feet (or 2,000 yards) as a nautical mile for all gunnery, navigation, and radar applications. Therefore, for naval purposes, the speed of light is 164,000 nautical miles, or 328,000,000 yards, per second.

Radio waves have four basic characteristics: **amplitude, cycle, frequency**, and **wavelength.**

Amplitude is the measure of a wave's energy level. It is the maximum instantaneous value of the wave's alternating current, measured in either a positive or a negative direction from the average level.

A *cycle* is one complete reversal of an alternating current, starting at zero and going through a positive peak, then a negative peak, and back to zero. See figure 5-4

Wave *frequency (f)* is the number of cycles occurring in 1 second. The standard unit of measurement of radio frequency (RF) is the *hertz*. One cycle per second is equal to 1 hertz (Hz). Most radio frequencies are expressed in kilohertz (1 kHz = 1,000 hertz) or in megahertz (1 MHz = 1,000,000 hertz).

Since cycles occur at a regular rate, a definite interval of time is required to complete each cycle. This time interval is known as the wave's *period* (T). Mathematically, the time required for one cycle is the reciprocal of the wave's frequency; that is, $T=1/f$. A wave that has a frequency of 200,000,000 hertz has a period of 0.000,000,005 second.

Wavelength (λ) is the space occupied by one cycle; it may vary from several miles to a fraction of an inch. Wavelength is usually measured in meters, but on occasion it is expressed in feet. Since a radio wave travels at a constant speed, wavelength may be determined by dividing wave velocity (v) by wave frequency (f).

Q3. What are the four basic characteristics of radio waves?

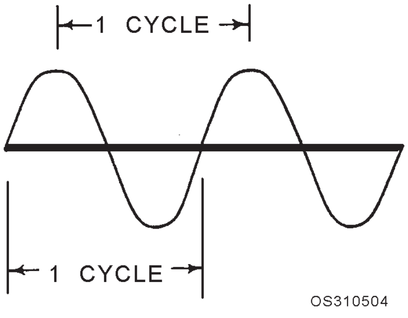

Figure 5-4.—The cycle.

RADAR SYSTEM CONSTANTS

Earlier you learned that radio waves travel through space at 164,000 nautical miles per second. This is a constant that is common to all radars. It is one of several constants that you must be familiar with to gain maximum performance from your radar equipment. Every radar system has a certain set of constants, based on its tactical use, accuracy required, range to be covered, and physical size. (Although the term *constant is* used, some characteristics are often variable, such as pulse repetition rate and pulse width.). We discuss some of those constants below.

CARRIER FREQUENCY

Carrier frequency (f_c) is the frequency at which the transmitter operates. System designers base the selection of this frequency on the desired directivity and range of the radar. The carrier frequency, in turn, dictates the physical size of the radar antenna.

Inside radar transmitters, specially constructed electron tubes, called magnetrons, generate and amplify RF energy. The output frequency of this energy is the radar's carrier frequency. As long as the pulse from the modulator is applied, the magnetron will continue to oscillate. The modulator, then, determines how often and for how long the RF oscillator is turned on.

PULSE REPETITION RATE (PRR)

The modulator turns the transmitter on long enough for it to put out a short pulse of RF energy, and then turns it off for a relatively long period. During the long period between pulses, the receiver "listens" for a returning echo. The number of times the transmitter is turned on each second is known as the *pulse repetition rate (PRR)* of the radar. For example, a radar that is turned on 500 times each second has a pulse repetition rate of 500 pulses per second (pps).

PULSE REPETITION TIME

Pulse repetition time varies inversely with pulse repetition rate; that is, PRT = 1/PRR. A radar having a PRR of 500 pps, for example, has a PRT of 0.002 second, or 2,000 microseconds.

REST TIME

Rest time (RT) is the time between radar pulses. It is during this time that the radar receiver "listens" for returning echoes.

PULSEWIDTH

Pulsewidth (PW) is the actual time that a radar transmits. The duration of the trigger pulse from the modulator to the transmitter determines the pulse width of a radar. Since the amount of energy transmitted during each radar pulse is proportional to pulsewidth, a radar's pulsewidth affects its detection range. The chances of detecting distant targets are better if more energy is transmitted. For this reason, a long-range search radar normally has a very large pulsewidth. Figure 5-5 shows the relationship between PRR, PRT, RT, and PW.

POWER RELATIONSHIP

There are two types of RF power associated with a radar transmitter: peak power and average power. *Peak power* is the power contained in the radiated pulse. This is the useful power of the transmitter. Peak power only occurs while the transmitter is transmitting. If the value of peak power is spread over an entire "operating-resting" transmitter cycle, it becomes a lower value, called *average power.* Because the radar transmitter rests for a long period of time, average power is relatively low compared to peak power.

You should have noticed by now that all of the constants are related in some manner. Consider the following relationships. If all other factors remain constant, the greater the pulsewidth, the higher the average power. Also; the longer the pulse repetition time, the lower the average power. These general relationships are shown in Figure 5-6.

The constants also affect the radar's physical characteristics. Every transmitter has an operating (duty) cycle. The duty cycle is simply the ratio (expressed as a percentage) of the time the transmitter spends transmitting RF energy to the entire time it is on during a transmit-rest cycle. Since the physical size of many electronic components is determined by the amount of power they have to radiate, the physical size of a radar transmitter is determined by its average power requirement, which is indicated by its duty cycle.

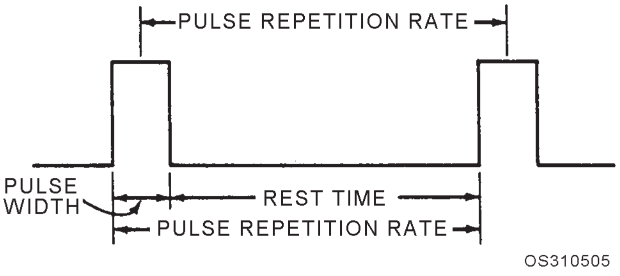

Figure 5-5.—Radar pulse relationships

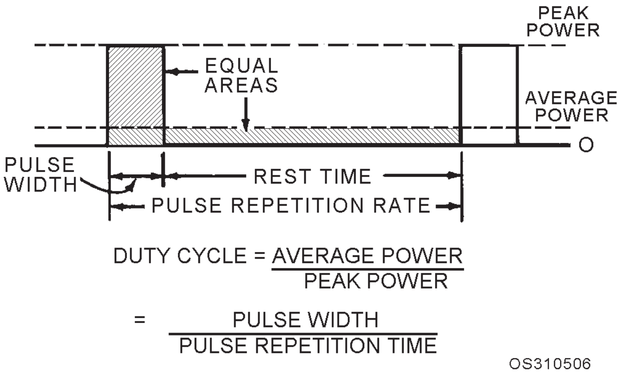

Figure 5-6.—Relationship of peak power and average power.

The transmitter's pulse repetition rate also affects the radar's physical size. A transmitter with a low PRR can provide very high peak power with reasonably low average power. A high peak power is desirable in order to produce a strong echo over the maximum range of the equipment. On the other hand, low average power permits the transmitter tubes and circuit components to be smaller and more compact. Thus, it is advantageous to have a low PRR (reflected by a low duty cycle).

TIME-RANGE RELATIONSHIP

The radar indicator (scope) provides a video presentation of the targets detected by the radar system. The indicator is basically a timing device that accurately displays, on a time base (sweep), the positions of radar targets. It does this by computing the time lapse between the instant the radar is pulsed and the instant the radar detects a returning echo. See figure 5-7. Each time the modulator triggers the radar transmitter, it also triggers the sweep in the indicator and starts the timing. The sweep moves across the scope for a period of time equal to the PRT of the radar. At the end of this time, the radar pulses again, and the indicator sweep jumps back to its point of origin and starts all over again. If an echo returns during the sweep time, the radar receiver instantaneously converts it into a video signal and applies it to the indicator on a grid that indicates the range of the target from the radar. Depending on the type of indicator, target pips are

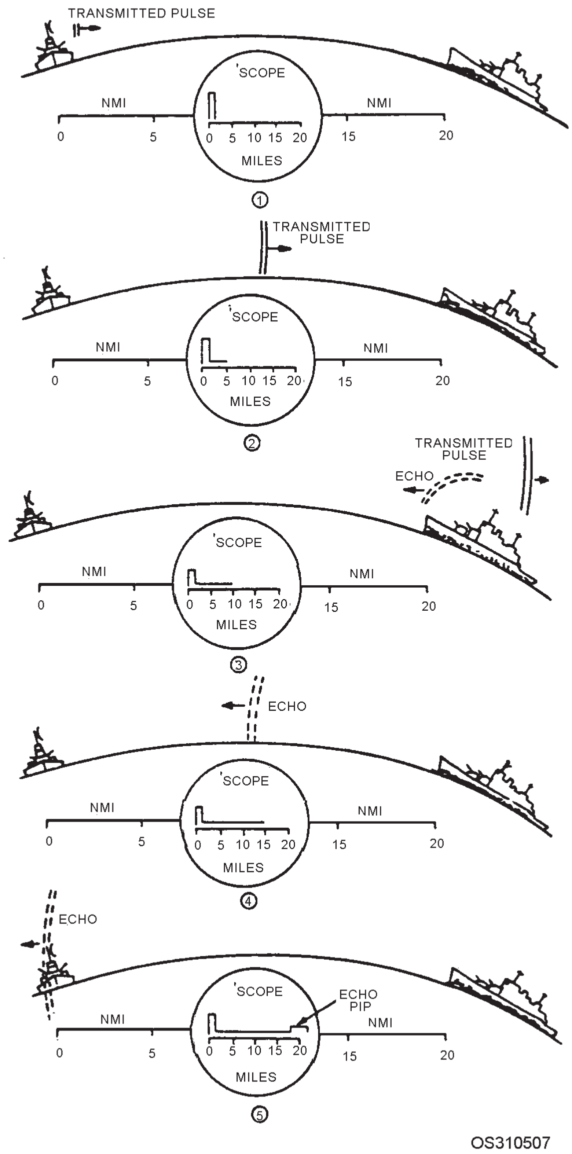

Figure 5-7.—Radar range determination.

displayed either as vertical displacements on a horizontal sweep or as intensified spots on a circular sweep.

The propagation velocity of RF energy is 328 yards per microsecond (μs). Search radars are calibrated on the basis of 2,000 yards per nautical mile, which provides sufficient accuracy for their function. For search radars, then, it takes 6.1 μs for an RF pulse to travel 1 nautical mile, or 12.2 μs per radar nautical mile (round-trip distance).

Assume that a pulse of 1 μs duration is transmitted toward a ship 20 nautical miles away. In part 1 of Figure 5-7, the pulse is just leaving the antenna. In part 2, 61 μs later, the pulse has traveled 10 nautical miles toward the target. The scope is marked off in nautical miles, and at this point the horizontal trace on the scope has reached only the 5-nautical-mile mark, or half the distance actually traveled by the pulse. In part 3, the pulse has reached the target 20 nautical miles away; the echo has started back, and part of the transmitted pulse continues beyond the target; 122 μs have elapsed, and the scope reads 10 nautical miles. In part 4, 183 μs after the start of the initial pulse, the echo has returned half the distance from the target. In view 5, the echo has returned to the receiver, and a pip is displayed on the scope at the 20-nautical mile mark. Actual distance traveled by the pulse is 40 nautical miles, and total elapsed time is 244 μs.

Various kinds of indicators are used as radar repeaters. The most familiar indicator in use today is the plan position indicator (PPI).

The PPI scope (fig. 5-8) provides a bird's-eye view of the area covered by the radar. Your ship is in the center. The sweep originates in the center of the scope and moves to the outside edge. This straight-line sweep is synchronized with the radar antenna and rotates 360°. Therefore, the PPI provides bearing and range information. Each time a target is detected it appears as an intensified spot on the scope.

To obtain target position, the PPI is equipped with a bearing cursor and a range strobe. The bearing cursor, like the sweep, appears as a bright line. It can be rotated manually through 360°. Bearing information is obtained by rotating the cursor to the center of the target. The target bearing is then read directly from the bearing dial. The range strobe appears as a bright spot riding on the cursor. As the range crank is turned clockwise, the strobe moves out from the center. Range is obtained by placing the strobe on the leading edge (edge closest to the center of the PPI) of the target. The target range is then read directly from the range dials, either in nautical miles or yards.

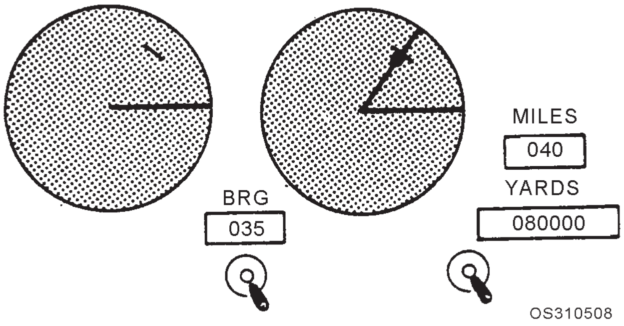

Figure 5-8.—(U) PPI displays.

MAXIMUM RANGE

One of the factors considered when a radar is being designed is the range to be covered. Many of the system constants have some effect on maximum range. But the constant that has the most effect is the PRR. Therefore, we say that the maximum theoretical range of a radar is determined by the PRR.

Sufficient time must be allowed between each transmitter pulse for an echo to return from any target located within the maximum range of the system. If the PRR is increased, the time between pulses decreases. This means that the transmitter pulse travels a shorter distance before the radar pulses again. Therefore, the range covered by the radar is decreased when the PRR is increased.

Suppose you need to determine the maximum theoretical range of a radar. One formula you may use, if you know the radar's PRT, is:

$$\text{maximum range} = \frac{PRT}{12.2} \text{ (in } \mu\text{s)}$$

Suppose radar #1 has a PRR of 500 pps, with a PRT of 2,000 μs. The maximum theoretical range is 164 nautical miles, computed as follows:

$$\text{maximum range} = \frac{2{,}000}{12.2} = 164 \text{ nautical miles}$$

Now consider radar #2, which has a PRR of 2,000 pps. The PRT is 500 microseconds (1/2,000 pps), and the maximum theoretical range is 41 nautical miles.

$$\text{maximum range} = \frac{500}{12.2} = 41 \text{ nautical miles}$$

Another formula you can use to determine maximum theoretical range is the following:

$$\text{maximum range} = \frac{82{,}000}{PRR}$$

Considering round trip time at the speed of light, we know that RF energy will travel 82,000 nautical miles and return in 1 second. The total distance traveled, of course, is 164,000 nautical miles; thus, the 82,000 factor in our second formula. Now apply this formula to the two radars we just discussed.

For radar #1:

$$\text{maximum range} = \frac{82{,}000}{500} = 164 \text{ nautical miles}$$

For radar #2:

$$\text{maximum range} = \frac{82{,}000}{2{,}000} = 41 \text{ nautical miles}$$

As you can see, the end result is the same using either of the two methods. The situation will dictate which of the two methods you should use. The important point is that you understand both methods.

If all conditions were perfect, the *actual* maximum range capabilities of a radar would be equal to the theoretical maximum range. However, a target is seldom detected at the maximum theoretical range, because many other factors affect the actual maximum range. You cannot determine the effects of these factors mathematically; but since they exist, we will discussed them at this point.

Frequency. Radio-frequency waves are attenuated as they travel through space (We will explain attenuation later.). The higher the frequency, the greater the attenuation. Lower frequencies, therefore, have generally been superior for use in long-range radars.

Pulsewidth. The longer the pulsewidth, the greater the range capabilities. If the amount of radiated energy is increased, the chances of detecting targets at greater ranges are increased.

Beamwidth. A more concentrated beam has a greater range capability since it provides higher energy density per unit area.

Antenna rotation rate. The slower an antenna rotates, the greater the detection range of the radar. When the antenna rotates at 10 rpm, the beam of energy strikes each target for one-half the time it would if the rotation were 5 rpm. During this time, a sufficient number of pulses must be transmitted in order to return an echo that is strong enough to be detected. Long-range search radars normally have a slower antenna rotation rate than radars designed for short-range coverage.

Target composition. Targets that are large can be detected at greater ranges. Conducting materials, such as metals, give the best reflections. Non-conducting materials, such as wood, return very weak echoes. An aircraft carrier will be detected at a greater range than a destroyer will. Likewise, a metal craft will be detected at a greater range than a wooden craft of comparable size.

Receiver sensitivity. A more sensitive receiver will detect a weak echo sooner. Radar receivers are tuned frequently to ensure maximum performance.

MINIMUM RANGE

We know that RF energy travels at the rate of 328 yards per microsecond. If an echo is received 1 microsecond after a radar pulses, the range to the target is 164 yards. The energy traveled 164 yards to the target and 164 yards back to the radar system, a total distance of 328 yards, in 1 microsecond. Here again, we must consider round-trip distance. For radar ranging, in terms of yards, the velocity is considered to be one-half of its true value, or 164 yards of range per microsecond. This principle is applied in determining the minimum range of a radar.

The minimum range at which a target can be detected is determined largely by the width of the transmitted pulse. If a target is so close to the radar that the echo is returned to the receiver before the transmitter is turned off, the reception of the echo will be masked by the transmitter pulse. For example, a radar that has a PW of 1 microsecond cannot detect an echo returned within 1 microsecond. In other words, this particular radar cannot detect a target located within 164 yards. The formula for minimum range is:

minimum range = PW (in μs) $\times$ 164.

If a radar has a PW of 5 microseconds, its minimum range is

PW $\times$ 164 = 5 $\times$ 164 = 820 yards.

This means that any target located within 820 yards of this radar will not be detected. Only those targets located at distances greater than 820 yards will be detected.

Receiver recovery time also affects minimum range. So that the receiver will be protected while the radar is transmitting, the path to the receiver is blocked. When the transmission ends, an electronic switch is triggered and a very slight delay is created. This delay is called receiver recovery time. Although normally quite small, receiver recovery time does have some effect on minimum range.

RANGE RESOLUTION

Individual contacts in a group do not show up separately on a scope unless there is sufficient distance between them. The ability of a radar to give separate indications of individual targets is called *resolution*. Range resolution is the ability of a radar to distinguish between two targets on the same bearing but at slightly different ranges. See figure 5-9. Range resolution, like minimum range, is determined by the pulsewidth of the radar.

Energy is reflected from a target for the duration of the transmitted pulse. To the radar that has a pulsewidth of 1 microsecond, every target appears to be 164 yards wide. If a 1-microsecond pulse is sent toward two objects that are on the same bearing but separated by 164 yards, the leading edge of the echo from the distant target will coincide in space with the trailing edge of the echo from the nearer target (fig. 5-10). As a result, the echoes from the two objects will blend into a single pip, and range can be measured only to the nearer object.

For a radar to distinguish between two targets on the same bearing, they must be separated by a distance greater than PW × 164. For instance, a radar that has a PW of 3 microseconds will distinguish each of two targets on the same bearing if they are separated by a distance greater than 3 × 164, or 492 yards.

Q4. What radar constant is the actual time the radar transmits?

Q5. To determine maximum range of a radar, what radar constant must you know?

ANTENNA SYSTEMS

We mentioned earlier that radar systems are used to obtain range and bearing information on targets. Antennas are the primary devices that allow radar systems to provide this information. Some of the early radars used single, omnidirectional antennas for both

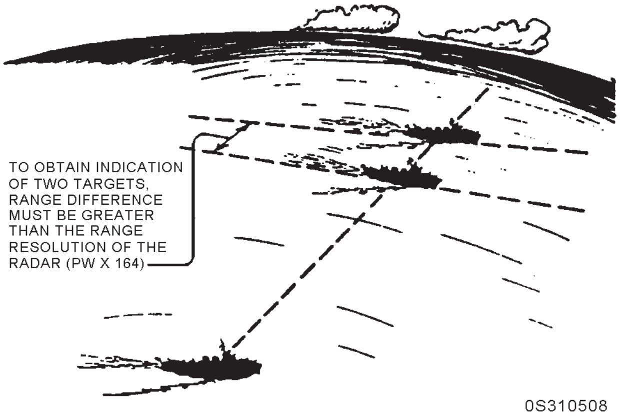

Figure 5-9.—Range resolution.

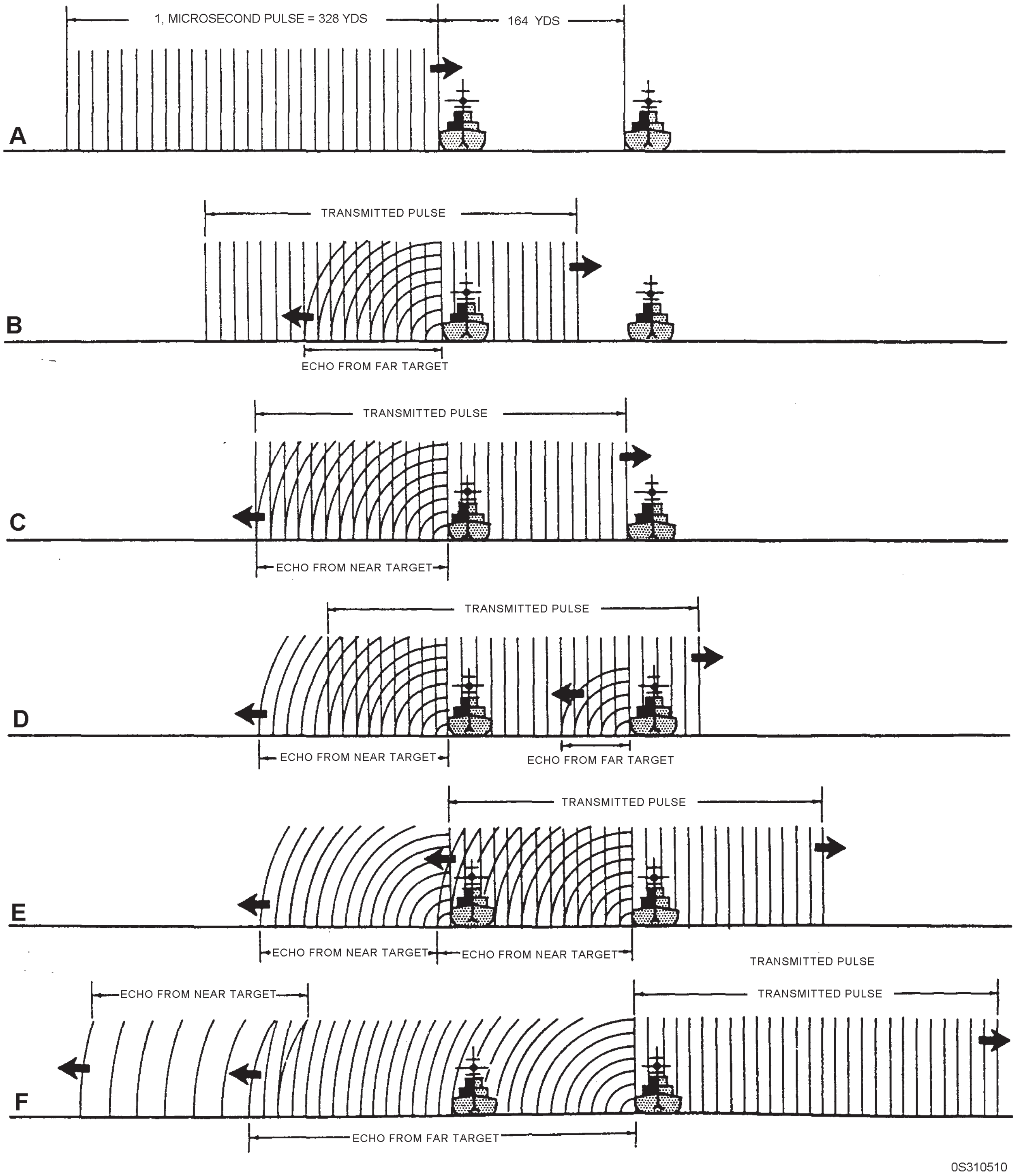

Figure 5-10.—Minimum target separation required for range resolution.

sending and receiving. Others used two antenna systems, one for transmitting and one for receiving. Neither of these methods is acceptable in search radar applications today because they can provide only range information.

Today's search radars use a single rotating antenna or a fixed antenna with a rotating beam. Each of these antennas radiates the energy from the transmitter in a specific direction that continually changes. It then receives returning echoes and passes them to the receiver. A typical single radar antenna system consists of the following three essential components:

1. An antenna that radiates the RF energy as a concentrated beam and receives any returning echoes. (In general, the term *antenna* is applied to the entire antenna array, which includes the actual radiating element and associated directors and reflectors.)
2. Transmission lines to conduct the RF energy from the transmitter to the antenna and from the antenna to the receiver.
3. An electronic switch (duplexer) that alternately shifts the system between transmit and receive functions.

ANTENNAS

An antenna can be as complex as the AN/SPY-1 fixed array found on AEGIS ships or as simple as the parabolic reflector used with the AN/SPS-67 radar. Each antenna operates basically in the same manner but will provide different presentations and information to the operator.

Radar antennas radiate RF energy in patterns of LOBES or BEAMS that extend outward from the antenna in only one direction for a given antenna position. The radiation pattern also contains minor lobes, but these lobes are weak and normally have little effect on the main radiation pattern. The main lobe may vary in angular width from one or two degrees for some antennas to 15 to 20 degrees for other antennas. The width depends on the radar system's purpose and the degree of accuracy required.

Directional antennas have two important characteristics, DIRECTIVITY and POWER GAIN. The *directivity* of an antenna refers to the degree of sharpness of its beam. If the beam is narrow in either the horizontal or vertical plane, the antenna is said to have high directivity in that plane. Conversely, if the beam is broad in either plane, the directivity of the antenna in that plane is low. Thus, if an antenna has a narrow horizontal beam and a wide vertical beam, the horizontal directivity is high and the vertical directivity is low.

When the directivity of an antenna is increased, that is, when the beam is narrowed, less power is required to cover the same range because the power is concentrated. Thus, the other characteristic of an antenna, *power gain*, is introduced. This characteristic is directly related to directivity.

The power gain of an antenna is the ratio of its radiated power to that of a reference (basic) dipole. The higher the gain of an antenna, the more efficient the antenna. The gain of a particular antenna is determined the manufacturer or another designated agency using laboratory-type measurement techniques. The basic dipole has long been used as the basic standard for measuring gain. During gain measurements, both antennas are excited or fed in the same manner and radiate from the same position. A single point of measurement for the power-gain ratio is set up within the radiation field of each antenna. An antenna with high directivity has a high power gain, and vice versa. The power gain of a single dipole with no reflector is unity. An array of several dipoles in the same position as the single dipole and fed from the same line has a power gain of more than one; the exact figure depending on the directivity of the array.

Common Antenna Types

We mentioned earlier that one of the purposes of an antenna is to focus the transmitted RF energy into a beam having a particular shape. In the next few paragraphs, we will discuss the more common shapes of antennas and the beams they produce.

PARABOLIC REFLECTOR.— Radio waves (microwaves) behave similarly to light waves. Both travel in straight lines; both may be focused and reflected. If radio waves are radiated from a point source into open space, they will travel outward in a spherical pattern, like light waves from a light bulb. This spherical pattern is neither too sharp nor too directive. To be effective, radio waves must be sharply defined, with a PLANE wave front, so that all of the wave front moves move forward in the same direction. A parabolic reflector is one means of changing a spherical wave front into a plane wave front.

In figure 5-11, a point-radiation source is placed at the focal point **F.** The field leaves this antenna with a spherical wave front. As each part of the wave front reaches the reflecting surface, it is shifted 180, degrees in phase and sent outward at angles that cause all parts of the field to travel in parallel paths. Because of the shape of a parabolic surface, all paths from **F** to the reflector and back to line **XY** are the same length. Therefore, all parts of the field arrive at line **XY** the same time after reflection.

If a dipole is used as the source of radiation, there will be radiation from the antenna into space (dotted lines in figure 5-11) as well as toward the reflector.

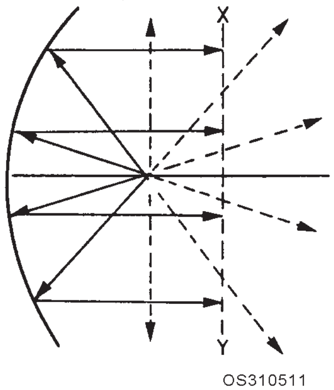

Figure 5-11.—Parabolic reflector radiation.

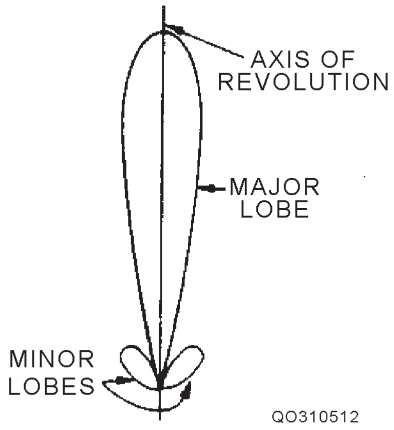

Figure 5-12.—Parabolic radiation pattern.

Energy that is not directed toward the paraboloid has a wide-beam characteristic that would destroy the narrow pattern from the parabolic reflector. This occurrence is prevented by the use of a hemispherical shield (not shown) that directs most radiation toward the parabolic surface. By this means, direct radiation is eliminated, the beam is made sharper, and power is concentrated in the beam. Without the shield, some of the radiated field would leave the radiator directly. Since it would not be reflected, it would not become a part of the main beam and thus could serve no useful purpose. The same end can be accomplished through the use of a PARASITIC array, which directs the radiated field back to the reflector, or through the use of a feed horn pointed at the paraboloid.

The radiation pattern of a parabola contains a major lobe, which is directed along the axis of revolution, and several minor lobes, as shown in figure 5-12. Very narrow beams are possible with this type of reflector. View A of figure 5-13 illustrates the parabolic reflector.

Truncated Paraboloid.—View B of figure 5-13 shows a horizontally truncated (cut off) paraboloid. Since the reflector is parabolic in the horizontal plane, the energy is focused into a narrow horizontal beam. With the reflector truncated, so that it is shortened vertically, the beam spreads out vertically instead of being focused. Since the beam is wide vertically, it will detect aircraft at different altitudes without changing the tilt of the antenna. It also works well for surface search radars to overcome the pitch and roll of the ship.

The truncated paraboloid reflector may be used in height-finding systems if the reflector is rotated 90 degrees, as shown in view C. Because the reflector is now parabolic in the vertical plane, the energy is focused into a narrow beam vertically. With the reflector truncated, or cut, so that it is shortened horizontally, the beam spreads out horizontally instead of being focused. Such a fan-shaped beam can be used to determine elevation very accurately.

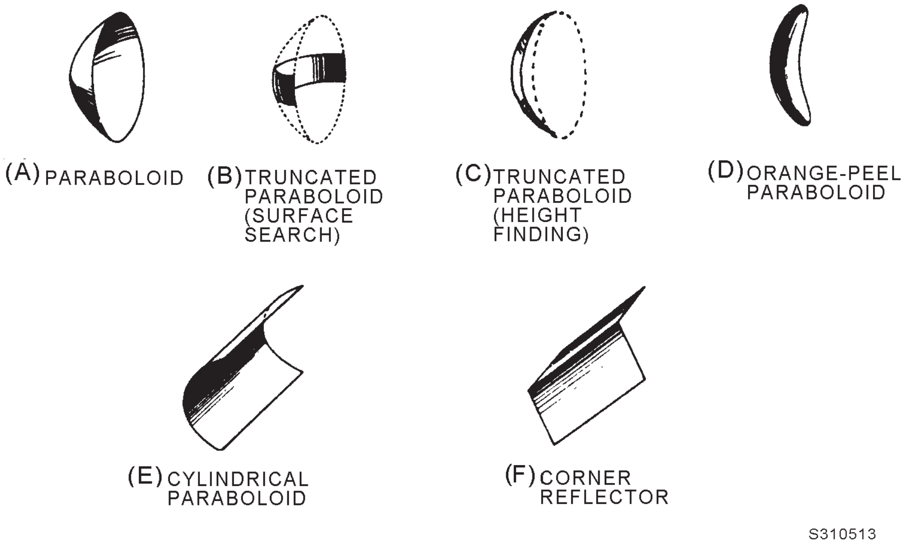

Figure 5-13.—Reflector shapes.

Orange-Peel Paraboloid.—A section of a complete circular paraboloid, often called an ORANGE-PEEL REFLECTOR because of its shape, is shown in view D of figure 5-13. Since the reflector is narrow in the horizontal plane and wide in the vertical, it produces a beam that is wide in the horizontal plane and narrow in the vertical. In shape, the beam resembles a huge beaver tail. This type of antenna system is generally used in height-finding equipment.

Cylindrical Paraboloid.—When a beam of radiated energy noticeably wider in one cross-sectional dimension than in the other is desired, a cylindrical paraboloidal section approximating a rectangle can be used. View E of figure 5-13 illustrates this antenna. A parabolic cross section is in one dimension only; therefore, the reflector is directive in one plane only. The cylindrical paraboloid reflector can be fed by a linear array of dipoles, a slit in the side of a wave guide, or by a thin wave guide radiator. Rather than a single focal point, this type of reflector has a series of focal points forming a straight line. Placing the radiator, or radiators, along this focal line produces a directed beam of energy. As the width of the parabolic section is changed, different beam shapes are obtained. This type of antenna system is used in search and in ground control approach (gca) systems.

BROADSIDE ARRAY.—The desired beam widths are provided for some vhf radars by a broadside array. The broadside array consists of two or more half-wave dipole elements and a flat reflector. The elements are placed one-half wavelength apart and parallel to each other. Because they are in phase, most of the radiation is perpendicular or broadside to the plane of elements.

SPECIAL ANTENNA TYPES.—The 3-D (air search, surface search, and height finder) radars use an antenna composed of several horizontally positioned dipole arrays stacked one on top the other. The antenna is frequency sensitive and radiates multiple frequency RF pulses, each at an elevation angle determined by the pulse's frequency. Figure 5-14 shows an example of a 3-D antenna.

The *fixed-array* antenna is the radar antenna of the future. It has numerous radiating/receiving elements placed into the face of the antenna. These elements transmit the pulse and receive the returning echoes. The fixed array antenna (Figure 5-15) is also a 3-D antenna.

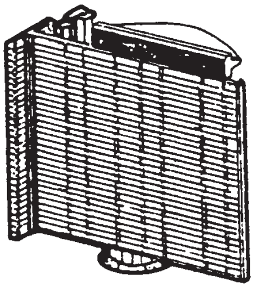

Figure 5-14.—3-D frequency scanning antenna.

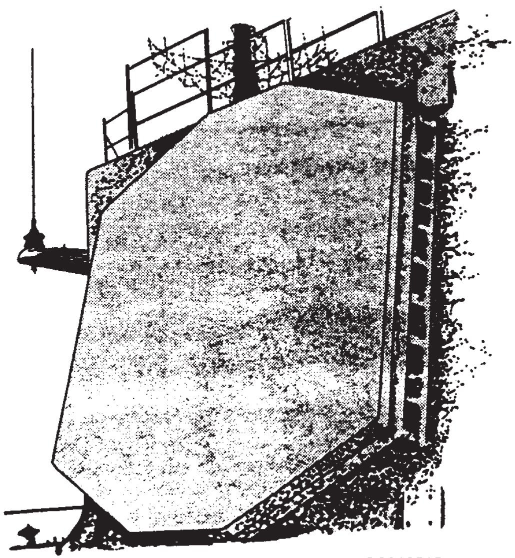

Figure 5-15.—Fixed array antenna.

ANTENNA COMPONENTS

A radar system is made up of several pieces of equipment. The antenna must be able to receive RF energy from the transmitter and to provide returning RF energy to the receiver.

To accomplish these tasks, a radar system uses transmission lines to connect the antenna to the transmitter and the receiver and a duplexer to allow the use of one antenna for both transmitting and receiving.

Transmission Lines

Transmission lines may be described as any set of conductors used to carry signals or energy from one location to another. In radar systems, they are used to carry RF energy to and from the antenna. Various types of transmission lines can be used, depending on the frequency of the radar. The two most common types are coaxial cables and waveguides.

A *coaxial cable* (fig. 5-16) consists of one conductor surrounded by another, the two being insulated from each other. The efficiency of coaxial cable decreases as frequency increases. Therefore, it is normally used only in radars that operate in the lower frequency ranges.

A *waveguide* is a hollow pipe made of a metal alloy and is either circular or rectangular in shape. This configuration allows RF energy to be transferred with very little loss in power. The size of a waveguide is determined by the frequency and power requirements of the radiated energy. In the case of the rectangular waveguide (fig. 5-17), the longer dimension is equal to one-half the wavelength of the lowest frequency it must pass. The shorter dimension determines the power-handling capability.

Duplexer

The duplexer is an electronic switching device that permits fitting a radar with a single antenna for both transmitting and receiving. During transmission, the duplexer connects the transmitter to the antenna and disconnects the receiver. This isolates the sensitive receiver from the high-powered transmitter pulse. For close targets to be seen, the duplexer must disconnect the transmitter and connect the receiver to the antenna immediately after transmission. During the reception time, the transmitter is isolated so that the returning echoes are channeled straight into the receiver with a minimum loss in signal strength.

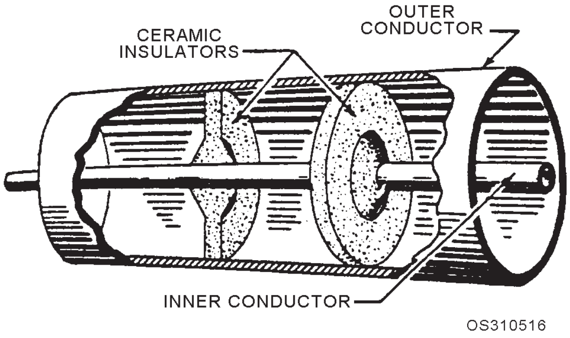

Figure 5-16.—Cross section of a coaxial cable.

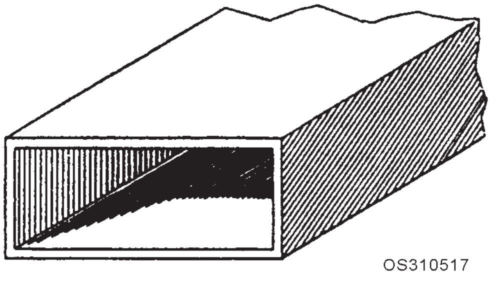

Figure 5-17.—Waveguide.

Q6. What type of radar antenna is generally used for height-finding radars?

Q7. What determines the size of the waveguide for a particular radar?

FACTORS AFFECTING RADAR OPERATION

Several factors affect radar operation. The most important of these are (1) *atmospheric conditions*, (2) *sea return*, (3) *weather*, and (4) *target height in relation to antenna height*.

ATMOSPHERIC CONDITIONS

The characteristics of the medium through which waves pass affect the manner of their transmission. Although we often assume that both light and radar waves follow straight paths, the composition of the atmosphere sometimes causes the waves to follow curved paths. Atmospheric conditions can also cause abnormally long or abnormally short radar ranges. Under certain conditions, a target that might normally be detected at 20 nautical miles may be detected at 125 nautical miles. Or the target may not be detected at all. Every radar operator must become familiar with these conditions and their causes and effects. The primary conditions that you must be familiar with are *refraction*, *diffraction*, *attenuation*, and *ducting*.

Refraction

A natural property of light rays (and radio waves) is that the direction of their transmission path changes as they pass between media having different densities. This phenomenon is called *refraction.* You can see light waves refract at sunrise and sunset. If light traveled only in a straight path, none of the sunlight would be visible whenever the Sun is below the horizon. However, this is not the case. In the short time just before sunrise and just after sunset, the sky toward the Sun is colored bright red. This is because the lower frequency rays of the sunlight, which are in the red area of the light spectrum, are refracted toward the Earth by the atmosphere, allowing you to see them. It follows, then, that lower frequency waves are affected most by refraction. Refraction is another reason why most long-range radars operate in the low frequency ranges. If it weren't for refraction, the radar horizon would be the same as the visual horizon, when in reality; the radar horizon is approximately 25 percent farther away than the visual horizon.

Diffraction

The means by which a wave bends around the edges of an object and penetrates into the shadow region behind it is called *diffraction*. Because of diffraction, radar is sometimes capable of detecting a ship located on the opposite side of an island, or an aircraft flying behind a mountain peak.

Attenuation

Attenuation is the scattering and absorption of energy as it passes through a medium. Gases and water vapor in the atmosphere absorb some of the radio wave energy. The higher the frequency, the greater the absorption of energy.

Ducting (or trapping)

The temperature and moisture content of the atmosphere normally decrease with height above the surface of Earth. Under certain conditions, temperature may first decrease with height and then begin to increase. Such a situation is called a *temperature inversion*. The moisture content may decrease more rapidly than normal with height just above a body of water. This effect is called *moisture lapse*. Either a temperature inversion or moisture lapse, alone or in combination, may produce significant changes in refraction in the lower altitudes of the atmosphere, causing the radar signal to be “trapped” between two atmospheric layers for a certain distance, like water in a pipe. This condition may greatly extend or reduce radar ranges, depending on the direction in which the waves are bent. This is illustrated in figure 5-18.

A serious consequence of ducting is that it can mislead radar operators regarding the overall performance of their equipment. Long-range echoes caused by ducting have frequently been assumed to indicate that the equipment is in good condition when the opposite was true.

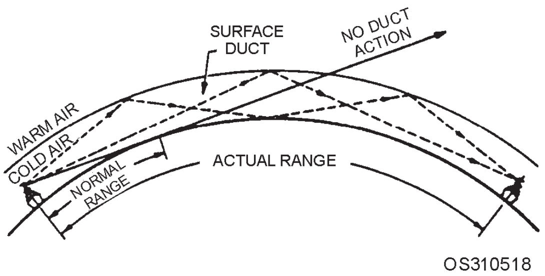

Figure 5-18.—Ducting effect on the radar wave.

SEA RETURN

Some of the energy radiated by a radar strikes the surface of the sea near the ship. Most of this energy is reflected off the waves at various angles away from the ship. Some of it is reflected back to the radar where it is detected as target echoes. These echoes are called *sea return*. In very calm waters there is almost no sea return. In rough weather, however, sea return may extend for several miles in the up-sea direction. It is very difficult to see actual targets located within the sea return because their pips are lost in the clutter of echoes caused by the sea return. Figure 5-19 illustrates how sea return appears on the PPI scope. Radars are equipped with special circuits to reduce the effects of sea return. We will discuss the manipulation of the controls for these circuits in a later chapter.

WEATHER

Since water is a very good reflector, microwave radars are very effective in detecting storm clouds and rainsqualls; large storms may completely clutter a radarscope. However, an operator can usually recognize the pips caused by ships, aircraft, or land when the scope is cluttered by weather. Pips caused by weather are normally very large and fuzzy or misty in appearance, while pips caused by ships, aircraft, or land are bright and well defined.

HEIGHT

Radar antenna and target heights are factors that help determine the initial detection range of a target. The higher the radar antenna, the greater the detection

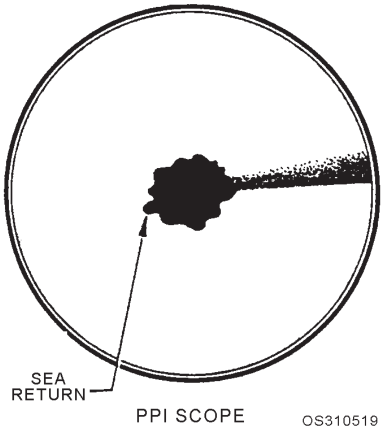

Figure 5-19.—Sea return on a PPI.

range, because the radar's field of "vision" is extended. The higher the target is above the water, the sooner it will enter the radar's field of vision. A high-flying aircraft will be detected at a far greater range than a ship; a mountain will be seen before a low coastline; and an aircraft carrier will be picked up sooner than a destroyer.

The radar range nomogram (fig. 5-20) is a convenient means of predicting the initial detection range of a particular target by your ship's radars. The height of your ship's antenna is plotted on the **h scale,** and the height of the target is plotted on the **H scale**. A line is then drawn from the point on the **h scale** to the point on the **H scale**. The point at which the line crosses the **R scale** is the predicted initial detection range. For instance, if your radar antenna is 100 feet above the waterline, an aircraft flying at 10,000 feet should be detected at 135 nautical miles. You should be aware, however, that nomogram-predicted ranges may not always be realized because of variations in atmospheric conditions (ducting) and equipment capabilities. Therefore, you must not take the predicted range capabilities as absolute.

Q8. What atmospheric condition exists when radio waves bend around the edge of an object and penetrate into the shadow region behind the object?

ANSWERS TO CHAPTER QUESTIONS

A1. Transmitter.

A2. Receiver.

A3. Amplitude, Cycle, Frequency, and Wavelength.

A4. Pulse width.

A5. Pulse Repetition Time (PRT).

A6. range-peel paraboloid.

A7. The frequency and power requirements for the radar.

A8. Diffraction.

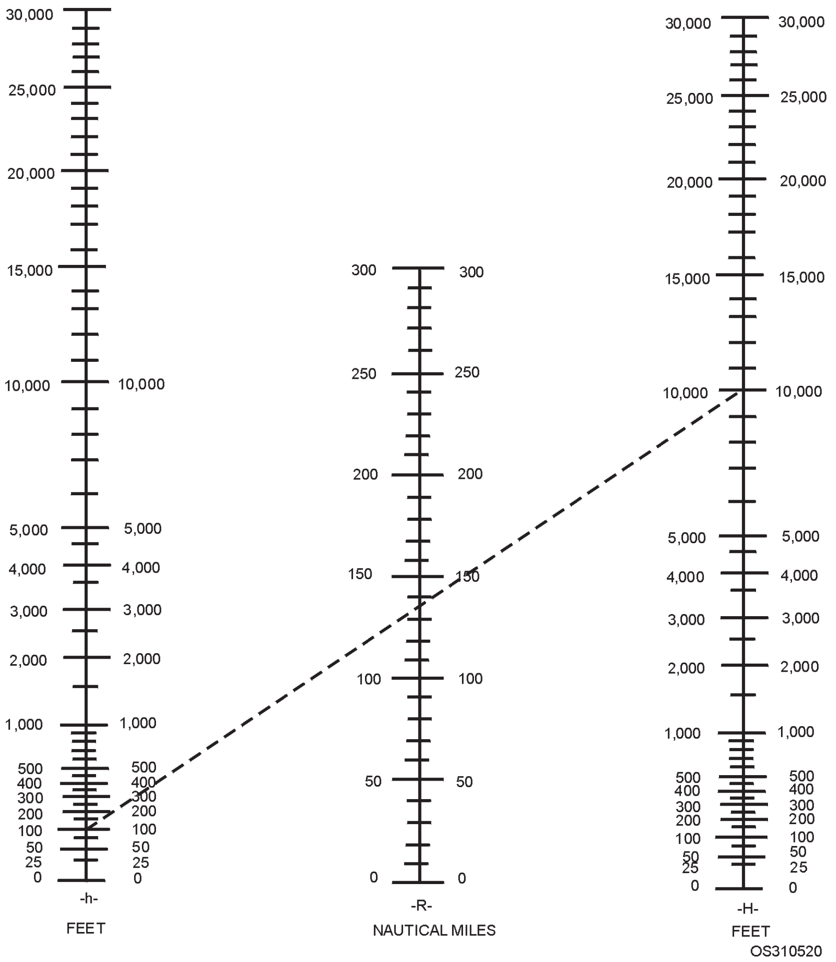

Figure 5-20.—Radar range nomogram.