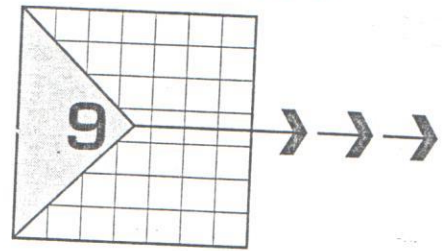


CHAPTER



Wave Propagation

INTRODUCTION

In Chapter 8 we explained how a metallic wire is used as a transmission medium to propagate electromagnetic waves from one point to another. However, very often in communications systems it is impractical or impossible to interconnect two pieces of equipment with a physical facility such as a wire, for example, across large spans of water, rugged mountains, or desert terrain, or to and from satellite transponders parked 22,000 mi above the earth. Also, when the transmitters and receivers are mobile, as with two-way radio or mobile telephone, metallic facilities are impossible. Therefore, free space or Earth's atmosphere is often used as a transmission medium. Free-space propagation of electromagnetic waves is often called *radio frequency (RF) propagation* or simply *radio propagation*.

To propagate TEM waves through Earth's atmosphere, it is necessary that energy be radiated from the source; then the energy must be *captured* at the receive end. Radiating and capturing energy are antenna functions and are explained in Chapter 10; and the properties of electromagnetic waves were explained in Chapter 8.

RAYS AND WAVEFRONTS

Electromagnetic waves are invisible. Therefore, they must be analyzed by indirect methods using schematic diagrams. The concepts of *rays* and *wavefronts* are aids to illustrating the effects of electromagnetic wave propagation through free space. A ray is a line drawn along the direction of propagation of an electromagnetic wave. Rays are used to show the relative direction of electromagnetic wave propagation. However, a ray does not necessarily represent the propagation of a single electromagnetic wave. Several rays are shown in Figure 9-1 (R_a , R_b , R_c , and so on). A wavefront shows a surface of constant phase of a wave. A wavefront is formed when points of equal phase on rays propagated from the same source are joined together. Figure 9-1 shows a wavefront with a surface that is perpendicular to the direction of propagation (rectangle $ABCD$). When a surface is

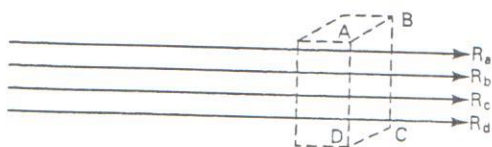


FIGURE 9-1 Plane wave

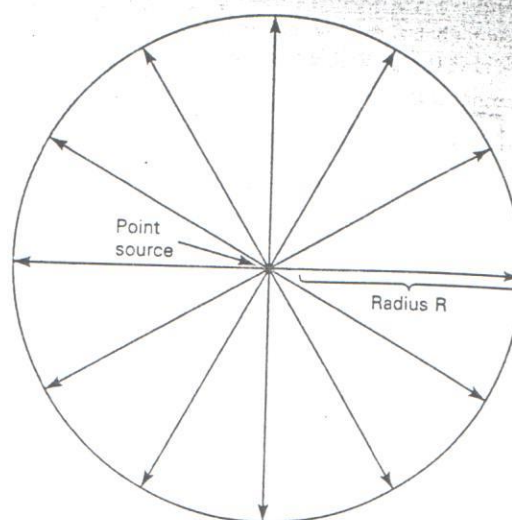


FIGURE 9-2 Wavefront from a point source

plane, its wavefront is perpendicular to the direction of propagation. The closer to the source, the more complicated the wavefront becomes.

Most wavefronts are more complicated than a simple plane wave. Figure 9-2 shows a point source, several rays propagating from it, and the corresponding wavefront. A *point source* is a single location from which rays propagate equally in all directions (an *isotropic source*). The wavefront generated from a point source is simply a sphere with radius R and its center located at the point of origin of the waves. In free space and a sufficient distance from the source, the rays within a small area of a spherical wavefront are nearly parallel. Therefore, the farther from a source, the more wave propagation appears as a plane wavefront.

ELECTROMAGNETIC RADIATION

Power Density and Field Intensity

Electromagnetic waves represent the flow of energy in the direction of propagation. The rate at which energy passes through a given surface area in free space is called *power density*. Therefore, power density is energy per unit time per unit of area and is usually given in watts per square meter. *Field intensity* is the intensity of the electric and magnetic fields of an electromagnetic wave propagating in free space. Electric field intensity is usually given in volts per meter and magnetic field intensity in ampere-turns per meter (At/m). Mathematically, power density is

$$\mathcal{P} = \mathcal{E}\mathcal{H} \quad \text{W/m}^2 \quad (9-1)$$

where \mathcal{P} = power density (watts per meter squared)
 \mathcal{E} = rms electric field intensity (volts per meter)
 \mathcal{H} = rms magnetic field intensity (ampere-turns per meter)

Characteristic Impedance of Free Space

The electric and magnetic field intensities of an electromagnetic wave in free space are related through the characteristic impedance (resistance) of free space. The characteristic impedance of a lossless transmission medium is equal to the square root of the ratio of its magnetic permeability to its electric permittivity. Mathematically, the characteristic impedance of free space (Z_0) is

$$Z_s = \sqrt{\frac{\mu_0}{\epsilon_0}} \quad (9-2)$$

where Z_s = characteristic impedance of free space (ohms)
 μ_0 = magnetic permeability of free space (1.26×10^{-6} H/m)
 ϵ_0 = electric permittivity of free space (8.85×10^{-12} F/m)

Substituting into Equation 9-2, we have

$$Z_s = \sqrt{\frac{1.26 \times 10^{-6}}{8.85 \times 10^{-12}}} = 377 \Omega$$

Therefore, using Ohm's law, we obtain

$$\mathcal{P} = \frac{\mathcal{E}^2}{377} = 377 \mathcal{H}^2 \quad \text{W/m}^2 \quad (9-3)$$

$$\mathcal{H} = \frac{\mathcal{E}}{377} \quad \text{At/m} \quad (9-4)$$

SPHERICAL WAVEFRONT AND THE INVERSE SQUARE LAW

Spherical Wavefront

Figure 9-3 shows a point source that radiates power at a constant rate uniformly in all directions. Such a source is called an *isotropic radiator*. A true isotropic radiator does not exist. However, it is closely approximated by an *omnidirectional antenna*. An isotropic radiator produces a spherical wavefront with radius R . All points distance R from the source lie on the surface of the sphere and have equal power densities. For example, in Figure 9-3 points A and B are an equal distance from the source. Therefore, the power densities at points A and B are equal. At any instant of time, the total power radiated, P_r watts, is uniformly distributed over the total surface of the sphere (this assumes a lossless transmission medium). Therefore, the power density at any point on the sphere is the total radiated power divided by the total area of the sphere. Mathematically, the power density at any point on the surface of a spherical wavefront is

$$\mathcal{P}_a = \frac{P_r}{4\pi R^2} \quad (9-5)$$

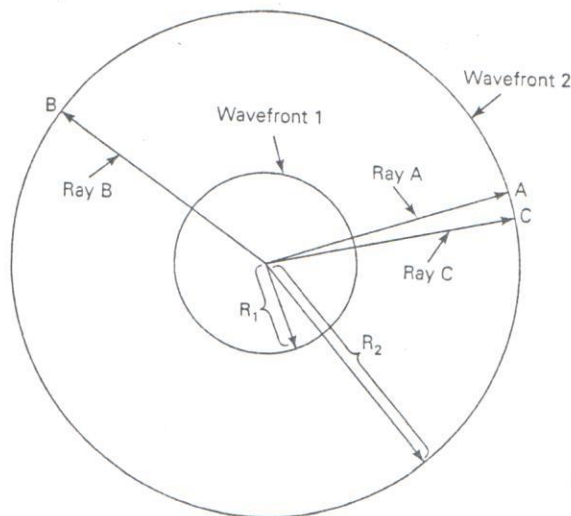


FIGURE 9-3 Spherical wavefront from an isotropic source

where P_r = total power radiated (watts)
 R = radius of the sphere (which is equal to the distance from any point on the surface of the sphere to the source)
 $4\pi R^2$ = area of the sphere

and for a distance R_a meters from the source, the power density is

$$\mathcal{P}_a = \frac{P_r}{4\pi R_a^2}$$

Equating Equations 9-3 and 9-5 gives

$$\frac{P_r}{4\pi R^2} = \frac{\mathcal{E}^2}{377}$$

Therefore, $\mathcal{E}^2 = \frac{377P_r}{4\pi R^2}$ and $\mathcal{E} = \frac{\sqrt{30P_r}}{R}$ (9-6)

Inverse Square Law

From Equation 9-5 it can be seen that the farther the wavefront moves from the source, the smaller the power density (R_a and R_c move farther apart). The total power distributed over the surface of the sphere remains the same. However, because the area of the sphere increases in direct proportion to the distance from the source squared (that is, the radius of the sphere squared), the power density is inversely proportional to the square of the distance from the source. This relationship is called the *inverse square law*. Therefore, the power density at any point on the surface of the outer sphere is

$$\mathcal{P}_2 = \frac{P_r}{4\pi R_2^2}$$

and the power density at any point on the inner sphere is

$$\mathcal{P}_1 = \frac{P_r}{4\pi R_1^2}$$

Therefore,

$$\frac{\mathcal{P}_2}{\mathcal{P}_1} = \frac{P_r/4\pi R_2^2}{P_r/4\pi R_1^2} = \frac{R_1^2}{R_2^2} = \left(\frac{R_1}{R_2}\right)^2 \quad (9-7)$$

From Equation 9-7 it can be seen that as the distance from the source doubles the power density decreases by a factor of 2^2 , or 4. When deriving the inverse square law of radiation (Equation 9-7), it was assumed that the source radiates isotropically, although it is not necessary. However, it is necessary that the velocity of propagation in all directions be uniform. Such a propagation medium is called an *isotropic medium*.

Example 9-1

For an isotropic antenna radiating 100 W of power, determine

- (a) Power density 1000 m from the source.
- (b) Power density 2000 m from the source.

Solution (a) Substituting into Equation 9-5 yields

$$\mathcal{P}_1 = \frac{100}{4\pi 1000^2} \approx 7.96 \mu\text{W/m}^2$$

(b) Again, substituting into Equation 9-5 gives

$$\mathcal{P}_2 = \frac{100}{4\pi 2000^2} = 1.99 \mu\text{W/m}^2$$

or, substituting into Equation 9-7, we have

$$\frac{\mathcal{P}_2}{\mathcal{P}_1} = \frac{1000^2}{2000^2} = 0.25$$

or

$$\mathcal{P}_2 = 7.96 \mu\text{W/m}^2 (0.25) = 1.99 \mu\text{W/m}^2$$

WAVE ATTENUATION AND ABSORPTION

Attenuation

The inverse square law for radiation mathematically describes the reduction in power density with distance from the source. As a wavefront moves away from the source, the continuous electromagnetic field that is radiated from that source spreads out. That is, the waves move farther away from each other and, consequently, the number of waves per unit area decreases. None of the radiated power is lost or dissipated because the wavefront is moving away from the source; the wave simply spreads out or disperses over a larger area, decreasing the power density. The reduction in power density with distance is equivalent to a power loss and is commonly called *wave attenuation*. Because the attenuation is due to the spherical spreading of the wave, it is sometimes called the *space attenuation* of the wave. Wave attenuation is generally expressed in terms of the common logarithm of the power density ratio (dB loss). Mathematically, wave attenuation (γ_a) is

$$\gamma_a = 10 \log \frac{\mathcal{P}_1}{\mathcal{P}_2} \quad (9-8)$$

The reduction in power density due to the inverse square law presumes free-space propagation (a vacuum or nearly a vacuum) and is called wave attenuation. The reduction in power density due to nonfree-space propagation is called *absorption*.

Absorption

Earth's atmosphere is not a vacuum. Rather, it is made up of atoms and molecules of various substances, such as gases, liquids, and solids. Some of these materials are capable of absorbing electromagnetic waves. As an electromagnetic wave propagates through Earth's atmosphere, energy is transferred from the wave to the atoms and molecules of the atmosphere. Wave absorption by the atmosphere is analogous to an I^2R power loss. Once absorbed, the energy is lost forever and causes an attenuation in the voltage and magnetic field intensities and a corresponding reduction in power density.

Absorption of radio frequencies in a normal atmosphere depends on frequency and is relatively insignificant below approximately 10 GHz. Figure 9-4 shows atmospheric absorption in decibels per kilometer due to oxygen and water vapor for radio frequencies above 10 GHz. It can be seen that certain frequencies are affected more or less by absorption, creating peaks and valleys in the curves. Wave attenuation due to absorption does not depend on distance from the radiating source, but rather the total distance that the wave propagates through the atmosphere. In other words, for a *homogeneous medium* (one with uniform properties throughout), the absorption experienced during the first mile of propagation is the same as for the last mile. Also, abnormal atmospheric conditions such as heavy rain or dense fog absorb more energy than a normal atmosphere. Atmospheric absorption (γ) for a wave propagating from R_1 to R_2 is $\gamma(R_2 - R_1)$, where γ is the absorption coefficient. Therefore, wave attenuation depends on the ratio R_2/R_1 , and wave absorption depends on the distance between R_1 and R_2 . In a more practical situation (that is, an *inhomogeneous medium*), the absorption coefficient varies considerably with location, thus, creating a difficult problem for radio systems engineers.

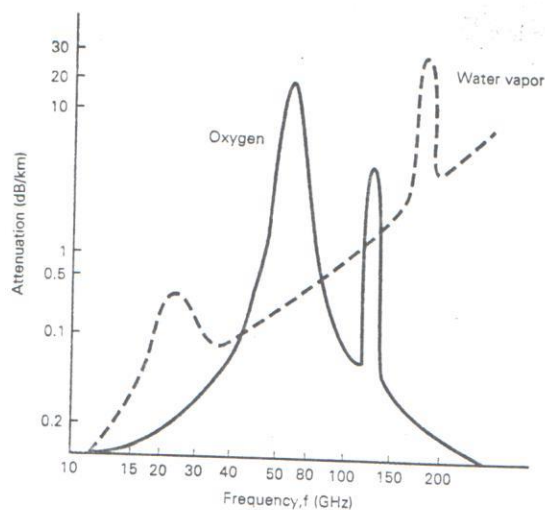


FIGURE 9-4 Atmospheric absorption of electromagnetic waves

OPTICAL PROPERTIES OF RADIO WAVES

In Earth's atmosphere, ray-wavefront propagation may be altered from free-space behavior by *optical* effects such as *refraction*, *reflection*, *diffraction*, and *interference*. Using rather unscientific terminology, refraction can be thought of as *bending*, reflection as *bouncing*, diffraction as *scattering*, and interference as *colliding*. Refraction, reflection, diffraction, and interference are called optical properties because they were first observed in the science of optics, which is the behavior of light waves. Because light waves are high-frequency electromagnetic waves, it stands to reason that optical properties will also apply to radio wave propagation. Although optical principles can be analyzed completely by application of Maxwell's equations, this is necessarily complex. For most applications, *geometric ray tracing* can be substituted for analysis by Maxwell's equations.

Refraction

Electromagnetic *refraction* is the change in direction of a ray as it passes obliquely from one medium to another with different velocities of propagation. The velocity at which an electromagnetic wave propagates is inversely proportional to the density of the medium in which it is propagating. Therefore, refraction occurs whenever a radio wave passes from one medium into another medium of different density. Figure 9-5 shows refraction of a wavefront at a *plane* boundary between two media with different densities. For this example, medium 1 is less dense than medium 2 ($v_1 > v_2$). It can be seen that ray A enters the more dense medium before ray B. Therefore, ray B propagates more rapidly than ray A and travels distance B-B' during the same time that ray A travels distance A-A'. Therefore, wavefront (A'B') is *tilted* or bent in a downward direction. Because a ray is defined as being perpendicular to the wavefront at all points, the rays in Figure 9-5 have changed direction at the interface of the two media. Whenever a ray passes from a less dense to a more dense medium, it is effectively bent toward the *normal*. (The normal is simply an imaginary line drawn perpendicular to the interface at the point of incidence.) Conversely, whenever a ray passes from a more dense to a less dense medium, it is effectively bent away from the normal. The *angle of incidence* is the angle formed between the incident wave and the normal, and the *angle of refraction* is the angle formed between the refracted wave and the normal.

The amount of bending or refraction that occurs at the interface of two materials of different densities is quite predictable and depends on the *refractive index* (also called the *index of refraction*) of the two materials. The refractive index is simply the ratio of the

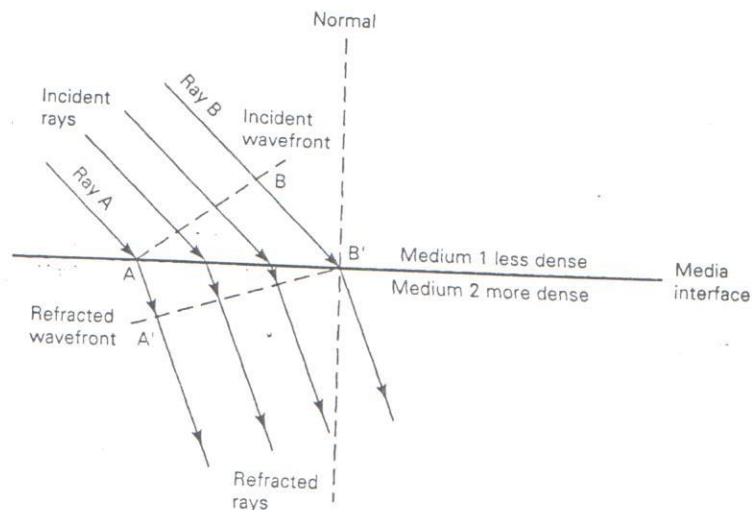


FIGURE 9-5 Refraction at a plane boundary between two media

velocity of propagation of a light ray in free space to the velocity of propagation of a light ray in a given material. Mathematically, the refractive index is

$$n = \frac{c}{v} \quad (9-9)$$

where n = refractive index (unitless)

c = speed of light in free space (3×10^8 m/s)

v = speed of light in a given material (meters per second)

The refractive index is also a function of frequency. However, the variation in most applications is insignificant and, therefore, is omitted from this discussion. How an electromagnetic wave reacts when it meets the interface of two transmissive materials that have different indexes of refraction can be explained with *Snell's law*. Snell's law simply states that

$$n_1 \sin \theta_1 = n_2 \sin \theta_2 \quad (9-10)$$

and

$$\frac{\sin \theta_1}{\sin \theta_2} = \frac{n_2}{n_1}$$

where n_1 = refractive index of material 1

n_2 = refractive index of material 2

θ_1 = angle of incidence (degrees)

θ_2 = angle of refraction (degrees)

and because the refractive index of a material is equal to the square root of its dielectric constant,

$$\frac{\sin \theta_1}{\sin \theta_2} = \sqrt{\frac{\epsilon_{r2}}{\epsilon_{r1}}} \quad (9-11)$$

where ϵ_{r1} = dielectric constant of medium 1

ϵ_{r2} = dielectric constant of medium 2

Refraction also occurs when a wavefront propagates in a medium that has a *density gradient* that is perpendicular to the direction of propagation (that is, parallel to the

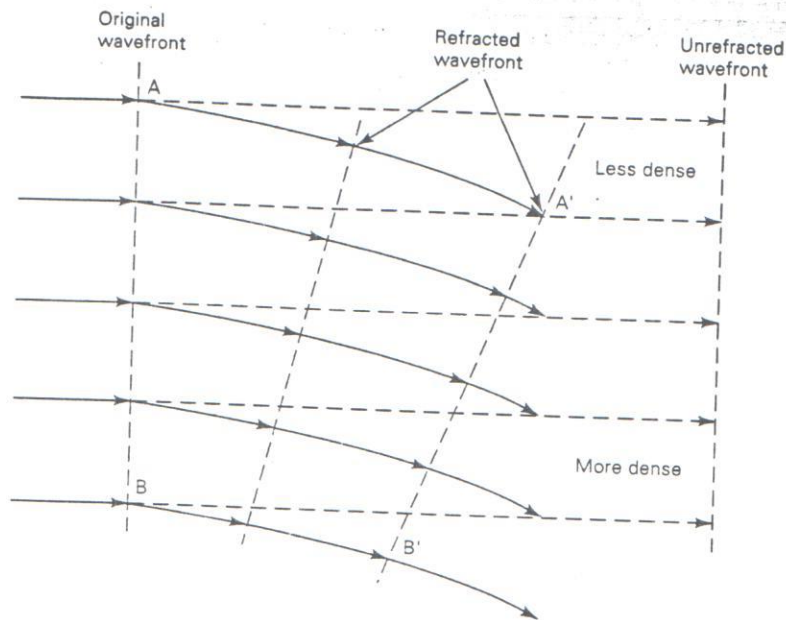


FIGURE 9-6 Wavefront refraction in a gradient medium

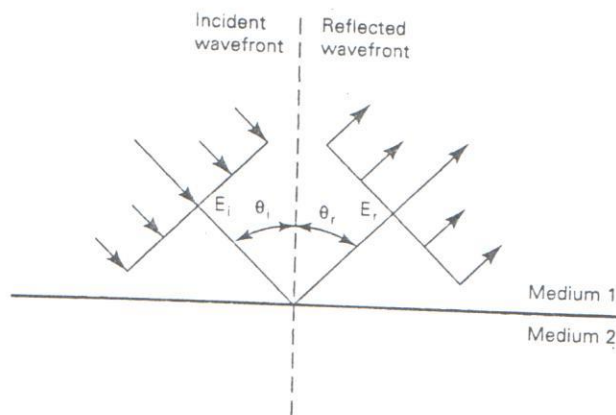


FIGURE 9-7 Electromagnetic reflection at a plane boundary of two media

wavefront). Figure 9-6 shows wavefront refraction in a transmission medium that has a gradual variation in its refractive index. The medium is more dense near the bottom and less dense at the top. Therefore, rays traveling near the top travel faster than rays near the bottom and, consequently, the wavefront tilts downward. The tilting occurs in a gradual fashion as the wave progresses, as shown.

Reflection

Reflect means to cast or turn back, and *reflection* is the act of reflecting. Electromagnetic reflection occurs when an incident wave strikes a boundary of two media and some or all of the incident power does not enter the second material. The waves that do not penetrate the second medium are reflected. Figure 9-7 shows electromagnetic wave reflection at a plane boundary between two media. Because all the reflected waves remain in medium 1, the velocities of the reflected and incident waves are equal. Consequently, the angle of

reflection equals the *angle of incidence* ($\theta_i = \theta_r$). However the reflected voltage field intensity is less than the incident voltage field intensity. The ratio of the reflected to the incident voltage intensities is called the *reflection coefficient*, Γ (sometimes called the *coefficient of reflection*). For a perfect conductor, $\Gamma = 1$. Γ is used to indicate both the relative amplitude of the incident and reflected fields and also the phase shift that occurs at the point of reflection. Mathematically, the reflection coefficient is

$$\Gamma = \frac{E_r e^{j\theta_r}}{E_i e^{j\theta_i}} = \frac{E_r}{E_i} e^{j(\theta_r - \theta_i)} \quad (9-12)$$

where Γ = reflection coefficient (unitless)
 E_i = incident voltage intensity (volts)
 E_r = reflected voltage intensity (volts)
 θ_i = incident phase (degrees)
 θ_r = reflected phase (degrees)

The ratio of the reflected and incident power densities is Γ . The portion of the total incident power that is not reflected is called the *power transmission coefficient* (T) (or simply the *transmission coefficient*). For a perfect conductor, $T = 0$. The *law of conservation of energy* states that for a perfect reflective surface the total reflected power must equal the total incident power. Therefore,

$$T + |\Gamma|^2 = 1 \quad (9-13)$$

For imperfect conductors, both $|\Gamma|^2$ and T are functions of the angle of incidence, the electric field polarization, and the dielectric constants of the two materials. If medium 2 is not a perfect conductor, some of the incident waves penetrate it and are absorbed. The absorbed waves set up currents in the resistance of the material and the energy is converted to heat. The fraction of power that penetrates medium 2 is called the *absorption coefficient* (or sometimes the *coefficient of absorption*).

When the reflecting surface is not plane (that is, it is curved), the curvature of the reflected wave is different from that of the incident wave. When the wavefront of the incident wave is curved and the reflective surface is plane, the curvature of the reflected wavefront is the same as that of the incident wavefront.

Reflection also occurs when the reflective surface is *irregular* or *rough*. However, such a surface may destroy the shape of the wavefront. When an incident wavefront strikes an irregular surface, it is randomly scattered in many directions. Such a condition is called *diffuse reflection*, whereas reflection from a perfectly smooth surface is called *specular* (mirrorlike) *reflection*. Surfaces that fall between smooth and irregular are called *semirough surfaces*. Semirough surfaces cause a combination of diffuse and specular reflection. A semirough surface will not totally destroy the shape of the reflected wavefront. However, there is a reduction in the total power. The *Rayleigh criterion* states that a semirough surface will reflect as if it were a smooth surface whenever the cosine of the angle of incidence is greater than $\lambda/8d$, where d is the depth of the surface irregularity and λ is the wavelength of the incident wave. Reflection from a semirough surface is shown in Figure 9-8. Mathematically, Rayleigh's criterion is

$$\cos \theta_i > \frac{\lambda}{8d} \quad (9-14)$$

Diffraction

Diffraction is defined as the modulation or redistribution of energy within a wavefront when it passes near the edge of an *opaque* object. Diffraction is the phenomenon that allows light or radio waves to propagate (*peek*) around corners. The previous discussions of refraction and reflection assumed that the dimensions of the refracting and reflecting

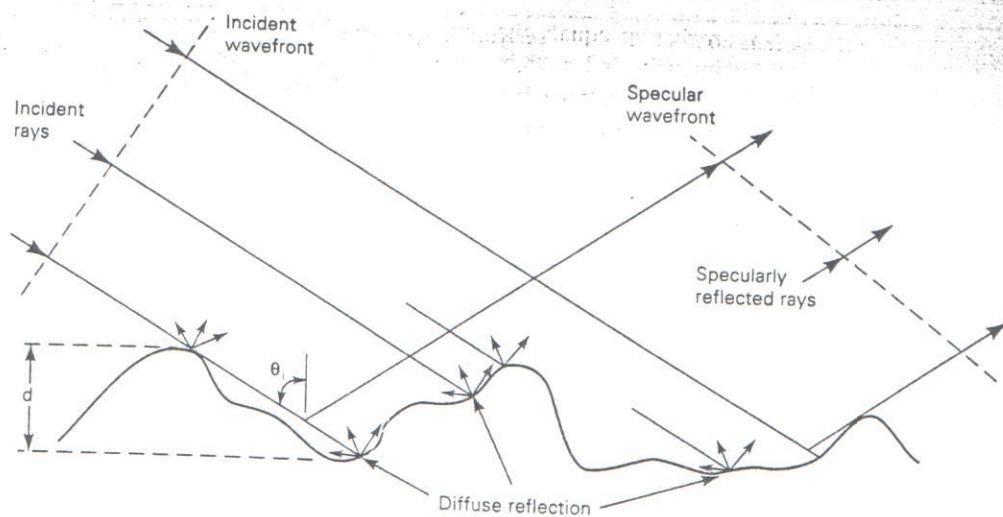


FIGURE 9-8 Reflection from a semirough surface

surfaces were large with respect to a wavelength of the signal. However, when a wavefront passes near an obstacle or discontinuity with dimensions comparable in size to a wavelength, simple geometric analysis cannot be used to explain the results and *Huygens's principle* (which is deduced from Maxwell's equations) is necessary.

Huygens's principle states that every point on a given spherical wavefront can be considered as a secondary point source of electromagnetic waves from which other secondary waves (wavelets) are radiated outward. Huygens's principle is illustrated in Figure 9-9. Normal wave propagation considering an infinite plane is shown in Figure 9-9a. Each secondary point source (p_1 , p_2 , and so on) radiates energy outward in all directions. However, the wavefront continues in its original direction rather than spreading out, because cancellation of the secondary wavelets occurs in all directions except straight forward. Therefore, the wavefront remains plane.

When a finite plane wavefront is considered, as in Figure 9-9b, cancellation in random directions is incomplete. Consequently, the wavefront spreads out or *scatters*. This scattering effect is called *diffraction*. Figure 9-9c shows diffraction around the edge of an obstacle. It can be seen that wavelet cancellation occurs only partially. Diffraction occurs around the edge of the obstacle, which allows secondary waves to "sneak" around the corner of the obstacle into what is called the *shadow zone*. This phenomenon can be observed when a door is opened into a dark room. Light rays diffract around the edge of the door and illuminate the area behind the door.

Interference

Interfere means to come into opposition, and *interference* is the act of interfering. Radio wave interference occurs when two or more electromagnetic waves combine in such a way that system performance is degraded. Refraction, reflection, and diffraction are categorized as geometric optics, which means that their behavior is analyzed primarily in terms of rays and wavefronts. Interference, on the other hand, is subject to the principle of *linear superposition* of electromagnetic waves and occurs whenever two or more waves simultaneously occupy the same point in space. The principle of linear superposition states that the total voltage intensity at a given point in space is the sum of the individual wave vectors. Certain types of propagation media have nonlinear properties; however, in an ordinary medium (such as air or Earth's atmosphere), linear superposition holds true.

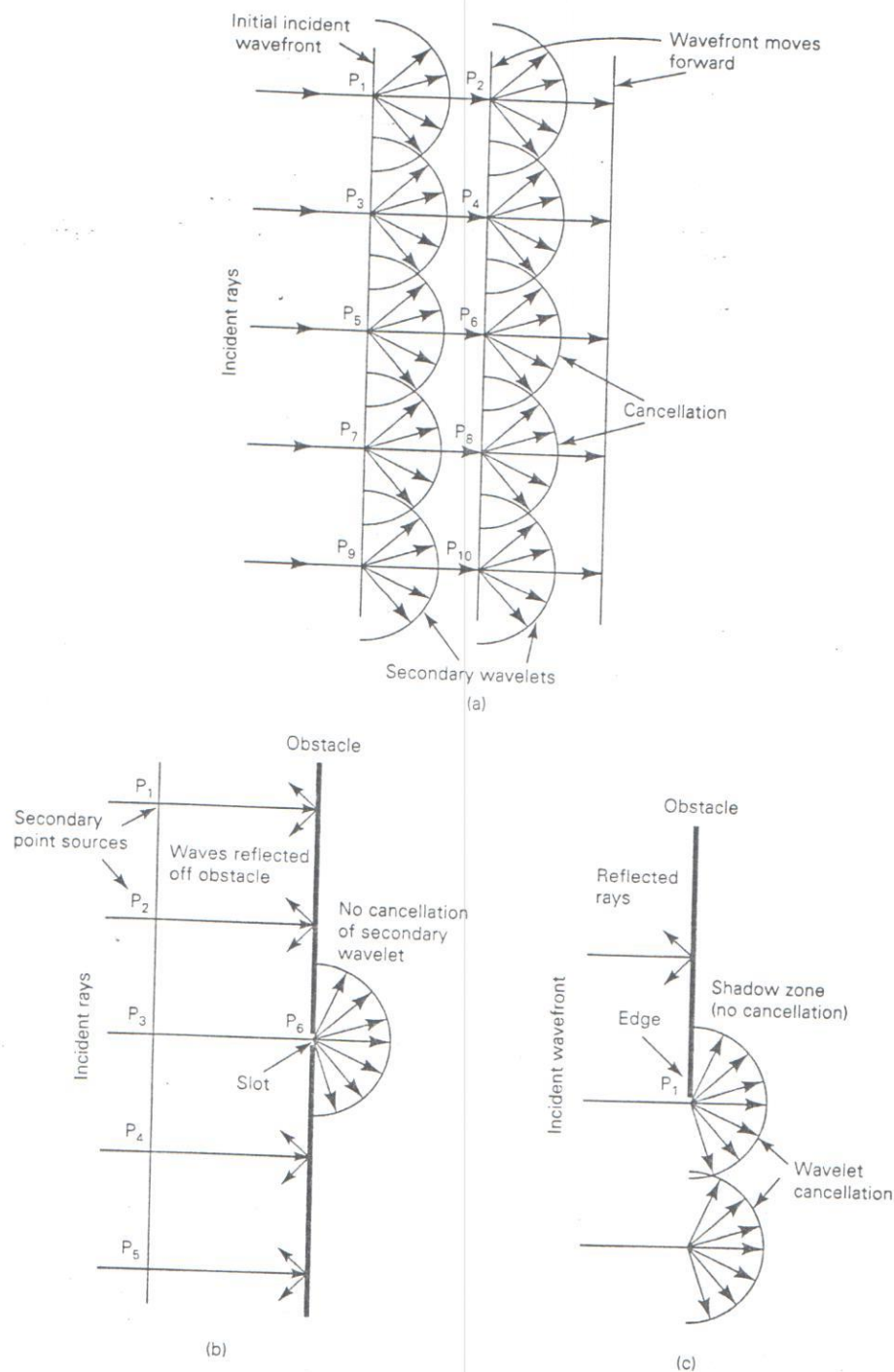


FIGURE 9-9 Electromagnetic wave diffraction: (a) Huygen's principle for a plane wavefront; (b) finite wavefront through a slot; (c) around an edge

Figure 9-10 shows the linear addition of two instantaneous voltage vectors whose phase angles differ by angle θ . It can be seen that the total voltage is not simply the sum of the two vector magnitudes, but rather the phasor addition of the two. With free-space propagation, a phase difference may exist simply because the *electromagnetic polarizations* of two waves differ. Depending on the phase angles of the two vectors, either

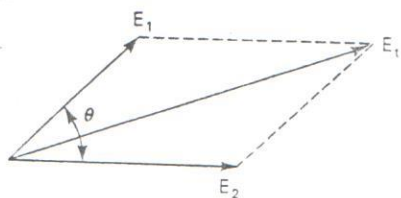


FIGURE 9-10 Linear addition of two vectors with differing phase angles

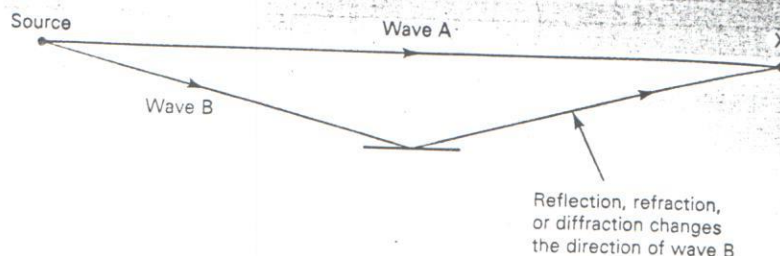


FIGURE 9-11 Electromagnetic wave interference

addition or subtraction can occur. (This implies simply that the result may be more or less than either vector because the two electromagnetic waves can reinforce or cancel.)

Figure 9-11 shows interference between two electromagnetic waves in free space. It can be seen that at point *X* the two waves occupy the same area of space. However, wave *B* has traveled a different path than wave *A*, and, therefore, their relative phase angles may be different. If the difference in distance traveled is an odd integral multiple of one-half wavelength, reinforcement takes place. If the difference is an even integral multiple of one-half wavelength, total cancellation occurs. More likely the difference in distance falls somewhere between the two and partial cancellation occurs. For frequencies below VHF, the relatively large wavelengths prevent interference from being a significant problem. However, with UHF and above, wave interference can be severe.

PROPAGATION OF WAVES

In radio communications systems, waves can be propagated in several ways, depending on the type of system and the environment. Also, as previously explained, electromagnetic waves travel in straight lines except when Earth and its atmosphere alter their path. There are three ways of propagating electromagnetic waves: ground-wave, space-wave (which includes both direct and ground-reflected waves), and sky-wave propagation.

Figure 9-12 shows the normal modes of propagation between two radio antennas. Each of these modes exists in every radio system; however, some are negligible in certain frequency ranges or over a particular type of terrain. At frequencies below 1.5 MHz, ground waves provide the best coverage. This is because ground losses increase rapidly with frequency. Sky waves are used for high-frequency applications, and space waves are used for very high frequencies and above.

Ground-Wave Propagation

A *ground wave* is an electromagnetic wave that travels along the surface of Earth. Therefore, ground waves are sometimes called *surface waves*. Ground waves must be vertically polarized. This is because the electric field in a horizontally polarized wave would be parallel to Earth's surface, and such waves would be short-circuited by the conductivity of the ground. With ground waves, the changing electric field induces voltages in Earth's surface, which cause currents to flow that are very similar to those in a transmission line. Earth's surface also has resistance and dielectric losses. Therefore, ground waves are attenuated as they propagate. Ground waves propagate best over a surface that is a good conductor, such as salt water, and poorly over dry desert areas. Ground-wave losses increase rapidly with frequency. Therefore, ground-wave propagation is generally limited to frequencies below 2 MHz.

Figure 9-13 shows ground-wave propagation. Earth's atmosphere has a *gradient density* (that is, the density decreases gradually with distance from Earth's surface), which

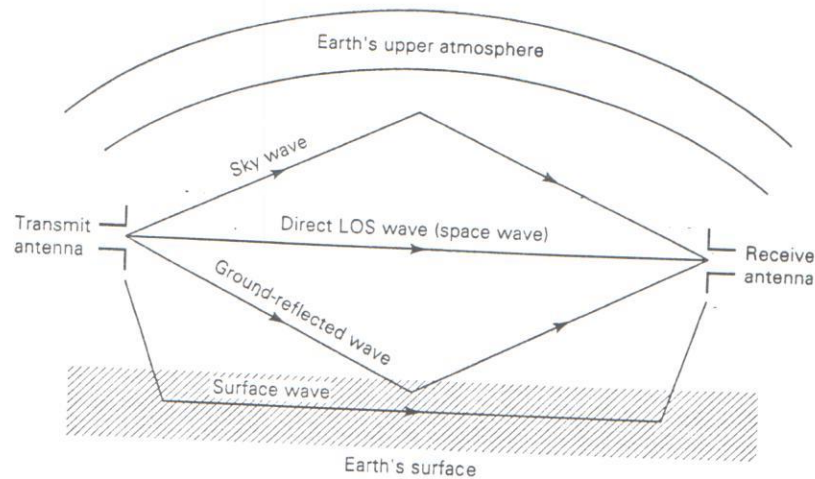


FIGURE 9-12 Normal modes of wave propagation

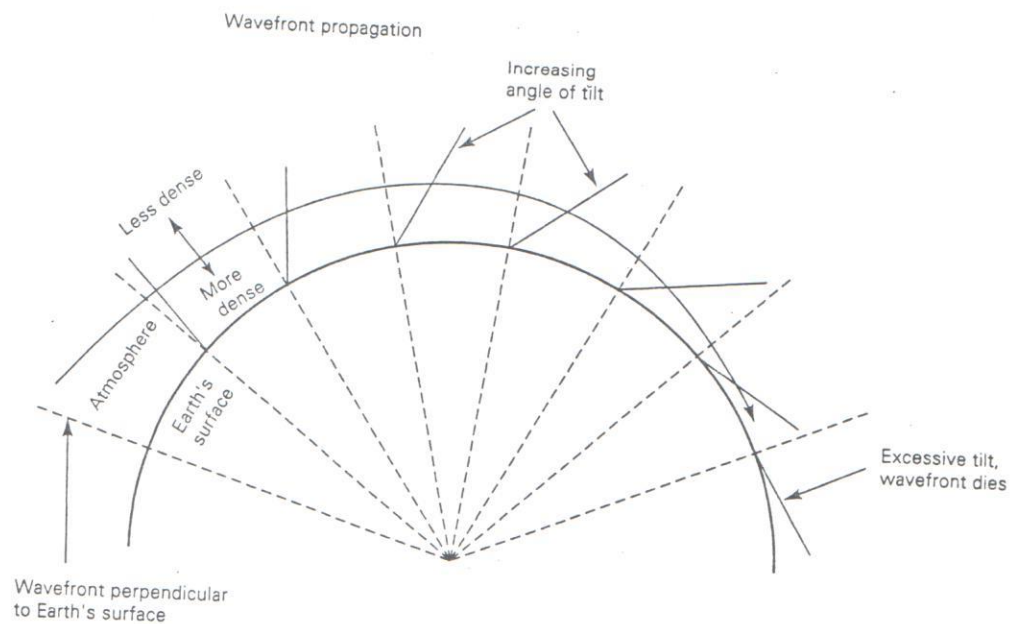


FIGURE 9-13 Ground-wave propagation

causes the wavefront to tilt progressively forward. Therefore, the ground wave propagates around Earth, remaining close to its surface, and if enough power is transmitted, the wavefront could propagate beyond the horizon or even around the entire circumference of Earth. However, care must be taken when selecting the frequency and the terrain over which the ground wave will propagate to ensure that the wavefront does not tilt excessively and simply turn over, lie flat on the ground, and cease to propagate.

Ground-wave propagation is commonly used for ship-to-ship and ship-to-shore communications, for radio navigation, and for maritime mobile communications. Ground waves are used at frequencies as low as 15 kHz.

The disadvantages of ground-wave propagation are as follows:

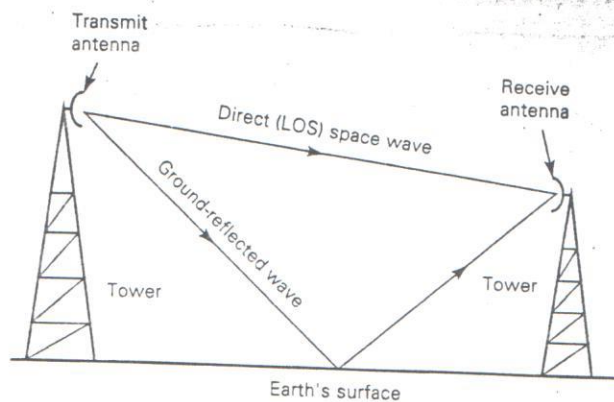


FIGURE 9-14 Space-wave propagation

1. Ground waves require a relatively high transmission power.
2. Ground waves are limited to very low, low, and medium frequencies (VLF, LF, and MF) requiring large antennas (the reason for this is explained in Chapter 11).
3. Ground losses vary considerably with surface material.

The advantages of ground-wave propagation are as follows:

1. Given enough transmit power, ground waves can be used to communicate between any two locations in the world.
2. Ground waves are relatively unaffected by changing atmospheric conditions.

Space-Wave Propagation

Space-wave propagation includes radiated energy that travels in the lower few miles of Earth's atmosphere. Space waves include both direct and ground-reflected waves (see Figure 9-14). *Direct waves* travel essentially in a straight line between the transmit and receive antennas. Space-wave propagation with direct waves is commonly called *line-of-sight (LOS) transmission*. Therefore, space-wave propagation is limited by the curvature of the earth. Ground-reflected waves are waves reflected by Earth's surface as they propagate between the transmit and receive antennas.

Figure 9-14 shows space-wave propagation between two antennas. It can be seen that the field intensity at the receive antenna depends on the distance between the two antennas (attenuation and absorption) and whether the direct and ground-reflected waves are in phase (interference).

The curvature of Earth presents a horizon to space-wave propagation commonly called the *radio horizon*. Due to atmospheric refraction, the radio horizon extends beyond the *optical horizon* for the common *standard atmosphere*. The radio horizon is approximately four-thirds that of the optical horizon. Refraction is caused by the troposphere, due to changes in its density, temperature, water-vapor content, and relative conductivity. The radio horizon can be lengthened simply by elevating the transmit or receive antennas (or both) above Earth's surface with towers or by placing them on top of mountains or high buildings.

Figure 9-15 shows the effect of antenna height on the radio horizon. The line-of-sight radio horizon for a single antenna is given as

$$d = \sqrt{2h} \quad (9-15)$$

where d = distance to radio horizon (miles)
 h = antenna height above sea level (feet)

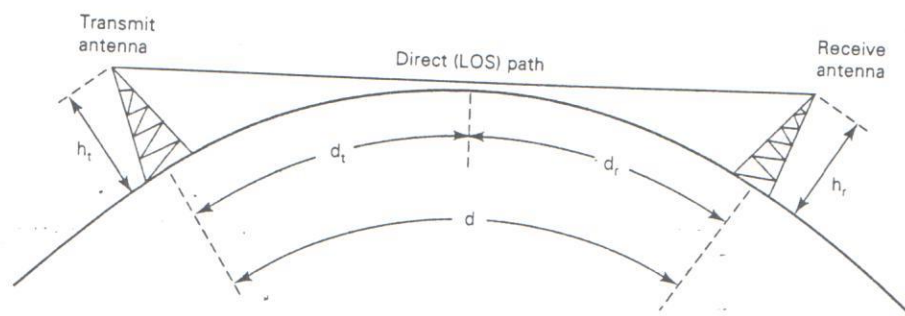


FIGURE 9-15 Space waves and radio horizon

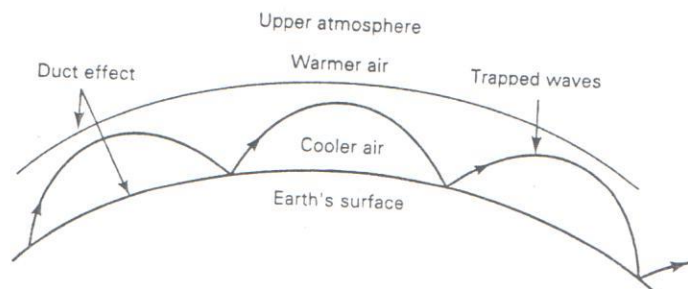


FIGURE 9-16 Duct propagation

Therefore, for a transmit and receive antenna, the distance between the two antennas is

$$d = d_t + d_r$$

or

$$d = \sqrt{2h_t} + \sqrt{2h_r} \quad (9-16)$$

where

- d = total distance (miles)
- d_t = radio horizon for transmit antenna (miles)
- d_r = radio horizon for receive antenna (miles)
- h_t = transmit antenna height (feet)
- h_r = receive antenna height (feet)

or

$$d = \sqrt{4}\sqrt{h_t} + \sqrt{4}\sqrt{h_r} \quad (9-17)$$

where d_t and d_r are distance in kilometers and h_t and h_r are height in meters.

From Equations 9-16 and 9-17, it can be seen that the space-wave propagation distance can be extended simply by increasing either the transmit or receive antenna height, or both.

Because the conditions in Earth's lower atmosphere are subject to change, the degree of refraction can vary with time. A special condition called *duct propagation* occurs when the density of the lower atmosphere is such that electromagnetic waves are trapped between it and Earth's surface. The layers of the atmosphere act as a duct, and an electromagnetic wave can propagate for great distances around the curvature of Earth within this duct. Duct propagation is shown in Figure 9-16.

Sky-Wave Propagation

Electromagnetic waves that are directed above the horizon level are called *sky waves*. Typically, sky waves are radiated in a direction that produces a relatively large angle with

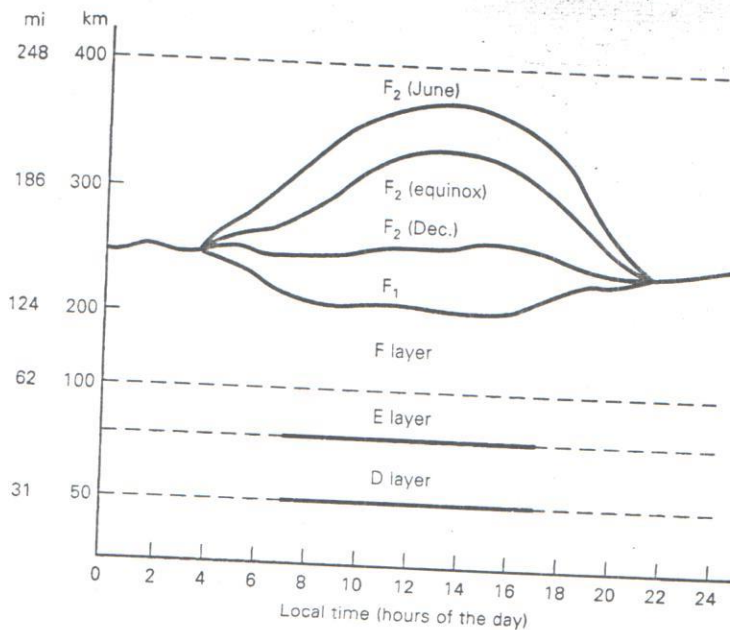


FIGURE 9-17 Ionospheric layers

reference to Earth. Sky waves are radiated toward the sky, where they are either reflected or refracted back to Earth by the ionosphere. The ionosphere is the region of space located approximately 50 km to 400 km (30 mi to 250 mi) above Earth's surface. The ionosphere is the upper portion of Earth's atmosphere. Therefore, it absorbs large quantities of the sun's radiant energy, which ionizes the air molecules, creating free electrons. When a radio wave passes through the ionosphere, the electric field of the wave exerts a force on the free electrons, causing them to vibrate. The vibrating electrons decrease current, which is equivalent to reducing the dielectric constant. Reducing the dielectric constant increases the velocity of propagation and causes electromagnetic waves to bend away from the regions of high electron density toward regions of low electron density (that is, increasing refraction). As the wave moves farther from Earth, ionization increases. However, there are fewer air molecules to ionize. Therefore, in the upper atmosphere, there is a higher percentage of ionized molecules than in the lower atmosphere. The higher the ion density is, the more refraction. Also, due to the ionosphere's nonuniform composition and its temperature and density variations, it is stratified. Essentially, three layers comprise the ionosphere (the D, E, and F layers), which are shown in Figure 9-17. It can be seen that all three layers of the ionosphere vary in location and in ionization density with the time of day. They also fluctuate in a cyclic pattern throughout the year and according to the 11-year sunspot cycle. The ionosphere is most dense during times of maximum sunlight (during the daylight hours and in the summer).

D layer. The D layer is the lowest layer of the ionosphere and is located between 30 mi and 60 mi (50 km to 100 km) above Earth's surface. Because it is the layer farthest from the sun, there is very little ionization in this layer. Therefore, the D layer has very little effect on the direction of propagation of radio waves. However, the ions in the D layer can absorb appreciable amounts of electromagnetic energy. The amount of ionization in the D layer depends on the altitude of the sun above the horizon. Therefore, it disappears at night. The D layer reflects VLF and LF waves and absorbs MF and HF waves. (See Table 1-1 for VLF, LF, MF, and HF frequency regions.)

E layer. The *E layer* is located between 60 mi and 85 mi (100 km to 140 km) above Earth's surface. The E layer is sometimes called the *Kennelly-Heaviside layer* after the two scientists who discovered it. The E layer has its maximum density at approximately 70 mi at noon, when the sun is at its highest point. As with the D layer, the E layer almost totally disappears at night. The E layer aids MF surface-wave propagation and reflects HF waves somewhat during the daytime. The upper portion of the E layer is sometimes considered separately and is called the sporadic E layer because it seems to come and go rather unpredictably. The sporadic E layer is caused by *solar flares* and *sunspot activity*. The sporadic E layer is a thin layer with a very high ionization density. When it appears, there generally is an unexpected improvement in long-distance radio transmission.

F layer. The *F layer* is actually made up of two layers, the F_1 and F_2 layers. During the daytime, the F_1 layer is located between 85 mi and 155 mi (140 km to 250 km) above Earth's surface, and the F_2 layer is located 85 mi to 185 mi (140 km to 300 km) above Earth's surface during the winter and 155 mi to 220 mi (250 km to 350 km) in the summer. During the night, the F_1 layer combines with the F_2 layer to form a single layer. The F_1 layer absorbs and attenuates some HF waves, although most of the waves pass through to the F_2 layer, where they are refracted back to Earth.

PROPAGATION TERMS AND DEFINITIONS

Critical Frequency and Critical Angle

Frequencies above the UHF range are virtually unaffected by the ionosphere because of their extremely short wavelengths. At these frequencies, the distances between ions are appreciably large and, consequently, the electromagnetic waves pass through them with little noticeable effect. Therefore, it stands to reason that there must be an upper frequency limit for sky-wave propagation. *Critical frequency* (f_c) is defined as the highest frequency that can be propagated directly upward and still be returned to Earth by the ionosphere. The critical frequency depends on the ionization density and, therefore, varies with the time of day and the season. If the vertical angle of radiation is decreased, frequencies at or above the critical frequency can still be refracted back to Earth's surface because they will travel a longer distance in the ionosphere and, thus, have a longer time to be refracted. Therefore, critical frequency is used only as a point of reference for comparison purposes. However, every frequency has a maximum vertical angle at which it can be propagated and still be refracted back by the ionosphere. This angle is called the *critical angle*. The critical angle θ_c is shown in Figure 9-18.

Virtual Height

Virtual height is the height above Earth's surface from which a refracted wave appears to have been reflected. Figure 9-19 shows a wave that has been radiated from Earth's surface toward the ionosphere. The radiated wave is refracted back to Earth and follows path B. The actual maximum height that the wave reached is height h_x . However, path A shows the projected path that a reflected wave could have taken and still been returned to Earth at the same location. The maximum height that this hypothetical reflected wave would have reached is the virtual height (h_v).

Maximum Usable Frequency

The *maximum usable frequency* (MUF) is the highest frequency that can be used for sky-wave propagation between two specific points on Earth's surface. It stands to reason, then, that there are as many values possible for MUF as there are points on Earth and frequencies—an infinite number. MUF, as with the critical frequency, is a limiting frequency for sky-wave propagation. However, the maximum usable frequency is for a

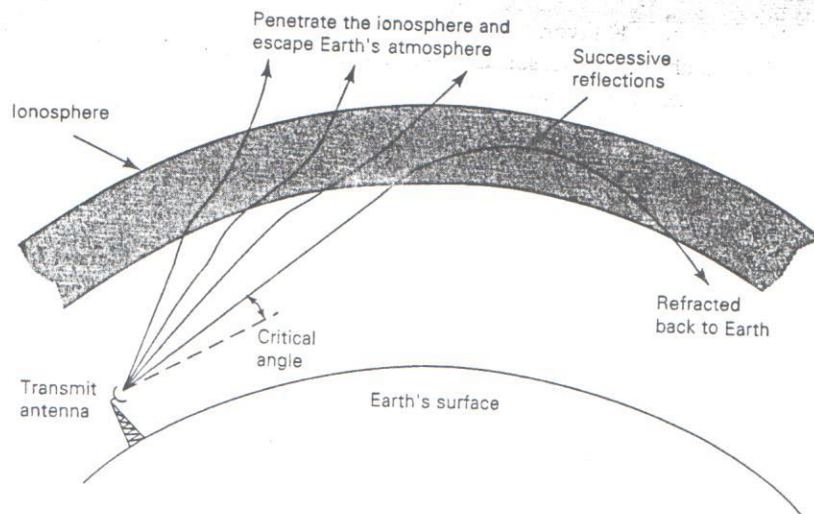


FIGURE 9-18 Critical angle

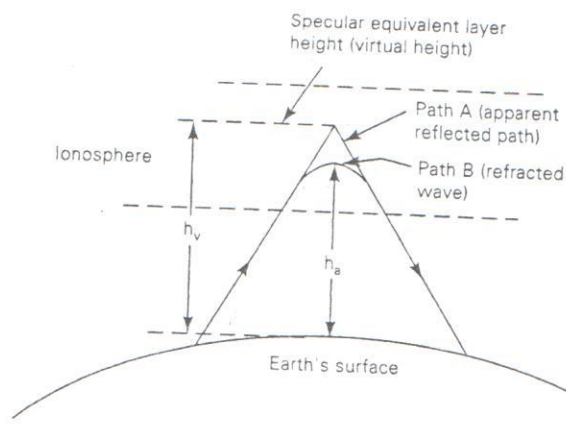


FIGURE 9-19 Virtual and actual height

specific angle of incidence (the angle between the incident wave and the normal). Mathematically, MUF is

$$\text{MUF} = \frac{\text{critical frequency}}{\cos \theta} \quad (9-18a)$$

$$= \text{critical frequency} \times \sec \theta \quad (9-18b)$$

where θ is the angle of incidence.

Equation 9-18 is called the *secant law*. The secant law assumes a flat Earth and a flat reflecting layer, which, of course, can never exist. Therefore, MUF is used only for making preliminary calculations.

Skip Distance

The *skip distance* (d_s) is the minimum distance from a transmit antenna that a sky wave of given frequency (which must be less than the MUF) will be returned to Earth. Figure 9-20a shows several rays with different elevation angles being radiated from the same point on Earth. It can be seen that the point where the wave is returned to Earth moves

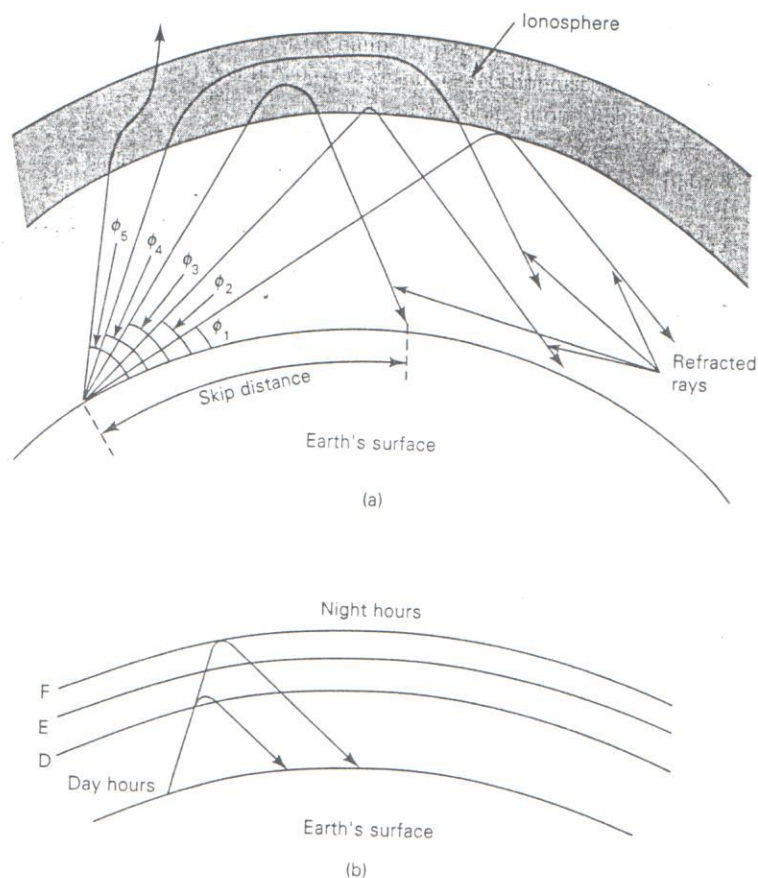


FIGURE 9-20 (a) Skip distance; (b) daytime-versus-nighttime propagation

closer to the transmitter as the elevation angle (ϕ) is increased. Eventually, however, the angle of elevation is sufficiently high that the wave penetrates through the ionosphere and totally escapes Earth's atmosphere.

Figure 9-20b shows the effect on the skip distance of the disappearance of the D and E layers during nighttime. Effectively, the *ceiling* formed by the ionosphere is raised, allowing sky waves to travel higher before being refracted back to Earth. This effect explains how faraway radio stations are sometimes heard during the night that cannot be heard during daylight hours.

Free-Space Path Loss

Free-space path loss is defined as the loss incurred by an electromagnetic wave as it propagates in a straight line through a vacuum with no absorption or reflection of energy from nearby objects. The expression for free-space path loss is given as

$$L_p = \left(\frac{4\pi D}{\lambda} \right)^2 = \left(\frac{4\pi f D}{c} \right)^2 \quad (9-19)$$

where L_p = free-space path loss
 D = distance
 f = frequency
 λ = wavelength
 c = velocity of light in free space (3×10^8 m/s)

Converting to dB yields

$$L_{p(\text{dB})} = 20 \log \frac{4\pi f D}{c} = 20 \log \frac{4\pi}{c} + 20 \log f + 20 \log D$$

When the frequency is given in MHz and the distance in km,

$$\begin{aligned} L_{p(\text{dB})} &= 20 \log \frac{4\pi(10)^6 (10)^3}{3 \times 10^8} + 20 \log f_{(\text{MHz})} + 20 \log D_{(\text{km})} \\ &= 32.4 + 20 \log f_{(\text{MHz})} + 20 \log D_{(\text{km})} \end{aligned} \quad (9-20a)$$

When the frequency is given in GHz and the distance in km,

$$L_{p(\text{dB})} = 92.4 + 20 \log f_{(\text{GHz})} + 20 \log D_{(\text{km})} \quad (9-20b)$$

Similar conversions can be made using distance in miles, frequency in kHz, and so on.

Example 9-2

For a carrier frequency of 6 GHz and a distance of 50 km, determine the free-space path loss.

Solution

$$\begin{aligned} L_p &= 32.4 + 20 \log 6000 + 20 \log 50 \\ &= 32.4 + 75.6 + 34 = 142 \text{ dB} \end{aligned}$$

or

$$\begin{aligned} L_p &= 92.4 + 20 \log 6 + 20 \log 50 \\ &= 92.4 + 15.6 + 34 = 142 \text{ dB} \end{aligned}$$

Fade Margin

Radio communications between remote locations, whether earth-to-earth or earth-to-satellite, require propagating electromagnetic signals through free space. As an electromagnetic wave propagates through Earth's atmosphere, the signal may experience intermittent losses in signal strength beyond the normal path loss. This loss can be attributed to several different phenomena and can include both short- and long-term effects. This variation in signal loss is called fading and can be attributed to weather disturbance, such as rainfall, snow, hail, and so forth; multiple transmission paths; and an irregular Earth surface. To accommodate temporary fading, an additional loss is added to the normal path loss. This loss is called fade margin.

Essentially, *fade margin* is a "fudge factor" included in the system gain equation that considers the nonideal and less predictable characteristics of radio wave propagation, such as *multipath propagation* (*multipath loss*) and *terrain sensitivity*. These characteristics cause temporary, abnormal atmospheric conditions that alter the free-space path loss and are usually detrimental to the overall system performance. Fade margin also considers system reliability objectives. Thus, fade margin is included in the system gain equation as a loss.

Solving the Barnett-Vigniant reliability equations for a specified annual system availability for an unprotected, nondiversity system yields the following expression:

$$F_m = \underbrace{30 \log D}_{\text{multipath effect}} + \underbrace{10 \log (6ABf)}_{\text{terrain sensitivity}} - \underbrace{10 \log (1 - R)}_{\text{reliability objectives}} - \underbrace{70}_{\text{constant}} \quad (9-21)$$

where

F_m = fade margin (decibels)

D = distance (kilometers)

f = frequency (gigahertz)

R = reliability expressed as a decimal (i.e., 99.99% = 0.9999 reliability)

$1 - R$ = reliability objective for a one-way 400-km route

- A = roughness factor
 = 4 over water or a very smooth terrain
 = 1 over an average terrain
 = 0.25 over a very rough, mountainous terrain
 B = factor to convert a worst-month probability to an annual probability
 = 1 to convert an annual availability to a worst-month basis
 = 0.5 for hot humid areas
 = 0.25 for average inland areas
 = 0.125 for very dry or mountainous areas

Example 9-3

Determine the fade margin for the following conditions: distance between sites, $D = 40$ km; frequency, $f = 1.8$ GHz; smooth terrain; humid climate; and a reliability objective 99.99%.

Solution Substituting into Equation 9-21 yields,

$$\begin{aligned}
 F_m &= 30 \log 40 + 10 \log[(6)(4)(0.5)(1.8)] - 10 \log(1 - 0.9999) - 70 \\
 &= 48.06 + 13.34 - (-40) - 70 = 31.4 \text{ dB}
 \end{aligned}$$

QUESTIONS

- 9-1. Describe an electromagnetic ray; a wavefront.
- 9-2. Describe power density; voltage intensity.
- 9-3. Describe a spherical wavefront.
- 9-4. Explain the inverse square law.
- 9-5. Describe wave attenuation.
- 9-6. Describe wave absorption.
- 9-7. Describe refraction. Explain Snell's law for refraction.
- 9-8. Describe reflection.
- 9-9. Describe diffraction. Explain Huygens's principle.
- 9-10. Describe the composition of a good reflector.
- 9-11. Describe the atmospheric conditions that cause electromagnetic refraction.
- 9-12. Define *electromagnetic wave interference*.
- 9-13. Describe ground-wave propagation. List its advantages and disadvantages.
- 9-14. Describe space-wave propagation.
- 9-15. Explain why the radio horizon is at a greater distance than the optical horizon.
- 9-16. Describe the various layers of the ionosphere.
- 9-17. Describe sky-wave propagation.
- 9-18. Explain why ionospheric conditions vary with time of day, month of year, and so on.
- 9-19. Define *critical frequency*; *critical angle*.
- 9-20. Describe virtual height.
- 9-21. Define *maximum usable frequency*.
- 9-22. Define *skip distance* and give the reasons that it varies.
- 9-23. Describe path loss.
- 9-24. Describe fade margin.
- 9-25. Describe fading.

PROBLEMS

- 9-1. Determine the power density for a radiated power of 1000 W at distance of 20 km from an isotropic antenna.

- 9-2. Determine the power density for Problem 9-1 for a point that is 30 km from the antenna.
- 9-3. Describe the effects on power density if the distance from a transmit antenna is tripled.
- 9-4. Determine the radio horizon for a transmit antenna that is 100 ft high and a receiving antenna that is 50 ft high, and for antennas at 100 m and 50 m.
- 9-5. Determine the maximum usable frequency for a critical frequency of 10 MHz and an angle of incidence of 45° .
- 9-6. Determine the electric field intensity for the same point in Problem 9-1.
- 9-7. Determine the electric field intensity for the same point in Problem 9-2.
- 9-8. For a radiated power $P_r = 10$ kW, determine the voltage intensity at a distance 20 km from the source.
- 9-9. Determine the change in power density when the distance from the source increases by a factor of 4.
- 9-10. If the distance from the source is reduced to one-half its value, what effect does this have on the power density?
- 9-11. The power density at a point from a source is $0.001 \mu\text{W}$ and the power density at another point is $0.00001 \mu\text{W}$; determine the attenuation in decibels.
- 9-12. For a dielectric ratio $\sqrt{\epsilon_{r2}/\epsilon_{r1}} = 0.8$ and an angle of incidence $\theta_i = 26^\circ$, determine the angle of refraction, θ_r .
- 9-13. Determine the distance to the radio horizon for an antenna located 40 ft above sea level.
- 9-14. Determine the distance to the radio horizon for an antenna that is 40 ft above the top of a 4000-ft mountain peak.
- 9-15. Determine the maximum distance between identical antennas equally distant above sea level for Problem 9-13.
- 9-16. Determine the power density for a radiated power of 1200 W at distance of 50 km from an isotropic antenna.
- 9-17. Determine the power density for Problem 9-16 for a point 100 km from the same antenna.
- 9-18. Describe the effects on power density if the distance from a transmit antenna is reduced by a factor of 3.
- 9-19. Determine the radio horizon for a transmit antenna that is 200 ft high and a receiving antenna that is 100 ft high, and for antennas at 200 m and 100 m.
- 9-20. Determine the maximum usable frequency for a critical frequency of 20 MHz and an angle of incidence of 35° .
- 9-21. Determine the voltage intensity for the same point in Problem 9-16.
- 9-22. Determine the voltage intensity for the same point in Problem 9-17.
- 9-23. Determine the change in power density when the distance from the source decreases by a factor of 8.
- 9-24. Determine the change in power density when the distance from the source increases by a factor of 8.
- 9-25. If the distance from the source is reduced to one-quarter its value, what effect does this have on the power density?
- 9-26. The power density at a point from a source is $0.002 \mu\text{W}$ and the power density at another point is $0.00002 \mu\text{W}$, determine the attenuation in dB.
- 9-27. For a dielectric ratio of 0.4 and an angle of incidence $\theta_i = 18^\circ$, determine the angle of refraction θ_r .
- 9-28. Determine the distance to the radio horizon for an antenna located 80 ft above sea level.
- 9-29. Determine the distance to the radio horizon for an antenna that is 80 ft above the top of a 5000 ft mountain.
- 9-30. Determine the maximum distance between identical antennas equally distant above sea level for Problem 9-29.