TC 9-64

COMMUNICATIONS-ELECTRONICS FUNDAMENTALS

Wave Propagation, Transmission Lines, and Antennas

JULY 2004

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Communications-Electronics Fundamentals: Wave Propagation, Transmission Lines, and Antennas

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Preface

This manual is a reference text for trainees and other personnel in the communications-electronics field. It provides information about wave propagation, transmission lines, and antennas. This manual also identifies important safety practices to follow when working with electromagnetic radiation.

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Unless this publication states otherwise, masculine nouns and pronouns do not refer exclusively to men.

Chapter 1

Wave Propagation

The methods used to propagate (transmit) waves through space are based on the same physical principles today as they were 70 years ago. In this chapter, we discuss propagation theory on an introductory level, without going into the technical details that concern the engineer. Understanding wave propagation requires you to use your imagination to visualize the associated concepts and how they are used in practical application. To help you in this process, this chapter includes many illustrations and step-by-step descriptions that guide you from simple concepts to more complex ideas. This chapter covers the fundamentals of wave propagation and the physical factors that affect propagation. Many of the principles discussed are observable in common, everyday occurrences with which you are already familiar.

LEARNING OBJECTIVES

1-1. Learning objectives are included at the beginning of each chapter and serve as a preview of the information you are expected to learn. Comprehensive check questions are included at the end of the chapters and are based on the learning objectives. Upon completing this chapter, you should be able to do the following:

- State what wave motion is; define the terms reflection, refraction, and diffraction; and describe the Doppler effect.
- State what sound waves are and define a propagating medium.
- List and define terms as applied to sound waves, such as cycle, frequency, wavelength, and velocity.
- List the three requirements for sound.
- Define pitch, intensity, loudness, and quality and their application to sound waves.
- State the acoustical effects that echoes, reverberation, resonance, and noise have on sound waves.
- Define light waves and list their characteristics.
- List the various colors of light and define the terms reflection, refraction, diffusion, and absorption as applied to light waves.
- State the difference between sound waves and light waves.
- State the electromagnetic wave theory and list the components of the electromagnetic wave.

WHAT IS PROPAGATION?

1-2. Early man was quick to recognize the need to communicate beyond the range of the human voice. To satisfy this need, he developed alternate methods of communication, such as hand gestures, beating on a hollow log, and smoke signals. Although these methods were effective, they were still greatly limited in range. Eventually, the range limitations were overcome by the development of courier and postal systems; but there was then a problem of speed. For centuries the time required to deliver a message depended on the speed of a horse.

1-3. During the latter part of the nineteenth century, both distance and time limitations were largely overcome. The invention of the telegraph made possible instantaneous communication over long wires. Then a short time later, man discovered how to transmit messages in the form of radio waves.

1-4. As you will learn in this chapter, radio waves are propagated. Propagation means “movement through a medium.” Light rays most easily illustrate this concept. When a light is turned on in a darkened room, light rays travel from the light bulb throughout the room. When a flashlight is turned on, light rays also radiate from its bulb, but are focused into a narrow beam. You can use these examples to picture how radio waves propagate. Like the light in the room, radio waves may spread out in all directions. They can also be focused (concentrated) like the flashlight, depending upon the need. Radio waves are a form of radiant energy, similar to light and heat. Although they can neither be seen nor felt, their presence can be detected through the use of sensitive measuring devices. The speed at which both forms of waves travel is the same; they both travel at the speed of light.

1-5. You may wonder why you can see light but not radio waves, which consist of the same form of energy as light. The reason is that you can see only what your eyes can detect. Your eyes can detect radiant energy only within a fixed range of frequencies. Because the frequencies of radio waves are below the frequencies your eyes can detect, you cannot see radio waves.

PRINCIPLES OF WAVE MOTION

1-6. All things on the land, or in the water are showered continually with waves of energy. Some of these waves stimulate our senses and can be seen, felt, or heard. For instance, we can see light, hear sound, and feel heat. However, there are some waves that do not stimulate our senses. For example, radio waves, such as those received by our portable radio or television sets, cannot be seen, heard, or felt. A device must be used to convert radio waves into light (TV pictures) and sound (audio) for us to sense them.

1-7. A wave can be defined as a disturbance (e.g., sound, light, radio waves) that moves through a medium (e.g., air, water, vacuum). To help you understand what is meant by “a disturbance that moves through a medium,” picture the following illustration. You are standing in the middle of a wheat field. As the wind blows across the field toward you, you can see the wheat stalks bending and rising as the force of the wind moves into and across them. The wheat appears to be moving toward you, but it isn’t. Instead, the stalks are actually moving back and forth. We can then say that the "medium" in this illustration is the wheat and the "disturbance" is the wind moving the stalks of wheat.

1-8. Wave motion can be defined as a recurring disturbance advancing through space with or without the use of a physical medium. Wave motion, therefore, is a means of moving or transferring energy from one point to another point. For example, when sound waves strike a microphone, sound energy is converted into electrical energy. When light waves strike a phototransistor or radio waves strike an antenna, they are likewise converted into electrical energy. Therefore, sound, light, and radio waves are all forms of energy that are moved by wave motion. We discuss sound waves, light waves, and radio waves later in this chapter.

WAVE MOTION IN WATER

1-9. A type of wave motion familiar to almost everyone is the movement of waves in water. We explain these waves first to help you understand wave motion and the terms used to describe it.

1-10. Basic wave motion can be shown by dropping a stone into a pool of water (see figure 1-1). As the stone enters the water, a surface disturbance is created, resulting in an expanding series of circular waves.

Figure 1-1. Formation of Waves in Water

1-11. Figure 1-2 is a diagram of this action. View A shows the falling stone just an instant before it strikes the water. View B shows the action taking place at the instant the stone strikes the surface, pushing the water that is around it upward and outward. In view C, the stone has sunk deeper into the water, which has closed violently over it causing some spray, while the leading wave has moved outward. An instant later, the stone has sunk out of sight, leaving the water disturbed as shown in view D. Here the leading wave has continued to move outward and is followed by a series of waves gradually diminishing in amplitude. Meanwhile, the disturbance at the original point of contact has gradually subsided.

1-12. In this example, the water is not actually being moved outward by the motion of the waves, but up and down as the waves move outward. The up and down motion is transverse, or at right angles, to the outward motion of the waves. This type of wave motion is called transverse wave motion.

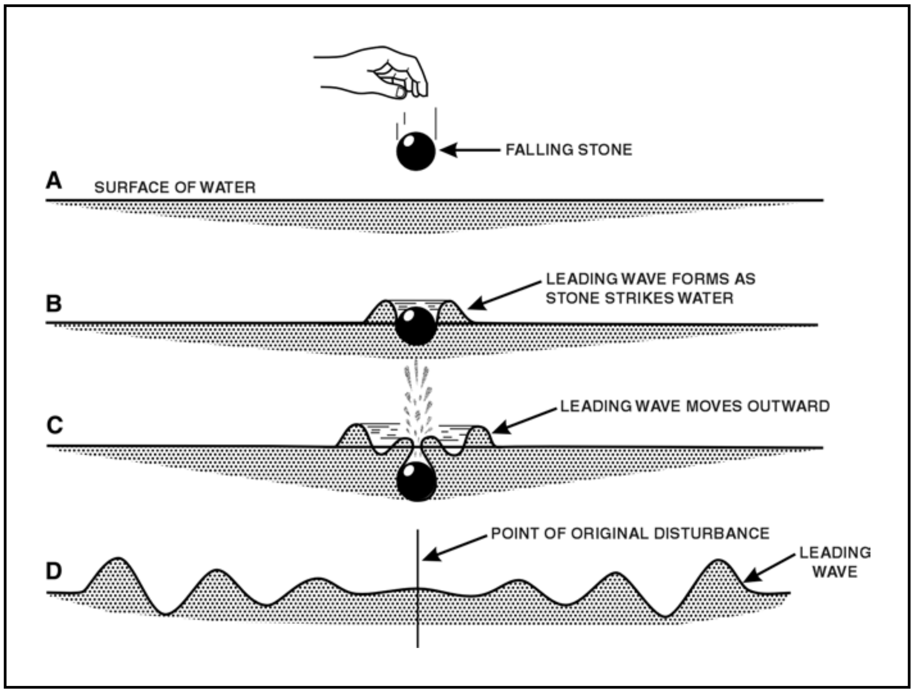


Figure 1-2. How a Falling Stone Creates Wave Motion on Water's Surface

TRANSVERSE WAVES

1-13. To explain transverse waves, we again use our example of water waves. Figure 1-3 is a cross-section diagram of waves viewed from the side. Notice that the waves are a succession of crests and troughs. The wavelength (one 360-degree cycle) is the distance from the crest of one wave to the crest of the next, or between any two similar points on adjacent waves. The amplitude of a transverse wave is half the distance measured vertically from the crest to the trough. Water waves are known as transverse waves because the motion of the water is up and down, or at right angles to the direction in which the waves are traveling. You can see this by observing a cork bobbing up and down on water as the waves pass by; the cork moves very little in a sideways direction.

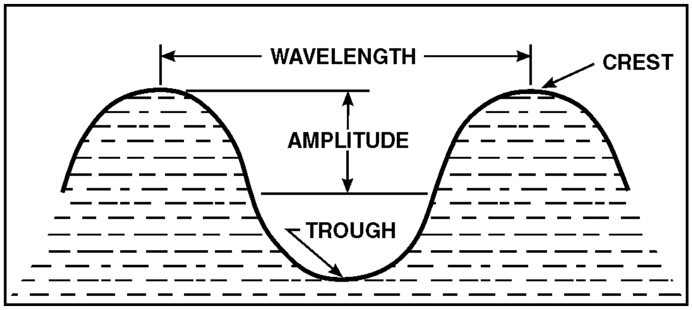


Figure 1-3. Elements of a Wave

1-14. In figure 1-4, the small arrows show the up-and-down direction the cork moves as the transverse wave is set in motion. The large arrow shows the direction the wave travels. Radio waves, light waves, and heat waves are examples of transverse waves.

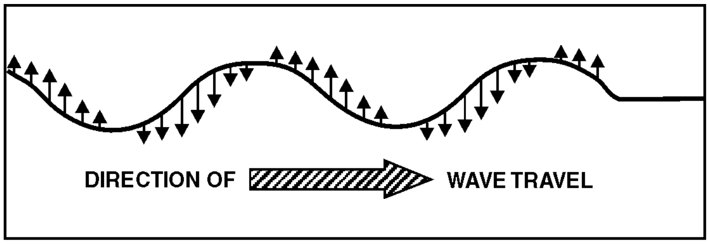


Figure 1-4. Transverse Wave

LONGITUDINAL WAVES

1-15. In the previous discussion, we listed radio waves, light waves, and heat waves as examples of transverse waves, but we did not mention sound waves. Why? Simply because sound waves are longitudinal waves. Unlike transverse waves, which travel at right angles to the direction of propagation, sound waves travel back and forth in the same direction as the wave motion. Therefore, longitudinal waves are waves in which the disturbance takes place in the direction of propagation. Longitudinal waves are sometimes called compression waves.

1-16. Waves that make up sound, such as those set up in the air by a vibrating tuning fork, are longitudinal waves. When struck, the tuning fork in figure 1-5 sets up vibrations. As the tine moves in an outward direction, the air immediately in front of it is compressed (made more dense) so that its momentary pressure is raised above that at other points in the surrounding medium (air). Because air is elastic, the disturbance is transmitted in an outward direction as a compression wave. When the tine returns and moves in the inward direction, the air in front of the tine is rarefied (made less dense or expanded) so that its pressure is lowered below that of the other points in the surrounding air. The rarefied wave is propagated from the tuning fork and follows the compressed wave through the medium (air).

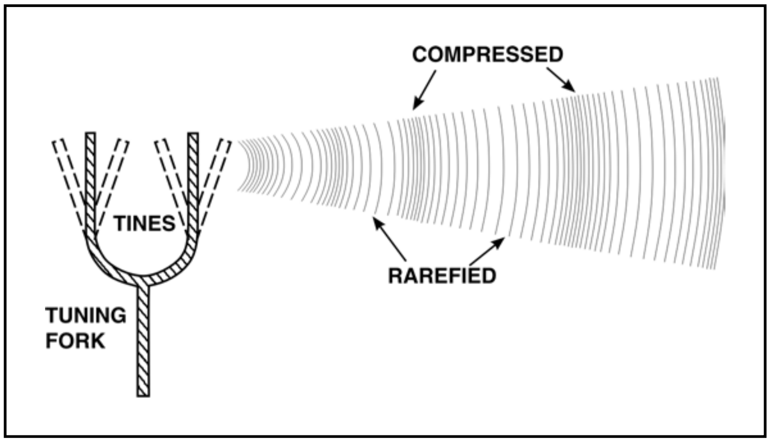


Figure 1-5. Sound Propagation by a Tuning Fork

MEDIUM

1-17. We have used the term medium in describing the motion of waves. Because medium is a term that is used frequently in discussing propagation, it needs to be defined so you will understand what a medium is and its application to propagation.

1-18. A medium is the vehicle through which the wave travels from one point to the next. The vehicle that carries a wave can be just about anything. An example of a medium, already mentioned, is air. Air, as defined by the dictionary, is the mixture of invisible, odorless, tasteless gases that surrounds the earth (the atmosphere). Air is made up of molecules of various gases (and impurities). We will call these molecules of air particles of air or simply particles. Figure 1-6 can help you to understand how waves travel through air. The object producing the waves is called the source—a bell in this illustration. The object responding to the waves is called a detector or receiver; in this case, the human ear. The medium is air, which is the means of conveying the waves from the source to the detector. The source, detector, and medium are all necessary for wave motion and wave propagation (except for electromagnetic waves, which require no medium). The waves shown in figure 1-6 are sound waves. As the bell is rung, the particles of air around the bell are compressed and then expanded. This compression and expansion of particles of air set up a wave motion in the air. As the waves are produced, they carry energy from particle to particle through the medium (air) to the detector (ear).

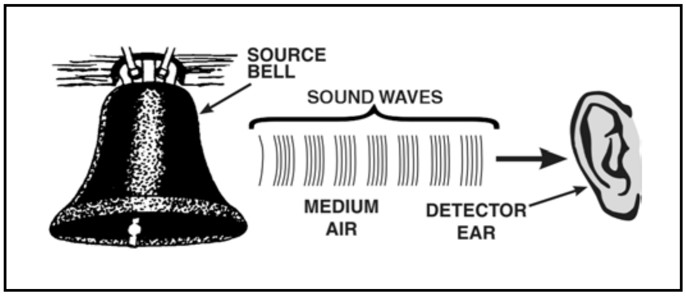


Figure 1-6. The Three Elements of Sound

TERMS USED IN WAVE MOTION

1-19. There are a number of special terms concerning waves that you should know. Many of the terms, such as cycle, wavelength, amplitude, and frequency, were introduced in TC 9-60. We now discuss these terms in detail as they pertain to wave propagation. Before we begin our discussion, however, note that in figure 1-7, wave 1 and wave 2 have equal frequency and wavelength but different amplitudes. The reference line (also known as rest position or point of zero displacement) is the position that a particle of matter would have if it were not disturbed by wave motion. For example, in the case of the water wave, the reference line is the level of the water when no wave motion is present. With this in mind, let us go on to our discussion of the four terms, as shown in figure 1-7.

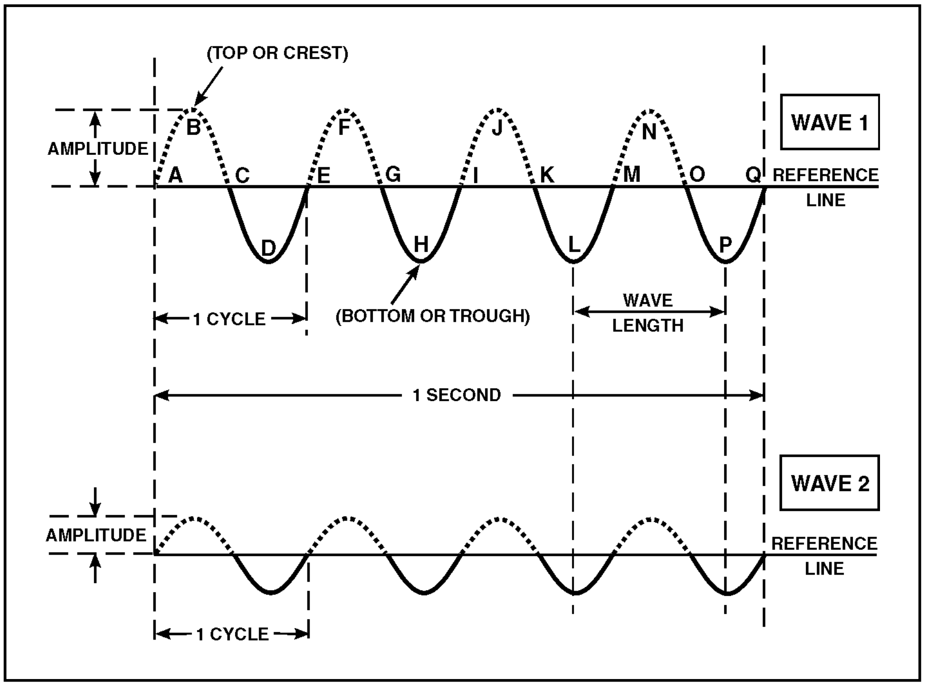


Figure 1-7. Comparison of Waves with Different Amplitudes

Wave Cycles

1-20. Refer to wave 1 in figure 1-7. Notice how similar it is to the sine wave you have already studied. All transverse waves appear as sine waves when viewed from the side. In figure 1-7, wave 1 has four complete wave cycles. Points ABCDE comprise one complete cycle having a maximum value above and a maximum value below the reference line. The portion above the reference line (between points A and C) is called a positive alternation and the portion below the reference line (between points C and E) is known as a negative alternation. The combination of one complete positive and one complete negative alternation represents one cycle of the wave. At point E, the wave begins to repeat itself with a second cycle completed at point I, a third at point M, and so forth. The peak of the positive alternation (maximum value above the line) is sometimes referred to as the top or crest, and the peak of the negative alternation (maximum value below the line) is sometimes called the bottom or trough, as depicted in the figure. Therefore, one cycle has one crest and one trough.

Wavelength

1-21. A wavelength is the distance in space occupied by one cycle of a radio wave at any given instant. If the wave could be frozen in place and measured, the wavelength would be the distance from the leading edge of one cycle to the corresponding point on the next cycle. Wavelengths vary from a few hundredths of an inch at extremely high frequencies to many miles at extremely low frequencies; however, common practice is to express wavelengths in meters. In figure 1-7 (wave 1), the distance between A and E, or B and F, etc., is one wavelength. The Greek letter lambda (λ) is used to signify wavelength. Why lambda and not "l" or "L"? This is because "L" is used conventionally as the symbol for inductance, and “l” is used for dimensional length; therefore, λ is used to indicate the length of waves.

Amplitude

1-22. Two waves may have the same wavelength, but the crest of one may rise higher above the reference line than the crest of the other. Compare wave 1 and wave 2 of figure 1-7 again. The height of a wave crest above the reference line is called the amplitude of the wave. The amplitude of a wave gives a relative indication of the amount of energy the wave transmits. A continuous series of waves, such as A through Q, having the same amplitude and wavelength, is called a train of waves or wave train.

Frequency and Time

1-23. Time is an important factor in wave studies. When a wave train passes through a medium, a certain number of individual waves pass a given point in a specific unit of time. For example, if a cork on a water wave rises and falls once every second, the wave makes one complete up-and-down vibration every second. The number of vibrations, or cycles, of a wave train in a unit of time is called the frequency of the wave train and is measured in hertz. If 5 waves pass a point in one second, the frequency of the wave train is 5 cycles per second. In figure 1-7, the frequency of both wave 1 and wave 2 is four cycles per second (abbreviated as cps).

1-24. In 1967, in honor of the German physicist Heinrich Hertz, the term hertz was designated for use in lieu of the term “cycle per second” when referring to the frequency of radio waves. It may seem confusing that in one place the term “cycle” is used to designate the positive and negative alternations of a wave, but in another instance the term “hertz” is used to designate what appears to be the same thing. The key is the time factor. The term cycle refers to any sequence of events, such as the positive and negative alternations, comprising one cycle of electrical current. The term hertz refers to the number of occurrences that take place in one second.

CHARACTERISTICS OF WAVE MOTION

1-25. The two types of wave motion, transverse and longitudinal, have many of the same characteristics, such as frequency, amplitude, and wavelength. Another important characteristic that these two types of wave motion share is velocity. Velocity of propagation is the rate at which the disturbance travels through the medium, or the velocity with which the crest of the wave moves along. The velocity of the wave depends both on the type of wave (e.g., light, sound, or radio) and type of medium (e.g., air, water, or metal). If longitudinal waves are plotted as a graph, they appear as transverse waves. This fact is illustrated in figure 1-8. The frequency of a longitudinal wave, like that of a transverse wave, is the number of complete cycles the wave makes during a specific unit of time. The higher the frequency, the greater is the number of compressions and expansions per unit of time.

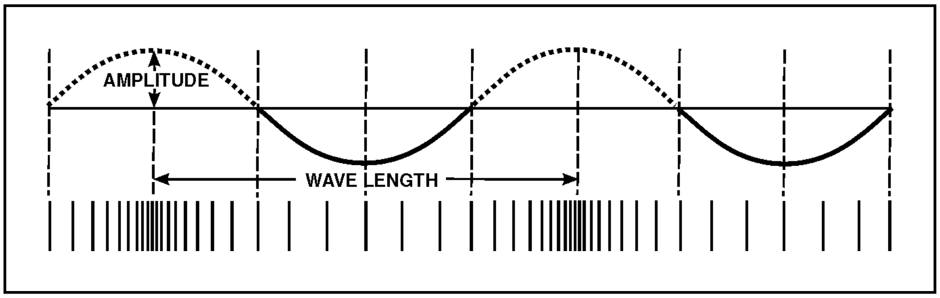


Figure 1-8. Longitudinal Wave Represented Graphically by a Transverse Wave

1-26. In the two types of wave motion described in the preceding discussion, the following quantities are of interest:

- The period, which is the time (T) in which one complete vibratory cycle of events occurs.
- The frequency of vibration (f), which is the number of cycles taking place in one second.
- The wavelength (λ), which is the distance the disturbance travels during one period of vibration.

1-27. Now, consider the following concept. If a vibrating object makes a certain number of vibrations per second, then 1 second divided by the number of vibrations is equal to the period of time of 1 vibration. In other words, the period, or time of 1 vibration is the reciprocal of the frequency. Thus—

$$\text{Time (T) of one vibration} = \frac{1}{\text{frequency (f)}}$$

Or

$$T = \frac{1}{f}$$

1-28. If you know the velocity of a wave, you can determine the wavelength by dividing the velocity by the frequency. As an equation—

$$\lambda = \frac{v}{f}$$

Where:

λ = wavelength
v = velocity of propagation
f = frequency of vibration

1-29. When you use the above equation, be careful to express velocity and wavelength in the proper units of length. For example, in the English system, if the velocity (expressed in feet per second) is divided by the frequency (expressed in cycles per second, or Hz), the wavelength is given in feet per cycle. If the metric system is used and the velocity (expressed in meters per second) is divided by the frequency (expressed in cycles per second), the wavelength is given in meters per cycle. Be sure to express both the wavelength and the frequency in the same units. (Feet per cycle and meters per cycle are normally abbreviated as feet or meters because one wavelength indicates one cycle.) Because this equation holds true for both transverse and longitudinal waves, it is used in the study of both electromagnetic waves and sound waves.

1-30. Consider the following example:

> Two cycles of a wave pass a fixed point every second, and the velocity of the wave train is 4 feet per second. What is the wavelength? The formula for determining wavelength is as follows:

$$\lambda = \frac{v}{f}$$

Where:

$\lambda =$ wavelength in feet

$v =$ velocity in feet per second

$f =$ frequency in Hz

Given:

$v =$ 4 feet per second

$f =$ 2 Hz

Solution:

$$\lambda = \frac{v}{f}$$

$$\lambda = \frac{\text{4 feet per second}}{\text{2 Hz}}$$

$$\lambda = \text{2 feet}$$

1-31. In problems of this kind, be sure not to confuse wave velocity with frequency. Frequency is the number of cycles per unit of time (Hz). Wave velocity is the speed with which a wave train passes a fixed point.

1-32. Here is another problem:

> If a wave has a velocity of 1,100 feet per second and a wavelength of 30 feet, what is the frequency of the wave?

By transposing the general equation:

$$f = \frac{v}{\lambda}$$

We have the equation:

$$\lambda = \frac{v}{f}$$

Given:

$v =$ 1,100 feet per second

$\lambda =$ 30 feet

Solution:

$$f = \frac{\text{1,100 feet per second}}{\text{30 feet}}$$

$$f = \text{36.67 Hz}$$

To find the velocity, rewrite the equation as follows:

$$v = \lambda f$$

1-33. Let us work one more problem, this time using the metric system.

Suppose the wavelength is 0.4 meters and the frequency is 12 kHz. What is the velocity? Use the following formula:

velocity = wavelength x frequency ($v = \lambda f$)

Given:

$\lambda =$ 0.4 meters
f = 12 kHz

Solution:

$v = \lambda \times f$
v = 0.4 meters x 12,000 Hz
v = 4,800 meters per second

1-34. Other important characteristics of wave motion are reflection, refraction, diffraction, and the Doppler effect. Big words, but the concept of each is easy to see. For ease of understanding, we explain the first two characteristics using light waves, and the last two characteristics using sound waves. You should keep in mind that all waves react in a similar manner.

1-35. Within mediums, such as air, solids, or gases, a wave travels in a straight line. When the wave leaves the boundary of one medium and enters the boundary of a different medium, the wave changes direction. For our purposes, a boundary is an imaginary line that separates one medium from another.

1-36. When a wave passes through one medium and encounters a medium having different characteristics, three things can occur—

- Some of the energy can be reflected back into the initial medium.
- Some of the energy can be transmitted into the second medium where it may continue at a different velocity.
- Some of the energy can be absorbed by the medium. In some cases, all three processes (reflection, transmission, and absorption) may occur to some degree.

Reflection

1-37. Reflection waves are simply waves that are neither transmitted nor absorbed, but are reflected from the surface of the medium they encounter. If a wave is directed against a reflecting surface, such as a mirror, it will reflect or “bounce” from the mirror. Refer to figure 1-9. A wave directed toward the surface of the mirror is called the incident wave. When the wave bounces off of the mirror, it becomes known as the reflected wave. An imaginary line perpendicular to the mirror at the point at which the incident wave strikes the mirror’s surface is called the normal, or perpendicular. The angle between the incident wave and the normal is called the angle of incidence. The angle between the reflected wave and the normal is called the angle of reflection. If the reflecting surface is smooth and polished, the angle between the incident ray and the normal will be the same as the angle between the reflected ray and the normal. This conforms to the law of reflection, which states: *The angle of incidence is equal to the angle of reflection.*

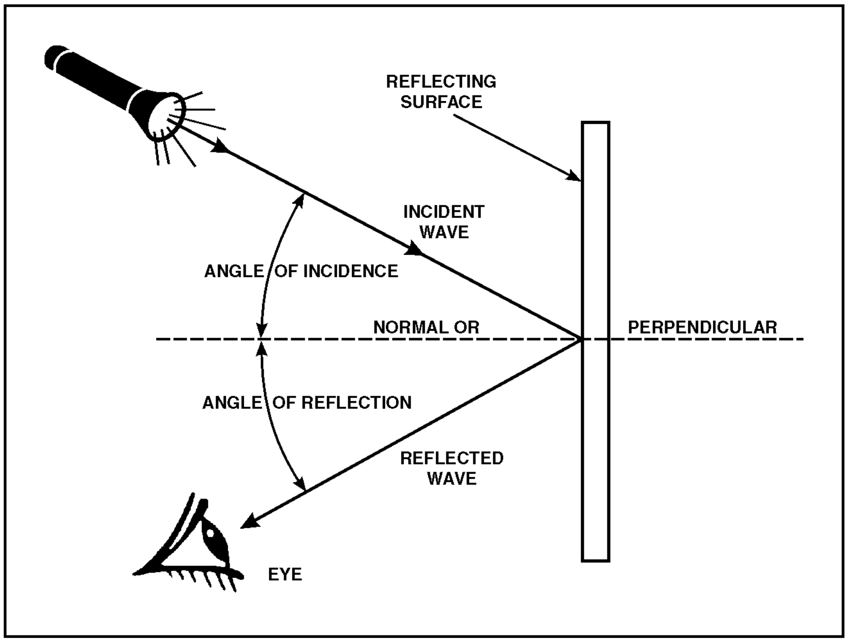


Figure 1-9. Reflection of a Wave

1-38. The amount of incident wave energy reflected from a given surface depends on the nature of the surface and the angle at which the wave strikes the surface. As the angle of incidence increases, the amount of wave energy reflected increases. The reflected energy is the greatest when the wave is nearly parallel to the reflecting surface. When the incident wave is perpendicular to the surface, more of the energy is transmitted into the substance and less is reflected. At any incident angle, a mirror reflects almost all of the wave energy, while a dull, black surface reflects very little.

Refraction

1-39. When a wave passes from one medium into another medium that has a different velocity of propagation, a change in the direction of the wave will occur. This changing of direction as the wave enters the second medium is called refraction. As in the discussion of reflection, the wave striking the boundary (surface) is called the incident wave, and the imaginary line perpendicular to the boundary is called the normal. The angle between the incident wave and the normal is called the angle of incidence. As the wave passes through the boundary, it is bent either toward or away from the normal. The angle between the normal and the path of the wave through the second medium is the angle of refraction.

1-40. A light wave passing through a block of glass is shown in figure 1-10. The wave moves from point A to B at a constant speed. This is the incident wave. As the wave penetrates the glass boundary at point B, the velocity of the wave is slowed down. This causes the wave to bend toward the normal. The wave then takes the path from point B to C through the glass and becomes both the refracted wave from the top surface and the incident wave to the lower surface. As the wave passes from the glass to the air (the second boundary), it is again refracted—this time away from the normal—and takes the path from point C to D. As the wave passes through the last boundary, its velocity increases to the original velocity. As figure 1-10 shows, refracted waves can bend toward or away from the normal. This bending depends on the velocity of the wave through each medium. The broken line between points B and E is the path that the wave would travel if the two mediums (air and glass) had the same density.

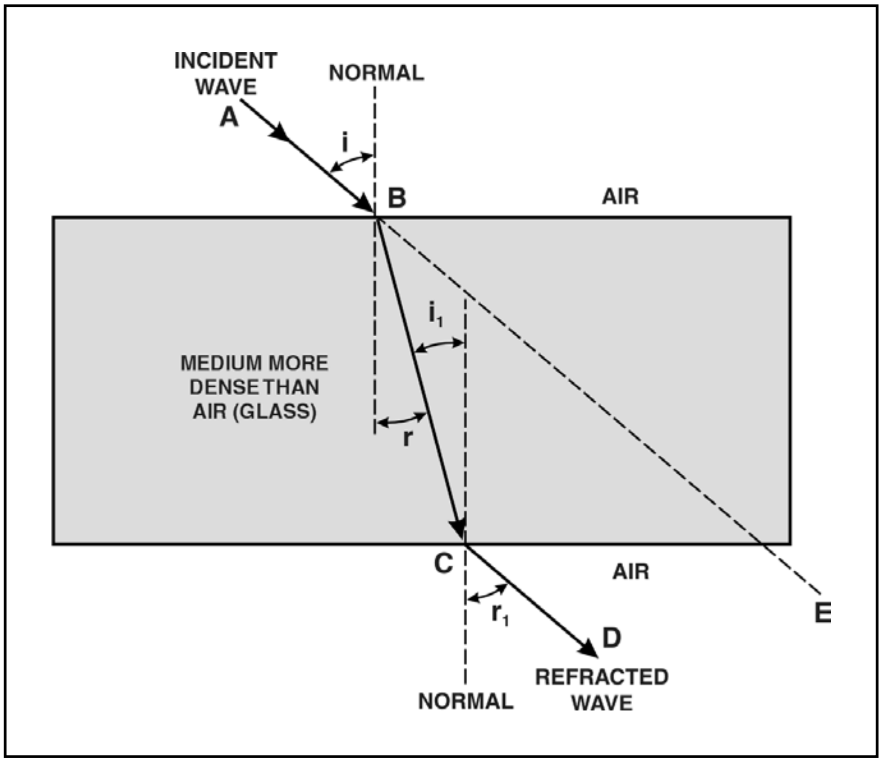


Figure 1-10. Refraction of a Wave

1-41. To summarize what figure 1-10 shows—

- If the wave passes from a less dense medium to a denser medium, it is bent toward the normal, and the angle of refraction (r) is less than the angle of incidence (i).
- If the wave passes from a denser to a less dense medium, it is bent away from the normal, and the angle of refraction (r_1) is greater than the angle of incidence (i_1).

1-42. You can more easily understand refraction by looking at figure 1-11. There is a plowed field in the middle of a parade ground. Think of the incident wave as a company of recruits marching four abreast at an angle across the parade ground to the plowed field, then crossing the plowed field and coming out on the other side onto the parade ground again. As the recruits march diagonally across the parade ground and begin to cross the boundary onto the plowed field, the front line is slowed down. Because the recruits arrive at the boundary at different times, they will begin to slow down at different times (number 1 slows down first and number 4 slows down last in each line). The net effect is a bending action. When the recruits leave the plowed field and reenter the parade ground, the reverse action takes place.

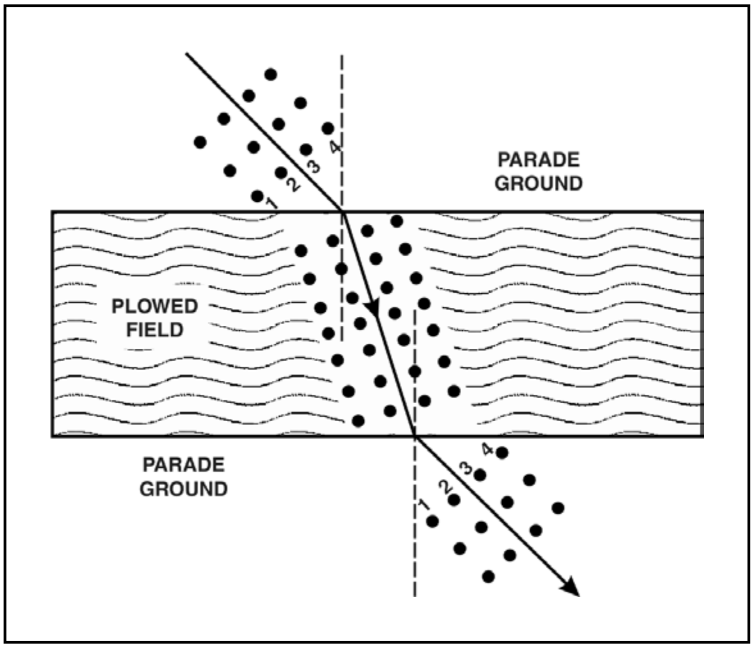


Figure 1-11. Analogy of Reflection

Diffraction

1-43. Diffraction is the bending of the wave path when the waves meet an obstruction. The amount of diffraction depends on the wavelength of the wave. Higher frequency waves are rarely diffracted in the normal world that surrounds us. Because light waves are high frequency waves, you will rarely see light diffracted. You can, however, observe diffraction in sound waves by listening to music. Suppose you are outdoors listening to a band. If you step behind a solid obstruction, such as a brick wall, you will hear mostly low notes. This is because the higher notes, having short wave lengths, undergo little or no diffraction and pass by or over the wall without wrapping around the wall and reaching your ears. The low notes, having longer wavelengths, wrap around the wall and reach your ears. This leads to the general statement that lower frequency waves tend to diffract more than higher frequency waves. Broadcast band (AM band) radio waves (lower frequency waves) often travel over a mountain to the opposite side from their source because of diffraction, while higher frequency TV and FM signals from the same source tend to be stopped by the mountain.

Doppler Effect

1-44. The last, but equally important, characteristic of a wave that we discuss is the Doppler effect. The Doppler effect is the apparent change in frequency or pitch when a sound source moves either toward or away from the listener, or when the listener moves either toward or away from the sound source. This principle, discovered by the Austrian physicist Christian Doppler, applies to all wave motion.

1-45. The apparent change in frequency between the source of a wave and the receiver of the wave is because of relative motion between the source and the receiver. To understand the Doppler effect, first assume that the frequency of a sound from a source is held constant. The wavelength of the sound will also remain constant. If both the source and the receiver of the sound remain stationary, the receiver will hear the same frequency sound produced by the source. This is because the receiver is receiving the same number of waves per second that the source is producing. Now, if either the source or the receiver or both move toward the other, the receiver will perceive a higher frequency sound. This is because the receiver will receive a greater number of sound waves per second and interpret the greater number of waves as a higher frequency sound. Conversely, if the source and the receiver are moving apart, the receiver will receive a smaller number of sound waves per second and will perceive a lower frequency sound. In both cases, the frequency of the sound produced by the source will have remained constant.

1-46. For example, the frequency of the whistle on a fast-moving train sounds increasingly higher in pitch as the train is approaching than when the train is departing. Although the whistle is generating sound waves of a constant frequency, and though they travel through the air at the same velocity in all directions, the distance between the approaching train and the listener is decreasing. As a result, each wave has less distance to travel to reach the observer than the wave preceding it. Thus, the waves arrive with decreasing intervals of time between them.

1-47. These apparent changes in frequency, called the Doppler effect, affect the operation of equipment used to detect and measure wave energy. In dealing with electromagnetic wave propagation, the Doppler principle is used in equipment such as radar, target detection, weapons control, navigation, and sonar.

SOUND WAVES

1-48. As you know, sound travels through a medium by wave motion. Although sound waves and the electromagnetic waves used in the propagation of radio and radar differ, both types of waves have many of the same characteristics. Studying the principles of sound-wave motion will help you understand the actions of both sound waves and the more complex radio and radar electromagnetic waves. The major differences among sound waves, heat waves, and light waves are as follows:

- Their frequencies.
- Their types.
- The mediums through which they travel.
- The velocities at which they travel.

SOUND—WHAT IS IT?

1-49. The word sound is used in everyday speech to signify a variety of things. One definition of sound is the sensation of hearing. Another definition refers to a stimulus that is capable of producing the sensation of hearing. A third definition limits sound to what is actually heard by the human ear.

1-50. In the study of physics, sound is defined as a range of compression-wave frequencies to which the human ear is sensitive. For the purpose of this chapter, however, we need to broaden the definition of sound to include compression waves that are not always audible to the human ear. To distinguish frequencies in the audible range from those outside that range, the words sonic, ultrasonic, and infrasonic are used. Sounds capable of being heard by the human ear are called sonics. The normal hearing range extends from about 20 to 20,000 hertz. In the Army to eliminate confusion when referring to different ranges of frequencies, an arbitrary dividing line has been established at 10,000 Hz. Even though the average person can hear sounds above 10,000 hertz, it is standard practice to refer to sounds above that frequency as ultrasonic. Sounds between 15 hertz and 10,000 hertz are called sonic. Sounds below 15 hertz are known as infrasonic (formerly referred to as subsonic) sounds.

REQUIREMENTS FOR SOUND

1-51. Recall that sound waves are compression waves. The existence of compression waves depends on the transfer of energy. To produce vibrations that become sounds, a mechanical device (the source) must first receive an input of energy. Next, the device must be in contact with a medium that will receive the sound energy and carry it to a receiver. If the device is not in contact with a medium, the energy will not be transferred to a receiver, and there will be no sound. Thus, three basic elements for transmission and reception of sound must be present before a sound can be produced. They are as follows:

- The source (or transmitter).
- A medium for carrying the sound (e.g., air, water, metal).
- The detector (or receiver).

1-52. A simple experiment provides convincing evidence that a medium must be present if sound is to be transferred. In figure 1-12, an electric bell is suspended by rubber bands in a bell jar from which the air can be removed. An external switch is connected from a battery to the bell so the bell may be rung intermittently. As the air is pumped out, the sound from the bell becomes weaker and weaker. If a perfect vacuum could be obtained, and if no sound were conducted out of the jar by the rubber bands, the sound from the bell would be completely inaudible. In other words, sound cannot be transmitted through a vacuum. When the air is admitted again, the sound is as loud as it was at the beginning. This experiment shows that when air is in contact with the vibrating bell, it carries energy to the walls of the jar, which in turn are set in vibration. Thus, the energy passes into the air outside of the jar and then on to the ear of the observer. This experiment illustrates that sound cannot exist in empty space (or a vacuum).

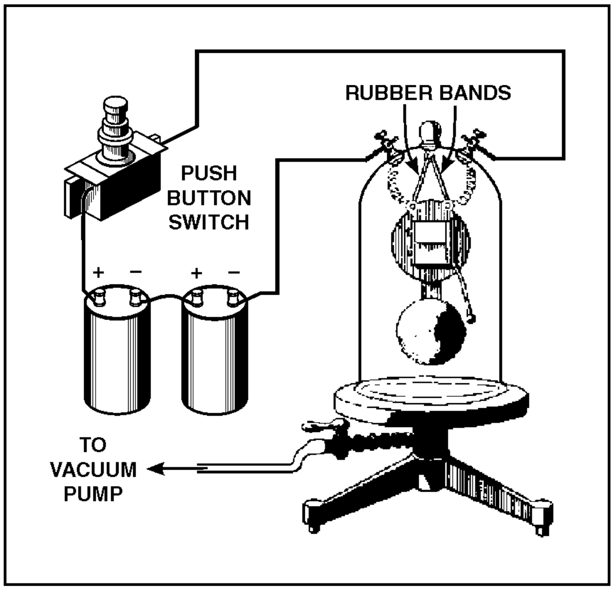


Figure 1-12. No Air, No Sound

1-53. Any object that moves rapidly back and forth, or vibrates, and thus disturbs the medium around it may be considered a source for sound. Bells, speakers, and stringed instruments are familiar sound sources.

1-54. The material through which sound waves travel is called the medium. The density of the medium determines the ease, distance, and speed of sound transmission. The higher the density of the medium, the slower sound travels through it.

1-55. The detector acts as the receiver of the sound wave. Because it does not surround the source of the sound wave, the detector absorbs only part of the energy from the wave and sometimes requires an amplifier to boost the weak signal.

1-56. As an illustration of what happens if one of these three elements is not present, let us refer to our experiment in which a bell was placed in a jar containing a vacuum. You could see the bell being struck, but you could hear no sound because there was no medium to transmit sound from the bell to you. Now let us look at another example in which the third element, the detector, is missing. You see a source (such as an explosion) apparently producing a sound, and you know the medium (air) is present, but you are too far away to hear the noise. Thus, as far as you are concerned, there is no detector and, therefore, no sound. We must assume, then, that sound can exist only when a source transmits sound through a medium, which passes it to a detector. Therefore, in the absence of any one of the basic elements (source, medium, and detector) there can be no sound.

TERMS USED IN SOUND WAVES

1-57. Sound waves vary in length according to their frequency. A sound having a long wavelength is heard at a low pitch (low frequency); one with a short wavelength is heard at a high pitch (high frequency). A complete wavelength is called a cycle. The distance from one point on a wave to the corresponding point on the next wave is a wavelength. The number of cycles per second (hertz) is the frequency of the sound. The frequency of a sound wave is also the number of vibrations per second produced by the sound source.

CHARACTERISTICS OF SOUND

1-58. Sound waves travel at great distances in a very short time, but as the distance increases the waves tend to spread out. As the sound waves spread out, their energy simultaneously spreads through an increasingly larger area. Thus, the wave energy becomes weaker as the distance from the source is increased.

1-59. Sounds may be broadly classified into two general groups. One group is noise, which includes sounds such as the pounding of a hammer or the slamming of a door. The other group is musical sounds, or tones. The distinction between noise and tone is based on the regularity of the vibrations, the degree of damping, and the ability of the ear to recognize components having a musical sequence. You can best understand the physical difference between these kinds of sound by comparing the waveshape of a musical note, depicted in view A of figure 1-13, and the waveshape of noise, shown in view B. You can see by the comparison of the two waveshapes that noise makes a very irregular and haphazard curve and a musical note makes a uniform and regular curve.

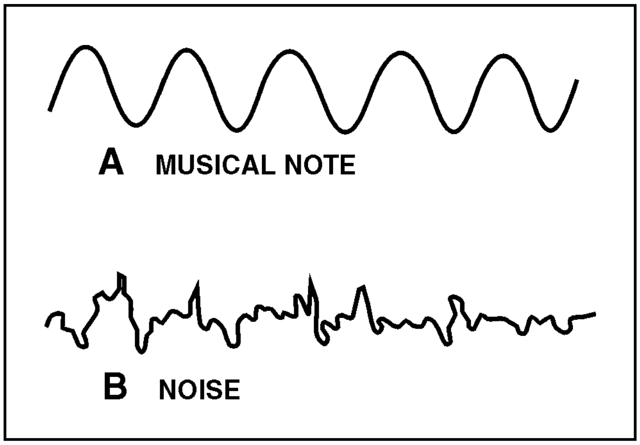


Figure 1-13. Musical Sound Versus Noise

1-60. Sound has three basic characteristics: pitch, intensity, and quality. Each of these three characteristics is associated with one of the properties of the source or the type of waves that it produces. The pitch depends upon the frequency of the waves, the intensity depends upon the amplitude of the waves, and the quality depends upon the form of the waves. With the proper combination of these characteristics, the tone is pleasant to the ear. With the wrong combination, the sound quality turns into noise.

Sound Pitch

1-61. The term pitch is used to describe the frequency of a sound. An object that vibrates many times per second produces a sound with a high pitch, as with a police whistle. The slow vibrations of the heavier strings of a violin cause a low-pitched sound. Thus, the frequency of the wave determines pitch. When the frequency is low, sound waves are long; when it is high, the waves are short. A sound can be so high in frequency that the waves reaching the ear cannot be heard. Likewise, some frequencies are so low that the eardrums do not convert them into sound. The range of sound that the human ear can detect varies with each individual.

Sound Intensity

1-62. The intensity of sound, at a given distance, depends upon the amplitude of the waves. Thus, a tuning fork gives out more energy in the form of sound when struck hard than when struck gently. You should remember that when a tuning fork is struck, the sound is omnidirectional (heard in all directions), because the sound waves spread out in all directions, as shown in figure 1-14. You can see from the figure that as the distance between the waves and the sound source increases, the energy in each wave spreads over a greater area; hence, the intensity of the sound decreases. The speaking tubes sometimes used aboard a ship prevent the sound waves from spreading in all directions by concentrating them in one desired direction (unidirectional), producing greater intensity. Therefore, the sound is heard almost at its original intensity at the opposite end of the speaking tube. The unidirectional megaphone and the directional loudspeaker also prevent sound waves from spreading in all directions.

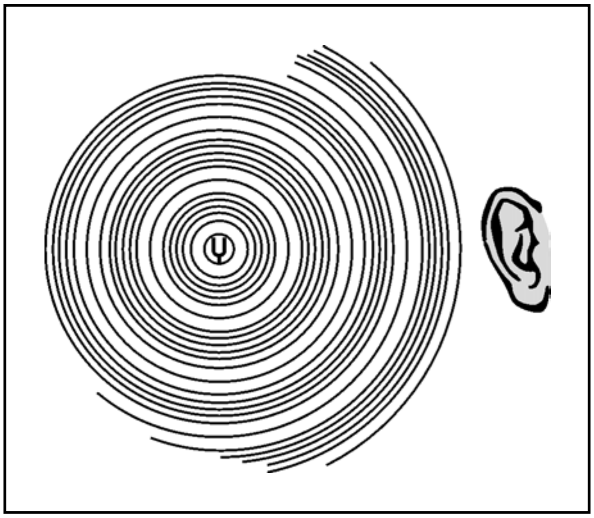


Figure 1-14. Sound Waves Spread in All Directions

1-63. Sound intensity and loudness are often mistakenly interpreted as having the same meaning. Although they are related, they are not the same. Sound intensity is a measure of the sound energy of a wave. Loudness, on the other hand, is the sensation the intensity (and sometimes frequency) the sound wave produces on the ear. Increasing the intensity causes an increase in loudness but not in a direct proportion. For instance, doubling the loudness of a sound requires about a tenfold increase in the intensity of the sound.

Sound Quality

1-64. Most sounds, including musical notes, are not pure tones. They are a mixture of different frequencies (tones). A tuning fork, when struck, produces a pure tone of a specific frequency. This pure tone is produced by regular vibrations of the source (tines of the tuning fork). On the other hand, scraping your fingernails across a blackboard creates only noise, because the vibrations are irregular. Each individual pipe of a pipe organ is similar to a tuning fork, and each pipe produces a tone of a specific frequency. But sounding two or more pipes at the same time produces a complex waveform. A tone that closely imitates any of the vowel sounds can be produced by selecting the proper pipes and sounding them at the same time. Figure 1-15 illustrates the combining of two pure tones to make a complex wave.

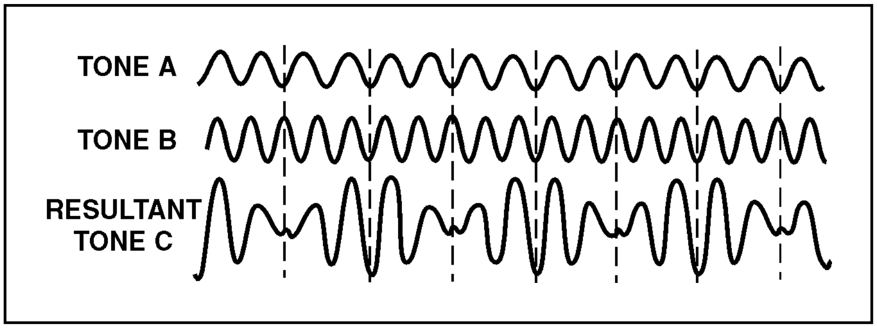


Figure 1-15. Combination of Tones

1-65. The quality of a sound depends on the complexity of its sound waves, such as the waves shown in tone C of figure 1-15. Almost all sounds (musical and vocal included) have complicated (complex) waveforms. Tone A is a simple wave of a specific frequency that can be produced by a tuning fork, piano, organ, or other musical instrument. Tone B is also a simple wave but at a different frequency. When the two tones are sounded together, the complex waveform in tone C is produced. Note that tone C has the same frequency as tone A with an increase in amplitude. The human ear could easily distinguish between tones A and tone C because of the quality. Therefore, we can say that quality distinguishes tones of like pitch and loudness when sounded on different types of musical instruments. It also distinguishes the voices of different persons.

VELOCITY OF TRANSMISSION

1-66. Sound waves travel through any medium to a velocity that is controlled by the medium. Varying the frequency and intensity of the sound waves will not affect the speed of propagation. The elasticity and density of a medium are the two basic physical properties that govern the velocity of sound through the medium.

1-67. Elasticity is the ability of a strained body to recover its shape after deformation, as from a vibration or compression. The measure of elasticity of a body is the force it exerts to return to its original shape.

1-68. The density of a medium or substance is the mass per unit volume of the medium or substance. Raising the temperature of the medium (which decreases its density) has the effect of increasing the velocity of sound through the medium.

1-69. The velocity of sound in an elastic medium is expressed by the formula:

$$V = \sqrt{\frac{E}{d}}$$

1-70. Even though solids such as steel and glass are far denser than air, their elasticities are so much greater that the velocities of sound in them are 15 times greater than the velocity of sound in air. Using elasticity as a rough indication of the speed of sound in a given medium, we can state as a general rule that sound travels faster in harder materials (such as steel), slower in liquids, and slowest in gases. Density has the opposite effect on the velocity of sound, that is, with other factors constant, a denser material (such as lead) passes sound more slowly.

1-71. At a given temperature and atmospheric pressure, all sound waves travel in air at the same speed. Thus the velocity that sound will travel through air at 32°F (0°C) is 1,087 feet per second. But for practical purposes, the speed of sound in air may be considered as 1,100 feet per second. Table 1-1 gives a comparison of the velocity of sound in various mediums.

Table 1-1. Comparison of Velocity of Sound in Various Mediums

MEDIUM	*TEMPERATURE*		*VELOCITY (Ft/Sec)*
	ºF	*ºC*	
Air	32	0	1,087
Air	68	20	1,127
Aluminum	68	20	16,700
Carbon Dioxide	32	0	856
Fresh Water	32	0	4,629
Fresh Water	68	20	4,805
Hydrogen	32	0	4,219
Lead	32	20	4,030
Salt Water	32	0	4,800
Salt Water	68	20	4,953
Steel	32	0	16,410
Steel	68	20	16,850

ACOUSTICS

1-72. The science of sound is called acoustics. This subject could fill volumes of technical books, but we scratch only the surface in this chapter. We present the important points that you need for a better understanding of sound waves. Acoustics, like sound, relates to the sense of hearing. It also deals with the production, control, transmission, reception, and effects of sound. For the present, we are concerned only with the last relationship—the effects of sound. These same effects will be used throughout your study of wave propagation.

Echo

1-73. An echo is the reflection of the original sound wave as it bounces off a distant surface. Just as a rubber ball bounces back when it is thrown against a hard surface, sound waves also bounce off most surfaces. As you have learned from the study of the law of conservation of energy, a rubber ball never bounces back with as much energy as the initial bounce. Similarly, a reflected sound wave is not as loud as the original sound wave. In both cases, some of the energy is absorbed by the reflecting surface. Only a portion of the original sound is reflected, and only a portion of the reflected sound returns to the listener. For this reason, an echo is never as loud as the original sound. Sound reflections (echoes) have many applications. The most important of these applications can be found in the use of depth-finding equipment (the fathometer) and sonar. The fathometer sends sound-wave pulses from the bottom of a ship and receives echoes from the ocean floor to indicate the depth of the ocean beneath the ship. The sonar transmits a pulse of sound energy and receives the echo to indicate range and bearing of objects or targets in the ocean depths.

Refraction

1-74. When sound waves traveling at different velocities pass obliquely (at an angle) from one medium into another, the waves are refracted; that is, their line of travel is bent. Refraction occurs gradually when one part of a sound wave is traveling faster than the other parts. For example, the wind a few feet above the surface of the earth has a greater velocity than that near the surface because friction retards the lower layers (see figure 1-16). The velocity of the wind is added to the velocity of the sound through the air. The result is that the upper portion of the sound wave moves faster than the lower portion and causes a gradual change in the direction of travel of the wave. Refraction causes sound to travel farther with the wind than against it.

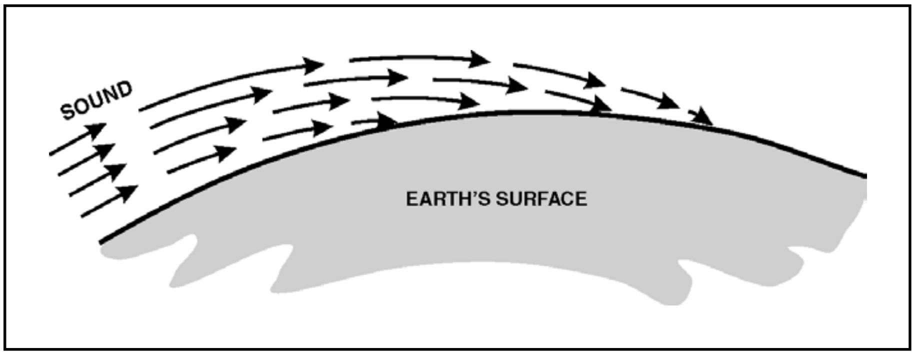


Figure 1-16. Refraction of Sound

Reverberation

1-75. In empty rooms or other confined spaces, sound may be reflected several times to cause what is known as reverberation. Reverberation is the multiple reflections of sound waves. Reverberations seem to prolong the time during which a sound is heard. Examples of this effect often occur in nature. For instance, the discharge of lightning causes a sharp, quick sound. By the time this sound has reached the ears of a distant observer, it is usually drawn out into a prolonged roar by reverberations that we call thunder. A similar case often arises with underwater sound equipment. Reverberations from nearby points may continue for such a long time that they interfere with the returning echoes from targets.

Interference

1-76. Any disturbance, man-made or natural, that causes an undesirable response or the degradation of a wave is referred to as interference. Two sound waves moving simultaneously through the same medium will advance independently, each producing a disturbance as if the other were not present. If the two waves have the same frequency—are in phase with each other and are moving in the same direction—they are additive and are said to interfere constructively. If the two waves have the same frequency and are moving in the same direction, but out of phase with each other, they are subtractive and are said to interfere destructively. If these two subtractive waves have equal amplitudes, the waves cancel each other. This addition or subtraction of waves is often called interference.

Resonance

1-77. At some time during your life you probably observed someone putting his or her head into an empty barrel or other cavity and making noises varying in pitch. When that person's voice reached a certain pitch, the tone produced seemed much louder than the others. The reason for this phenomenon is that at that a certain pitch the frequency of vibrations of the voice matched the resonant (or natural) frequency of the cavity. The resonant frequency of a cavity is the frequency at which the cavity body will begin to vibrate and create sound waves. When the resonant frequency of the cavity was reached, the sound of the voice was reinforced by the sound waves created by the cavity, resulting in a louder tone. This phenomenon occurs whenever the frequency of vibrations is the same as the natural frequency of a cavity, and is called resonance.

Noise

1-78. The most complex sound wave that can be produced is noise. Noise has no tonal quality. It distracts and distorts the sound quality that was intended to be heard. Noise is generally an unwanted disturbance caused by spurious waves originating from man-made or natural sources, such as a jet breaking the sound barrier, or thunder.

LIGHT WAVES

1-79. The concepts used to describe the behavior of waves—including reflection, refraction, and diffraction—can help you understand the behavior of light and light waves described below. The relationship between light and light waves (rays) is the same as for sound and sound waves.

1-80. Light is a form of electromagnetic energy. It can be produced by various means (e.g., mechanical, electrical, and chemical). We can see objects because the light waves (rays) they give off or reflect reach our eyes.

PROPAGATION OF LIGHT

1-81. The exact nature of light is not fully understood, although scientists have been studying the subject for many centuries. Some experiments seem to show that light is composed of tiny particles, and some suggest that it is made up of waves.

1-82. One theory after another attracted the approval and acceptance of physicists. Today, some scientific phenomena can be explained only by the wave theory and others only by the particle theory. Physicists, constantly searching for some new discovery that would bring these two theories into agreement, gradually have come to accept a theory that combines the principles of the two theories.

1-83. According to the view now generally accepted, light is a form of electromagnetic radiation; that is, light and similar forms of radiation are made up of moving electric and magnetic fields. These two fields are explained thoroughly later in this chapter.

ELECTROMAGNETIC THEORY OF LIGHT

1-84. James Clark Maxwell, a brilliant Scottish scientist of the mid-nineteenth century, constructed an oscillating electrical circuit, which he used to show that electromagnetic waves could move through empty space. Light eventually was proved to be electromagnetic.

1-85. Current light theory says that light is made up of very small packets of electromagnetic energy called photons (the smallest unit of radiant energy). These photons move at a constant speed in the medium through which they travel. Photons move at a faster speed through a vacuum than they do in the atmosphere, and at a slower speed through water than air.

1-86. The electromagnetic energy of light is a form of electromagnetic radiation. Light and similar forms of radiation are made up of moving electric and magnetic forces and move as waves. Electromagnetic waves move in a manner similar to the waves produced by the pebble dropped in the pool of water discussed earlier in this chapter. The transverse waves of light from a light source spread out in expanding circles much like the waves in the pool. However, the waves in the pool are very slow and clumsy in comparison with light, which travels approximately 186,000 miles per second.

1-87. Light radiates from its source in all directions until absorbed or diverted by some substance (figure 1-17). The lines drawn from the light source (a light bulb in the example in figure 1-17) to any point on one of these waves indicate the direction in which the waves are moving. These lines, called radii of the spheres, are formed by the waves and are called light rays. Although single rays of light do not exist, light “rays” are used in illustrations as a convenient method to show the direction in which light is traveling at any point.

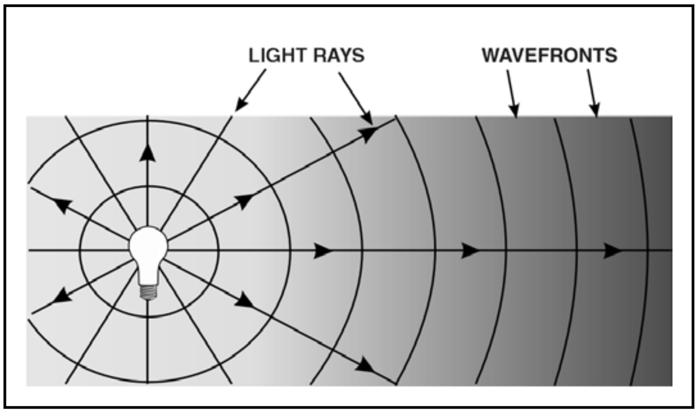


Figure 1-17. Waves and Radii from a Nearby Light Source

1-88. A large volume of light is called a beam; a narrow beam is called a pencil; and the smallest portion of a pencil is called a light ray. A ray of light can be illustrated as a straight line. This straight line drawn from a light source represents an infinite number of rays radiating in all directions from the source.

FREQUENCIES AND WAVELENGTHS

1-89. Compared to sound waves, the frequency of light waves is very high and the wavelength is very short. To measure these wavelengths conveniently, a special unit of measure called an angstrom unit, or more usually, an angstrom (Å), was devised. Another common unit used to measure these waves is the millimicron (mm), which is one millionth of a millimeter. One mF equals ten angstroms. One angstrom equals 10^{-10} meters.

FREQUENCIES AND COLOR

1-90. For our discussion of light wave waves, we use the millimicron measurement. The wavelength of a light determines the color of the light. Figure 1-18 indicates that light with a wavelength of 700 millimicrons is red, and that light with a wavelength of 500 millimicrons is blue-green. This illustration shows approximate wavelengths of the different colors in the visible spectrum. In fact, the color of light depends on its frequency, not its wavelength. However, light is measured in wavelengths. When the wavelength of 700 millimicrons is measured in a medium such as air, it produces the color red, but the same wave measured in a different medium will have a different wavelength. When red light that has been traveling in air enters glass, it loses speed. Its wavelength becomes shorter or compressed, but it continues to be red. This phenomenon indicates that the color of light depends on frequency and not on wavelength. The color scale in figure 1-18 is based on the wavelengths in air.

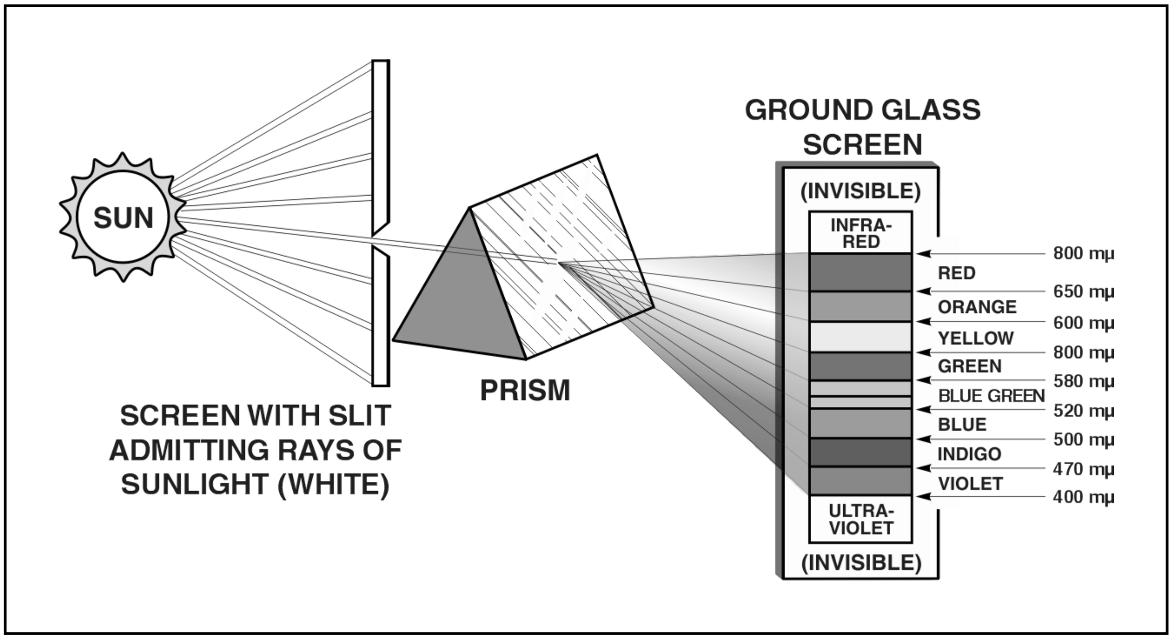


Figure 1-18. Use of a Prism to Split White Light into Different Colors

1-91. When a beam of white light (sunlight) is passed through a prism, as shown in figure 1-18, it is refracted and broken down into its component wavelengths. (This phenomenon of breaking light down into its component wavelengths is known as dispersion.) Each of these wavelengths causes a different reaction of the eye, which sees the various colors that compose the visible spectrum. The visible spectrum is recorded as a mixture of red, orange, yellow, green, blue, indigo, and violet. White light results when the primaries (red, green, and blue) are mixed together in overlapping beams of light. (These are not the primary colors used in mixing pigments, such as in paint.) Furthermore, the complementary or secondary colors (magenta, yellow, and cyan) may be shown with equal ease by mixing any two of the primary colors in overlapping beams of light. Thus, red and green light mixed in equal intensities make yellow light; green and blue produce cyan (blue-green light); and blue and red correctly mixed produce magenta (a purplish red light).

LIGHT AND COLOR

1-92. All objects absorb some of the light that falls on them. An object appears to be a certain color because it absorbs all of the light waves except those whose frequency corresponds to that particular color. Those waves are reflected from the surface, strike your eye, and cause you to see the particular color. The color of an object therefore depends on the frequency of the electromagnetic wave reflected.

LUMINOUS BODIES

1-93. If an object is the source of light energy, it is called luminous. If the object is not the source of light but reflects light, it is called an illuminated body.

1-94. Certain bodies, such as the sun, a gas flame, and an electric light filament are visible because they are light sources. They are called self-luminous bodies. Objects other than self-luminous bodies become visible only when they are in the presence of light from luminous bodies.

1-95. Most nonluminous bodies are visible because they diffuse or reflect the light that falls on them. A good example of a nonluminous diffusing body is the moon, which shines only because the sunlight falling onto its surface is diffused.

1-96. Black objects do not diffuse or reflect light. They are visible only when outlined against a background of light from a luminous or diffusing body.

PROPERTIES OF LIGHT

1-97. When light waves, which travel in straight lines, encounter any substance, they are transmitted, reflected, or absorbed. These effects are illustrated in figure 1-19. When light strikes a substance, some absorption and some reflection always take place. No substance completely transmits, reflects, or absorbs all of the light rays that reach its surface. Substances that transmit almost all the light waves that fall upon them are said to be transparent. A transparent substance is one through which you can see clearly. Clear glass is transparent because it transmits light rays without diffusing them (figure 1-20, view A). There is no known perfectly transparent substance, but many substances are nearly so. Substances through which some light rays can pass but through which objects cannot be seen clearly because the rays are diffused are called translucent (figure 1-20, view B). The frosted glass of a light bulb and a piece of oiled paper are examples of translucent materials. Substances that do not transmit any light rays are called opaque (figure 1-20, view C). Opaque substances can either reflect or absorb virtually all of the light rays that fall upon them.

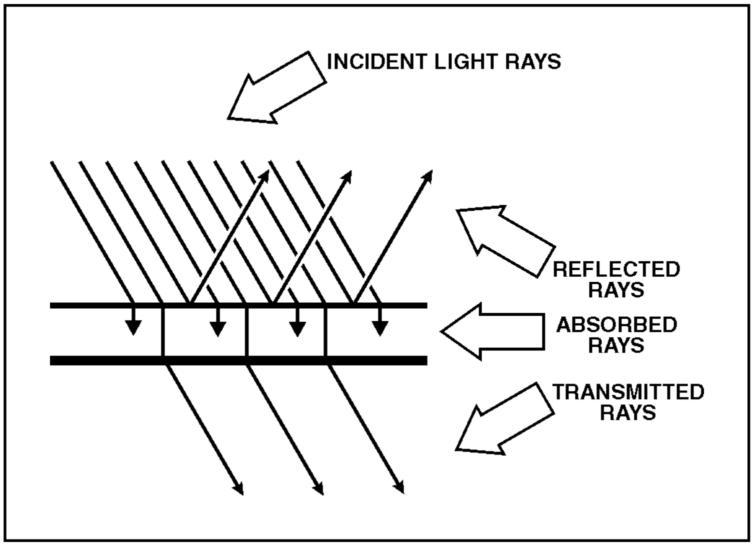


Figure 1-19. Light Waves Reflected, Absorbed, and Transmitted

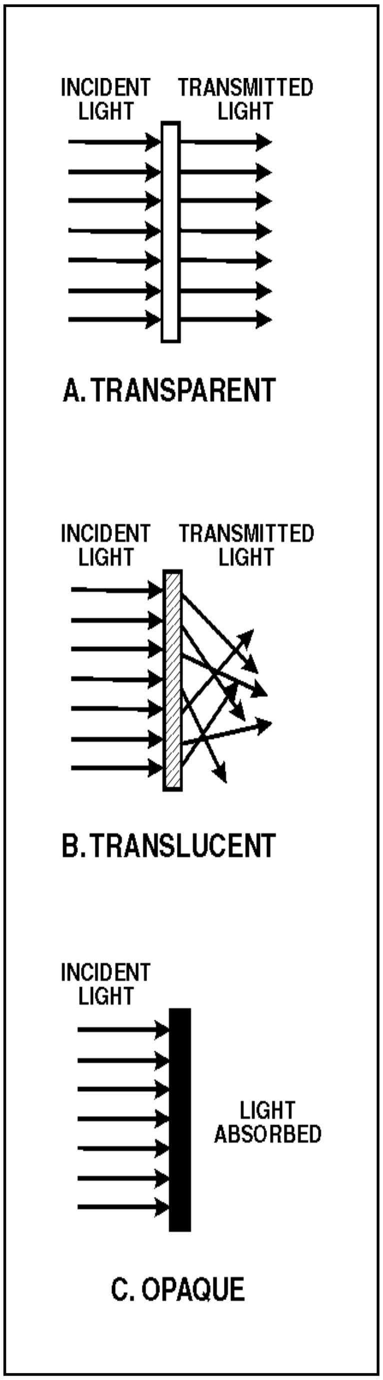


Figure 1-20. Transparent, Translucent, and Opaque Substances

Speed of Light

1-98. You probably have heard people say, “quick as lightning” or “fast as light” to describe rapid motion; nevertheless, it is difficult to realize how fast light actually travels. Not until recent years have scientists been able to measure accurately the speed of light.

1-99. Prior to the mid-seventeenth century, scientists thought that light required no time at all to pass from the source to the observer. Then, in 1675, Ole Roemer, a Danish astronomer, discovered that light travels approximately 186,000 miles per second in space. At this velocity, a light beam can circle the earth 7 1/2 times in one second.

1-100. The speed of light depends on the medium through which the light travels. In empty space, the speed is 186,000 (1.86×10^5) miles per second. It is almost the same in air. In water, it slows down to approximately 140,000 (1.4×10^5) miles per second. In glass, the speed of light is 124,000 (1.24×10^5) miles per second. In other words, the speed of light decreases as the density of the substance through which the light passes increases.

1-101. The velocity of light, which is the same as the velocity of other electromagnetic waves, is considered to be constant, at 186,000 miles per second. If expressed in meters, the velocity of light is 300,000,000 meters per second.

Reflection of Light

1-102. Light waves obey the law of reflection in the same manner as other types of waves. Consider the straight path of a light ray admitted through a narrow slit into a darkened room. The straight path of the beam is made visible by illuminated dust particles suspended in the air. If the light beam is made to fall onto the surface of a mirror or other reflecting surface, however, the direction of the beam changes sharply. The light can be reflected in almost any direction, depending on the angle at which the mirror is held.

1-103. As shown earlier in figure 1-9, if a light beam strikes a mirror, the angle at which the beam is reflected depends on the angle at which it strikes the mirror. The beam approaching the mirror is the incident or striking beam, and the beam leaving the mirror is the reflected beam.

1-104. The term “reflected light” simply refers to light waves that are neither transmitted nor absorbed, but are thrown back from the surface of the medium they encounter. This phenomenon is described more fully in the discussions of radio waves (chapter 2) and antennas (chapter 4).

Refraction of Light

1-105. The change of direction that occurs when a ray of light passes from one transparent substance into another of different density is called refraction. Refraction is due to the fact that light travels at various speeds in different transparent substances. For example, water never appears as deep as it really is, and objects under water appear to be closer to the surface than they really are. A bending of the light rays causes these impressions.

1-106. Another example of refraction is the apparent bending of a spoon when it is immersed in a cup of water. The bending seems to take place at the surface of the water, or exactly at the point where there is a change of density. Obviously, the spoon does not bend from the pressure of the water. The light forming the image of the spoon is bent as it passes from the water (a medium of high density) to the air (a medium of comparatively low density).

1-107. Without refraction, light waves would pass in straight lines through transparent substances without any change of direction. Refer back to figure 1-10, which shows refraction of a wave. As you can see, all rays striking the glass at any angle other than perpendicular are refracted. However, the perpendicular ray, which enters the glass normal to the surface, continues through the glass and into the air in a straight line—no refraction takes place.

Diffusion of Light

1-108. When light is reflected from a mirror, the angle of reflection of each ray equals the angle of incidence. When light is reflected from a piece of plain white paper, however, the reflected beam is scattered, or diffused, as shown in figure 1-21. Because the surface of the paper is not smooth, the reflected light is broken up into many light beams that are reflected in all directions.

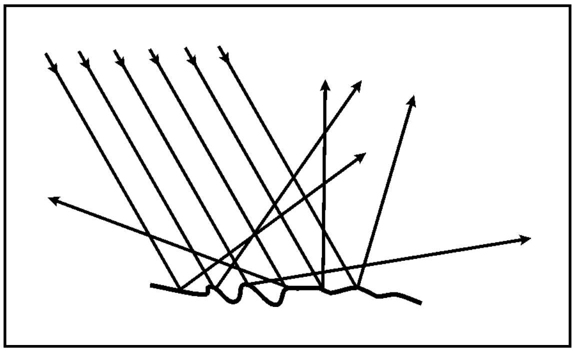


Figure 1-21. Diffusion of Light

Absorption of Light

1-109. As illustrated in figure 1-21, a light beam is reflected and diffused when it falls onto a piece of white paper. If a light beam falls onto a piece of black paper, the black paper absorbs most of the light rays and very little light is reflected from the paper. If the surface on which the light beam falls is perfectly black, there is no reflection; that is, the light is totally absorbed. No matter what kind of surface light falls on, however, some of the light is absorbed.

COMPARISON OF LIGHT WAVES WITH SOUND WAVES

1-110. There are two main differences between sound waves and light waves. The first difference is in velocity. Sound waves travel through air at the speed of approximately 1,100 feet per second; light waves travel through air and empty space at a speed of approximately 186,000 miles per second (300,000,000 meters per second). The second difference is that sound is composed of longitudinal waves (alternate compressions and expansions of matter) and light is composed of transverse waves in an electromagnetic field.

1-111. Although both are forms of wave motion, sound requires a solid, liquid, or gaseous medium, whereas light can travel through empty space. The denser the medium, the greater the speed of sound. The opposite is true of light. Light travels approximately one-third slower in water than in air. Sound travels through all substances, but light cannot pass through opaque materials.

1-112. Frequency affects both sound and light. A certain range of sound frequencies produces sensations that you can hear. A slow vibration (low frequency) in sound gives the sensation of a low note. A more rapid sound vibration (higher frequency) produces a higher note. Likewise, a certain range of light frequencies produces sensations that you can see. Violet light is produced at the high-frequency end of the light spectrum, while red light is produced at the low-frequency end of the light spectrum. A change in frequency of sound waves causes an audible sensation—a difference in pitch. A change in the frequency of a light wave causes a visual sensation—a difference in color. For a comparison of light waves with sound waves, see Table 1-2.

Table 1-2. Comparison of Light Waves and Sound Waves

	SOUND WAVES	***LIGHT WAVES***
Velocity in air	Approximately 1,100 feet per second.	Approximately 186,000 miles per second (300,000,000 meters per second).
Form	A form of wave motion.	A form of wave motion.
Wave composition	Longitudinal.	Transverse.
Transmitting medium	All substances.	Empty space and all substances except opaque materials.
Relation of transmitting medium velocity to velocity	The denser the medium, the greater the speed.	The denser the medium, the slower the speed.
Sensations produced	Hearing.	Seeing.
Variations in sensations produced	A low frequency causes a low note; a high frequency causes a high note.	A low frequency causes red light; a high frequency causes violet light.

ELECTROMAGNETIC SPECTRUM

1-113. Light is one kind of electromagnetic energy. There are many other types of electromagnetic energy, including heat energy and radio energy. The only difference between the various types of electromagnetic energy is the frequency of their waves (rate of vibration). The term spectrum is used to designate the entire range of electromagnetic waves arranged in order of their frequencies. The visible spectrum contains only those waves that stimulate the sense of sight. As a technician, you might be expected to maintain equipment that uses electromagnetic waves within, above, and below the visible spectrum.

1-114. There are neither sharp dividing lines nor gaps in the electromagnetic spectrum. Figure 1-22 illustrates how portions of the electromagnetic spectrum overlap. Notice that only a small portion of the electromagnetic spectrum contains visible waves, or light, that can be seen by the human eye.

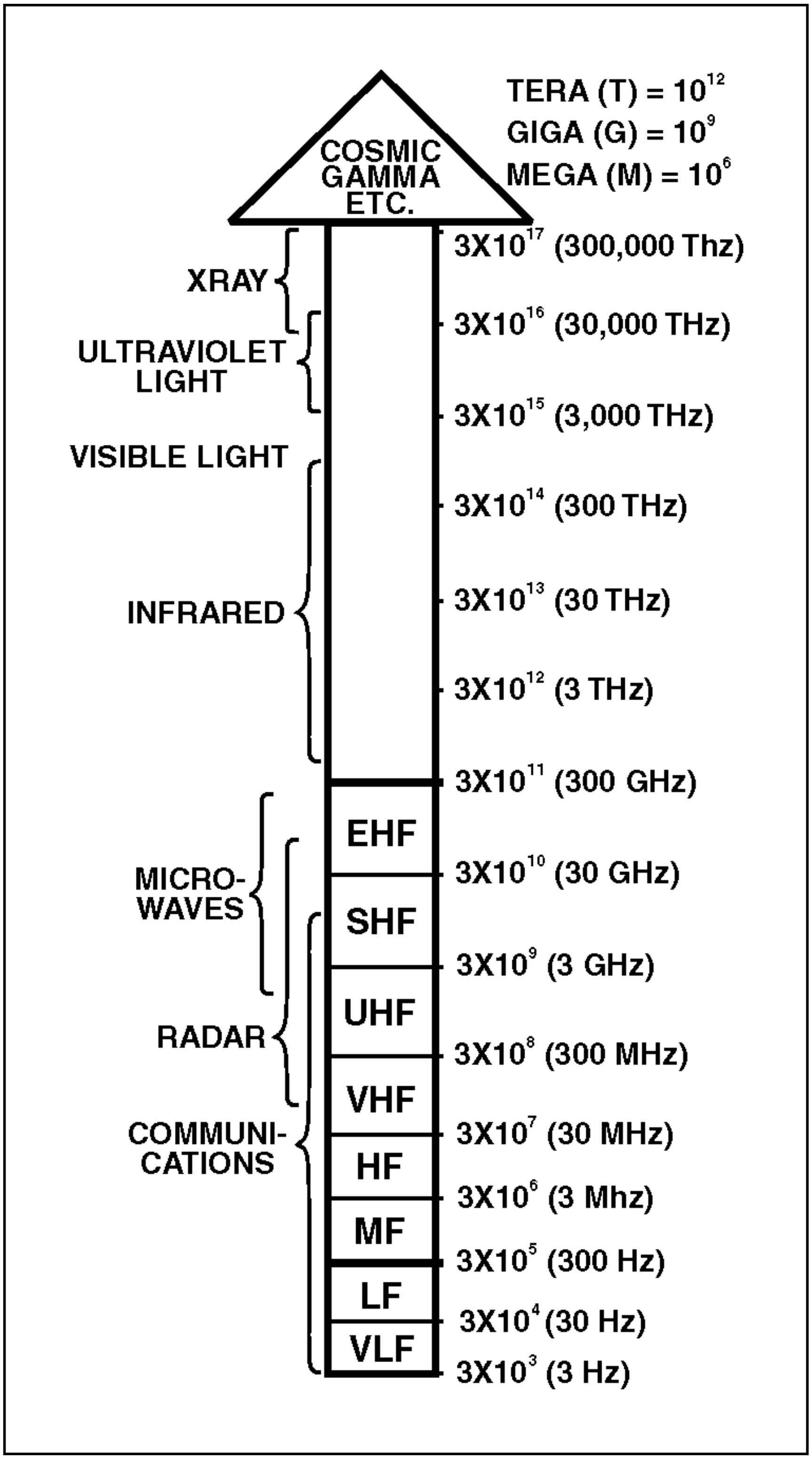


Figure 1-22. Electromagnetic Spectrum

ELECTROMAGNETIC WAVES

1-115. In general, the same principles and properties of light waves apply to the communications electromagnetic waves you are about to study. The electromagnetic field is used to transfer energy (as communications) from point to point. The basic antenna is a propagation source of these electromagnetic waves.

THE BASIC ANTENNA

1-116. The study of antennas and electromagnetic wave propagation is essential to a complete understanding of radio communication, radar, loran, and other electronic systems. Figure 1-23 shows a simple radio communication system. In the illustration, the transmitter is an electronic device that generates radio-frequency energy. The energy travels through a transmission line (discussed in chapter 3) to an antenna. The antenna converts the energy into radio waves that radiate into space from the antenna at the speed of light. The radio waves travel through the atmosphere or space until they are either reflected by an object or absorbed. If another antenna is placed in the path of the radio waves, it absorbs part of the waves and converts them to energy. This energy travels through another transmission line and is fed to a receiver. From this example, you can see that the requirements for a simple communications system are as follows:

- Transmitting equipment.
- Transmission line.
- Transmitting antenna.
- Medium.
- Receiving antenna.
- Receiving equipment.

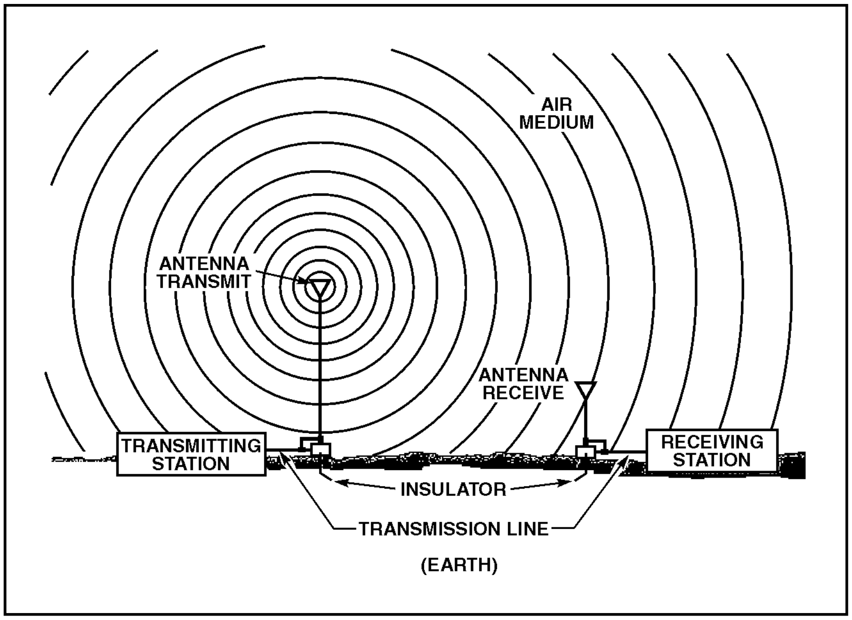


Figure 1-23. Simple Radio Communication System

1-117. An antenna is a conductor or a set of conductors used either to radiate electromagnetic energy into space or to collect this energy from space. Figure 1-24 shows an antenna. View A is a drawing of an actual antenna; view B is a cut-away view of the antenna; and view C is a simplified diagram of the antenna.

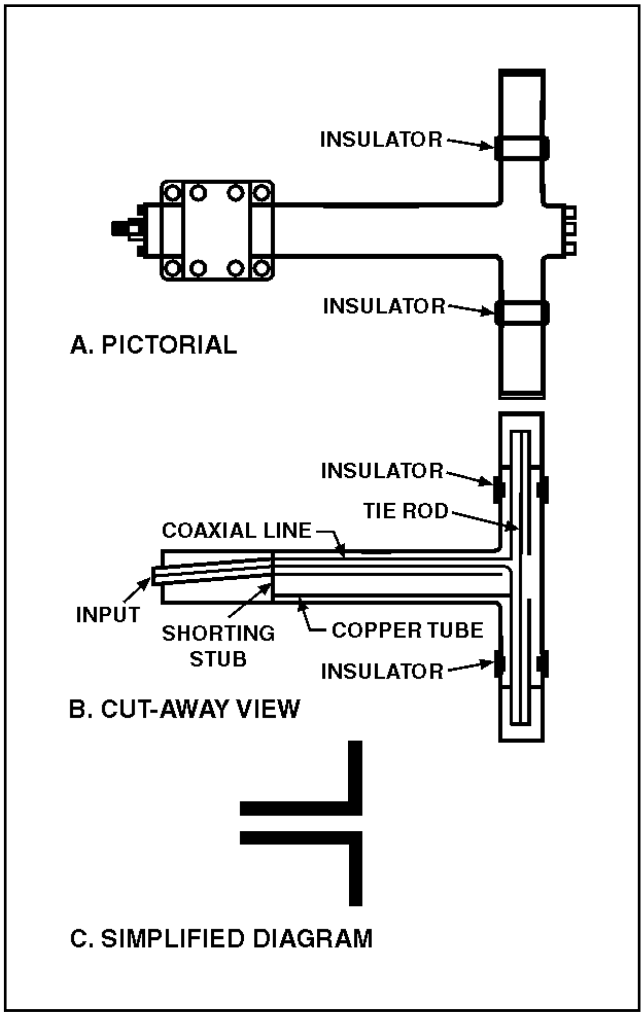


Figure 1-24. Antenna

COMPONENTS OF THE ELECTROMAGNETIC WAVE

1-118. An electromagnetic wave consists of two primary components—an electric field and a magnetic field. The electric field results from the force of voltage, and the magnetic field results from the flow of current.

1-119. Although electromagnetic fields that are radiated are commonly considered to be waves, under certain circumstances their behavior makes them appear to have some of the properties of particles. In general, however, it is easier to picture electromagnetic radiation in space as horizontal and vertical lines of force oriented at right angles to each other. These lines of force are made up of an electric field (E) and a magnetic field (H), which together make up the electromagnetic field in space.

1-120. The electric and magnetic fields radiated from an antenna form the electromagnetic field. This field is responsible for the transmission and reception of electromagnetic energy through free space. An antenna, however, is also part of the electrical circuit of a transmitter or a receiver and is equivalent to a circuit containing inductance, capacitance, and resistance. Therefore, the antenna can be expected to display definite voltage and current relationships with respect to a given input. A current through the antenna produces a magnetic field, and a charge on the antenna produces an electric field. These two fields combine to form the induction field. To help you gain a better understanding of antenna theory, the following subsections review some basic electrical concepts, including voltage and its electric field, current and its magnetic field, and their relationship to the propagation of electrical energy.

Electric Field

1-121. Around every electrically charged object is a force field that can be detected and measured. This force field can cause electric charges to move in the field. When an object is charged electrically, there is either a greater or a smaller concentration of electrons than normal. Thus, a difference of potential exists between a charged object and an uncharged object. An electric field is, therefore, associated with a difference of potential, or a voltage.

1-122. Lines that are drawn to show the paths along which the force acts commonly represent this invisible field of force. The lines representing the electric field are drawn in the direction that a single positive charge would normally move under the influence of that field. A large electric force is shown by a large concentration of lines; a few lines indicate a weak force.

1-123. When a capacitor is connected across a source of voltage, such as a battery, it is charged by a particular amount, depending on the voltage and the value of capacitance (see figure 1-25). Because of the EMF (electromotive force) of the battery, negative charges flow to the lower plate, leaving the upper plate positively charged. Along with the growth of charge, the electric field is also building up. The flux lines are directed from the positive to the negative charges and at right angles to the plates. When the capacitor is fully charged, the voltage of the capacitor is equal to the voltage of the source and opposite in polarity. The charged capacitor stores the energy in the form of an electric field. It can be said, therefore, that an electric field indicates voltage.

1-124. If the two plates of the capacitor are spread farther apart, the electric field must curve to meet the plates at right angles (figure 1-26). The straight lines in view A of figure 1-26 become arcs in view B, and approximately semicircles in view C, where the plates are in a straight line. Instead of flat metal plates, as in the capacitor, the two elements can take the form of metal rods or wires and form the basic antenna.

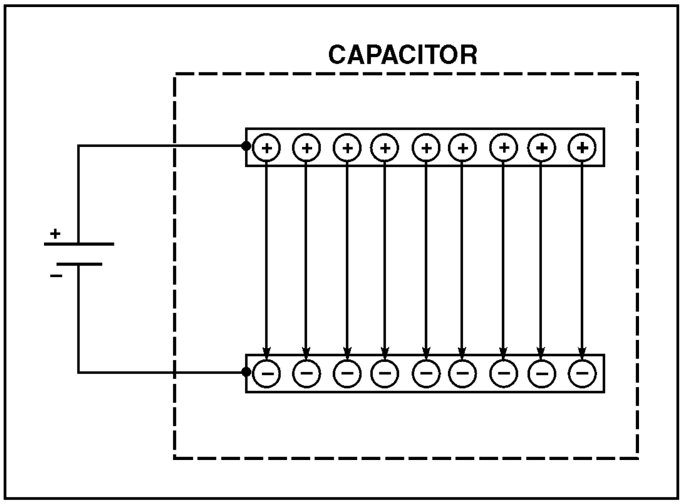


Figure 1-25. Electric Fields between Plates

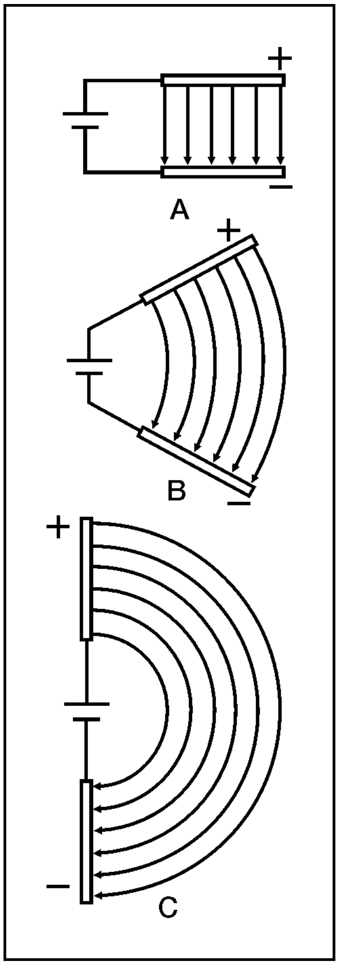


Figure 1-26. Electric Fields between Plates at Different Angles

1-125. In figure 1-27, two rods replace the plates of the capacitor, and the battery is replaced by an AC source generating a 60-hertz signal. On the positive alternation of the 60-hertz generator, the electric field extends from the positively charged rod to the negatively charged rod, as shown. On the negative alternation, the charge is reversed. The previous explanation of electrons moving from one plate to the other of the capacitor in figure 1-25 can also be applied to the rods in figure 1-27.

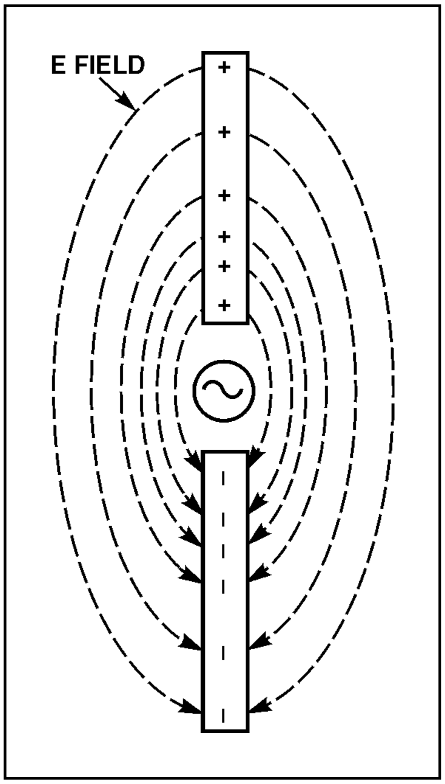


Figure 1-27. Electric Fields between Elements

1-126. The polarity of charges and the direction of the electric fields will reverse polarity and direction periodically at the frequency of the voltage source. The electric field will build up from zero to maximum in one direction and then collapse back to zero. Next, the field will build up to maximum in the opposite direction and then collapse back to zero. This complete reversal occurs during a single cycle of the source voltage. The half-wave dipole antenna (two separate rods in line as illustrated in figure 1-27) is the fundamental element normally used as a starting point of reference in any discussion concerning the radiation of electromagnetic energy into space. If RF energy from the AC generator (or transmitter) is supplied to the element of an antenna, the voltage across the antenna lags the current by 90 degrees. The antenna acts as if it were a capacitor.

Magnetic Field

1-127. When current flows through a conductor, a magnetic field is set up in the area surrounding the conductor. In fact, any moving electrical charge will create a magnetic field. The magnetic field is a region in space where a magnetic force can be detected and measured. There are two other fields involved—an induction field, which exists close to the conductor carrying the current, and the radiation field, which becomes detached from the current-carrying rod and travels through space.

1-128. To represent the magnetic field, lines of force are again used to illustrate the energy. Magnetic lines are not drawn between the rods, nor between high- and low-potential points, as the E lines that were discussed earlier. The flow of current rather than the force of voltage creates magnetic lines. The magnetic lines of force, therefore, are drawn at right angles to the direction of current flow.

1-129. The magnetic fields that are set up around two parallel rods, as shown in figure 1-28 view A, are in maximum opposition. Rod 1 contains a current flowing from the generator, while rod 2 contains a current flowing toward the generator. As a result, the direction of the magnetic field surrounding rod 1 is opposite the direction of the magnetic field surrounding rod 2. This will cause cancellation of part or all of both magnetic fields with a resultant decrease in radiation of the electromagnetic energy. View B illustrates that if the far ends of rods 1 and 2 are separated from each other while the rods are still connected to the generator at the near ends, more space—and consequently less opposition—will occur between the magnetic fields of the two rods. View C illustrates that placing the rods in line makes the currents through both rods flow in the same direction. Therefore, the two magnetic fields are in the same direction; thus, maximum electromagnetic radiation into space can be obtained.

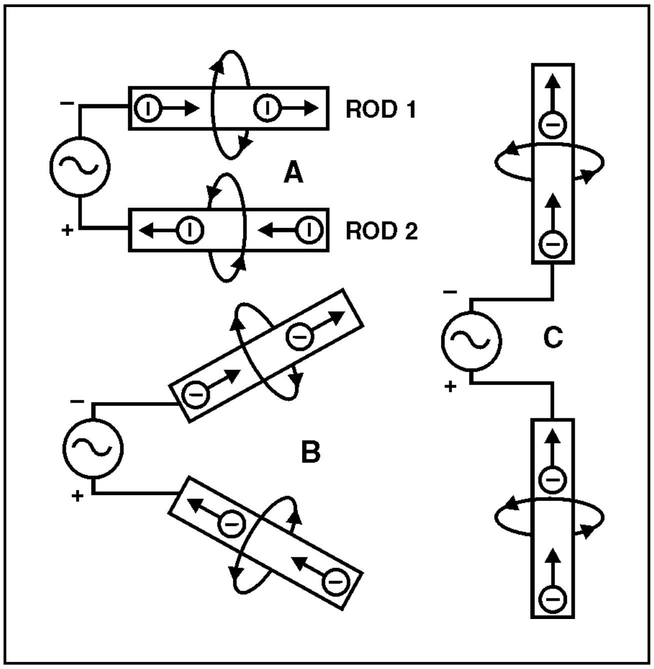


Figure 1-28. Magnetic Fields around Elements

1-130. Magnetic lines of force are indicated by the letter H and are called H lines. The direction of the magnetic lines may be determined by use of the left-hand rule for a conductor: If you grasp the conductor in your left hand with the thumb extended in the direction of the current flow, your fingers will point in the direction of the magnetic lines of force. In view C of figure 1-28, the direction of current flow is upward along both halves of the elements (conductors). The lines of magnetic force (flux) form concentric loops that are perpendicular to the direction of current flow. The arrowheads on the loops indicate the direction of the field. The left-hand rule, illustrated in figure 1-29, is used to determine the direction of the magnetic field. The direction of the magnetic lines may be determined as follows: If you grasp the conductor in your left hand with the thumb extended in the direction of the current flow, then the rough circles formed by the fingers indicate the direction of the magnetic field.

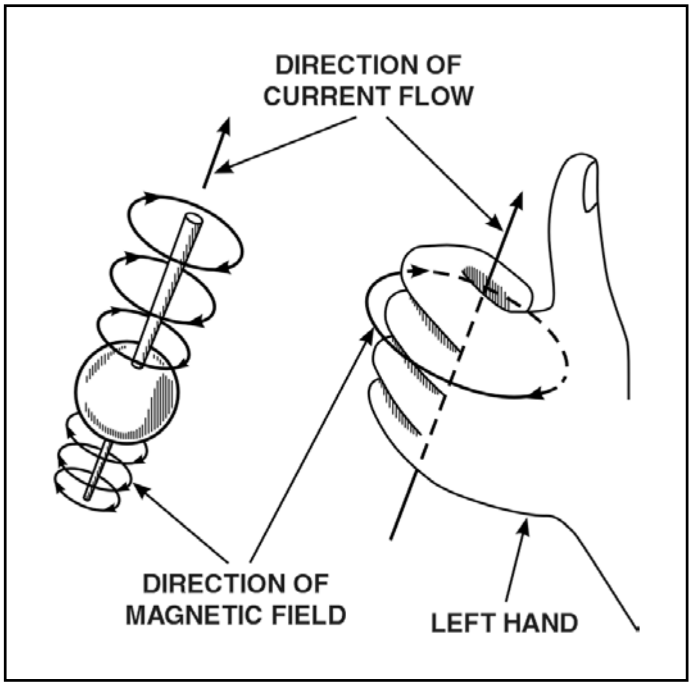


Figure 1-29. Left-Hand Rule for Conducting Elements

Combined Electric and Magnetic Fields

1-131. The generator, shown in figure 1-30, provides the voltage, which creates an electric field, and current, which creates a magnetic field. This source voltage and current build up to maximum values in one direction during one half-cycle, and then build up to maximum values in the other direction during the next half-cycle. Both the electric and magnetic fields alternate from minimum through maximum values in synchronization with the changing voltage and current. The electric and magnetic fields reach their maximum intensity one quarter-cycle apart. These fields form the induction field. Because the current and voltage that produce these E and H fields are 90 degrees out of phase, the fields will also be 90 degrees out of phase.

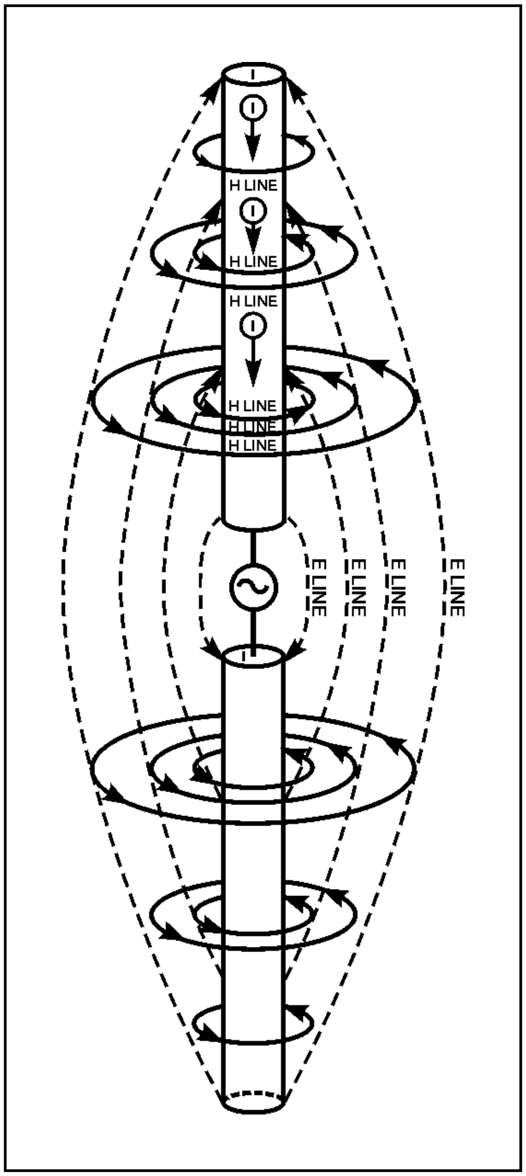


Figure 1-30. Relationship of E-Lines and Current Flow

SUMMARY

Now that you have completed this chapter, let us review some of the new terms, concepts, and ideas you have learned. You should have a thorough understanding of these principles before moving on to chapter 2.

Wave propagation is an invisible force that enables man to communicate over long distances. Wave transmission can take many forms, such as light, sound, and radio.

Light is a form of wave motion that can be seen. Heat cannot normally be seen, but can be felt. Radio waves cannot be seen or felt.

Wave motion can be seen in action by throwing a pebble into a pool of still water. The ripples that move toward the edge of the pool demonstrate the propagation theory.

Figure 1-Sum 1. Formation of Waves in Water

The transverse wave is a type of wave motion. Radio, light, and heat waves are examples of transverse waves.

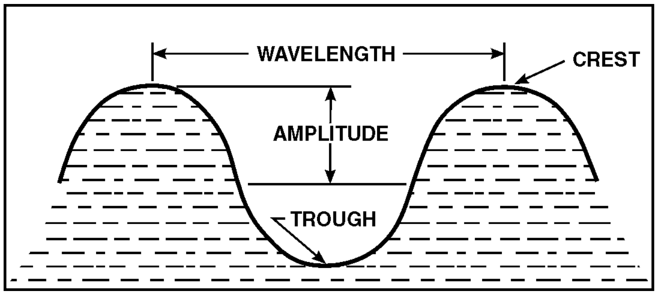


Figure 1-Sum 2. Elements of a Wave

The longitudinal wave is another type of wave motion. The sound wave is the only example of a longitudinal wave given in this text.

Source, medium, and detector (receiver) are the three requirements for all wave motion.

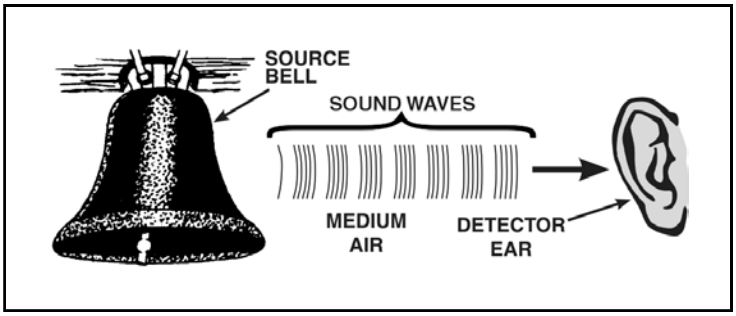


Figure 1-Sum 3. The Three Elements of Sound

A source can be anything that emits or expends energy (waves).

The medium is the vehicle for carrying waves from one point to another. Water, air, metal, and empty space are examples of mediums. Empty space can serve as a medium for electromagnetic waves but not for sound waves.

The sound detector absorbs the waves emitted by the source. The human ear is an example of a detector.

Hertz, which is abbreviated Hz, is used in lieu of “cycle per second” when referring to radio frequencies.

Velocity of propagation is the speed (or rate) at which the crest of a wave moves through a medium. Velocity can be calculated by using the formula:

$$v = \lambda f$$

Where v is velocity of propagation and is expressed in feet (meters) per second, λ is the wavelength in feet (meters), and f is the frequency in hertz.

Reflection occurs when a wave strikes an object and bounces back (toward the source). The wave that moves from the source to the object is called the incident wave, and the wave that moves away from the object is called the reflected wave.

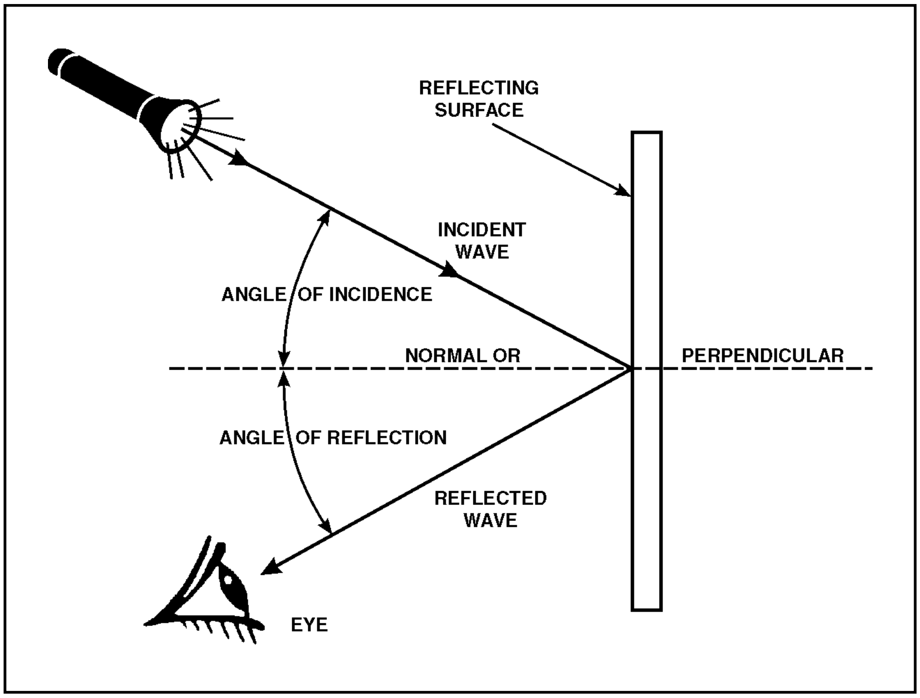


Figure 1-Sum 4. Reflection of a Wave

The law of reflection states that *the angle of incidence is equal to the angle of reflection*.

Refraction occurs when a wave traveling through two different mediums passes through the boundary of the mediums and bends toward or away from the normal.

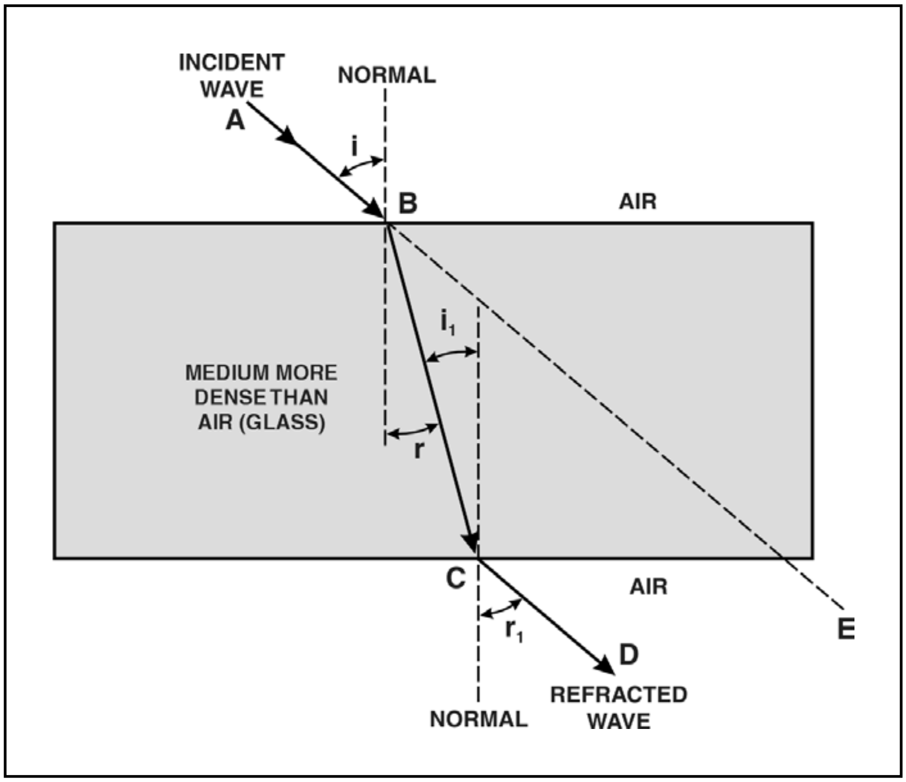


Figure 1-Sum 5. Refraction of a Wave

Diffraction can account for the ability of the AM radio waves (due to their low frequency) to travel over a mountain, while FM and TV signals (due to their higher frequencies) are blocked.

The Doppler effect is the apparent change in frequency of a source as it moves toward or away from a detector. It can affect the operation of equipment used to detect and measure wave energy.

Characteristics of sound can be audible to the human ear or it can be outside the hearing range.

Noise and tones are the two general groups that broadly classify all sounds.

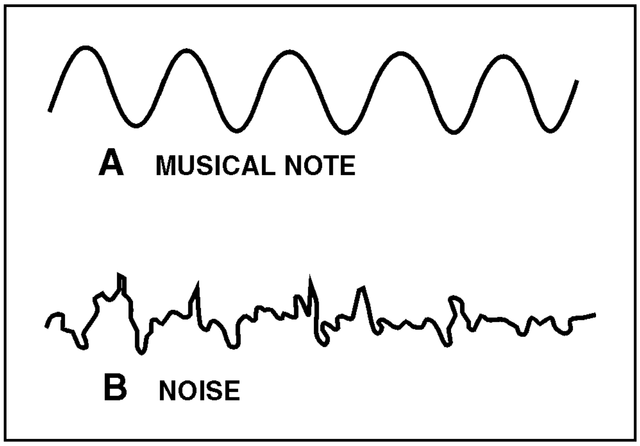


Figure 1-Sum 6. Musical Sound Versus Noise

Pitch, intensity, and quality are the three basic characteristics of sound. Pitch describes the frequency of sound. Intensity describes how much energy is transmitted. Quality enables us to distinguish one sound from another.

The density of a medium, temperature, and atmospheric pressure affect the velocity of sound. If temperature, density, or pressure increases, the velocity of sound increases and vice versa.

Acoustics is the science of sound and relates to the sense of hearing.

Echo is an example of reflection. Sound echoes are used in sonar and depth finders to determine or measure the range of an object or the depth of the ocean bottom.

Reverberation is the multiple reflections of sound waves. The prolonged roar of thunder is caused by reverberations. With underwater sound equipment, reverberations of nearby objects may interfere with returning echoes from actual targets.

Interference occurs when two waves move simultaneously through a medium. They can interfere constructively, destructively, or produce a resultant of zero.

Resonance occurs when an objects vibrates (or resonates) at its natural frequency. When different frequencies are produced inside a cavity, the sound from the cavity sounds louder at its resonant frequency than at all other frequencies.

Noise is any disturbance that distracts from or distorts the quality of sound.

A photon is the smallest unit of radiant energy that makes up light waves and radio waves.

Angstrom (Å) units are used for measuring the wavelength of light. One angstrom = 10^{-10} meters .

The visible spectrum contains all the colors between infrared and ultraviolet. Infrared and ultraviolet are invisible to the human eye.

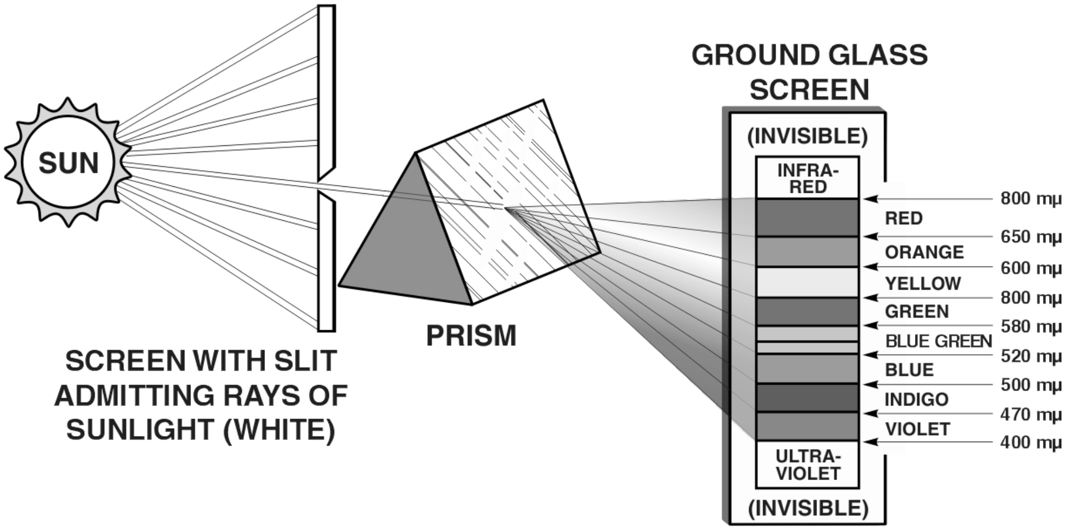


Figure 1-Sum 7. Use of a Prism to Split White Light into Different Colors

The primary colors of light are red, green, and blue. These primaries can be mixed to make any color between red and violet. If the three colors are mixed equally, they produce white light.

The complementary colors of light are magenta, yellow, and cyan. Mixing any two of the primary colors together in overlapping beams produces them.

The speed of light in empty space is considered to be 186,000 miles per second (or 300,000,000 meters per second). This speed varies in different mediums, but the constant of 186,000 miles per second is always used as the speed of light.

The electromagnetic spectrum is the complete range of electromagnetic frequencies from 3 kHz to beyond 300,000 THz. Audio frequencies (15 Hz to 20 kHz) are not electromagnetic energy and are not included in the electromagnetic spectrum. The electromagnetic field consists of an electric field and a magnetic field. These fields are responsible for the transmission and reception of electromagnetic energy through free space.

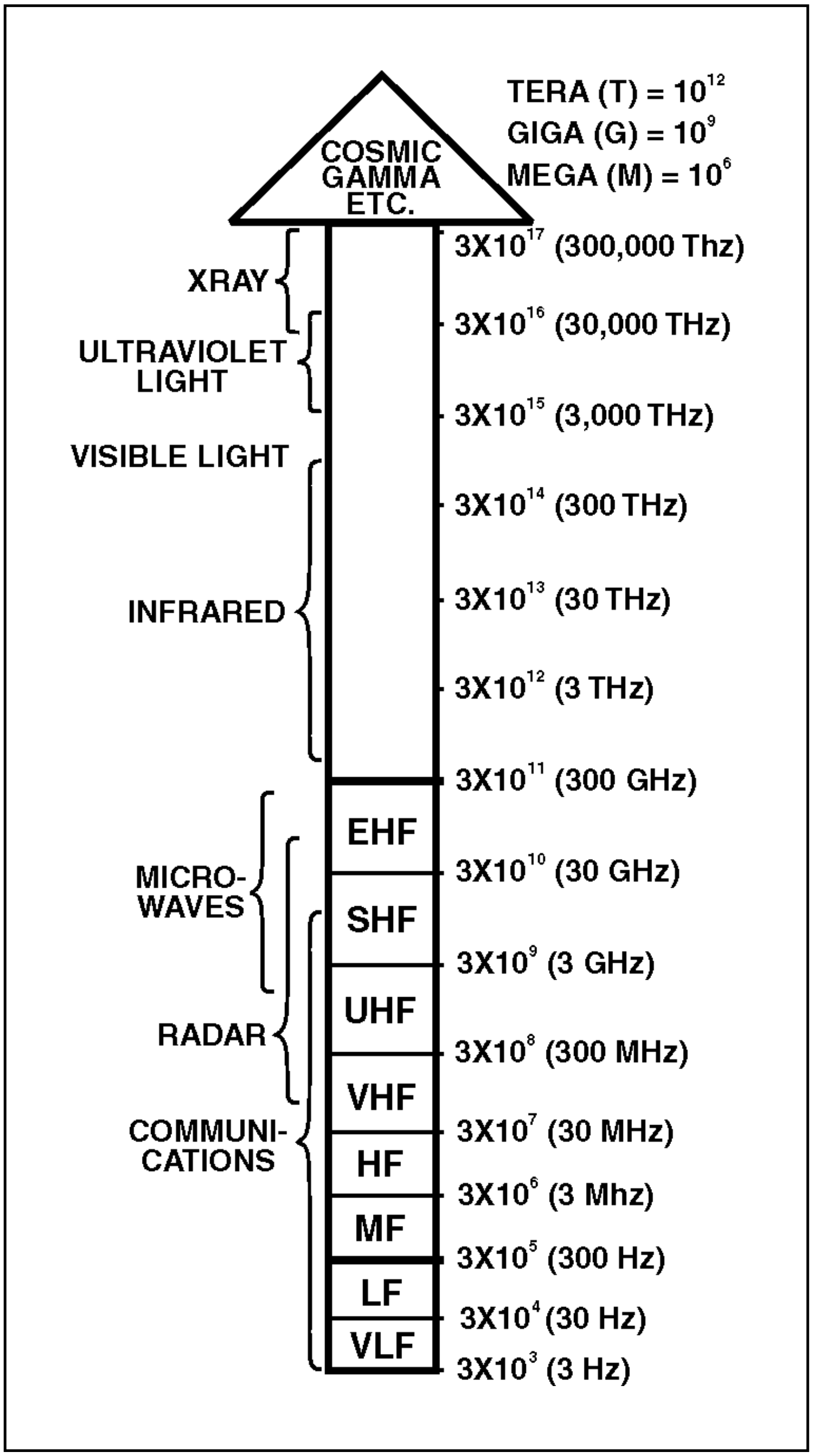


Figure 1-Sum 8. Electromagnetic Spectrum

Check-on-Learning Questions

Wave Propagation

When you are satisfied that you have answered every question to the best of your ability, check your answers using appendix A. If you missed eight or more questions, you should review the chapter, paying particular attention to the areas in which your answers were incorrect.

1. What is propagation?
2. How is a wave defined as it applies to wave propagation?
3. What is wave motion?
4. What are some examples of wave motion?
5. What type of wave motion is represented by the motion of water?
6. What are some examples of transverse waves?
7. What example of a longitudinal wave was given in the text?
8. What are the three requirements for a wave to be propagated?
9. What is a cycle?
10. What is wavelength (λ)?
11. What is the law of reflection?
12. When a wave is reflected from a surface, energy is transferred. When is the transfer of energy greatest?
13. When is the transfer of energy minimum?
14. A refracted wave occurs when a wave passes from one medium into another medium. What determines the angle of refraction?
15. The apparent change in frequency or pitch because of motion is explained by what effect?
16. What term describes sounds capable of being heard by the human ear?
17. Are all sounds audible to the human ear? Why?
18. Sound waves transmitted from a source are sometimes weak when they reach the detector. What instrument is needed to boost the weak signal?
19. What are the three basic requirements for sound?
20. What are the two general groups of sound?
21. What are the three basic characteristics of sound?
22. What is the normal audible range of the human ear?
23. What is intensity as it pertains to sound?
24. What characteristic of sound enables a person to distinguish one musical instrument from another, if they are all playing the same note?
25. How do density and temperature affect the velocity of sound?
26. What term is used to mean the science of sound?

27. A sound wave that is reflected back toward the source is known as what type of sound?
28. What is the term for multiple reflections of sound waves?
29. A cavity that vibrates at its natural frequency produces a louder sound than at other frequencies. What term is used to describe this phenomenon?
30. What do we call a disturbance that distracts or distorts the quality of sound?
31. What are three means of producing light?
32. What is the smallest unit of radiant energy?
33. What unit is used to measure the different wavelengths of light?
34. What are the three primary colors of light?
35. What are the three secondary colors of light?
36. White light falls upon a dull, rough, dark-brown object. Will the light primarily be reflected, diffused, or absorbed by the object?
37. What color will be emitted by a dull, rough, black object when white light falls upon it?
38. A substance that transmits light but through which an object cannot be seen clearly is known as what kind of substance?
39. At what speed does light travel?
40. A light wave enters a sheet of glass at a perfect right angle to the surface. Is the majority of the wave reflected, refracted, transmitted, or absorbed?
41. When light strikes a piece of white paper, the light is reflected in all directions. What do we call this scattering of light?
42. What three examples of electromagnetic energy are mentioned in the text?
43. What is the main difference between the bulk of the electromagnetic spectrum and the visible spectrum?
44. What are the two components (fields) that make up the electromagnetic wave?
45. What do we call a conductor (or set of conductors) that radiates electromagnetic energy into space?
46. What do we call the field that is created between two rods when a voltage is applied to them?
47. When current flows through a conductor, a field is created around the conductor. What do we call this field?
48. An induction field is created around a conductor when current flows through it. What do we call the field that detaches itself from the conductor and travels through space?

Chapter 2

Radio Wave Propagation

LEARNING OBJECTIVES

2-1. Upon completing this chapter, you should be able to do the following:

- State what the electromagnetic field is and what components make up the electromagnetic field.
- State the difference between the induction field and the radiation field.
- State what radio waves are.
- List the components of a radio wave and define the terms cycle, frequency, harmonics, period, wavelength, and velocity as applied to radio wave propagation.
- Compute the wavelength of radio waves.
- State how radio waves are polarized, vertically and horizontally.
- State what reflection, refraction, and diffraction are as applied to radio waves.
- State what influence the earth's atmosphere has on radio waves and list the different layers of the earth's atmosphere.
- Identify a ground wave and a sky wave, and describe the effects of the ionosphere on the sky wave.
- Identify the structure of the ionosphere.
- Define density of layer, frequency, angle of incidence, skip distance, and skip zone.
- Describe propagation paths.
- Describe fading, multipath fading, and selective fading. Describe propagation paths.
- State how transmission losses affect radio wave propagation.
- State how electromagnetic interference, man-made/natural interference, and ionospheric disturbances affect radio wave propagation. State how transmission losses affect radio wave propagation.
- Identify variations in the ionosphere.
- Identify the maximum, optimum, and lowest usable frequencies of radio waves.
- State what temperature inversion is, how frequency predictions are made, and how weather affects frequency.
- State what tropospheric scatter is and how it affects radio wave propagation.

ELECTROMAGNETIC FIELDS

2-2. The way energy is propagated into free space is a source of great dispute among people concerned with it. Although many theories have been proposed, the following theory adequately explains the phenomena and has been widely accepted. There are two basic fields associated with every antenna; an induction field and a radiation field. The field associated with the energy stored in the antenna is the induction field. This field is said to provide no part in the transmission of electromagnetic energy through free space. However, without the presence of the induction field, there would be no energy radiated.

INDUCTION FIELD

2-3. Figure 2-1, which illustrates a low-frequency generator connected to an antenna, will help you understand how the induction field is produced. Let us follow the generator through one cycle of operation.

2-4. Initially, you can consider that the generator output is zero and that no fields exist about the antenna, as shown in figure 2-1, view A. Now assume that the generator produces a slight potential and has the instantaneous polarity shown in view B. Because of this slight potential, the antenna capacitance acts as a short, allowing a large flow of current (I) through the antenna in the direction shown. This current flow, in turn, produces a large magnetic field about the antenna. Because the flow of current at each end of the antenna is minimum, the corresponding magnetic fields at each end of the antenna are also minimum. As time passes, charges—which oppose antenna current and produce an electrostatic field (E field)—collect at each end of the antenna. Eventually, the antenna capacitance becomes fully charged and stops current flow through the antenna. Under this condition, the electrostatic field is maximum, and the magnetic field (H field) is fully collapsed, as shown in view C.

2-5. As the generator potential decreases back to zero, the potential of the antenna begins to discharge. During the discharging process, the electrostatic field collapses and the direction of current flow reverses, as shown in figure 2-1, view D. When the current again begins to flow, an associated magnetic field is generated. Eventually, the electrostatic field completely collapses, the generator potential reverses, and current is maximum, as shown in view E. As charges collect at each end of the antenna, an electrostatic field is produced and current flow decreases. This causes the magnetic field to begin collapsing. The collapsing magnetic field produces more current flow, a greater accumulation of charge, and a greater electrostatic field. The antenna gradually reaches the condition shown in view F, where current is zero and the collected charges are maximum.

2-6. As the generator potential again decreases toward zero, the antenna begins to discharge and the electrostatic field begins to collapse. When the generator potential reaches zero, discharge current is maximum and the associated magnetic field is maximum. A brief time later, generator potential reverses, and the condition shown in view B recurs.

Note: The electric field (E field) and the electrostatic field (E field) are the same. The terms are used interchangeably throughout this text.

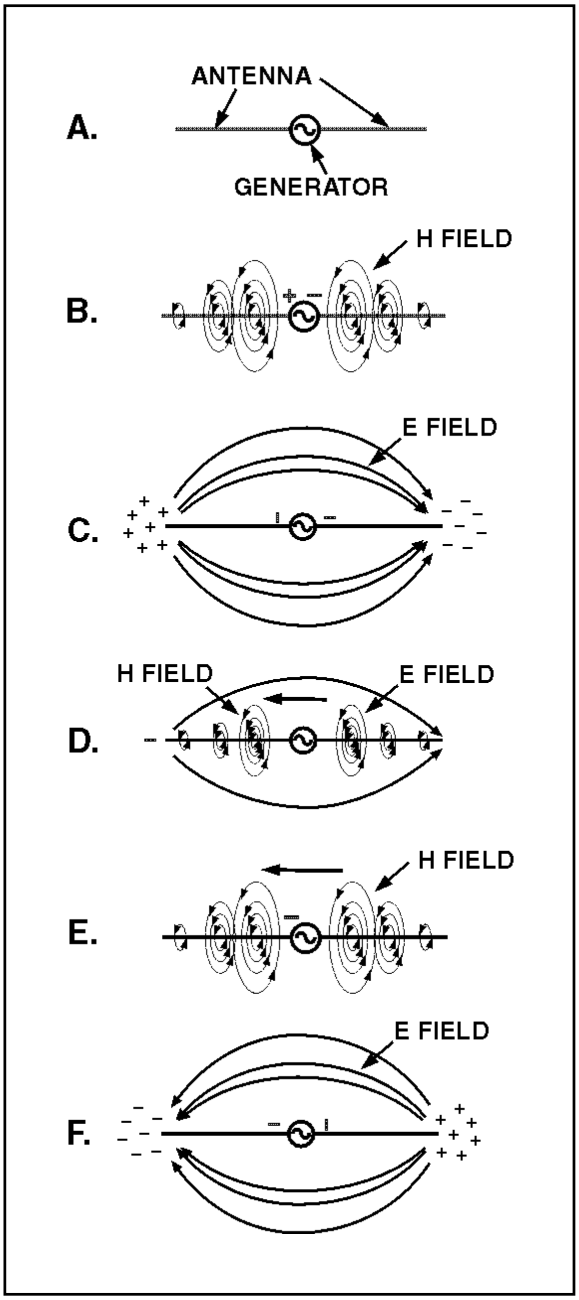


Figure 2-1. Induction Field about an Antenna

2-7. The graph shown in figure 2-2 shows the relationship between the magnetic (H) field and the electric (E) field plotted against time. Note that the two fields are 90 degrees out of phase with each other. If you compare the graph in figure 2-2 with figure 2-1, you will notice that the two fields around the antenna are displaced 90 degrees from each other in space. (The H field exists in a plane perpendicular to the antenna. The E field exists in a plane parallel with the antenna, as shown in figure 2-1.)

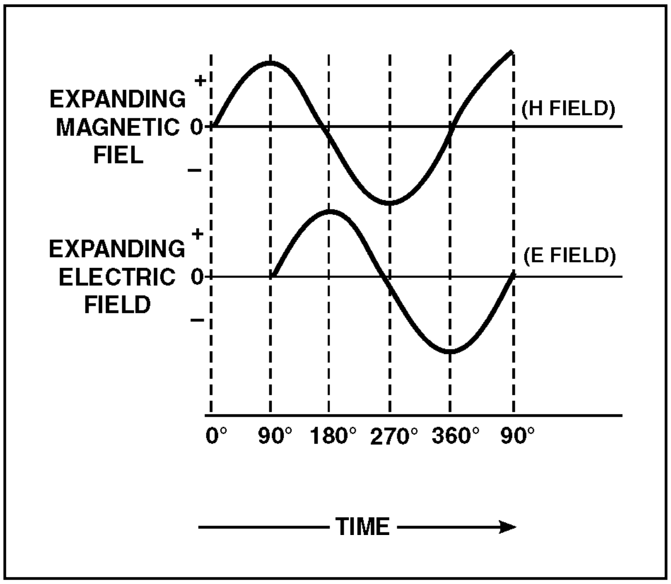


Figure 2-2. Phase Relationship of Induction Field Components

2-8. All the energy supplied to the induction field is returned to the antenna by the collapsing E and H fields. No energy from the induction field is radiated from the antenna. Therefore, the induction field is considered a local field and plays no part in the transmission of electromagnetic energy. The induction field represents only the stored energy in the antenna and is responsible only for the resonant effects that the antenna reflects to the generator.

RADIATION FIELD

2-9. The E and H fields that are set up in the transfer of energy through space are known collectively as the radiation field. This radiation field is responsible for electromagnetic radiation from the antenna. The radiation field decreases as the distance from the antenna is increased. Because the decrease is linear, the radiation field reaches great distances from the antenna.

2-10. Let us look at a half-wave antenna to illustrate how this radiation actually takes place. Simply stated, a half-wave antenna is one that has an electrical length equal to half the wavelength of the signal being transmitted. Assume, for example, that a transmitter is operating at 30 megahertz. If a half-wave antenna is used with the transmitter, the antenna's electrical length would have to be at least 16 feet long. (The formula used to compute the electrical length of an antenna is explained in chapter 4.) When power is delivered to the half-wave antenna, both an induction field and a radiation field are set up by the fluctuating energy. At the antenna, the intensities of these fields are proportional to the amount of power delivered to the antenna from a source such as a transmitter. At a short distance from the antenna and beyond, only the radiation field exists. This radiation field is made up of an electric component and a magnetic component at right angles to each other in space and varying together in intensity.

2-11. With a high-frequency generator (a transmitter) connected to the antenna, the induction field is produced as described in the previous section. However, the generator potential reverses before the electrostatic field has had time to collapse completely. The reversed generator potential neutralizes the remaining antenna charges, leaving a resultant E field in space.

2-12. Figure 2-3 is a simple picture of an E field detaching itself from an antenna. (The H field is not considered in this example, although it is present.) In view A, the voltage is maximum and the electric field has maximum intensity. The lines of force begin at the end of the antenna that is positively charged and extend to the end of the antenna that is negatively charged. Note that the outer E lines are stretched away from the inner lines. This is because of the repelling force that takes place between lines of force in the same direction. As the voltage drops (view B), the separated charges come together, and the ends of the lines move toward the center of the antenna. However, because lines of force in the same direction repel each other, the centers of the lines are still being held out.

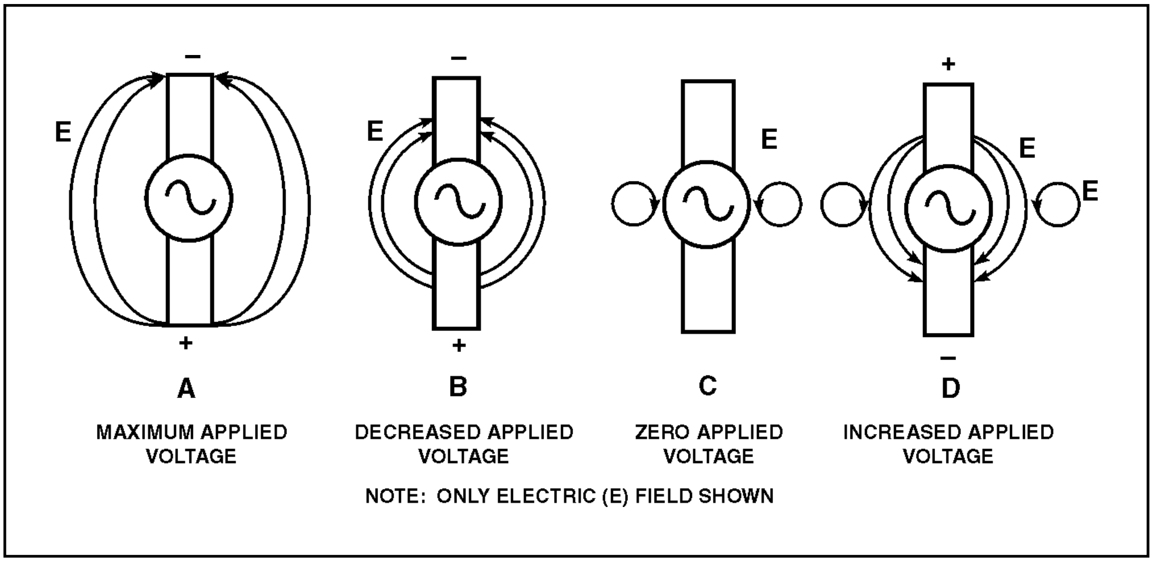


Figure 2-3. Radiation from an Antenna

2-13. As the voltage approaches zero (view B), some of the lines collapse back into the antenna. At the same time, the ends of other lines begin to come together to form a complete loop. Notice the direction of these lines of force next to the antenna in view C. At this point the voltage on the antenna is zero. As the charge starts to build up in the opposite direction (view D), electric lines of force again begin at the positive end of the antenna and stretch to the negative end of the antenna. These lines of force, being in the same direction as the sides of the closed loops next to the antenna, repel the closed loops and force them out into space at the speed of light. As these loops travel through space, they generate a magnetic field in phase with them.

2-14. Because each successive E field is generated with a polarity that is opposite the preceding E field (that is, the lines of force are opposite), an oscillating electric field is produced along the path of travel. When an electric field oscillates, a magnetic field having an intensity that varies directly with that of the E field is produced. The variations in magnetic field intensity, in turn, produce another E field. Thus, the two varying fields sustain each other, resulting in electromagnetic wave propagation.

2-15. During this radiation process, the E and H fields are in phase in time but physically displaced 90 degrees in space. Thus, the varying magnetic field produces a varying electric field; and the varying electric field, in turn, sustains the varying magnetic field. Each field supports the other, and neither can be propagated by itself. Figure 2-4 shows a comparison between the induction field and the radiation field.

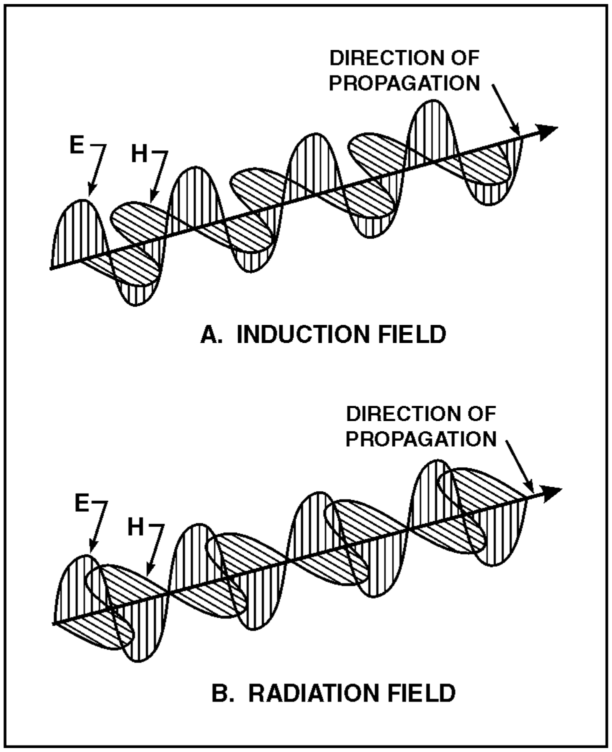


Figure 2-4. E and H Components of Induction and Radiation Fields

RADIO WAVES

2-16. An energy wave generated by a transmitter is called a radio wave. The radio wave radiated into space by the transmitting antenna is a very complex form of energy containing both electric and magnetic fields. Because of this combination of fields, radio waves are also referred to as electromagnetic radiation. The discussion that follows explains the earth's atmosphere and its effect on radio waves. All the principles of wave motion that were discussed in chapter 1 also apply to radio waves.

Note. The term radio wave is not limited to communications equipment alone. The term applies to all equipment that generates signals in the form of electromagnetic energy.

CHARACTERISTICS OF RADIO WAVES

2-17. **Shape**. The basic shape of the wave generated by a transmitter is that of a sine wave. The wave radiated out into space, however, may or may not retain the characteristics of the sine wave.

2-18. A sine wave can be one cycle or many cycles. Recall from chapter 1 that the number of cycles of a sine wave that are completed in 1 second is known as the frequency of the sine wave. For example, 60 cycles of ordinary house current occur each second, so house current is said to have a frequency of 60 cycles per second or 60 hertz.

2-19. **Frequency**. The frequencies falling between 3000 hertz (3 kHz) and 300,000,000,000 hertz (300 GHz) are called radio frequencies (abbreviated RF) because they are commonly used in radio communications. This part of the radio frequency spectrum is divided into bands, each band being 10 times higher in frequency than the one immediately below it. This arrangement serves as a convenient way to remember the range of each band. The RF bands are shown in Table 2-1. The usable radio-frequency range is roughly 10 kilohertz to 100 gigahertz.

Table 2-1. Radio Frequency Bands

DESCRIPTION	*ABBREVIATION*	*FREQUENCY*
Very low	VLF	3 to 30 kHz
Low	LF	30 to 300 kHz
Medium	MF	300 to 3000 kHz
High	HF	3 to 30 MHz
Very high	VHF	30 to 300 MHz
Ultrahigh	UHF	300 to 3000 MHz
Superhigh	SHF	3 to 30 GHz
Extremely high	EHF	30 to 300 GHz

2-20. **Harmonics**. Any frequency that is a whole number multiple of a smaller basic frequency is known as a harmonic of that basic frequency. The basic frequency itself is called the first harmonic or, more commonly, the fundamental frequency. A frequency that is twice as great as the fundamental frequency is called the second harmonic; a frequency three times as great is the third harmonic; and so on. For example:

First harmonic (fundamental frequency)	3000 kHz
Second harmonic	6000 kHz
Third harmonic	9000 kHz

2-21. **Period**. The period of a radio wave is simply the amount of time required to complete one full cycle. If a sine wave has a frequency of 2 hertz, each cycle has a duration, or period, of one-half second. If the frequency is 10 hertz, the period of each cycle is one-tenth of a second. Because the frequency of a radio wave is the number of cycles that are completed in one second, you should be able to see that as the frequency of a radio wave increases, its period decreases.

2-22. **Wavelength**. A wavelength is the space occupied by one full cycle of a radio wave at any given instant. Wavelengths are expressed in meters (1 meter is equal to 3.28 feet). You need to have a good understanding of frequency and wavelength to be able to select the proper antenna(s) to use for successful communications. The relationship between frequency, wavelength, and antennas are discussed in chapter 4.

2-23. **Velocity**. The velocity (or speed) of a radio wave radiated into free space by a transmitting antenna is equal to the speed of light, which is 186,000 miles per second or 300,000,000 meters per second. Because of various factors, such as barometric pressure, humidity, and molecular content, radio waves travel inside the earth's atmosphere at a speed slightly less than the speed of light. Normally, in discussions of the velocity of radio waves, the velocity referred to is the speed at which radio waves travel in free space.

2-24. The frequency of a radio wave has nothing to do with its velocity. A 5-megahertz wave travels through space at the same velocity as a 10-megahertz wave. However, the velocity of radio waves is an important factor in making wavelength-to-frequency conversions, the subject of our next discussion.

WAVELENGTH-TO-FREQUENCY CONVERSIONS

2-25. Radio waves are often referred to by their wavelength in meters rather than by frequency. For example, most people have heard commercial radio stations make announcements similar to the following: "Station WXYZ operating on 240 meters." To tune receiving equipment that is calibrated by frequency to such a station, you must first convert the designated wavelength to its equivalent frequency.

2-26. As discussed earlier, a radio wave travels 300,000,000 meters per second (speed of light); therefore, a radio wave of 1 hertz would have traveled a distance (or wavelength) of 300,000,000 meters. Obviously then, if the frequency of the wave is increased to 2 hertz, the wavelength will be cut in half to 150,000,000 meters. This illustrates the principle that the higher the frequency, the shorter the wavelength.

2-27. Wavelength-to-frequency conversions of radio waves are really quite simple because wavelength and frequency are reciprocals: Either one divided into the velocity of a radio wave yields the other. Remember, the formula for wavelength is:

$$\lambda = \frac{v}{f} \quad \text{or} \quad f = \frac{v}{\lambda}$$

Where:

λ = wavelength in meters

v = velocity of radio of radio wave (in Hz, kHz, or MHz)

f = frequency of radio wave (in Hz, kHz, or MHz)

2-28. The wavelength in meters divided into 300,000,000 yields the frequency of a radio wave in hertz. Likewise, the wavelength divided into 300,000 yields the frequency of a radio wave in kilohertz, and the wavelength divided into 300 yields the frequency in megahertz.

2-29. Now, let us apply the formula to determine the frequency to which the receiving equipment must be tuned to receive station WXYZ operating on 240 meters. Radio wave frequencies are normally expressed in kilohertz or megahertz.

2-30. To find the frequency in hertz, use the formula:

$$f = \frac{v}{\lambda}$$

Given:

v = 300,000,000 meters per second

λ = 240 meters

Solution:

$$f = \frac{300{,}000{,}000 \text{ meters per second}}{240 \text{ meters}}$$

f = 1,250,000 Hz

2-31. To find the frequency in kilohertz, use the formula:

$$f\ (\text{kHz}) = \frac{300{,}000}{\lambda}$$

Given:

λ = 240 meters

Solution:

$$f\ (\text{kHz}) = \frac{300{,}000}{240 \text{ meters}}$$

f = 1,250 kHz

2-32. To find the frequency in megahertz, use the formula:

$$f\ (\text{MHz}) = \frac{300}{\lambda}$$

Given:

λ = 240 meters

Solution:

$$f\ (\text{MHz}) = \frac{300}{240 \text{ meters}}$$

f = 1.25 MHz

POLARIZATION

2-33. For maximum absorption of energy from the electromagnetic fields, the receiving antenna must be located in the plane of polarization. This places the conductor of the antenna at right angles to the magnetic lines of force moving through the antenna and parallel to the electric lines, causing maximum induction.

2-34. Normally, the plane of polarization of a radio wave is the plane in which the E field propagates with respect to the earth. If the E field component of the radiated wave travels in a plane perpendicular to the earth's surface (vertical), the radiation is said to be vertically polarized, as shown in figure 2-5, view A. If the E field propagates in a plane parallel to the earth's surface (horizontal), the radiation is said to be horizontally polarized, as shown in view B.

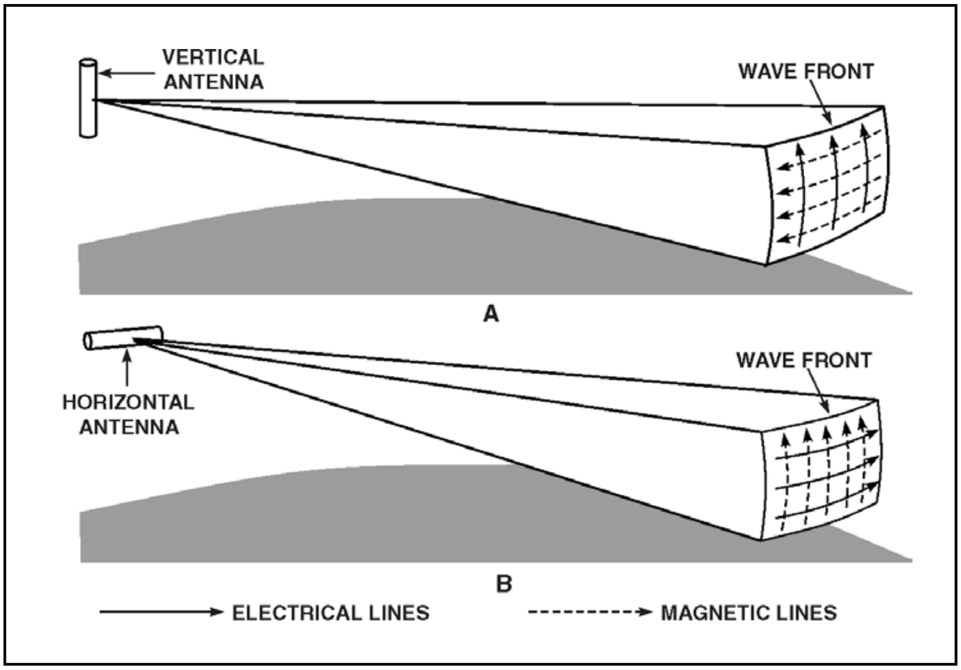


Figure 2-5. Vertical and Horizontal Polarization

2-35. The position of the antenna in space is important because it affects the polarization of the electromagnetic wave. When the transmitting antenna is close to the ground, vertically polarized waves cause greater signal strength along the earth's surface. On the other hand, antennas high above the ground should be horizontally polarized to get the greatest possible signal strength to the earth's surface. Vertically and horizontally polarized antennas are discussed in more detail in chapter 4.

2-36. The radiated energy from an antenna is in the form of an expanding sphere. Any small section of this sphere is perpendicular to the direction the energy travels and is called a wavefront. All energy on a wavefront is in phase. Usually all points on the wavefront are at equal distances from the antenna. The farther the wavefront is from the antenna, the less spherical the wave appears. At a considerable distance the wavefront can be considered as a plane surface at a right angle to the direction of propagation.

2-37. If you know the directions of the E and H components, you can use the "right-hand rule" to determine the direction of wave propagation (see figure 2-6). This rule states that if the thumb, forefinger, and middle finger of the right hand are extended so they are mutually perpendicular, the middle finger will point in the direction of wave propagation if the thumb points in the direction of the E field and the forefinger points in the direction of the H field. Because both the E and H fields reverse directions simultaneously, propagation of a particular wavefront is always in the same direction (away from the antenna).

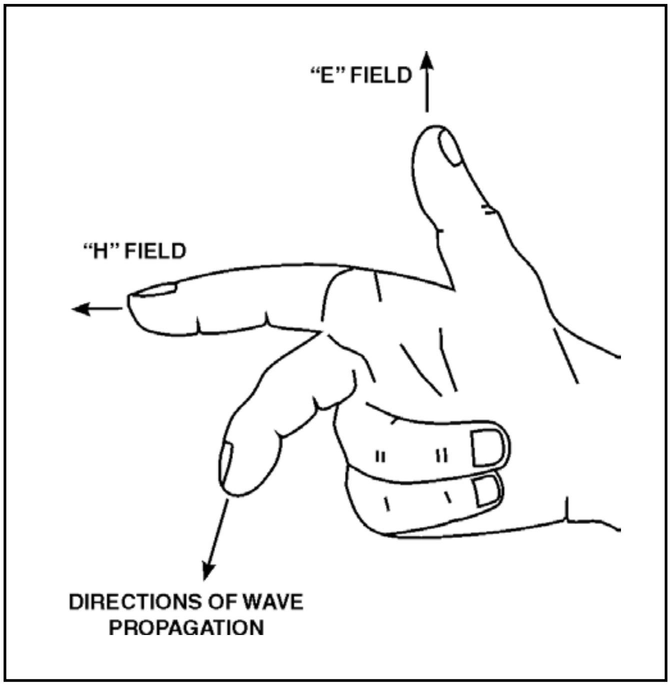


Figure 2-6. Right-Hand Rule for Propagation

ATMOSPHERIC PROPAGATION

2-38. Within the atmosphere, radio waves can be reflected, refracted, and diffracted in the same manner as light and heat waves.

Reflection

2-39. Radio waves may be reflected from various substances or objects they meet during travel between the transmitting and receiving sites. The amount of reflection depends on the reflecting material. Smooth metal surfaces of good electrical conductivity are efficient reflectors of radio waves. The surface of the earth itself is a fairly good reflector. The radio wave is not reflected from a single point on the reflector but rather from an area on its surface. The size of the area required for reflection to take place depends on the wavelength of the radio wave and the angle at which the wave strikes the reflecting substance.

2-40. When radio waves are reflected from flat surfaces, a phase shift in the alternations of the wave occurs. Figure 2-7 shows two radio waves being reflected from the earth's surface. Notice that the positive and negative alternations of radio waves (A) and (B) are in phase with each other in their paths toward the earth's surface. After reflection takes place, however, the waves are approximately 180 degrees out of phase. The amount of phase shift that occurs is not constant. It depends on the polarization of the wave and the angle at which the wave strikes the reflecting surface. Radio waves that keep their phase relationships after reflection normally produce a stronger signal at the receiving site. Those that are received out of phase produce a weak or fading signal. The shifting in the phase relationships of reflected radio waves is one of the major reasons for fading. Fading is discussed in more detail later in this chapter.

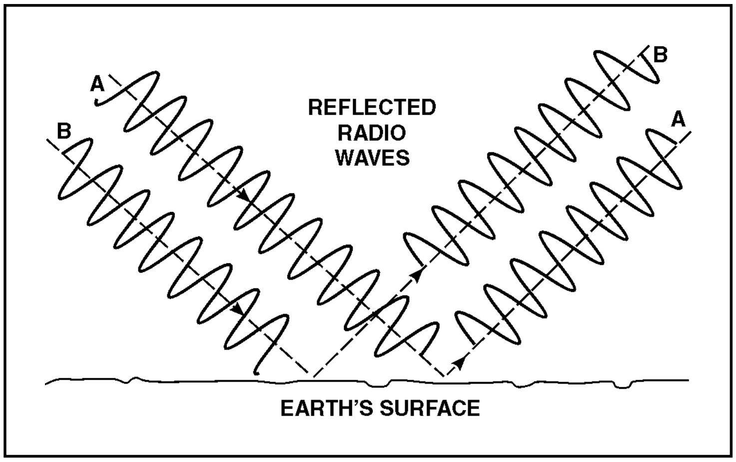


Figure 2-7. Phase Shift of Reflected Radio Waves

Refraction

2-41. Another phenomenon common to most radio waves is the bending of the waves as they move from one medium into another in which the velocity of propagation is different. This bending of the waves is called refraction. For example, suppose you are driving down a smoothly paved road at a constant speed and suddenly one wheel goes off onto the soft shoulder. The car tends to veer off to one side. The change of medium, from hard surface to soft shoulder, causes a change in speed or velocity. The tendency is for the car to change direction. This same principle applies to radio waves as changes occur in the medium through which they are passing. As an example, the radio wave shown in figure 2-8 is traveling through the earth's atmosphere at a constant speed. As the wave enters the dense layer of electrically charged ions, the part of the wave that enters the new medium first travels faster than the parts of the wave that have not yet entered the new medium. This abrupt increase in velocity of the upper part of the wave causes the wave to bend back toward the earth. This bending, or change of direction, is always toward the medium that has the lower velocity of propagation.

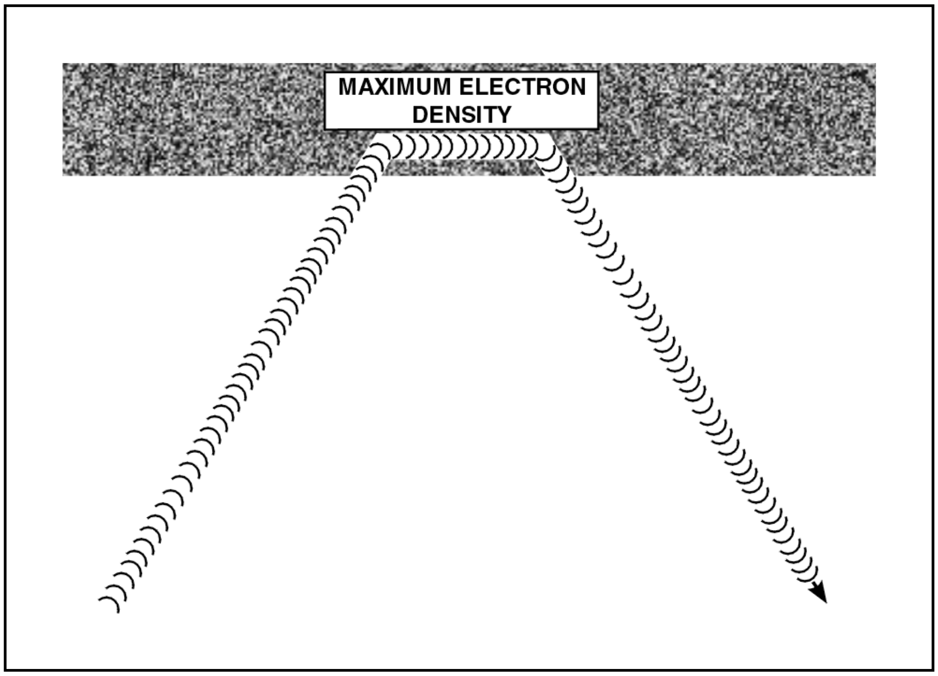


Figure 2-8. Radio Wave Refraction

2-42. Radio waves passing through the atmosphere are affected by certain factors, such as temperature, pressure, humidity, and density. These factors can cause the radio waves to be refracted. This effect is discussed in greater detail later in this chapter.

Diffraction

2-43. A radio wave that meets an obstacle has a natural tendency to bend around the obstacle, as illustrated in figure 2-9. The bending, called diffraction, results in a change of direction of part of the wave energy from the normal line-of-sight path. This change makes it possible to receive energy around the edges of an obstacle as shown in figure 2-9, view A or at some distances below the highest point of an obstruction, as shown in view B. Although diffracted RF energy usually is weak, it can still be detected by a suitable receiver. The principal effect of diffraction extends the radio range beyond the visible horizon. In certain cases, by using high power and very low frequencies, radio waves can be made to encircle the earth by diffraction.

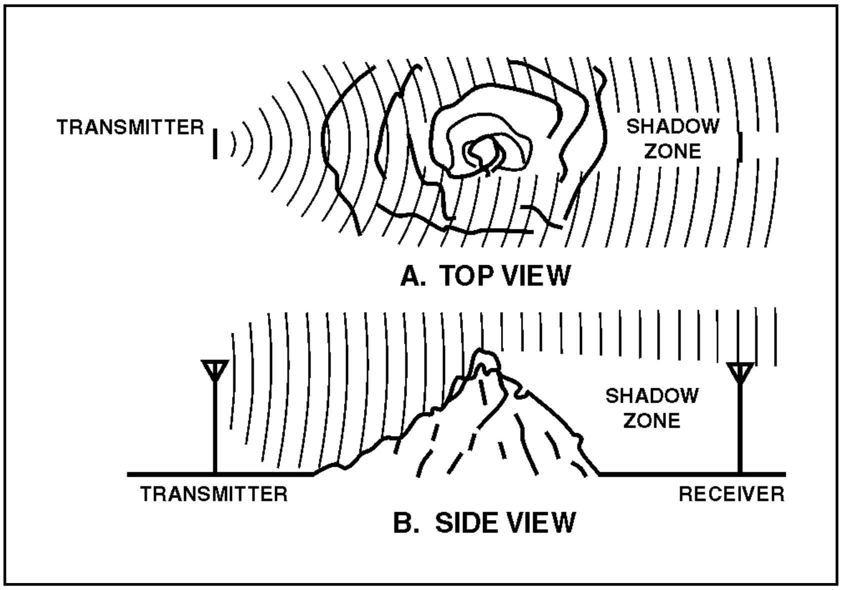


Figure 2-9. Diffraction around an Object

EFFECT OF THE EARTH'S ATMOSPHERE ON RADIO WAVES

2-44. The discussion of electromagnetic wave propagation is concerned mainly with the properties and effects of the medium located between the transmitting antenna and the receiving antenna. While radio waves traveling in free space have little outside influence affecting them, radio waves traveling within the earth's atmosphere are affected by varying conditions. The influence exerted on radio waves by the earth's atmosphere adds many new factors to complicate what at first seems to be a relatively simple problem. These complications are because of a lack of uniformity within the earth's atmosphere. Atmospheric conditions vary with changes in height, geographical location, and even with changes in time (day, night, season, and year). Knowledge of the composition of the earth's atmosphere is extremely important for understanding wave propagation.

2-45. The earth's atmosphere is divided into three separate regions, or layers. They are the troposphere, the stratosphere, and the ionosphere. The layers of the atmosphere are illustrated in figure 2-10.

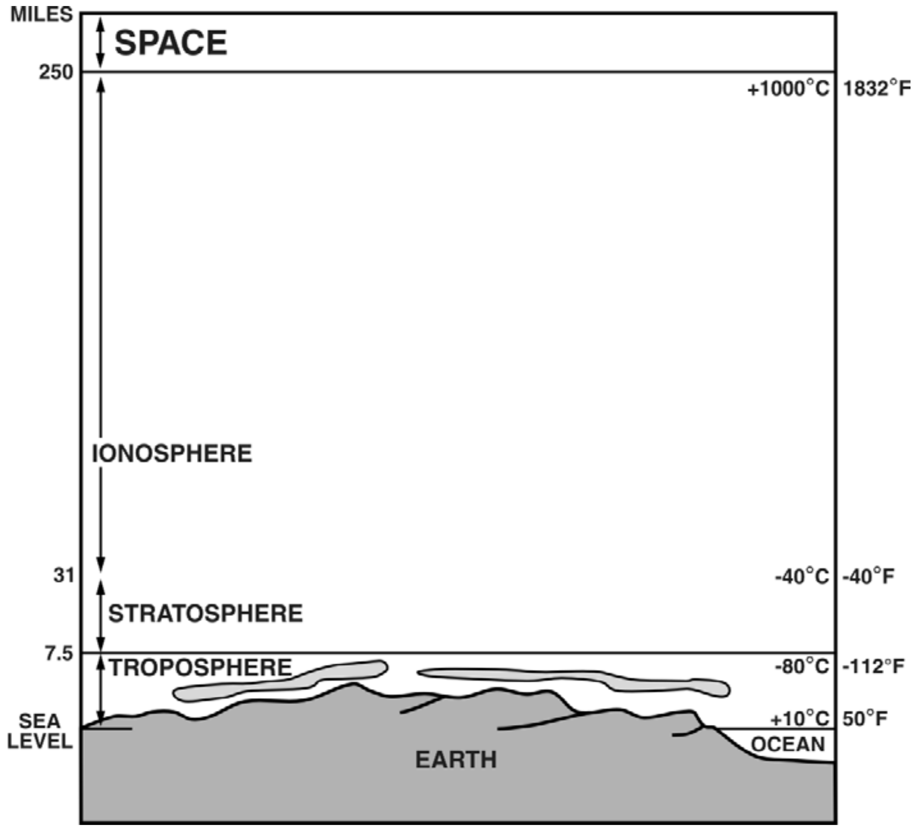


Figure 2-10. Layers of the Earth's Atmosphere

Troposphere

2-46. The troposphere is the portion of the earth's atmosphere that extends from the surface of the earth to a height of about 3.7 miles (6 km) at the North Pole or the South Pole, and 11.2 miles (18 km) at the equator. Virtually all weather phenomena take place in the troposphere. The temperature in this region decreases rapidly with altitude, clouds form, and there may be much turbulence because of variations in temperature, density, and pressure. These conditions have a great effect on the propagation of radio waves, as explained later in this chapter.

Stratosphere

2-47. The stratosphere is located between the troposphere and the ionosphere. The temperature throughout this region is considered to be almost constant and there is little water vapor present. The stratosphere has relatively little effect on radio waves because it is a relatively calm region with little or no temperature changes.

Ionosphere

2-48. The ionosphere extends upward from about 31.1 miles (50 km) to a height of about 250 miles (402 km). It contains four cloud-like layers of electrically charged ions, which enable radio waves to be propagated to great distances around the earth. This is the most important region of the atmosphere for long distance point-to-point communications. This region is discussed in detail later in this chapter.

RADIO WAVE TRANSMISSION PATHS

2-49. There are two principal ways in which electromagnetic (radio) energy travels from a transmitting antenna to a receiving antenna. One way is by ground waves and the other is by sky waves. Ground waves are radio waves that travel near the surface of the earth (surface and space waves). Sky waves are radio waves that are reflected back to Earth from the ionosphere (see figure 2-11).

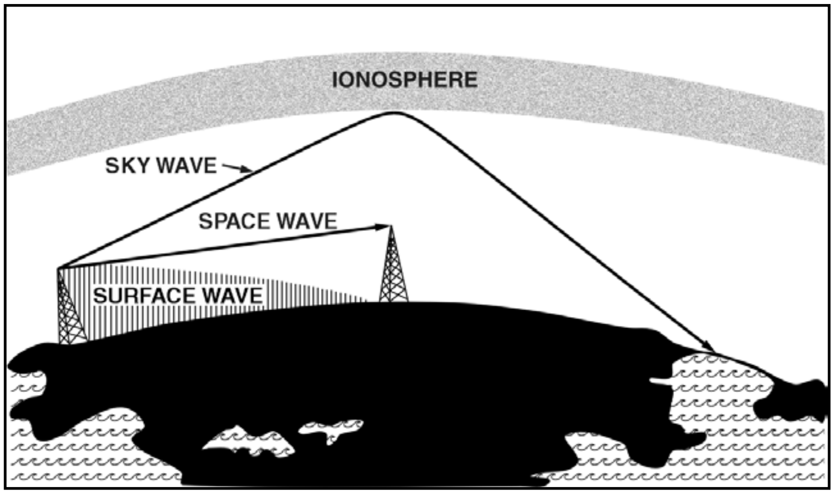


Figure 2-11. Ground Waves and Sky Waves

Ground Waves

2-50. The ground wave is actually composed of two separate component waves. These are known as the surface wave and the space wave (figure 2-11). The determining factor in whether a ground wave component is classified as a space wave or a surface wave is simple. A surface wave travels along the surface of the earth. A space wave travels over the surface.

2-51. **Surface wave**. The surface wave reaches the receiving site by traveling along the surface of the ground as shown in figure 2-12. A surface wave can follow the contours of the earth because of the process of diffraction. When a surface wave meets an object and the dimensions of the object do not exceed its wavelength, the wave tends to curve or bend around the object. The smaller the object, the more pronounced the diffractive action will be.

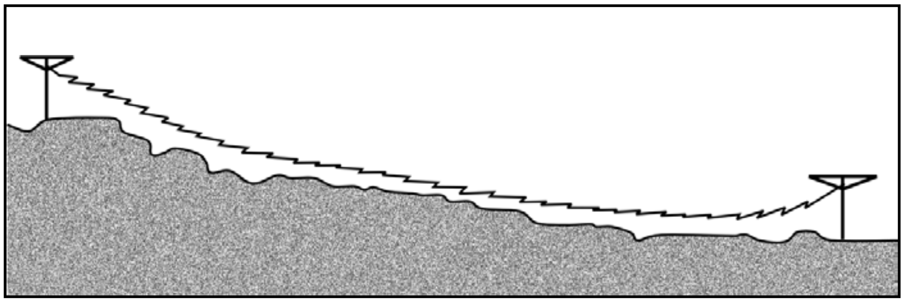


Figure 2-12. Surface Wave Propagation

2-52. As a surface wave passes over the ground, the wave induces a voltage in the earth. The induced voltage takes energy away from the surface wave, thereby weakening, or attenuating, the wave as it moves away from the transmitting antenna. To reduce the attenuation, the amount of induced voltage must be reduced. This is done by using vertically polarized waves that minimize the extent to which the electric field of the wave is in contact with the earth. When a surface wave is horizontally polarized, the electric field of the wave is parallel with the surface of the earth and, therefore, is constantly in contact with it. The wave is then completely attenuated within a short distance from the transmitting site. On the other hand, when the surface wave is vertically polarized, the electric field is perpendicular to the earth and merely dips into and out of the earth's surface. For this reason, vertical polarization is vastly superior to horizontal polarization for surface wave propagation.

2-53. The attenuation that a surface wave undergoes because of induced voltage also depends on the electrical properties of the terrain over which the wave travels. The best type of surface is one that has good electrical conductivity. The better the conductivity, the less the attenuation. Table 2-2 gives the relative conductivity of various Earth surfaces.

Table 2-2. Surface Conductivity

SURFACE	***RELATIVE CONDUCTIVITY***
Sea water	Good
Flat, loamy soil	Fair
Large bodies of fresh water	Fair
Rocky terrain	Poor
Desert	Poor
Jungle	Unusable

2-54. Another major factor in the attenuation of surface waves is frequency. Recall from earlier discussions on wavelength that the higher the frequency of a radio wave, the shorter its wavelength will be. These high frequencies, with their shorter wavelengths, are not normally diffracted but are absorbed by the earth at points relatively close to the transmitting site. You can assume, therefore, that as the frequency of a surface wave is increased, the more rapidly the surface wave will be absorbed, or attenuated, by the earth.

Because of this loss by attenuation, the surface wave is impractical for long-distance transmissions at frequencies above 2 megahertz. On the other hand, when the frequency of a surface wave is low enough to have a very long wavelength, the earth appears to be very small, and diffraction is sufficient for propagation well beyond the horizon. In fact, by lowering the transmitting frequency into the very low frequency (VLF) range and using very high-powered transmitters, the surface wave can be propagated great distances.

2-55. **Space wave**. The space wave follows two distinct paths from the transmitting antenna to the receiving antenna—one through the air directly to the receiving antenna, the other reflected from the ground to the receiving antenna. These paths are illustrated in figure 2-13. The primary or direct path of the space wave is directly from the transmitting antenna to the receiving antenna. So, the receiving antenna must be located within the radio horizon of the transmitting antenna. Because space waves are refracted slightly, even when propagated through the troposphere, the radio horizon is actually about one-third farther than the line-of-sight or natural horizon.

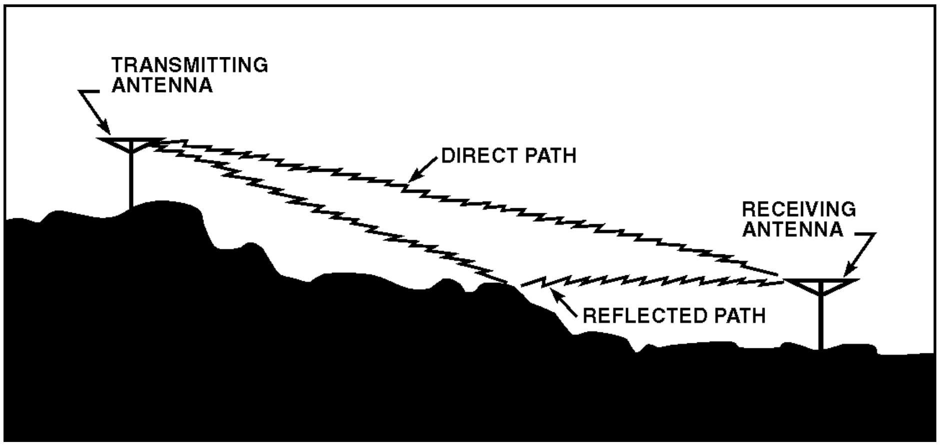


Figure 2-13. Space Wave Propagation

2-56. Although space waves suffer little ground attenuation, they nevertheless are susceptible to fading. This is because space waves actually follow two paths of different lengths (direct path and ground reflected path) to the receiving site and, therefore, may arrive in or out of phase. If these two component waves are received in phase, the result is a reinforced or stronger signal. Likewise, if they are received out of phase, they tend to cancel one another, which results in a weak or fading signal.

Sky Wave

2-57. The sky wave, often called the ionospheric wave, is radiated in an upward direction and returned to Earth at some distant location because of refraction from the ionosphere. This form of propagation is relatively unaffected by the earth's surface and can propagate signals over great distances. Usually the high frequency (HF) band is used for sky wave propagation. The following study of the ionosphere and its effect on sky waves will help you understand the nature of sky wave propagation.

STRUCTURE OF THE IONOSPHERE

2-58. As stated previously, the ionosphere is the region of the atmosphere that extends from about 31.1 miles (50 km) above the surface of the earth to about 250 miles (402 km) above the surface. It is appropriately named the ionosphere because it consists of several layers of electrically charged gas atoms called ions. A process called ionization forms the ions.

Ionization

2-59. Ionization occurs when high-energy ultraviolet light waves from the sun enter the ionospheric region of the atmosphere, strike a gas atom, and literally knock an electron free from its parent atom. A normal atom is electrically neutral because it contains equal numbers of positively charged protons in its nucleus and negatively charged electrons that orbit the nucleus. When an electron is knocked free from the atom, the atom becomes positively charged (called a positive ion) and remains in space along with the free electron, which is negatively charged. This process of upsetting electrical neutrality is known as ionization.

2-60. The free negative electrons subsequently absorb part of the ultraviolet energy, which initially freed them from their atoms. As the ultraviolet light wave continues to produce positive ions and negative electrons, its intensity decreases because of the absorption of energy by the free electrons, and an ionized layer is formed. The rate at which ionization occurs depends on the density of atoms in the atmosphere and the intensity of the ultraviolet light wave, which varies with the activity of the sun.

2-61. Because the atmosphere is bombarded by ultraviolet light waves of different frequencies, several ionized layers are formed at different altitudes. Lower frequency ultraviolet waves penetrate the atmosphere the least; therefore, they produce ionized layers at the higher altitudes. Conversely, ultraviolet waves of higher frequencies penetrate deeper and produce layers at the lower altitudes. An important factor in determining the density of ionized layers is the elevation angle of the sun, which changes frequently. For this reason, the height and thickness of the ionized layers vary, depending on the time of day and even the season of the year.

Recombination

2-62. Recall that the process of ionization involves ultraviolet light waves knocking electrons free from their atoms. A reverse process called recombination occurs when the free electrons and positive ions collide with each other. Because these collisions are inevitable, the positive ions return to their original neutral atom state.

2-63. The recombination process also depends on the time of day. Between the hours of early morning and late afternoon, the rate of ionization exceeds the rate of recombination. During this period, the ionized layers reach their greatest density and exert maximum influence on radio waves. During the late afternoon and early evening hours, however, the rate of recombination exceeds the rate of ionization, and the density of the ionized layers begins to decrease. Throughout the night, density continues to decrease, reaching a low point just before sunrise.

Four Distinct Layers

2-64. The ionosphere is composed of three layers designated D, E, and F, from lowest level to highest level as shown in figure 2-14. The F layer is further divided into two layers designated F1 (the lower layer) and F2 (the higher layer). The presence or absence of these layers in the ionosphere and their height above the earth varies with the position of the sun. At high noon, radiation in the ionosphere directly above a given point is greatest. At night it is minimum. When the radiation is removed, many of the particles that were ionized recombine. The time interval between these conditions finds the position and number of the ionized layers within the ionosphere changing. Because the position of the sun varies daily, monthly, and yearly, with respect to a specified point on the earth, the exact position and number of layers present are extremely difficult to determine. However, the following general statements can be made:

- The D layer ranges from about 30 to 55 miles. Ionization in the D layer is low because it is the lowest region of the ionosphere. This layer has the ability to refract signals of low frequencies. High frequencies pass right through it and are attenuated. After sunset, the D layer disappears because of the rapid recombination of ions.
- The E layer limits are from about 55 to 90 miles. This layer is also known as the Kennelly-Heaviside layer, because these two men were the first to propose its existence. The rate of ionic recombination in this layer is rather rapid after sunset and the layer is almost gone by midnight. This layer has the ability to refract signals as high as 20 megahertz. For this reason, it is valuable for communications in ranges up to about 1500 miles.
- The F layer exists from about 90 to 240 miles. During the daylight hours, the F layer separates into two layers, the F1 and F2 layers. The ionization level in these layers is quite high and varies widely during the day. At noon, this portion of the atmosphere is closest to the sun and the degree of ionization is maximum. Because the atmosphere is rarefied at these heights, recombination occurs slowly after sunset. Therefore, a fairly constant ionized layer is always present. The F layers are responsible for high frequency, long distance transmission.

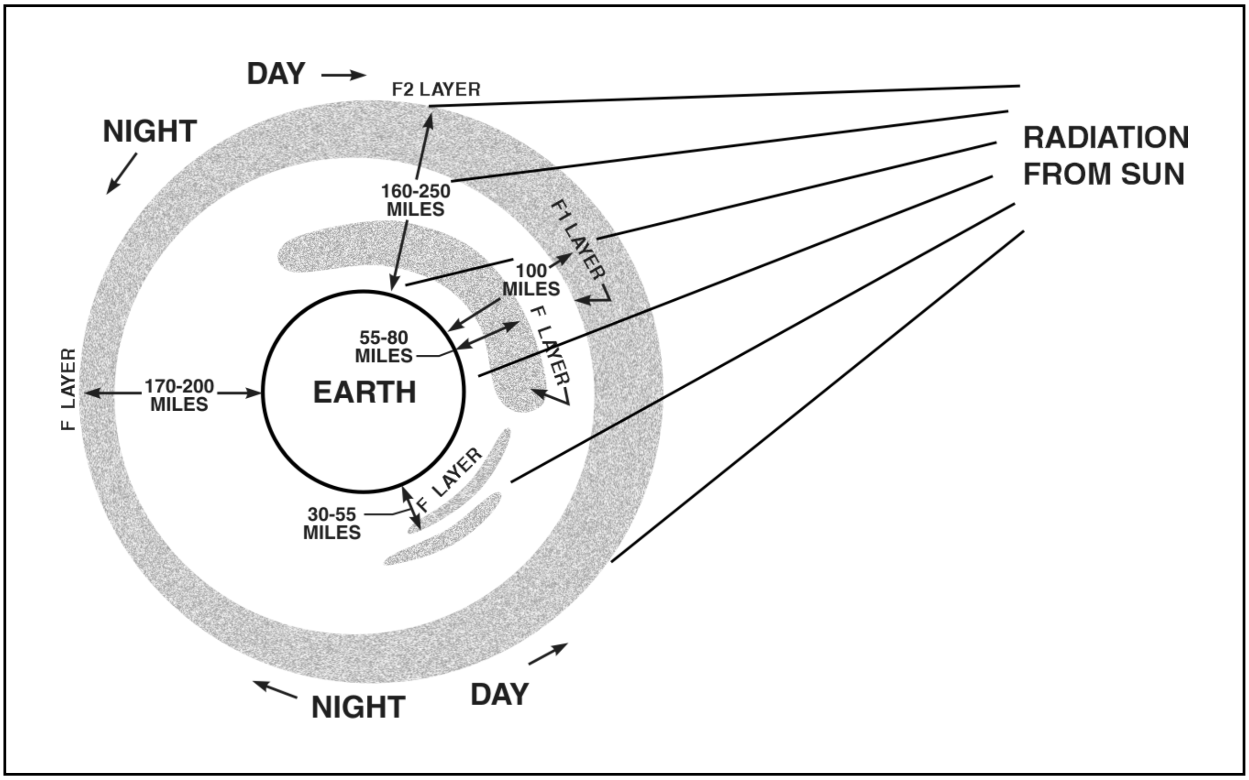


Figure 2-14. Layers of the Ionosphere

REFRACTION IN THE IONOSPHERE

2-65. When a radio wave is transmitted into an ionized layer, refraction, or bending of the wave, occurs. As we discussed earlier, refraction is caused by an abrupt change in the velocity of the upper part of a radio wave as it strikes or enters a new medium. The amount of refraction that occurs depends on three main factors: (1) the density of ionization of the layer, (2) the frequency of the radio wave, and (3) the angle at which the wave enters the layer.

Density of Layer

2-66. Figure 2-15 illustrates the relationship between radio waves and ionization density. Each ionized layer has a central region of relatively dense ionization, which tapers off in intensity both above and below the maximum region. As a radio wave enters a region of increasing ionization, the increase in velocity of the upper part of the wave causes it to be bent back toward the earth. While the wave is in the highly dense center portion of the layer, however, refraction occurs more slowly because the density of ionization is almost uniform. As the wave enters into the upper part of the layer of decreasing ionization, the velocity of the upper part of the wave decreases, and the wave is bent away from the earth. If a wave strikes a thin, very highly ionized layer, the wave may be bent back so rapidly that it appears to have been reflected instead of refracted back to Earth. To reflect a radio wave, the highly ionized layer must be approximately no thicker than one wavelength of the radio wave. Because the ionized layers are often several miles thick, ionospheric reflection is more likely to occur at long wavelengths (low frequencies).

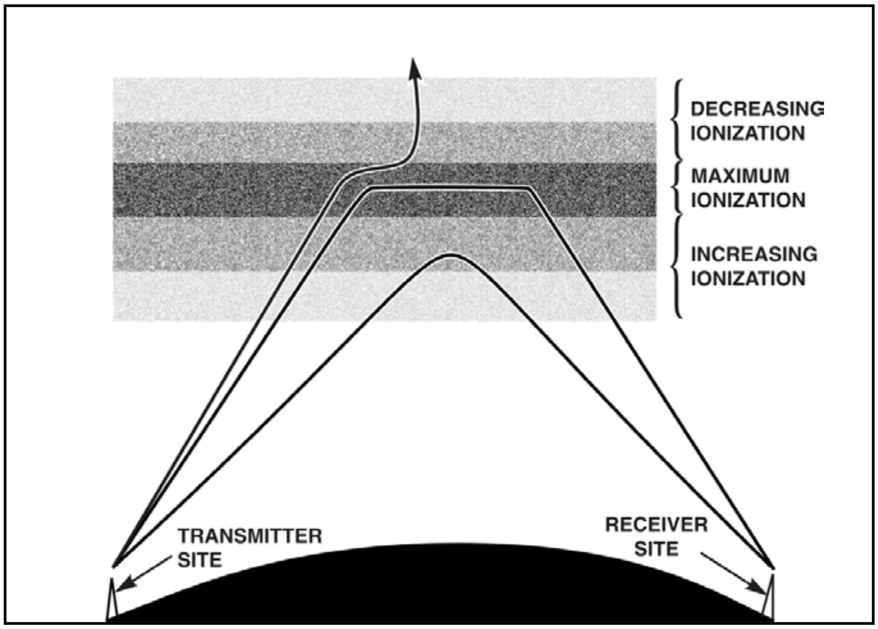


Figure 2-15. Effects of Ionospheric Density on Radio Waves

Frequency

2-67. For any given time, each ionospheric layer has a maximum frequency at which radio waves can be transmitted vertically and refracted back to Earth. This frequency is known as the critical frequency. It is a term that you will hear frequently in any discussion of radio wave propagation. Radio waves transmitted at frequencies higher than the critical frequency of a given layer will pass through the layer and be lost in space; but if these same waves enter an upper layer with a higher critical frequency, they will be refracted back to Earth. Radio waves of frequencies lower than the critical frequency will also be refracted back to Earth unless they are absorbed or have been refracted from a lower layer. The lower the frequency of a radio wave, the more rapidly the wave is refracted by a given degree of ionization. Figure 2-16 shows three separate waves of different frequencies entering an ionospheric layer at the same angle. Notice that the 5-megahertz wave is refracted quite sharply. The 20-megahertz wave is refracted less sharply and returned to Earth at a greater distance. The 100-megahertz wave is obviously greater than the critical frequency for that ionized layer and, therefore, is not refracted but is passed into space.

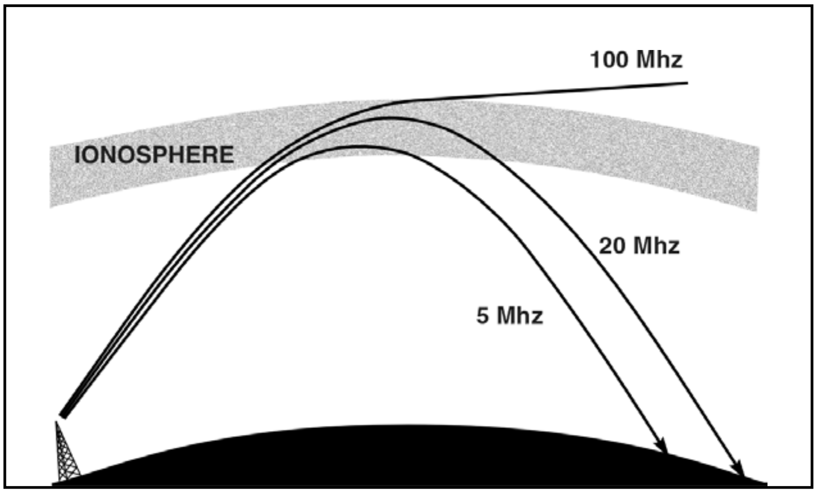


Figure 2-16. Frequency Versus Refraction and Distance

Angle of Incidence

2-68. The rate at which a wave of a given frequency is refracted by an ionized layer depends on the angle at which the wave enters the layer. Figure 2-17 shows three radio waves of the same frequency entering a layer at different angles. The angle at which wave A strikes the layer is too nearly vertical for the wave to be refracted to Earth. As the wave enters the layer, it is bent slightly but passes through the layer and is lost. When the wave is reduced to an angle that is less than vertical (wave B), it strikes the layer and is refracted back to Earth. The angle made by wave B is called the critical angle for that particular frequency. Any wave that leaves the antenna at an angle greater than the critical angle will penetrate the ionospheric layer for that frequency and then be lost in space. Wave C strikes the ionosphere at the smallest angle at which the wave can be refracted and still return to Earth. At any smaller angle, the wave will be refracted but will not return to Earth.

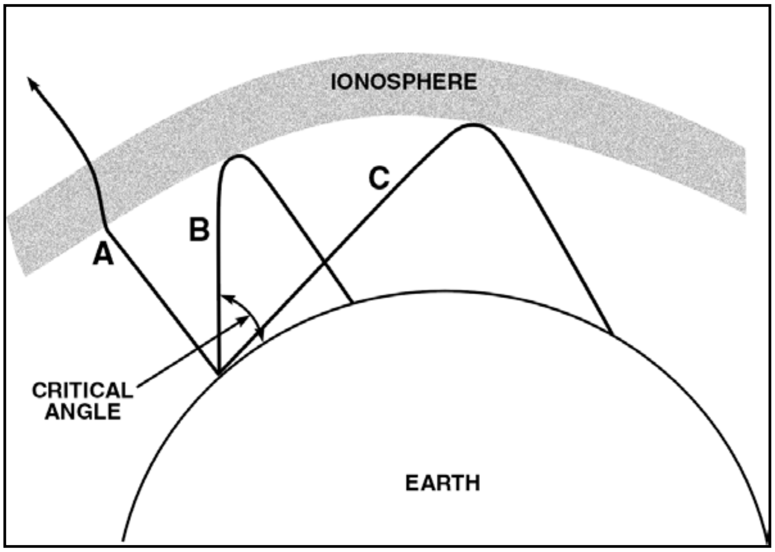


Figure 2-17. Different Incident Angles of Radio Waves

2-69. As the frequency of the radio wave is increased, the critical angle must be reduced for refraction to occur. This point is illustrated in figure 2-18. The 2-megahertz wave strikes the layer at the critical angle for that frequency and is refracted back to Earth. Although the 5-megahertz wave (broken line) strikes the ionosphere at a lesser angle, it nevertheless penetrates the layer and is lost. As the angle is lowered from the vertical, however, a critical angle for the 5-megahertz wave is reached, and the wave is then refracted to Earth.

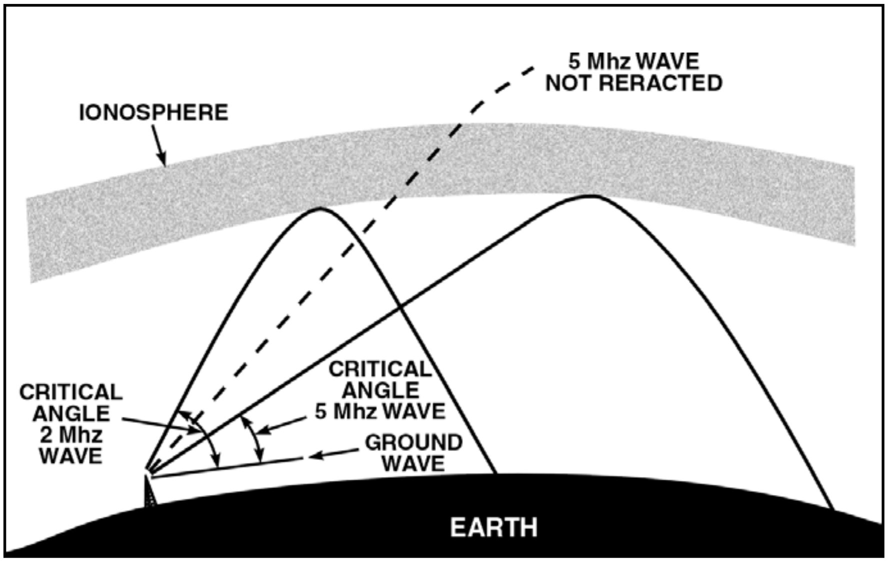


Figure 2-18. Effects of Frequency on the Critical Angle

Skip Distance/Skip Zone

2-70. In figure 2-19, note the relationship between the sky wave skip distance, the skip zone, and the ground wave coverage. The skip distance is the distance from the transmitter to the point where the sky wave is first returned to Earth. The size of the skip distance depends on the frequency of the wave, the angle of incidence, and the degree of ionization present.

2-71. The skip zone is a zone of silence between the point where the ground wave becomes too weak for reception and the point at which the sky wave is first returned to Earth. The size of the skip zone depends on the extent of the ground wave coverage and the skip distance. When the ground wave coverage is great enough or the skip distance is short enough that no zone of silence occurs, there is no skip zone.

2-72. Occasionally, the first sky wave will return to Earth within the range of the ground wave. If the sky wave and ground wave are nearly of equal intensity, the sky wave alternately reinforces and cancels the ground wave, causing severe fading. This fading is caused by the phase difference between the two waves, a result of the longer path traveled by the sky wave.

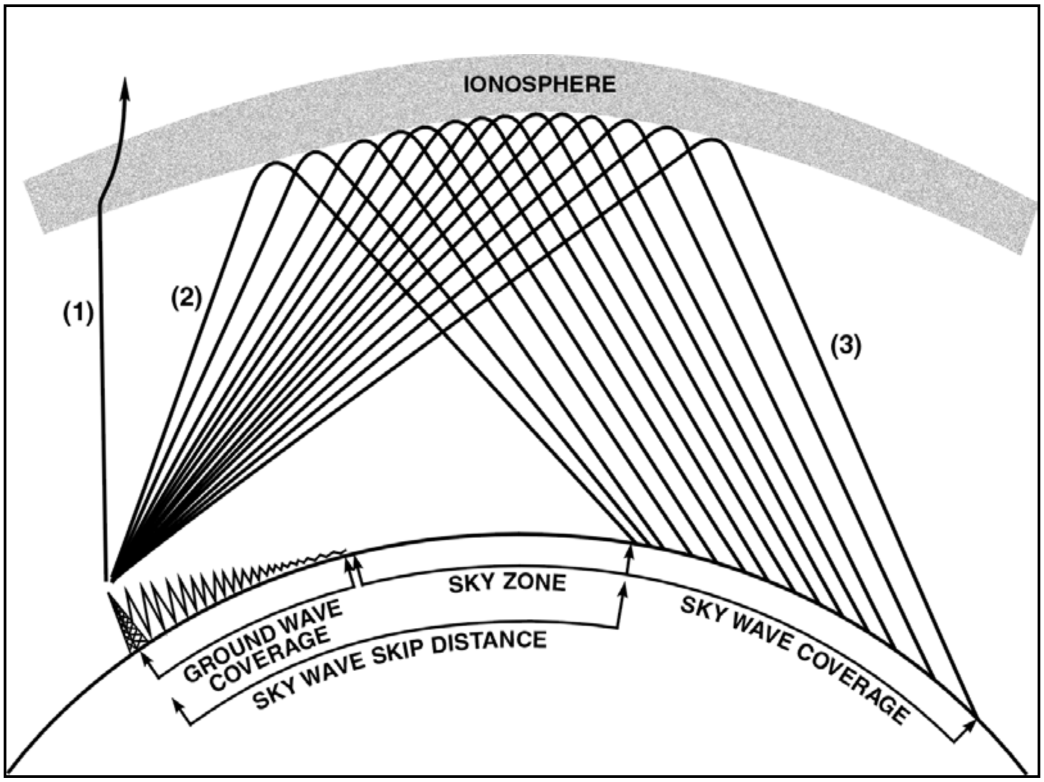


Figure 2-19. Relationship between Skip Zone, Skip Distance, and Ground Wave

Propagation Paths

2-73. The path that a refracted wave follows to the receiver depends on the angle at which the wave strikes the ionosphere. You should remember, however, that the RF energy radiated by a transmitting antenna spreads out with distance. The energy therefore strikes the ionosphere at many different angles rather than a single angle.

2-74. After the RF energy of a given frequency enters an ionospheric region, the paths that this energy might follow are many. It may reach the receiving antenna via two or more paths through a single layer. It may also, reach the receiving antenna over a path involving more than one layer, by multiple hops between the ionosphere and Earth, or by any combination of these paths.

2-75. Figure 2-20 shows how radio waves may reach a receiver via several paths through one layer. The various angles at which RF energy strikes the layer are represented by dark lines and designated as rays 1 through 6.

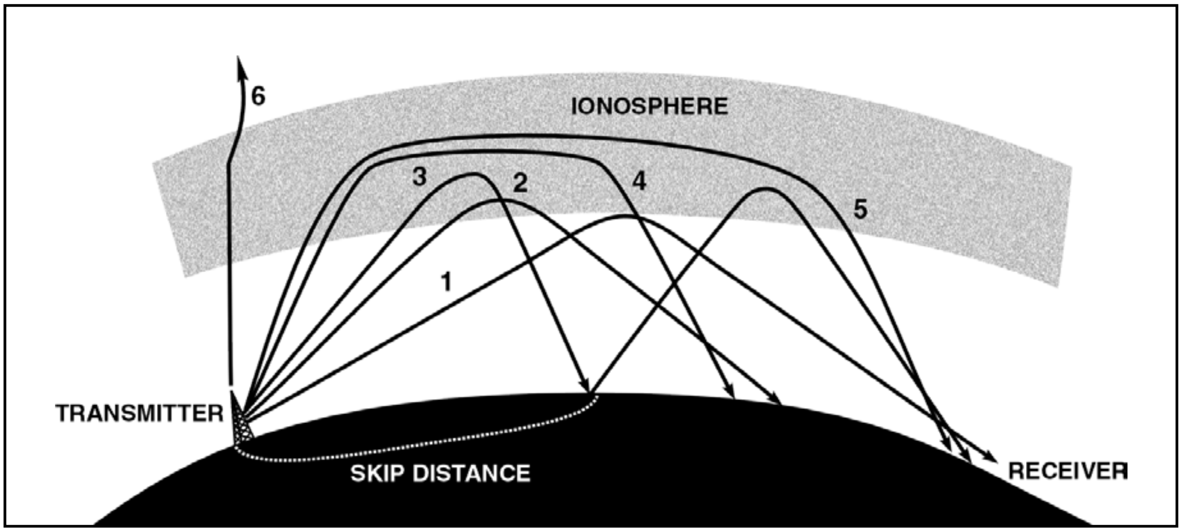


Figure 2-20. Ray Paths for a Fixed Frequency with Varying Angles of Incidence

2-76. When the angle is relatively low with respect to the horizon (ray 1), there is only slight penetration of the layer and the propagation path is long. When the angle of incidence is increased (rays 2 and 3), the rays penetrate deeper into the layer but the range of these rays decreases. When a certain angle is reached (ray 3), the penetration of the layer and rate of refraction are such that the ray is first returned to Earth at a minimal distance from the transmitter. Notice, however, that ray 3 still manages to reach the receiving site on its second refraction (called a hop) from the ionospheric layer.

2-77. As the angle is increased still more (rays 4 and 5), the RF energy penetrates the central area of maximum ionization of the layer. These rays are refracted rather slowly and are eventually returned to Earth at great distances. As the angle approaches vertical incidence (ray 6), the ray is not returned at all, but passes on through the layer.

ABSORPTION IN THE IONOSPHERE

2-78. Many factors affect a radio wave in its path between the transmitting and receiving sites. The factor that has the greatest adverse effect on radio waves is absorption. Absorption results in the loss of energy of a radio wave and has a pronounced effect on both the strength of received signals and the ability to communicate over long distances.

2-79. As discussed previously in the section on ground waves, surface waves suffer most of their absorption losses because of ground-induced voltage. Sky waves, on the other hand, suffer most of their absorption losses because of conditions in the ionosphere. Note that some absorption of sky waves may also occur at lower atmospheric levels because of the presence of water and water vapor. However, this becomes important only at frequencies above 10,000 megahertz.

2-80. Most ionospheric absorption occurs in the lower regions of the ionosphere where ionization density is greatest. As a radio wave passes into the ionosphere, it loses some of its energy to the free electrons and ions. If these high-energy free electrons and ions do not collide with gas molecules of low energy, most of the energy lost by the radio wave is reconverted into electromagnetic energy, and the wave continues to be propagated with little change in intensity. However, if the high-energy free electrons and ions do collide with other particles, much of this energy is lost, resulting in absorption of the energy from the wave. Because absorption of energy depends on collision of the particles, the greater the density of the ionized layer, the greater the probability of collisions; therefore, the greater the absorption. The highly dense D and E layers provide the greatest absorption of radio waves.

2-81. Because the amount of absorption of the sky wave depends on the density of the ionosphere, which varies with seasonal and daily conditions, it is impossible to express a fixed relationship between distance and signal strength for ionospheric propagation. Under certain conditions, the absorption of energy is so great that communicating over any distance beyond the line of sight is difficult.

FADING

2-82. The most troublesome and frustrating problem in receiving radio signals is variations in signal strength, most commonly known as fading. There are several conditions that can produce fading. When a radio wave is refracted by the ionosphere or reflected from the earth's surface, random changes in the polarization of the wave may occur. Vertically and horizontally mounted receiving antennas are designed to receive vertically and horizontally polarized waves, respectively. Therefore, changes in polarization cause changes in the received signal level because of the inability of the antenna to adjust to the polarization changes.

2-83. Fading also results from absorption of the RF energy in the ionosphere. Absorption fading occurs for a longer period than other types of fading, because absorption takes place slowly. Usually, however, fading on ionospheric circuits is mainly a result of multipath propagation.

Multipath Fading

2-84. Multipath is simply a term used to describe the multiple paths a radio wave may follow between transmitter and receiver. Such propagation paths include the ground wave, ionospheric refraction, reradiation by the ionospheric layers, reflection from the earth's surface or from more than one ionospheric layer, and others. Figure 2-21 shows a few of the paths that a signal can travel between two sites in a typical circuit. One path, XYZ, is the basic ground wave. Another path, XEA, refracts the wave at the E layer and passes it on to the receiver at A. Still another path, XFZFA, results from a greater angle of incidence and two refractions from the F layer. At point Z, the received signal is a combination of the ground wave and the sky wave. These two signals having traveled different paths arrive at point Z at different times. Thus, the arriving waves may or may not be in phase with each other. Radio waves that are received in phase reinforce each other and produce a stronger signal at the receiving site. Conversely, those that are received out of phase produce a weak or fading signal. Small alternations in the transmission path may change the phase relationship of the two signals, causing periodic fading. This condition occurs at point A. At this point, the double-hop F layer signal may be in or out of phase with the signal arriving from the E layer.

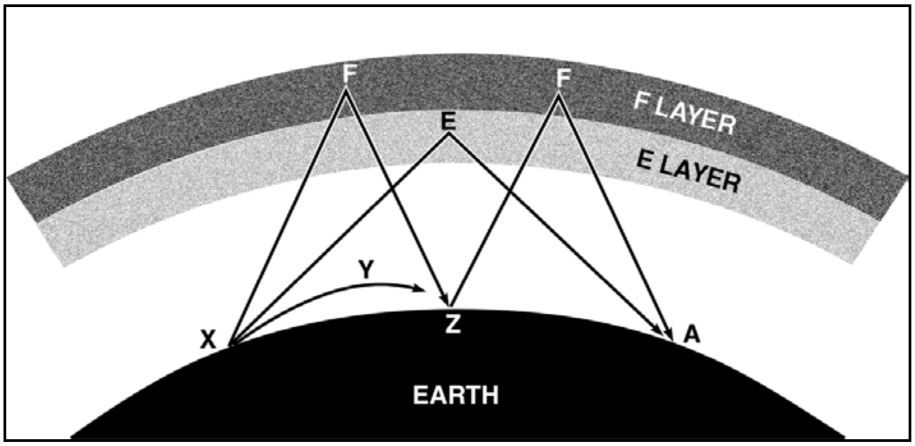


Figure 2-21. Multipath Transmission

2-85. Multipath fading may be minimized by practices called space diversity and frequency diversity. In space diversity, two or more receiving antennas are spaced some distance apart. Fading does not occur simultaneously at both antennas; therefore, enough output is almost always available from one of the antennas to provide a useful signal. In frequency diversity, two transmitters and two receivers are used, each pair tuned to a different frequency, with the same information being transmitted simultaneously over both frequencies. One of the two receivers will almost always provide a useful signal.

Selective Fading

2-86. Fading resulting from multipath propagation varies by frequency because each frequency arrives at the receiving point via a different radio path. When a wide band of frequencies is transmitted simultaneously, each frequency will vary in the amount of fading. This variation is called selective fading. When selective fading occurs, all frequencies of the transmitted signal do not retain their original phases and relative amplitudes. This fading causes severe distortion of the signal and limits the total signal transmitted.

TRANSMISSION LOSSES

2-87. All radio waves propagated over ionospheric paths undergo energy losses before arriving at the receiving site. As discussed earlier, absorption in the ionosphere and lower atmospheric levels account for a large part of these energy losses. There are two other types of losses that also significantly affect the ionospheric propagation of radio waves. These losses are known as ground reflection loss and freespace loss. The combined effects of absorption, ground reflection loss, and freespace loss account for most of the energy losses of radio transmissions propagated by the ionosphere.

Ground Reflection Loss

2-88. When propagation is accomplished via multihop refraction, RF energy is lost each time the radio wave is reflected from the earth's surface. The amount of energy lost depends on the frequency of the wave, the angle of incidence, ground irregularities, and the electrical conductivity of the point of reflection.

Freespace Loss

2-89. Normally, the major loss of energy is because of the spreading out of the wavefront as it travels away from the transmitter. As the distance increases, the area of the wavefront spreads out, much like the beam of a flashlight. This means the amount of energy contained within any unit of area on the wavefront decreases as distance increases. By the time the energy arrives at the receiving antenna, the wavefront is so spread out that the receiving antenna extends into only a very small fraction of the wavefront, as illustrated in figure 2-22.

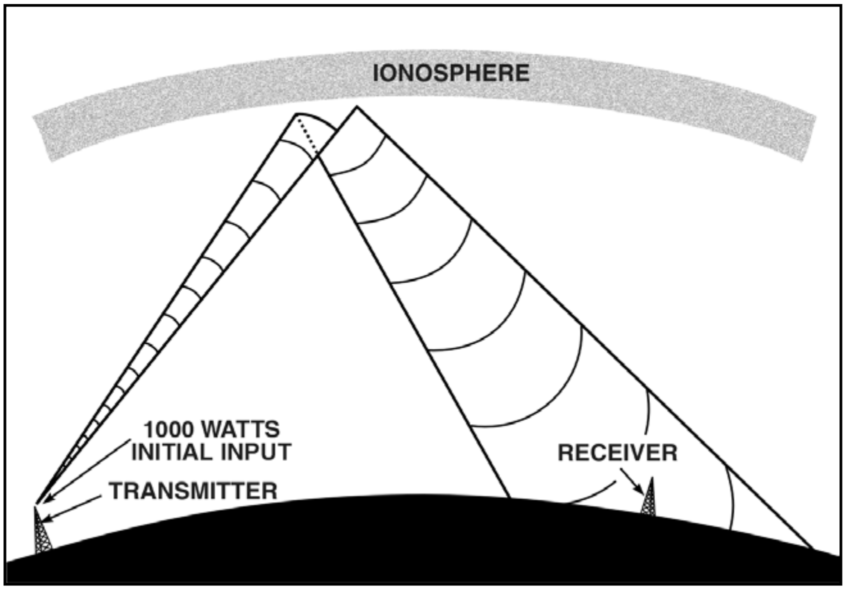


Figure 2-22. Freespace Loss Principle

ELECTROMAGNETIC INTERFERENCE (EMI)

2-90. The transmission losses just discussed are not the only factors that interfere with communications. An additional factor that can interfere with radio communications is the presence of electromagnetic interference (EMI). This interference can result in annoying or impossible operating conditions. Sources of EMI are both man-made and natural.

Man-Made Interference

2-91. Man-made interference may come from several sources. Some of these sources, such as oscillators, communications transmitters, and radio transmitters, may be specifically designed to generate radio frequency energy. Some electrical devices also generate radio frequency energy, although they are not specifically designed for this purpose. Examples are ignition systems, generators, motors, switches, relays, and voltage regulators. The intensity of man-made interference may vary throughout the day and drop off to a low level at night when many of these sources are not being used. Man-made interference may be a critical limiting factor at radio receiving sites located near industrial areas.

Natural Interference

2-92. Natural interference refers to the static that you often hear when listening to a radio. This interference is generated by natural phenomena, such as thunderstorms, snowstorms, cosmic sources, and the sun. The energy released by these sources is transmitted to the receiving site in roughly the same manner as radio waves. As a result, when ionospheric conditions are favorable for the long distance propagation of radio waves, they are likewise favorable for the propagation of natural interference. Natural interference is very erratic, particularly in the HF band, but generally decreases as the operating frequency is increased and wider bandwidths are used. There is little natural interference above 30 megahertz.

Control of EMI

2-93. Electromagnetic interference can be reduced or eliminated by using various suppression techniques. The amount of EMI that is produced by a radio transmitter can be controlled by cutting transmitting antennas to the correct frequency, limiting bandwidth, and using electronic filtering networks and metallic shielding.

2-94. Radiated EMI during transmission can be controlled by the physical separation of the transmitting and receiving antennas, the use of directional antennas, and limiting antenna bandwidth.

VARIATIONS IN THE IONOSPHERE

2-95. Because the existence of the ionosphere is directly related to radiations emitted from the sun, the movement of the earth about the sun or changes in the sun's activity will result in variations in the ionosphere. These variations are of two general types:

- Those that are more or less regular and occur in cycles and, therefore, can be predicted in advance with reasonable accuracy.
- Those that are irregular as a result of abnormal behavior of the sun and, therefore, cannot be predicted in advance. Both regular and irregular variations have important effects on radio wave propagation.

Regular Variations

2-96. The regular variations that affect the extent of ionization in the ionosphere can be divided into four main classes: daily, seasonal, 11-year, and 27-day variations.

2-97. **Daily**. Daily variations in the ionosphere are a result of the 24-hour rotation of the earth about its axis. Daily variations of the different layers (figure 2-14) are summarized as follows:

- The D layer reflects VLF waves, is important for long range VLF communications, refracts LF and MF waves for short-range communications, absorbs HF waves, has little effect on VHF and above, and disappears at night.
- In the E layer, ionization depends on the angle of the sun. The E layer refracts HF waves during the day up to 20 megahertz to distances of about 1200 miles. Ionization is greatly reduced at night.

- The structure and density of the F region depend on the time of day and the angle of the sun. This region consists of one layer during the night and splits into two layers during daylight hours.
- Ionization density of the F1 layer depends on the angle of the sun. Its main effect is to absorb HF waves passing through to the F2 layer.
- The F2 layer is the most important layer for long distance HF communications. It is a particularly variable layer and its height and density change with time of day, season, and sunspot activity.

2-98. **Seasonal**. Seasonal variations are the result of the earth revolving around the sun; the relative position of the sun moves from one hemisphere to the other with changes in seasons. Seasonal variations of the D, E, and F1 layers correspond to the highest angle of the sun; thus the ionization density of these layers is greatest during the summer. The F2 layer, however, does not follow this pattern; its ionization is greatest in winter and least in summer, the reverse of what might be expected. As a result, operating frequencies for F2 layer propagation are higher in the winter than in the summer.

2-99. **Eleven-year sunspot cycle**. One of the most notable phenomena on the surface of the sun is the appearance and disappearance of dark, irregularly shaped areas known as sunspots. The exact nature of sunspots is not known, but scientists believe they are caused by violent eruptions on the sun and are characterized by unusually strong magnetic fields. These sunspots are responsible for variations in the ionization level of the ionosphere. Sunspots can, of course, occur unexpectedly, and the life span of individual sunspots is variable; however, a regular cycle of sunspot activity has also been observed. This cycle has both a minimum and maximum level of sunspot activity that occurs approximately every 11 years.

2-100. During periods of maximum sunspot activity, the ionization density of all layers increases. Because of this, absorption in the D layer increases and the critical frequencies for the E, F1, and F2 layers are higher. At these times, higher operating frequencies must be used for long distance communications.

2-101. **27-Day sunspot cycle**. The number of sunspots in existence at any one time is continually subject to change as some disappear and new ones emerge. As the sun rotates on its own axis, these sunspots are visible at 27-day intervals, the approximate period required for the sun to make one complete rotation.

2-102. The 27-day sunspot cycle causes variations in the ionization density of the layers on a day-to-day basis. The fluctuations in the F2 layer are greater than for any other layer. For this reason, precise predictions on a day-to-day basis of the critical frequency of the F2 layer are not possible. In calculating frequencies for long-distance communications, one must make allowances for the fluctuations of the F2 layer.

Irregular Variations

2-103. Irregular variations in ionospheric conditions also have an important effect on radio wave propagation. Because these variations are irregular and unpredictable, they can drastically affect communications capabilities without any warning. The more common irregular variations are sporadic E, sudden ionospheric disturbances, and ionospheric storms.

2-104. **Sporadic E**. Irregular cloud-like patches of unusually high ionization, called sporadic E, often form at heights near the normal E layer. Exactly what causes this phenomenon is not known, nor can its occurrence be predicted. It is known to vary significantly with latitude, and in the northern latitudes, it appears to be closely related to the aurora borealis or northern lights.

2-105. At times the sporadic E is so thin that radio waves penetrate it easily and are returned to earth by the upper layers. At other times, it extends up to several hundred miles and is heavily ionized.

2-106. These characteristics may be either harmful or helpful to radio wave propagation. For example, sporadic E may blank out the use of higher, more favorable ionospheric layers or cause additional absorption of the radio wave at some frequencies. Also, it can cause additional multipath problems and delay the arrival times of the rays of RF energy.

2-107. On the other hand, the critical frequency of the sporadic E is very high and can be greater than double the critical frequency of the normal ionospheric layers. This condition may permit the long distance transmission of signals at unusually high frequencies. It may also permit short distance communications to locations that would normally be in the skip zone.

2-108. The sporadic E can form and disappear in a short time during either the day or night. However, it usually does not occur at the same time at all transmitting or receiving stations.

2-109. **Sudden ionospheric disturbances**. The most startling of the ionospheric irregularities is known as a sudden ionospheric disturbance (SID). These disturbances may occur without warning and may prevail for any length of time, from a few minutes to several hours. When SID occurs, long distance propagation of HF radio waves is almost totally "blanked out." The immediate effect is that radio operators listening on normal frequencies are inclined to believe that their receivers have gone dead.

2-110. When SID has occurred, examination of the sun has revealed a bright solar eruption. All stations lying wholly, or in part, on the sunward side of the earth are affected. The solar eruption produces an unusually intense burst of ultraviolet light, which is not absorbed by the F2, F1, and E layers, but instead causes a sudden abnormal increase in the ionization density of the D layer. As a result, frequencies above 1 or 2 megahertz are unable to penetrate the D layer and are usually completely absorbed by the layer.

2-111. **Ionospheric storms**. Ionospheric storms are disturbances in the earth's magnetic field. They are associated, in a manner not fully understood, with both solar eruptions and the 27-day intervals, thus corresponding to the rotation of the sun.

2-112. Scientists believe that ionospheric storms result from particle radiation from the sun. Particles radiated from a solar eruption have a slower velocity than ultraviolet light waves produced by the eruption. This would account for the 18-hour or so time difference between a SID and an ionospheric storm. An ionospheric storm that is associated with sunspot activity may begin anytime from 2 days before an active sunspot crosses the central meridian of the sun until four days after it passes the central meridian. At times, however, active sunspots have crossed the central region of the sun without any ionospheric storms occurring. Conversely, ionospheric storms have occurred when there were no visible spots on the sun and no preceding SID. As you can see, some correlation between ionospheric storms, SID, and sunspot activity is possible, but there are no hard and fast rules. Ionospheric storms can occur suddenly without warning.

2-113. The most prominent effects of ionospheric storms are a turbulent ionosphere and very erratic sky wave propagation. Critical frequencies are lower than normal, particularly for the F2 layer. Ionospheric storms affect the higher F2 layer first, reducing its ion density. Lower layers are not appreciably affected by the storms unless the disturbance is great. The practical effect of ionospheric storms is that the range of frequencies that can be used for communications on a given circuit is much smaller than normal and communications are possible only at the lower working frequencies.

FREQUENCY SELECTION CONSIDERATIONS

2-114. Up to this point, we have covered various factors that control the propagation of radio waves through the ionosphere, such as the structure of the ionosphere, the incidence angle of radio waves, and operating frequencies. There is a very good reason for studying radio wave propagation. One must have a thorough knowledge of radio wave propagation to exercise good judgment when selecting transmitting and receiving antennas and operating frequencies. Selection of a suitable operating frequency (within the bounds of frequency allocations and availability) is of prime importance in maintaining reliable communications.

Note. For successful communications between any two specified locations at any given time of the day, there is a maximum frequency, a lowest frequency, and an optimum frequency that can be used.

Maximum Usable Frequency

2-115. As discussed earlier, the higher the frequency of a radio wave, the lower the rate of refraction by an ionized layer. Therefore, for a given angle of incidence and time of day, there is a maximum frequency that can be used for communications between two given locations. This frequency is known as the maximum usable frequency (MUF).

2-116. Waves at frequencies above the MUF are normally refracted so slowly that they return to Earth beyond the desired location, or pass on through the ionosphere and are lost. You should understand, however, that use of an established MUF certainly does not guarantee successful communications between a transmitting site and a receiving site. Variations in the ionosphere may occur at any time and consequently raise or lower the predetermined MUF. This is particularly true for radio waves being refracted by the highly variable F2 layer. The MUF is highest around noon when ultraviolet light waves from the sun are the most intense. It then drops rather sharply as recombination begins to take place.

Lowest Usable Frequency

2-117. As there is a maximum operating frequency that can be used for communications between two points, there is also a minimum operating frequency. This is known as the lowest usable frequency (LUF). As the frequency of a radio wave is lowered, the rate of refraction increases. So a wave whose frequency is below the established LUF is refracted back to Earth at a shorter distance than desired, as shown in figure 2-23.

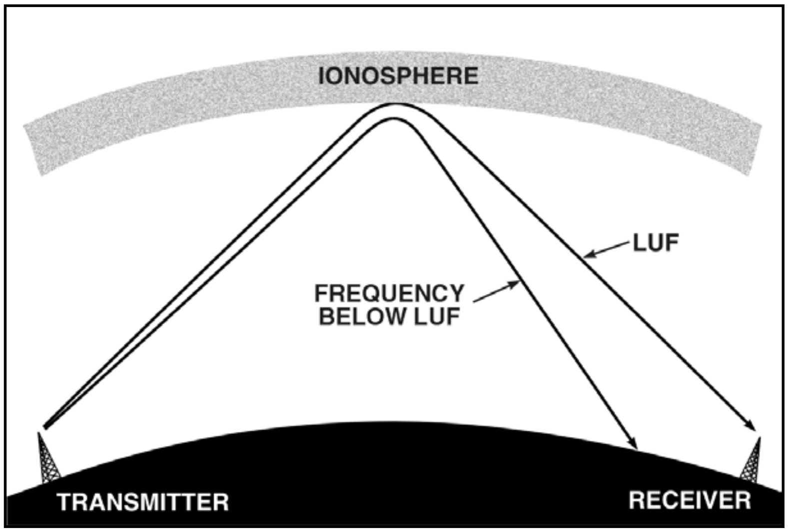


Figure 2-23. Refraction of Frequency below the Lowest Usable Frequency (LUF)

2-118. The transmission path that results from the rate of refraction is not the only factor that determines the LUF. As a frequency is lowered, absorption of the radio wave increases. A wave whose frequency is too low is absorbed to such an extent that it is too weak for reception. Likewise, atmospheric noise is greater at lower frequencies; thus, a low-frequency radio wave may have an unacceptable signal-to-noise ratio.

2-119. For a given angle of incidence and set of ionospheric conditions, the LUF for successful communications between two locations depends on the refraction properties of the ionosphere, absorption considerations, and the amount of atmospheric noise present.

Optimum Working Frequency

2-120. Neither the MUF nor the LUF is a practical operating frequency. While radio waves at the LUF can be refracted back to Earth at the desired location, the signal-to-noise ratio is still much lower than at the higher frequencies, and the probability of multipath propagation is much greater. Operating at or near the MUF can result in frequent signal fading and dropouts when ionospheric variations alter the length of the transmission path.

2-121. The most practical operating frequency is one that you can rely on with the least amount of problems. It should be high enough to avoid the problems of multipath propagation, absorption, and noise encountered at the lower frequencies; but not so high as to result in the adverse effects of rapid changes in the ionosphere.

2-122. A frequency that meets the above criteria has been established and is known as the optimum working frequency. It is abbreviated “FOT” from the initial letters of the French words for optimum working frequency, “frequence optimum de travail.” The FOT is roughly about 85 percent of the MUF but the actual percentage varies and may be either considerably more or less than 85 percent.

EFFECTS OF WEATHER ON PROPAGATION

2-123. Weather is an additional factor that affects the propagation of radio waves. In this section, we explain how and to what extent the various weather phenomena affect wave propagation.

2-124. Wind, air temperature, and the water content of the atmosphere can combine in many ways. Certain combinations can cause radio signals to be heard hundreds of miles beyond the ordinary range of radio communications. Conversely, a different combination of factors can cause such attenuation of the signal that it may not be heard even over a normally satisfactory path. Unfortunately, there are no hard and fast rules on the effects of weather on radio transmissions because the weather is extremely complex and subject to frequent change. Therefore, we limit our discussion on the effects of weather on radio waves to general terms.

Precipitation Attenuation

2-125. Calculating the effect of weather on radio wave propagation would be comparatively simple if there were no water or water vapor in the atmosphere. However, some form of water (vapor, liquid, or solid) is always present and must be considered in all calculations. Before we begin discussing the specific effects that individual forms of precipitation (rain, snow, and fog) have on radio waves, you should understand that attenuation because of precipitation is generally proportionate to the frequency and wavelength of the radio wave. For example, rain has a pronounced effect on waves at microwave frequencies. However, rain hardly affects waves with long wavelengths (HF range and below). You can assume, then, that as the wavelength becomes shorter with increases in frequency, precipitation has an increasingly important attenuation effect on radio waves. Conversely, you can assume that as the wavelength becomes longer with decreases in frequency, precipitation has little attenuation effect.

2-126. **Rain**. Attenuation because of raindrops is greater than attenuation because of other forms of precipitation. Attenuation may be caused by absorption, in which the raindrop, acting as a poor dielectric, absorbs power from the radio wave and dissipates the power by heat loss or by scattering (figure 2-24). Raindrops cause greater attenuation by scattering than by absorption at frequencies above 100 megahertz. At frequencies above 6 gigahertz, attenuation by raindrop scatter is even greater.

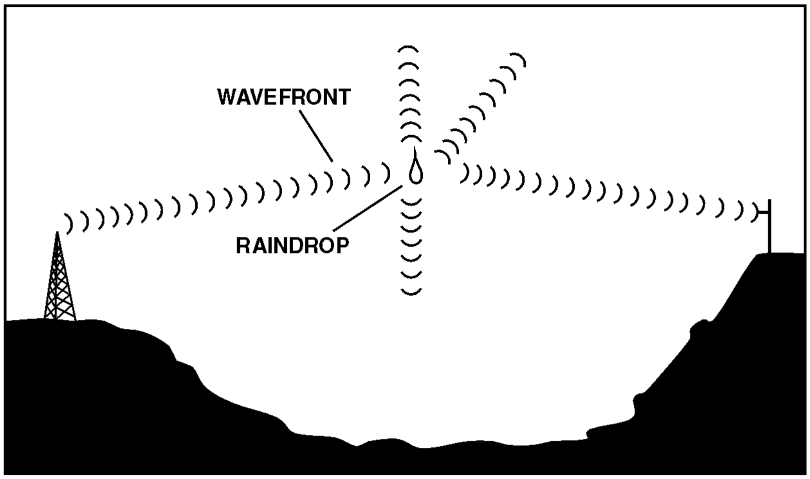


Figure 2-24. RF Energy Losses from Scattering

2-127. **Fog**. In the discussion of attenuation, fog may be considered as another form of rain. Because fog remains suspended in the atmosphere, the attenuation is determined by the quantity of water per unit volume and by the size of the droplets. Attenuation because of fog is of minor importance at frequencies lower than 2 gigahertz. However, fog can cause serious attenuation by absorption at frequencies above 2 gigahertz.

2-128. **Snow**. The scattering effect because of snow is difficult to compute because of irregular sizes and shapes of the flakes. While information on the attenuating effect of snow is limited, scientists assume that attenuation from snow is less than from rain falling at an equal rate. This assumption is borne out by the fact that the density of rain is eight times the density of snow. As a result, rain falling at 1 inch per hour would have more water per cubic inch than snow falling at the same rate.

2-129. **Hail**. Attenuation by hail is determined by the size of the stones and their density. Attenuation of radio waves by scattering because of hailstones is considerably less than by rain.

Temperature Inversion

2-130. Under normal atmospheric conditions, the warmest air is found near the surface of the earth. The air gradually becomes cooler as altitude increases. At times, however, an unusual situation develops in which layers of warm air are formed above layers of cool air. This condition is known as temperature inversion. These temperature inversions cause channels, or ducts, of cool air to be sandwiched between the surface of the earth and a layer of warm air, or between two layers of warm air.

2-131. If a transmitting antenna extends into such a duct of cool air, or if the radio wave enters the duct at a very low angle of incidence, VHF and UHF transmissions may be propagated far beyond normal line-of-sight distances. When ducts are present as a result of temperature inversions, good reception of VHF and UHF television signals from a station located hundreds of miles away is not unusual. These long distances are possible because of the different densities and refractive qualities of warm and cool air. The sudden change in density when a radio wave enters the warm air above a duct causes the wave to be refracted back toward Earth. When the wave strikes the earth or a warm layer below the duct, it is again reflected or refracted upward and proceeds on through the duct with a multiple-hop type of action. An example of the propagation of radio waves by ducting is shown in figure 2-25.

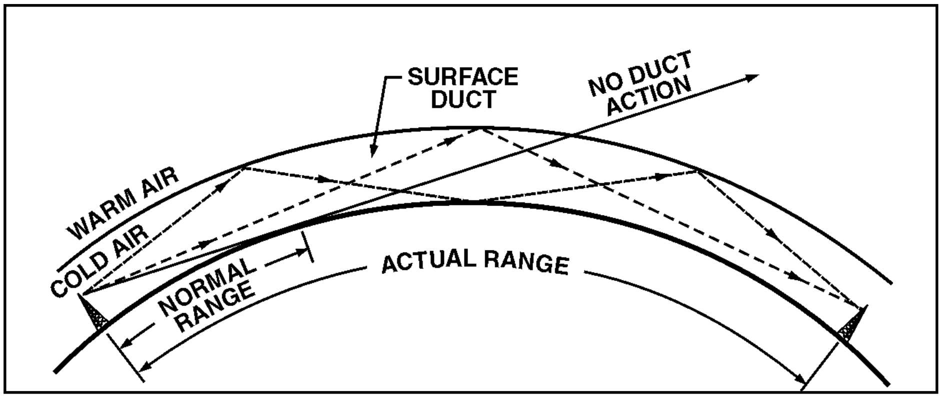


Figure 2-25. Duct Effect Caused by Temperature Inversion

TROPOSPHERIC PROPAGATION

2-132. As the lowest region of the earth's atmosphere, the troposphere extends from the earth's surface to a height of slightly over 7 miles. Virtually all weather phenomena occur in this region. Generally, the troposphere is characterized by a steady decrease in both temperature and pressure as height is increased. However, the many changes in weather phenomena cause variations in humidity and an uneven heating of the earth's surface. As a result, the air in the troposphere is in constant motion. This motion causes small turbulences, or eddies, to be formed, as shown by the bouncing of aircraft entering turbulent areas of the atmosphere. These turbulences are most intense near the earth's surface and gradually diminish with height. They have a refractive quality that permits the refracting or scattering of radio waves with short wavelengths. This scattering provides enhanced communications at higher frequencies.

2-133. Recall that in the relationship between frequency and wavelength, wavelength decreases as frequency increases and vice versa. Radio waves of frequencies below 30 megahertz normally have wavelengths longer than the size of weather turbulences. These radio waves are, therefore, affected very little by the turbulences. On the other hand, as the frequency increases into the VHF range and above, the wavelengths decrease in size, to the point that they become subject to tropospheric scattering. The usable frequency range for tropospheric scattering is from about 100 megahertz to 10 gigahertz.

Tropospheric Scattering

2-134. When a radio wave passing through the troposphere meets turbulence, it makes an abrupt change in velocity. This causes a small amount of the energy to be scattered in a forward direction and returned to Earth at distances beyond the horizon. This phenomenon is repeated as the radio wave meets other turbulences in its path. The total received signal is an accumulation of the energy received from each of the turbulences.

2-135. This scattering mode of propagation enables VHF and UHF signals to be transmitted far beyond the normal line-of-sight. To understand how these signals are transmitted over greater distances, you must first consider the propagation characteristics of the space wave used in VHF and UHF line-of-sight communications. When the space wave is transmitted, it undergoes very little attenuation within the line-of-sight horizon. When it reaches the horizon, the wave is diffracted and follows the earth's curvature. Beyond the horizon, the rate of attenuation increases very rapidly and signals soon become very weak and unusable.

2-136. Tropospheric scattering, on the other hand, provides a usable signal at distances beyond the point where the diffracted space wave drops to an unusable level. This is because of the height at which scattering takes place. The turbulence that causes the scattering can be visualized as a relay station located above the horizon; it receives the transmitted energy and then reradiates it in a forward direction to some point beyond the line-of-sight distance. A high gain-receiving antenna aimed toward this scattered energy can then capture it.

2-137. The magnitude of the received signal depends on the number of turbulences causing scatter in the desired direction and the gain of the receiving antenna. The scatter area used for tropospheric scatter is known as the scatter volume. The angle at which the receiving antenna must be aimed to capture the scattered energy is called the scatter angle. The scatter volume and scatter angles are shown in figure 2-26.

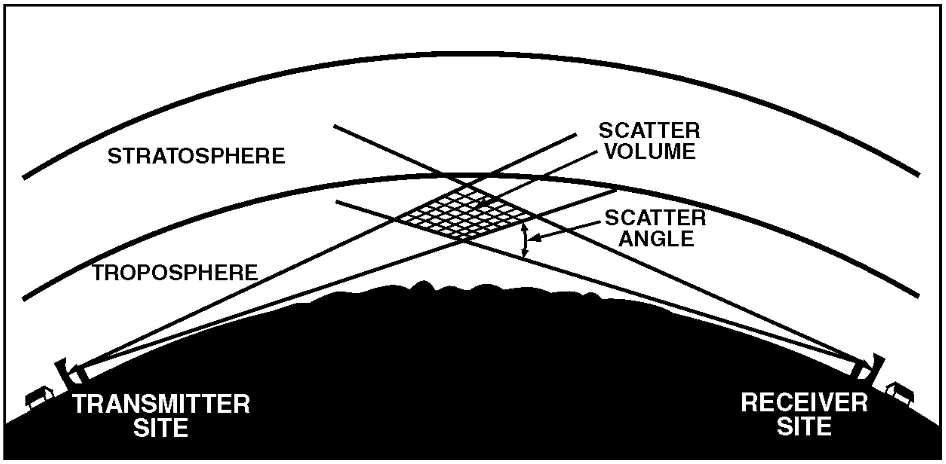


Figure 2-26. Tropospheric Scattering Propagation

2-138. The signal take-off angle (transmitting antenna's angle of radiation) determines the height of the scatter volume and the size of the scatter angle. A low signal take-off angle produces a low scatter volume, which in turn permits a receiving antenna that is aimed at a low angle to the scatter volume to capture the scattered energy.

2-139. As the signal take-off angle is increased, the height of the scatter volume is increased. When this occurs, the amount of received energy decreases. There are two reasons for this: (1) the scatter angle increases as the height of the scatter volume is increased; (2) the amount of turbulence decreases with height. As the distance between the transmitting and receiving antennas is increased, the height of the scatter volume must also be increased. The received signal level, therefore, decreases as circuit distance is increased.

2-140. The tropospheric region that contributes most strongly to tropospheric scatter propagation lies near the midpoint between the transmitting and receiving antennas and just above the radio horizon of the antennas.

2-141. Because tropospheric scatter depends on turbulence in the atmosphere, changes in atmospheric conditions have an effect on the strength of the received signal. Both daily and seasonal variations in signal strength occur as a result of changes in the atmosphere. These variations are called long-term fading.

2-142. In addition to long-term fading, the tropospheric scatter signal often is characterized by very rapid fading because of multipath propagation. Because the turbulent condition is constantly changing, the path lengths and individual signal levels are also changing, resulting in a rapidly changing signal. Although the signal level of the received signal is constantly changing, the average signal level is stable; therefore, no complete fade-out occurs.

2-143. Another characteristic of a tropospheric scatter signal is its relatively low power level. Because very little of the scattered energy is reradiated toward the receiver, the efficiency is very low and the signal level at the final receiver point is low. Initial input power must be high to compensate for the low efficiency in the scatter volume. This is accomplished by using high-power transmitters and high-gain antennas, which concentrate the transmitted power into a beam, thus increasing the intensity of energy of each turbulence in the volume. The receiver must also be very sensitive to detect the low-level signals.

Application of Tropospheric Scattering

2-144. Tropospheric scatter propagation is used for point-to-point communications. A correctly designed tropospheric scatter circuit will provide highly reliable service for distances ranging from 50 miles to 500 miles. Tropospheric scatter systems may be particularly useful for communications to locations in rugged terrain that are difficult to reach with other methods of propagation. One reason for this is that the tropospheric scatter circuit is not affected by ionospheric and auroral disturbances.

SUMMARY

Now that you have completed this chapter, let us review some of the new terms, concepts, and ideas that you have learned. You should have a thorough understanding of these principles before moving on to chapter 3.

The induction field contains an E field and an H field and is localized near the antenna. The E and H fields of the induction field are 90 degrees out of phase with each other.

The radiation field contains E and H fields that are propagated from the antenna into space in the form of electromagnetic waves. The E and H fields of the radiation field are in phase with each other.

A harmonic frequency is any frequency that is a whole number multiple of a smaller basic frequency. For example, a radio wave transmitted at a fundamental frequency of 3000 hertz can have a second harmonic of 6000 hertz, a third harmonic frequency of 9000 hertz, and so on, transmitted at the same time.

A vertically polarized antenna transmits an electromagnetic wave with the E field perpendicular to the earth's surface. A horizontally polarized antenna transmits a radio wave with the E field parallel to the earth's surface.

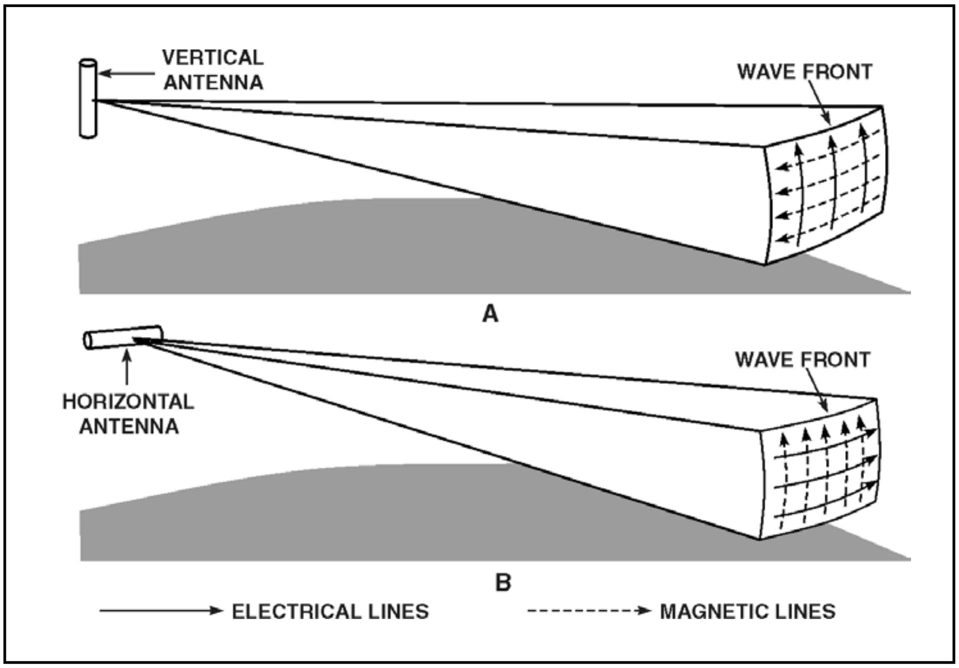


Figure 2-Sum 1. Vertical and Horizontal Polarization

A wavefront is a small section of an expanding sphere of radiated energy and is perpendicular to the direction of travel from the antenna.

Radio waves are electromagnetic waves that can be reflected, refracted, and diffracted in the atmosphere in the same manner as light and heat waves.

Reflected radio waves are waves that have been reflected from a surface and are 180 degrees out of phase with the initial wave.

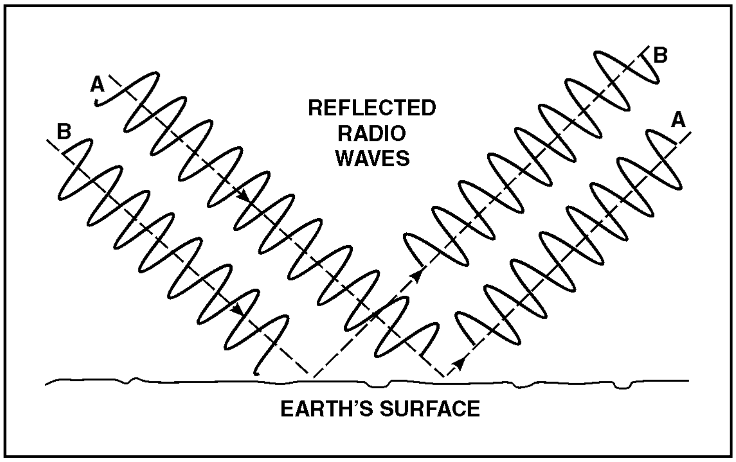


Figure 2-Sum 2. Phase Shift of Reflected Radio Waves

The earth's atmosphere is divided into three separate layers: the troposphere, the stratosphere, and the ionosphere.

The troposphere is the region of the atmosphere where virtually all weather phenomena take place. In this region, RF energy is greatly affected.

The stratosphere has a constant temperature and has little effect on radio waves.

The ionosphere contains four cloud-like layers of electrically charged ions, which aid in long distance communications.

Ground waves and sky waves are the two basic types of radio waves that transmit energy from the transmitting antenna to the receiving antenna.

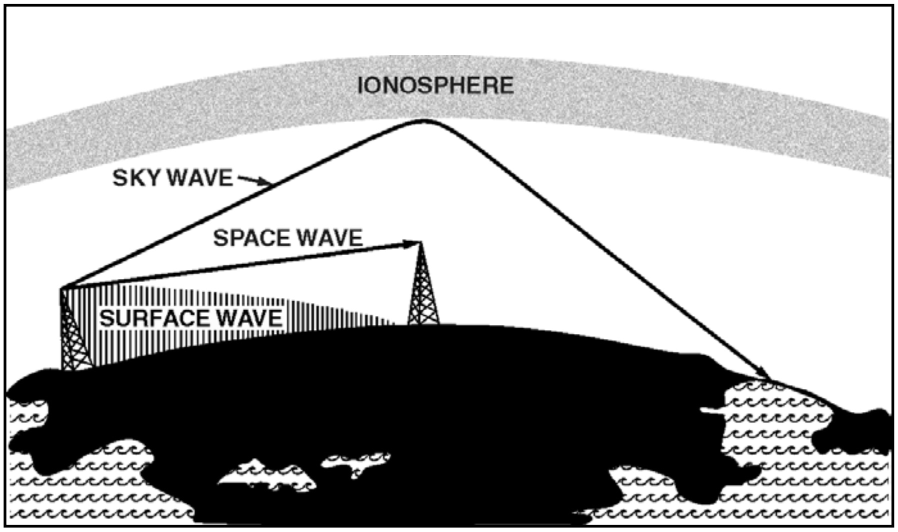


Figure 2-Sum 3. Ground and Sky Waves

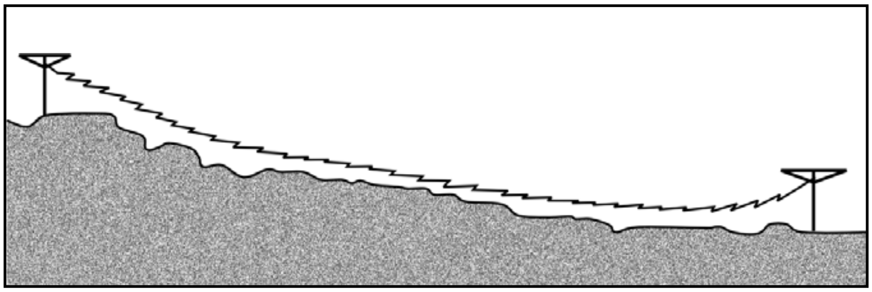


Figure 2-Sum 4. Surface Wave Propagation

Ground waves are composed of two separate component waves: the surface wave and the space wave.

Surface waves travel along the contour of the earth by diffraction.

Space waves can travel through the air directly to the receiving antenna or can be reflected from the surface of the earth.

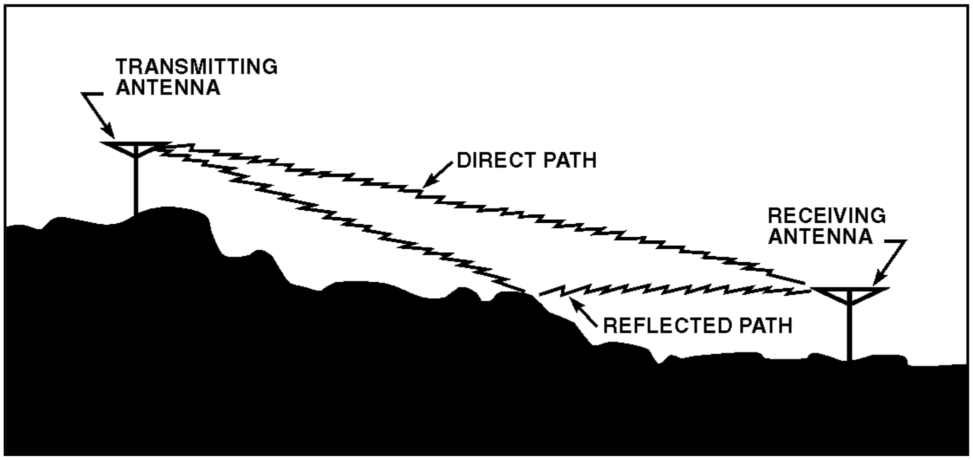


Figure 2-Sum 5. Space Wave Propagation

Sky waves, often called ionospheric waves, are radiated in an upward direction and returned to Earth at some distant location because of refraction.

Natural horizon is the line-of-sight horizon.

Radio horizon is one-third farther than the natural horizon.

The ionosphere consists of several layers of ions, formed by the process called ionization.

Ionization is the process of knocking electrons free from their parent atom, thus upsetting electrical neutrality.

Recombination is the opposite of ionization; that is, the free ions combine with positive ions, causing the positive ions to return to their original neutral atom state.

The D layer is the lowest region of the ionosphere and refracts signals of low frequencies back to Earth.

The E layer is present during the daylight hours, refracts signals as high as 20 megahertz back to Earth; and is used for communications up to 1500 miles.

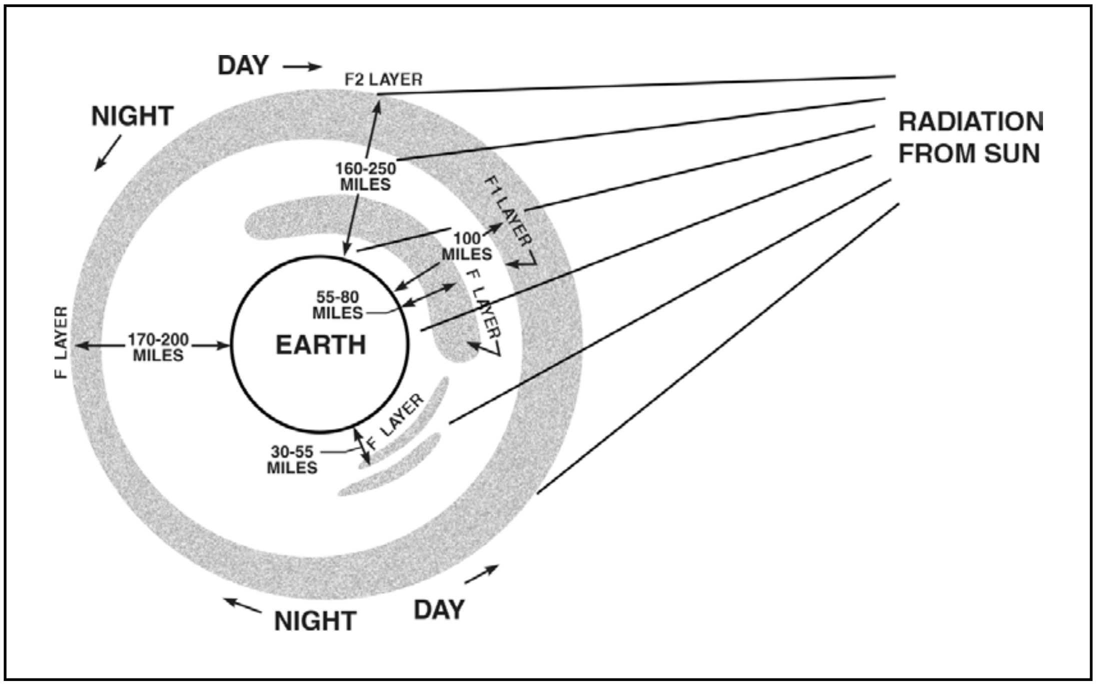


Figure 2-Sum 6. Layers of the Ionosphere

The F layer is divided into the F1 and F2 layers during the day but combine at night to form one layer. This layer is responsible for high frequency, long-range transmission.

The critical frequency is the maximum frequency that a radio wave can be transmitted vertically and still be refracted back to Earth.

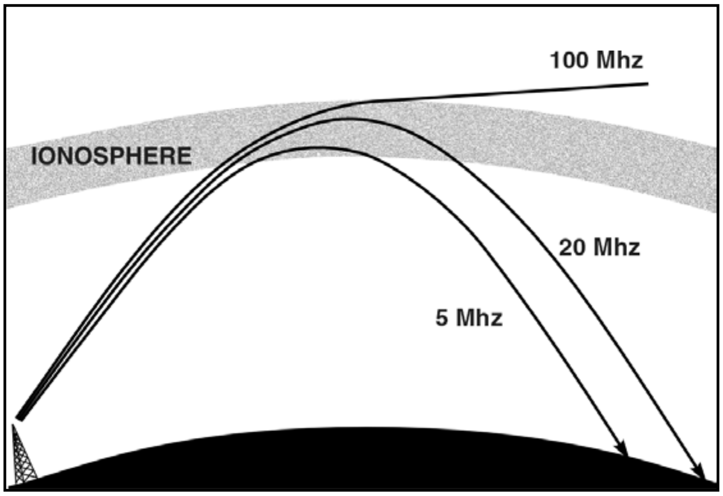


Figure 2-Sum 7. Frequency Versus Refraction and Distance

The critical angle is the maximum and/or minimum angle at which a radio wave can be transmitted and still be refracted back to Earth.

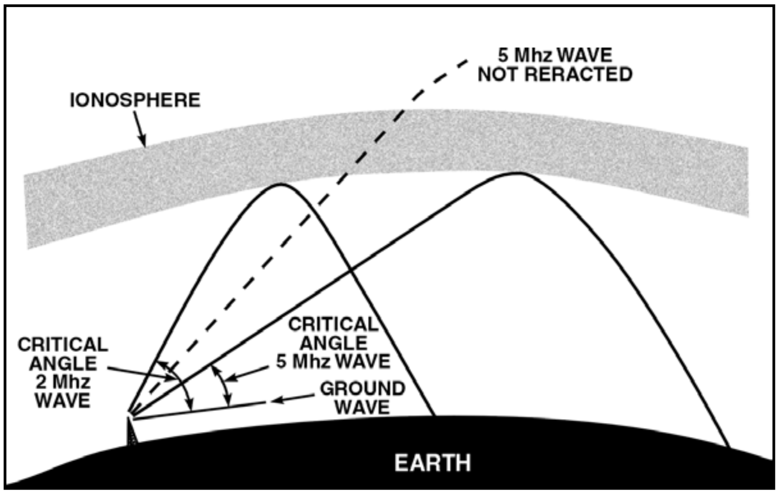


Figure 2-Sum 8. Effects of Frequency on Critical Angle

Skip distance is the distance between the transmitter and the point where the sky wave first returns to Earth.

Skip zone is the zone of silence between the point where the ground wave becomes too weak for reception and the point where the sky wave is first returned to Earth.

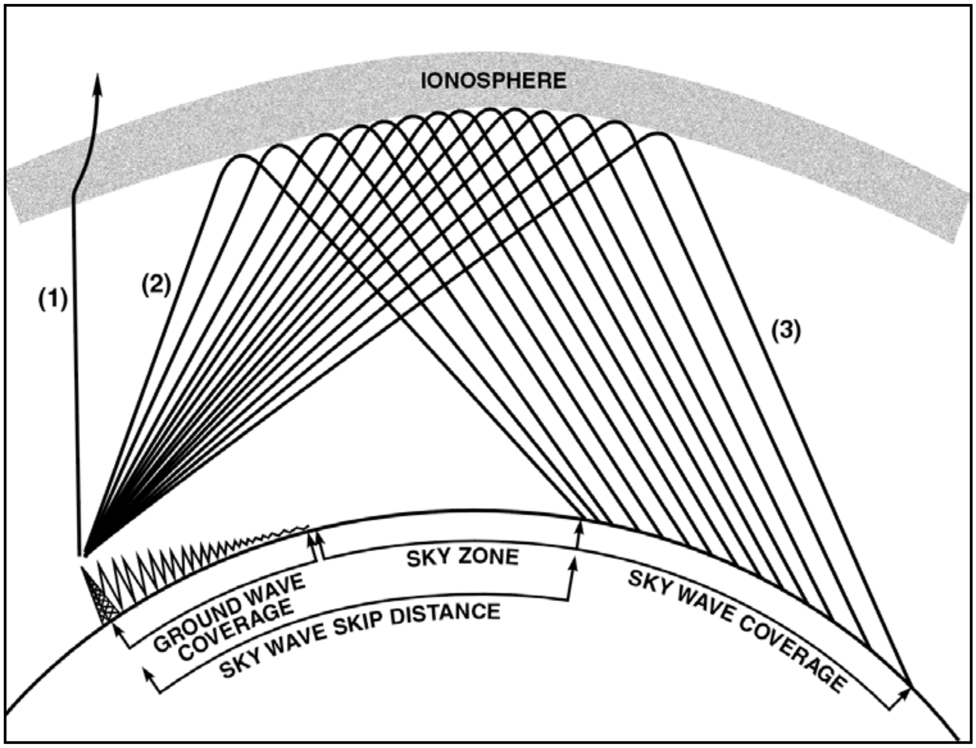


Figure 2-Sum 9. Relationship between Skip Zone, Skip Distance, and Ground Wave

Fading is caused by variations in signal strength, such as absorption of the RF energy by the ionosphere.

Multipath fading occurs when a transmitted signal divides and takes more than one path to a receiver and some of the signals arrive out of phase, resulting in a weak or fading signal.

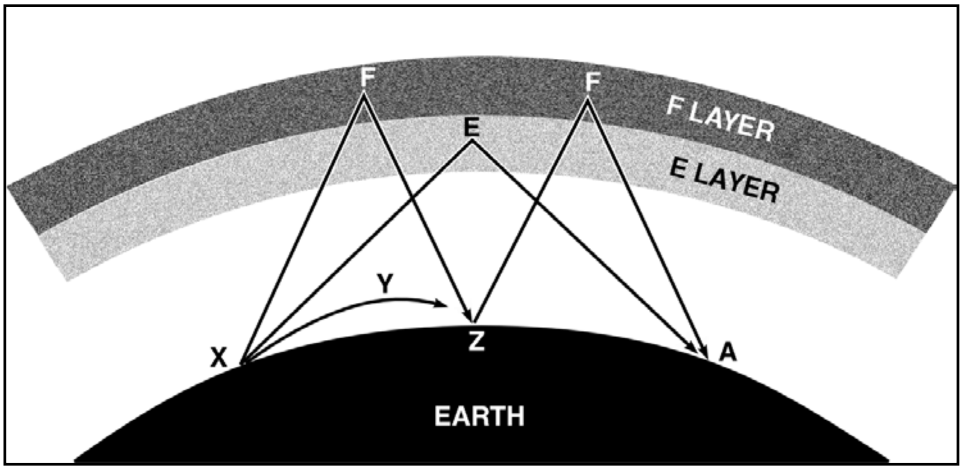


Figure 2-Sum 10. Multipath Transmission

Some transmission losses that affect radio-wave propagation are ionospheric absorption, ground reflection, and free-space losses.

Electromagnetic interference (EMI), both natural and man-made, interferes with radio communications.

The maximum usable frequency (MUF) is the highest frequency that can be used for communications between two locations at a given angle of incidence and time of day.

The lowest usable frequency (LUF) is the lowest frequency that can be used for communications between two locations.

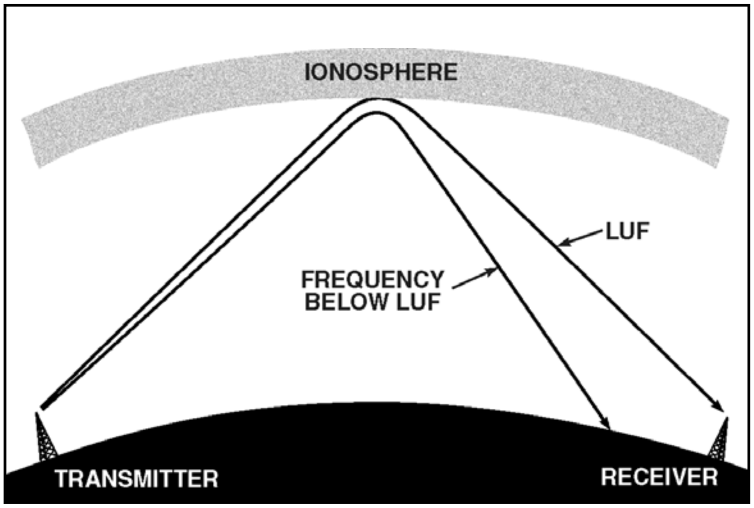


Figure 2-Sum 11. Refraction of Frequency below the Lowest Usable Frequency (LUF)

Optimum working frequency (FOT) is the most practical operating frequency and the one that can be relied on to have the fewest problems.

Precipitation attenuation can be caused by rain, fog, snow, and hail, and can affect overall communications considerably.

Temperature inversion causes channels, or ducts, of cool air to form between layers of warm air, which can cause radio waves to travel far beyond the normal line-of-sight distances.

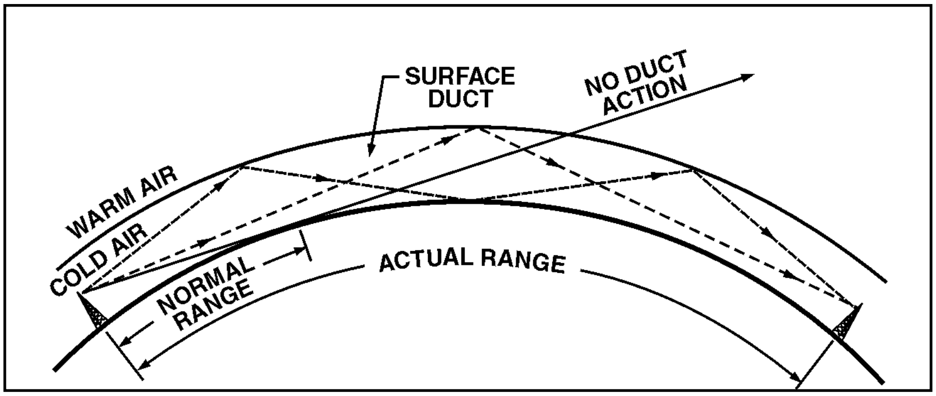


Figure 2-Sum 12. Duct Effect Caused by Temperature Inversion

Tropospheric propagation uses the scattering principle to achieve beyond the line-of-sight radio communications within the troposphere.

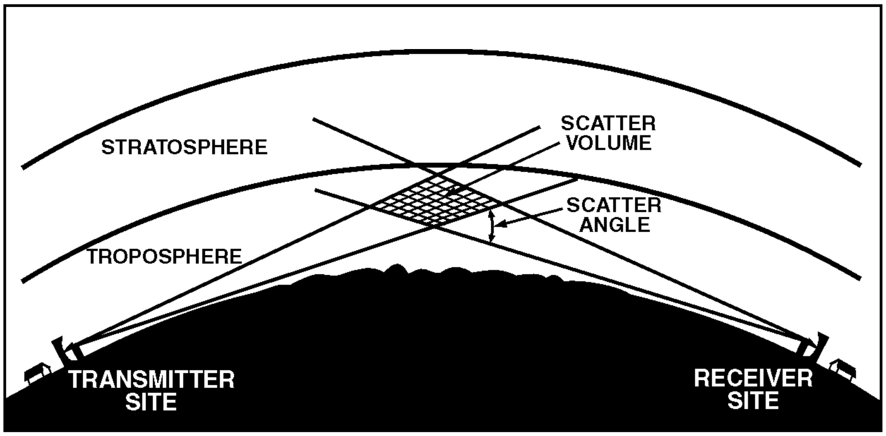


Figure 2-Sum 13. Tropospheric Scattering Propagation

Check-on-Learning Questions

Radio Wave Propagation

1. Which two composite fields (composed of E and H fields) are associated with every antenna?
2. What composite field (composed of E and H fields) is found stored in the antenna?
3. What composite field (composed of E and H fields) is propagated into free space?
4. What is the term used to describe the basic frequency of a radio wave?
5. What is the term used to describe a whole number multiple of the basic frequency of a radio wave?
6. It is known that WWV operates on a frequency of 10 megahertz. What is the wavelength of WWV?
7. A station is known to operate at 60 meters. What is the frequency of the unknown station?
8. If a transmitting antenna is placed close to the ground, how should the antenna be polarized to give the greatest signal strength?
9. In the right-hand rule for propagation, the thumb points in the direction of the E field and the forefinger points in the direction of the H field. In what direction does the middle finger point?
10. What is one of the major reasons for the fading of radio waves that have been reflected from a surface?
11. What are the three layers of the atmosphere?
12. Which layer of the atmosphere has relatively little effect on radio waves?
13. What is the determining factor in classifying whether a radio wave is a ground wave or a space wave?
14. What is the best type of surface or terrain to use for radio wave transmission?
15. What is the primary difference between the radio horizon and the natural horizon?
16. What three factors must be considered in the transmission of a surface wave to reduce attenuation?
17. What causes ionization to occur in the ionosphere?
18. How are the four distinct layers of the ionosphere designated?
19. What is the height of the individual layers of the ionosphere?
20. What factor determines whether a radio wave is reflected or refracted by the ionosphere?
21. There is a maximum frequency at which vertically transmitted radio waves can be refracted back to Earth. What is this maximum frequency called?
22. What three main factors determine the amount of refraction in the ionosphere?
23. What is the skip zone of a radio wave?
24. Where does the greatest amount of ionospheric absorption occur in the ionosphere?
25. What is meant by the term “multipath”?
26. When a wide band of frequencies is transmitted simultaneously, each frequency will vary in the amount of fading. What is this variable fading called?

27. What are the two main sources of electromagnetic interference (EMI) with which radio waves must compete?
28. Thunderstorms, snowstorms, cosmic sources, and the sun are a few examples of EMI sources. What type of EMI comes from these sources?
29. Motors, switches, voltage regulators, and generators are a few examples of EMI sources. What type of EMI comes from these sources?
30. What are three ways of controlling the amount of transmitter-generated EMI?
31. What are three ways of controlling radiated EMI during transmission?
32. What are the two general types of variations in the ionosphere?
33. What is the main difference between these two types of variations?
34. What are the four main classes of regular variation that affect the extent of ionization in the ionosphere?
35. What are the three more common types of irregular variations in the ionosphere?
36. What do the letters MUF, LUF, and FOT stand for?
37. When is MUF at its highest and why?
38. What happens to the radio wave if the LUF is too low?
39. What are some disadvantages of operating transmitters at or near the LUF?
40. What are some disadvantages of operating a transmitter at or near the MUF?
41. What is FOT?
42. How do raindrops affect radio waves?
43. How does fog affect radio waves at frequencies above 2 gigahertz?
44. How is the term “temperature inversion” used when referring to radio waves?
45. How does temperature inversion affect radio transmission?
46. In what layer of the atmosphere does virtually all weather phenomena occur?
47. Which radio frequency bands use the tropospheric scattering principle for propagation of radio waves?
48. Where is the tropospheric region that contributes most strongly to tropospheric scatter propagation?

Chapter 3

Principles of Transmission Lines

LEARNING OBJECTIVES

3-1. Upon completing this chapter, you should be able to do the following:

- State what a transmission line is and how transmission lines are used.
- Explain the operating principles of transmission lines.
- Describe the five types of transmission lines.
- State the length of a transmission line.
- Explain the theory of the transmission line.
- Define the term “lumped constants” in relation to a transmission line.
- Define the term “distributed constants” in relation to a transmission line.
- Define leakage current.
- Describe how the electromagnetic lines of force around a transmission line are affected by the distributed constants.
- Define the term “characteristic impedance” and explain how it affects the transfer of energy along a transmission line.
- State how the energy transfer along a transmission line is affected by characteristic impedance and the infinite line.
- Identify the cause of and describe the characteristics of reflections on a transmission line.
- Define the term “standing waves” as applied to a transmission line.
- Describe how standing waves are produced on a transmission line and identify the types of terminations.
- Describe the types of standing-wave ratios.

INTRODUCTION TO TRANSMISSION LINES

3-2. A transmission line is a device designed to guide electrical energy from one point to another. It is used, for example, to transfer the output RF energy of a transmitter to an antenna. This energy will not travel through normal electrical wire without great losses. Although the antenna can be connected directly to the transmitter, the antenna is usually located some distance away from the transmitter. A transmission line is used to connect the transmitter and the antenna.

3-3. The transmission line has a single purpose for both the transmitter and the antenna. This purpose is to transfer the energy output of the transmitter to the antenna with the least possible power loss. How well this is done depends on the special physical and electrical characteristics (impedance and resistance) of the transmission line.

TERMINOLOGY

3-4. All transmission lines have two ends (see figure 3-1). The end of a two-wire transmission line connected to a source is ordinarily called the input end or the generator end. Other names given to this end are transmitter end, sending end, and source. The other end of the line is called the output end or receiving end. Other names given to the output end are load end and sink.

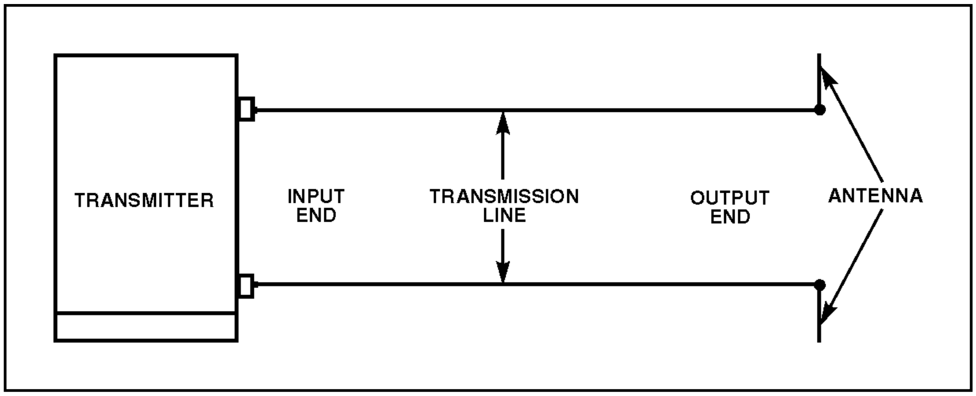


Figure 3-1. Basic Transmission Line

3-5. You can describe a transmission line in terms of its impedance. The ratio of voltage to current (E_{in}/I_{in}) at the input end is known as the input impedance (Z_{in}). This is the impedance presented to the transmitter by the transmission line and its load, the antenna. The ratio of voltage to current at the output (E_{out}/I_{out}) end is known as the output impedance (Z_{out}). This is the impedance presented to the load by the transmission line and its source. If an infinitely long transmission line could be used, the ratio of voltage to current at any point on that transmission line would be some particular value of impedance. This impedance is known as the characteristic impedance.

TYPES OF TRANSMISSION MEDIUMS

3-6. The Army uses many different types of transmission mediums in its electronic applications. Each medium (line or waveguide) has a certain characteristic impedance value, current-carrying capacity, and physical shape and is designed to meet a particular requirement.

3-7. The five types of transmission mediums discussed in this chapter include parallel line, twisted pair, shielded pair, coaxial line, and waveguides. The use of a particular line depends, among other things, on the applied frequency, the power-handling capabilities, and the type of installation.

Note. In the following paragraphs, we mention losses several times. Losses are discussed more thoroughly later in this chapter.

Parallel Line

3-8. One type of parallel line is the two-wire open line illustrated in figure 3-2. This line consists of two wires that are generally spaced from 2 to 6 inches apart by insulating spacers. This type of line is most often used for power lines, rural telephone lines, and telegraph lines. It is sometimes used as a transmission line between a transmitter and an antenna or between an antenna and a receiver. An advantage of this type of line is its simple construction. The principal disadvantages of this type of line are the high radiation losses and electrical noise pickup because of the lack of shielding. The changing fields created by the changing current in each conductor produce radiation losses.

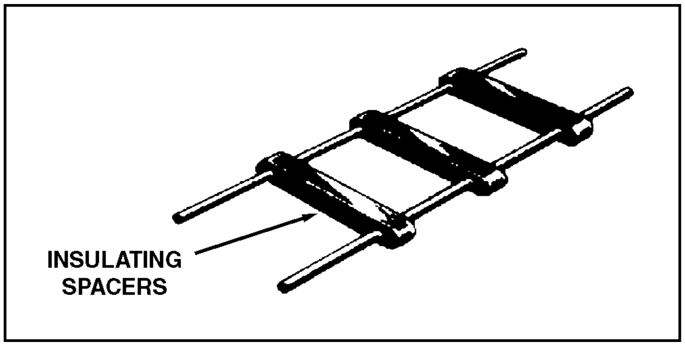


Figure 3-2. Parallel Two-Wire Open Line

3-9. Another type of parallel line is the two-wire ribbon (twin lead) illustrated in figure 3-3. This type of transmission line is commonly used to connect a television-receiving antenna to a home television set. This line is essentially the same as the two-wire open line except that uniform spacing is assured by embedding the two wires in a low-loss dielectric, usually polyethylene. Because the wires are embedded in the thin ribbon of polyethylene, the dielectric space is partly air and partly polyethylene.

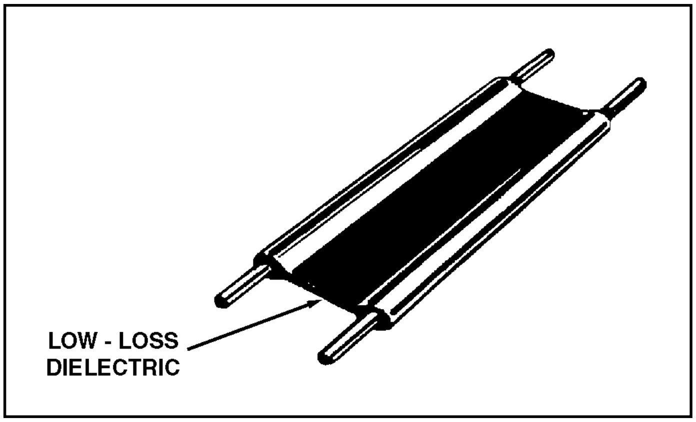


Figure 3-3. Two-Wire Ribbon Line

Twisted Pair

3-10. The twisted pair transmission line is illustrated in figure 3-4. As the name implies, the line consists of two insulated wires twisted together to form a flexible line without the use of spacers. It is not used for transmitting at high frequency because of the high dielectric losses that occur in the rubber insulation. When the line is wet, the losses increase greatly.

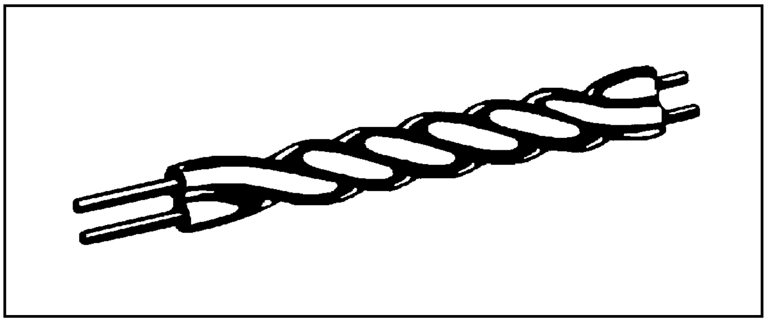


Figure 3-4. Twisted Pair

Shielded Pair

3-11. The shielded pair, shown in figure 3-5 consists of parallel conductors separated from each other and surrounded by a solid dielectric. The conductors are contained within braided copper tubing that acts as an electrical shield. The assembly is covered with a rubber or flexible composition coating that protects the line from moisture and mechanical damage. Outwardly, it looks much like the power cord of a washing machine or refrigerator.

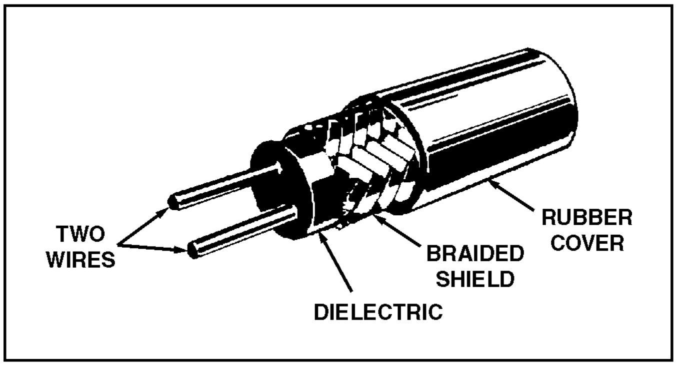


Figure 3-5. Shielded Pair

3-12. The principal advantage of the shielded pair is that the conductors are balanced to ground; that is, the capacitance between the wires is uniform throughout the length of the line. This balance is due to the uniform spacing of the grounded shield that surrounds the wires along their entire length. The braided copper shield isolates the conductors from stray magnetic fields.

Coaxial Lines

3-13. There are two types of coaxial lines: rigid (air) and flexible (solid) coaxial line. The physical construction of both types is basically the same; that is, each contains two concentric conductors.

3-14. The rigid coaxial line consists of a central, insulated wire (inner conductor) mounted inside a tubular outer conductor. This line is shown in figure 3-6. In some applications, the inner conductor is also tubular. Insulating spacers or beads at regular intervals insulates the inner conductor from the outer conductor. The spacers are made of pyrex, polystyrene, or some other material that has good insulating characteristics and low dielectric losses at high frequencies.

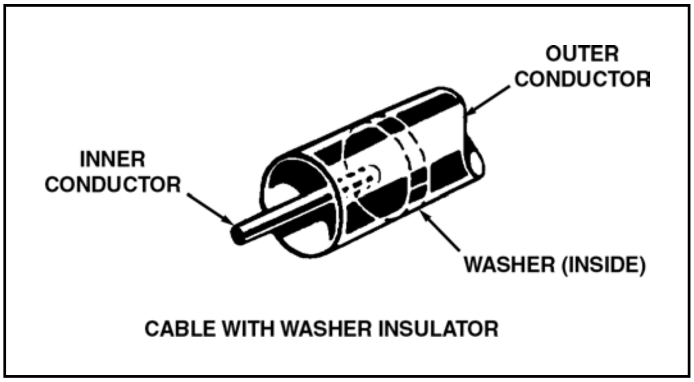


Figure 3-6. Rigid (Air) Coaxial Line

3-15. The chief advantage of the rigid line is its ability to minimize radiation losses. The electric and magnetic fields in a two-wire parallel line extend into space for relatively great distances and radiation losses occur. However, in a coaxial line no electric or magnetic fields extend outside of the outer conductor. The fields are confined to the space between the two conductors, resulting in a perfectly shielded coaxial line. Another advantage is that interference from other lines is reduced.

3-16. The rigid line has the following disadvantages: (1) it is expensive to construct; (2) it must be kept dry to prevent excessive leakage between the two conductors; and (3) although high-frequency losses are somewhat less than in previously mentioned lines, they are still excessive enough to limit the practical length of the line.

3-17. Leakage caused by the condensation of moisture is prevented in some rigid line applications by the use of an inert gas, such as nitrogen, helium, or argon. It is pumped into the dielectric space of the line at a pressure that can vary from 3 to 35 pounds per square inch. The inert gas is used to dry the line when it is first installed and pressure is maintained to ensure that no moisture enters the line.

3-18. Flexible coaxial lines (figure 3-7) are made with an inner conductor that consists of flexible wire insulated from the outer conductor by a solid, continuous insulating material. The outer conductor is made of metal braid, which gives the line flexibility. Early attempts at gaining flexibility involved using rubber insulators between the two conductors. However, the rubber insulators caused excessive losses at high frequencies.

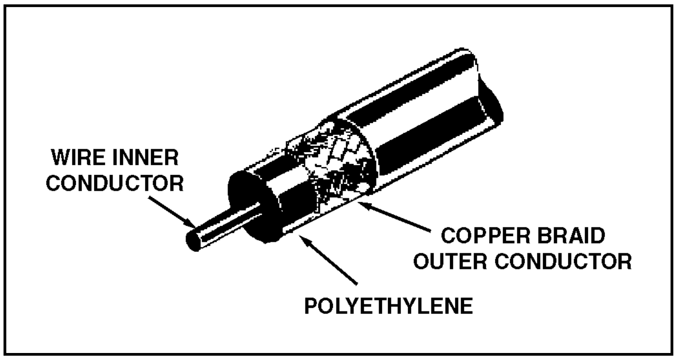


Figure 3-7. Flexible (Solid) Coaxial Line

3-19. Because of the high-frequency losses associated with rubber insulators, polyethylene plastic was developed to replace rubber and eliminate these losses. Polyethylene plastic is a solid substance that remains flexible over a wide range of temperatures. It is unaffected by seawater, gasoline, oil, and most other liquids that may be found aboard ship. The use of polyethylene as an insulator results in greater high-frequency losses than the use of air as an insulator. However, these losses are still lower than the losses associated with most other solid dielectric materials.

Waveguides

3-20. The waveguide is classified as a transmission line. However, the method by which it transmits energy down its length differs from the conventional methods. Waveguides are cylindrical, elliptical, or rectangular (cylindrical and rectangular shapes are shown in figure 3-8). The rectangular waveguide is used more frequently than the cylindrical waveguide.

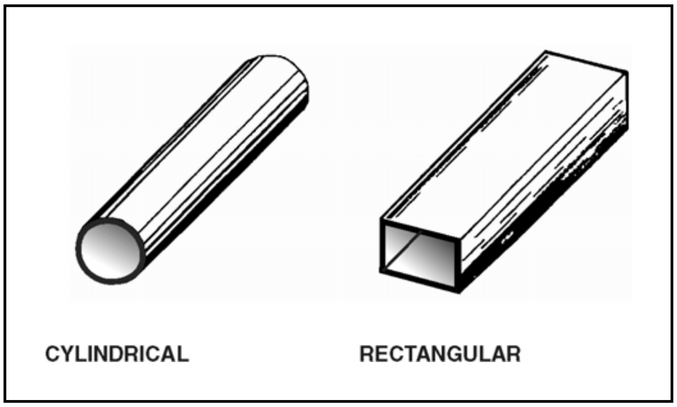


Figure 3-8. Waveguides

3-21. The term waveguide can be applied to all types of transmission lines in the sense that they are all used to guide energy from one point to another. However, usage has generally limited the term to mean a hollow metal tube or a dielectric transmission line. In this chapter, we use the term waveguide only to mean “hollow metal tube.” It is interesting to note that the transmission of electromagnetic energy along a waveguide travels at a velocity somewhat slower than electromagnetic energy traveling through free space.

3-22. A waveguide may be classified according to its cross section (rectangular, elliptical, or circular), or according to the material used in its construction (metallic or dielectric). Dielectric waveguides are seldom used because the dielectric losses for all known dielectric materials are too great to transfer the electric and magnetic fields efficiently.

3-23. The installation of a complete waveguide transmission system is somewhat more difficult than the installation of other types of transmission lines. The radius of bends in the waveguide must measure greater than two wavelengths at the operating frequency of the equipment to avoid excessive attenuation. The cross section must remain uniform around the bend. These requirements hamper installation in confined spaces. If the waveguide is dented, or if solder is permitted to run inside the joints, the attenuation of the line is greatly increased. Dents and obstructions in the waveguide also reduce its breakdown voltage, thus limiting the waveguide's power-handling capability because of possible arc-over. Great care must be exercised during installation; one or two carelessly made joints can seriously inhibit the advantage of using the waveguide.

LOSSES IN TRANSMISSION LINES

3-24. The discussion of transmission lines so far has not directly addressed line losses; actually some line losses occur in all lines. Line losses may be any of three types—copper, dielectric, and radiation or induction losses.

Note. Transmission lines are sometimes referred to as RF lines. In this text the terms are used interchangeably.

Copper Losses

3-25. One type of copper loss is I2R loss. In RF lines, the resistance of the conductors is never equal to zero. Whenever current flows through one of these conductors, some energy is dissipated in the form of heat. This heat loss is a power loss. With copper braid, which has a higher resistance than solid tubing, this power loss is higher.

3-26. Another type of copper loss is due to skin effect. When DC flows through a conductor, the movement of electrons through the conductor's cross section is uniform. The situation is somewhat different when AC is applied. The expanding and collapsing fields about each electron encircle other electrons. This phenomenon, called self-induction, retards the movement of the encircled electrons. The flux density at the center is so great that electron movement at this point is reduced. As frequency is increased, the opposition to the flow of current in the center of the wire increases. Current in the center of the wire becomes smaller and most of the electron flow is on the wire surface. When the frequency applied is 100 megahertz or higher, the electron movement in the center is so small that the center of the wire could be removed without any noticeable effect on current. You should be able to see that the effective cross-sectional area decreases as the frequency increases.

3-27. Because resistance is inversely proportional to the cross-sectional area, the resistance will increase as the frequency is increased. Also, because power loss increases as resistance increases, power losses increase with an increase in frequency because of skin effect. Skin effect is a tendency for alternating current (AC) to flow mostly near the outer surface of a solid electrical conductor, such as metal wire, at frequencies above the audio range. The effect becomes more and more apparent as the frequency increases.

3-28. Copper losses can be minimized and conductivity increased in an RF line by plating the line with silver. Because silver is a better conductor than copper, most of the current will flow through the silver layer. The tubing then serves primarily as a mechanical support.

Dielectric Losses

3-29. Dielectric losses result from the heating effect on the dielectric material between the conductors. Power from the source is used in heating the dielectric. The heat produced is dissipated into the surrounding medium. When there is no potential difference between two conductors, the atoms in the dielectric material between them are normal and the orbits of the electrons are circular. When there is a potential difference between two conductors, the orbits of the electrons change. The excessive negative charge on one conductor repels electrons on the dielectric toward the positive conductor and thus distorts the orbits of the electrons. A change in the path of electrons requires more energy, introducing a power loss.

3-30. The atomic structure of rubber is more difficult to distort than the structure of some other dielectric materials. The atoms of materials, such as polyethylene, distort easily. Therefore, polyethylene is often used as a dielectric because less power is consumed when its electron orbits are distorted.

Radiation and Induction Losses

3-31. Radiation and induction losses are similar in that the fields surrounding the conductors cause both. Induction losses occur when the electromagnetic field about a conductor cuts through any nearby metallic object and a current is induced in that object. As a result, power is dissipated in the object and is lost.

3-32. Radiation losses occur because some magnetic lines of force about a conductor do not return to the conductor when the cycle alternates. These lines of force are projected into space as radiation and this results in power losses. That is, power is supplied by the source, but is not available to the load.

LENGTH OF A TRANSMISSION LINE

3-33. A transmission line is considered to be electrically short when its physical length is short compared to a quarter-wavelength (¼λ) of the energy it is to carry.

Note. In this document, for ease of reading, the value of the wavelength is spelled out in some cases, and in other cases, the numerical value is used.

3-34. A transmission line is electrically long when its physical length is long compared to a quarter-wavelength of the energy it is to carry. You must understand that the terms “short” and “long” are relative ones. For example, a line that has a physical length of 3 meters (approximately 10 feet) is considered quite short electrically if it transmits a radio frequency of

30 kilohertz. On the other hand, the same transmission line is considered electrically long if it transmits a frequency of 30,000 megahertz.

3-35. To show the difference in physical and electrical lengths of the lines mentioned above, compute the wavelength of the two frequencies, taking the 30-kilohertz example first—

Given:

$$\lambda = \frac{v}{f}$$

Where:

λ = wavelength

v = velocity of RF in free space

f = frequency of transmission

Hz = cycles per second

Solution:

$$\lambda = \frac{300 \times 10^6 \text{ meters/second}}{30 \times 10^3 \text{ cycles/second (Hz)}}$$

$$\lambda = 10 \times 10^3 \text{ meters/cycle}$$

$\lambda =$ 10,000 meters, or approximately 6 miles for a complete wavelength

3-36. Now, computing the wavelength for the line carrying 30,000 megahertz—

$$\lambda = \frac{v}{f}$$

$$\lambda = \frac{300 \times 10^6 \text{ meters/second}}{30{,}000 \times 10^6 \text{ cycles/second (Hz)}}$$

$$\lambda = \frac{1}{100} \text{ meter/cycle}$$

$\lambda =$ .01 meter or approximately .03 foot for a complete wavelength

3-37. Thus, you can see that a 3-meter line is electrically very short for a frequency of 30 kilohertz. Also, the 3-meter line is electrically very long for a frequency of 30,000 megahertz.

3-38. When power is applied to a very short transmission line, practically all of it reaches the load at the output end of the line. This very short transmission line is usually considered to have practically no electrical properties of its own, except for a small amount of resistance.

3-39. However, the picture changes considerably when a long line is used. Because most transmission lines are electrically long (because of the distance from transmitter to antenna), the properties of such lines must be considered. Frequently, the voltage necessary to drive a current through a long line is considerably greater than the amount that can be accounted for by the impedance of the load in series with the resistance of the line.

TRANSMISSION LINE THEORY

3-40. The electrical characteristics of a two-wire transmission line depend primarily on the construction of the line. The two-wire line acts like a long capacitor. The change of its capacitive reactance is noticeable as the frequency applied to it is changed. Because the long conductors have a magnetic field about them when electrical energy is being passed through them, they also exhibit the properties of inductance. The values of inductance and capacitance presented depend on the various physical factors that we discussed earlier in this chapter. For example, the type of line used, the dielectric in the line, and the length of the line must be considered. The effects of the inductive and capacitive reactances of the line depend on the frequency applied. Because no dielectric is perfect, electrons manage to move from one conductor to the other through the dielectric. Each type of two-wire transmission line also has a conductance value. This conductance value represents the value of the current flow that may be expected through the insulation. If the line is uniform (all values equal at each unit length), then one small section of the line may represent several feet. This illustration of a two-wire transmission line is used throughout the following discussion of transmission lines; but keep in mind that the principles presented here apply to all transmission lines. We explain the theories using lumped constants and distributed constants to simplify these principles further.

LUMPED CONSTANTS

3-41. A transmission line has the properties of inductance, capacitance, and resistance, just as the more conventional circuits have. Usually, however, the constants in conventional circuits are lumped into a single device or component. For example, a coil of wire has the property of inductance. When a certain amount of inductance is needed in a circuit, a coil of the proper dimensions is inserted. The inductance of the circuit is lumped into the one component. Two metal plates separated by a small space can be used to supply the required capacitance for a circuit. In such a case, most of the capacitance of the circuit is lumped into this one component. Similarly, a fixed resistor can be used to supply a certain value of circuit resistance as a lumped sum. Ideally, a transmission line would also have its constants of inductance, capacitance, and resistance lumped together, as shown in figure 3-9. Transmission line constants are distributed, as described below.

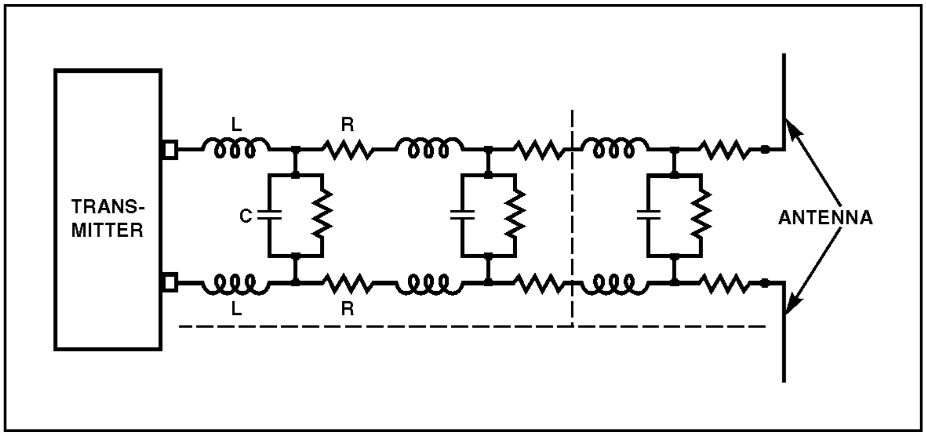


Figure 3-9. Equivalent Circuit of a Two-Wire Transmission Line

DISTRIBUTED CONSTANTS

3-42. Transmission line constants, called distributed constants, are spread along the entire length of the transmission line and cannot be distinguished separately. The amount of inductance, capacitance, and resistance depends on the length of the line, the size of the conducting wires, the spacing between the wires, and the dielectric (air or insulating medium) between the wires.

Inductance of a Transmission Line

3-43. When current flows through a wire, magnetic lines of force are set up around the wire. As the current increases and decreases in amplitude, the field around the wire expands and collapses accordingly. The energy produced by the magnetic lines of force collapsing back into the wire tends to keep the current flowing in the same direction. This represents a certain amount of inductance, which is expressed in microhenrys per unit length. Figure 3-10 illustrates the inductance and magnetic fields of a transmission line.

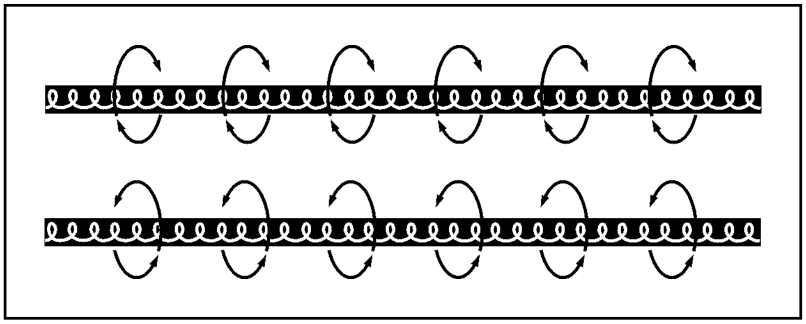


Figure 3-10. Distributed Inductance

Capacitance of a Transmission Line

3-44. Capacitance also exists between the transmission line wires, as illustrated in figure 3-11. Notice that the two parallel wires act as plates of a capacitor and that the air between them acts as a dielectric. The capacitance between the wires is usually expressed in picofarads per unit length. This electric field between the wires is similar to the field that exists between the two plates of a capacitor.

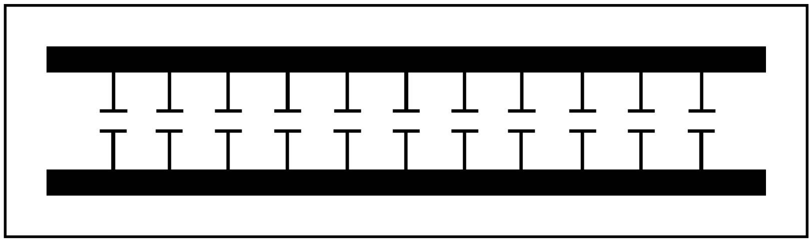


Figure 3-11. Distributed Capacitance

Resistance of a Transmission Line

3-45. The transmission line shown in figure 3-12 has electrical resistance along its length. This resistance is usually expressed in ohms per unit length and is shown as existing continuously from one end of the line to the other.

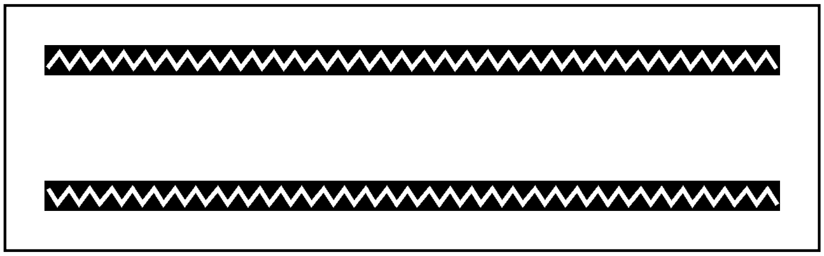


Figure 3-12. Distributed Resistance

Leakage Current

3-46. Because any dielectric, even air, is not a perfect insulator, a small current known as leakage current flows between the two wires. In effect, the insulator acts as a resistor, permitting current to pass between the two wires. Figure 3-13 shows this leakage path as resistors in parallel connected between the two lines. This property is called conductance (G) and is the opposite of resistance. Conductance in transmission lines is expressed as the reciprocal of resistance and is usually given in micromhos per unit length.

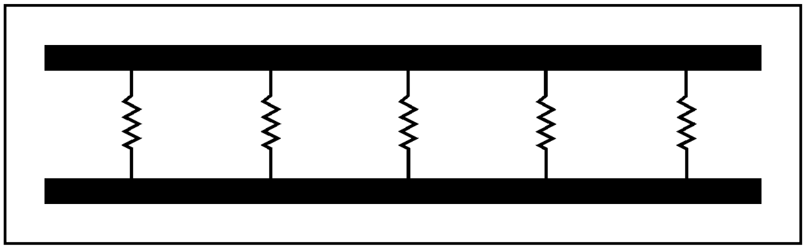


Figure 3-13. Leakage in a Transmission Line

ELECTROMAGNETIC FIELDS ABOUT A TRANSMISSION LINE

3-47. The distributed constants of resistance, inductance, and capacitance are basic properties common to all transmission lines and exist whether or not any current flow exists. As soon as current flow and voltage exist in a transmission line, another property becomes quite evident. This is the presence of an electromagnetic field, or lines of force, about the wires of the transmission line. The lines of force themselves are not visible; however, understanding the force that an electron experiences while in the field of these lines is very important to your understanding of energy transmission.

3-48. There are two kinds of fields; one is associated with voltage and the other with current. The field associated with voltage is called the electric (E) field. It exerts a force on any electric charge placed in it. The field associated with current is called a magnetic (H) field, because it tends to exert a force on any magnetic pole placed in it. Figure 3-14 illustrates the way in which the E fields and H fields tend to orient themselves between conductors of a typical two-wire transmission line. The illustration shows a cross section of the transmission lines. The E field is represented by solid lines and the H field by dotted lines. The arrows indicate the direction of the lines of force. Both fields normally exist together and are spoken of collectively as the electromagnetic field.

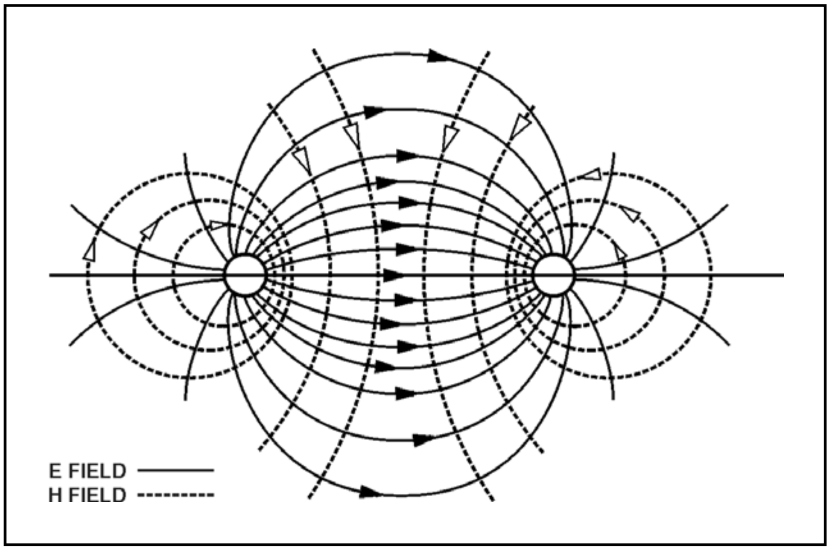


Figure 3-14. Fields between Conductors

CHARACTERISTIC IMPEDANCE OF A TRANSMISSION LINE

3-49. You learned earlier that the maximum (and most efficient) transfer of electrical energy takes place when the source impedance is matched to the load impedance. This fact is very important in the study of transmission lines and antennas. If the characteristic impedance of the transmission line and the load impedance are equal, energy from the transmitter will travel down the transmission line to the antenna with no power loss caused by reflection.

Definition and Symbols

3-50. Every transmission line possesses certain characteristic impedance, usually designated as Z_0. Z_0 is the ratio of E to I at every point along the line. If a load equal to the characteristic impedance is placed at the output end of any length of line, the same impedance will appear at the input terminals of the line. The characteristic impedance is the only value of impedance for any given type and size of line that acts in this way. The characteristic impedance determines the amount of current that can flow when a given voltage is applied to an infinitely long line. Characteristic impedance is comparable to the resistance that determines the amount of current that flows in a DC circuit.

3-51. Lumped and distributed constants were explained earlier in this chapter. Figure 3-15, view A, shows the properties of resistance (R), inductance (L), capacitance (C), and conductance (G) combined in a short section of two-wire transmission line. The illustration shows the evenly distributed capacitance as a single lumped capacitor and the distributed conductance as a lumped leakage path. Lumped values may be used for transmission line calculations if the physical length of the line is very short compared to the wavelength of energy being transmitted. Figure 3-15, view B, shows all four properties lumped together and represented by their conventional symbols.

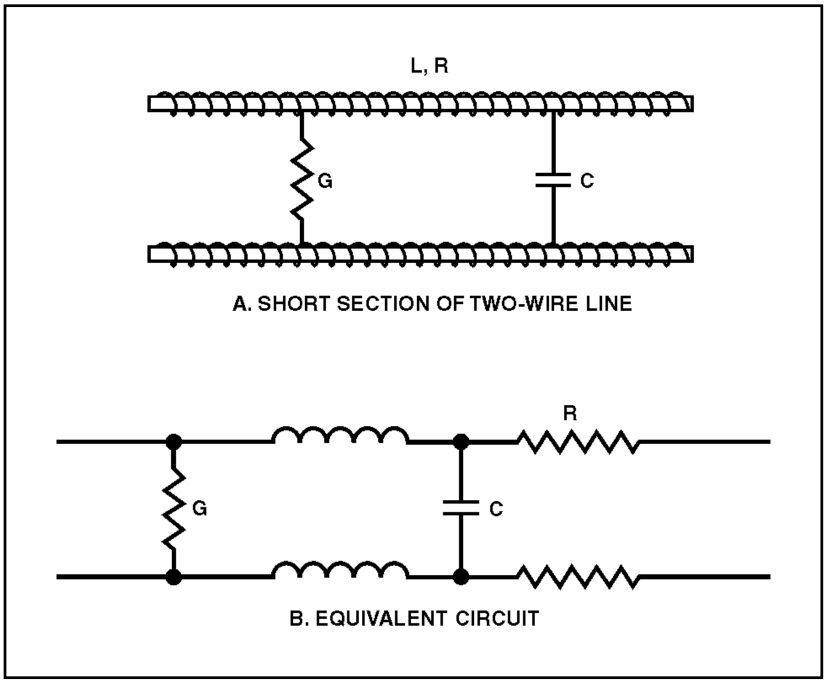


Figure 3-15. Short Section of Two-Wire Transmission Line and Equivalent Circuit

Characteristic Impedance and the Infinite Line

3-52. Like those shown in figure 3-15, several short sections can be combined to form a large transmission line, as shown in figure 3-16. Current will flow if voltage is applied across points K and L. In fact, any circuit, such as that represented in figure 3-16, view A, has a certain current flow for each value of applied voltage. The ratio of the voltage to the current is the impedance (Z), as expressed in the following formula:

$$Z = \frac{E}{I}$$

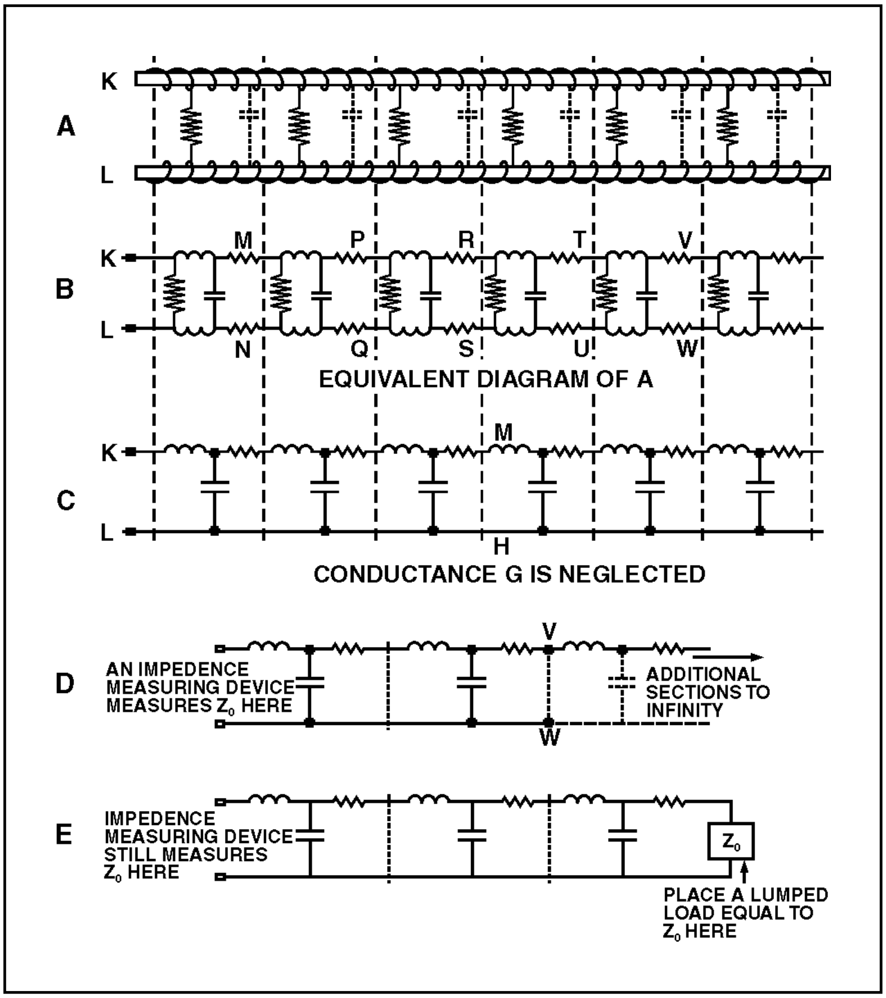


Figure 3-16. Characteristic Impedance

3-53. The impedance presented to the input terminals of the transmission line is not merely the resistance of the wire in series with the impedance of the load. The effects of series inductance and shunt capacitance of the line itself may overshadow the resistance, and even the load, as far as the input terminals are concerned.

3-54. To find the input impedance of a transmission line, determine the impedance of a single section of line. The impedance between points K and L, in figure 3-16, view B, can be calculated by the use of series-parallel impedance formulas, provided the impedance across points M and N is known. But because this section is merely one small part of a longer line, another similar section is connected to points M and N. Again, the impedance across points K and L of the two sections can be calculated, provided the impedance of the third section is known. This process of adding one section to another can be repeated endlessly. The addition of each section produces an impedance across points K and L of a new and lower value. However, after many sections have been added, each successive added section has less and less effect on the impedance across points K and L. If sections are added to the line endlessly, the line is infinitely long, and a certain finite value of impedance across points K and L is finally reached.

3-55. In this discussion of transmission lines, the effect of conductance (G) is minor compared to that of inductance (L) and capacitance (C), and is frequently neglected. In figure 3-16, view C, G is omitted and the inductance and resistance of each line can be considered as one line.

3-56. Let us assume that the sections of figure 3-16, view C continue to the right with an infinite number of sections. When an infinite number of sections extends to the right, the impedance appearing across K and L is Z_0. If the line is cut at R and S, an infinite number of sections still extends to the right because the line is endless in that direction. Therefore, the impedance now appearing across points R and S is also Z_0, as illustrated in view D. You can see that if only the first three sections are taken and a load impedance of Z_0 is connected across points R and S, the impedance across the input terminals K and L is still Z_0. The line continues to act as an infinite line, as illustrated in view E.

3-57. Figure 3-17, view A illustrates how the characteristic impedance of an infinite line can be calculated. Resistors are added in series parallel across terminals K and L in eight steps, and the resultant impedances are noted. In step 1 the impedance is infinite; in step 2 the impedance is 110 ohms. In step 3 the impedance becomes 62.1 ohms, a change of 47.9 ohms. In step 4 the impedance is 48.5 ohms, a change of only 13.6 ohms. The resultant changes in impedance from each additional increment become progressively smaller. Eventually, practically no change in impedance results from further additions to the line. The total impedance of the line at this point is said to be at its characteristic impedance; which, in this case, is 37 ohms. This means that an infinite line constructed as indicated in step 8 could be effectively replaced by a 37-ohm resistor. View B shows a 37-ohm resistor placed in the line at various points to replace the infinite line of step 8 in view A. There is no change in total impedance.

3-58. In figure 3-17, resistors were used to show impedance characteristics for the sake of simplicity. Figuring the actual impedance of a line having reactance is very similar, with inductance taking the place of the series resistors and capacitance taking the place of the shunt resistors. The characteristic impedance of lines in actual use normally lies between 50 and 600 ohms.

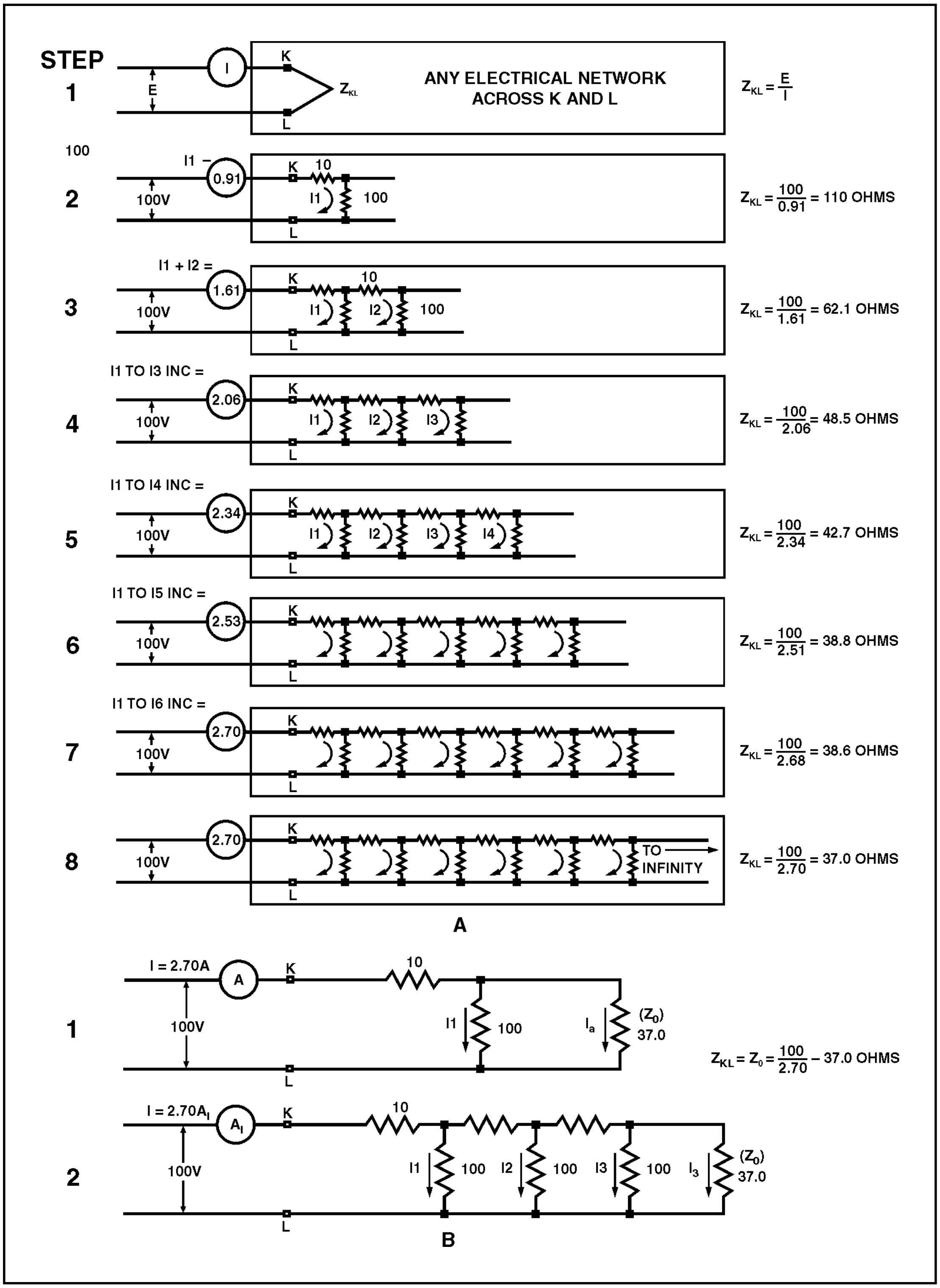


Figure 3-17 Termination of a Line

3-59. When a transmission line is “short” compared to the length of the RF waves it carries, the opposition presented to the input terminals is determined primarily by the load impedance. A small amount of power is dissipated in overcoming the resistance of the line. However, when the line is “long” and the load is an incorrect impedance, the voltages necessary to drive a given amount of current through the line cannot be accounted for by considering just the impedance of the load in series with the impedance of the line. The line has properties other than resistance that affect input impedance. These properties are inductance in series with the line, capacitance across the line, resistance leakage paths across the line, and certain radiation losses.

VOLTAGE CHANGE ALONG A TRANSMISSION LINE

3-60. Let us summarize what we have just discussed. In an electric circuit, energy is stored in electric and magnetic fields. These fields must be brought to the load to transmit that energy. At the load, energy contained in the fields is converted to the desired form of energy.

Transmission of Energy

3-61. When the load is connected directly to the source of energy, or when the transmission line is short, problems concerning current and voltage can be solved by applying Ohm’s law. When the transmission line becomes long enough so the time difference between a change occurring at the generator and the change appearing at the load becomes appreciable, analysis of the transmission line becomes important.

DC Applied to a Transmission Line

3-62. In figure 3-18, a battery is connected through a relatively long two-wire transmission line to a load at the far end of the line. At the instant the switch is closed, neither current nor voltage exists on the line. When the switch is closed, point A becomes a positive potential, and point B becomes negative. These points of difference in potential move down the line. However, as the initial points of potential leave points A and B, they are followed by new points of difference in potential which the battery adds at A and B. This is merely saying that the battery maintains a constant potential difference between points A and B. A short time after the switch is closed, the initial points of difference in potential have reached points A' and B'; the wire sections from points A to A' and points B to B' are at the same potential as A and B, respectively. The points of charge are represented by plus (+) and minus (-) signs along the wires. The directions of the currents in the wires are represented by the arrowheads on the line, and the direction of travel is indicated by an arrow below the line. Conventional lines of force represent the electric field that exists between the opposite kinds of charge on the wire sections from A to A' and B to B'. Crosses (tails of arrows) indicate the magnetic field created by the electric field moving down the line. The moving electric field and the accompanying magnetic field constitute an electromagnetic wave that is moving from the generator (battery) toward the load. This wave travels at approximately the speed of light in free space. The energy reaching the load is equal to that developed at the battery (assuming there are no losses in the transmission line). If the load absorbs all of the energy, the current and voltage will be evenly distributed along the line.

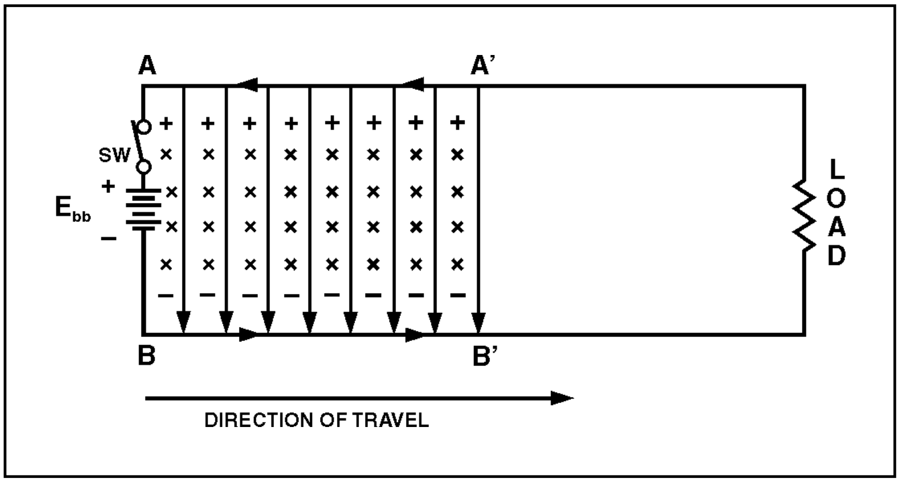


Figure 3-18. DC Voltage Applied to a Line

AC Applied to a Transmission Line

3-63. When the battery of figure 3-18 is replaced by an AC generator (figure 3-19), each successive instantaneous value of the generator voltage is propagated down the line at the speed of light. The action is similar to the wave created by the battery except that the applied voltage is sinusoidal instead of constant. Assume that the switch is closed at the moment the generator voltage is passing through zero and that the next half cycle makes point A positive. At the end of one cycle of generator voltage, the current and voltage distribution will be as shown in figure 3-19.

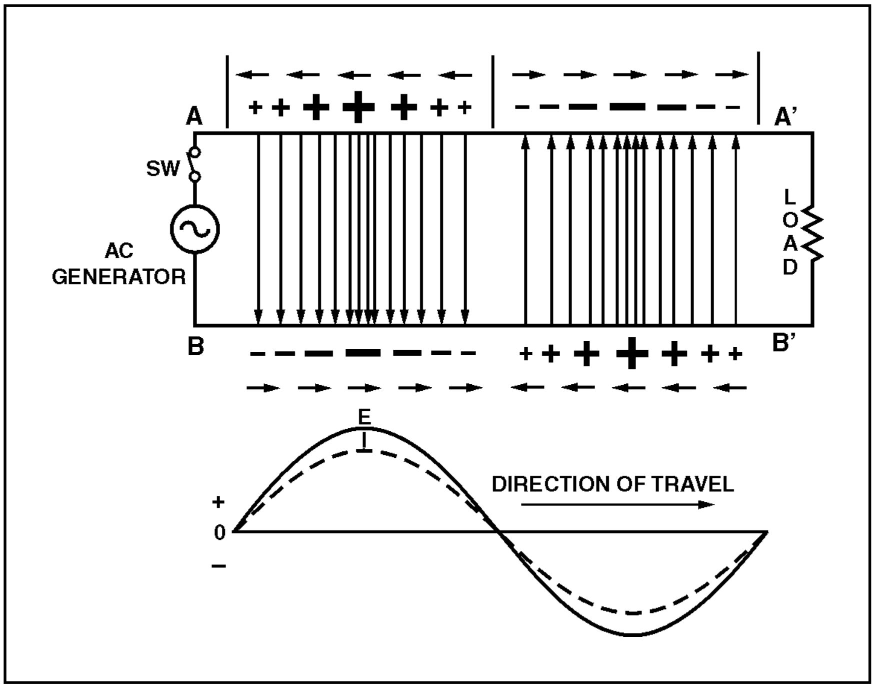


Figure 3-19. AC Voltage Applied to a Transmission Line

3-64. In this illustration the conventional lines of force represent the electric fields. For simplicity, the magnetic fields are not shown. Points of charge are indicated by plus (+) and minus (-) signs, the larger signs indicating points of higher amplitude of both voltage and current. Short arrows indicate direction of current (electron flow). The waveform drawn below the transmission line represents the voltage (E) and current (I) waves. The line is assumed to be infinite in length so there is no reflection. Thus, traveling sinusoidal voltage and current waves continually travel in phase from the generator toward the load, or far end of the line. Waves traveling from the generator to the load are called incident waves. Waves traveling from the load back to the generator are called reflected waves and are explained later in this chapter.

DC Applied to an Infinite Line

3-65. Figure 3-20 shows a battery connected to a circuit that is the equivalent of a transmission line. In this line, the series resistance and shunt conductance are not shown. Also, in the discussion that follows, the line is considered to have no losses.

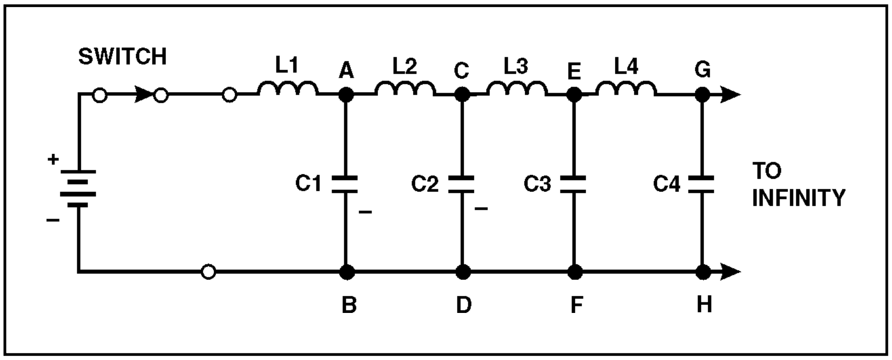


Figure 3-20. DC Applied to an Equivalent Transmission Line

3-66. As the switch shown in figure 3-20 is closed, the battery voltage is applied to the input terminals of the line. Now, C1 has no charge and appears, effectively, as a short circuit across points A and B. The full battery voltage appears across inductor L1. Inductor L1 opposes the change of current (0 now) and limits the rate of charge of C1.

3-67. Capacitor C2 cannot begin to charge until after C1 has charged. No current can flow beyond points A and B until C1 has acquired some charge. As the voltage across C1 increases, current through L2 and C2 charges C2. This action continues down the line and charges each capacitor, in turn, to the battery voltage. Thus, a voltage wave is traveling along the line. Beyond the wavefront, the line is uncharged. Because the line is infinitely long, there will always be more capacitors to be charged, and current will not stop flowing. Thus, current will flow indefinitely in the line.

3-68. Notice that current flows to charge the capacitors along the line. The flow of current is not advanced along the line until a voltage is developed across each preceding capacitor. In this manner voltage and current move down the line together in phase.

AC Applied to an Infinite Line

3-69. An RF line displays similar characteristics when an AC voltage is applied to its sending end or input terminals. In figure 3-21, view A, an AC voltage is applied to the line represented by the circuit shown.

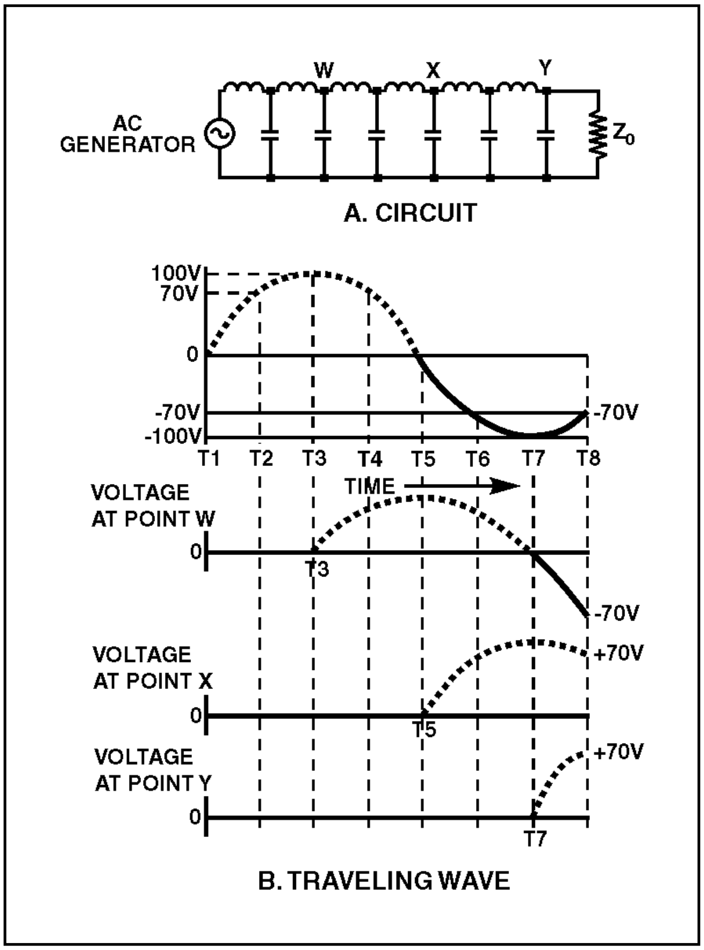


Figure 3-21. AC Applied to an Equivalent Transmission Line

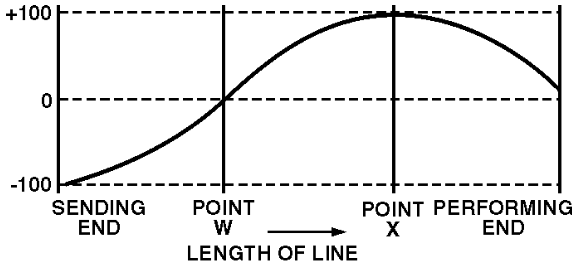
3-70. In figure 3-21, view B, the generator voltage starts from zero (T1) and produces the voltage shown. As soon as a small voltage change is produced, it starts its journey down the line while the generator continues to produce new voltages along a sine curve. At T2 the generator voltage is 70 volts. The voltages still move along the line until, at T3, the first small change arrives at point W, and the voltage at that point starts increasing. At T5, the same voltage arrives at point X on the line. Finally, at T7, the first small change arrives at the receiving end of the line. Meanwhile, all the changes in the sine wave produced by the generator pass each point in turn. The amount of time required for the changes to travel the length of the line is the same as that required for a DC voltage to travel the same distance.

3-71. At T7, the voltage at the various points on the line is as follows:

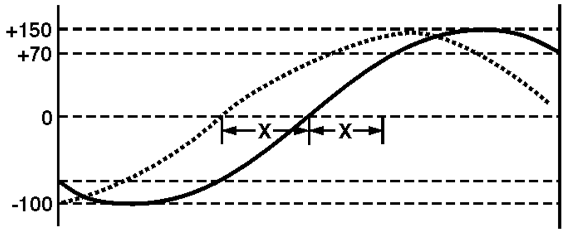
- At the generator: –100 V
- At point W: 0 V
- At point X: +100 V
- At point Y: 0 V

3-72. If these voltages are plotted along the length of the line, the resulting curve is like the one shown in figure 3-22, view A. Note that such a curve of instantaneous voltages resembles a sine wave. The changes in voltage that occur between T7 and T8 are as follows:

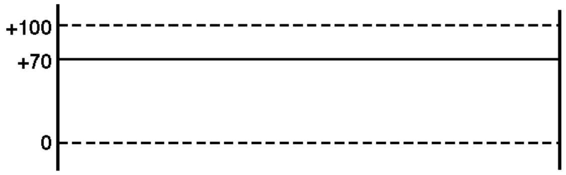
• At the generator:	Rise from	–100 V to –70 V
• At point W:	Drop from	0 V to –70 V
• At point X:	Drop from	+100 V to +70 V
• At point Y:	Rise from	0 V to +70 V



A. VOLTAGE ON LINE AT TIME T7



B. VOLTAGES ON LINE AT TIME T8
(DOTTED LINE IS T7 VOLTAGE
PER REFERENCE)



C. A CURVE OF READINGS ON AN AC METER
WOULD SHOW THE EFFECTIVE OR
RMS VOLTAGE TO BE THE SAME
OVER LENGTH OF LINE

Figure 3-22. Instantaneous Voltages along a Transmission Line

3-73. A plot of these new voltages produces the solid curve shown in figure 3-22, view B. For reference, the curve from T7 is drawn as a dotted line. The solid curve has exactly the same shape as the dotted curve, but has moved to the right by the distance X. Another plot at T9 would show a new curve similar to the one at T8, but moved to the right by the distance Y.

3-74. By analyzing the points along the graph just discussed, you should be able to see that the actions associated with voltage changes along an RF line are as follows:

- All instantaneous voltages of the sine wave produced by the generator travel down the line in the order they are produced.
- At any point, a sine wave can be obtained if all the instantaneous voltages passing the point are plotted. An oscilloscope can be used to plot these values of instantaneous voltages against time.
- The instantaneous voltages (oscilloscope displays) are the same in all cases except that a phase difference exists in the displays seen at different points along the line. The phase changes continually with respect to the generator until the change is 360 degrees over a certain length of line.
- All parts of a sine wave pass every point along the line. A plot of the readings of an AC meter (which reads the effective value of the voltage over a given time) taken at different points along the line shows that the voltage is constant at all points (see figure 3-22, view C).
- Because the line is terminated with a resistance equal to Z_0, the energy arriving at the end of the line is absorbed by the resistance.

VELOCITY OF WAVE PROPAGATION

3-75. If a voltage is initially applied to the sending end of a line, that same voltage will appear later some distance from the sending end. This is true regardless of any change in voltage, whether the change is a jump from zero to some value or a drop from some value to zero. The voltage change will be conducted down the line at a constant rate.

3-76. Recall that the inductance of a line delays the charging of the line capacitance. The velocity of propagation is therefore related to the values of L and C. If the inductance and capacitance of the RF line are known, the time required for any waveform to travel the length of the line can be determined. To see how this works, observe the following relationship:

$$Q = IT$$

This formula shows that the total charge or quantity is equal to the current multiplied by the time the current flows. Also—

$$Q = CE$$

This formula shows that the total charge on a capacitor is equal to the capacitance multiplied by the voltage across the capacitor.

3-77. If the switch in figure 3-23 is closed for a given time, the quantity (Q) of electricity leaving the battery can be computed by using the equation Q = IT. The electricity leaves the battery and goes into the line, where a charge is built up on the capacitors. The amount of this charge is computed by using the equation Q = CE.

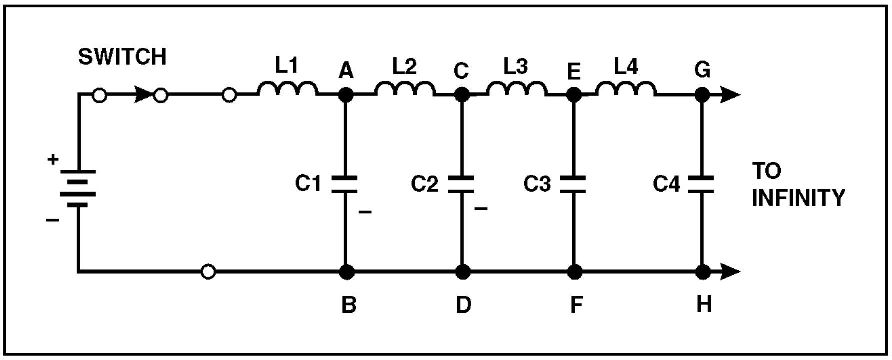


Figure 3-23. DC Applied to an Equivalent Transmission Line

3-78. Because none of the charge is lost, the total charge leaving the battery during T is equal to the total charge on the line. Therefore:

$Q = IT = CE$

3-79. As each capacitor accumulates a charge equal to CE, the voltage across each inductor must change. As C1 in figure 3-23 charges to a voltage of E, point A rises to a potential of E volts while point B is still at zero volts. This makes E appear across L2. As C2 charges, point B rises to a potential of E volts as did point A. At this time, point B is at E volts and point C rises. Thus, there is a continuing action of voltage moving down the infinite line.

3-80. In an inductor, these circuit components are related, as shown in the formula—

$$E = L \left(\frac{\Delta I}{\nabla T} \right)$$

3-81. 1-79. This shows that the voltage across the inductor is directly proportional to inductance and the change in current, but inversely proportional to a change in time. Because current and time start from zero, the change in time (ΔT) and the change in current (ΔI) are equal to the final time (T) and final current (I). For this case the equation becomes:

$ET = LI$

3-82. If voltage E is applied for time (T) across the inductor (L), the final current (I) will flow. The following equations show how T, L, and C are related:

$ET = LI$

$IT = CE$

3-83. For convenience, you can find T in terms of L and C by multiplying the left and right members of each of the above equations, and solving for T, as follows:

$(IT)(ET) = (CE)(LI)$

$EIT^2 = LCEI$

$T^2 = LC$

$T = \sqrt{LC}$

3-84. This final equation is used for finding the time required for a voltage change to travel a unit length, because L and C are given in terms of unit length. The velocity of the waves may be found by the following equation, where D is the physical length of a unit:

$$v = \frac{D}{T} \quad \text{Or} \quad v = \frac{D}{\sqrt{LC}}$$

3-85. This is the rate at which the wave travels over a unit length. The units of L and C are henrys and farads, respectively. T is in seconds per unit length and V is in unit lengths per second.

DETERMINING CHARACTERISTIC IMPEDANCE

3-86. As previously discussed, an infinite transmission line exhibits a definite input impedance. This impedance is the characteristic impedance and is independent of line length. The exact value of this impedance is the ratio of the input voltage to the input current. If the line is infinite or is terminated in a resistance equal to the characteristic impedance, voltage and current waves traveling the line are in phase. Recall the following equations:

$$ET = LI$$

$$IT = CE$$

To determine the characteristic impedance or voltage-to-current ratio, use the following procedure:

Divide the equations:

$$ET = LI \text{ and } IT = CE$$

$$\frac{ET}{IT} = \frac{LI}{CE}$$

Multiply the result by $\frac{E}{I}$

$$\frac{E^2T}{I^2T} = \frac{LIE}{CEI}$$

Simplify:

$$\frac{E^2}{I^2} = \frac{L}{C}$$

Take the square root:

$$\frac{E}{I} = \sqrt{\frac{L}{C}} = Z_0 \text{ (characteristic impedance)}$$

3-87. A problem using this equation illustrates how to determine the characteristics of a transmission line.

Assume that the line shown in figure 3-23 is 1,000 feet long. A 100-foot (approximately 30.5 meter) section is measured to determine L and C. The section is found to have an inductance of 0.25 millihenry and a capacitance of 1000 picofarads. Find the characteristic impedance of the line and the velocity of the wave on the line. The characteristic impedance is—

$$Z_0 = \sqrt{LC}$$

$$Z_0 = \sqrt{\frac{0.25\text{x}10^{-3}}{1000\text{x}10^{-12}}}$$

$$Z_0 = \sqrt{0.25\text{x}10^{6}}$$

$$Z_0 = 0.5\text{x}10^{3}$$

$$Z_0 = 500\Omega$$

If any other unit length had been considered, the values of L and C would be different, but their ratio would remain the same as would the characteristic impedance.

The formula for T is:

$$T = \sqrt{LC}$$

$$T = \sqrt{0.25\text{x}10^{-3}\text{x}1000\text{x}10^{-12}}$$

$$T = \sqrt{0.25\text{x}10^{-12}}$$

$$T = 0.5\text{x}10^{-6}\ \text{second}$$

$$T = 0.5\ \text{microsecond}$$

The formula for the velocity of a wave is:

$$V = \frac{D}{T}$$

$$V = \frac{100\ \text{feet}}{0.5\text{x}10^{-6}\ \text{second}}$$

$$V = 200\text{x}10^{6}\ \text{feet/second}$$

$$V = 200{,}000{,}000\ \text{feet/second}$$

REFLECTIONS ON A TRANSMISSION LINE

3-88. Transmission line characteristics are based on an infinite line. A line cannot always be terminated in its characteristic impedance because it is sometimes operated as an open-ended line and at other times as a short-circuit at the receiving end. If the line is open-ended, it has a terminating impedance that is infinitely large. If a line is not terminated in characteristic impedance (Z_0), it is said to be finite.

3-89. When a line is not terminated in characteristic impedance, the incident energy is not absorbed but is returned along the only path available—the transmission line. Thus, the behavior of a finite line may be quite different from that of the infinite line.

Reflection of DC Voltage from an Open Circuit

3-90. The equivalent circuit of an open-ended transmission line is shown in figure 3-24, view A. Again, losses are to be considered as negligible, and L is lumped in one branch. Assume that (1) the battery in this circuit has an internal impedance equal to the characteristic impedance of the transmission line ($Z_i = Z_0$); (2) the capacitors in the line are not charged before the battery is connected; and (3) because the line is open-ended, the terminating impedance is infinitely large.

3-91. When the battery is connected to the sending end as shown in figure 3-24, view A, a negative voltage moves down the line. This voltage charges each capacitor, in turn, through the preceding inductor. Because Z_i equals Z_0, one-half the applied voltage will appear across the internal battery impedance, Z_i, and one-half across the impedance of the line, Z_0. Each capacitor is then charged to E/2 (view B). When the last capacitor in the line is charged, there is no voltage across the last inductor and current flow through the last inductor stops. With no current flow to maintain it, the magnetic field in the last inductor collapses and forces current to continue to flow in the same direction into the last capacitor. Because the direction of current has not changed, the capacitor charges in the same direction, thereby increasing the charge in the capacitor. Because the energy in the magnetic field equals the energy in the capacitor, the energy transfer to the capacitor doubles the voltage across the capacitor. The last capacitor is now charged to E volts and the current in the last inductor drops to zero.

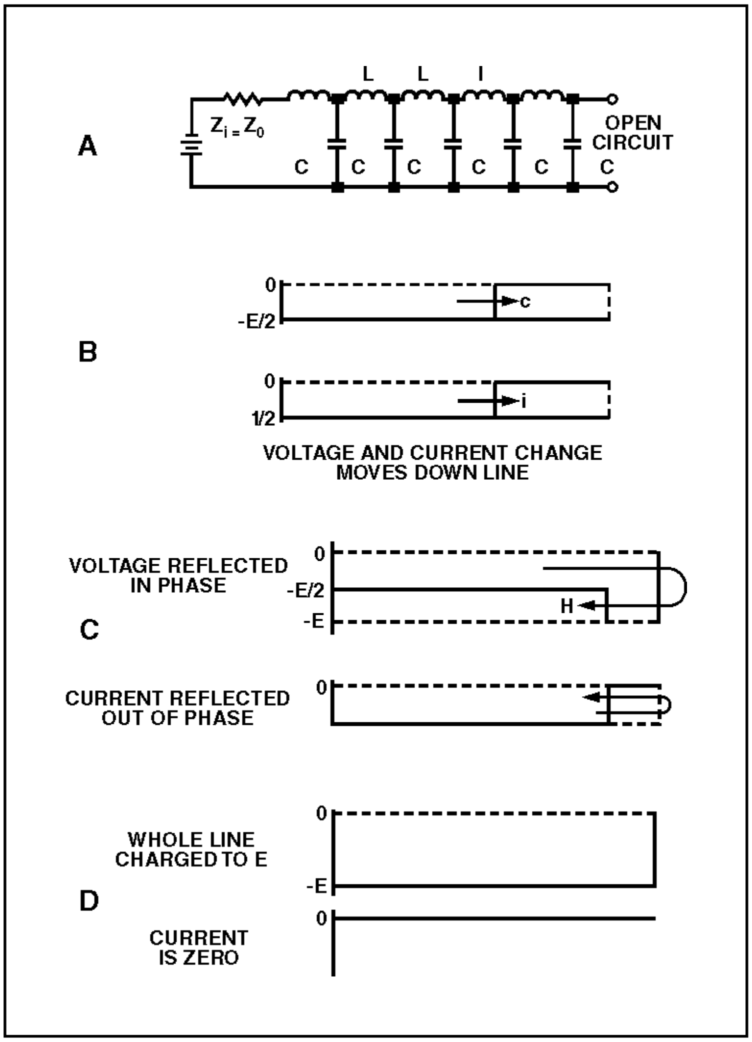


Figure 3-24. Reflection from an Open-Ended Line

3-92. At this point, the same process takes place with the next to the last inductor and capacitor. When the magnetic field about the inductor collapses, current continues to flow into the next to the last capacitor, charging it to E volts. This action continues backward down the line until the first capacitor has been fully charged to the applied voltage. This change of voltage, moving backward down the line, can be thought of in the following manner. The voltage, arriving at the end of the line, finds no place to go and returns to the sending end with the same polarity (figure 3-24, view C). Such action is called reflection.

3-93. When a reflection of voltage occurs on an open-ended line, the polarity is unchanged. The voltage change moves back to the source, charging each capacitor in turn until the first capacitor is charged to the source voltage and the action stops (figure 3-24, view D). As each capacitor is charged, current in each inductor drops to zero, effectively reflecting the current with the opposite polarity (view C). Reflected current of opposite polarity cancels the original current at each point, and the current drops to zero at that point.

When the last capacitor is charged, the current from the source stops flowing (view D).

3-94. Important facts to remember in the reflection of DC voltages in open-ended lines are—

- Voltage is reflected from an open end without change in polarity, amplitude, or shape.
- Current is reflected from an open end with opposite polarity and without change in amplitude or shape.

Reflection of DC Voltage from a Short Circuit

3-95. A short-circuited line affects voltage change differently than the way an open-circuited line affects it. The voltage across a perfect short circuit must be zero; therefore, no power can be absorbed in the short, and the energy is reflected toward the generator.

3-96. The initial circuit is shown in figure 3-25, view A. The initial voltage and current waves (view B) are the same as those given for an infinite line. In a short-circuited line the voltage change arrives at the last inductor in the same manner as the waves on an open-ended line. In this case, however, there is no capacitor to charge. The current through the final inductor produces a voltage with the polarity shown in view C. When the field collapses, the inductor acts as a battery and forces current through the capacitor in the opposite direction, causing it to discharge (view D). Because the amount of energy stored in the magnetic field is the same as that in the capacitor, the capacitor discharges to zero.

3-97. Now there is no voltage to maintain the current through the next to the last inductor. Therefore, this inductor discharges the next to the last capacitor.

3-98. As each capacitor is discharged to zero, the next inductor effectively becomes a new source of voltage. The amplitude of each of these voltages is equal to E/2, but the polarity is the opposite of the battery at the input end of the line. The collapsing field around each inductor, in turn, produces a voltage that forces the current to continue flowing in the same direction, adding to the current from the source to make it 2I. This action continues until all the capacitors are discharged (view E).

3-99. Reflected waves from a short-circuited transmission line are characterized as follows:

- The reflected voltage has the opposite polarity but the same amplitude as the incident wave.
- The reflected current has the same polarity and the same amplitude as the incident current.

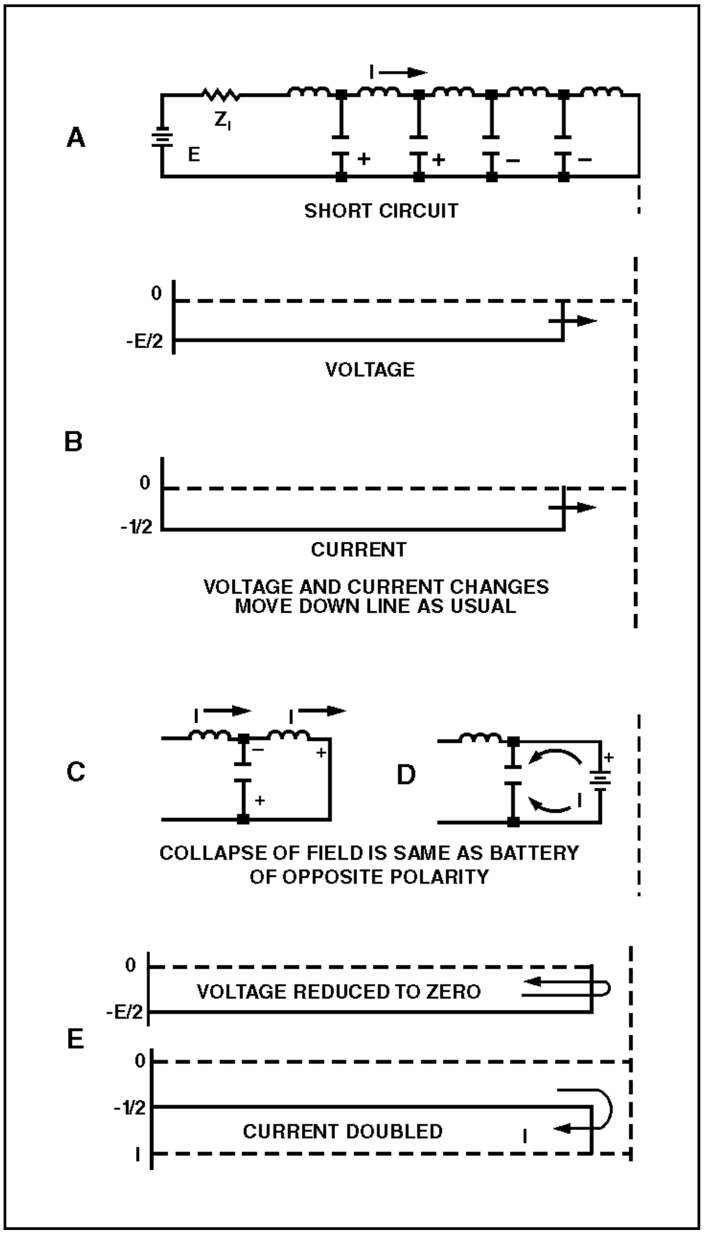


Figure 3-25. Reflection from a Short-Circuited Line

Reflection of AC Voltage from an Open Circuit

3-100. In most cases where RF lines are used, the voltages applied to the sending end are AC voltages. The action at the receiving end of the line is exactly the same for AC as for DC. In the open-ended line, as shown in figure 3-26, view A, the generated AC voltage is distributed along the line, shown in view B. This voltage is distributed in such a way that as each instantaneous voltage arrives at the end, it is reflected with the same polarity and amplitude. When AC is used, this reflection is in phase. Each of the reflected voltages travels back along the line until it reaches the generator. If the generator impedance is the same as the line impedance, energy arriving at the generator is absorbed and not reflected again. Now two voltages are on the line.

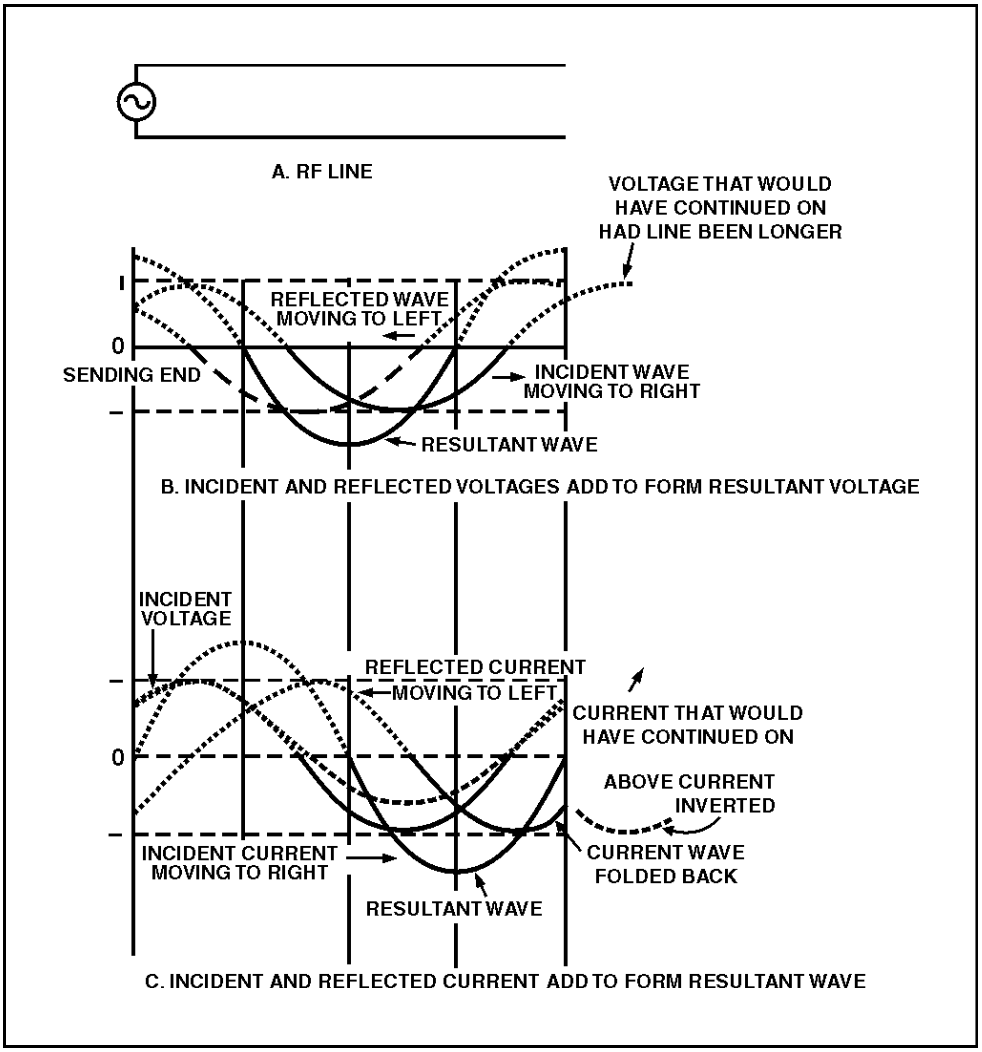


Figure 3-26. Formation of Standing Waves

3-101. View B of figure 3-26 shows how two waves of the same frequency and amplitude moving in opposite directions on the same conductor will combine to form a resultant wave. The small solid line is moving steadily from left to right and is the incident wave (from the source). The broken-line waveform is moving from right to left and is the reflected wave. The resultant waveform, the heavy line, is found by algebraically adding instantaneous values of the two waveforms. The resultant waveform has an instantaneous peak amplitude that is equal to the sum of the peak amplitudes of the incident and reflected waves. Because most indicating instruments are unable to separate these voltages, they show the vector sum. An oscilloscope is usually used to study the instantaneous voltages on RF lines.

3-102. Because two waves of voltage are moving on the line, you need to know how to distinguish between the two. The voltages moving toward the receiving end are called incident voltages, and the whole waveshape is called the incident wave. The wave moving back to the sending end after reflection is called the reflected wave. The resultant voltage curve (view B of figure 3-26) shows that the voltage is maximum at the end of the line, a condition that occurs across an open circuit.

3-103. Another step in investigating the open-circuited RF line is to see how the current waves act. The incident current wave is the solid line in figure 3-26, view C. The voltage is represented by the dotted line. The current is in phase with the voltage while traveling toward the receiving end. At the end of the line, the current is reflected in the opposite polarity; that is, it is shifted 180 degrees in phase, but its amplitude remains the same. Dashed lines show the reflected wave of current in view C. The heavy-line curve represents the sum of the two instantaneous currents and is the resultant wave. Notice that current is zero at the end of the line. This is reasonable, because there can be no current flow through an open circuit.

3-104. Views B and C of figure 3-26 show the voltage and current distribution along a transmission line at a point about one-eighth wavelength after a maximum voltage or current reaches the end of the line. Because the instantaneous values are continuously changing during the generation of a complete cycle, a large number of these pictures are required to show the many different relationships.

3-105. Figure 3-27 shows the incident and reflected waveshapes at several different times. The diagrams in the left column of figure 3-27 (representing voltage) show the incident wave and its reflection without change in polarity. In figure 3-27, waveform (1), the incident wave and the reflected wave are added algebraically to produce the resultant wave indicated by the heavy line. In waveform (2), a zero point preceding the negative-going cycle of the incident wave is at the end of the line. The reflected wave and incident wave are 180 degrees out of phase at all points. (The reflected wave is the positive cycle that just preceded the negative cycle now approaching the end of the line.) The resultant of the incident and reflected waves is zero at all points along the line. In waveform (3), the waves have moved 1/8 wavelength along the line; the incident wave has moved 45 degrees to the right, and the reflected wave has moved 45 degrees to the left. The resultant voltage, shown by the heavy line, has a maximum negative at the end of the line and a maximum positive 1/2 wavelength from the end of the line.

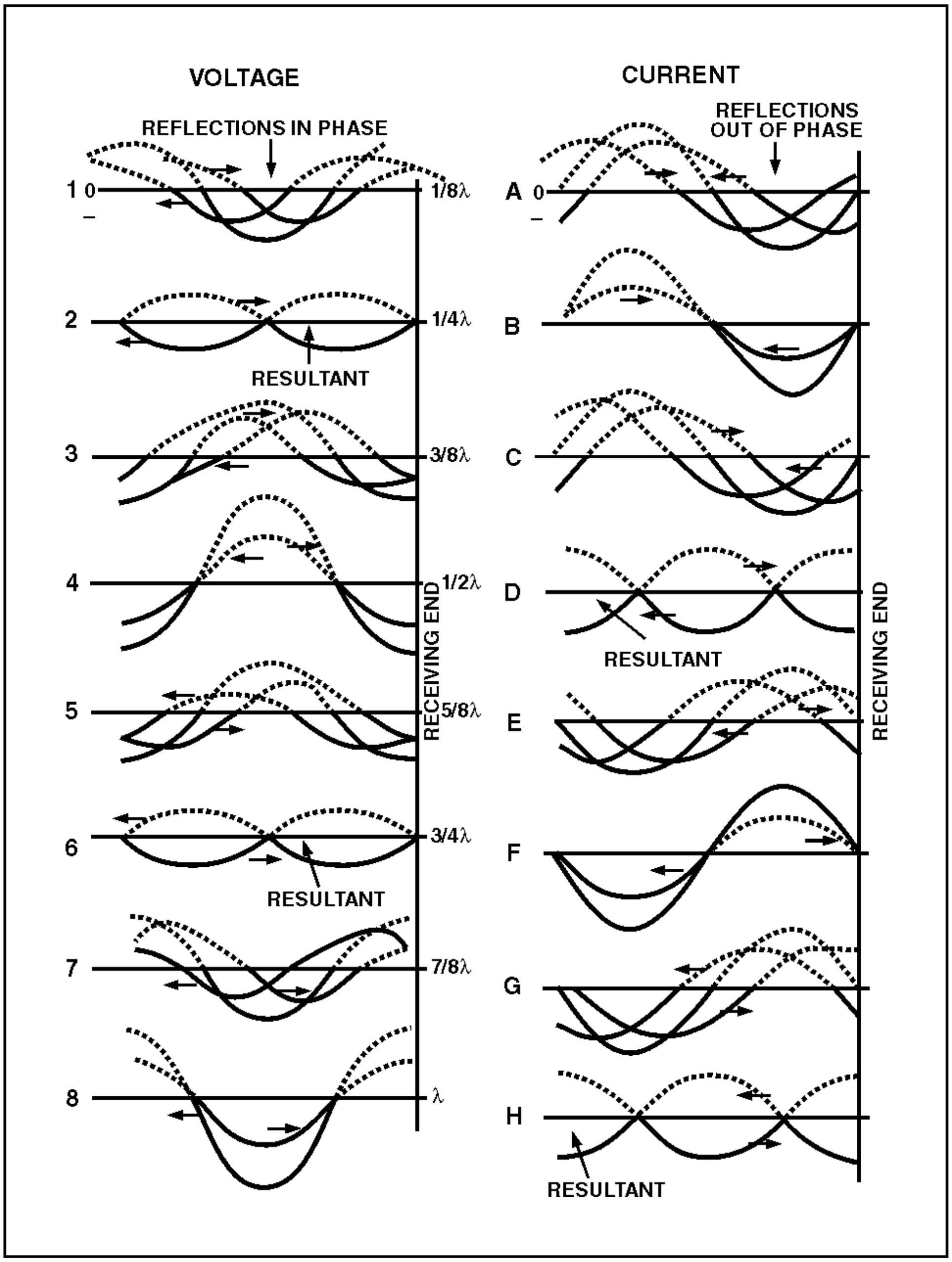


Figure 3-27. Instantaneous Values of Incident and Reflected Waves on an Open-Ended Line

3-106. In waveform (4) of figure 3-27, the incident wave is at a maximum negative value at the end of the line. The wave has moved another 45 degrees to the right from the wave in the preceding illustration. The reflected wave has also moved 45 degrees, but to the left. The reflected wave is in phase with the incident wave. The resultant of these two waves, shown by the dark line, again has a negative maximum at the end of the line and a positive maximum 1/2λ from the end of the line. Notice that these maxima have a greater amplitude than those in waveform (3).

3-107. In waveform (5) of figure 3-27, the incident wave has moved another 45 degrees to the right and the reflected wave 45 degrees to the left. The resultant again is maximum negative at the end and positive maximum 1/2 wavelength from the end. The maxima are lower than those in waveform (4). In waveform (6), the incident and reflected wave have moved another 1/8λ. The two waves again are 180 degrees out of phase, giving a resultant wave with no amplitude. The incident and reflected waves continue moving in opposite directions, adding to produce the resultant waveshapes shown in waveforms (7) and (8). Notice that the maximum voltage in each resultant wave is at the end and 1/2λ from the end.

3-108. Study each part of figure 3-27 carefully and you will get a clear picture of how the resultant waveforms of voltage are produced. You will also see that the resultant voltage wave on an open-ended line is always zero at 1/4λ and 3/4λ from the end of the transmission line. Because the zero and maximum points are always in the same place, the resultant of the incident and the reflected wave is called a standing wave of voltage.

3-109. The right-hand column in figure 3-27 shows the current waveshapes on the open-ended line. Because the current is reflected out of phase at an open end, the resultant waveshapes differ from those for voltage. The two out-of-phase components always cancel at the end of the transmission line, so the resultant is always zero at that point. If you check all the resultant waveshapes shown in the right-hand column of figure 3-27, you will see that a zero point always occurs at the end and at a point 1/2λ from the end. Maximum voltages occur 1/4λ and 3/4λ from the end.

3-110. When an AC meter is used to measure the voltages and currents along a line, the polarity is not indicated. If you plot all the current and voltage readings along the length of the line, you will get curves like the ones shown in figure 3-28. Notice that all are positive. These curves are the conventional method of showing current and voltage standing waves on RF lines.

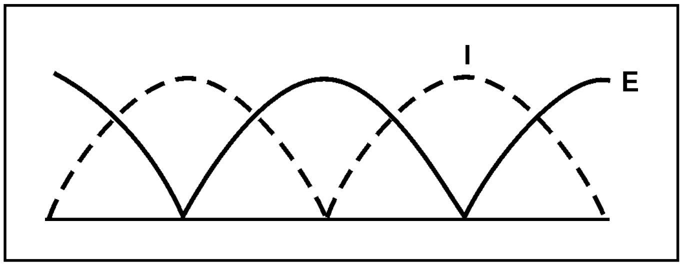


Figure 3-28. Conventional Picture of Standing Waves

3-111. When an RF line is terminated in a short circuit, reflection is complete, but the effect on voltage and current differs from that in an open-ended line. Voltage is reflected in opposite phase, while current is reflected in phase. Again refer to the series of pictures shown in figure 3-27. However, this time the left column represents current, because it shows reflection in phase; and the right column of pictures now represents the voltage changes on the shorted line, because it shows reflection out of phase.

3-112. The composite diagram in figure 3-29 shows all resultant curves on a full-wavelength section of line over a complete cycle. Notice that the amplitude of the voltage varies between zero and maximum in both directions at the center and at both ends as well, but one-fourth of the distance from each end the voltage is always zero. The resultant waveshape is referred to as a standing wave of voltage. Standing waves, then, are caused by reflections, which occur only when the line is not terminated in its characteristic impedance.

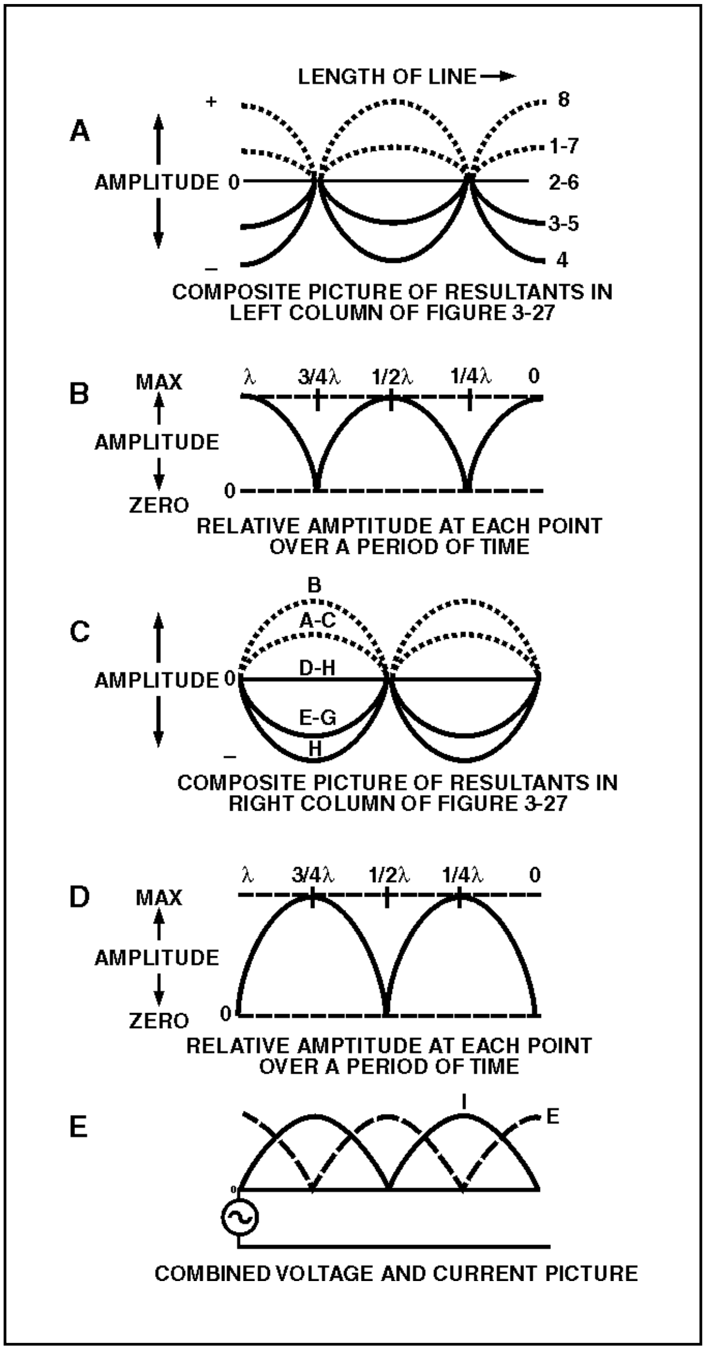


Figure 3-29. Composite Results of Instantaneous Waves

3-113. The voltage at the center and the ends varies at a sinusoidal rate between the limits shown. At the one-fourth and three-fourths points, the voltage is always zero. A continuous series of diagrams such as these is difficult to see with conventional test equipment, which reads the effective or average voltage over several cycles. The curve of amplitude over the length of line for several cycles is shown in figure 3-29, view B. A meter will read zero at the points shown and will show a maximum voltage at the center, no matter how many cycles pass.

3-114. As shown in figure 3-29, view D, the amplitude varies along the length of the line. In this case it is zero at the end and center but maximum at the one-fourth and three-fourths points. The entire diagram of the open-ended line conditions is shown in view E. The standing waves of voltage and current appear together. Observe that one is maximum when the other is minimum. The current and voltage standing waves are one-quarter cycle, or 90 degrees, out of phase with one another.

Reflection of AC Voltage from a Short Circuit

3-115. Reflection is complete when an RF line is terminated in a short circuit, but the effect on voltage and current differs from the effect obtained in an open-ended line. Voltage is reflected in opposite phase, while current is reflected in phase. Again look at the series of diagrams in figure 3-27. The left column represents current, and the right column shows voltage changes on the shorted line. The standard representation of standing waves on a shorted line is shown in figure 3-30; the voltage is a solid line, and the current is a dashed line. The voltage is zero at the end and center (1/2λ) and maximum at the 1/4λ and 3/4λ points, while the current is maximum at the end and center and minimum at the 1/4λ and 3/4λ points.

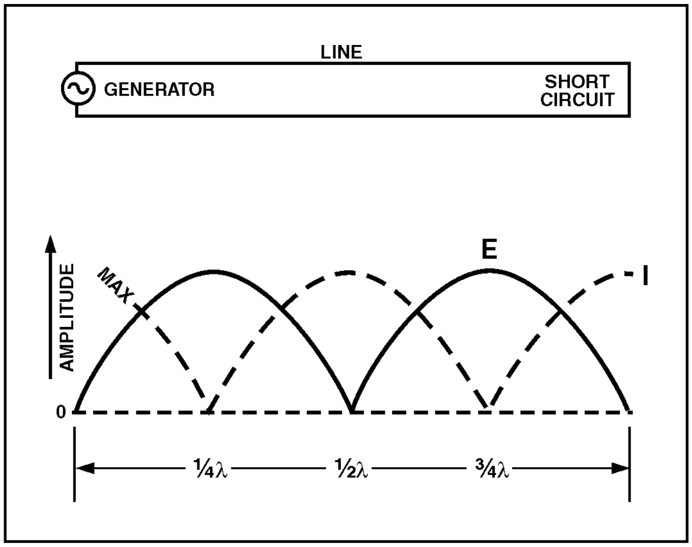


Figure 3-30. Standing Waves on a Shorted Line

3-116. As previously discussed, there are several differences between open and shorted lines in the voltage and current waves on transmission lines. Basic differences also appear in the standing-wave patterns for open and shorted lines. You can see these differences by comparing figure 3-29, view E and figure 3-30. Notice that the current and voltage standing waves are shifted 90 degrees with respect to the termination. At the open end of a line, voltage is maximum (zero if there are no losses in the line). At a short circuit, current is maximum and voltage is minimum.

TERMINATING A TRANSMISSION LINE

3-117. A transmission line is either nonresonant or resonant. A nonresonant line is a line that has no standing waves of current and voltage. A resonant line is a line that has standing waves of current and voltage.

Nonresonant Lines

3-118. A nonresonant line is either infinitely long or terminated in its characteristic impedance. Because no reflections occur, all the energy traveling down the line is absorbed by the load that terminates the line. Because no standing waves are present, this type of line is sometimes spoken of as a flat line. In addition, because the load impedance of such a line is equal to Z_0, no special tuning devices are required to effect a maximum power transfer; hence, the line is also called an untuned line.

Resonant Lines

3-119. A resonant line has a finite length and is not terminated in its characteristic impedance. Therefore reflections of energy do occur. The load impedance is different from the Z_0 of the line; therefore, the input impedance may not be purely resistive but may have reactive components. Tuning devices are used to eliminate the reactance and to bring about maximum power transfer from the source to the line. Therefore, a resonant line is sometimes called a tuned line. The line also may be used for a resonant or tuned circuit.

3-120. A resonant line is sometimes said to be resonant at an applied frequency. This means that at one frequency the line acts as a resonant circuit. It may act either as a high-resistive circuit (parallel resonant) or as a low-resistive circuit (series resonant). The line may be made to act in this manner by either open- or short-circuiting it at the output end and cutting it to some multiple of a quarter-wavelength.

3-121. At the points of voltage maxima and minima on a short-circuited or open-circuited line, the line impedance is resistive. On a short-circuited line, each point at an odd number of quarter-wavelengths from the receiving end has a high impedance (figure 3-31, view A). If the frequency of the applied voltage to the line is varied, this impedance decreases as the effective length of the line changes. This variation is exactly the same as the change in the impedance of a parallel-resonant circuit when the applied frequency is varied.

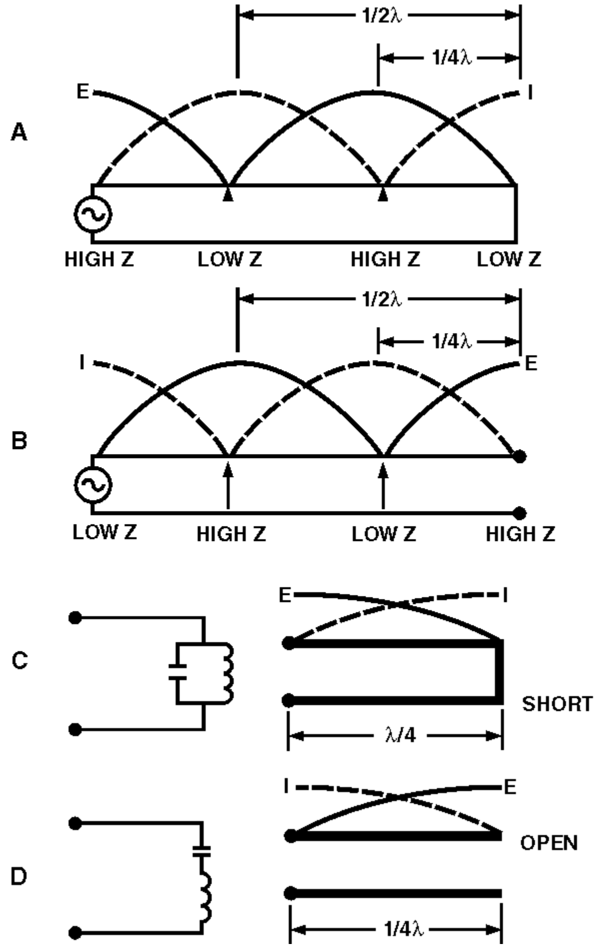


Figure 3-31. Sending-End Impedance of Various Lengths and Terminations

3-122. At all even numbered quarter-wavelength points from the short circuit, the impedance is extremely low. When the frequency of the voltage applied to the line is varied, the impedance at these points increases just as the impedance of a series-resonant circuit varies when the frequency applied to it is changed. The same is true for an open-ended line (figure 3-31, view B), except that the points of high and low impedance are reversed.

3-123. At this point let us review some of the characteristics of resonant circuits so we can see how resonant line sections may be used in place of LC circuits.

3-124. A parallel-resonant circuit has the following characteristics:

- At resonance, the impedance appears as a very high resistance. A loss-free circuit has infinite impedance (an open circuit). Other than at resonance, the impedance decreases rapidly.
- If the circuit is resonant at a point above the generator frequency (the generator frequency is too low), more current flows through the coil than through the capacitor. This happens because X_L decreases with a decrease in frequency, but X_C increases.

3-125. A series-resonant circuit has these characteristics:

- At resonance, the impedance appears as a very low resistance. A loss-free circuit has zero impedance (a short circuit). Other than at resonance, the impedance increases rapidly.
- If the circuit is resonant at a point above the generator frequency (the generator frequency is too low), then X_C is larger than X_L and the circuit acts capacitively.
- If the circuit is resonant at a point below the generator frequency (the generator frequency is too high), then X_L is larger than X_C and the circuit acts inductively.

3-126. Because the impedance a generator sees at the quarter-wave point in a shorted line is that of a parallel-resonant circuit, a shorted quarter-wave-length of line may be used as a parallel-resonant circuit (figure 3-31, view C). An open quarter-wavelength of line may be used as a series-resonant circuit (view D). The Q of such a resonant line is much greater than can be obtained with lumped capacitance and inductance.

Impedance for Various Lengths of Open Lines

3-127. In figure 3-32, the impedance (Z) the generator sees for various lengths of line is shown at the top. The curves above the letters of various heights show the relative value of the impedances presented to the generator for the various line lengths. The circuit symbols indicate the equivalent electrical circuits for the transmission lines at each particular length. The standing waves of voltage and current are shown on each length of line.

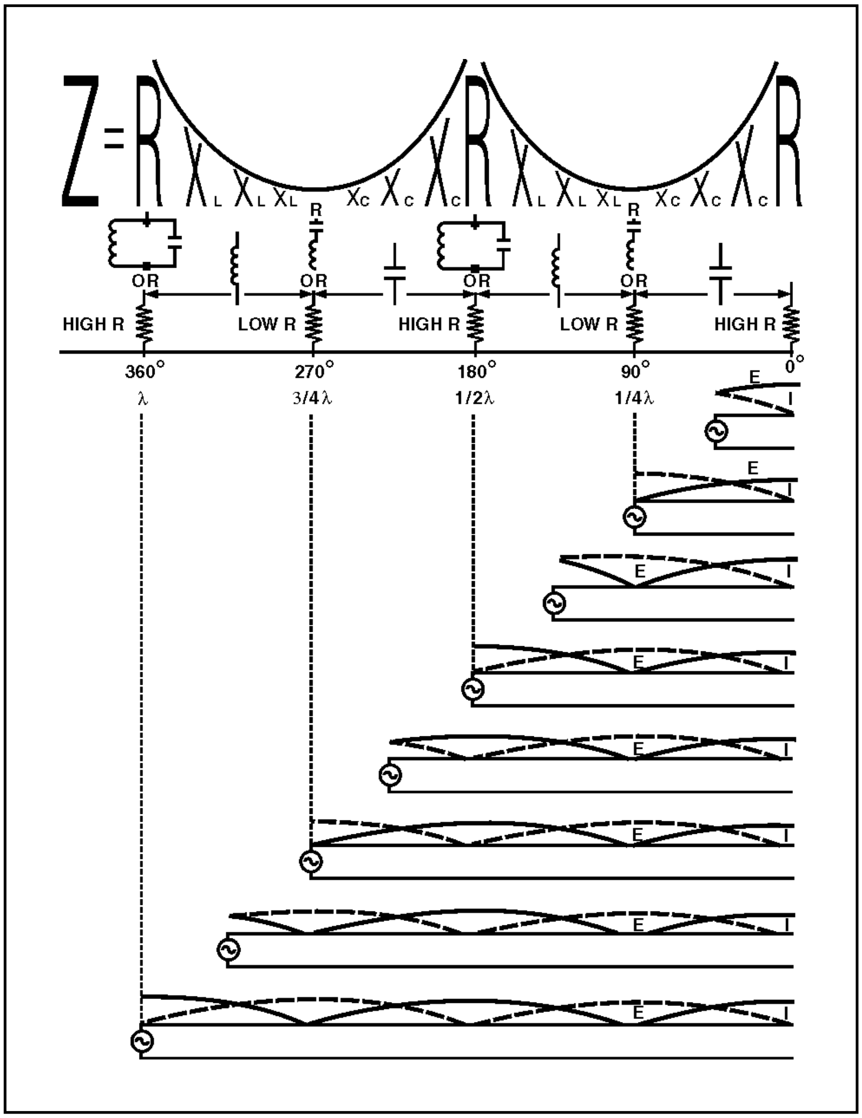


Figure 3-32. Voltage, Current, and Impedance on Open Line

3-128. At all odd quarter-wave points (1/4λ, 3/4λ, etc.), the voltage is minimum, the current is maximum, and the impedance is minimum. Thus, at all odd quarter-wave points, the open-ended transmission line acts as a series-resonant circuit. The impedance is equivalent to a very low resistance, prevented from being zero only by small circuit losses.

3-129. At all even quarter-wave points (1/2λ, 1λ, 3/2λ, etc.), the voltage is maximum, the current is minimum, and the impedance is maximum. Comparison of the line with an LC resonant circuit shows that at an even number of quarter-wavelengths, an open line acts as a parallel-resonant circuit. The impedance is therefore an extremely high resistance.

3-130. In addition, resonant open lines may also act as nearly pure capacitances or inductances. The illustration shows that an open line less than a quarter-wavelength long acts as a capacitance. Also, it acts as an inductance from 1/4 to 1/2 wavelength, as a capacitance from 1/2 to 3/4 wavelength, and as an inductance from 3/4 to 1 wavelength, and so forth. A number of open transmission lines, with their equivalent circuits, are shown in the illustration.

Impedance of Various Lengths of Shorted Lines

3-131. Refer to figure 3-33 in the following discussion of the shorted line. At the odd quarter-wavelength points, the voltage is high, the current is low, and the impedance is high. Because these conditions are similar to those found in a parallel-resonant circuit, the shorted transmission line acts as a parallel-resonant circuit at these lengths.

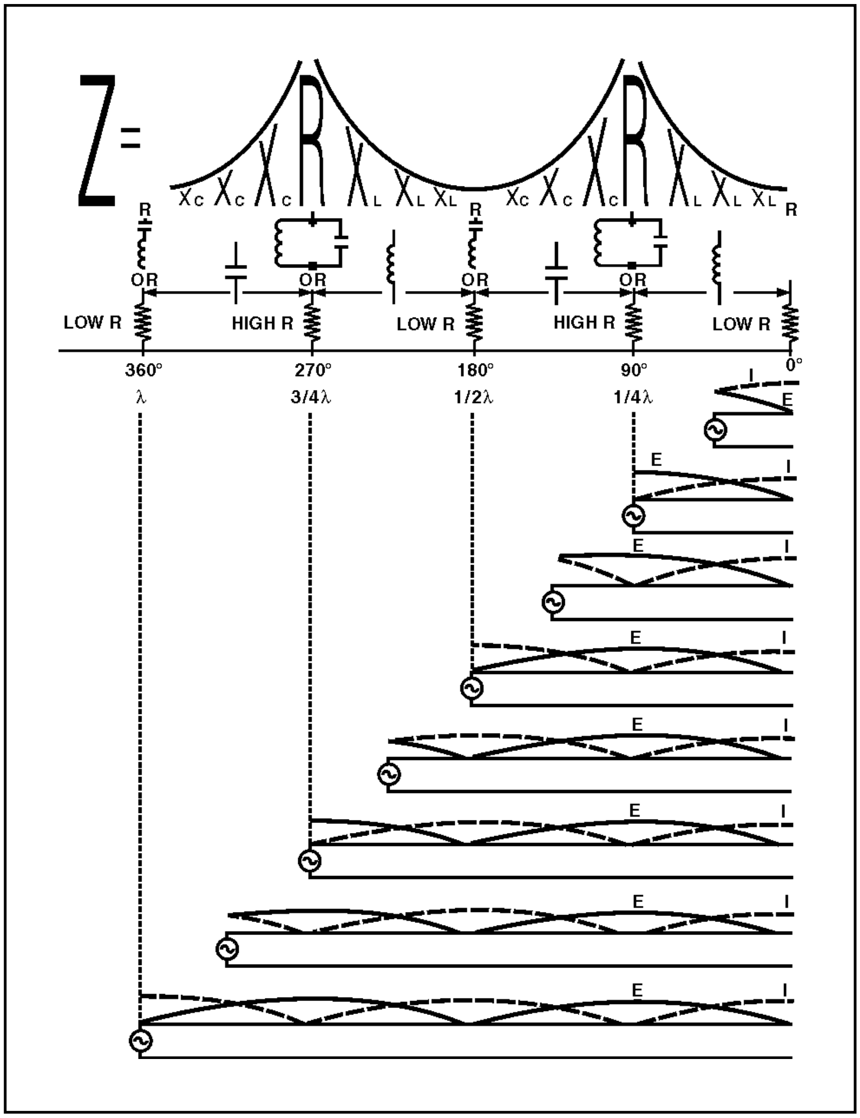


Figure 3-33. Voltage, Current, and Impedance on Shorted Line

3-132. At the even quarter-wave points in figure 3-33, voltage is minimum, current is maximum, and impedance is minimum. Because these characteristics are similar to those of a series-resonant LC circuit, a shorted transmission line whose length is an even number of quarter-wavelengths acts as a series-resonant circuit.

3-133. Resonant shorted lines, like open-end lines, also may act as pure capacitances or inductances. The illustration shows that a shorted line less than 1/4 wavelength long acts as an inductance. A shorted line with a length of from 1/4 to 1/2 wavelength acts as a capacitance. From 1/2 to 3/4 wavelength, the line acts as an inductance; and from 3/4 to 1 wavelength, it acts as a capacitance, and so on. The equivalent circuits of shorted lines of various lengths are shown in the illustration. Thus, properly chosen line segments may be used as parallel-resonant, series-resonant, inductive, or capacitive circuits.

EFFECT OF TERMINATION ON STANDING WAVES

3-134. There is a large variety of terminations for RF lines. Each type of termination has a characteristic effect on the standing waves on the line. From the nature of the standing waves, you can determine the type of termination that produces the waves.

TERMINATION IN Z_0

3-135. Termination in Z_0 (characteristic impedance) will cause a constant reading on an AC meter when it is moved along the length of the line. As illustrated in figure 3-34, view A, the curve—provided there are no losses in the line—will be a straight line. If there are losses in the line, the amplitude of the voltage and current will diminish as they move down the line (view B). The losses are due to DC resistance in the line itself.

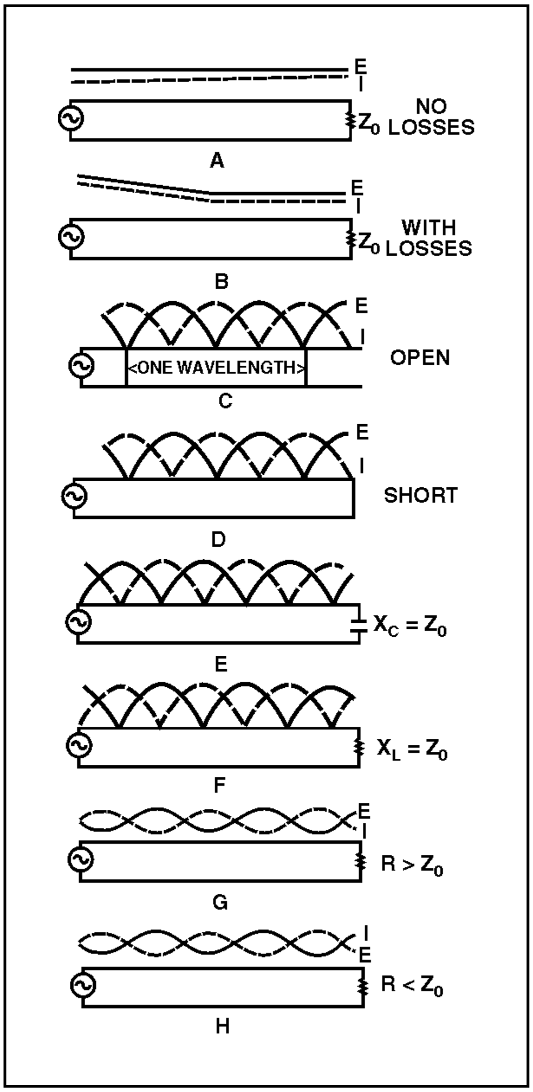


Figure 3-34. Effects of Various Terminations on Standing Waves

TERMINATION IN AN OPEN CIRCUIT

3-136. In an open-circuited RF line (figure 3-34, view C), the voltage is maximum at the end, but the current is minimum. The distance between two adjacent zero current points is 1/2λ, and the distance between alternate zero current points is 1λ. The voltage is zero at a distance of 1/4λ from the end of the line. This is true at any frequency. A voltage peak occurs at the end of the line, at 1/2λ from the end, and at each 1/2λ thereafter.

TERMINATION IN A SHORT CIRCUIT

3-137. On the line terminated in a short circuit, shown in figure 3-34, view D, the voltage is zero at the end and maximum at 1/4λ from the end. The current is maximum at the end, zero at 1/4λ from the end, and alternately maximum and zero every 1/4λ thereafter.

TERMINATION IN CAPACITANCE

3-138. When a line is terminated in capacitance, the capacitor does not absorb energy, but returns all of the energy to the circuit. This means there is 100 percent reflection. The current and voltage relationships are somewhat more involved than in previous types of termination. For this explanation, assume that the capacitive reactance is equal to the characteristic impedance (Z_0) of the line. Current and voltage are in phase when they arrive at the end of the line, but in flowing through the capacitor and the characteristic impedance connected in series, they shift in phase relationship. Current and voltage arrive in phase and leave out of phase. This results in the standing-wave configuration shown in figure 3-34, view E. The standing wave of voltage is minimum at a distance of exactly 1/8λ from the end. If the capacitive reactance is greater than Z_0 (smaller capacitance), the termination looks more like an open circuit; the voltage minimum moves away from the end. If the capacitive reactance is smaller than Z_0, the minimum moves toward the end.

TERMINATION IN INDUCTANCE

3-139. When the line is terminated in an inductance, both the current and voltage shift in phase as they arrive at the end of the line. When X_L is equal to Z_0, the resulting standing waves are as shown in figure 3-34, view F. The current minimum is located 1/8λ from the end of the line. When the inductive reactance is increased, the standing waves appear closer to the end. When the inductive reactance is decreased, the standing waves move away from the end of the line.

TERMINATION IN A RESISTANCE NOT EQUAL TO THE CHARACTERISTIC IMPEDANCE (Z_0)

3-140. Whenever the termination is not equal to Z_0, reflections occur on the line. For example, if the terminating element contains resistance, it absorbs some energy, but if the resistive element does not equal the Z_0 of the line, some of the energy is reflected. The amount of voltage reflected may be found by using the equation:

$$E_R = E_i\left(\frac{R_L - Z_O}{R_L + Z_O}\right)$$

Where:

E_R = the reflected voltage

E_i = the incident voltage

R_L = the terminating resistance

Z_0= the characteristic impedance of the line

3-141. If you try different values of RL in the preceding equation, you will find that the reflected voltage is equal to the incident voltage only when RL equals 0 or is infinitely large. When RL equals Z_0, no reflected voltage occurs. When RL is greater than Z_0, ER is positive, but less than Ei. As RL increases and approaches an infinite value, ER increases and approaches Ei in value. When RL is smaller than Z_0, ER has a negative value. This means that the reflected voltage is of opposite polarity to the incident wave at the termination of the line. As RL approaches zero, ER approaches Ei in value. The smaller the value of ER, the smaller is the peak amplitude of the standing waves and the higher are the minimum values.

TERMINATION IN A RESISTANCE GREATER THAN Z_0

3-142. When RL is greater than Z_0, the end of the line is somewhat like an open circuit; that is, standing waves appear on the line. The voltage maximum appears at the end of the line and also at half-wave intervals back from the end. The current is minimum (not zero) at the end of the line and maximum at the odd quarter-wave points. Because part of the power in the incident wave is consumed by the load resistance, the minimum voltage and current are less than for the standing waves on an open-ended line. Figure 3-34, view G, illustrates the standing waves for this condition.

TERMINATION IN A RESISTANCE LESS THAN Z_0

3-143. When R_L is less than Z_0, the termination appears as a short circuit. The standing waves are shown in figure 3-34, view H. Notice that the line terminates in a current loop (peak) and a voltage node (minimum). The values of the maximum and minimum voltage and current approach those for a shorted line as the value of RL approaches zero.

3-144. A line does not have to be any particular length to produce standing waves; however, it cannot be an infinite line. Voltage and current must be reflected to produce standing waves. For reflection to occur, a line must not be terminated in its characteristic impedance. Reflection occurs on lines terminated in opens, shorts, capacitances, and inductances, because the load absorbs no energy. If the line is terminated in a resistance not equal to the characteristic impedance of the line, some energy will be absorbed and the rest will be reflected.

3-145. The voltage and current relationships for open-ended and shorted lines are opposite to each other, as shown in figure 3-34, views C and D. The points of maximum and minimum voltage and current are determined from the output end of the line, because reflection always begins at that end.

STANDING-WAVE RATIO

3-146. The measurement of standing waves on a transmission line yields information about equipment operating conditions. Maximum power is absorbed by the load when $Z_L = Z_0$. If a line has no standing waves, the termination for that line is correct and maximum power transfer takes place.

3-147. You have probably noticed that the variation of standing waves shows how near the RF line is to being terminated in Z_0. A wide variation in voltage along the length means a termination far from Z_0. A small variation means termination near Z_0. Therefore, the ratio of the maximum to the minimum is a measure of the perfection of the termination of a line. This ratio is called the standing-wave ratio (SWR) and is always expressed in whole numbers. For example, a ratio of 1:1 describes a line terminated in its characteristic impedance (Z_0).

Voltage Standing-Wave Ratio

3-148. The ratio of maximum voltage to minimum voltage on a line is called the voltage standing-wave ratio (VSWR). Therefore—

$$\text{VSWR} = \frac{E_{max}}{E_{min}}$$

3-149. The vertical lines in the formula indicate that the enclosed quantities are absolute and that the two values are taken without regard to polarity. Depending on the nature of the standing waves, the numerical value of VSWR ranges from a value of 1 ($Z_L = Z_0$, no standing waves) to an infinite value for theoretically complete reflection. Because there is always a small loss on a line, the minimum voltage is never zero and the VSWR is always some finite value. However, if the VSWR is to be a useful quantity, the power losses along the line must be small in comparison to the transmitted power.

Power Standing-Wave Ratio

3-150. The square of the voltage standing-wave ratio is called the power standing-wave ratio (PSWR). Therefore—

$$\text{PSWR} = \frac{P_{max}}{P_{min}}$$

3-151. This ratio is useful because the instruments used to detect standing waves react to the square of the voltage. Because power is proportional to the square of the voltage, the ratio of the square of the maximum and minimum voltages is called the PSWR. In a sense, the name is misleading because the power along a transmission line does not vary.

Current Standing-Wave Ratio

3-152. The ratio of maximum to minimum current along a transmission line is called current standing-wave ratio (ISWR). Therefore—

$$\text{ISWR} = \frac{I_{max}}{I_{min}}$$

3-153. This ratio is the same as that for voltages. It can be used where measurements are made with loops that sample the magnetic field along a line. It gives the same results as VSWR measurements.

SUMMARY

This chapter has presented information on the characteristics of transmission lines. The information that follows summarizes the important points of this chapter.

Transmission lines are devices for guiding electrical energy from one point to another.

Input impedance is the ratio of voltage to current at the input end of a transmission line.

Output impedance is the ratio of voltage to current at the output end of the line.

Two-wire open lines are parallel lines and have uses such as power lines, rural telephone lines, and telegraph lines. This type of line has high radiation losses and is subject to noise pickup.

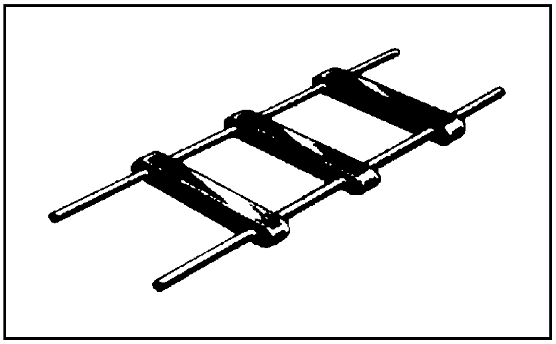


Figure 3-Sum 1. Two-Wire Open Line

The two-wire ribbon (twin lead) has parallel lines and is most often used to connect televisions to their antennas.

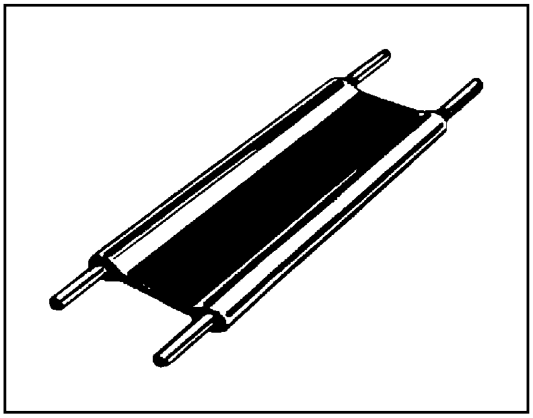


Figure 3-Sum 2. Two-Wire Ribbon Type Line

A twisted pair consists of two insulated wires twisted together. This line has high insulation loss.

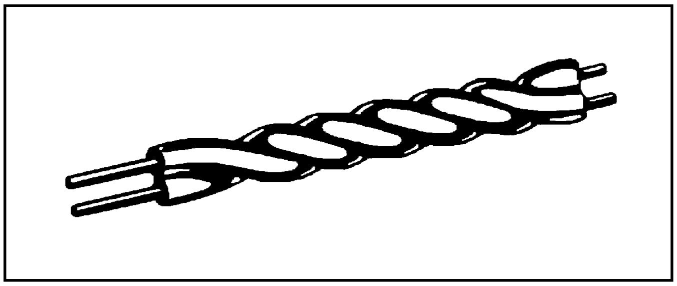


Figure 3-Sum 3. Twisted Pair

A shielded pair has parallel conductors separated by a solid dielectric and surrounded by copper braided tubing. The conductors are balanced to ground.

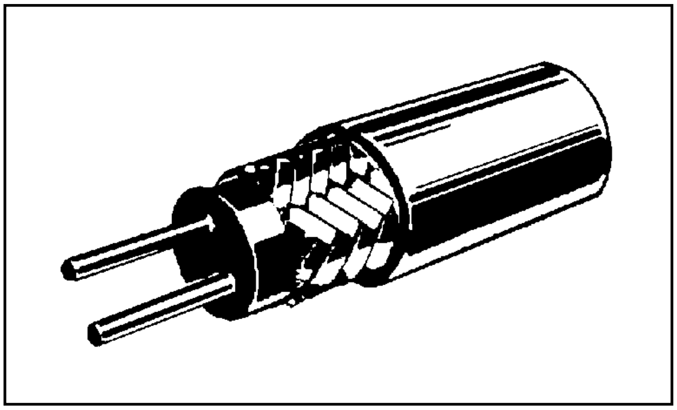


Figure 3-Sum 4. Shielded Pair

Rigid coaxial line contains two concentric conductors insulated from each other by spacers. Some rigid coaxial lines are pressurized with an inert gas to prevent moisture from entering. High-frequency losses are less than with other lines.

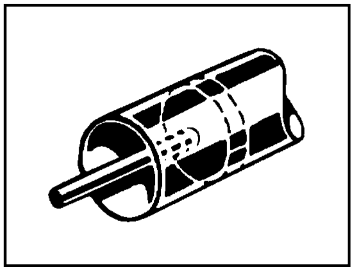


Figure 3-Sum 5. Rigid (Air) Coaxial Line

Flexible coaxial lines consist of a flexible inner conductor and a concentric outer conductor of metal braid. A continuous insulating material separates the two.

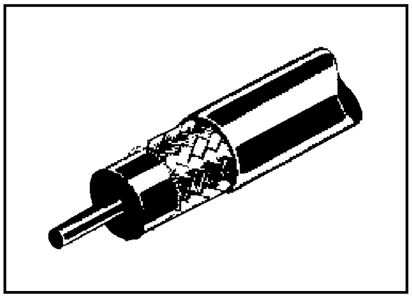


Figure 3-Sum 6. Flexible (Solid) Coaxial Lines

Waveguides are hollow metal tubes used to transfer energy from one point to another. The energy travels slower in a waveguide than in free space.

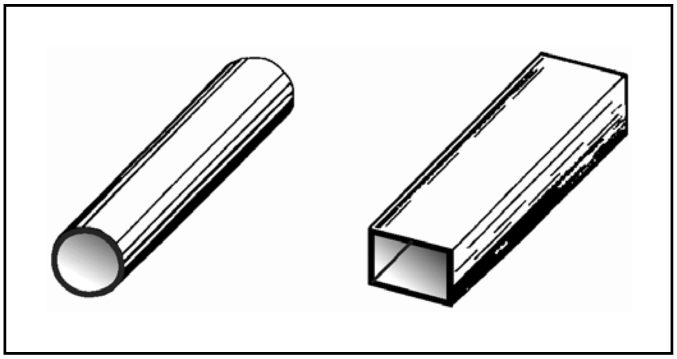


Figure 3-Sum 7. Waveguides

Copper losses can result from power (I2R) loss, in the form of heat, or skin effect. These losses decrease the conductivity of a line.

Dielectric losses are caused by the heating of the dielectric material between conductors, taking power from the source.

Radiation and induction losses are caused by part of the electromagnetic fields of a conductor being dissipated into space or nearby objects.

A transmission line is either electrically long or short if its physical length is not equal to 1/4λ for the frequency it is to carry.

Lumped constants are theoretical properties (inductance, resistance, and capacitance) of a transmission line that are lumped into a single component.

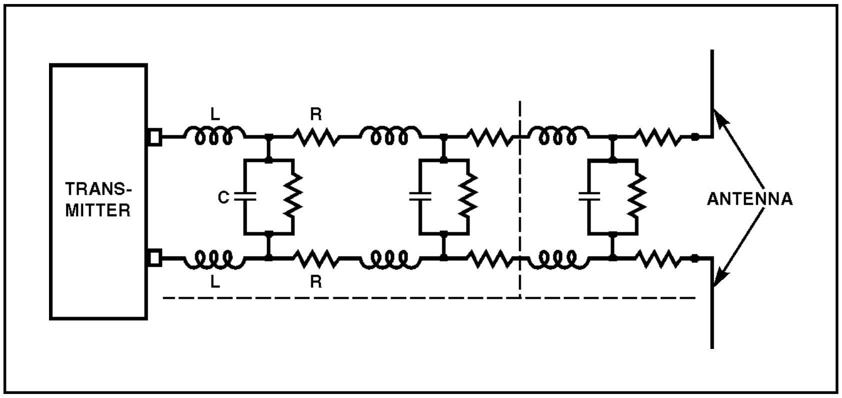


Figure 3-Sum 8. Equivalent Circuit of a Two-Wire Transmission Line

Distributed constants are constants of inductance, capacitance, and resistance that are distributed along the transmission line.

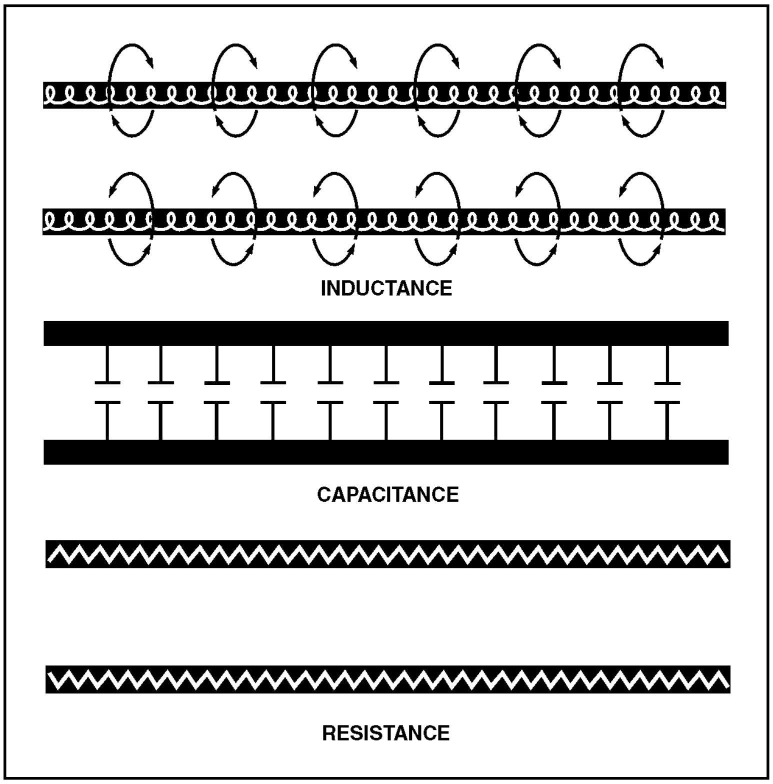


Figure 3-Sum 9. Distributed Constants

Leakage current flows between the wires of a transmission line through the dielectric. The dielectric acts as a resistor.

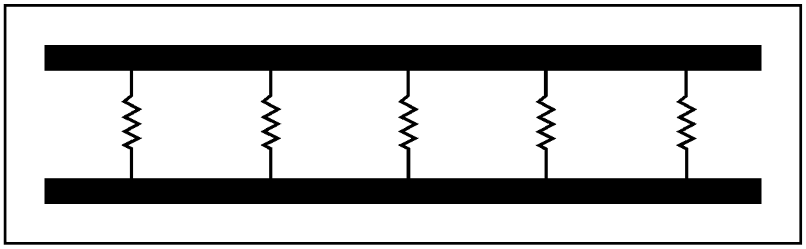


Figure 3-Sum 10. Leakage in a Transmission Line

An electromagnetic field exists along a transmission line when current flows through it.

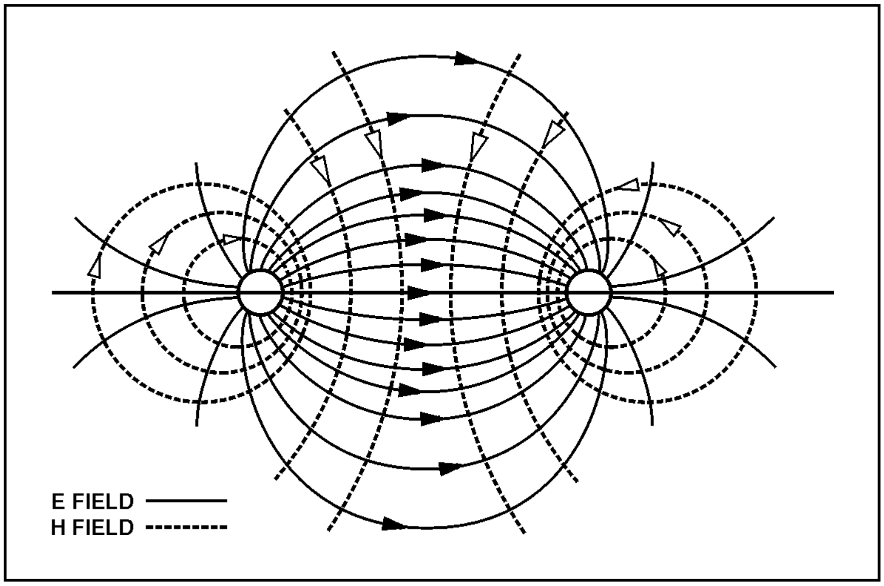


Figure 3-Sum 11. Fields between Conductors

Characteristic impedance, Z_0, is the ratio of E to I at every point along the line. For maximum transfer of electrical power, the characteristic impedance and load impedance must be matched.

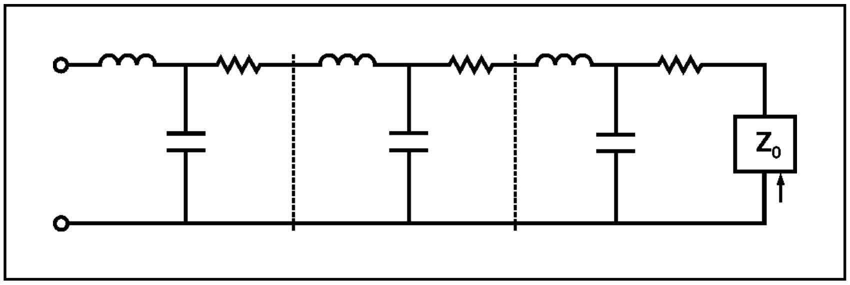


Figure 3-Sum 12. Characteristic Impedance

The velocity at which a wave travels over a given length of transmission line can be found by using the formula:

A transmission line that is not terminated in its characteristic impedance is said to be finite.

When DC is applied to an open-ended line, the voltage is reflected back from the open end without any change in polarity, amplitude, or shape. Current is reflected back with the same amplitude and shape but with opposite polarity.

When DC is applied to a short-circuited line, the current is reflected back with the same amplitude and polarity. The voltage is reflected back with the same amplitude but with opposite polarity.

When AC is applied to an open-end line, voltage is always reflected back in phase with the incident wave and current is reflected back out of phase.

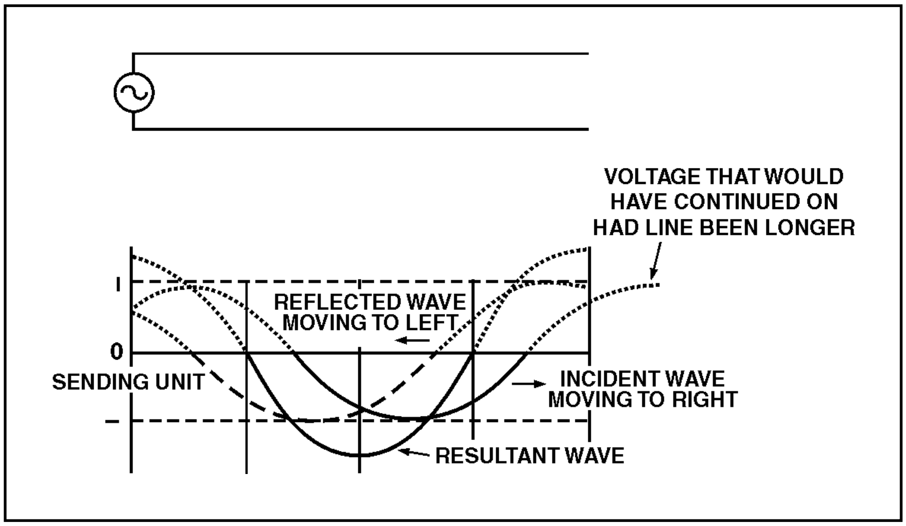


Figure 3-Sum 13. Formation of Standing Wave

When AC is applied to a short-circuited line, voltage is reflected out of phase, while current is reflected in phase.

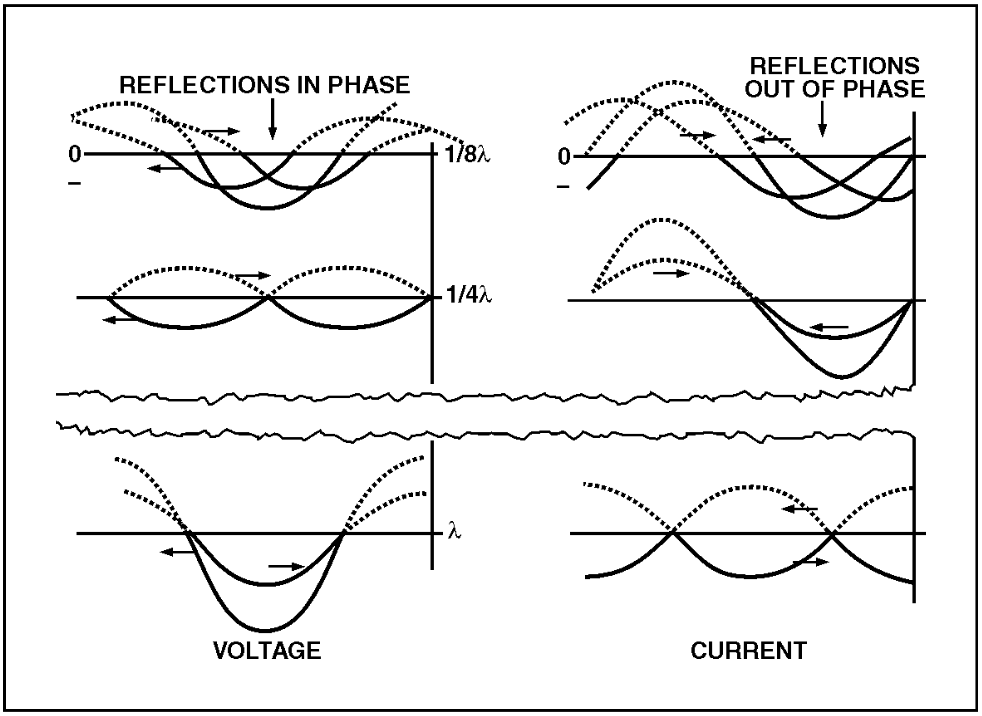


Figure 3-Sum 14. Instantaneous Values of Incident and Reflected Waves

A nonresonant line has no standing waves of current and voltage and is either infinitely long or terminated in its characteristic impedance.

A resonant line has standing waves of current and voltage and is of finite length and is not terminated in its characteristic impedance.

At all odd one-quarter wavelength points on an open-ended resonant line, the voltage is minimum, the current is maximum, and the impedance is minimum. At all even ¼λ points, the voltage is maximum, the current is minimum and the impedance is maximum.

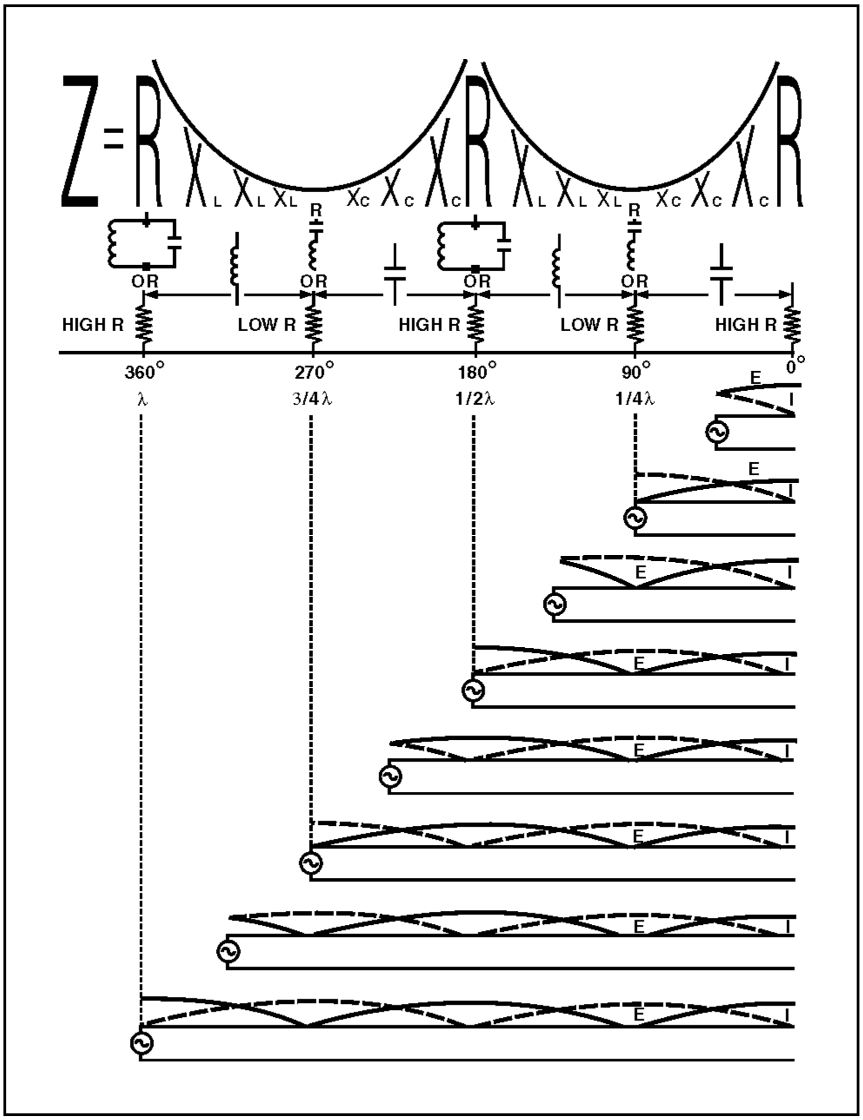


Figure 3-Sum 15. Voltage, Current, and Impedance on a Shorted Line

There are a variety of terminations for RF lines. Each termination has an effect on the standing waves on the line.

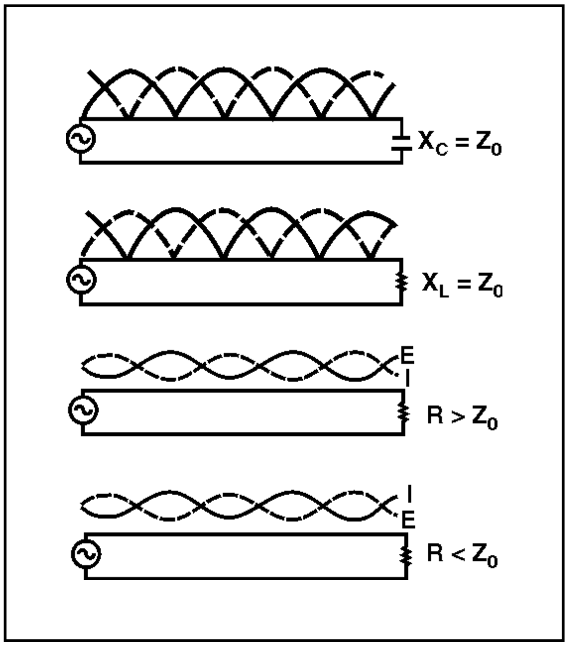


Figure 3-Sum 16. Various Termination Effects on Standing Waves

A transmission line can be terminated in its characteristic impedance as an open- or short-circuit, or in capacitance or inductance.

Whenever the termination on a transmission line is not equal to Z_0, there are reflections on the line. The amount of voltage reflected may be found by using the equation:

$$E_R = E_i \left(\frac{R_L - Z_O}{R_L + Z_O}\right)$$

When the termination on a transmission line equals Z_0, there is no reflected voltage.

The measurement of standing waves on a transmission line yields information about operating conditions. If there are no standing waves, the termination for that line is correct and maximum power transfer takes place.

The standing-wave ratio is the measurement of maximum voltage (current) to minimum voltage (current) on a transmission line and measures the perfection of the termination of the line. A ratio of 1:1 describes a line terminated in its characteristic impedance.

Check-On-Learning Questions

Principles of Transmission Lines

1. What connecting link is used to transfer energy from a radio transmitter to its antenna located on the mast of a ship?
2. What terms are used to describe the end of the transmission line that is connected to a transmitter?
3. What terms are used to describe the end of the transmission line that is connected to an antenna?
4. List the five types of transmission lines in use today.
5. Name two of the three described uses of a two-wire open line.
6. What are the two primary disadvantages of a two-wire open line?
7. What type of transmission line is often used to connect a television set to its antenna?
8. What is the primary advantage of the shielded pair?
9. What are the two types of coaxial lines in use today?
10. What is the chief advantage of the air coaxial line?
11. List the three disadvantages of the air coaxial line.
12. List the two common types of waveguides in use today.
13. What are the three types of line losses associated with transmission lines?
14. Losses caused by skin effect and the I2R (power) loss are classified as what type of loss?
15. What types of losses cause the dielectric material between the conductors to be heated?
16. What must the physical length of a transmission line be if it will be operated at 15,000,000 Hz? Use the formula:

$$\lambda = \frac{v}{f}$$

17. What are two of the three physical factors that determine the values of capacitance and inductance of a transmission line?
18. A transmission line is said to have distributed constants of inductance, capacitance, and resistance along the line. What units of measurement are used to express these constants?
19. Describe the leakage current in a transmission line and in what unit it is expressed.
20. All the power sent down a transmission line from a transmitter can be transferred to an antenna under what optimum conditions?
21. What symbol is used to designate the characteristic impedance of a line, and what two variables does it compare?
22. What is the range of the characteristic impedance of lines used in actual practice?
23. Two types of waves are formed on a transmission line. What names are given to these waves?
24. In figure 3-27, which waveforms on the left have a resultant wave of zero, and what is indicated by these waves?

25. On an open-ended transmission line, the voltage is always zero at what distance from each end of the line?
26. A nonresonant line is a line that has no standing waves of current and voltage on it and is considered to be flat. Why is this true?
27. On an open line, the voltage and impedance are maximum at what points on the line?
28. At what point on an open-circuited RF line do voltage peaks occur?
29. What is the square of the voltage standing-wave ratio called?
30. What does VSWR measure?

Chapter 4

Antennas

If you had been around in the early days of electronics, you would have considered an antenna (aerial) to be little more than a piece of wire strung between two trees or upright poles. In those days, technicians assumed that longer antennas automatically provided better reception than shorter antennas. They also believed that a mysterious medium filled all space, and that an antenna used this medium to send and receive its energy. These two assumptions have since been discarded. Modern antennas have evolved to the point that highly directional, specially designed antennas are used to relay worldwide communications in space through the use of satellites and Earth station antennas (figure 4-1). Present transmission theories are based on the assumption that space itself is the only medium necessary to propagate (transmit) radio energy.

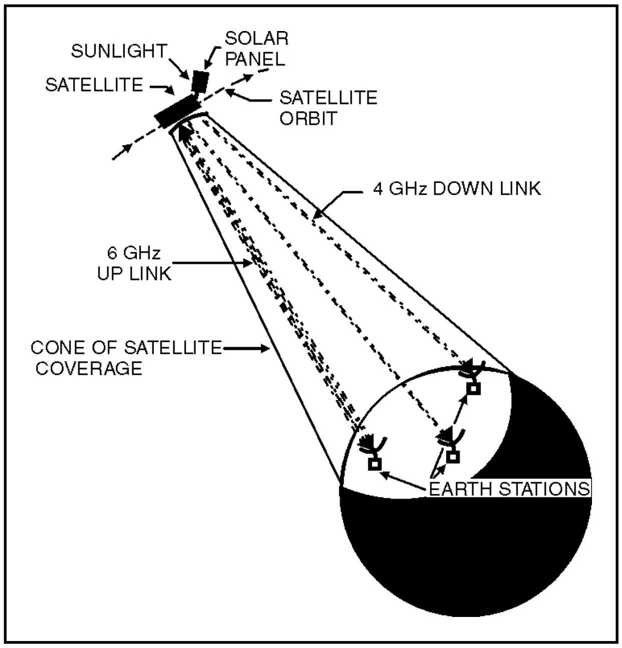


Figure 4-1. Satellite/Earth Station Communications System

4-1. A tremendous amount of knowledge and information has been gained about the design of antennas and radio wave propagation. Still, many old-time technicians will tell you that when it comes to designing the length of an antenna, the best procedure is to perform all calculations and try out the antenna. If it doesn't work right, use a cut-and-try method until it does. Fortunately, enough information has been collected over the last few decades that it is now possible to predict the behavior of antennas. This chapter discusses and explains the basic design and operation of antennas.

LEARNING OBJECTIVES

4-2. Upon completing this chapter, you should be able to do the following:

- State the basic principles of antenna radiation and list the parts of an antenna.
- Explain current and voltage distribution on an antenna.
- Describe how electromagnetic energy is radiated from an antenna.
- Explain polarization, gain, and radiation resistance characteristics of an antenna.
- Describe the theory of operation of half-wave and quarter-wave antennas.
- List the various array antennas.
- Describe the directional array antennas presented and explain the basic operation of each.
- Identify various special antennas presented, such as long-wire, V, rhombic, turnstile, ground-plane, and corner-reflector; describe the operation of each.
- List safety precautions when working aloft and around antennas.

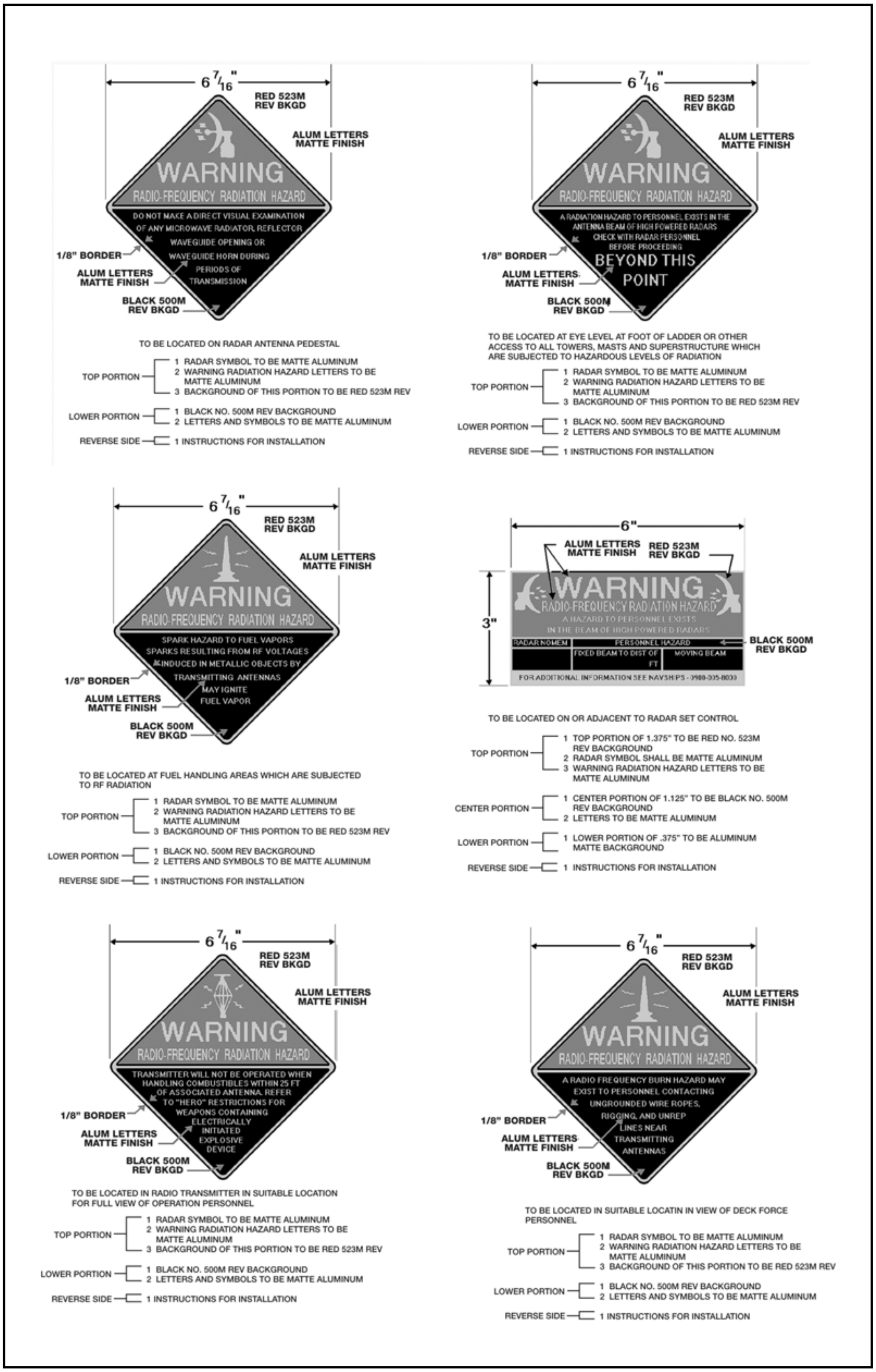
RADIO FREQUENCY SAFETY PRECAUTIONS

4-3. Although electromagnetic radiation from transmission lines and antennas is usually of insufficient strength to electrocute personnel, it can lead to other accidents and compound injuries. Voltages may be induced in ungrounded metal objects, such as wire guys, wire cable (hawser), handrails, or ladders. If you come in contact with these objects, you could receive a shock or radio frequency (RF) burn. This shock can cause you to jump or fall into nearby mechanical equipment or, when working aloft, to fall from an elevated work area. Take care to ensure that all transmission lines or antennas are deenergized before working near or on them.

4-4. Either check or have someone check all guys, cables, rails, and ladders around your work area for RF shock dangers. Use working aloft "chits" and safety harnesses for your own safety. Signing a "working aloft chit" signifies that all equipment is in a nonradiating status. The person who signs the chit should ensure that no RF danger exists in areas where you or other personnel will be working.

4-5. Nearby ships, vans or parked aircraft are another source of RF energy that you must consider when you check a work area for safety. Combustible materials can be ignited and cause severe fires from arcs or heat generated by RF energy. Also, RF radiation can detonate ordnance devices by inducing currents in the internal wiring of the devices or in the external test equipment or leads connected to them.

4-6. Always obey RF radiation warning signs and keep a safe distance from radiating antennas. The six types of warning signs for RF radiation hazards are shown in figure 4-2.



TO BE LOCATED ON RADAR ANTENNA PEDESTAL

TOP PORTION
1 RADAR SYMBOL TO BE MATTE ALUMINUM
2 WARNING RADIATION HAZARD LETTERS TO BE MATTE ALUMINUM
3 BACKGROUND OF THIS PORTION TO BE RED 523M REV

LOWER PORTION
1 BLACK NO. 500M REV BACKGROUND
2 LETTERS AND SYMBOLS TO BE MATTE ALUMINUM

REVERSE SIDE
1 INSTRUCTIONS FOR INSTALLATION

TO BE LOCATED AT EYE LEVEL AT FOOT OF LADDER OR OTHER ACCESS TO ALL TOWERS, MASTS AND SUPERSTRUCTURE WHICH ARE SUBJECTED TO HAZARDOUS LEVELS OF RADIATION

TOP PORTION
1 RADAR SYMBOL TO BE MATTE ALUMINUM
2 WARNING RADIATION HAZARD LETTERS TO BE MATTE ALUMINUM
3 BACKGROUND OF THIS PORTION TO BE RED 523M REV

LOWER PORTION
1 BLACK NO. 500M REV BACKGROUND
2 LETTERS AND SYMBOLS TO BE MATTE ALUMINUM

REVERSE SIDE
1 INSTRUCTIONS FOR INSTALLATION

TO BE LOCATED AT FUEL HANDLING AREAS WHICH ARE SUBJECTED TO RF RADIATION

TOP PORTION
1 RADAR SYMBOL TO BE MATTE ALUMINUM
2 WARNING RADIATION HAZARD LETTERS TO BE MATTE ALUMINUM
3 BACKGROUND OF THIS PORTION TO BE RED 523M REV

LOWER PORTION
1 BLACK NO. 500M REV BACKGROUND
2 LETTERS AND SYMBOLS TO BE MATTE ALUMINUM

REVERSE SIDE
1 INSTRUCTIONS FOR INSTALLATION

TO BE LOCATED ON OR ADJACENT TO RADAR SET CONTROL

TOP PORTION
1 TOP PORTION OF 1.375" TO BE RED NO. 523M REV BACKGROUND
2 RADAR SYMBOL SHALL BE MATTE ALUMINUM
3 WARNING RADIATION HAZARD LETTERS TO BE MATTE ALUMINUM

CENTER PORTION
1 CENTER PORTION OF 1.125" TO BE BLACK NO. 500M REV BACKGROUND
2 LETTERS TO BE MATTE ALUMINUM

LOWER PORTION
1 LOWER PORTION OF .375" TO BE ALUMINUM MATTE BACKGROUND

REVERSE SIDE
1 INSTRUCTIONS FOR INSTALLATION

TO BE LOCATED IN RADIO TRANSMITTER IN SUITABLE LOCATION FOR FULL VIEW OF OPERATION PERSONNEL

TOP PORTION
1 RADAR SYMBOL TO BE MATTE ALUMINUM
2 WARNING RADIATION HAZARD LETTERS TO BE MATTE ALUMINUM
3 BACKGROUND OF THIS PORTION TO BE RED 523M REV

LOWER PORTION
1 BLACK NO. 500M REV BACKGROUND
2 LETTERS AND SYMBOLS TO BE MATTE ALUMINUM

REVERSE SIDE
1 INSTRUCTIONS FOR INSTALLATION

TO BE LOCATED IN SUITABLE LOCATIN IN VIEW OF DECK FORCE PERSONNEL

TOP PORTION
1 RADAR SYMBOL TO BE MATTE ALUMINUM
2 WARNING RADIATION HAZARD LETTERS TO BE MATTE ALUMINUM
3 BACKGROUND OF THIS PORTION TO BE RED 523M REV

LOWER PORTION
1 BLACK NO. 500M REV BACKGROUND
2 LETTERS AND SYMBOLS TO BE MATTE ALUMINUM

REVERSE SIDE
1 INSTRUCTIONS FOR INSTALLATION

Figure 4-2. Warning Signs for Radio Frequency Radiation Hazards

RF BURNS

4-7. Close or direct contact with RF transmission lines or antennas may result in RF burns. These are usually deep, penetrating, third-degree burns. To heal properly, these burns must heal from the inside to the skin's surface. To prevent infection, you must give proper attention to all RF burns, including the small "pinhole" burns. Petrolatum gauze can be used to cover these burns temporarily, before the injured person reports to medical facilities for further treatment.

DIELECTRIC HEATING

4-8. Dielectric heating is the heating of an insulating material by placing it in a high-frequency electric field. The heat results from internal losses during the rapid reversal of polarization of molecules in the dielectric material.

4-9. In the case of a human in an RF field, the body acts as a dielectric. If the power in the RF field exceeds 10 milliwatts per centimeter, a person in that field will have a noticeable rise in body temperature. The eyes are highly susceptible to dielectric heating. For this reason, you should not look directly into devices radiating RF energy. The vital organs of the body also are susceptible to dielectric heating. For your own safety, you must not stand directly in the path of RF radiating devices.

PRECAUTIONS WHEN WORKING ALOFT

4-10. When radio or radar antennas are energized by transmitters, you must not go aloft unless advance tests show that little or no danger exists. A casualty can occur from even a small spark drawn from a charged piece of metal or rigging. Although the spark itself may be harmless, the "surprise" may cause you to let go of the antenna involuntarily and you may fall. There is also a shock hazard if nearby antennas are energized.

4-11. Rotating antennas also might cause you to fall when you are working aloft. Motor safety switches controlling the motion of rotating antennas must be tagged and locked open before you go aloft near such antennas.

PRINCIPLES OF ANTENNA RADIATION

4-12. After an RF signal has been generated in a transmitter, some means must be used to radiate this signal through space to a receiver. The device that does this job is the antenna. The transmitter signal energy is sent into space by a transmitting antenna; the RF signal is then picked up from space by a receiving antenna.

4-13. The RF energy is transmitted into space in the form of an electromagnetic field. As the traveling electromagnetic field arrives at the receiving antenna, a voltage is induced into the antenna (a conductor). The RF voltages induced into the receiving antenna are then passed into the receiver and converted back into the transmitted RF information.

4-14. The design of the antenna system is very important in a transmitting station. The antenna must be able to radiate efficiently so the power supplied by the transmitter is not wasted. An efficient transmitting antenna must have exact dimensions. The dimensions are determined by the transmitting frequencies. The dimensions of the receiving antenna are not critical for relatively low radio frequencies. However, as the frequency of the signal being received increases, the design and installation of the receiving antenna become more critical. An example of this is a television-receiving antenna. If you raise it a few more inches from the ground or give it a slight turn in direction, you can change a snowy blur into a clear picture.

4-15. The conventional antenna is a conductor, or system of conductors, that radiates or intercepts electromagnetic wave energy. An ideal antenna has a definite length and a uniform diameter, and is completely isolated in space. However, this ideal antenna is not realistic. Many factors make the design of an antenna for a communications system a more complex problem than you would expect. These factors include the height of the radiator above the earth, the conductivity of the earth below it, and the shape and dimensions of the antenna. All of these factors affect the radiated-field pattern of the antenna in space. Another problem in antenna design is that the radiation pattern of the antenna must be directed between certain angles in a horizontal or vertical plane, or both.

4-16. Most practical transmitting antennas are divided into two basic classifications, hertz (half-wave) antennas and Marconi (quarter-wave) antennas. Hertz antennas are generally installed some distance above the ground and are positioned to radiate either vertically or horizontally. Marconi antennas operate with one end grounded and are mounted perpendicular to the earth or to a surface acting as a ground. Hertz antennas are generally used for frequencies above 2 megahertz. Marconi antennas are used for frequencies below 2 megahertz and may be used at higher frequencies in certain applications.

4-17. A complete antenna system consists of the following three parts (figure 4-3):

- The coupling device (coupling coil).
- The feeder.
- The antenna.

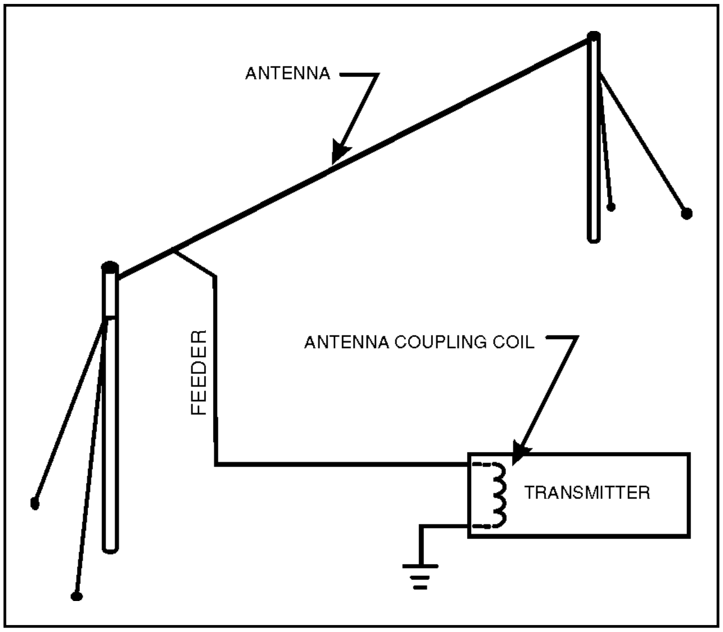


Figure 4-3. Typical Antenna System

4-18. The coupling device (coupling coil) connects the transmitter to the feeder. The feeder is a transmission line that carries energy to the antenna. The antenna radiates this energy into space.

4-19. The factors that determine the type, size, and shape of the antenna are as follows:

- The frequency of operation of the transmitter.
- Amount of power to be radiated.
- General direction of the receiving set.

Some typical antennas are illustrated in figure 4-4.

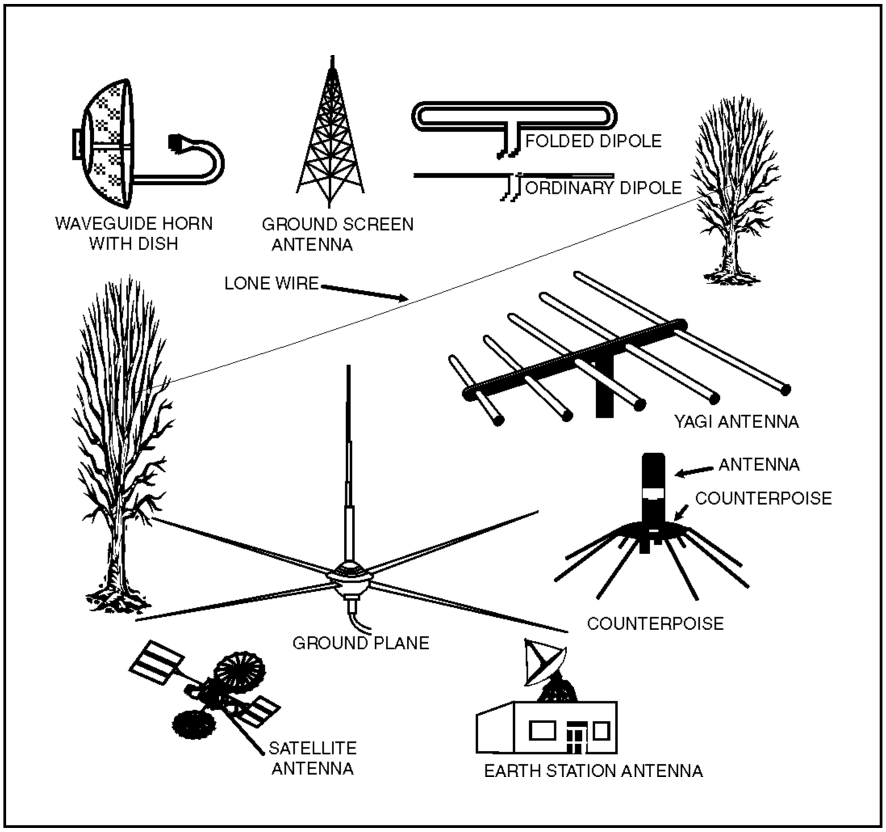


Figure 4-4. Typical Antennas

CURRENT AND VOLTAGE DISTRIBUTION ON AN ANTENNA

4-20. A current flowing in a wire whose length is properly related to the RF produces an electromagnetic field. This field is radiated from the wire and is set free in space. We discuss how these waves are set free later in this chapter. Remember, the principles of radiation of electromagnetic energy are based on two laws:

- A moving electric field creates a magnetic (H) field.
- A moving magnetic field creates an electric (E) field.

4-21. In space, these two fields are in phase and perpendicular to each other at any given time. Although a conductor is usually considered present when a moving electric or magnetic field is mentioned, the laws that govern these fields say nothing about a conductor. Therefore, these laws hold true whether a conductor is present or not.

4-22. Figure 4-5 shows the current and voltage distribution on a half-wave (hertz) antenna. In figure 4-5, view A, a piece of wire is cut in half and attached to the terminals of a high-frequency AC generator. The frequency of the generator is set so that each half of the wire is one-quarter wavelength of the output. The result is a common type of antenna known as a dipole.

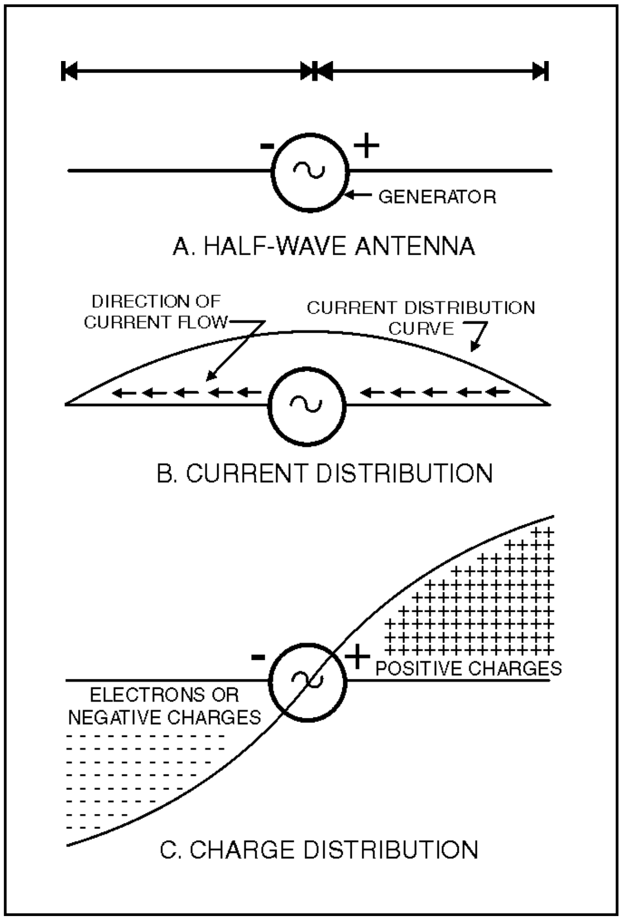


Figure 4-5. Current and Voltage Distribution on a Antenna

4-23. At a given time, the right side of the generator is positive and the left side negative. Remember that like charges repel. Because of this, electrons will flow away from the negative terminal as far as possible, but will be attracted to the positive terminal. Figure 4-5, view B shows the direction and distribution of electron flow. The distribution curve shows that most current flows in the center and none flows at the ends. The current distribution over the antenna will always be the same no matter how much or how little current is flowing. However, current at any given point on the antenna will vary directly with the amount of voltage developed by the generator.

4-24. One-quarter cycle after electrons have begun to flow, the generator will develop its maximum voltage and the current will decrease to 0. At that time the condition shown in figure 4-5 view C will exist. No current will be flowing, but a maximum number of electrons will be at the left end of the line and a minimum number at the right end. The charge distribution along the wire will vary as the voltage of the generator varies. Therefore, you may draw the following conclusions:

- A current flows in the antenna with an amplitude that varies with the generator voltage.
- A sinusoidal distribution of charge exists on the antenna. Every one-half cycle, the charges reverse polarity.
- The sinusoidal variation in charge magnitude lags the sinusoidal variation in current by one-quarter cycle.

RADIATION OF ELECTROMAGNETIC ENERGY

4-25. The electromagnetic radiation from an antenna is made up of two components: the E field and the H field. These fields are discussed in chapters 1 and 2. The two fields occur 90 degrees out of phase with each other. These fields combine and produce a single electromagnetic field. The total energy in the radiated wave remains constant in space except for some absorption of energy by the earth. However, as the wave advances, the energy spreads out over a greater area and, at any given point, decreases as the distance increases.

4-26. Various factors in the antenna circuit affect the radiation of these waves. In figure 4-6, for example, if an alternating current is applied at the A end of the length of wire that stretches from A to B, the wave will travel along the wire until it reaches the B end. Because the B end is free, an open circuit exists and the wave cannot travel farther. This is a point of high impedance. The wave bounces back (reflects) from this point of high impedance and travels toward the starting point, where it is again reflected. Through this back-and-forth motion (oscillation), the resistance of the wire would gradually dissipate the energy of the wave; however, each time the wave reaches the starting point, it is reinforced by an amount sufficient to replace the energy lost. This results in continuous oscillations of energy along the wire and a high voltage at the A end of the wire. These oscillations are applied to the antenna at a rate equal to the frequency of the RF voltage.

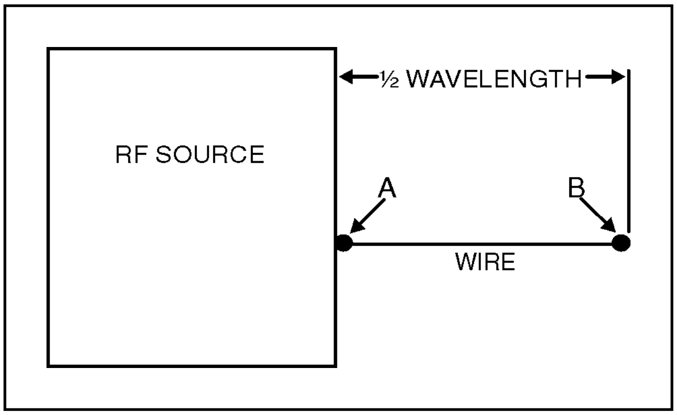


Figure 4-6. Antenna and RF Source

4-27. These impulses must be properly timed to sustain oscillations in the antenna. The rate at which the waves travel along the wire is constant at approximately 300,000,000 meters per second. The length of the antenna must be such that a wave will travel from one end to the other and back again during the period of 1 cycle of the RF voltage. Remember, the distance a wave travels during the period of 1 cycle is known as the wavelength and is found by dividing the rate of travel by the frequency.

4-28. Look at the current and voltage (charge) distribution on the antenna in figure 4-7. A maximum movement of electrons is in the center of the antenna at all times; therefore, the center of the antenna is at low impedance. This condition is called a standing wave of current. The points of high current and high voltage are known as current and voltage loops. The points of minimum current and minimum voltage are known as current and voltage nodes.

4-29. Figure 4-7, view A shows a current loop and current nodes. View B shows voltage loops and a voltage node. View C shows the resultant voltage and current loops and nodes. The presence of standing waves describes the condition of resonance in an antenna. At resonance, the waves travel back and forth in the antenna reinforcing each other and the electromagnetic waves are transmitted into space at maximum radiation. When the antenna is not at resonance, the waves tend to cancel each other and lose energy in the form of heat.

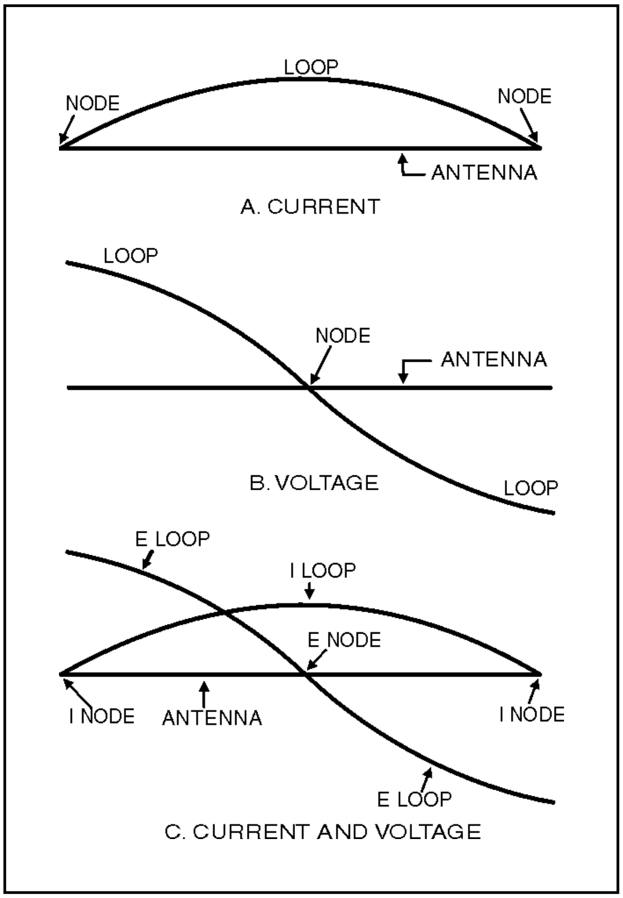


Figure 4-7. Standing Waves of Voltage and Current on an Antenna

ANTENNA CHARACTERISTICS

4-30. You can define an antenna as a conductor or group of conductors used either for radiating electromagnetic energy into space or for collecting it from space. Electrical energy from the transmitter is converted into electromagnetic energy by the antenna and radiated into space. On the receiving end, electromagnetic energy is converted into electrical energy by the antenna and is fed into the receiver.

4-31. Fortunately, separate antennas seldom are required for both transmitting and receiving RF energy. Any antenna can transfer energy from space to its input receiver with the same efficiency that it transfers energy from the transmitter into space. Of course, this is assuming that the same frequency is used in both cases. This property of interchangeability of the same antenna for transmitting and receiving is known as antenna reciprocity. Antenna reciprocity is possible because antenna characteristics are essentially the same for sending and receiving electromagnetic energy.

RECIPROCITY OF ANTENNAS

4-32. In general, the various properties of an antenna apply equally, regardless of whether you use the antenna for transmitting or receiving. The more efficient a certain antenna is for transmitting, the more efficient it will be for receiving on the same frequency. Likewise, the directive properties of a given antenna also will be the same whether it is used for transmitting or receiving.

4-33. Assume, for example, that a certain antenna used with a transmitter radiates a maximum amount of energy at right angles to the axis of the antenna, as shown in figure 4-8, view A. Note the minimum amount of radiation along the axis of the antenna. Now, if this same antenna were used as a receiving antenna, as shown in view B, it would receive best in the same directions in which it produced maximum radiation; that is, at right angles to the axis of the antenna.

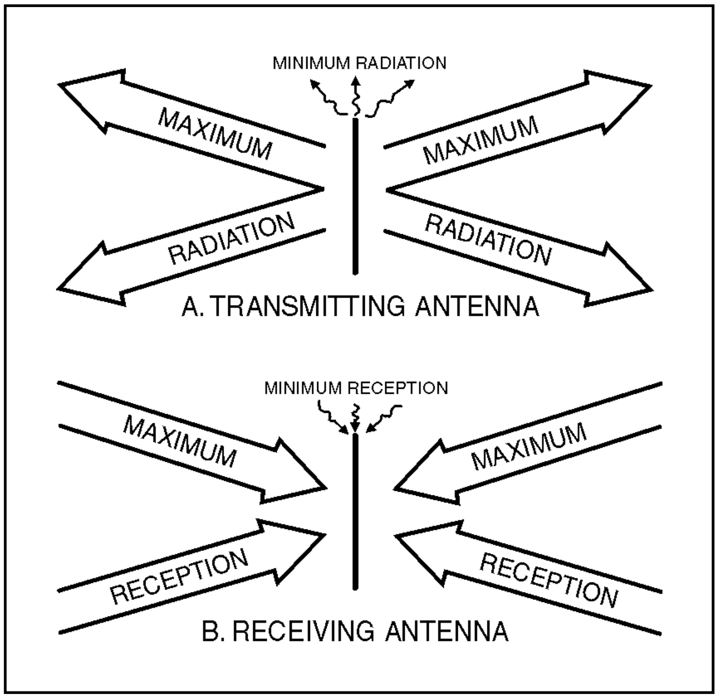


Figure 4-8. Reciprocity of Antenna

ANTENNA GAIN

4-34. Another characteristic of a given antenna that remains the same whether the antenna is used for transmitting or receiving is gain. Some antennas are highly directional; that is, more energy is propagated in certain directions than in others. The ratio between the amount of energy propagated in these directions compared to the energy that would be propagated if the antenna were not directional is known as its gain. When a transmitting antenna with a certain gain is used as a receiving antenna, it will also have the same gain for receiving.

POLARIZATION

4-35. Let us review polarization briefly. In chapter 2 you learned that the radiation field is composed of electric and magnetic lines of force. These lines of force are always at right angles to each other. Their intensities rise and fall together, reaching their maximums 90 degrees apart. The electric field determines the direction of polarization of the wave. In a vertically polarized wave, the electric lines of force lie in a vertical direction. In a horizontally polarized wave, the electric lines of force lie in a horizontal direction. Circular polarization has the electric lines of force rotating through 360 degrees with every cycle of RF energy.

4-36. The electric field was chosen as the reference field because the intensity of the wave is usually measured in terms of the electric field intensity (volts, millivolts, or microvolts per meter). When a single-wire antenna is used to extract energy from a passing radio wave, maximum pickup will result when the antenna is oriented in the same direction as the electric field. Thus, a vertical antenna is used for the efficient reception of vertically polarized waves, and a horizontal antenna is used for the reception of horizontally polarized waves. In some cases the orientation of the electric field does not remain constant. Instead, the field rotates as the wave travels through space. Under these conditions both horizontal and vertical components of the field exist and the wave is said to have an elliptical polarization.

Polarization Requirements for Various Frequencies

4-37. Ground-wave transmission is widely used at medium and low frequencies. Horizontal polarization cannot be used at these frequencies because the electric lines of force are parallel to and touch the earth. Because the earth acts as a fairly good conductor at low frequencies, it would short out the horizontal electric lines of force and prevent the radio wave from traveling very far. Vertical electric lines of force, on the other hand are bothered very little by the earth. Therefore vertical polarization is used for ground-wave transmission, allowing the radio wave to travel a considerable distance along the ground surface with minimum attenuation.

4-38. Sky-wave transmission is used at high frequencies. Either horizontal or vertical polarization can be used with sky-wave transmission because the sky wave arrives at the receiving antenna elliptically polarized. This is the result of the wave traveling obliquely through the earth's magnetic field and striking the ionosphere. The radio wave is given a twisting motion as it strikes the ionosphere. Its orientation continues to change because of the unstable nature of the ionosphere. The relative amplitudes and phase differences between the horizontal and vertical components of the received wave also change. Therefore, the transmitting and receiving antennas can be mounted either horizontally or vertically.

4-39. Although either horizontally or vertically polarized antennas can be used for high frequencies, horizontally polarized antennas have certain advantages and are therefore preferred. One advantage is that vertically polarized interference signals, such as those produced by automobile ignition systems and electrical appliances, are minimized by horizontal polarization. Also, less absorption of radiated energy by buildings or wiring occurs when these antennas are used. Another advantage is that support structures for these antennas are of more convenient size than those for vertically polarized antennas.

4-40. For frequencies in the VHF or UHF range, either horizontal or vertical polarization is satisfactory. These radio waves travel directly from the transmitting antenna to the receiving antenna without entering the ionosphere. The original polarization produced at the transmitting antenna is maintained throughout the entire travel of the wave to the receiver. Therefore, if a horizontally polarized antenna is used for transmitting, a horizontally polarized antenna must be used for receiving. The requirements would be the same for a vertical transmitting and receiving antenna system.

4-41. For satellite communications, parallel frequencies can be used without interference by using polarized radiation. The system setup is shown in figure 4-9. One pair of satellite antennas is vertically polarized and another pair is horizontally polarized. Either vertically or horizontally polarized transmissions are received by the respective antenna and retransmitted in the same polarization. For example, transmissions may be made in the 3.7 to 3.74 GHz range on the vertical polarization path and in the 3.72 to 3.76 GHz range on the horizontal polarization path without adjacent frequency (co-channel) interference.

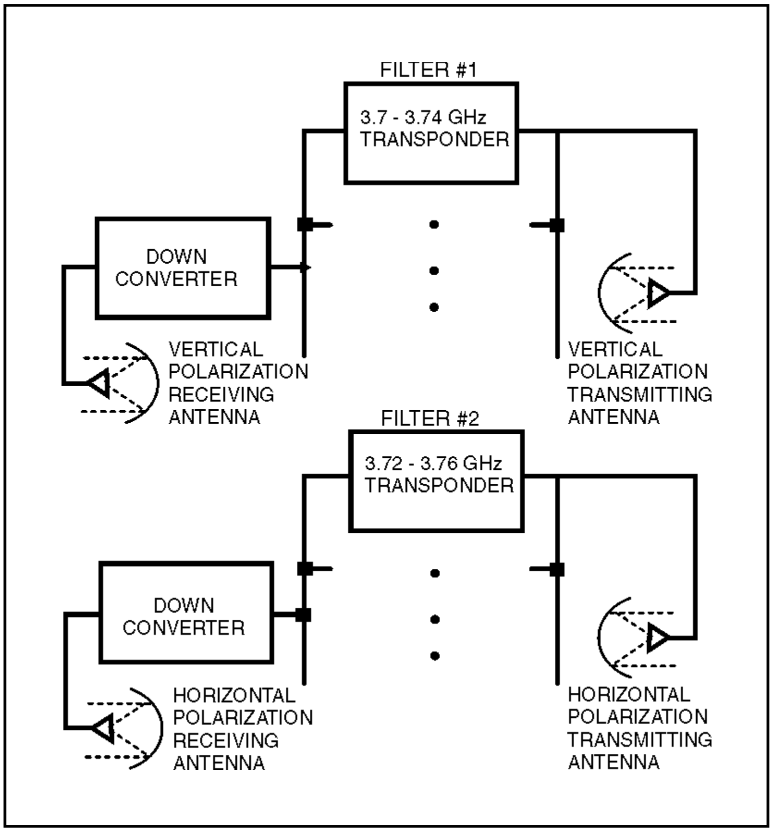


Figure 4-9. Satellite Transmissions Using Polarized Radiation

Advantages of Vertical Polarization

4-42. Simple vertical antennas can be used to provide omnidirectional (all directions) communication. This is an advantage when communications must take place from a moving vehicle.

4-43. In some overland communications, such as in vehicular installations, antenna heights are limited to 3 meters (10 feet) or less. In such instances vertical polarization results in a stronger receiver signal than does horizontal polarization at frequencies up to about 50 megahertz. From approximately 50 to 100 megahertz, vertical polarization results in a slightly stronger signal than does horizontal polarization with antennas at the same height. Above 100 megahertz, the difference in signal strength is negligible.

4-44. For transmission over bodies of water, vertical polarization is much better than horizontal polarization for antennas at the lower heights. As the frequency increases, the minimum antenna height decreases. At 30 megahertz, vertical polarization is better for antenna heights below about 91 meters (300 feet); at 85 megahertz, antenna heights below 15 meters (50 feet); and still lower heights at the high frequencies. Therefore, at ordinary antenna mast heights of 12 meters (40 feet), vertical polarization is advantageous for frequencies less than about 100 megahertz.

4-45. Radiation is somewhat less affected by reflections from aircraft flying over the transmission path when vertical polarization is used instead of horizontal polarization. With horizontal polarization, such reflections cause variations in received signal strength. This factor is important in locations where aircraft traffic is heavy.

4-46. When vertical polarization is used, less interference is produced or picked up because of strong VHF and UHF broadcast transmissions (television and FM). This is because VHF and UHF transmissions use horizontal polarization. This factor is important when an antenna must be located in an urban area having several television and FM broadcast stations.

Advantages of Horizontal Polarization

4-47. A simple horizontal antenna is bidirectional. This characteristic is useful when you wish to minimize interference from certain directions. Horizontal antennas are less likely to pick up man-made interference, which ordinarily is vertically polarized.

4-48. When antennas are located near dense forests or among buildings, horizontally polarized waves suffer lower losses than vertically polarized waves, especially above 100 megahertz. Small changes in antenna locations do not cause large variations in the field intensity of horizontally polarized waves. When vertical polarization is used, a change of only a few meters in the antenna location may have a considerable effect on the received signal strength. This is the result of interference patterns that produce standing waves in space when spurious reflections from trees or buildings occur.

4-49. When simple antennas are used, a horizontally-mounted antenna less affects the transmission line, which is usually vertical. When the antenna is mounted at right angles to the transmission line and horizontal polarization is used, the line is kept out of the direct field of the antenna. As a result, the radiation pattern and electrical characteristics of the antenna are practically unaffected by the presence of the vertical transmission line.

RADIATION RESISTANCE

4-50. Radiated energy is the useful part of the transmitter's signal. However, it represents as much of a loss to the antenna as the energy lost in heating the antenna wire. In either case, the dissipated power is equal to I^2R. In the case of heat losses, the R is real resistance. In the case of radiation, R is an assumed resistance; if this resistance were actually present, it would dissipate the same amount of power that the antenna takes to radiate the energy. This assumed resistance is referred to as the radiation resistance.

4-51. Radiation resistance varies at different points on the antenna. This resistance is always measured at a current loop. For the antenna in free space, that is, entirely removed from any objects that might affect its operation, the radiation resistance is 73 ohms. A practical antenna located over a ground plane may have any value of radiation resistance from 0 to approximately 100 ohms. The exact value of radiation resistance depends on the height of the antenna above the ground. For most half-wave wire antennas, the radiation resistance is about 65 ohms. It will usually vary between 55 and 600 ohms for antennas constructed of rod or tubing. The actual value of radiation resistance, so long as it is 50 ohms or more, has little effect on the radiation efficiency of the antenna. This is because the ohmic resistance is about 1 ohm for conductors of large diameter. The ohmic resistance does not become important until the radiation resistance drops to a value less than 10 ohms. This may be the case when several antennas are coupled together.

RADIATION TYPES AND PATTERNS

4-52. The energy radiated from an antenna forms a field having a definite radiation pattern. A radiation pattern is a plot of the radiated energy from an antenna. This energy is measured at various angles at a constant distance from the antenna. The shape of this pattern depends on the type of antenna used. The following sections introduce the basic types of radiation (isotropic and anisotropic) and their radiation patterns.

Isotropic Radiation

4-53. Some antenna sources radiate energy equally in all directions. Radiation of this type is known as isotropic radiation. We all know the sun radiates energy in all directions. The energy radiated from the sun measured at any fixed distance and from any angle will be approximately the same. Assume that a measuring device is moved around the sun and stopped at the points indicated in figure 4-10 to make a measurement of the amount of radiation. At any point around the circle, the distance from the measuring device to the sun is the same. The measured radiation will also be the same. The sun is therefore considered an isotropic radiator.

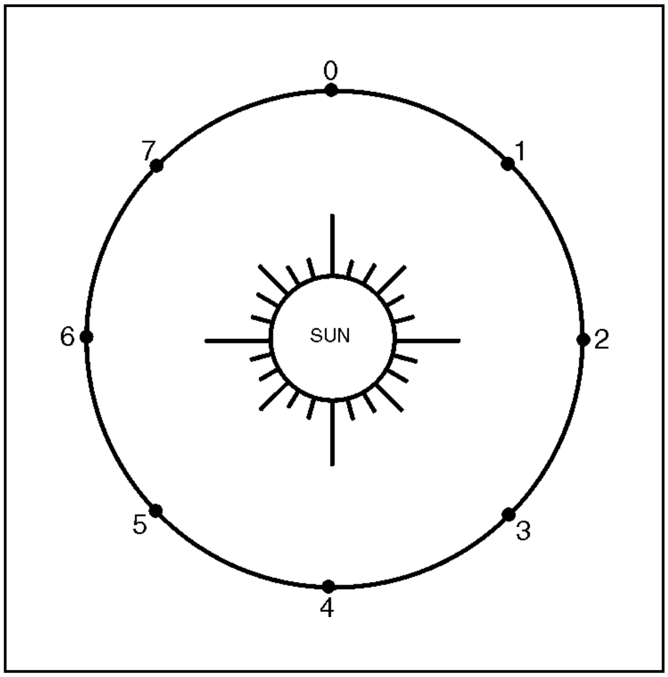


Figure 4-10. Isotropic Radiator

4-54. To plot the pattern shown in figure 4-10, assume that the radiation is measured on a scale of 0 to 10 units and that the measured amount of radiation is 7 units at all points. The measurements can be plotted on two different types of graphs: rectangular-and polar-coordinate graphs. The rectangular-coordinate graph of the measured radiation, shown in figure 4-11, view A, is a straight line plotted against positions around the circle. View B shows the polar-coordinate graph for the same isotropic source.

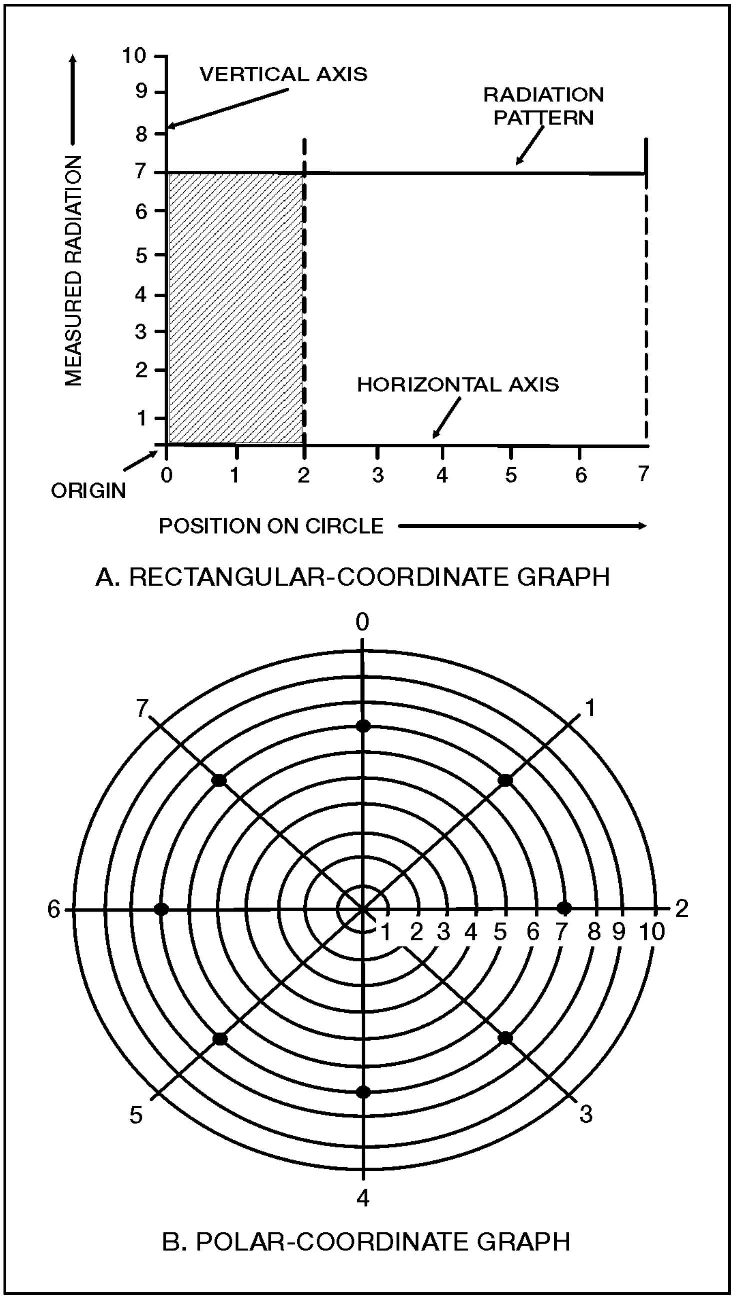


Figure 4-11. Comparison of Rectangular and Polar-Coordinate Graph for an Isotropic Source

4-55. In the rectangular-coordinate graph, points are located by projection from a pair of stationary, perpendicular axes. In the polar-coordinate graph, points are located by projection along a rotating axis (radius) to an intersection with one of several concentric, equally spaced circles. The horizontal axis on the rectangular-coordinate graph corresponds to the circles on the polar-coordinate graph. The vertical axis on the rectangular-coordinate graph corresponds to the rotating axis (radius) on the polar-coordinate graph.

Rectangular-Coordinate Pattern

4-56. Look at figure 4-11, view A. The numbered positions around the circle are laid out on the horizontal axis of the graph from 0 to 7 units. The measured radiation is laid out on the vertical axis of the graph from 0 to 10 units. The units on both axes are chosen so the pattern occupies a convenient part of the graph.

4-57. The horizontal and vertical axes are at a right angle to each other. The point where the axes cross each other is known as the origin. In this case, the origin is 0 on both axes. Now, assume that a radiation value of 7 units is measured at position 2. From position 2 on the horizontal axis, a dotted line that runs parallel to the vertical axis is projected upwards. From position 7 on the vertical axis, a line that runs parallel to the horizontal axis is projected to the right. The point where the two lines cross (intercept) represents a value of 7 radiation units at position 2. This is the only point on the graph that can represent this value.

4-58. As you can see from the figure, the lines used to plot the point form a rectangle. For this reason, this type of plot is called a rectangular-coordinate graph. A new rectangle is formed for each different point plotted. In this example, the points plotted lie in a straight line extending from 7 units on the vertical scale to the projection of position 7 on the horizontal scale. This is the characteristic pattern in rectangular coordinates of an isotropic source of radiation.

Polar-Coordinate Pattern

4-59. The polar-coordinate graph has proved to be of great use in studying radiation patterns. Compare views A and B of figure 4-11. Note the great difference in the shape of the radiation pattern when it is transferred from the rectangular-coordinate graph in view A to the polar-coordinate graph in view B. The scale of radiation values used in both graphs is identical, and the measurements taken are both the same. However, the shape of the pattern is drastically different.

4-60. Look at figure 4-11, view B, and assume that the center of the concentric circles is the sun. Assume that a radius is drawn from the sun (center of the circle) to position 0 of the outermost circle. When you move to position 1, the radius moves to position 1; when you move to position 2, the radius also moves to position 2, and so on.

4-61. The positions where a measurement was taken are marked as 0 through 7 on the graph. Note how the position of the radius indicates the actual direction from the source at which the measurement was taken. This is a distinct advantage over the rectangular-coordinate graph in which the position is indicated along a straight-line axis and has no physical relation to the actual direction of measurement. Now that we have a way to indicate the direction of measurement, we must devise a way to indicate the magnitude of the radiation.

4-62. Notice that the rotating axis is always drawn from the center of the graph to some position on the edge of the graph (figure 4-11, view B). As the axis moves toward the edge of the graph, it passes through a set of equally spaced, concentric circles. In this example, they are numbered successively from 1 to 10 from the center out. These circles are used to indicate the magnitude of the radiation.

4-63. The advantages of the polar-coordinate graph are immediately evident. The source, which is at the center of the observation circles, is also at the center of the graph. By looking at a polar-coordinate plot of a radiation pattern, you can immediately see the direction and strength of radiation put out by the source. Therefore, the polar-coordinate graph is more useful than the rectangular-coordinate graph in plotting radiation patterns.

Anisotropic Radiation

4-64. Most radiators emit (radiate) stronger radiation in one direction than in another. A radiator such as this is referred to as anisotropic. An example of an anisotropic radiator is an ordinary flashlight. The beam of the flashlight lights only a portion of the space surrounding it. If a circle is drawn with the flashlight as the center, as shown in figure 4-12, view B, the radiated light can be measured at different positions around the circle. Again, as with the isotropic radiator, all positions are the same distance from the center, but at different angles. However, in this illustration the radiated light is measured at 16 different positions on the circle.

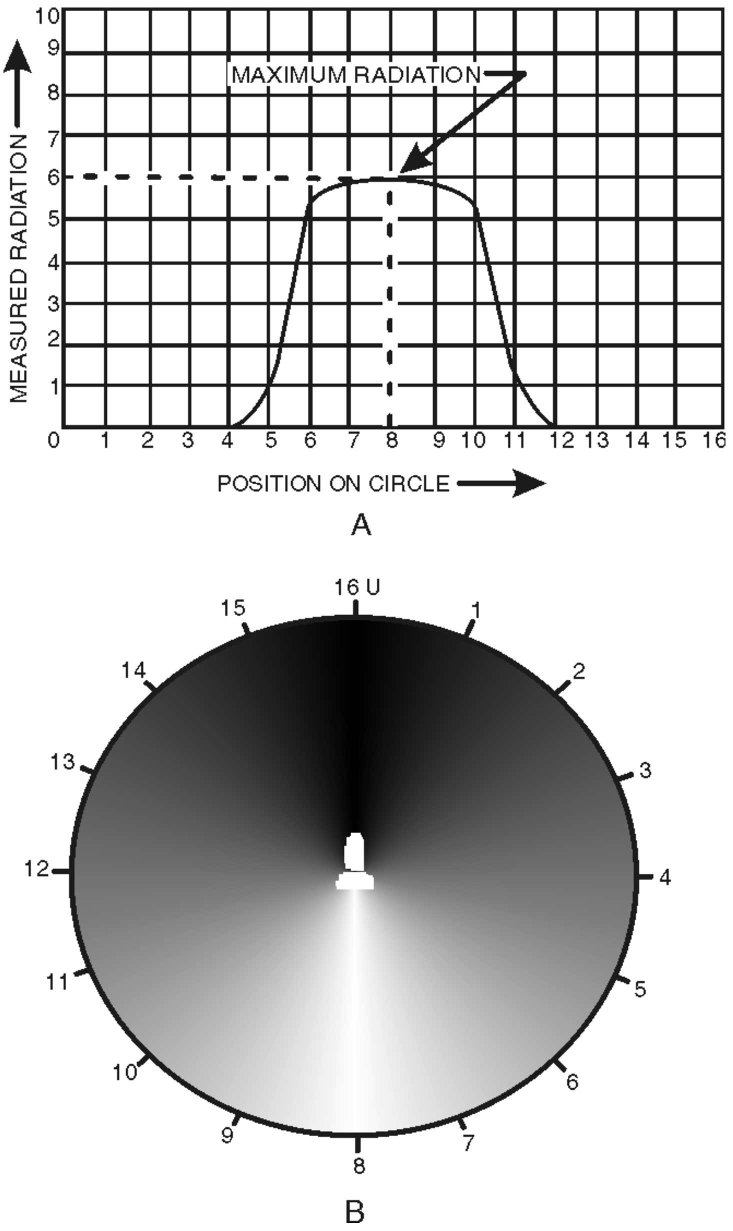


Figure 4-12. Anisotropic Radiator

4-65. Directly behind the flashlight (position 0) the radiation measured is minimum. Accordingly, a 0 value is assigned to this position in the rectangular-coordinate graph (figure. 4-12, view A). This radiation remains at minimum until position 4 is reached. Between positions 4 and 6, the measuring device enters the flashlight beam. You can see this transition from darkness to brightness easily in view B. Radiation is fairly constant between positions 6 and 10. Maximum brightness occurs at position 8, which is directly in the path of the flashlight beam. From positions 10 to 12, the measuring device leaves the flashlight beam and the radiation measurement falls off sharply. At position 13 the radiation is again at 0 and stays at this value back to position 0.

4-66. Radiation from a light source and radiation from an antenna are both forms of electromagnetic waves. Therefore, the measurement of radiation of an antenna follows the same basic procedure as that just described for the sun and the flashlight. Before proceeding further with the study of antenna patterns, you should be sure you understand the methods used to graph the measured radiation (magnitude of the radiation). Study the rectangular and polar coordinate systems of plotting presented in the following paragraphs.

4-67. In figure 4-12, view A, the radiation pattern of the flashlight is graphed in rectangular coordinates. The illustration of the flashlight beam in figure 4-12, view B clearly indicates the shape of the flashlight beam. This shape is not evident in the radiation pattern plotted on the rectangular-coordinate graph. Now look at figure 4-13. The radiation pattern shown in this figure looks very much like the actual flashlight beam. The pattern in figure 4-13 is plotted using the same values as those of figure 4-12, view A, but is drawn using polar coordinates.

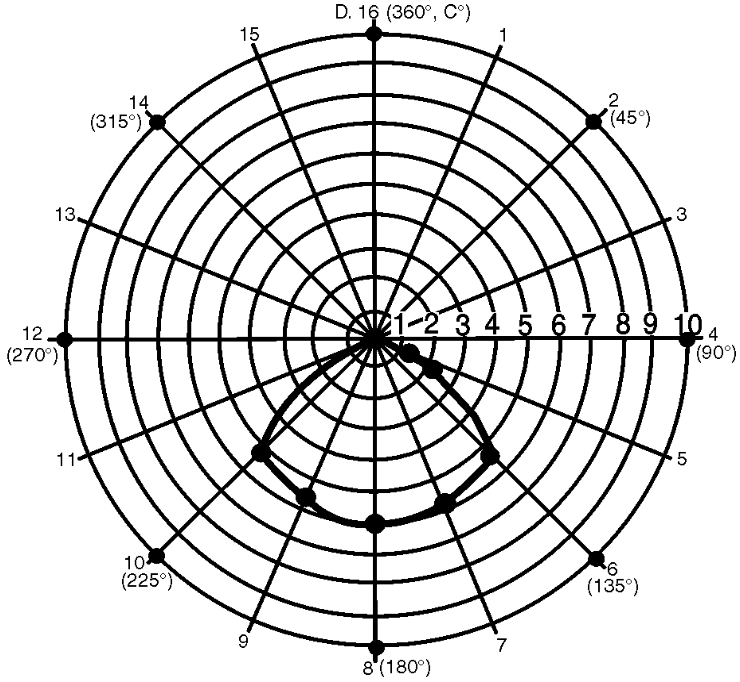


Figure 4-13. Polar-Coordinate Graph for Anisotropic Radiator

4-68. The positions marked off on the two polar-coordinate graphs in figures 4-11 and 4-13 were selected and numbered arbitrarily. However, a standard method allows the positions around a source to be marked off so that one radiation pattern can easily be compared with another. This method is based on the fact that a circle has a radius of 360 degrees. The radius extending vertically from the center (position 0 in figure 4-11) is designated 0 degrees. At position 4 the radius is at a right angle to the 0-degree radius. Accordingly, the radius at position 4 is marked 90 degrees, position 8 is 180 degrees, position 12 is 270 degrees, and position 16 is 360 degrees. The various radii drawn on the graph are all marked according to the angle each radius makes with the reference radius at 0 degrees.

4-69. The radiation pattern in figure 4-13 is obtained by using the same procedure that was used for figure 4 -10, view B. The radiation measured at positions 1, 2, 3, and 4 is 0. Position 5 measures approximately 1 unit. This is marked on the graph and the rotating radius moves to position 6. At this position a reading of 5.5 units is taken. As before, this point is marked on the graph. The procedure is repeated around the circle and a reading is obtained from positions 6 through 11. At position 12 no radiation is indicated, and this continues on to position 16.

4-70. The polar-coordinate graph now shows a definite area enclosed by the radiation pattern. This pattern indicates the general direction of radiation from the source. The enclosed area is called a lobe. Outside of this area, minimum radiation is emitted in any direction. For example, at position 2 the radiation is 0. Such a point is called a null. In real situations, some radiation is usually transmitted in all directions. Therefore, a null is used to indicate directions of minimum radiation. The pattern of figure 4-13 shows one lobe and one continuous null.

ANTENNA LOADING

4-71. You will sometimes want to use one antenna system for transmitting and receiving on several different frequencies. Because the antenna must always be in resonance with the applied frequency, you may need to lengthen or shorten the antenna physically or electrically.

4-72. Except for trailing-wire antennas used in aircraft installations (which may be lengthened or shortened), physically lengthening the antenna is not very practical. But you can achieve the same result by changing the electrical length of the antenna. To change the electrical length, you can insert either an inductor or a capacitor in series with the antenna. This is shown in figure 4-14, views A and B. Changing the electrical length by this method is known as lumped-impedance tuning, or loading. The electrical length of any antenna wire can be increased or decreased by loading. If the antenna is too short for the wavelength being used, it is resonant at a higher frequency than that at which it is being excited. Therefore, it offers a capacitive reactance at the excitation frequency. This capacitive reactance can be compensated for by introducing a lumped-inductive reactance, as shown in figure 4-14, view A. Similarly, if the antenna is too long for the transmitting frequency, it offers an inductive reactance. Inductive reactance can be compensated for by introducing a lumped-capacitive reactance, as shown in view B. An antenna without loading is represented in view C.

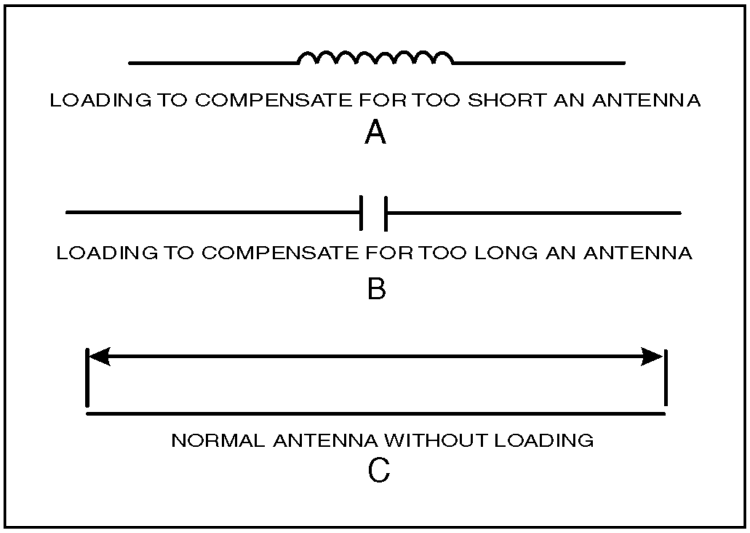


Figure 4-14. Electrically Equal Antenna

BASIC ANTENNAS

4-73. Before you look at the various types of antennas, consider the relationship between the wavelength at which the antenna is being operated and the actual length of the antenna. An antenna does not necessarily radiate or receive more energy when it is made longer. Specific dimensions must be used for efficient antenna operation.

4-74. Nearly all antennas have been developed from two basic types, the Hertz and the Marconi. The basic Hertz antenna is one-half wavelength long at the operating frequency and is insulated from ground. It is often called a dipole or a doublet. The basic Marconi antenna is one-quarter wavelength long and is either grounded at one end or connected to a network of wires called a counterpoise. The ground or counterpoise provides the equivalent of an additional one-quarter wavelength, which is required for the antenna to resonate.

HALF-WAVE ANTENNAS

4-75. A half-wave antenna (referred to as a dipole, Hertz, or doublet) consists of two lengths of wire rod, or tubing, each one-quarter wavelength long at a certain frequency. It is the basic unit from which many complex antennas are constructed. The half-wave antenna operates independently of ground; therefore, it may be installed far above the surface of the earth or other absorbing bodies. For a dipole, the current is maximum at the center and minimum at the ends. Voltage is minimum at the center and maximum at the ends, as shown in figure 4-7.

Radiation Patterns

4-76. In the following discussion, the term dipole is used to mean the basic half-wave antenna. The term doublet is used to indicate an antenna that is very short compared with the wavelength of the operating frequency. Physically, it has the same shape as the dipole.

4-77. **Radiation pattern of a doublet**. The doublet is the simplest form of a practical antenna. Its radiation pattern can be plotted in the same way as the radiation pattern of the flashlight shown in figure 4-13. Figure 4-15 illustrates the development of vertical and horizontal patterns for a doublet. This is not a picture of the radiation, but three-dimensional views of the pattern itself that the radiation makes. In three views (views B, C, and D), the pattern resembles a doughnut. From the dimensions in these views, two types of polar-coordinate patterns can be drawn: horizontal and vertical. The horizontal pattern shown in view A is derived from the solid pattern shown in view C by slicing it horizontally. This produces view B, which is converted to the polar coordinates seen in view A. The horizontal pattern illustrates that the radiation is constant in any direction along the horizontal plane.

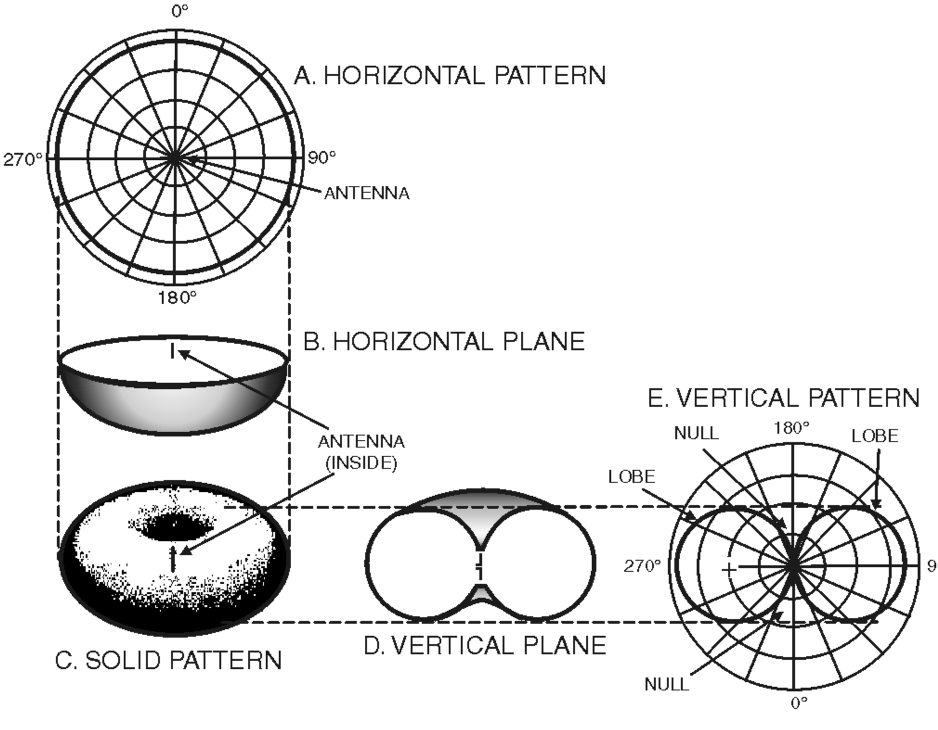


Figure 4-15. Development of Vertical and Horizontal Pattern

4-78. A vertical pattern shown in figure 4-15, view E is depicted from the drawing of the vertical plane (view D) of the radiation pattern shown in view C. The radiation pattern in view C is sliced in half along a vertical plane through the antenna. This produces the vertical plane pattern shown in view D. Note how the vertical plane in view D of the radiation pattern differs from the horizontal plane in view B. The vertical pattern in view E exhibits two lobes and two nulls. The difference between the two patterns is caused by two facts: (1) no radiation is emitted from the ends of the doublet; and (2) maximum radiation comes from the doublet in a direction perpendicular to the antenna axis. This type of radiation pattern is both nondirectional (in a horizontal plane) and directional (in a vertical plane).

4-79. From a practical viewpoint, the doublet antenna can be mounted either vertically or horizontally. The doublet shown in figure 4-15 is mounted vertically, and the radiated energy spreads out about the antenna in every direction in the horizontal plane. Because ordinarily the horizontal plane is the useful plane, this arrangement is termed nondirectional. The directional characteristics of the antenna in other planes are ignored. If the doublet were mounted horizontally, it would have the effect of turning the pattern on edge, reversing the patterns given in figure 4-15. The antenna would then be directional in the horizontal plane. The terms “directional” and “nondirectional” are used for convenience in describing specific radiation patterns. A complete description always involves a figure in three dimensions, as in the radiation pattern of figure 4-15.

4-80. **Radiation pattern of a dipole**. The radiation pattern of a dipole (figure 4-16) is similar to that of the doublet (figure 4-15). Increasing the length of the doublet to one-half wavelength has the effect of flattening out the radiation pattern. The radiation pattern in the horizontal plane of a dipole is a larger circle than that of the doublet. The vertical-radiation pattern lobes are no longer circular. They are flattened out and the radiation intensity is greater.

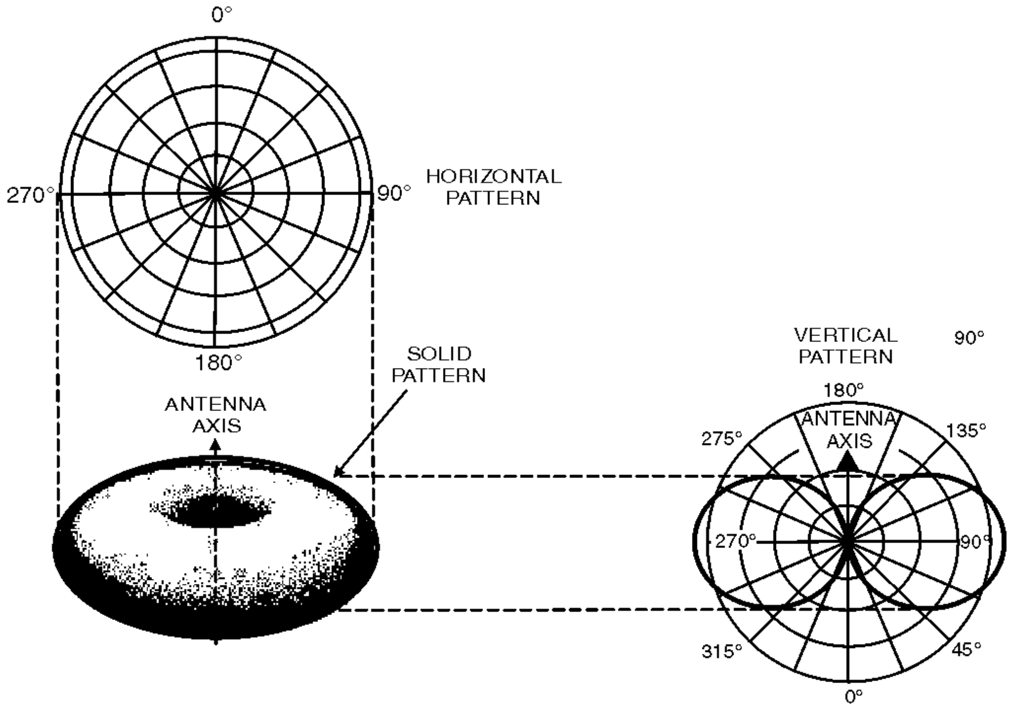


Figure 4-16. Radiation Pattern of a Dipole

Methods of Feeding Energy to an Antenna

4-81. Voltage and current distribution for the half-wave antenna (shown in figure 4-17) is the same as that for the antenna discussed earlier in this chapter. A point closely related to the voltage and current distribution on an antenna is the method of feeding the transmitter output to the antenna. The simplest method of feeding energy to the half-wave antenna is to connect one end through a capacitor to the final output stage of the transmitter. This method is often called the end-feed or voltage-feed method. In this method the antenna is fed at a point of high voltage (the end).

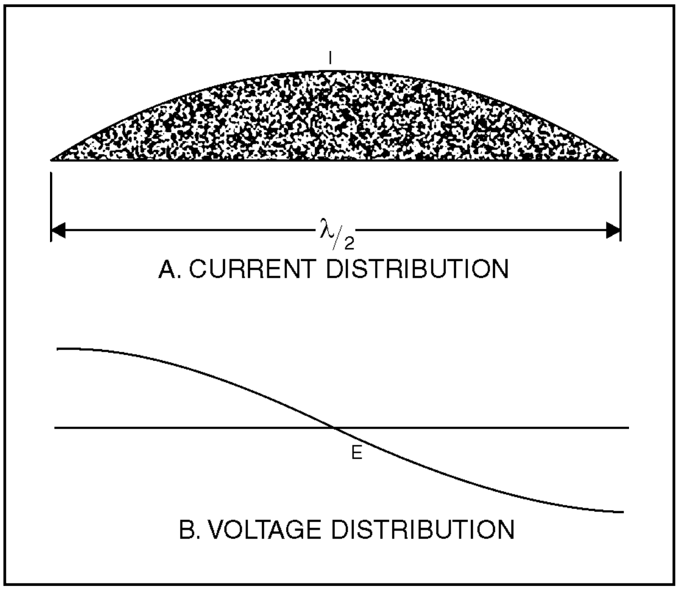


Figure 4-17. Standing Waves of Current and Voltage

4-82. Energy may also be fed to the half-wave antenna by dividing the antenna at its center and connecting the transmission line from the final transmitter output stage to the two center ends of the halved antenna. Because the antenna is now being fed at the center (a point of low voltage and high current), this type of feed is known as the center-feed or current-feed method. The point of feed is important in determining the type of transmission line to be used.

QUARTER-WAVE ANTENNAS

4-83. As you have studied in the previous sections, a one-half wavelength antenna is the shortest antenna that can be used in free space. If we cut a half-wave antenna in half and then ground one end, we will have a grounded quarter-wave or Marconi antenna. This antenna will resonate at the same frequency as the ungrounded half-wave antenna. Quarter-wave antennas are widely used in the military. Most mobile transmitting and receiving antennas (illustrated in figure 4-18) are quarter-wave antennas.

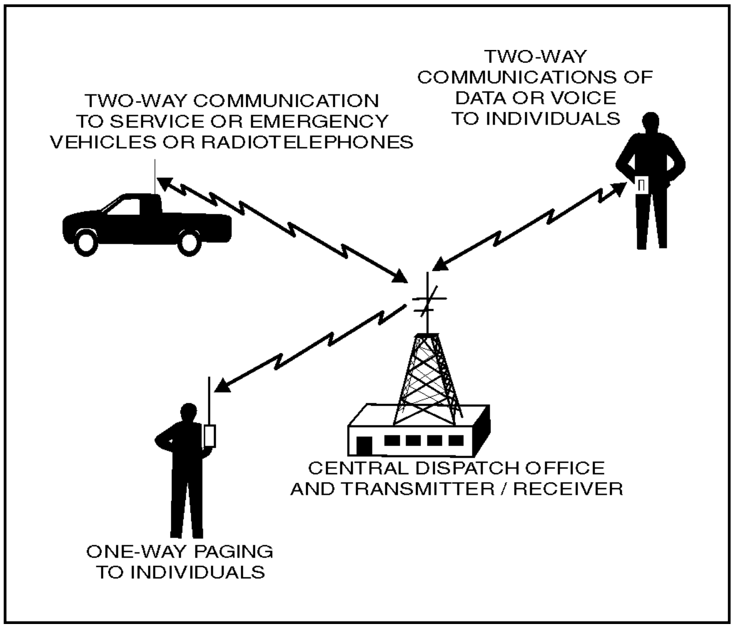


Figure 4-18. Mobile Antennas

4-84. As stated above, a grounded quarter-wave antenna will resonate at the same frequency as an ungrounded half-wave antenna. This is because the ground has high conductivity and acts as an electrical mirror image. This characteristic provides the missing half of the antenna, as shown in the bottom part of figure 4-19. In other words, the grounded quarter-wave antenna acts as if another quarter-wave were actually down in the earth.

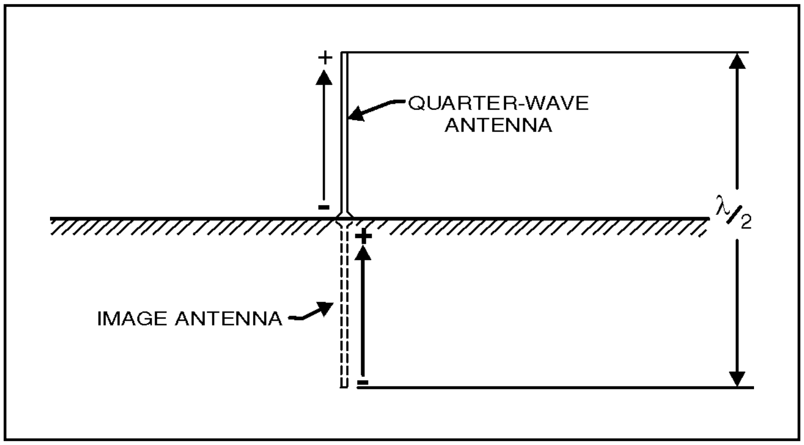


Figure 4-19. Grounded Quarter-Wave Antenna Image

Characteristics of Quarter-Wave Antennas

4-85. The grounded end of the quarter-wave antenna has a low input impedance and has low voltage and high current at the input end, as shown in figure 4-19. The ungrounded end has a high impedance, which causes high voltage and low current. The directional characteristics of a grounded quarter-wave antenna are the same as those of a half-wave antenna in free space.

4-86. As explained earlier, ground losses affect radiation patterns and cause high signal losses for some frequencies. Such losses may be greatly reduced if a perfectly conducting ground is provided in the vicinity of the antenna. This is the purpose of a ground screen (figure 4-20, view A) and counterpoise (view B).

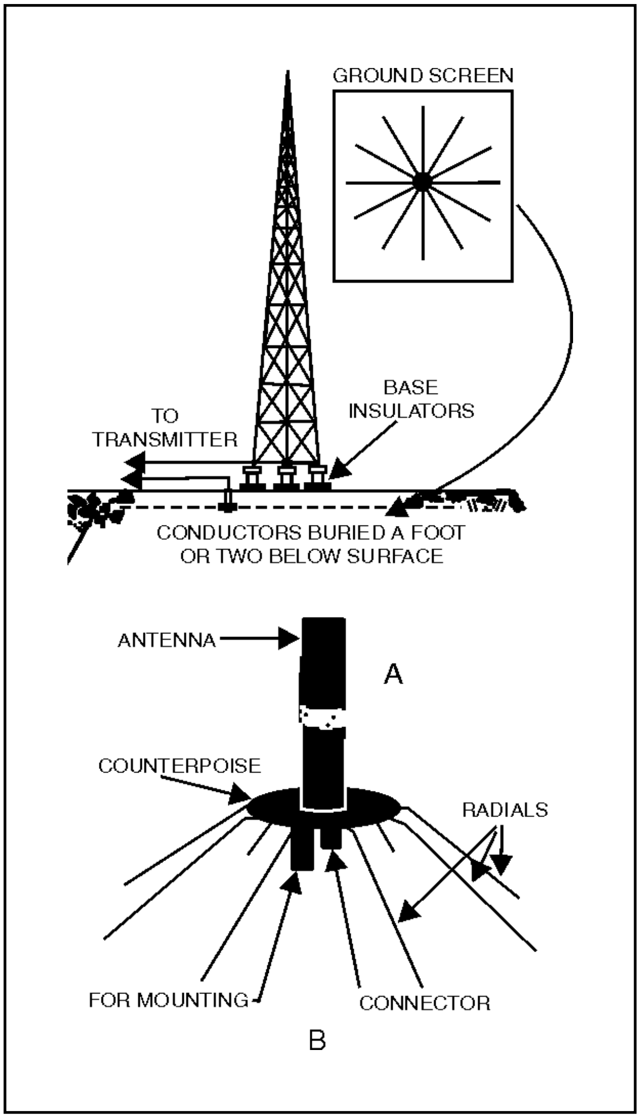


Figure 4-20. Ground Screen and Counterpoise

4-87. The ground screen in figure 4-20, view A is composed of a series of conductors buried 1 to 2 feet (0.3 to 0.6 meter) below the surface of the earth and arranged in a radial pattern. These conductors reduce losses in the ground in the immediate vicinity of the antenna. Such a radial system of conductors is usually one-half wavelength in diameter.

4-88. A counterpoise, as shown in figure 4-20, view B, is used when easy access to the base of the antenna is necessary. It is also used when the earth is not a good conducting surface, such as ground that is sandy or solid rock. The counterpoise serves the same purpose as the ground screen but it is usually elevated above the earth. No specific dimensions are necessary in the construction of a counterpoise nor is the number of wires particularly critical. A practical counterpoise may be assembled from a large screen of chicken wire or some similar material. This screen may be placed on the ground, but better results are obtained if it is placed a few feet above the ground.

FOLDED DIPOLE

4-89. The use of parasitic elements and various stacking arrangements causes a reduction in the radiation resistance of a center-fed, half-wave antenna. Under these conditions, obtaining a proper impedance match between the radiator and the transmission line is often difficult. A convenient method of overcoming these difficulties is to use a folded dipole in place of the center-fed radiator. (See figure 4-21, views A and B).

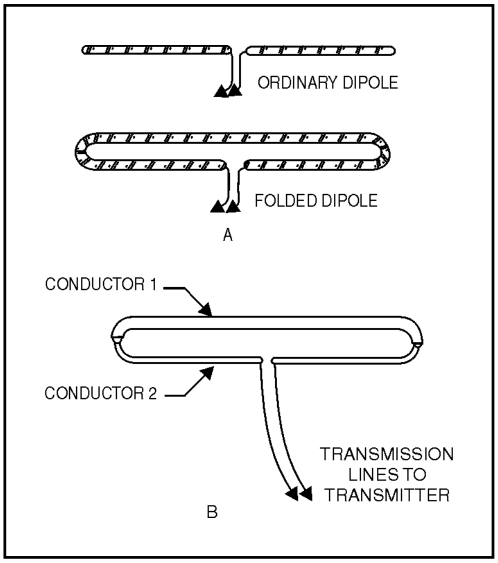


Figure 4-21. Folded-Dipole Antennas

4-90. A folded dipole is an ordinary half-wave antenna that has one or more additional conductors connected across its ends. Additional conductors are mounted parallel to the dipole elements at a distance equal to a very small fraction of a wavelength. Spacing of several inches is common.

4-91. The feed-point impedance can be further increased by using three or four properly spaced parallel conductors. Standard feed-line spreaders are used to maintain this spacing when required. In any folded dipole, the increase of impedance is the square of the number of conductors used in the radiator. Thus, a three-wire dipole has nine times (3^2) the feed-point impedance of a simple center-fed dipole. A second method of stepping up the impedance of a folded dipole is to use two conductors with different radii, as shown in figure 4-21, view B.

4-92. The directional characteristics of a folded dipole are the same as those of a simple dipole. However, the reactance of a folded dipole varies much more slowly as the frequency is varied from resonance. Because of this difference, the folded dipole can be used over a much wider frequency range than is possible with a simple dipole.

ARRAY ANTENNAS

4-93. An array antenna is a special arrangement of basic antenna components. The discussion of array antennas includes the following new terms that you should study before moving on to the section on phasing.

DEFINITION OF TERMS

4-94. An *array antenna* is made up of more than one element, but the basic element is generally the dipole. Sometimes the basic element is made longer or shorter than a half-wave, but the deviation usually is not great.

4-95. A *driven element* is similar to the dipole you have been studying and is connected directly to the transmission line. It obtains its power directly from the transmitter or, as a receiving antenna; it delivers the received energy directly to the receiver. A parasitic element is located near the driven element from which it gets its power. It is placed close enough to the driven element to permit coupling.

4-96. A *parasitic element* is sometimes placed so it will produce maximum radiation (during transmission) from its associated driver. When it operates to reinforce energy coming from the driver toward itself, the parasitic element is referred to as a *director*. If a parasitic element is placed so it causes maximum energy radiation in a direction away from itself and toward the driven element, that parasitic element is called a reflector.

4-97. If all of the elements in an array are driven, the array is referred to as a *driven array* (sometimes as a *connected array*). If one or more elements are parasitic, the entire system usually is considered to be a *parasitic array*.

4-98. Multi-element arrays frequently are classified according to their directivity. A *bidirectional array* radiates in opposite directions along the line of maximum radiation. A *unidirectional array* radiates in only one general direction.

4-99. Arrays can be described with respect to their radiation patterns and the types of elements of which they are made. However, you will find it useful to identify them by the physical placement of the elements and the direction of radiation with respect to these elements. Generally speaking, the term *broadside array* designates an array in which the direction of maximum radiation is perpendicular to the plane containing these elements. In actual practice, this term is confined to those arrays in which the elements themselves are also broadside, or parallel, with respect to each other.

4-100. A *collinear array* is one in which all the elements lie in a straight line with no radiation at the ends of the array. The direction of maximum radiation is perpendicular to the axis of the elements.

4-101. An *end-fire array* is one in which the principal direction of radiation is along the plane of the array and perpendicular to the elements. Radiation is from the end of the array, which is the reason this arrangement is referred to as an end-fire array.

4-102. Sometimes a system uses the characteristics of more than one of the three types mentioned. For instance, some of the elements may be collinear while others may be parallel. Such an arrangement is often referred to as a *combination array* or an *array of arrays*. Because maximum radiation occurs at right angles to the plane of the array, the term *broadside array* is also used.

4-103. The *front-to-back ratio* is the ratio of the energy radiated in the principal direction compared to the energy radiated in the opposite direction for a given antenna.

PHASING

4-104. Various reflected and refracted components of the propagated wave create effects of reinforcement and cancellation. At certain distant points from the transmitter, some of the wave components meet in space. Reception at these points is either impaired or improved. If the different components arrive at a given point in the same phase, they add, making a stronger signal available. If they arrive out of phase, they cancel, reducing the signal strength.

Radiation Pattern

4-105. Effects similar to those described in the preceding paragraph can be produced at the transmitting point itself. Consider the antennas shown in figure 4-22, views A and B. View A shows an unobstructed view of the radiation pattern of a single dipole. In view B, two dipoles, shown as points 1 and 2, are perpendicular to the plane of the page. They are spaced one-quarter wavelength apart at the operating frequency. The radiation pattern from either antenna 1 or 2, operating alone, would be uniform in all directions in this plane, as shown in view A. Suppose that current is being fed to both antennas from the same transmitter in such a way that the current fed to antenna 2 lags the current in antenna 1 by 90 degrees. Energy radiating from antenna 1 toward receiving location X will reach antenna 2 after one-quarter cycle of operation. The energy from both antennas will add, and propagation toward X will be strong.

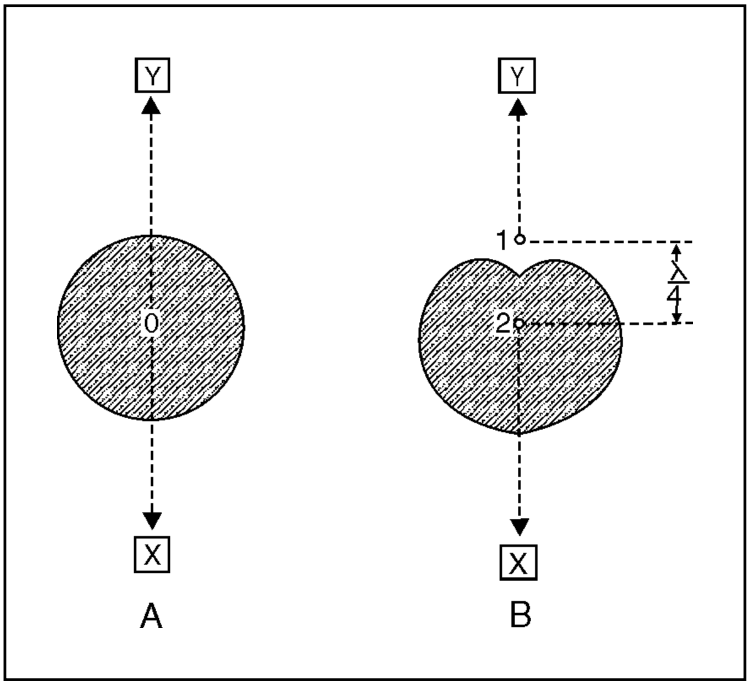


Figure 4-22. Phasing of Antenna in Free Space

4-106. Radiation from antenna 2 toward receiving location Y will reach antenna 1 after one-quarter cycle. The energy in antenna 1 was one-quarter cycle behind that of antenna 2 to begin with; therefore, the radiation from antenna 1 toward receiving point Y will be exactly 180 degrees out of phase with that of antenna 2. As a result, the radiation fields will cancel and there will be no radiation toward Y.

4-107. At receiving points away from the line of radiation, phase differences occur between 0 and 180 degrees, producing varying amounts of energy in that direction. The overall effect can be seen in the radiation pattern illustrated in view B. The physical phase relationship caused by the wavelength spacing between the two elements, as well as the phase of the currents in the elements, has acted to change the radiation pattern of the individual antennas.

Stub Phasing

4-108. In the case just discussed, the currents fed to the two antennas from the same transmitter were 90 degrees out of phase. Sections of transmission line, called stubs, are frequently used for this purpose. These stubs can be adjusted to produce any desired phase relationship between connected elements.

4-109. When two collinear half-wave elements are connected directly so their currents are in the same phase, the effect is the same as that of a full-wave antenna, as shown in figure 4-23, view A. The current in the first one-half wavelength is exactly 180 degrees out of phase with that in the second one-half wavelength. This is the opposite of the desired condition. In the illustration, arrows are used to indicate the direction of current flow in the antenna. (Using arrows is a convenient means of determining the phase on more complicated arrays.)

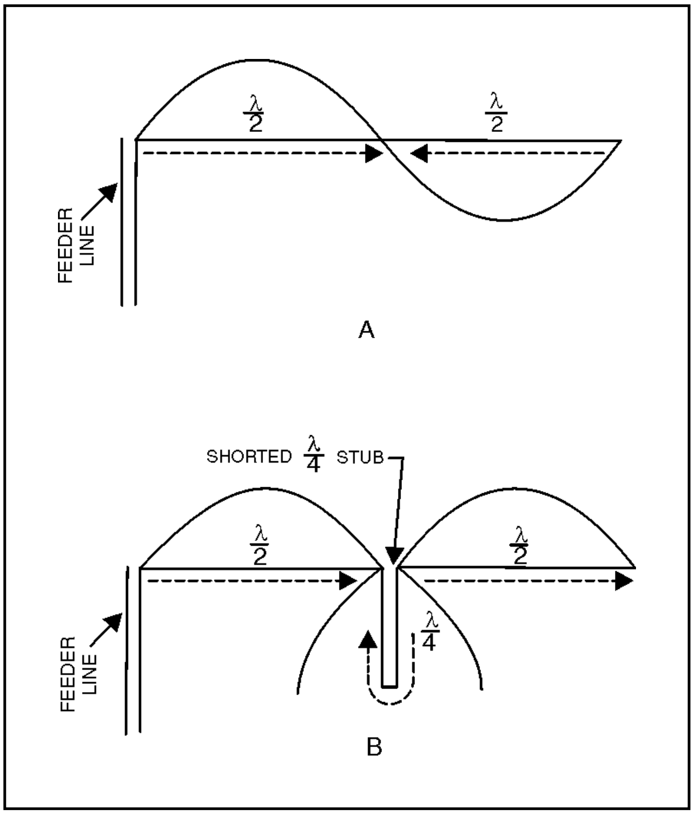


Figure 4-23. Phasing of Connected Elements

4-110. When the two elements are connected by a shorted one-quarter-wavelength stub, as shown in figure 4-23, view B, current travels down one side of the stub and up the other. It travels a distance of one-half wavelength in the stub itself. As a result, the current moves through one-half cycle of change. When the current reaches the second element, it is in the desired phase. Because the current on one side of the stub is equal and opposite to the current on the other side, the fields produced here cancel and no radiation is transmitted from the stub itself.

DIRECTIVITY

4-111. The directivity of an antenna or an array can be determined by looking at its radiation pattern. In an array propagating a given amount of energy, more radiation takes place in certain directions than in others. The elements in the array can be altered in such a way that they change the pattern and distribute it more uniformly in all directions. The elements can be considered as a group of antennas fed from a common source and facing different directions. On the other hand, the elements could be arranged so that the radiation would be focused in a single direction. With no increase in power from the transmitter, the amount of radiation in a given direction would be greater. Because the input power has no increase, this increased directivity is achieved at the expense of gain in other directions.

Directivity and Interference

4-112. In many applications, sharp directivity is desirable although no need exists for added gain. Examine the physical disposition of the units shown in figure 4-24. Transmitters 1 and 2 are sending information to receivers 1 and 2, respectively, along the paths shown by the solid arrows. The distance between transmitter 1 and receiver 1 or between transmitter 2 and receiver 2 is short and does not require high-power transmission. The antennas of the transmitters propagate well in all directions. However, receiver 1 picks up some of the signals from transmitter 2, and receiver 2 picks up some of the signals from transmitter 1, as shown by the broken arrows. This effect is emphasized if the receiving antennas intercept energy equally well in all directions.

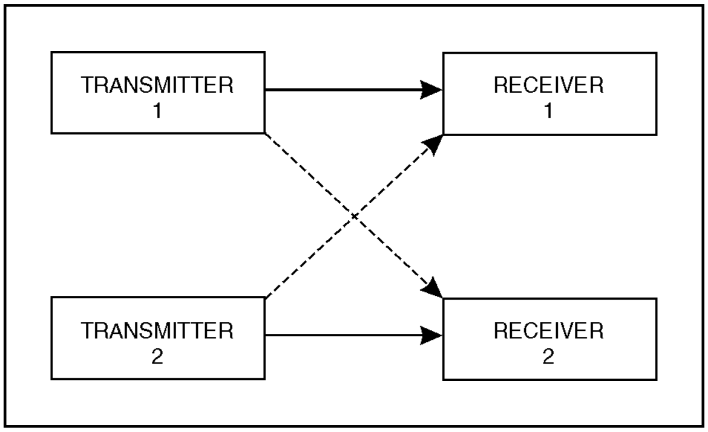


Figure 4-24. Directivity and Interference

4-113. The use of highly directional arrays as radiators from the transmitters tends to solve the problem. The signals are beamed along the paths of the solid arrows and provide very low radiation along the paths of the broken arrows. Further improvement along these lines is obtained by the use of narrowly directed arrays as receiving antennas. The effect of this arrangement is to select the desired signal while discriminating against all other signals. This same approach can be used to overcome other types of radiated interference. In such cases, preventing radiation in certain directions is more important than producing greater gain in other directions.

4-114. Look at the differences between the field patterns of the single-element antenna and the array, as illustrated in figure 4-25. View A shows the relative field-strength pattern for a horizontally polarized single antenna. View B shows the horizontal-radiation pattern for an array. The antenna in view A radiates fairly efficiently in the desired direction toward receiving point X. It radiates equally as efficiently toward Y, although no radiation is desired in this direction. The antenna in view B radiates strongly to point X, but very little in the direction of point Y, which results in more satisfactory operation.

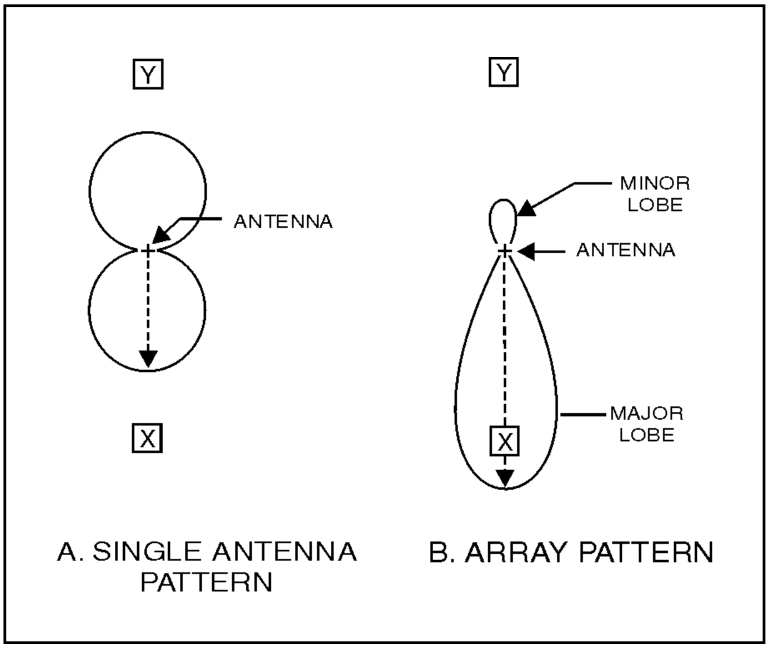


Figure 4-25. Single Antenna Versus Array

Major and Minor Lobes

4-115. The pattern shown in figure 4-25, view B has radiation concentrated in two lobes. The radiation intensity in one lobe is considerably stronger than in the other. The lobe toward point X is called a major lobe; the other is a minor lobe. Because the complex radiation patterns associated with arrays frequently contain several lobes of varying intensity, you should learn to use appropriate terminology. In general, major lobes are those in which the greatest amount of radiation occurs. Minor lobes are those in which the radiation intensity is least.

DIRECTIONAL ARRAYS

4-116. You have already learned about radiation patterns and directivity of radiation. These topics are important to you because using an antenna with an improper radiation pattern or with the wrong directivity will decrease the overall performance of the system. In the following paragraphs, we discuss in more detail the various types of directional antenna arrays mentioned earlier in this chapter.

Collinear Array

4-117. The pattern radiated by the collinear array is similar to that produced by a single dipole. The addition of the second radiator, however, tends to intensify the pattern. Compare the radiation pattern of the dipole (figure 4-26, view A) and the two-element antenna in view B. You will see that each pattern consists of two major lobes in opposite directions along the same axis, QQ1. There is little or no radiation along the PP1 axis. QQ1 represents the line of maximum propagation. You can see that radiation is stronger with an added element. The pattern in view B is sharper, or more directive, than that in view A. This means that the gain along the line of maximum energy propagation is increased and the beam width is decreased.

As more elements are added, the effect is heightened, as shown in view C. Unimportant minor lobes are generated as more elements are added.

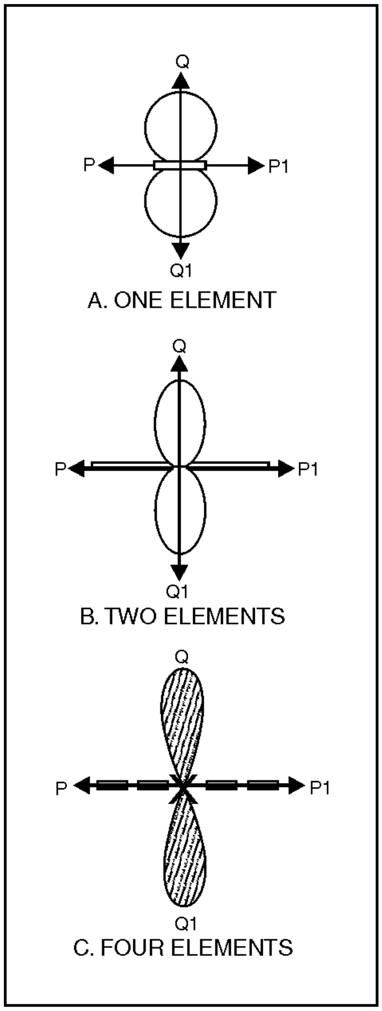


Figure 4-26. Single Half-Wave Antenna versus Two Half-Wave Antenna in Phase

4-118. More than four elements are seldom used because accumulated losses cause the elements farther from the point of feeding to have less current than the nearer ones. This introduces an unbalanced condition in the system and impairs its efficiency. Space limitations often are another reason for restricting the number of elements. Because this type of array is in a single line, rather than in a vertically stacked arrangement, the use of too many elements results in an antenna several wavelengths long.

4-119. **Radiation pattern**. The characteristic radiation pattern of a given array is obtained at the frequency or band of frequencies at which the system is resonant. The gain and directivity characteristics are lost when the antenna is not used at or near this frequency and the array tunes too sharply. A collinear antenna is more effective than an end-fire array when used off its tuned frequency. This feature is considered when transmission or reception is to be over a wide frequency band. When more than two elements are used, this advantage largely disappears.

4-120. **Length and phasing**. Although the one-half wavelength is the basis for the collinear element, you will find that greater lengths are often used. Effective arrays of this type have been constructed in which the elements are 0.7 and even 0.8 wavelength long. This type of array provides efficient operation at more than one frequency or over a wider frequency range. Whatever length is decided upon, all of the elements in a particular array should closely adhere to that length. If elements of different lengths are combined, current phasing and distribution are changed, throwing the system out of balance and seriously affecting the radiation pattern.

4-121. **Spacing**. The lower relative efficiency of collinear arrays of many elements, compared with other multi-element arrays, relates directly to spacing and mutual impedance effects. Mutual impedance is an important factor to be considered when any two elements are parallel and are spaced so that considerable coupling is between them. There is very little mutual impedance between collinear sections. Where impedance does exist, it is caused by the coupling between the ends of adjacent elements. Placing the ends of elements close together is frequently necessary because of construction problems, especially where long lengths of wire are involved.

4-122. The effects of spacing and the advantages of proper spacing can be demonstrated by some practical examples. A collinear array consisting of two half-wave elements with one-half-wavelength spacing between centers has a gain of 1.8 decibels (dB). If the ends of these same dipoles are separated so that the distance from center to center is three-quarters of a wavelength and they are driven from the same source, the gain increases to approximately 2.9 dB.

4-123. A three-dipole array with negligible spacing between elements gives a gain of 3.3 dB. In other words, when two elements are used with wider spacing, the gain obtained is approximately equal to the gain obtainable from three elements with close spacing. The spacing of this array permits simpler construction, because only two dipoles are used. It also allows the antenna to occupy less space. Construction problems usually dictate small-array spacing.

Broadside Arrays

4-124. A broadside array is shown in figure 4-27, view A. Physically, it looks somewhat like a ladder. When the array and the elements in it are polarized horizontally, it looks like an upright ladder. When the array is polarized vertically, it looks like a ladder lying on one side (view B). View C is an illustration of the radiation pattern of a broadside array. Horizontally polarized arrays using more than two elements are not common. This is because the requirement that the bottom of the array be a significant distance above the earth presents construction problems. Compared with collinear arrays, broadside arrays tune sharply, but lose efficiency rapidly when not operated on the frequencies for which they are designed.

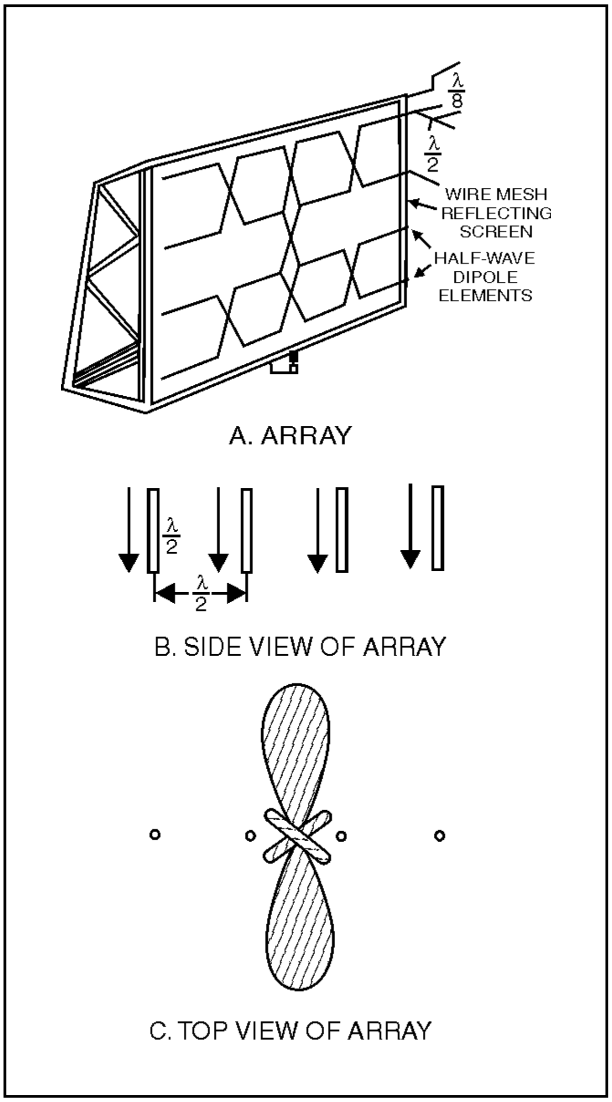


Figure 4-27. Typical Broadside Array

4-125. **Radiation pattern**. Figure 4-28 shows an end view of two parallel half-wave antennas (A and B) operating in the same phase and located one-half wavelength apart. At a point (P) far removed from the antennas, the antennas appear as a single point. Energy radiating toward P from antenna A starts out in phase with the energy radiating from antenna B in the same direction. Propagation from each antenna travels over the same distance to point P, arriving there in phase. The antennas reinforce each other in this direction, making a strong signal available at P. Field strength measured at P is greater than it would be if the total power supplied to both antennas had been fed to a single dipole. Radiation toward point P1 is built up in the same manner.

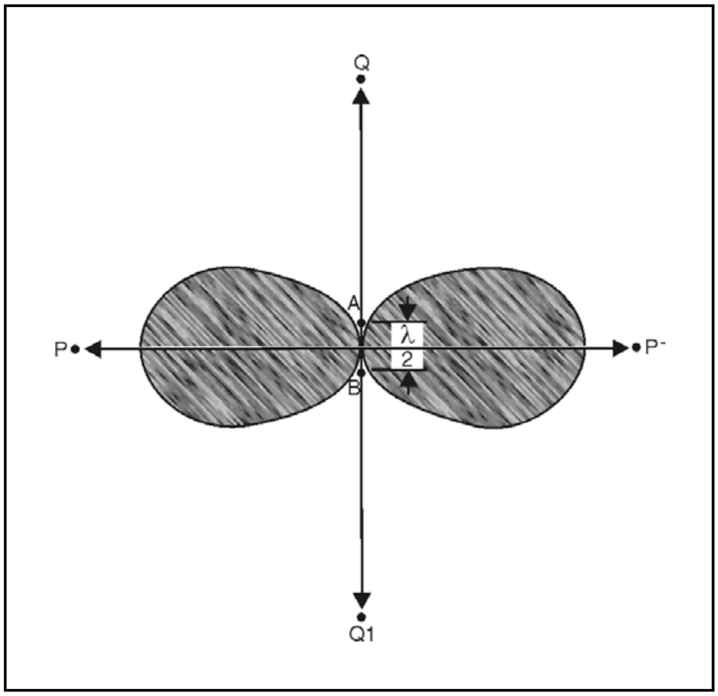


Figure 4-28. Parallel Elements in Phase

4-126. Next consider a wavefront traveling toward point Q from antenna B. By the time it reaches antenna A, one-half wavelength away, one-half cycle has elapsed. Therefore energy from antenna B meets the energy from antenna A 180 degrees out of phase. As a result, the energy moving toward point Q from the two sources cancels. In a like manner, radiation from antenna A traveling toward point Q1 meets and cancels the radiation in the same direction from antenna B. As a result, little propagation takes place in either direction along the QQ1 axis. Most of the energy is concentrated in both directions along the PP1 axis. When both antenna elements are fed from the same source, the result is the basic broadside array.

4-127. When more than two elements are used in a broadside arrangement, they are all parallel and in the same plane, as shown in figure 4-27, view B. Current phase, indicated by the arrows, must be the same for all elements. The radiation pattern shown in figure 4-27, view C, and is always bidirectional. This pattern is sharper than the one shown in figure 4-28 because of the additional two elements. Directivity and gain depend on the number of elements and the spacing between them.

4-128. **Gain and directivity**. The physical disposition of dipoles operated broadside to each other allows for much greater coupling between them than can occur between collinear elements. Moving the parallel antenna elements closer together or farther apart affects the actual impedance of the entire array and the overall radiation resistance as well. As the spacing between broadside elements increases, the effect on the radiation pattern is a sharpening of the major lobes. When the array consists of only two dipoles spaced exactly one-half wavelength apart, no minor lobes are generated at all. Increasing the distance between the elements beyond that point, however, tends to throw off the phase relationship between the original current in one element and the current induced in it by the other element. The result is that, although the major lobes are sharpened, minor lobes are introduced, even with two elements. These minor lobes, however, are not large enough to be of concern.

4-129. If you add the same number of elements to both a broadside array and a collinear array, the gain of the broadside array will be greater. Reduced radiation resistance resulting from the efficient coupling between dipoles accounts for most of this gain. However, certain practical factors limit the number of elements that may be used. The construction problem increases with the number of elements, especially when they are polarized horizontally.

End-Fire Arrays

4-130. An end-fire array looks similar to a broadside array. The ladder-like appearance is characteristic of both (figure 4-29, view A). The currents in the elements of the end-fire array, however, are usually 180 degrees out of phase with each other as indicated by the arrows. The construction of the end-fire array is like that of a ladder lying on its side (elements horizontal). The dipoles in an end-fire array are closer together (one-eighth wavelength to one-quarter wavelength spacing) than they are for a broadside array.

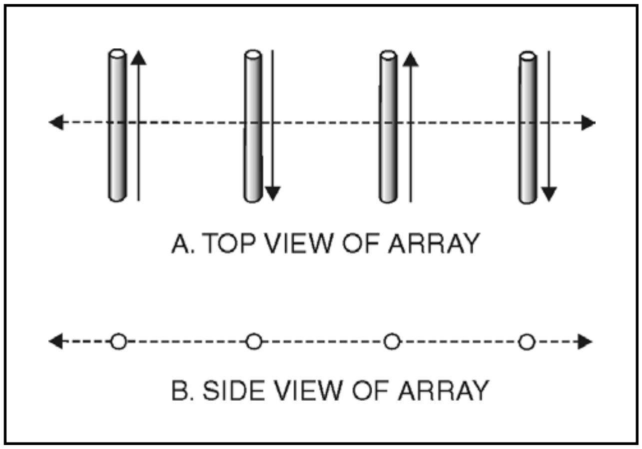


Figure 4-29. Typical End-Fire Array

4-131. Closer spacing between elements permits compactness of construction. For this reason, an end-fire array is preferred to other arrays when high gain or sharp directivity is desired in a confined space. However, the close coupling creates certain disadvantages. Radiation resistance is extremely low, sometimes as low as 10 ohms, making antenna losses greater. The end-fire array is confined to a single frequency. With changes in climatic or atmospheric conditions, the danger of detuning exists.

4-132. **Radiation pattern**. The radiation pattern for a pair of parallel half-wave elements fed 180 degrees out of phase is shown in figure 4-30, view A. The elements shown are spaced one-half wavelength apart. In practice, smaller spacings are used. Radiation from elements L and M traveling toward point P begins 180 degrees out of phase. Moving the same distance over approximately parallel paths, the respective wavefronts from these elements remain 180 degrees out of phase. In other words, maximum cancellation takes place in the direction of P. The same condition is true for the opposite direction (toward P1). The P to P1 axis is the line of least radiation for the end-fire array.

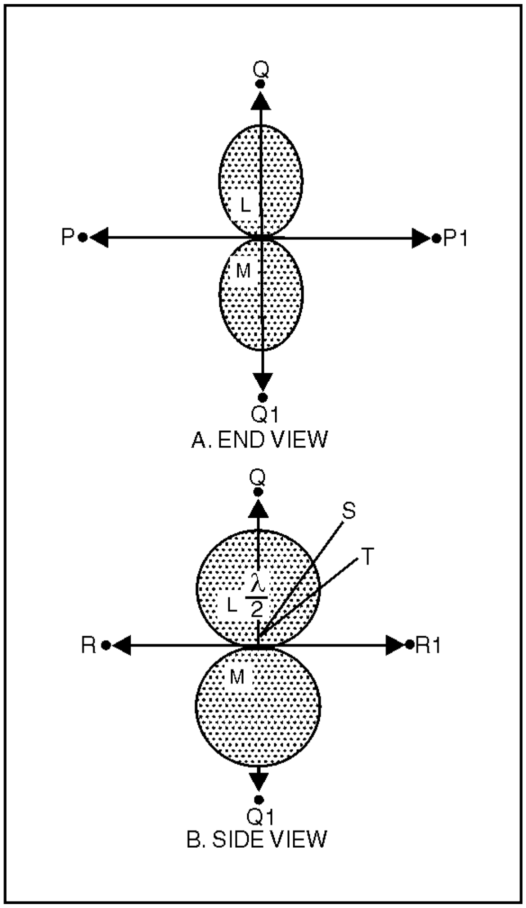


Figure 4-30. Parallel Elements 180 Degrees Out of Phase

4-133. Consider what happens along the QQ1 axis. Energy radiating from element M toward Q reaches element L in about one-half cycle (180 degrees) after it leaves its source. Because element L was fed 180 degrees out of phase with element M, the wavefronts are now in the same phase and are both moving toward Q and reinforcing each other. Similar reinforcement occurs along the same axis toward Q1. This simultaneous movement towards Q and Q1 develops a bidirectional pattern. This is not always true in end-fire operation. Another application of the end-fire principle is one in which the elements are spaced one-quarter wavelength apart and phased 90 degrees from each other to produce a unidirectional pattern.

4-134. In figure 4-30, view A, elements A and B are perpendicular to the plane represented by the page; therefore, only the ends of the antennas appear. In view B, the antennas are rotated a quarter of a circle in space around the QQ1 axis so that they are seen in the plane of the elements themselves. Therefore, the PP1 axis, now perpendicular to the page, is not seen as a line. The RR1 axis, now seen as a line, is perpendicular to the PP1 axis as well as to the QQ1 axis. The end-fire array is directional in this plane also, although not quite as sharply. The reason for the greater broadness of the lobes can be seen by following the path of energy radiating from the midpoint of element B toward point S in view B. This energy passes the A element at one end after traveling slightly more than the perpendicular distance between the dipoles. Energy, therefore, does not combine in exact phase toward point S. Although maximum radiation cannot take place in this direction, energy from the two sources combines closely enough in phase to produce considerable reinforcement. A similar situation exists for wavefronts traveling toward T. However; the wider angle from Q to T produces a greater phase difference and results in a decrease in the strength of the combined wave.

4-135. Directivity occurs from either one or both ends of the end-fire array, along the axis of the array, as shown by the broken arrows in figure 4-29, view A; hence, the term end-fire is used.

4-136. The major lobe or lobes occur along the axis of the array. The pattern is sharper in the plane that is at right angles to the plane containing the elements (figure 4-30, view A). If the elements are not exact half-wave dipoles, operation is not significantly affected. However, because of the required balance of phase relationships and critical feeding, the array must be symmetrical. Folded dipoles, such as the one shown in figure 4-21, view A, are used frequently because the impedance at their terminals is higher. This is an effective way of avoiding excessive antenna losses. Another expedient to reduce losses is the use of tubular elements of wide diameter.

4-137. **Gain and directivity**. In end-fire arrays, directivity increases with the addition of more elements and with spacings approaching the optimum. The directive pattern for a two-element, bidirectional system is illustrated in figure 4-30. View A shows radiation along the array axis in a plane perpendicular to the dipoles, and view B shows radiation along the array axis in the plane of the elements. These patterns were developed with a 180-degree phase difference between the elements. Additional elements introduce small, minor lobes.

4-138. With a 90-degree phase difference in the energy fed to a pair of end-fire elements spaced approximately one-quarter wavelength apart, unidirectional radiation can be obtained. The pattern perpendicular to the plane of the two elements is shown in figure 4-31, view A. The pattern shown in view B, taken in the same plane, is for a six-element array with 90-degree phasing between adjacent elements. Because both patterns show relative gain only, the increase in gain produced by the six-element array is not evident. End-fire arrays are the only unidirectional arrays wholly made up of driven elements.

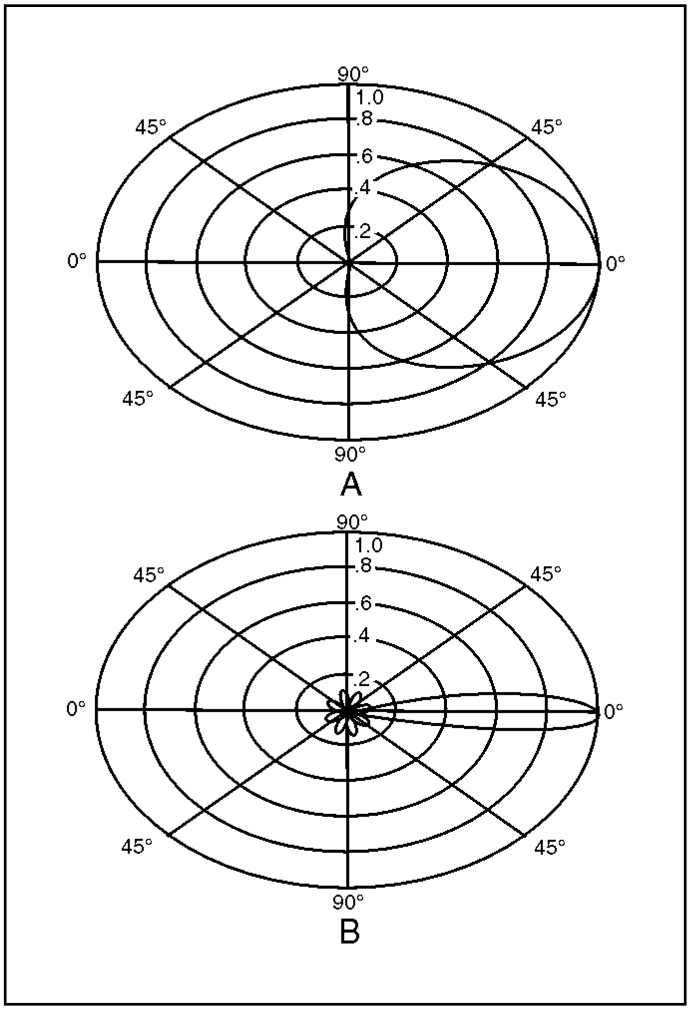


Figure 4-31. Unidirectional End-Fire Arrays

Parasitic Arrays

4-139. If a small light bulb were placed in the center of a large room, the illumination would be very poor. However, if a reflector were placed behind the bulb, the space in front of the reflector would be brighter and the space behind the reflector would be dimmer. The light rays would be concentrated. Also, if a lens were placed in front of the bulb, the light would be even more concentrated and a very bright spot would appear on the wall in front of the lens. A flashlight is a practical combination of the small bulb, the reflector, and the lens. The energy from an antenna can be reflected and concentrated in a similar manner.

4-140. Although we do not usually discuss the gain of a flashlight, we can continue the comparison of an antenna and a flashlight to explain the meaning of antenna gain. Suppose the spot on the wall in front of the flashlight becomes 10 times brighter than it was when only the open bulb was used. The lens and reflector have then produced a 10-fold gain in light. For antennas, the simple half-wave antenna corresponds to the open bulb in the flashlight. Suppose an antenna system concentrates the radio waves so that at a particular point the field strength is 10 times more than it would be at the same distance from a half-wave antenna. The antenna system is then said to have a gain of 10.

4-141. Parasitic arrays represent another method of achieving high antenna gains. A parasitic array consists of one or more parasitic elements placed in parallel with each other and, in most cases, at the same line-of-sight level. The parasitic element is fed inductively by radiated energy coming from the driven element connected to the transmitter. It is in no way connected directly to the driven element.

4-142. When the parasitic element is placed so that it radiates away from the driven element, the element is a director. When the parasitic element is placed so that it radiates toward the driven element, the parasitic element is a reflector.

4-143. The directivity pattern resulting from the action of parasitic elements depends on two factors:

- The tuning determined by the length of the parasitic element.
- The spacing between the parasitic and driven elements.

To a lesser degree, the directivity pattern also depends on the diameter of the parasitic element, because diameter has an effect on tuning.

4-144. **Operation**. When a parasitic element is placed a fraction of a wavelength away from the driven element and is of approximately resonant length, it will re-radiate the energy it intercepts. The parasitic element is effectively a tuned circuit coupled to the driven element, much as the two windings of a transformer are coupled together. The radiated energy from the driven element causes a voltage to be developed in the parasitic element, which, in turn, sets up a magnetic field. This magnetic field extends over to the driven element, which then has a voltage induced in it. The magnitude and phase of the induced voltage depend on the length of the parasitic element and the spacing between the elements. In actual practice the length and spacing are arranged so that the phase and magnitude of the induced voltage cause a unidirectional, horizontal-radiation pattern and an increase in gain.

4-145. In the parasitic array in figure 4-32, view A, the parasitic and driven elements are spaced one-quarter wavelength apart. The radiated signal coming from the driven element strikes the parasitic element after one-quarter cycle. The voltage developed in the parasitic element is 180 degrees out of phase with that of the driven element. This is because of the distance traveled (90 degrees) and because the induced current lags the inducing flux by 90 degrees (90 + 90 = 180 degrees). The magnetic field set up by the parasitic element induces a voltage in the driven element one-quarter cycle later because the spacing between the elements is one-quarter wavelength. This induced voltage is in phase with that in the driven element and causes an increase in radiation in the direction indicated in figure 4-32, view A. Because the direction of the radiated energy is stronger in the direction away from the parasitic element (toward the driven element), the parasitic element is called a reflector. The radiation pattern as it would appear if you were looking down on the antenna is shown in view B. The pattern as it would look if viewed from the ends of the elements is shown in view C.

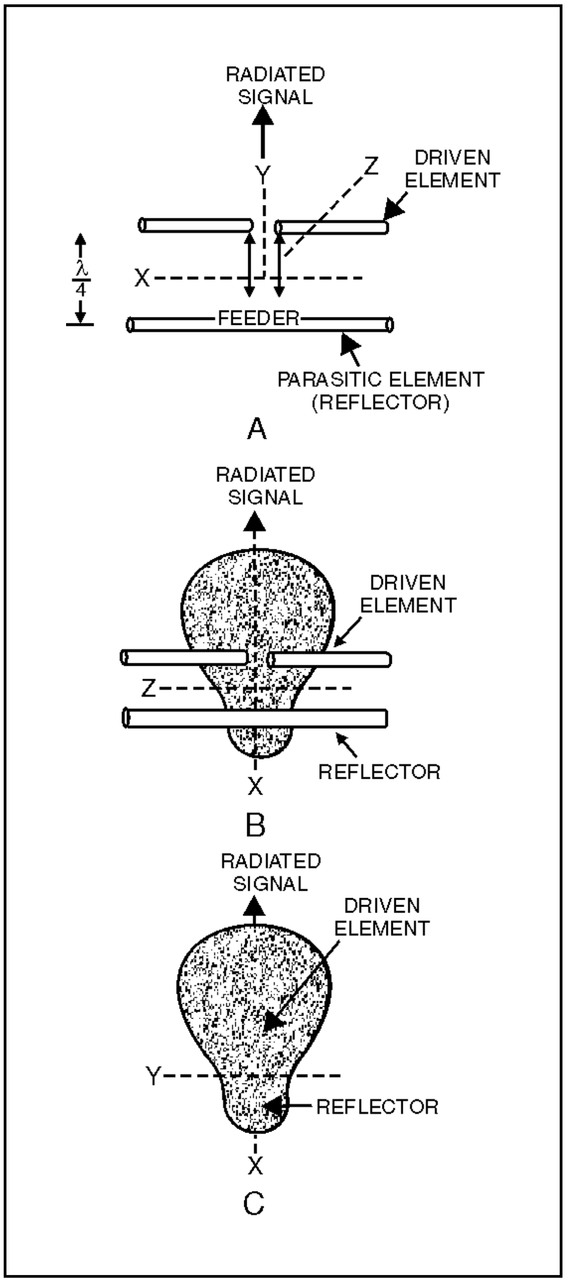


Figure 4-32. Patterns Obtained Using a Reflector with Proper Spacing

4-146. Because the voltage induced in the reflector is 180 degrees out of phase with the signal produced at the driven element, a reduction in signal strength exists behind the reflector. Because the magnitude of an induced voltage never quite equals that of the inducing voltage, even in very closely coupled circuits, the energy behind the reflector (minor lobe) is not reduced to 0.

4-147. The spacing between the reflector and the driven element can be reduced to about 15 percent of a wavelength. The parasitic element must be made electrically inductive before it will act as a reflector. If this parasitic element is made about 5 percent longer than one-half wavelength, it will act as a reflector when the spacing is 15 percent of a wavelength.

4-148. Changing the spacing and length can change the radiation pattern so that maximum radiation is on the same side of the driven element as the parasitic element. In this instance, the parasitic element is called a director.

4-149. Combining a reflector and a director with the driven element causes a decrease in back radiation and an increase in directivity. This combination results in the two main advantages of a parasitic array—unidirectivity and increased gain. If the parasitic array is rotated, it can pick up or transmit in different directions because of the reduction of transmitted energy in all but the desired direction. An antenna of this type is called a rotary array. Size for size, both the gain and directivity of parasitic arrays are greater than those of driven arrays. The disadvantage of parasitic arrays is that their adjustment is critical and they do not operate over a wide frequency range.

4-150. **Gain and directivity**. Changing the spacing between either the director or the reflector and the driven element results in a change in the radiation pattern. More gain and directivity are obtained by changing the length of the parasitic elements.

4-151. The front-to-back ratio of an array is the proportion of energy radiated in the principal direction of radiation to the energy radiated in the opposite direction. A high front-to-back ratio is desirable because this means that a minimum amount of energy is radiated in the undesired direction. Because completely suppressing all such radiation is impossible, an infinite ratio cannot be achieved. In actual practice, however, rather high values can be attained. Usually the length and spacing of the parasitic elements are adjusted so that a maximum front-to-back ratio is obtained, rather than maximum gain in the desired direction.

Multi-Element Parasitic Array

4-152. A multi-element parasitic array is one that contains two or more parasitic elements with the driven element. If the array contains two parasitic elements (a reflector and a director) in addition to the driven element, it is usually known as a three-element array. If three parasitic elements are used, the array is known as a four-element array, and so on. Generally speaking, if more parasitic elements are added to a three-element array, each added element is a director. The field behind a reflector is so small that additional reflectors would have little effect on the overall radiation pattern. In radar, from one to five directors are used.

4-153. **Construction**. The parasitic elements of a multi-element parasitic array usually are positioned as shown in figure 4-33, views A and B. Proper spacings and lengths are determined experimentally. A folded dipole (view B) is often used as the driven element to obtain greater values of radiation resistance.

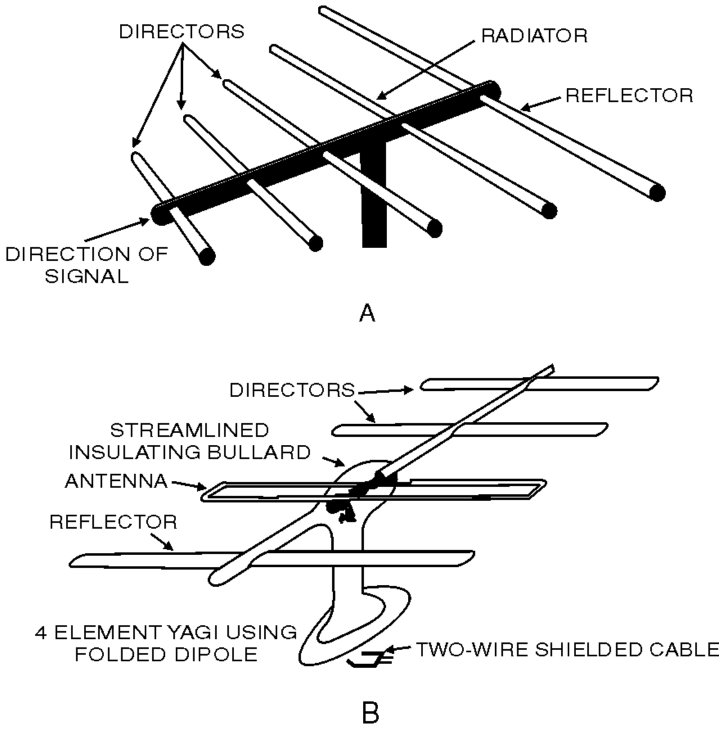


Figure 4-33. Yagi Antenna

4-154. **Yagi antennas**. An example of a multi-element parasitic array is the yagi antenna (figure 4-33, views A and B). The spacings between the elements are not uniform. The radiation from the different elements arrives in phase in the forward direction, but out of phase by various amounts in the other directions.

4-155. The director and the reflector in the yagi antenna are usually welded to a conducting rod or tube at their centers. This support does not interfere with the operation of the antenna. Because the driven element is center-fed, it is not welded to the supporting rod. Using a folded dipole as the driven element can increase the center impedance.

4-156. The yagi antenna shown in figure 4-33, view A, has three directors. In general, the greater number of parasitic elements used, the greater the gain. However, a greater number of such elements cause the array to have a narrower frequency response as well as a narrower beam width. Therefore, proper adjustment of the antenna is critical. The gain does not increase directly with the number of elements used. For example, a three-element yagi array has a relative power gain of 5 dB. Adding another director results in a 2 dB increase. Additional directors have less and less effect.

4-157. A typical yagi array used for receiving and transmitting energy is shown with a support frame in figure 4-34. This antenna is used by the military services. It operates at frequencies of from 12 to 50 megahertz and consists of two separate arrays (one high frequency and one low frequency antenna array) mounted on one frame. The various elements are indicated in the figure. The high-frequency (HF) array consists of one reflector, one driven element, and two directors; the low-frequency (LF) array has the same arrangement with one less director. The lengths of the elements in the high-frequency array are shorter than those in the low-frequency array. The physical lengths of the elements in the individual arrays are equal, but the electrical lengths can be varied by means of the tuning stubs at the center of the elements. The array can be rotated in any desired direction by a remotely controlled, electrically driven, antenna rotator.

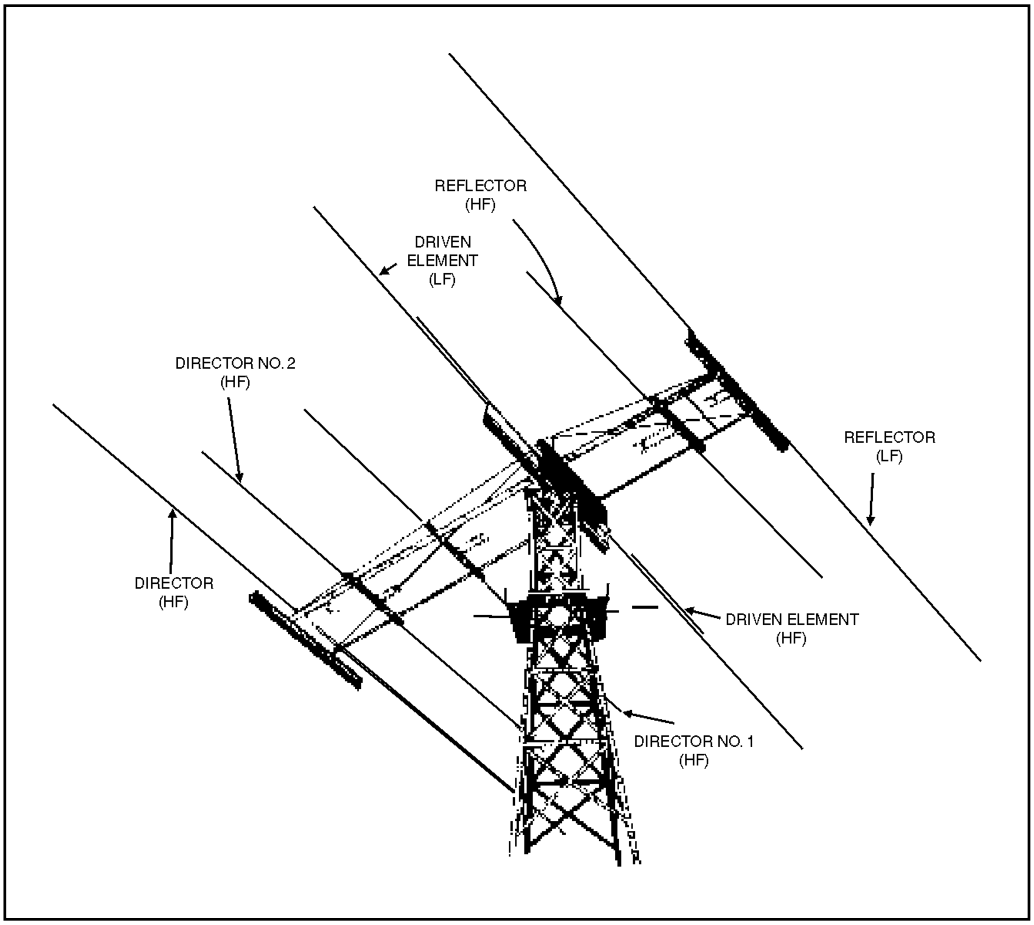


Figure 4-34. Typical Parasitic Array Used for Transmitting and Receiving

SPECIAL ANTENNAS

4-158. In this section we cover some special communications and radar antennas. Some of these antennas we touch on only briefly because they are covered thoroughly in other courses.

4-159. Previously discussed antennas operate with standing waves of current and voltage along the wires. This section deals principally with antenna systems in which the current is practically uniform in all parts of the antenna. In its basic form, such an antenna consists of a single wire grounded at the far end through a resistor. The resistor has a value equal to the characteristic impedance of the antenna. This termination, just as in the case of an ordinary transmission line, eliminates standing waves. The current, therefore, decreases uniformly along the wire as the terminated end is approached. This decrease is caused by the loss of energy through radiation. The energy remaining at the end of the antenna is dissipated in the terminating resistor. For such an antenna to be a good radiator, its length must be fairly long. Also, the wire must not be too close to the ground. The return path through the ground will cause cancellation of the radiation. If the wire is sufficiently long, it will be practically nonresonant over a wide range of operating frequencies.

Long-Wire Antenna

4-160. A long-wire antenna is an antenna that is one wavelength or longer at the operating frequency. In general, the gain achieved with long-wire antennas is not as great as the gain obtained from the multi-element arrays studied in the previous section. But the long-wire antenna has advantages of its own. The construction of long-wire antennas is simple, both electrically and mechanically, with no particularly critical dimensions or adjustments. The long-wire antenna will work well and give satisfactory gain and directivity over a frequency range up to twice the value for which it was cut. In addition, it will accept power and radiate it efficiently on any frequency for which its overall length is not less than approximately one-half wavelength. Another factor is that long-wire antennas have directional patterns that are sharp in both the horizontal and vertical planes. Also, they tend to concentrate the radiation at the low vertical angles.

4-161. Another type of long-wire antenna is the beverage antenna, also called a wave antenna. It is a horizontal, long-wire antenna designed especially for the reception and transmission of low frequency, vertically polarized ground waves. It consists of a single wire, two or more wavelengths long, supported 3 to 6 meters above the ground, and terminated in its characteristic impedance, as shown in figure 4-35.

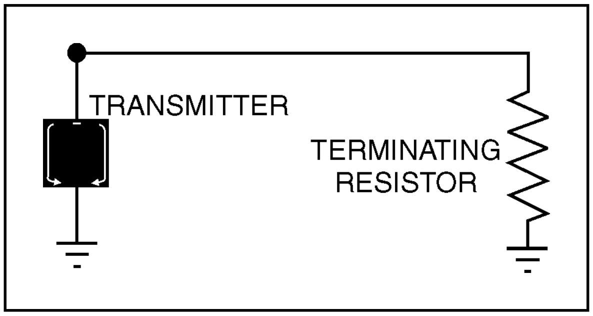


Figure 4-35. Beverage Antenna

V Antenna

4-162. A V antenna is a bidirectional antenna used widely in military and commercial communications. It consists of two conductors arranged to form a V. Each conductor is fed with currents of opposite polarity.

4-163. The V is formed at such an angle that the main lobes reinforce along the line bisecting the V and make a very effective directional antenna (see figure 4-36). Connecting the two-wire feed line to the apex of the V and exciting the two sides of the V 180 degrees out of phase causes the lobes to add along the line of the bisector and to cancel in other directions, as shown in figure 4-37. The lobes are designated 1, 2, 3, and 4 on leg AA', and 5, 6, 7, and 8 on leg BB'. When the proper angle between AA' and BB' is chosen, lobes 1 and 4 have the same direction and combine with lobes 7 and 6, respectively. This combination of two major lobes from each leg results in the formation of two stronger lobes, which lie along an imaginary line bisecting the enclosed angle. Lobes 2, 3, 5, and 8 tend to cancel each other, as do the smaller lobes, which are approximately at right angles to the wire legs of the V. The resultant waveform pattern is shown at the right of the V antenna in figure 4-37.

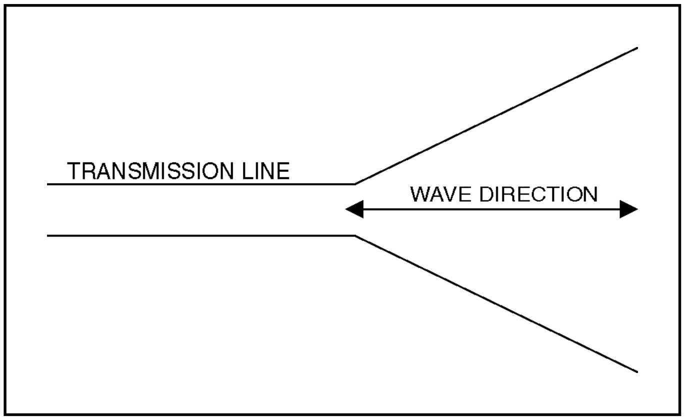


Figure 4-36. Basic V Antenna

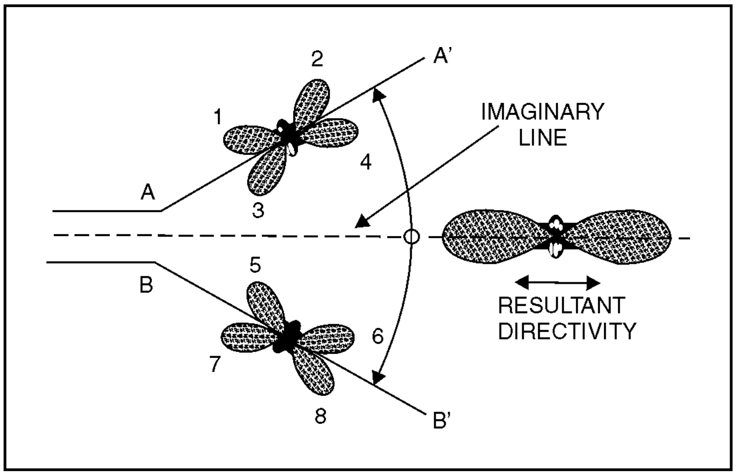


Figure 4-37. Formation of Directional Radiation from a Resonant V Antenna

Rhombic Antenna

4-164. The highest development of the long-wire antenna is the rhombic antenna (see figure 4-38). It consists of four conductors joined to form a rhombus, or diamond shape. The antenna is placed end to end and terminated by a noninductive resistor to produce a unidirectional pattern. A rhombic antenna can be made of two obtuse-angle V antennas that are placed side by side, erected in a horizontal plane, and terminated so the antenna is nonresonant and unidirectional. The rhombic antenna is widely used for long-distance, high-frequency transmission and reception. It is one of the most popular fixed-station antennas because it is very useful in point-to-point communications.

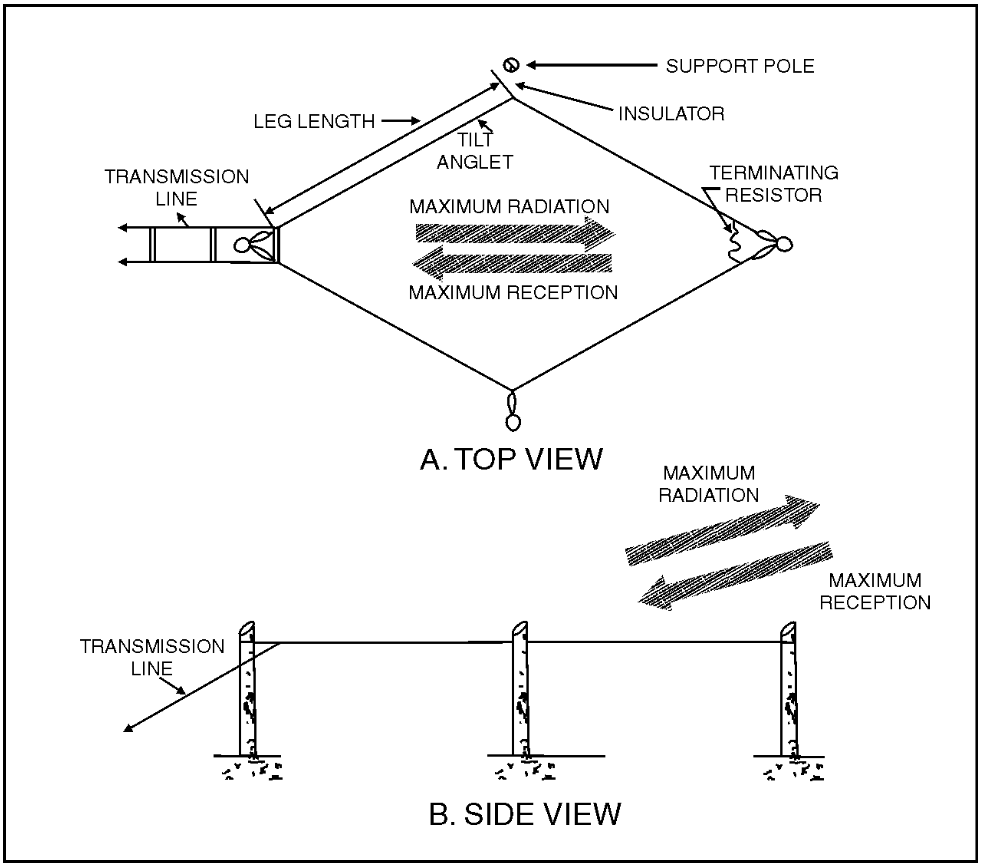


Figure 4-38. Basic Rhombic Antenna

4-165. **Advantages**. The rhombic antenna is useful over a wide frequency range. Although some changes in gain, directivity, and characteristic impedance do occur with a change in operating frequency, these changes are small enough to be ignored.

4-166. The rhombic antenna is much easier to construct and maintain than other antennas of comparable gain and directivity. Only four supporting poles of common heights from 15 to 20 meters are needed for the antenna.

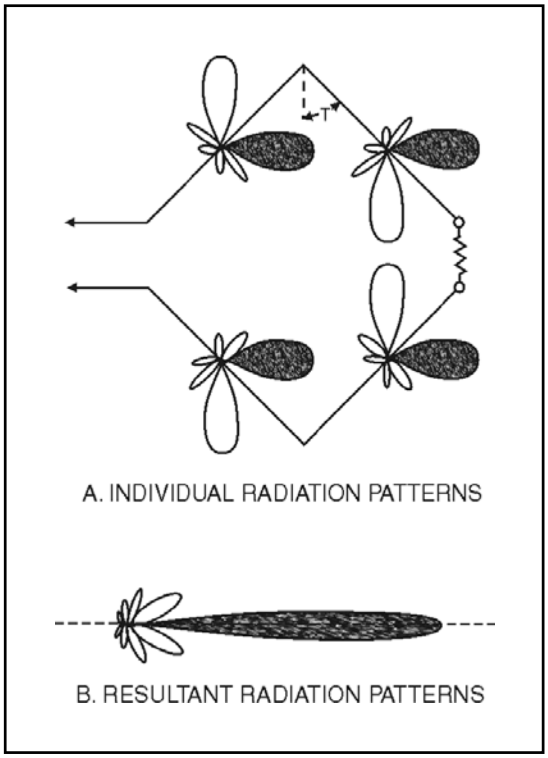
4-167. The rhombic antenna also has the advantage of being noncritical as far as operation and adjustment are concerned. This is because of the broad frequency characteristics of the antenna.

4-168. Still another advantage is that the voltages present on the antenna are much lower than those produced by the same input power on a resonant antenna. This is particularly important when high transmitter powers are used or when high-altitude operation is required.

4-169. **Disadvantages**. The rhombic antenna is not without its disadvantages. The principal one is that a fairly large antenna site is required for its erection. Each leg is made at least 1 or 2 wavelengths long at the lowest operating frequency. When increased gain and directivity are required, legs of from 8 to 12 wavelengths are used. These requirements mean that high-frequency rhombic antennas have wires of several hundred feet in length. Therefore, they are used only when a large plot of land is available.

4-170. Another disadvantage is that the horizontal and vertical patterns depend on each other. If a rhombic antenna is made to have a narrow horizontal beam, the beam is also lower in the vertical direction. Therefore, obtaining high vertical-angle radiation is impossible except with a very broad horizontal pattern and low gain. Rhombic antennas are used, however, for long-distance skywave coverage at the high frequencies. Under these conditions low vertical angles of radiation (less than 20 degrees) are desirable. With the rhombic antenna, a considerable amount of the input power is dissipated uselessly in the terminating resistor. However, this resistor is necessary to make the antenna unidirectional. The great gain of the antenna more than makes up for this loss.

4-171. **Radiation patterns**. Figure 4-39 shows the individual radiation patterns produced by the four legs of the rhombic antenna and the resultant radiation pattern. The principle of operation is the same as for the V and the half-rhombic antennas.



A. INDIVIDUAL RADIATION PATTERNS

B. RESULTANT RADIATION PATTERNS

Figure 4-39. Formation of a Rhombic Antenna Beam

4-172. **Terminating resistor**. The terminating resistor plays an important part in the operation of the rhombic antenna. Upon it depend the unidirectivity of the antenna and the lack of resonance effects. An antenna should be properly terminated so it will have constant impedance at its input. Terminating the antenna properly will also allow it to be operated over a wide frequency range without needing to change the coupling adjustments at the transmitter. The reduction of back radiation is perhaps of lesser importance for transmission. When an antenna is terminated with resistance, the energy that would be radiated backward is absorbed in the resistor.

Turnstile Antenna

4-173. The turnstile antenna is one of the many types that has been developed primarily for omnidirectional VHF communications. The basic turnstile consists of two horizontal half-wave antennas mounted at right angles to each other in the same horizontal plane. When these two antennas are excited with equal currents 90 degrees out of phase, the typical figure-eight patterns of the two antennas merge to produce the nearly circular pattern shown in figure 4-40, view A. Pairs of such antennas are frequently stacked, as shown in figure 4-41. Each pair is called a bay. In figure 4-41 two bays are spaced one-half wavelength apart. Their corresponding elements are excited in phase. These conditions cause a part of the vertical radiation from each bay to cancel that of the other bay. This cancellation results in a decrease in energy radiated at high vertical angles and increases the energy radiated in the horizontal plane. Stacking a number of bays can alter the vertical radiation pattern, causing a substantial gain in a horizontal direction without altering the overall horizontal directivity pattern. Figure 4-40, view B, compares the circular vertical radiation pattern of a single-bay turnstile with the sharp pattern of a four-bay turnstile array. A three-dimensional radiation pattern of a four-bay turnstile antenna is shown in figure 4-40, view C.

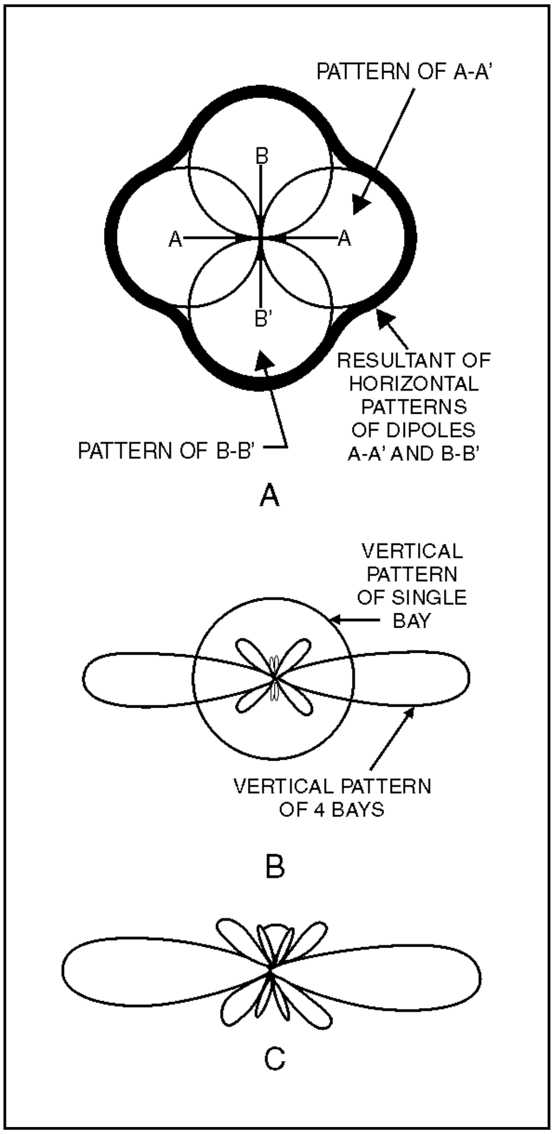


Figure 4-40. Turnstile Antenna Radiation Pattern

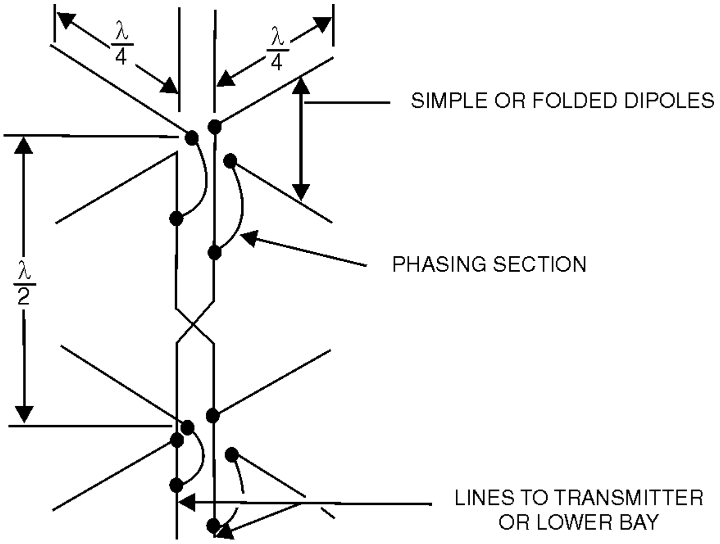


Figure 4-41. Stacked Turnstile Antenna

Ground-Plane Antenna

4-174. A vertical quarter-wave antenna several wavelengths above ground produces a high angle of radiation that is very undesirable at VHF and UHF frequencies. The most common means of producing a low angle of radiation from such an antenna is to work the radiator against a simulated ground called a ground plane. A simulated ground may be made from a large metal sheet or several wires or rods radiating from the base of the radiator. An antenna so constructed is known as a ground-plane antenna. Two ground-plane antennas are shown in figure 4-42, views A and B.

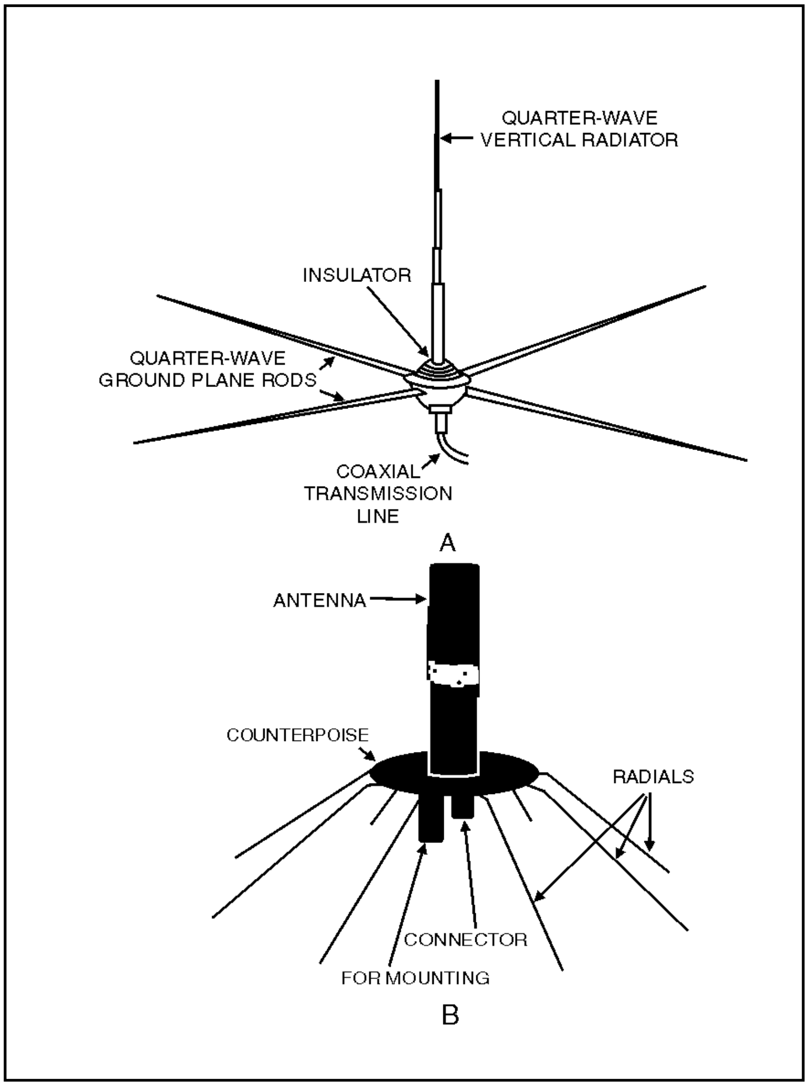


Figure 4-42. Ground-Plane Antenna

Corner Reflector

4-175. When a unidirectional radiation pattern is desired, it can be obtained by using a corner reflector with a half-wave dipole. A corner-reflector antenna is a half-wave radiator with a reflector. The reflector consists of two flat metal surfaces meeting at an angle immediately behind the radiator. In other words, the radiator is set in the plane of a line bisecting the corner angle formed by the reflector sheets. The construction of a corner reflector is shown in figure 4-43, view B Corner-reflector antennas are mounted with the radiator and the reflector in the horizontal position when horizontal polarization is desired. In such cases the radiation pattern is very narrow in the vertical plane, with maximum signal being radiated in line with the bisector of the corner angle. The directivity in the horizontal plane is approximately the same as for any half-wave radiator having a single-rod type reflector behind it. If the antenna is mounted with the radiator and the corner reflector in the vertical position, as shown in view A, maximum radiation is produced in a very narrow horizontal beam. Radiation in a vertical plane will be the same as for a similar radiator with a single-rod type reflector behind it.

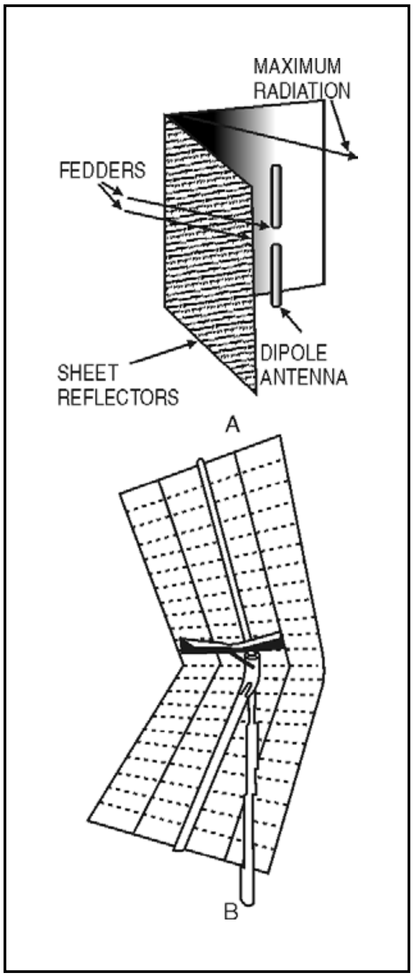


Figure 4-43. Corner-Reflector Antenna

SUMMARY

This chapter has presented information on the various types of antennas. The information that follows summarizes the important points of this chapter.

An antenna is a conductor, or system of conductors, that radiates or receives energy in the form of electromagnetic waves.

Hertz (half-wave) and Marconi (quarter-wave) are the two basic classifications of antennas.

Reciprocity of antennas means that the various properties of the antenna apply equally to transmitting and receiving.

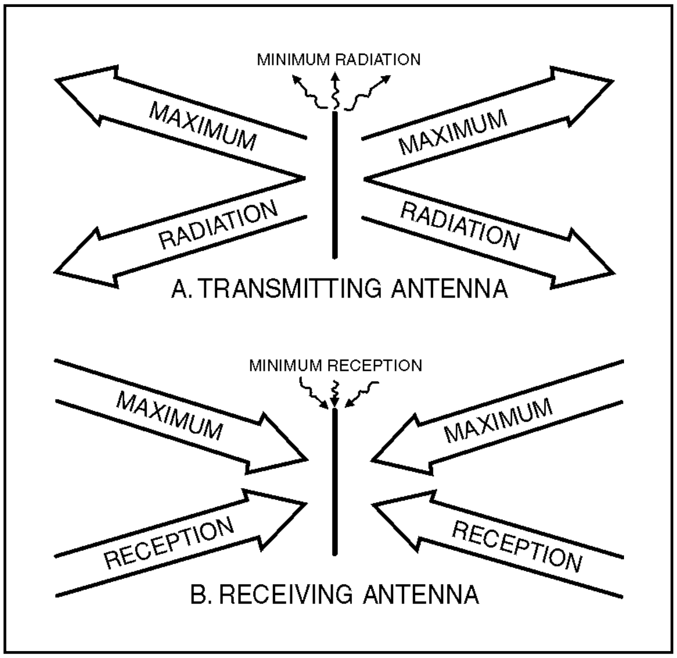


Figure 4-Sum 1. Reciprocity of Antennas

Radiation resistance is the amount of resistance that, if inserted in place of the antenna, would consume the same amount of power that is actually radiated by the antenna.

Radiation patterns can be plotted on a rectangular or polar-coordinate graph. These patterns are a measurement of the energy leaving an antenna.

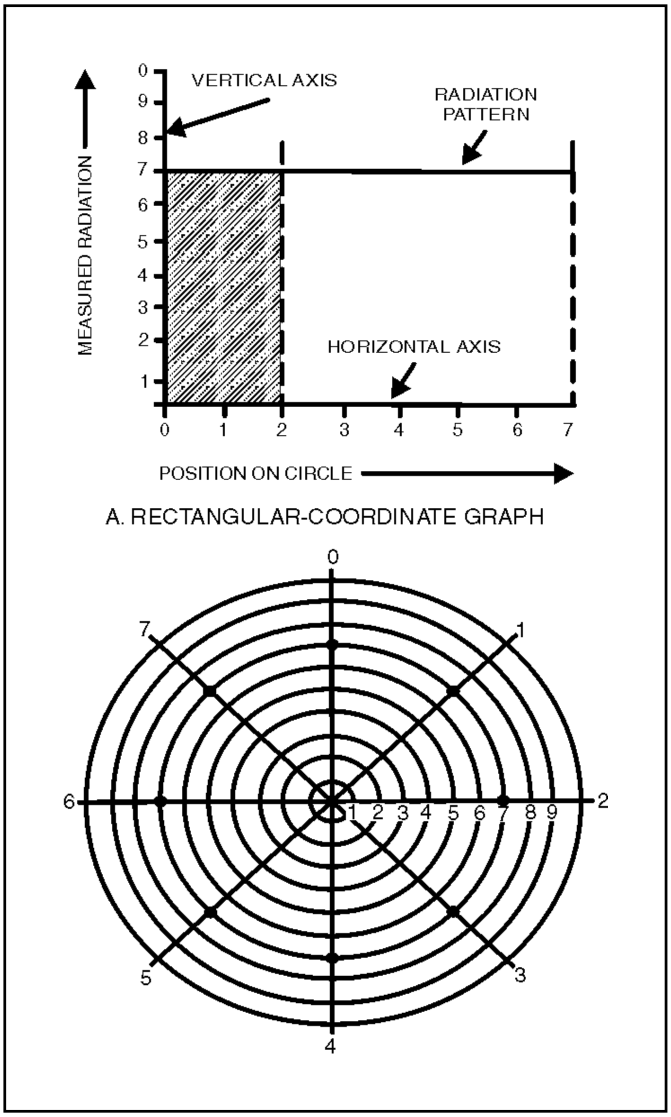


Figure 4-Sum 2. Radiation Patterns

An isotropic radiator radiates energy equally in all directions.

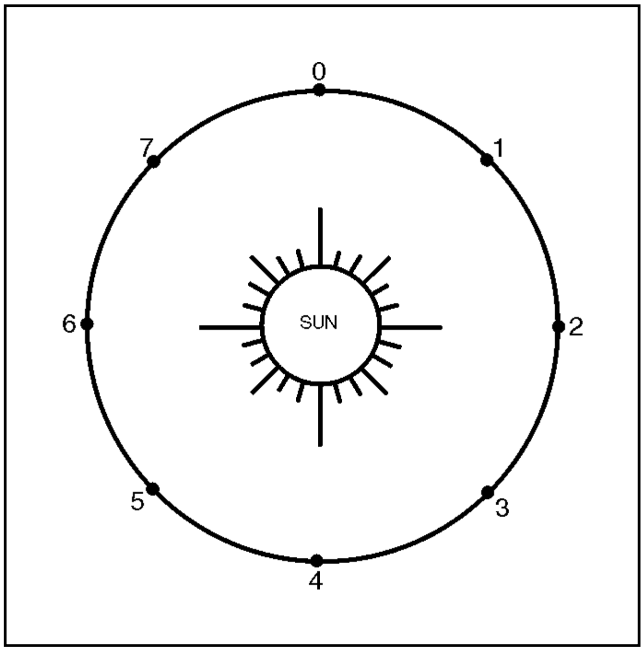


Figure 4-Sum 3. Radiating Energy of an Isotropic Radiator

An anisotropic radiator radiates energy directionally.

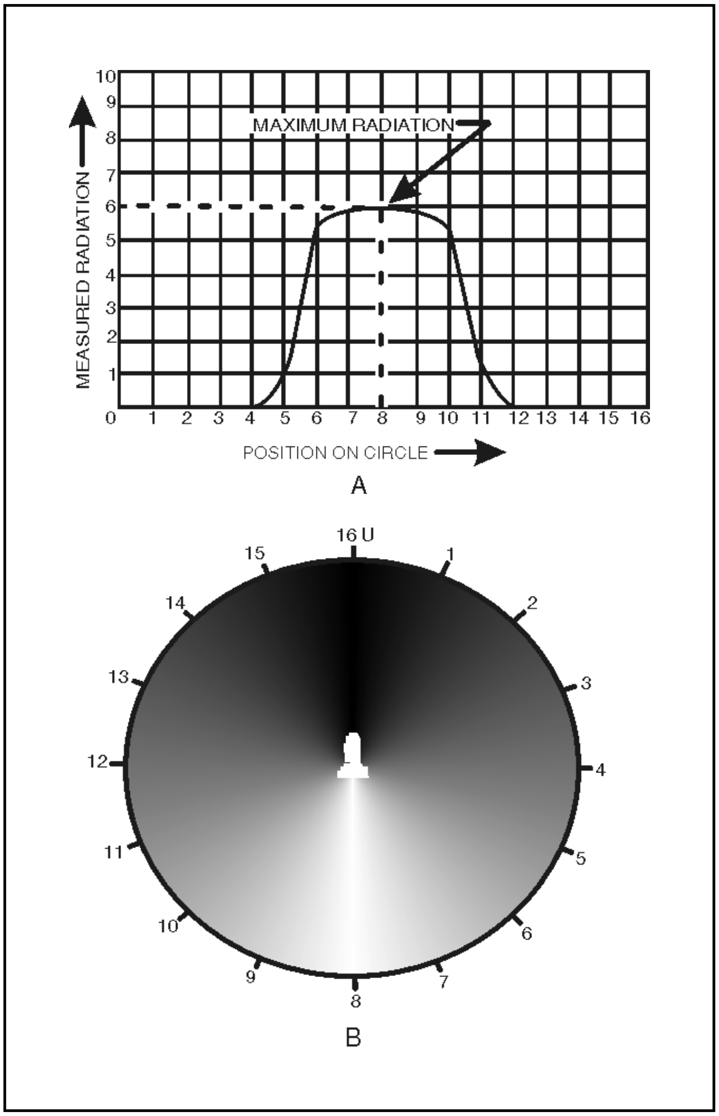


Figure 4-Sum 4. Directional Radiating Energy of an Anisotropic Radiator

A lobe is the area of a radiation pattern that is covered by radiation.

A null is the area of a radiation pattern that has minimum radiation.

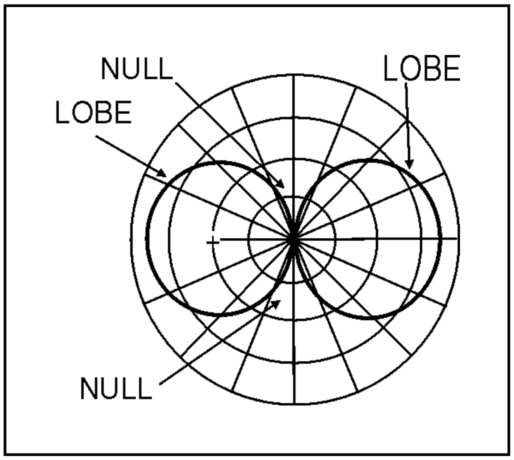


Figure 4-Sum 5. Null and Lobe Radiation Patterns

Antenna loading is the method used to change the electrical length of an antenna. This keeps the antenna in resonance with the applied frequency. It is accomplished by inserting a variable inductor or capacitor in series with the antenna.

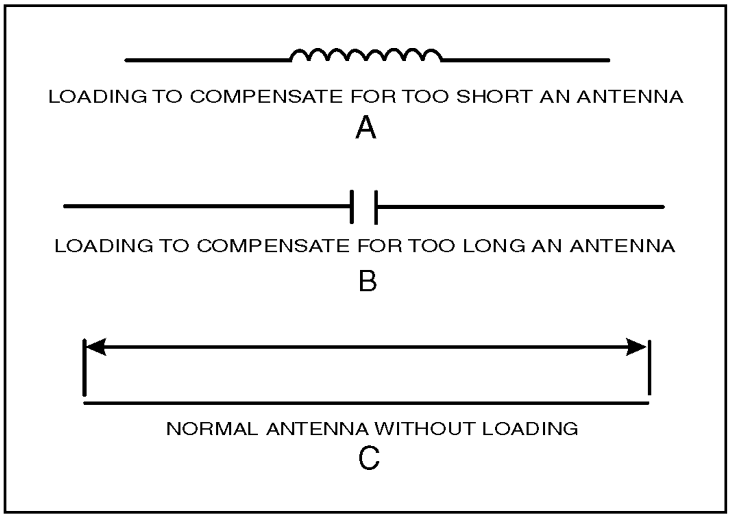


Figure 4-Sum 6. Antenna Loading

A half-wave antenna (Hertz) consists of two lengths of rod or tubing, each a quarter-wavelength long at a certain frequency, that radiate a doughnut pattern.

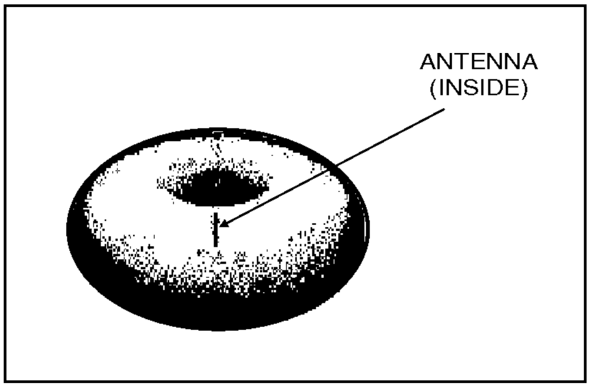


Figure 4-Sum 7. Half-Wave Antenna Pattern

A quarter-wave antenna (Marconi) is a half-wave antenna cut in half with one end grounded. The ground furnishes the missing half of the antenna.

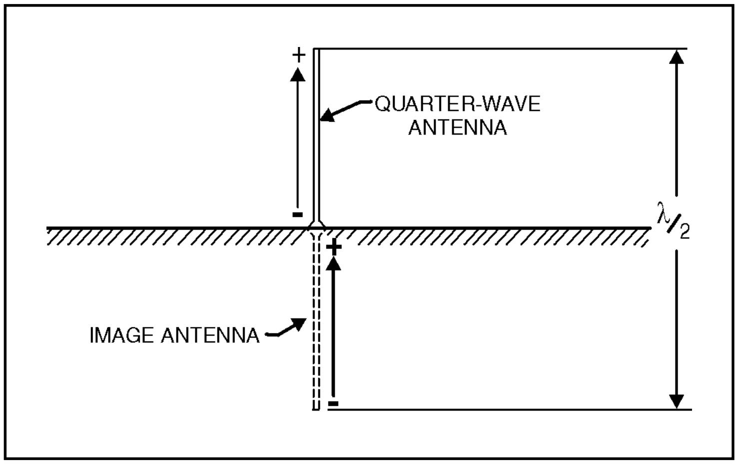


Figure 4-Sum 8. Quarter-Wave Antenna

The ground screen and the counterpoise are used to reduce losses caused by the ground in the immediate vicinity of the antenna. The ground screen is buried below the surface of the earth. The counterpoise is installed above the ground.

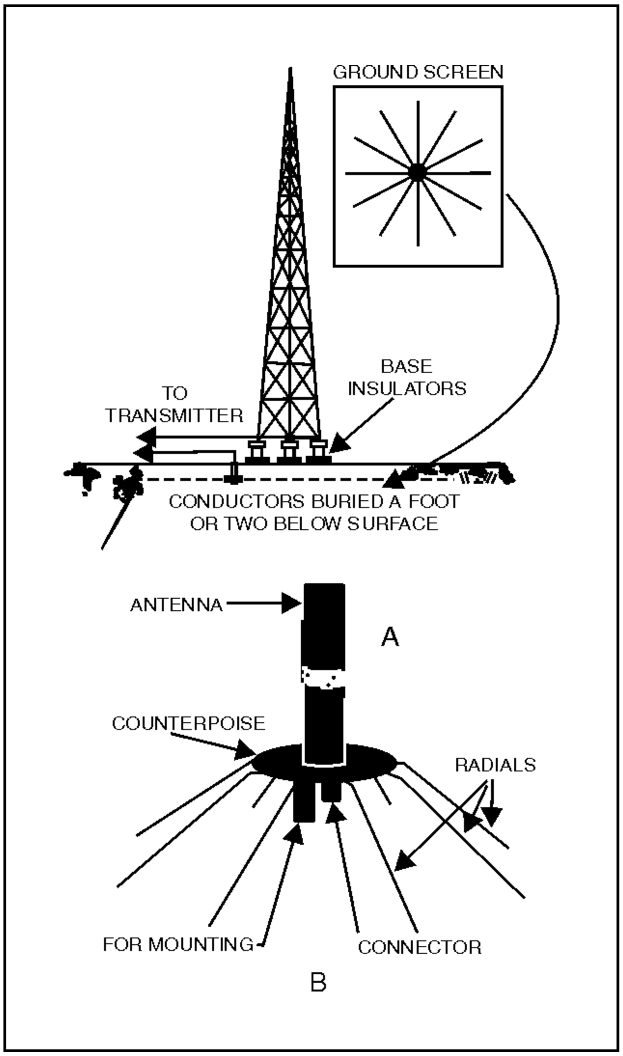


Figure 4-Sum 9. Ground Screen and Counterpoise Antennas

The folded dipole consists of a dipole radiator, which is connected in parallel at its ends to a half-wave radiator.

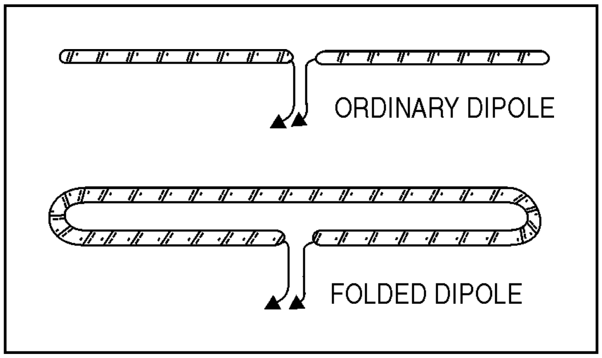


Figure 4-Sum 10. Folded Dipole

An array is a combination of half-wave elements operating together as a single antenna. It provides more gain and greater directivity than single element antennas.

A driven array derives its power directly from the source.

A parasitic array derives its power by coupling the energy from other elements of the antenna.

The bidirectional array radiates energy equally in two opposing directions.

The unidirectional array radiates energy efficiently in a single direction.

The collinear array has elements in a straight line. Maximum radiation occurs at right angles to this line.

The broadside array has elements parallel and in the same plane. Maximum radiation develops in the plane at right angles to the plane of the elements.

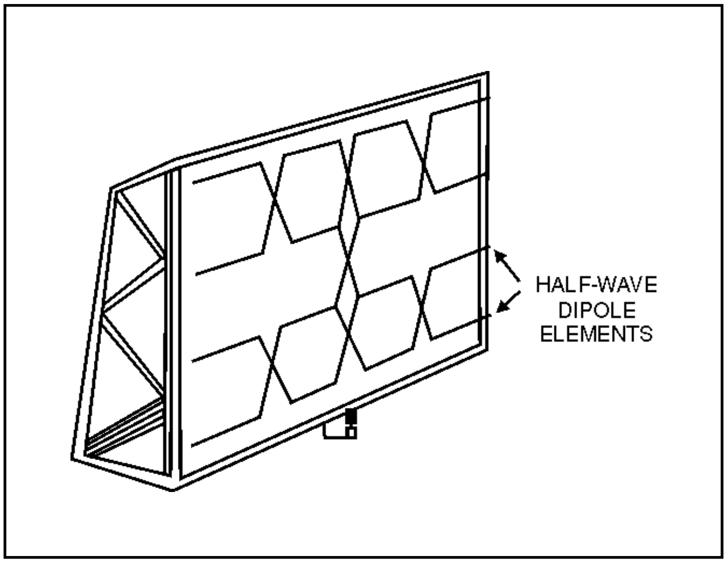


Figure 4-Sum 11. Broadside Array Elements

The end-fire array has elements parallel to each other and in the same plane. Maximum radiation occurs along the axis of the array.

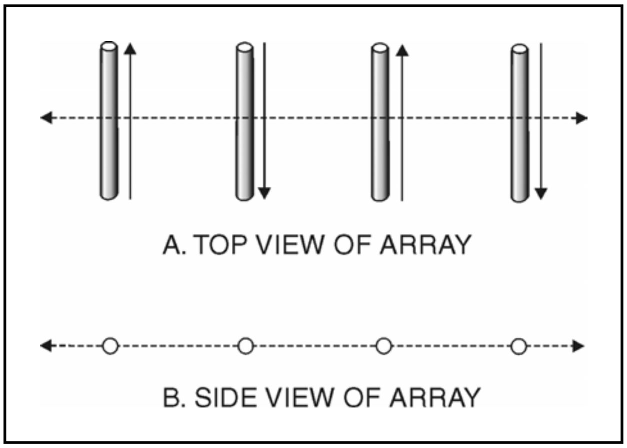


Figure 4-Sum 12. End-Fire Array

Matching stubs are used between elements to maintain current in the proper phase.

The gain of a collinear antenna is greatest when the elements are spaced from 0.4 to 0.5 wavelengths apart or when the number of elements is increased.

The optimum gain of a broadside array is obtained when the elements are spaced 0.65 wavelengths apart.

A parasitic array consists of one or more parasitic elements with a driven element. The amount of power gain and directivity depends on the lengths of the parasitic elements and the spacing between them.

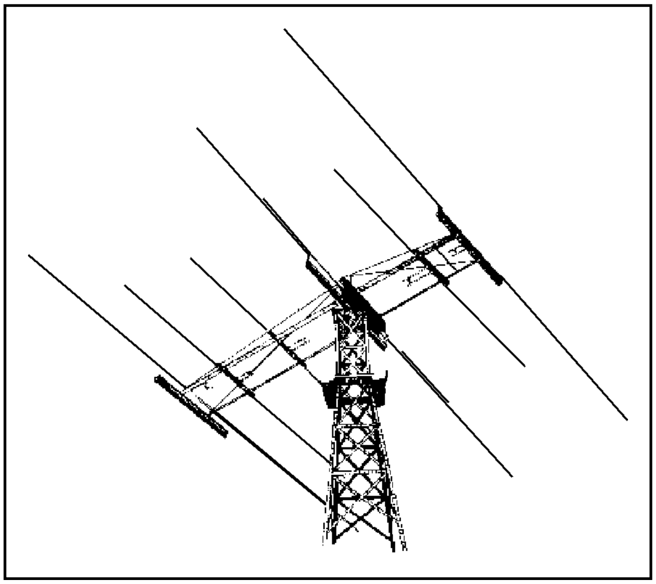


Figure 4-Sum 13. Parasitic Array

Multi-element arrays, such as the yagi, have a narrow frequency response as well as a narrow beam width.

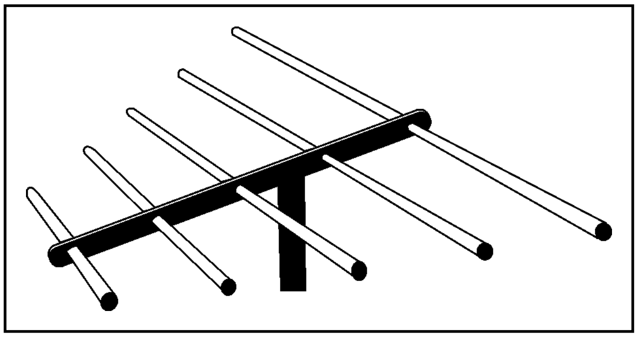


Figure 4-Sum 14. Multi-Element Arrays

A long-wire antenna is an antenna that is a wavelength or more long at the operating frequency. These antennas have directive patterns that are sharp in both the horizontal and vertical planes.

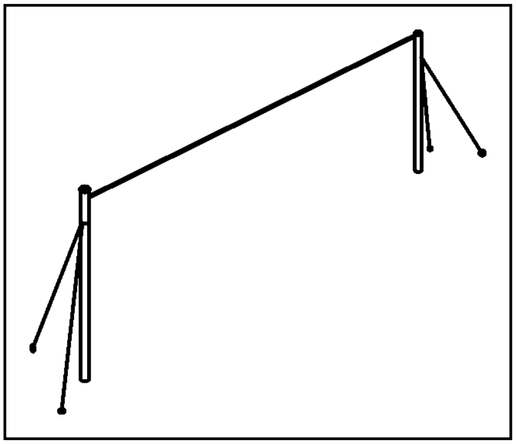


Figure 4-Sum 15. Long-Wire Antenna

Beverage antennas consist of a single wire that is two or more wavelengths long.

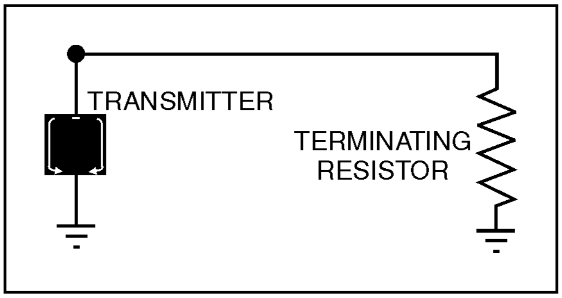


Figure 4-Sum 16. Beverage Antenna Wavelengths

A V antenna is a bidirectional antenna consisting of two horizontal, long wires arranged to form a V.

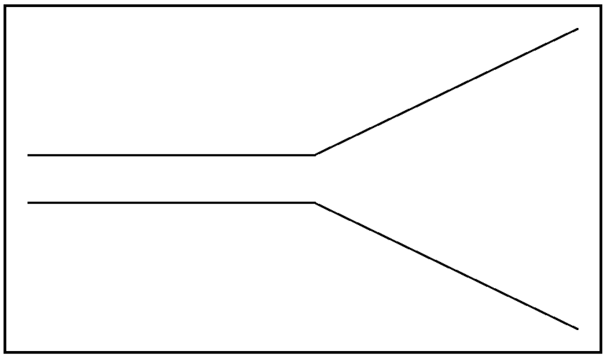


Figure 4-Sum 17. V Antenna Layout

The rhombic antenna uses four conductors joined to form a rhombus shape. This antenna has a wide frequency range, is easy to construct and maintain, and is noncritical as far as operation and adjustment are concerned.

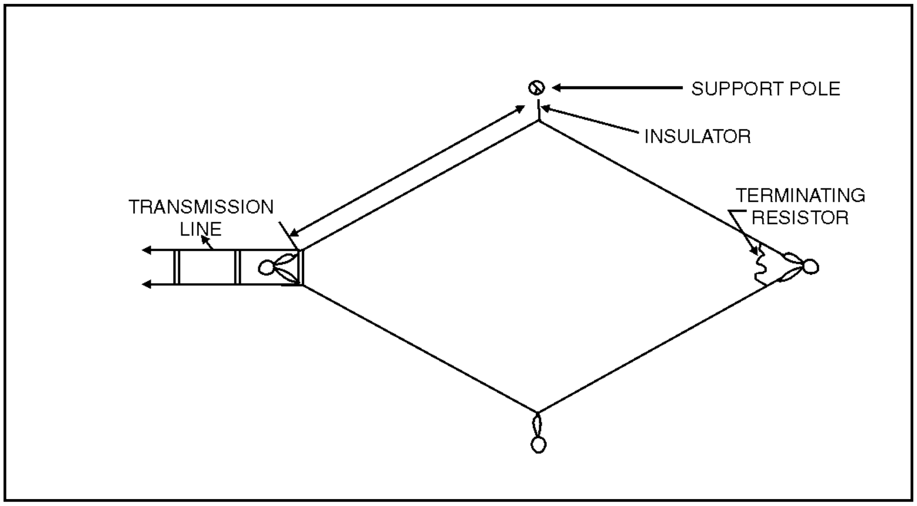


Figure 4-Sum 18. Rhombic Antenna Conductors

The turnstile antenna consists of two horizontal, half-wire antennas mounted at right angles to each other.

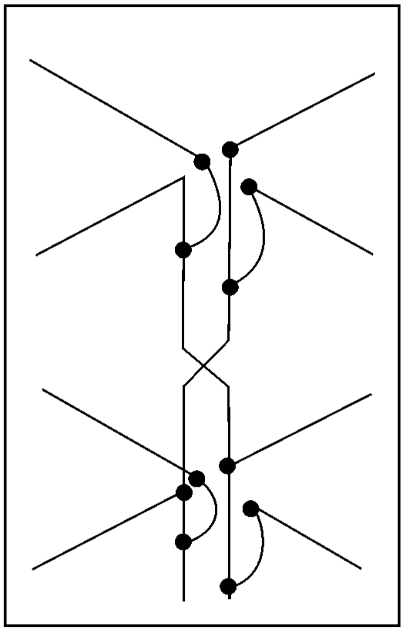


Figure 4-Sum 19. Turnstile Antenna

Check-On-Learning Questions

Antennas

When you are satisfied that you have answered every question to the best of your ability, check your answers using appendix A. If you missed eight or more questions, you should review the chapter, paying particular attention to the areas in which your answers were incorrect.

1. What are the two basic classifications of antennas?
2. What are the three parts of a complete antenna system?
3. What three factors determine the type, size, and shape of an antenna?
4. If a wave travels exactly the length of an antenna from one end to the other and back during the period of 1 cycle, what is the length of the antenna?
5. What are the terms used to identify the points of high current and high voltage on an antenna?
6. What is the term used to identify the points of minimum current and minimum voltage on an antenna?
7. The various properties of a transmitting antenna can apply equally to the same antenna when it is used as a receiving antenna. What term is used for this property?
8. The direction of what field is used to designate the polarization of a wave?
9. If a wave's electric lines of force rotate through 360 degrees with every cycle of RF energy, what is the polarization of this wave?
10. What type of polarization should be used at medium and low frequencies?
11. What is an advantage of using horizontal polarization at high frequencies?
12. What type of polarization should be used if an antenna is mounted on a moving vehicle at frequencies below 50 megahertz?
13. What is the radiation resistance of a half-wave antenna in free space?
14. A radiating source that radiates energy stronger in one direction than another is known as what type of radiator?
15. A radiating source that radiates energy equally in all directions is known as what type of radiator?
16. A flashlight is an example of what type of radiator?
17. What terms are often used to describe basic half-wave antennas?
18. If a basic half-wave antenna is mounted vertically, what type of radiation pattern will be produced?
19. In which plane will the half-wave antenna be operating if it is mounted horizontally?
20. Because the radiation pattern of a dipole is similar to that of a doublet, what will happen to the pattern if the length of the doublet is increased?
21. What is the simplest method of feeding power to the half-wave antenna?
22. What is the radiation pattern of a quarter-wave antenna?
23. Describe the physical arrangement of a ground screen.

24. What is the difference in the amount of impedance between a three-wire dipole and a simple center-fed dipole?
25. Which has a wider frequency range, a simple dipole or a folded dipole?
26. What is the purpose of antenna stubs?
27. What is the primary difference between the major and minor lobes of a radiation pattern?
28. What is the maximum number of elements ordinarily used in a collinear array?
29. Why is the number of elements used in a collinear array limited?
30. How can the frequency range of a collinear array be increased?
31. How is directivity of a collinear array affected when the number of elements is increased?
32. What is the primary cause of broadside arrays losing efficiency when not operating at their designed frequency?
33. When more than two elements are used in a broadside array, how are the elements arranged?
34. As the spacing between elements in a broadside array increases, what is the effect on the major lobes?
35. What are some disadvantages of the end-fire array?
36. Where does the major lobe in the end-fire array occur?
37. To maintain the required balance of phase relationships and critical feeding, how must the end-fire array be constructed?
38. What two factors determine the directivity pattern of the parasitic array?
39. What two main advantages of a parasitic array can be obtained by combining a reflector and a director with the driven element?
40. The parasitic array can be rotated to receive or transmit in different directions. What is the name given to such an antenna?
41. What are the disadvantages of the parasitic array?
42. What is the advantage of adding parasitic elements to a yagi array?
43. The yagi antenna is an example of what type of array?
44. To radiate power efficiently, a long-wire antenna must have what minimum overall length?
45. What is another name for the Beverage antenna?
46. What is the polarity of the currents that feed the V antenna?
47. What is the main disadvantage of the rhombic antenna?
48. What is the primary reason for the development of the turnstile antenna?

Appendix A

Check-On-Learning Answers

CHAPTER 1: WAVE PROPAGATION

1 Propagation means spreading out.

2. A wave is a disturbance that moves through a medium.

3 A means of transferring energy from one place to another.

4. Sound waves, light waves, radio waves, heat waves, water waves.

5. Transverse waves.

6. Radio waves, light waves, and heat waves.

7. A sound wave.

8. A source, medium, and detector (receiver).

9. A sequence of events, such as the positive and negative alternation of electrical current.

10. The space occupied by one cycle of a radio wave at any given instant.

11. The law of reflection states: The angle of incidence is equal to the angle of reflection.

12. When the incident wave is nearly parallel with the surface.

13. When the incident wave is perpendicular to the surface. Also a dull (or black) surface reflects very little regardless of the angle.

14. The density of the two mediums, and the velocity of the waves.

15. The Doppler effect.

16. Sonics.

17. No. The average human ear cannot hear all sounds in the infrasonic and ultrasonic regions.

18. An amplifier.

19. A source, medium, and detector (receiver).

20. Noise and tones.

21. Pitch, intensity, and quality.

22. 20 Hz to 20 kHz.

23. The amount of energy transmitted from a source.

24. Quality.

25. Velocity increases as density decreases and temperature increases.

26. Acoustics.

27. Echo.

28. Reverberation.

29. Resonance.

30. Noise.
31. Mechanical, electrical, and chemical.
32. A photon.
33. Angstrom unit.
34. Red, green and blue.
35. Magenta, yellow and cyan.
36. Reflected or absorbed.
37. None, all colors would be absorbed.
38. Translucent.
39. 186,000 miles per second or 300,000,000 meters per second.
40. Transmitted.
41. Diffused.
42. Light waves, heat waves, and radio waves.
43. The visible spectrum can be seen.
44. Electric field and magnetic field.
45. An antenna.
46. Electric field.
47. Magnetic field.
48. Radiation field.

CHAPTER 2: RADIO WAVE PROPAGATION

1. Induction field and radiation field.
2. Induction field.
3. Radiation field.
4. Fundamental frequency.
5. Harmonic frequency or harmonics.
6. 30 meters.
7. 5 megahertz.
8. Vertically polarized.
9. Direction of wave propagation.
10. Shifting in the phase relationships of the wave.
11. Troposphere, stratosphere, and ionosphere.
12. Stratosphere.
13. Whether the component of the wave is traveling along the surface or over the surface of the earth.
14. Sea water
15. Radio horizon is about one-third farther. .
16. (a) electrical properties of the terrain
    (b) frequency
    (c) polarization of the antenna
17. High energy ultraviolet light waves from the sun.

18 D, E, F1, and F2 layers.

19. D layer is 30 to 55 miles, E layer 55 to 90 miles, and F layers are 90 to 240 miles.
20. Thickness of ionized layer.
21. Critical frequency.
22. (a) density of ionization of the layer
    (b) frequency
    (c) angle at which it enters the layer
23. A zone of silence between the ground wave and sky wave where there is no reception.
24. Where ionization density is greatest.
25. A term used to describe the multiple pattern a radio wave may follow.
26. Selective fading.
27. Natural and man-made interference.
28. Natural.
29. Man-made.

30. (a) filtering and shielding of the transmitter
    (b) limiting bandwidth
    (c) cutting the antenna to the correct frequency
31. (a) physical separation of the antenna
    (b) limiting bandwidth of the antenna
    (c) use of directional antennas
32. Regular and irregular variations.
33. Regular variations can be predicted but irregular variations are unpredictable.
34. Daily, seasonal, 11-year, and 27-day variations.
35. Sporadic E, sudden disturbances, and ionospheric storms.
36. MUF is maximum usable frequency. LUF is lowest usable frequency. FOT is commonly known as optimum working frequency.
37. MUF is highest around noon. Ultraviolet light waves from the sun are most intense.
38. When LUF is too low it is absorbed and is too weak for reception.
39. Signal-to-noise ratio is low and the probability of multipath propagation is greater.
40. Frequent signal fading and dropouts.
41. FOT is the most practical operating frequency that can be relied on to avoid problems of multipath, absorption, and noise.
42. They can cause attenuation by scattering.
43. It can cause attenuation by absorption.
44. It is a condition where layers of warm air are formed above layers of cool air.
45. It can cause VHF and UHF transmission to be propagated far beyond normal line-of-sight distances.
46. Troposphere.
47. VHF and above.
48. Near the mid-point between the transmitting and receiving antennas, just above the radio horizon.

CHAPTER 3: PRINCIPLES OF TRANSMISSION LINES

1. Transmission line.
2. Input end, generator end, transmitter end, sending end, and source.
3. Output end, receiving end, load end and sink.
4. Parallel two-wire, twisted pair, shielded pair and coaxial line.
5. Power lines, rural telephone lines, and telegraph lines.
6. High radiation losses and noise pickup.
7. Twin lead.
8. The conductors are balanced to ground.
9. Air coaxial (rigid) and solid coaxial (flexible).
10. The ability to minimize radiation losses.
11. Expensive to construct, must be kept dry, and high frequency losses limit the practical length of the line.
12. Cylindrical and rectangular.
13. Copper, dielectric, and radiation.
14. Copper losses.
15. Dielectric losses.
16. $\lambda = 20$ meters.
17. (1) Type of line used, (2) dielectric in the line, and (3) length of line.
18. Inductance is expressed in microhenrys per unit length, capacitance is expressed in picofarads per unit length, and resistance is expressed in ohms per unit length.
19. The small amount of current that flows through the dielectric between two wires of a transmission line and is expressed in micromhos per unit length.
20. When the characteristic impedance of the transmission line and the load impedance are equal.
21. Z_0 and it is the ratio of E to I at every point along the line.
22. Between 50 and 600 ohms.
23. Incident waves from generator to load. Reflected waves from load back to generator.
24. 2 and 6 have zero resultant wave and they indicate that the incident and reflected waves are 180 degrees out of phase at all parts.
25. One-fourth the distance from each end of the line.
26. The load impedance of such a line is equal to Z_0.
27. Even quarter-wave points ($1/2\lambda$, l, $3/2\lambda$, etc.).
28. At 1/2 wavelength from the end and at every 1/2 wavelength along the line.
29. Power standing-wave ratio (PSWR).
30. The existence of voltage variations on a line.

CHAPTER 4: ANTENNAS

1. Half-wave (Hertz) and quarter-wave (Marconi).
2. Coupling device, feeder, and antenna.
3. Frequency of operation of the transmitter, amount of power to be radiated, and general direction of the receiving set.
4. One-half the wavelength.
5. Current and voltage loops.
6. Current and voltage nodes.
7. Reciprocity of antennas.
8. Electric (E) field.
9. Circular polarization.
10. Vertical polarization.
11. Less interference is experienced by man-made noise sources.
12. Vertical polarization.
13. 73 ohms.
14. Anisotropic radiator.
15. Isotropic radiator.
16. Anisotropic radiator.
17. Dipole, doublet and Hertz.
18. Nondirectional.
19. Vertical plane.
20. The pattern would flatten.
21. To connect one end through a capacitor to the final output stage of the transmitter.
22. A circular radiation pattern in the horizontal plane, or same as a half wave.
23. It is composed of a series of conductors arranged in a radial pattern and buried 1 to 2 feet below the ground.
24. Nine times the feed-point impedance.
25. Folded dipole.
26. To produce desired phase relationship between connected elements.
27. Major lobes have the greatest amount of radiation.
28. Four.
29. As more elements are added, an unbalanced condition in the system occurs which impairs efficiency.
30. By increasing the lengths of the elements of the array.
31. Directivity increases.

32. Lower radiation resistance.
33. Parallel and in the same plane.
34. They sharpen.
35. Extremely low radiation resistance, confined to one frequency, and affected by atmospheric conditions.
36. Along the major axis
37. Symmetrically.
38. Length of the parasitic element (tuning) and spacing between the parasitic and driven elements.
39. Increased gain and directivity.
40. Rotary array.
41. Their adjustment is critical and they do not operate over a wide frequency range.
42. Increased gain.
43. Multi-element parasitic array.
44. One-half wavelength.
45. Wave antenna.
46. Opposite.
47. It requires a large antenna site.
48. For omnidirectional VHF communications.

Glossary

absorption	(1) Absorbing light waves. Does not allow any reflection or refraction. (2) Atmospheric absorption of RF energy with no reflection or refraction (adversely affects long distance communications).
acoustics	The science of sound.
alternating current (AC)	An electrical current, which constantly changes amplitude and polarity at regular intervals.
amplitude	The portion of a cycle measured from a reference line to a maximum value above (or to a maximum value below) the line.
angle of incidence	The angle between the incident wave and the normal.
angle of reflection	The angle between the reflected wave and the normal.
angle of refraction	The angle between the normal and the path of a wave through the second medium.
angstrom unit	The unit used to define the wavelength of light waves.
anisotropic	The property of a radiator to emit strong radiation in one direction.
antenna	A conductor or set of conductors used either to radiate RF energy into space or to collect RF energy from space.
AR	Army regulation
array of arrays	Same as COMBINATION ARRAY.
bay	Part of an antenna array.
beverage antenna	A horizontal, longwire antenna designed for reception and transmission of low-frequency, vertically polarized ground waves.
bidirectional array	An array that radiates in opposite directions along the line of maximum radiation.
broadside array	An array in which the direction of maximum radiation is perpendicular to the plane containing the elements.

center-feed method	Connecting the center of an antenna to a transmission line, which is then connected to the final (output) stage of the transmitter.
characteristic impedance	The ratio of voltage to current at any given point on a transmission line. Represented by a value of impedance.
coaxial line	A type of transmission line that contains two concentric conductors.
collinear array	An array with all the elements in a straight line. Maximum radiation is perpendicular to the axis of the elements.
combination array	An array system that uses the characteristics of more than one array.
complementary (secondary) colors of light	The colors of light produced when two of the primaries are mixed in overlapping beams of light. The complementary colors of light are magenta, yellow, and cyan.
complex wave	A wave produced by combining two or more pure tones at the same time.
compression waves	Longitudinal waves that have been compressed (made more dense) as they move away from the source.
conductance	The opposite of resistance in transmission lines. The minute amount of resistance that is present in the insulator of a transmission line.
connected array	Another term for DRIVEN ARRAY.
copper losses	The I^2R loss in a conductor caused by the current flow through the resistance of the conductor.
corner-reflector antenna	A half-wave antenna with a reflector consisting of two flat metal surfaces meeting at an angle behind the radiator.
counterpoise	A network of wire that is connected to a quarter-wave antenna at one end and provides the equivalent of an additional one-quarter wavelength.
coupling device	A coupling coil that connects the transmitter to the feeder.
crest (top)	The peak of the positive alternation (maximum value above the line) of a wave.

critical angle	The maximum angle at which radio waves can be transmitted and still be refracted back to earth.
critical frequency	The maximum frequency at which a radio wave can be transmitted vertically and still be refracted back to earth.
current-feed method	Same as CENTER-FEED METHOD.
current standing-wave ratio (ISWR)	The ratio of maximum to minimum current along a transmission line.
cycle	One complete alternation of a sine wave that has a maximum value above and a maximum value below the reference line.
damping	Reduction of energy by absorption.
density	(1) The compactness of a substance. (2) Mass per unit volume.
detector	The device that responds to a wave or disturbance.
dielectric heating	The heating of an insulating material by placing it in a high frequency electric field.
dielectric losses	The losses resulting from the heating effect on the dielectric material between conductors.
diffraction	The bending of the paths of waves when the waves meet some form of obstruction.
diffusion	The scattering of reflected light waves (beams) from an object, such as white paper.
dipole	A common type of half-wave antenna made from a straight piece of wire cut in half. Each half operates at a quarter wavelength of the output.
direct current (DC)	An electric current that flows in one direction.
directional	Radiation that varies with direction.
director	The parasitic element of an array that reinforces energy coming from the driver toward itself.
directivity	The property of an array that causes more radiation to take place in certain directions than in others.
dispersion	The refraction of light waves that causes the different frequencies to bend at slightly different angles.

distributed constants	The constants of inductance, capacitance, and resistance in a transmission line. The constants are spread along the entire length of the line and cannot be distinguished separately.
Doppler effect	The apparent change in frequency or pitch when a sound source moves either toward or away from a listener.
doublet	Another name for the dipole antenna.
driven array	An array in which all of the elements are driven.
driven element	An element of an antenna (transmitting or receiving) that is connected directly to the transmission line.
echo	The reflection of the original sound wave as it bounces off a distant surface.
elasticity	The ability of a substance to return to its original state.
electromagnetic field	The combination of an electric (E) field and a magnetic (H) field.
electromagnetic interference	Man-made or natural interference that degrades the quality of reception of radio waves.
electromagnetic radiation	The radiation of radio waves into space.
electric (E) field	The field produced as a result of a voltage charge on a conductor or antenna.
electromagnetic interference (EMI)	Any electromagnetic disturbance that interrupts, obstructs, or otherwise degrades or limits the effective performance of electronics/electrical equipment.
electromotive force (EMF)	Electromotive force or voltage is electrical pressure that can force the free electrons to move in the direction of negative to positive.
element	A part of an antenna that can be either an active radiator or a parasitic radiator.
end-feed method	Connecting one end of an antenna through a capacitor to the final output stage of a transmitter.
end-fire array	An array in which the direction of radiation is parallel to the axis of the array.
fading	Variations in signal strength by atmospheric conditions.

feeder	A transmission line that carries energy to the antenna.
flat line	A transmission line that has no standing waves. This line requires no special tuning device to transfer maximum power.
flexible coaxial line	A coaxial line made with a flexible inner conductor insulated from the outer conductor by a solid, continuous insulating material.
FM	field manual
folded dipole	An ordinary half-wave antenna (dipole) that has one or more additional conductors connected across the ends parallel to each other.
four-element array	An array with three parasitic elements and one driven element.
free-space loss	The loss of energy of a radio wave because of the spreading of the wavefront as it travels from the transmitter.
frequency	The number of cycles that occur in one second. Usually expressed in hertz.
frequency diversity	Transmitting (and receiving) of radio waves on two different frequencies simultaneously.
frequency modulation (FM)	Frequency modulation is a method of impressing data onto an alternating-current wave by varying the instantaneous frequency of the wave. This scheme can be used with analog or digital data.
front-to-back ratio	The ratio of the energy radiated in the principal direction to the energy radiated in the opposite direction.
fundamental frequency	The basic frequency or first harmonic frequency.
gain	The ratio between the amount of energy propagated from an antenna that is directional to the energy from the same antenna that would be propagated if the antenna were not directional.
generator end	See INPUT END.
ground plane	The portion of a ground plane antenna that acts as ground.

ground-plane antenna	A type of antenna that uses a ground plane as a simulated ground to produce low-angle radiation.
ground reflection loss	The loss of RF energy each time a radio wave is reflected from the earth's surface.
ground screen	A series of conductors buried below the surface of the earth and arranged in a radial pattern. Used to reduce losses in the ground.
ground waves	Radio waves that travel near the surface of the earth.
half-wave dipole antenna	An antenna, consisting of two rods (one-quarter wavelength each) in a straight line, that radiates electromagnetic energy.
harmonic	A frequency that is a whole number multiple of a smaller base frequency.
Hertz antenna	A half-wave antenna installed some distance above ground and positioned either vertically or horizontally.
high frequency (HF)	The range of the radio frequency spectrum extending from 3 MHz to 30 MHz.
horizontal axis	On a graph, the straight line axis plotted from left to right.
horizontal pattern	The part of a radiation pattern that is radiated in all directions along the horizontal plane.
horizontally polarized	Waves that are radiated with their E field component parallel to the earth's surface.
incident wave	(1) The wave that strikes the surface of a medium. (2) The wave that travels from the sending end to the receiving end of a transmission line.
induction field	The electromagnetic field produced about an antenna when current and voltage are present on the same antenna.
induction losses	The losses that occur when the electromagnetic field around a conductor cuts through a nearby metallic object and induces a current into that object.
infrasonic (subsonic)	Sounds below 15 hertz.
input end	The end of a two-wire transmission line that is connected to a source.

input impedance	The impedance presented to the transmitter by the transmission line and its load.
intensity (of sound)	The measurement of the amplitude of sound energy. Sometimes mistakenly called loudness.
interecept	The point where two lines drawn on a graph cross each other.
interference	Any disturbance that produces an undesirable response or degrades a wave.
ionosphere	The most important region of the atmosphere extending from 31 miles to 250 miles above the earth. Contains four cloud-like layers that affect radio waves.
ionospheric storms	Disturbances in the earth's magnetic field that make communications practical only at lower frequencies.
ionization	The process of upsetting electrical neutrality.
isotropic radiation	The radiation of energy equally in all directions.
leakage current	The small amount of current that flows between the conductors of a transmission line through the dielectric.
light rays	Straight lines that represent light waves emitting from a source.
load end	See OUTPUT END.
loading	See LUMPED-IMPEDANCE TUNING.
lobe	An area of a radiation pattern plotted on a polar-coordinate graph that represents maximum radiation.
long-wire antenna	An antenna that is a wavelength or more long at its operating frequency.
longitudinal waves	Waves in which the disturbance (back and forth motion) takes place in the direction of propagation. Sometimes called compression waves.
loop	The curves of a standing wave or antenna that represent amplitude of current or voltage.
low frequency (LF)	The range of the radio frequency spectrum extending from 30 kHz to 300 kHz.
lowest usable frequency (luf)	The minimum operating frequency that can be used for communications between two points.

lumped constants	The properties of inductance, capacitance, and resistance in a transmission line.
lumped-impedance tuning	The insertion of an inductor or capacitor in series with an antenna to lengthen or shorten the antenna electrically.
magnetic (H) field	The field produced when current flows through a conductor or antenna.
major lobe	The lobe in which the greatest amount of radiation occurs.
Marconi antenna	A quarter-wave antenna oriented perpendicular to the earth and operated with one end grounded.
maximum usable frequency (muf)	Maximum frequency that can be used for communications between two locations for a given time of day and a given angle of incidence.
medium	The substance through which a wave travels from one point to the next. Air, water, and wood are examples of a medium.
medium frequency (MF)	The range of the radio frequency spectrum extending from 300 kHz to 3 MHz.
minor lobe	The lobe in which the radiation intensity is less than a major lobe.
multielement array	An array consisting of one or more arrays and classified as to directivity.
multielement parasitic array	An array that contains two or more parasitic elements and a driven element.
multipath	The multiple paths a radio wave may follow between transmitter and receiver.
natural horizon	The line-of-sight horizon.
negative alternation	The portion of a sine wave below the reference line.
node	The fixed minimum points of voltage or current on a standing wave or antenna.
noise (of sound)	An unwanted disturbance caused by spurious waves that originate from man-made or natural sources.
nondirectional	See OMNIDIRECTIONAL.

nonluminous bodies	Objects that either reflect or diffuse light that falls upon them.
nonresonant line	A transmission line that has no standing waves of current or voltage.
normal	The imaginary line perpendicular to the point at which the incident wave strikes the reflecting surface. Also called the perpendicular.
null	On a polar-coordinate graph, the area that represents minimum or 0 radiation.
omnidirectional	Transmitting in all directions.
opaque	A type of substance that does not transmit any light rays.
open-ended line	A transmission line that has an infinitely large terminating impedance.
optimum working frequency (fot)	The most practical operating frequency that can be used with the least amount of problems; roughly 85 percent of the maximum usable frequency.
origin	The point on a graph where the vertical and horizontal axes cross each other.
output end	The end of a transmission line that is opposite the source.
output impedance	The impedance presented to the load by the transmission line and its source.
parallel resonant circuit	A circuit that acts as a high impedance at resonance.
parallel-wire	A type of transmission line consisting of two parallel wires.
parasitic array	An array that has one or more parasitic elements.
parasitic element	The passive element of an antenna array that is connected to neither the transmission line nor the driven element.
period	The amount of time required for completion of one full cycle.
pitch	A term used to describe the frequency of a sound heard by the human ear.

plane of polarization	The plane (vertical or horizontal) with respect to the earth in which the E field propagates.
point of zero displacement	See REFERENCE LINE.
polar-coordinate graph	A graph whose axes consist of a series of circles with a common center and a rotating radius extending from the center of the concentric circles.
positive alternation	The portion of a sine wave above the reference line.
power loss	The heat loss in a conductor as current flows through it.
power standing-wave ratio (PSWR)	The ratio of the square of the maximum and minimum voltages of a transmission line.
primary colors (of light)	The three primary colors of light (red, green, and blue), from which all other colors may be derived.
prism	A triangular-shaped glass that refracts and disperses light waves into component wavelengths.
propagation	Waves traveling through a medium.
quality (of sound)	The factor that distinguishes tones of pitch and loudness.
quarter-wave antenna	Same as the Marconi antenna.
radiation field	The electromagnetic field that detaches itself from an antenna and travels through space.
radiation losses	The losses that occur when magnetic lines of force about a conductor are projected into space as radiation and are not returned to the conductor as the cycle alternates.
radiation pattern	A plot of the radiated energy from an antenna.
radiation resistance	The resistance, which if inserted in place of an antenna, would consume the same amount of power as that radiated by the antenna.
radio frequencies (RF)	Electromagnetic frequencies that fall between 3 kilohertz and 300 gigahertz and are used for radio communications.

radio horizon	The boundary beyond the natural horizon in which radio waves cannot be propagated over the earth's surface.
radio wave	(1) A form of radiant energy that can neither be seen nor felt. (2) An electromagnetic wave generated by a transmitter.
rarefied wave	A longitudinal wave that has been expanded or rarefied (made less dense) as it moves away from the source.
receiver	The object that responds to a wave or disturbance. Same as detector.
receiving antenna	The device used to pick up an RF signal from space.
receiving end	See OUTPUT END.
reciprocity	The property of interchangeability of the same antenna for transmitting and receiving.
rectangular-coordinate graph	A graph in which straight-line axes (horizontal and vertical) are perpendicular.
reference line	The position a particle of matter would occupy if it were not disturbed by wave motion.
reflected wave	(1) The wave that reflects back from a medium. (2) Waves traveling from the load back to the generator on a transmission line. (3) The wave moving back to the sending end of a transmission line after reflection has occurred.
reflection waves	Waves that are neither transmitted nor absorbed, but are reflected from the surface of the medium they encounter.
reflector	The parasitic element of an array that causes maximum energy radiation in a direction toward the driven element.
refraction	The changing of direction as a wave leaves one medium and enters another medium of a different density.
reradiation	The reception and retransmission of radio waves caused by turbulence in the troposphere.
resonance	The condition produced when the frequency of vibrations are the same as the natural frequency (of a cavity). The vibrations reinforce each other.

resonant line	A transmission line that has standing waves of current and voltage.
rest position	See REFERENCE LINE.
reverberation	The multiple reflections of sound waves.
rhombic antenna	frequency transmission and reception.
rigid coaxial line	A coaxial line consisting of a central, insulated wire (inner conductor) mounted inside a tubular outer conductor.
scatter angle	The angle at which the receiving antenna must be aimed to capture the scattered energy of tropospheric scatter.
self-induction	The phenomenon caused by the expanding and collapsing fields of an electron which encircles other electrons and retards the movement of the encircled electrons.
self-luminous bodies	Objects that produce their own light.
sending end	See INPUT END.
series resonant circuit	A circuit that acts as a low impedance at resonance.
shielded pair	A line consisting of parallel conductors separated from each other and surrounded by a solid dielectric.
short-circuited line	A transmission line that has a terminating impedance equal to 0.
sink	See OUTPUT END.
skin effect	Skin effect is a tendency for alternating current to flow mostly near the outer surface of a solid electrical conductor, such as metal wire, at frequencies above the audio range. .
skip distance	The distance from a transmitter to the point where the sky wave is first returned to earth.
skip zone	A zone of silence between the point where the ground wave becomes too weak for reception and the point where the sky wave is first returned to earth.
sky waves	Radio waves reflected back to earth from the ionosphere.

sonic	Pertaining to sounds capable of being heard by the human ear.
source	(1) The object that produces waves or disturbance. (2) The name given to the end of a two-wire transmission line that is connected to a source.
space diversity	Reception of radio waves by two or more antennas spaced some distance apart.
space wave	A radio wave that travels directly from the transmitter to the receiver and remains in the troposphere.
spectrum	(1) The entire range of electromagnetic waves. (2) VISIBLE. The range of electromagnetic waves that stimulate the sense of sight. (3) ELECTROMAGNETIC. The entire range of electromagnetic waves arranged in order of their frequencies.
sporadic E layer	Irregular cloud-like patches of unusually high ionization. Often forms at heights near the normal E layer.
spreader	Insulator used with transmission lines and antennas to keep the parallel wires separated.
standing wave	The distribution of voltage and current formed by the incident and reflected waves which have minimum and maximum points on a resultant wave that appears to stand still.
standing-wave ratio (SWR)	The ratio of the maximum (voltage, current) to the minimum (voltage, current) of a transmission line. Measures the perfection of the termination of the line.
stratosphere	Located between the troposphere and the ionosphere. Has little effect on radio waves.
stub	Short section of a transmission line used to match the impedance of a transmission line to an antenna. Can also be used to produce desired phase relationships between connected elements of an antenna.
sudden ionospheric disturbance (sid)	An irregular ionospheric disturbance that can totally blank out HF radio communications.
supersonic	Speed greater than the speed of sound.
surface wave	A radio wave that travels along the contours of the earth, thereby being highly attenuated.

TC	training circular
temperature inversion	The condition in which warm air is formed above a layer of cool air that is near the earth's surface.
three-element array	An array with two parasitic elements (reflector and director) and a driven element.
TM	technical manual
tones	Musical sounds.
translucent	A type of substance, such as frosted glass, through which some light rays can pass but through which objects cannot be seen clearly.
transmission line	A device designed to guide electrical energy from one point to another.
transmitting antenna	The device used to send the transmitted signal energy into space.
transparent	A type of substance, such as glass, that transmits almost all of the light waves that fall upon it.
transmission mediums	The various types of lines and waveguides used as transmission lines.
transmitter end	See INPUT END.
transverse wave motion	The up and down motion of a wave as the wave moves outward.
troposphere	The portion of the atmosphere closest to the earth's surface, where all weather phenomena take place.
tropospheric scatter	The propagation of radio waves in the troposphere by means of scatter.
trough (bottom)	The peak of the negative alternation (maximum value below the line).
tuned line	Another name for the resonant line. This line uses tuning devices to eliminate the reactance and to transfer maximum power from the source to the line.
turnstile antenna	A type of antenna used in VHF communications that is omnidirectional and consists of two horizontal half-wave antennas mounted at right angles to each other in the same horizontal plane.

twisted pair	A line consisting of two insulated wires twisted together to form a flexible line without the use of spacers.
two-wire open line	A parallel line consisting of two wires that are generally spaced from 2 to 6 inches apart by insulating spacers.
two-wire ribbon (twin lead)	A parallel line similar to a two-wire open line except that uniform spacing is assured by embedding the two-wires in a low-loss dielectric.
ultrahigh frequency (UHF)	The range of the radio frequency spectrum extending from 30 MHz to 3 GHz.
ultrasonic	Sounds above 20,000 hertz.
unidirectional array	An array that radiates in only one general direction.
untuned line	Another name for the flat or nonresonant line.
V antenna	A bidirectional antenna, shaped like a V, which is widely used for communications.
velocity	The rate at which a disturbance travels through a medium.
vertical axis	On a graph, the straight-line axis oriented from bottom to top.
vertical pattern	The part of a radiation pattern that is radiated in the vertical plane.
vertically polarized	Waves radiated with the E field component perpendicular to the earth's surface.
very high frequency (VHF)	The range of the radio frequency spectrum extending from 30 MHz to 300 MHz.
voltage-feed method	Same as END FEED METHOD.
voltage standing-wave ratio (VSWR)	The ratio of maximum to minimum voltage of a transmission line.
wave antenna	Same as BEVERAGE ANTENNA.
wave motion	A recurring disturbance advancing through space with or without the use of a physical medium.
wave train	A continuous series of waves with the same amplitude and wavelength.

wavefront	A small section of an expanding sphere of electromagnetic radiation, perpendicular to the direction of travel of the energy.
waveguide	A hollow metal tube used as a transmission line to guide energy from one point to another.
wavelength	(1) The distance in space occupied by 1 cycle of a radio wave at any given instant. (2) The distance a disturbance travels during one period of vibration.
yagi antenna	A multi-element parasitic array. Elements lie in the same plane as those of the end-fire array.

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