Chapter 2

Electromagnetic Signal Propagation

2.1 INTRODUCTION

Before describing the characteristics of EW systems it is important to understand some of the fundamental properties of propagating signals, or EM waves. For those familiar with this topic, this chapter can be skipped. For those readers interested in further reading, [1–7] are recommended.

The modes of signal propagation can be dependent on the frequency of the signal, while some of the modes are independent of the frequency. These characteristics are pointed out in the appropriate following discussions.

The design of the RF front ends, especially the antenna, of EW systems depends to a great extent upon how signals propagate. The fundamental equations that govern the movement of signals from a transmitter, through space, and at a receiver are explained in this chapter. In this case, signals refers to RF signals, which for our purposes are assumed to start around 500 kHz.

2.2 SIGNAL PROPAGATION

A signal generated in a transmitter leaves that transmitter at a specified power level and is sent to an associated antenna usually via interconnecting cables. The antenna typically has a gain, which increases the level of the signal in certain preferred directions. As the signal propagates through the atmosphere, it suffers losses due to the spreading of the signal in space and losses due to encountered obstacles. It arrives at a receive antenna at some power level, which usually has some characteristic gain, thus increasing the level of the signal. This signal is then presented to the receiver from the receive antenna.

There are two components that make up an EM wave: the electric field and the magnetic field. One cannot exist without the other. The electric field is designated as **E** and has units of volts per meter. The magnetic field is designated as **H** and has units of amperes per meter. These components are orthogonal to one another and they are both orthogonal to the direction of propagation of the EM wave. This is shown schematically in Figure 2.1.

A signal radiates from an *isotropic* antenna (approximated by a point source) in an ever-expanding sphere, until it encounters something that perturbs that sphere. (An isotropic antenna is one that radiates equally in all directions.) At a significant enough distance from the transmitter, typically taken to be at least 10 times the wavelength, the spherical wavefront is frequently approximated as a plane over the dimensions of most antennas.

There are several modes of signal propagation. The major modes that are of importance for communication EW system design are direct wave, surface wave, reflected wave, refracted wave, diffracted wave, and scatter wave. For ground-to-ground communications, useful VHF, and above, signal propagation is limited to the troposhperic layer of the atmosphere, which ranges in altitude from 9 km at the Earth's poles to about 17 km at the equator [8]. On the other hand, HF signal propagation phenomena takes advantage of the ionosphere for long-distance communication. For ground-to-air or air-to-air communications, the direct wave is the method most frequently used.

2.3 RF BAND DESIGNATIONS

The RF spectrum is divided into designated bands with the common designations shown in Table 2.1. Communication services of some sort are provided in

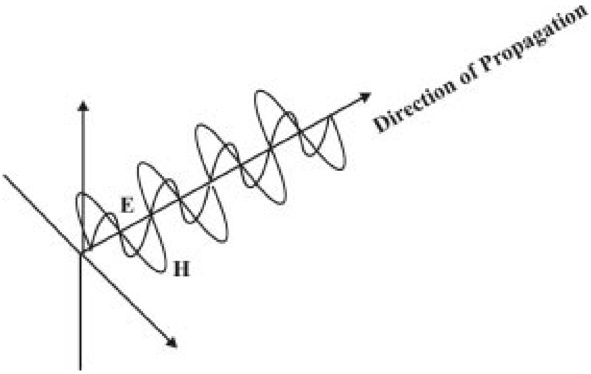

Figure 2.1 E and **H** fields associated with an EM wave.

Table 2.1 Frequency Band Designations

Frequency Band	Name	Designation
3–30 kHz	Very low frequency	VLF
30–300 kHz	Low frequency	LF
300–3,000 kHz	Medium frequency	MF
3–30 MHz	High frequency	HF
30–300 MHz	Very high frequency	VHF
300–3,000 MHz	Ultra high frequency	UHF
3–30 GHz	Super high frequency	SHF
30–300 GHz	Extra high frequency	EHF
300–3,000 GHz	Optical	Optical

virtually all of the RF bands.

The microwave band (500 MHz to 40 GHz) has long been subdivided into subbands. It has recently undergone a change in subband designation, however. The bands, along with their old and new designations, are given in Table 2.2.

Table 2.2 New Designations of the Higher-Frequency Bands

Frequency Band	Old Designation	New Designation
0.5–1 GHz	UHF	C
1–2 GHz	L	D
2–3 GHz	S	E
3–4 GHz	S	F
4–6 GHz	C	G
6–8 GHz	C	H
8–10 GHz	X	J
10–12.4 GHz	X	J
12.4–18 GHz	Ku	J
18–20 GHz	K	J
20–26.6 GHz	K	K
26.6–40 GHz	Ka	K

2.4 POLARIZATION

The *polarization* of an EM wave is the orientation, relative to the Earth, of the electric field component of the wave. Although the polarization of an EM wave can be anything, the most common forms of polarization are vertical, horizontal, circular, and elliptical. In these latter two categories the electric field is intentionally rotated as the signal traverses space. Manipulating the phase of the signal at the transmitter creates this rotation.

VHF and above signals close to the Earth propagate better in the vertical polarization mode than in the horizontal polarization mode. This characteristic occurs because the Earth's magnetic field tends to cancel the magnetic component of EM waves when this component is vertical (which occurs when the electric component is horizontal). Often when an antenna is used both for transmission and reception, orthogonal polarizations are used for the two signals since some degree of isolation is provided by the polarization diversity.

2.5 POWER DENSITY

The *power density* of an EM wave is a measure of the power in the wave at any point in space. Herein it is denoted as P_d and is given in units of watts/meter^2. The *field strength* of an EM wave, E, is a measure of the voltage potential differences in the wave as a function of distance and is given in units of volts/meter. As shown in Figure 2.1, the E and H waves can be considered as vectors, which have both an amplitude and a direction. As vectors they are denoted by **E** and **H**. According to the *Poynting theorem,*

$$P_\text{d} = \frac{1}{2}\left|\text{Re}\left(\mathbf{E} \otimes \mathbf{H}\right)\right| \tag{2.1}$$

where $\otimes$ represents the vector cross product. Let

$$\begin{aligned} \mathbf{E} &= E_\text{peak}\cos(2\pi f t)\mathbf{e} \\ \mathbf{H} &= H_\text{peak}\cos(2\pi f t)\mathbf{h} \end{aligned} \tag{2.2}$$

where **e** and **h** are unit vectors in the direction of **E** and **H**, respectively.

The *characteristic impedance*, Z_0, of the propagation medium is given by the ratio of the magnitudes of the electric wave to the magnetic wave. Thus,

$$Z_0 = \frac{E_{\text{peak}}}{H_{\text{peak}}} \tag{2.3}$$

In free space, Z_0 is equal to 120π, or 377 ohms. Therefore, since **e** and **h** are orthogonal,

$$\begin{aligned} P_{\text{d}} &= \frac{1}{2}\left|\text{Re}\left(E_{\text{peak}}\,\frac{E_{\text{peak}}}{Z_0}\right)\right| \\ &= \frac{1}{2}\frac{E_{\text{peak}}^2}{Z_0} \end{aligned} \tag{2.4}$$

However, since for sinusoidal waves, $E_{\text{rms}} = E_{\text{peak}}/\sqrt{2}$,

$$\begin{aligned} P_{\text{d}} &= \frac{E_{\text{rms}}^2}{Z_0} \\ &= \frac{E_{\text{rms}}^2}{120\pi} \end{aligned} \tag{2.5}$$

Therefore, the electric field strength is related to the power density by

$$E_{\text{rms}} = \sqrt{120\pi P_{\text{d}}} \tag{2.6}$$

From these equations the electric field strength can be calculated versus distance between the transmitter and receiver.

The *sensitivity* of receiving systems is often given in terms of microvolts per meter (μV/m), that is, in terms of field strength. This is a system-level specification in that it reflects the degree to which the system can extract EM wave energy. It best describes the ability of the system antenna to deliver signal power to the remainder of the system. Typical values are 1–5 μV/m. Equivalently, sensitivity is sometimes specified in terms of decibels relative to 1 μV/m. Since a decibel is a measure of power, conversion to power terms is necessary to change such a specification to absolute values. Recall that decibel is defined as

$$\text{dB} = 10\log\frac{P_2}{P_1} \tag{2.7}$$

When specifying decibels relative to 1 μV/m, the two power values are calculated assuming the same impedance value, usually the characteristic impedance of free space, Z_0. Thus,

$$\begin{aligned}\text{dB}_{1\mu\text{V/m}} &= 10\log\frac{(\text{v/m})^2 / Z_0}{(1\mu\text{V/m})^2 / Z_0} \\ &= 20\log\frac{\text{v/m}}{1\mu\text{V/m}}\end{aligned} \tag{2.8}$$

So

$$\text{v/m} \quad = \quad 10^{-6}\times 10^{\text{dB}_{\mu\text{V/m}}/20} \tag{2.9}$$

(of course, the 10^{-6} is not used if the results are desired in units of μV/m).

2.6 FREE-SPACE PROPAGATION

Free-space propagation refers to the propagation mode between two antennas where there is no obstacle between the antennas to interfere with the ever-expanding spherical surface of the signal emitted from the transmitting antenna, when the transmitting antenna is isotropic. Free-space propagation is only possible in outer space where there is relatively little matter. Some air-to-air, including satellite communications, approximate free-space situations fairly well, however.

An isotropic antenna is one that radiates equally in all directions simultaneously and is only a model—they do not exist in practice. It is used as a standard against which practical antennas are measured.

The power density at a distance R from the isotropic transmit antenna is the amount of EM wave power that passes through a unit area on the surface of the spherical surface. By simple calculus

$$P_\text{d} = \frac{P_\text{transmitted}}{4\pi R^2} \tag{2.10}$$

where $P_\text{transmitted}$ is the amount of power emitted by the transmitter.

The amount of power received by the receiver is given by the amount of this power density absorbed by the receive antenna. The effective area, A_{eff}, determines this. Therefore,

$$P_{\text{R}} = P_{\text{d}} A_{\text{eff}} \tag{2.11}$$

The effective area of an isotropic receive antenna is given by

$$A_{\text{eff}} = \frac{\lambda^2}{4\pi} \tag{2.12}$$

Therefore the power received in free-space propagation between two isotropic antennas is given by

$$\begin{aligned} P_{\text{received}} &= \frac{P_{\text{transmitted}}}{4\pi R^2} \frac{\lambda^2}{4\pi} \\ &= P_{\text{transmitted}} \left(\frac{\lambda}{4\pi R} \right)^2 \end{aligned} \tag{2.13}$$

The *gain* of an antenna is a measure of how particular directions are favored for propagation over others. More will be said about gain later. Suffice it here to say that the amount of power transmitted is given by

$$P_{\text{transmitted}} = G_{\text{T}} P_{\text{T}} \tag{2.14}$$

where P_{T} is the amount of signal power delivered to the antenna, and G_{T} is the transmit antenna gain in some direction. A similar relationship exists for the receive antenna,

$$P_{\text{R}} = G_{\text{R}} P_{\text{received}} \tag{2.15}$$

where G_{R} is the receive antenna gain in some direction and P_{R} is the power available from the antenna.

From above,

$$P_{\text{d}} = \frac{G_{\text{T}} P_{\text{T}}}{4\pi R^2} = \frac{E_{\text{rms}}^2}{120\pi} \tag{2.16}$$

so the free-space rms field strength can be calculated to be

$$E_{\text{rms}} = \frac{\sqrt{30 G_{\text{T}} P_{\text{T}}}}{R} \tag{2.17}$$

Define the *free-space path loss* as the ratio of the power out of the receive antenna to the power input to the transmit antenna

$$L = \frac{P_{\text{R}}}{P_{\text{T}}} = G_{\text{T}} G_{\text{R}} \frac{\lambda^2}{(4\pi R)^2} \tag{2.18}$$

This is known as *Friis' expression* for free-space path loss. In decibels it is

$$L_{\text{dB}} = \begin{Bmatrix} -32.2 \\ -36.6 \end{Bmatrix} - 20\log(f_{\text{MHz}}) - 20\log(R) + G_{\text{T,dB}} + G_{\text{R,dB}}, \begin{Bmatrix} \text{km} \\ \text{mile} \end{Bmatrix} \tag{2.19}$$

when G_{T} and G_{R} are expressed in decibels. Thus, again in decibels, when P_{T} is expressed in decibels relative to 1W

$$P_{\text{R}} = P_{\text{T}} - L_{\text{dB}} \tag{2.20}$$

or, when P_{T} is expressed in decibels relative to 1 mW

$$P_{\text{R}} = P_{\text{T}} - L_{\text{dB}} + 30 \tag{2.21}$$

This expression ignores the cable losses associated with the transmitter and receiver. Denoting these by L_{T} and L_{R}, when they are included the expressions become

$$P_{\text{R}} = P_{\text{T}} - L_{\text{dB}} - L_{\text{T}} - L_{\text{R}} \tag{2.22}$$

and

$$P_{\text{R}} = P_{\text{T}} - L_{\text{dB}} - L_{\text{T}} - L_{\text{R}} + 30 \tag{2.23}$$

respectively. Values for L_T and L_R for some common types of cable are given in Table 2.3. These loss values correspond to newly manufactured cable, and the actual loss will depend on such factors as installation parameters, age of the cable, and temperature.

2.7 DIRECT WAVE

If there is line of sight between the transmitter and the receiver then the principal mode of signal propagation is via the *direct wave*. As above, at sufficiently large distances above the Earth's surface, the free-space propagation model may apply to the direct wave. Closer to the Earth, however, that is not the case. In fact, as illustrated in Figure 2.2, the amount of power available from the receive antenna is given by

$$P_R = P_T \frac{G_T G_R \lambda^2}{(4\pi)^2 R^n} \tag{2.24}$$

where P_T = power input to the transmit antenna from the cable connecting the transmitter to the transmit antenna (watts); G_T = gain of the transmit antenna in the direction of the receive antenna (unit-less); G_R = gain of the receive antenna in the direction of the transmit antenna (unit-less); λ = wavelength of the signal (meters); R = distance between the transmitter and the receiver (meters); and n is discussed below.

The electric field strength versus distance for radios with an ERP of 40 and 50 dBm is shown in Figure 2.3. This chart assumes that the propagation exponent n = 2, corresponding to the free-space conditions discussed in Section 2.6. Figure 2.4 shows the electric field strength versus distance when the propagation

Table 2.3 Loss per Foot of Some Common Cable Types

	Loss per Foot (dB)		
Cable Type	**At 100 MHz**	**At 400 MHz**	**At 1,000 MHz**
RG6/U	0.019	0.043	0.065
RG58/U	0.05	0.11	0.2
RG59/U	0.038	0.075	0.11
RG8/U	0.025	0.054	0.092
RG174/U	0.11	0.22	0.32
RG188/U	0.105	0.18	0.3
RG213/U	0.025	0.055	0.095

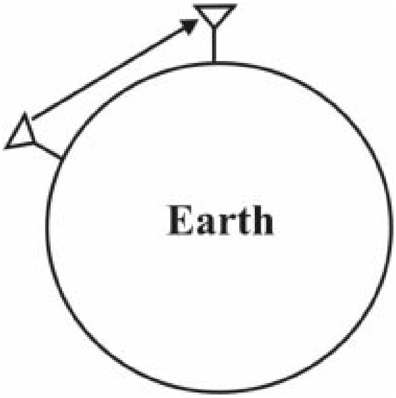

Figure 2.2 A direct wave travels in a straight line from the transmit antenna to the receive antenna.

exponent $n = 4$. Note the change in range on the abscissa. Clearly the signals fall off much more rapidly close to the Earth than high in the air.

Typical specifications for electronic support systems are a sensitivity of 1–5 μV/m. Therefore, the signals from these radios at low altitudes ($n = 4$) can be detected at ranges less than 10 km for ground ES systems. An airborne system, on the other hand, has an intercept range exceeding 150 km for air-to-air intercept with such targets. Thus, airborne systems typically have a substantial advantage for signal intercept.

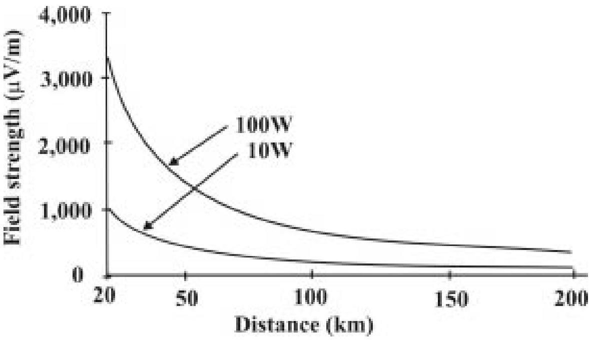

Figure 2.3 Electric field strength as a function of range for two emitter powers, where the propagation exponent $n = 2$.

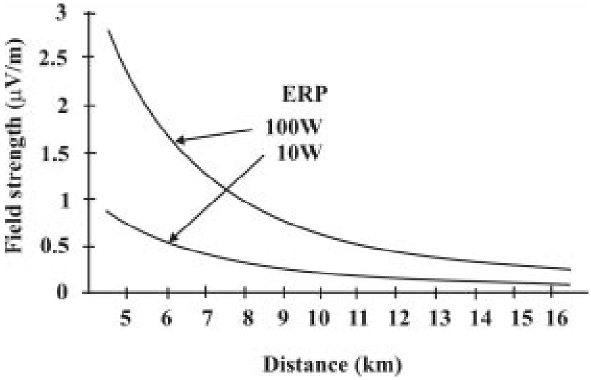

Figure 2.4 Electric field strength as a function of range for two emitter powers, where the propagation exponent $n = 4$.

Unavoidable electronic losses occur at the transmitter and receiver. These losses include cable-resistive loss, frequently expressed as I^2R losses because the loss increases as the current increases. Another source of signal loss at receiving antennas is due to mismatches in the polarization between the signal and the orientation of the antenna. Theoretically no signal is received at all if the signal is vertically polarized and the antenna is horizontally polarized or vice versa. In practice, some signal is received even in this case, however. Herein, these losses are included in the values of G_T and G_R.

There is a propagation model methodology based on the free-space model that is sometimes called the R^n model [9]. The mean path loss at a distance R from the transmitter is calculated as

$$L(R) = L(R_0) + 10n\log_{10}\left(\frac{R}{R_0}\right) \tag{2.25}$$

where R_0 is a suitably defined reference distance, frequently taken as 1 km for outdoor propagation conditions and 1m for indoor applications. $L(R_0)$ represents the path loss at the reference distance. It is frequently measured, but if it is not otherwise known, it can be estimated by

$$L(R_0) \approx 20\log_{10}\left(\frac{4\pi R_0}{\lambda}\right) \tag{2.26}$$

The parameter n, which depends on the environmental conditions, is discussed next. The received power then, at range R, is, as above,

$$P_{\mathrm{R}}(R) = \frac{P_{\mathrm{T}} G_{\mathrm{T}} G_{\mathrm{R}}}{L(R)} \tag{2.27}$$

Examination of (2.27) reveals several items of note about direct-wave signal propagation. First, lower frequencies propagate better than higher ones ($\lambda = 1/f$). Second, the level of the received signal decreases as a power n of the distance between the transmitter and the receiver. Away from the surface of the Earth, $n = 2$. Closer to the Earth's surface, the signal strength decreases faster than $1/R^2$, and $n = 4$ is often used. The actual exponent on R varies with each situation. It ranges from 2 to 16 or more. Therefore, it can be concluded that if an antenna is raised higher into the air, better signal propagation should result. In general this is true, but to obtain a dramatically improved performance, the antennas need to be substantially elevated.

The propagation loss at any range R is a statistical parameter. As such, the loss given above is an average. In many cases, the statistics follow a log-normal distribution. Thus, there is an associated standard deviation of measurements as well. The loss exponent n is given in Table 2.4 for various propagation conditions. For outdoor environments, the standard deviation is in the range of 8 to 14 dB. On the other hand, the propagation loss exponent n and standard deviation σ are given in Table 2.5 for *personal communication systems* (PCSs) in several indoor conditions [9].

All communication paths suffer losses with distance. This is due to the simple fact that the energy or power spreads out with distance, and so the energy and power density decrease. Communication links close to the Earth lose energy approximately as the reciprocal of this distance to the fourth power. Air-to-air links and other free-space direct paths suffer approximately a loss that is the reciprocal of the distance to the second power. Air-to-ground and ground-to-air links suffer loss in between these values. In this section the effects of this propagation loss will be illustrated.

Most lower echelon tactical battlefield radios used for real-time command and control of tactical forces have power levels into their associated antennas of

Table 2.4 Loss Exponent *n* for Various Conditions

Condition	**Loss Exponent, *n***
Free space	2
Urban area cellular, PCS	2.7–4.0
Shadowed urban cellular, PCS	3–5
In building line of sight	1.6–1.8
Obstructed in building	4–6
Obstructed in factories	2–3

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Table 2.5 Propagation Loss Exponent *n* and Associated Standard Deviation σ for Several Indoor Conditions

Conditions	**Frequency (MHz)**	***n***	**σ (dB)**
Indoor: Retail store	914	2.2	8.7
Indoor: Grocery store	914	1.8	5.2
Indoor: Hard partition office	900	3.0	7.0
Indoor: Soft partition office	900	2.4	9.6
Indoor: Soft partition office	1,900	2.6	14.1
Indoor: Factory (LOS)	1,300	1.6–2.0	3.0–5.8
Indoor: Factory (LOS)	4,000	2.1	7.0
Indoor: Suburban home	900	3.0	7.0
Indoor: Factory (obstructed)	1,300	3.3	6.8
Indoor: Factory (obstructed)	4,000	2.1	9.7
Indoor: Office same floor	914	2.76–3.27	5.2–12.9
Indoor: Office entire building	914	3.54–4.33	12.8–13.3
Indoor: Office wing	914	2.68–4.01	4.4– 8.1
Indoor: Average	914	3.14	16.3
Indoor: Through one floor	914	4.19	5.1
Indoor: Through two floors	914	5.04	6.5
Indoor: Through three floors	914	5.22	6.7

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10–100W (40–50 dBm). The typical antenna for these configurations is a tuned whip, which, if it's in good condition, has about 2 dB of gain. Most realistic scenarios, however, do not involve perfect hardware implementations. We will assume here that factors such as the net antenna gain and cable loss of these radios is a net 0 dB (no gain or loss).

The so-called *range to horizon* is the distance beyond which one no longer has visual *line of sight* (LOS) between the transmitter and receiver. Assuming that the Earth is a smooth sphere, the range to horizon can be calculated according to the equation obtained from simple geometric principles as

$$r^2=(R+h)^2-R^2 \tag{2.28}$$

or

$$r=\sqrt{2Rh+h^2} \tag{2.29}$$

where R is the radius of the Earth, h is the elevation of the transmitter, and r is the range to horizon. Frequently h^2 can be neglected relative to R, so

$$r=\sqrt{2Rh} \tag{2.30}$$

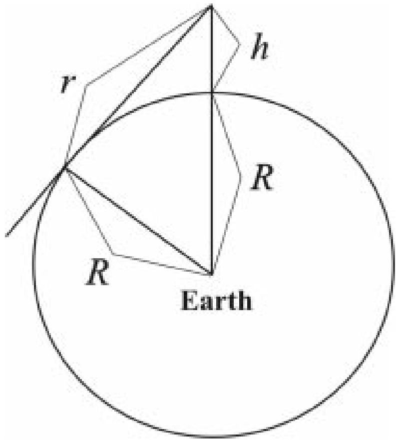

Figure 2.5 Range to horizon.

These distances are illustrated in Figure 2.5. Of course here, the Earth is assumed to be a sphere with an effective radius *R*.

Assuming that the Earth is a sphere of radius 3,960 miles, then the distance to the horizon for an aircraft at 20,000-feet is 173-miles. At VHF (30–300 MHz) and above frequencies the atmosphere close to the surface of the Earth refracts (bends) radio waves that pass through it as illustrated in Figure 2.6. The net effect is to

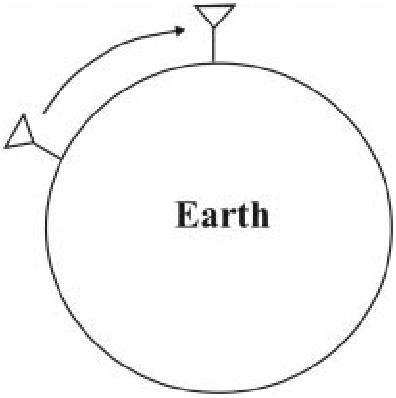

Figure 2.6 The troposphere close to the surface of the Earth refracts radio waves as they traverse through it, causing an extension of the propagation range.

increase the effective radius of the Earth by approximately 1/3. Therefore, a more correct value to use for R in (2.30) is 4/3 R, or 5,280 miles. The resultant calculation is called the *radio line of sight* (RLOS). The 4/3 factor does not always apply, however. In cases of *subrefraction*, the bending of the radio waves in the atmosphere is less than normal and the resultant path length is less than otherwise. In *super-refraction*, the waves are bent more than normal and the path length is longer than otherwise. Using similar arguments, assuming a 4/3-Earth model and a smooth Earth surface, a transmitter and receiver are within RLOS of each other as long as they are within a distance of

$$d = \sqrt{2h_\mathrm{T}} + \sqrt{2h_\mathrm{R}} \tag{2.31}$$

of each other, where d is in miles and h_T and h_R are in feet. Thus, if the transmit antenna is at a height of 20 feet and the receive antenna is at 50 feet, the RLOS is 16.3 miles. Caution should be used when applying these equations to transmitters and receivers close to the Earth's surface, however, because the Earth's surface is not smooth and, depending on the frequency, obstacles can (and frequently do) reduce this range or even preclude signal propagation at all. On the other hand, complex phenomena such as edge diffraction and reflections from surfaces can enhance signal propagation close to the Earth.

2.8 WAVE DIFFRACTION

Physical diffraction is caused by a wave impinging on an object. Some energy in the wave appears to be bent by the edge leaving in a direction different from the original direction. Some of the energy in the wave is changed in its propagation direction. At VHF and above, this diffraction accounts for why it is possible to receive signals even though there are significant obstacles between the transmitter and receiver.

When a radio wave encounters an obstacle, a physical phenomenon called *Huygen's principle* explains the wave diffraction that occurs. This principle says that each source on a wavefront generates secondary wavefronts called wavelets, and a new wavefront is built from the vector sum of these wavelets. The amplitude of the wavelets varies as $(1 + \cos \alpha)$, where α is the angle between the wavelet direction and the direction of propagation. Thus, the wavelet with the maximum amplitude is in the direction of propagation and there is zero amplitude in the reverse direction. In schematic form, the waves are generated as shown in Figure 2.7. Thus, the obstacle does not totally block the signal behind it. It is assumed here that the obstacle has small enough thickness that any impacts at the

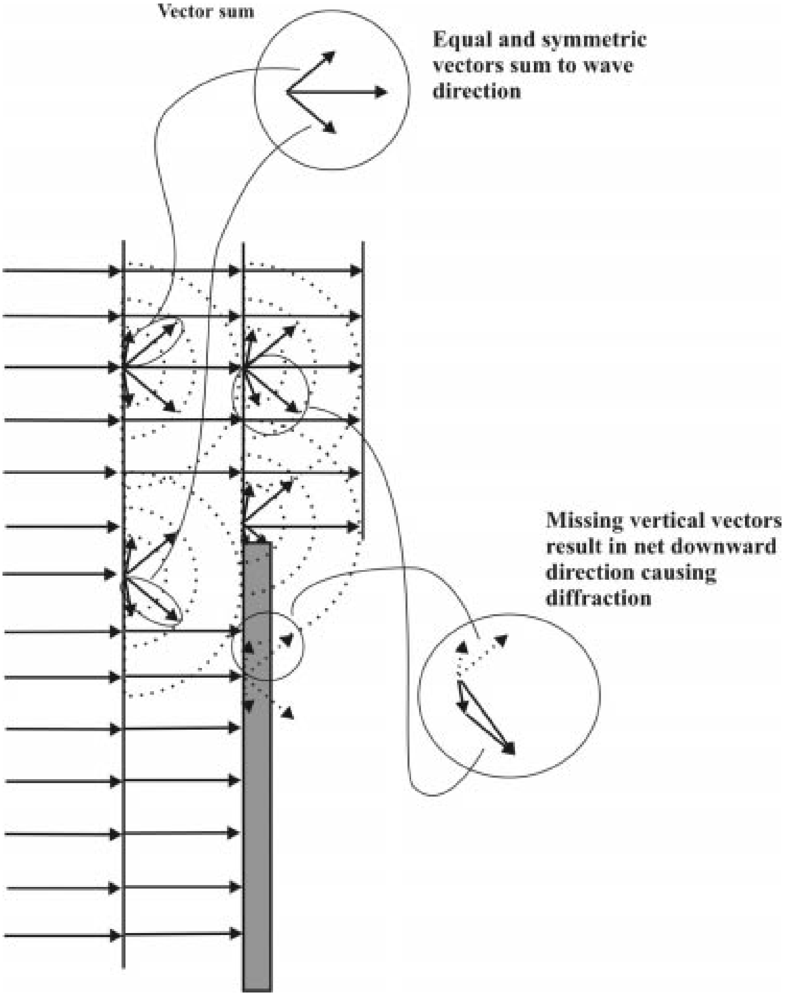

Figure 2.7 Diffraction at an obstacle produces signal energy behind the obstacle.

end of the obstruction are insignificant. In the far field from the obstruction, the E-field at the bottom of the figure has flipped 180°.

When the obstacle is located such that the path-length difference between the direct path and the length of the path made up of the path from the transmitter to the obstacle and the path length from the obstacle to the receiver is a multiple of $\lambda/2$, then the diffraction from the obstacle will tend to cancel the direct path signal at the receiver. The reason for this is that the portion of the signal not blocked by the obstacle will generate signal vectors behind the obstacle but π radians out of phase with the direct path signal. The situation depicted in Figure 2.7 and with the assumption that the thickness of the obstacle has insignificant impact is known as *knife-edge diffraction*. When there is a finite thickness, the attenuation at the edge can be substantially higher than at a knife edge. Diffraction effects also occur behind an obstruction such as a mountain.

2.9 REFLECTED WAVES

The ground and other large surfaces (large relative to the wavelength of the signal) can reflect EM waves. Reflected waves can arrive at a receive antenna out of phase with the direct wave, and, in the case where they are 180° out of phase, can cause considerable fading, depending on the magnitude of the reflected wave compared to the direct wave. These reflections can occur in many ways, one of which is off the ground when the transmitter and/or receiver are close to the Earth's surface. Another form of reflection is off nearby metallic objects, such as cyclone fences close to the transmitter and/or receiver. The ghosts that appear on a television set (when connected to a TV antenna as opposed to a cable or satellite antenna) are a manifestation of such reflections. In that case the reflected wave is received only slightly later than the direct wave, causing the picture to be delayed slightly. The geometrical shapes generated by setting the path difference equal to a constant are ellipsoids (three-dimensional ellipse) with the two antennas at the foci. When the path difference is set equal to $k\lambda/2$ for some integer k, the *Fresnel zones* are generated. For $k = 1$, it is the first Fresnel zone. These notions are depicted in Figure 2.8. Let $\delta_k = d_R - d_D$. Then the Fresnel zones are defined by

$$\delta_k = k\frac{\lambda}{2} \qquad k = 1,2,\ldots \tag{2.32}$$

In most cases, it is only necessary to consider the first Fresnel zone.

Signal reflections off objects also affect the signal level received. At low reflection angles of incidence (the case for reflections off the Earth with large path distances and the case of importance here), reflections off the ground impart a π radian phase shift in the reflected signal for both vertical and horizontal polarizations. A rule of thumb useful for determining at what distance such reflections cause propagation changes from $n = 2$ to $n > 2$ in (2.1) is given by

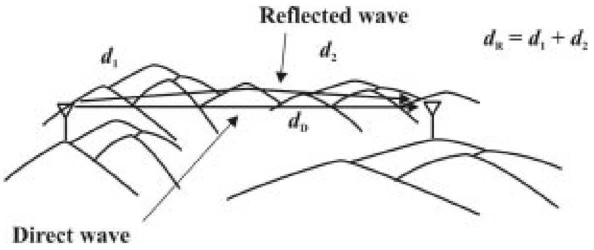

Figure 2.8 An EM wave with a significant reflected component at the receiver. The reflection is off a distant mountain in this case.

$$d_1 = \frac{4h_T h_R}{\lambda} \tag{2.33}$$

where h_T is the transmit antenna height, h_R is the receive antenna height, and λ is the wavelength, all in consistent units. This corresponds to the distance where the first Fresnel zone first touches a point of reflection. Beyond this distance the signal is grazing the Earth at the reflection point and a constant π radians is destructively added to the phase of the received signal. The amplitudes of the respective signals determine the amount of the destruction, so therefore the characteristics of the reflection point (e.g., smooth or rough Earth and trees) are important.

Reflection of radio waves off the surface of the Earth can be analyzed with the aid of Figure 2.9. For simplicity it is assumed that the Earth is flat in the region

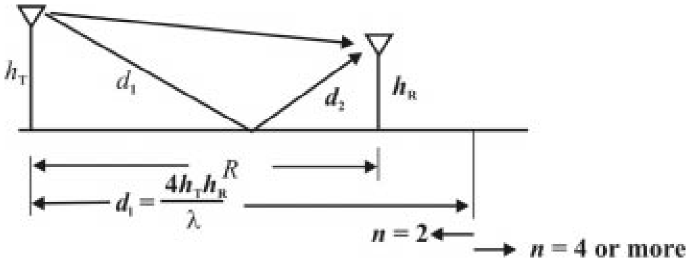

Figure 2.9 Distance d_1 is the distance where the first Fresnel zone touches flat Earth for the first time. Beyond this distance the attenuation exponent n changes for 2 to 4 or more.

between the transmitter and receiver. The power from the receive antenna due to both the direct wave and the reflected wave is given by

$$P_{\text{total}} = P_{\text{direct}} \left| 1 + \rho e^{-j\phi} \right|^2 \tag{2.34}$$

where ρ is the reflection coefficient at the point of reflection and the phase difference between the direct wave and reflected wave, ϕ, is given by

$$\phi = 2\pi \frac{c}{\lambda} \frac{\delta_{\text{r}}}{c} \tag{2.35}$$

where δ_{t} is the time difference between the two waves and δ_{r} is the path distance difference. Thus,

$$\phi = 2\pi \frac{\delta_{\text{r}}}{\lambda} \tag{2.36}$$

If $R >> h_{\text{T}}$ or h_{R}, then $\theta \approx 0$, $\rho \approx -1$ and

$$\phi \approx \frac{2\pi}{\lambda} \frac{2h_{\text{T}} h_{\text{R}}}{R} \tag{2.37}$$

Now

$$\begin{aligned} \left| 1 + \rho e^{-j\phi} \right|^2 &= \left| 1 - (\cos\phi - j \sin\phi \right|^2 \\ &= (1 - \cos\phi)^2 + \sin^2\phi \\ &= (1 - 2\cos\phi + \cos^2\phi + \sin^2\phi) \\ &= (2 - 2\cos\phi) \\ &= 2 - 2\cos\left(\frac{2\pi}{\lambda} \frac{2h_{\text{T}} h_{\text{R}}}{R} \right) \end{aligned} \tag{2.38}$$

so

$$\frac{P_{\text{total}}}{P_{\text{direct}}} = 2 - 2\cos\left(\frac{2\pi}{\lambda} \frac{2h_{\text{T}} h_{\text{R}}}{R} \right) \tag{2.39}$$

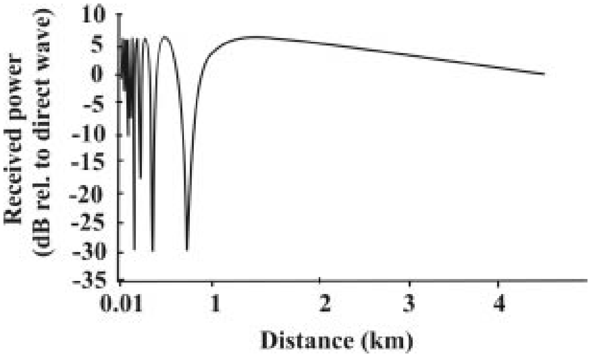

Figure 2.10 Power received due to both the direct wave and the ground reflected wave.

Equation (2.39) is plotted in Figure 2.10 in decibels relative to the direct wave for $h_T = 30\text{m}$ and $h_R = 2\text{m}$ at 1,850 MHz. When R is small, the total power oscillates dramatically, but for larger ranges between the transmitter and receiver the power decreases at a rate proportional to $1/R^4$. The reason for this is as follows. For small ϕ, $\cos\phi \approx 1 - \phi^2/2$, so

$$\begin{aligned}\left|1+\rho e^{-j\phi}\right|^2 &= 2\left(1-1+\frac{\phi^2}{2}\right)\\ &= \phi^2 \\ &= \left(\frac{2\pi}{\lambda}\frac{2h_T h_R}{R}\right)^2\end{aligned} \tag{2.40}$$

therefore

$$\left|1+\rho e^{-j\phi}\right|^2 \approx 16\left(\frac{\pi}{\lambda}\frac{h_T h_R}{R}\right)^2 \tag{2.41}$$

and

$$\begin{aligned}P_\text{total} &= \frac{P_T}{4\pi R^2}\frac{\lambda^2}{4\pi}16\left(\frac{\pi}{\lambda}\frac{h_T h_R}{R}\right)^2\\ &= \frac{P_T}{R^4}\left(h_T h_R\right)^2\end{aligned} \tag{2.42}$$

for isotropic antennas. Note that the total power is independent of frequency. Furthermore, the total power increases as the square of the antenna heights and decreases as the fourth power of the range.

When the antenna gains are considered, both for the transmitter and receiver, then this expression becomes (with G_T and G_R the gain relative to isotropic in the direction of each other)

$$P_\mathrm{total} = \frac{G_\mathrm{T} G_\mathrm{R} P_\mathrm{T}}{R^4}\left(h_\mathrm{T} h_\mathrm{R}\right)^2 \tag{2.43}$$

This expression will be referred to herein as the *ground reflection propagation model.* Although in (2.42) the received power is independent of frequency, when the gains are included, the power becomes frequency-dependent because the antenna gains are frequency-dependent.

Using this expression for the received power at all ranges underestimates the power at close ranges. Beyond distance d_l, given in (2.2), it more accurately reflects the total power received, however. At close range the propagation loss increases with $n = 2$ and the antennas are close enough together that the antenna heights do not have an effect. The propagation is effectively free-space.

Reflection amplitude characteristics are shown in Figure 2.11 when the frequency is 100 MHz [10] and the reflections are off the ground. Horizontally polarized waves undergo substantially less amplitude attenuation than vertically polarized signals. Reflection phase characteristics are shown in Figure 2.12. A

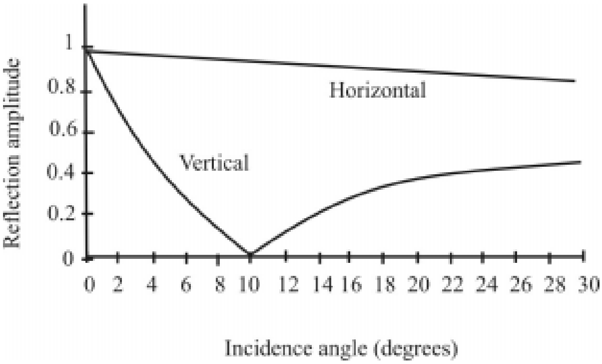

Figure 2.11 Amplitude characteristics of a reflected wave.

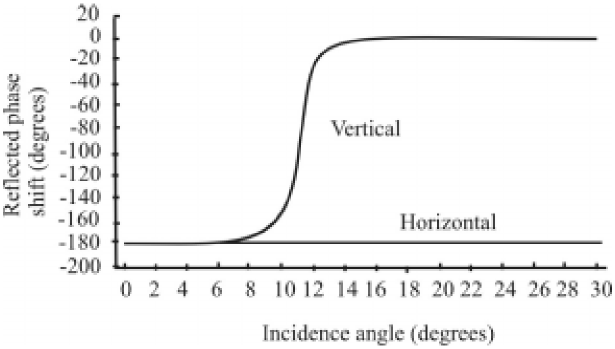

Figure 2.12 Phase shift imparted on a reflected wave.

horizontally polarized wave always undergoes a 180° phase shift, while a vertically polarized one only imparts a significant phase shift for incidence angles less than 12° or so. The region of primary interest for communication EW system design is for low incidence angles—typically less than 10°.

2.10 SURFACE WAVE

At frequencies below approximately 50 MHz, there is a mode of propagation referred to as the *surface wave*, or *ground wave*. This wave propagates along the surface of the Earth out to considerable distances, depending on conditions. At the higher frequencies the attenuation is too high to support propagation. This mode of propagation is illustrated in Figure 2.13.

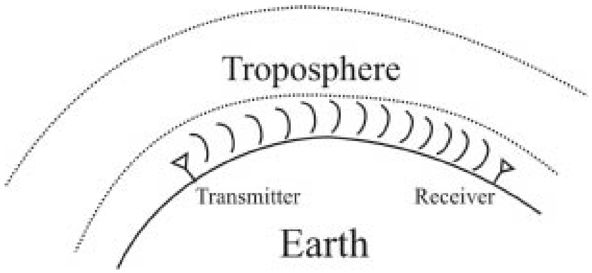

Figure 2.13 Propagation along a trough, one side of which is the Earth, is called surface-wave propagation.

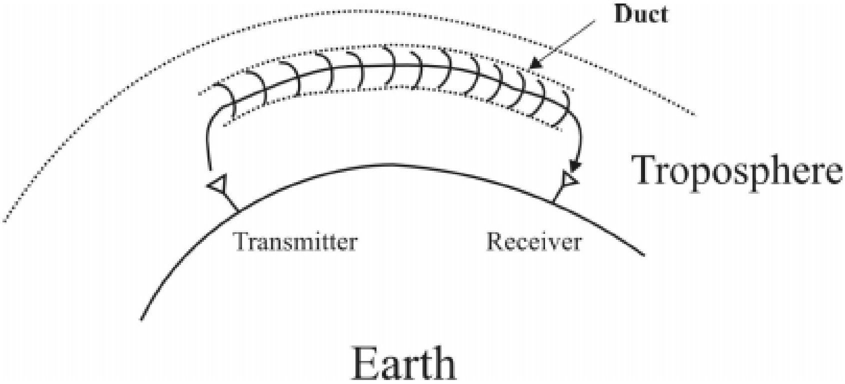

Figure 2.14 Ducting is when signals propagate between two tropospheric layers. Considerable distances can be traversed this way.

2.11 DUCTING

There is a phenomena called *ducting,* wherein VHF and above signals can travel considerably further than RLOS. Essentially the signals are reflected off regions in the troposphere where the refractive index decreases rapidly, forming a duct through which these signals will travel. This is shown in Figure 2.14. Two tropospheric layers or one layer and the Earth's surface can form such ducts.

In EW applications, ducting can be useful for ES from ranges and sites that otherwise would be too far away. On the other hand, determining the geolocation of such signals is difficult. This is because triangulation (defined in Section 11.3) usually will not work since ducts probably will not exist between the transmitter and two receiving sites simultaneously, a requirement for triangulation to work.

2.12 METEOR BURST

This form of communication relies on the thousands of meteors that enter the Earth's atmosphere each day [11]. It also can be classified as a reflected mode. At frequencies around 30–50 MHz, these meteors will reflect radio waves. The phenomenon is illustrated in Figure 2.15.

Signals need to have considerable redundancy in this scheme, and therefore it is only reliable for low data rate communication. Communication is limited to short bursts and the medium only supports digital communications in the low data rate range—up to 600 bps is typical. It is frequently used for relaying remote

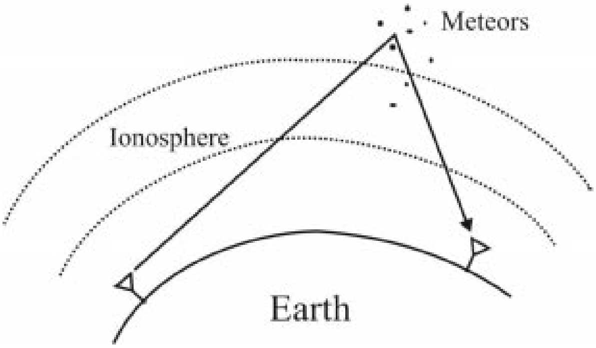

Figure 2.15 Meteor burst propagation reflects the EM wave off meteors. While considerable distance can be covered this way, data rates are quite low.

sensor data where messages are sent infrequently, and each such message consists of only a few hundred bits maximum. Frequently *acknowledgments* (ACKs) and *negative acknowledgments* (NACKs) are used to indicate that a message was received properly. An ACK is sent if the message was received properly and a NACK is replied if not. If not, the message is repeated until it gets through, which means that one or more meteors was in the right place to reflect the signal. Of course, these ACKs and NACKs rely on the same propagation path so they too must be kept short and infrequent since the meteor could very likely no longer be there when the reply needs to be sent.

2.13 SCATTERING

Scatter-wave propagation is caused by nonhomogeneous refractive indices in the troposphere caused by irregular ionization, or by rain. It is also caused by nonhomogeneous refractive indexes on the surface of the Earth. Objects that are smaller than a wavelength will cause scattering for EM waves as well. Typical of this latter category would be street signs and telephone posts scattering UHF signals, as typified by mobile phones in the 900-MHz range ($\lambda = 0.3$m) or PCS systems in the 1,800-MHz range ($\lambda = 0.15$m). At frequencies around 4–5 GHz, there is a reliable propagation phenomena known as *troposphere scattering*. A radio wave with properly oriented transmitting and receiving antennas can communicate over long distances. The configuration is shown in Figure 2.16.

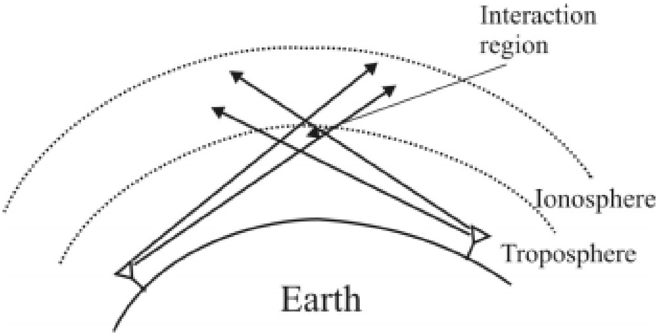

Figure 2.16 Tropospheric scatter propagation relies on the interaction to the two antenna beams at common areas within the troposphere. This type of propagation is possible in the 4–5 GHz range.

The two antenna beams interact in the region where they overlap and the radio wave is essentially reflected from within this region.

2.14 CHARACTERISTICS OF THE MOBILE VHF CHANNEL

Command and control of mobile, tactical military forces frequently are accomplished with RF communications, primarily in the VHF and UHF ranges. This type of communication is subject to slow and fast fading and distortion due to delay spread [12]. As pointed out earlier, $P_\text{d} \propto 1/R^n$. The value of n depends on several factors, such as obstacles in the path between the transmitter and receiver. Illustrated at the top of Figure 2.17 is the characteristic path loss for $n = 2$, 3, and 4.

At any given distance from the transmitter, there will be a statistical distribution of the path loss, which therefore imparts the statistical distribution onto the amount of power received. A Gaussian distribution (see Appendix A) as shown often accurately describes this distribution. Objects blocking the direct communication path, called *shadowing*, typically cause large fades. The mean path loss at some distance R due to shadowing produces *slow fades* as shown Figure 2.17. It causes (relatively) long-term variations in signal level at the receiver. This is typical of mobile communications where the receiver or transmitter moves behind large objects (e.g., a mountain). Small fades are caused by locally changing conditions such as changing multipath conditions.

On the other hand, fast fading also occurs in mobile communications. The amplitude of the received signal level is often approximated by a Rayleigh distribution, which is shown in Figure 2.17, middle right panel. The receiver or

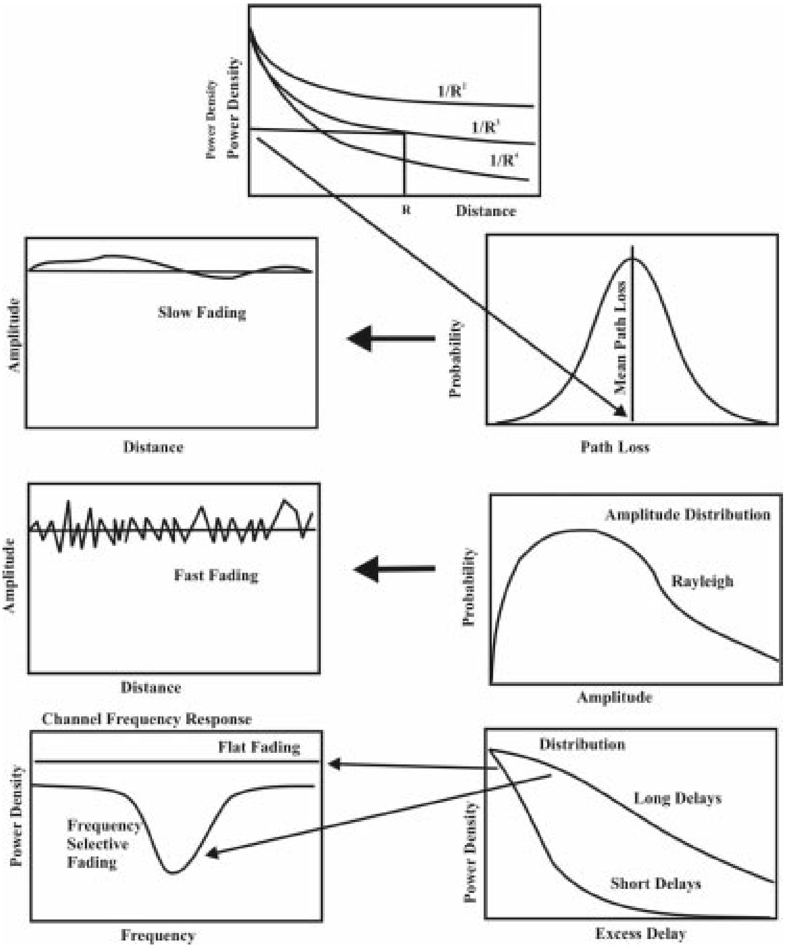

Figure 2.17 The mobile channel is characterized by slow and fast fading and stochastic propagation losses.

transmitter moving behind small objects, causing the signal to be attenuated, produces such fading.

In direct and surface-wave propagation fading can occur in mobile communication paths due to reflections off of large objects or changing diffraction or scattering situations. Even if the transmitter and receiver are not moving, objects moving in the environment surrounding them, such as vehicles or people, can change the propagation conditions. This fading can affect very narrow frequency bands, sometimes affecting only portions of the bandwidth of a signal, attenuating some portions of the frequency band much more than others. The longer-term attenuation characteristics of the ionosphere are attributable to the changing ionosphere, whereas fast fading occurs for other reasons.

The paths taken by reflected waves compared to the direct wave, such as the situation shown in Figure 2.8, are different. These waves add as vectors at the receiver causing the reflected wave to cancel to some degree the direct wave. This path length, of course, varies as the transmitter and/or receiver moves, causing variable fading effects. Even though an EM wave has a well-defined polarization as it leaves the transmitting antenna, the effects of the environment change this polarization as the EM wave propagates. A wave reflected off the Earth or some other surface can change the direction of the polarization and can change its direction of propagation. Typically reflected or refracted waves arrive at a receiver with elliptic orientation. Furthermore, this elliptic orientation varies with time due to the changing propagation conditions. If the receiver antenna is oriented in a particular direction, which it normally is, this changing elliptic polarization will be received as fading phenomena.

The RF channel can also cause time delays due to its impulse response. These time delays can be short or long, depending on the source of the delay. The delay is referred to *excess delay*, where excess is relative to the symbol rate. Long delays are caused by a frequency-selective impulse response. Short delays are due to a relatively flat channel frequency response. The frequency referred to in this case is relative to the bandwidth of the signal.

Reflected waves arrive at a receiver later than the direct or surface wave. This delay time is referred to as the *delay spread* and varies depending on the environmental conditions. In urban environments the delay spread is typically 3 μs; in suburban environments it is typically 0.5 μs, while in rural terrain it can vary considerably, ranging from less than 0.2 μs to 12 μs or more. These values are means since the delay spread is a random variable in most circumstances. The standard deviations of these distributions can vary considerably depending on the specific situation.

This multipath interference tends to smear digital signals and cause one symbol to interfere with others called *intersymbol interference* (ISI). This interference can be quite severe and limits the maximum data rate that the communication channel can support. In an urban channel, for example, when the delay spread is 3 μs, digital signals at 333 Kbps would have symbol n in the direct wave completely overlaid by the $n - 1$ symbol in the delayed signal. If the energy in the delayed signal is strong enough, reliable communication in that case would be impossible.

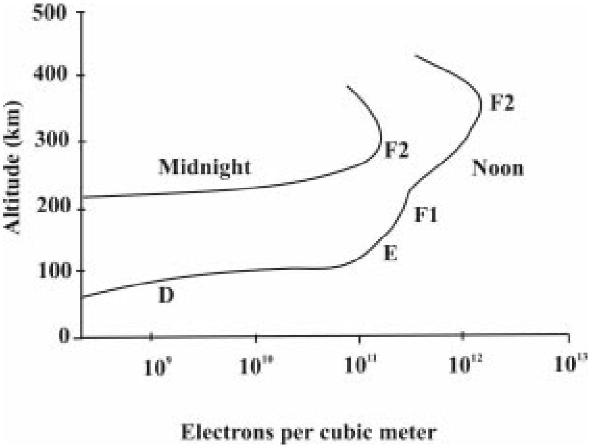

Figure 2.18 Layers in the ionosphere change with time. They determine how HF signals will be refracted.

2.15 PROPAGATION VIA THE IONOSPHERE

Propagation of communication signals via refraction and reflection from the ionosphere is one of the oldest, if not *the* oldest, forms of radio communication [13]. It is certainly the oldest commercial communication method. The signals, which radiate quite a distance by refraction through the ionosphere, are sometimes called *sky-wave* signals. These signals can frequently propagate for thousands of kilometers from the transmitter. Such propagation modes have been useful for communication with ships at sea and were virtually the only way to communicate with ships until communication satellites were invented [7, 13].

It is primarily the radiation from the Sun that generates the ions in the ionosphere. Therefore, there are differences in the propagation characteristics of the ionosphere depending on whether it is day or night. At dawn and dusk the ionosphere is turbulent due to the changing Sun radiation situation. The density of these ions varies with such factors as altitude and time of day.

2.15.1 Ionospheric Layers

The density of the ions in the ionosphere forms layers, designated by D, E, F1, and F2. However, there occasionally occurs a sporadic E layer, referred to as E_S. These layers are actually bands of ions of similar amounts of charge. Their altitude depends on circumstances, but the characteristics shown in Figure 2.18 [7] are representative. The altitudes shown in Figure 2.18 correspond to the height of the average electron density for that layer. Signals reflected off these different layers will have different coverage areas on the ground due to their differences in altitude. The electron density of these layers determines whether a signal is refracted or not. Regions with lower electron density will not refract the signals as well as regions with higher densities. Furthermore the refraction properties are frequency-dependent.

2.15.1.1 D Layer

The D layer is located at approximately 60–90 km above the surface of the Earth. Its half-thickness[1] is typically 10 km. This layer is only present during daylight hours and disappears at night. The ionization is highest at noon when the Sun is at its apogee. The D layer is not very useful for refracting signals, but it does attenuate them as they traverse through to the higher E and F layers.

2.15.1.2 E Layer

Maximum ionization in the E layer is at about 110 km with a typical half-thickness of 20 km. Like the D layer, the E layer only occurs during daylight hours with its maximum ionization occurring around noon.

2.15.1.3 E_s Layer

Occasionally there is an ionospheric layer that occurs somewhat higher than the E layer. It is called *sporadic E*, denoted by E_s, and is located at an altitude of 120 km. It typically is very thin, with a half-thickness ranging from a couple hundred of meters to about 1 km. The ionization, however, is quite intense.

2.15.1.4 F Layer

The F layer is comprised of two sublayers, F1 and F2. The F1 layer is located at an altitude of 170–220 km with a half-thickness of typically 50 km. Like the D and E layers, it only occurs during daylight hours. The F2 layer, on the other hand, is present at nighttime as well. It is located at an altitude of 225–450 km and is typically 100–200 km thick.

The two separate F layers only exist during daylight hours. At night, the two layers combine into one—simply the F layer. Therefore, the lower frequencies

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[1] Half-thickness is the thickness at which the electron density has dropped to half its maximum.

propagate further at night than during the daylight hours, and frequencies that are usable during the day simply pass on through the ionosphere at night.

The D layer discussed above, as well as the E_s layer, cause changing ionospheric conditions, affecting the attenuation characteristics of the ionosphere. This will cause fading at the receiver.

2.15.2 Refraction

Just as VHF and above signals are refracted by the troposphere as discussed earlier, high-frequency signals are refracted by the ionosphere. At frequencies below about 30 MHz, the ionosphere (altitude 50–500 km) can refract signals, as illustrated in Figure 2.19. Whether it does so depends on several factors. The ionosphere consists of ions (thus, the *ion*osphere), which carry a charge. The density of the charge of these ions is heterogeneous in the ionosphere. This is what the RF signals interact with when they enter the ionosphere, and this interaction is what causes the signals to be refracted or not. Most of the time an equivalent height is used for calculations involving this form of signal propagation. This height is the height of a layer, which would reflect the signal if it were a plane sheet, rather than refract the signal, which is the actual phenomenon involved.

This form of signal propagation is not limited to a single hop. Many hops are possible depending on the conditions of the ionosphere as well as the Earth where the signal returns. The two-hop case is shown in Figure 2.20.

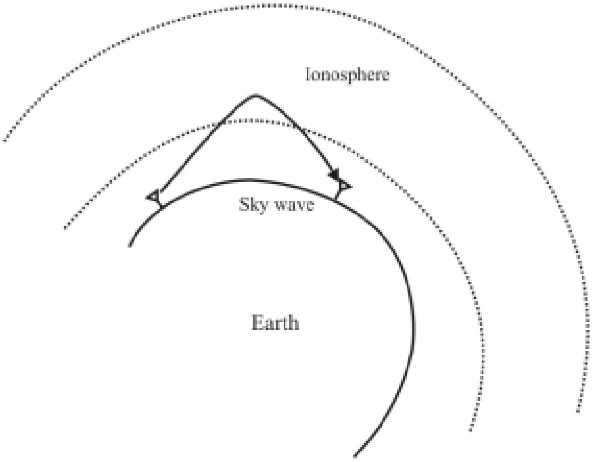

Figure 2.19 Long-range propagation is possible by signal refraction in the ionosphere.

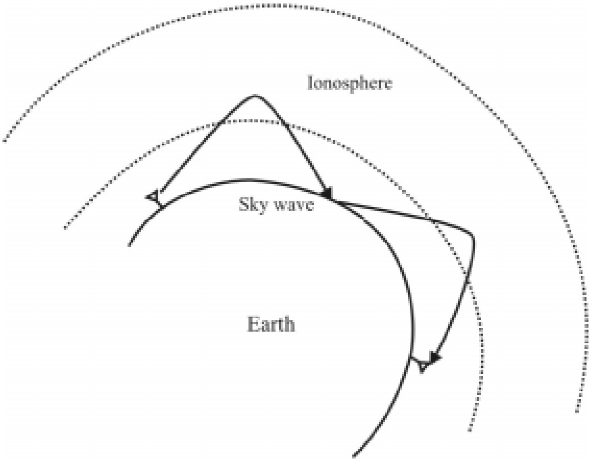

Figure 2.20 Multihop ionospheric refraction is a method to propagate HF signals to considerable distances.

The direct wave emanating from an antenna in the HF range will travel only so far before its energy gets too small to be useful. The sky-wave signal refracted by the ionosphere returns to the Earth beyond a certain distance as shown in

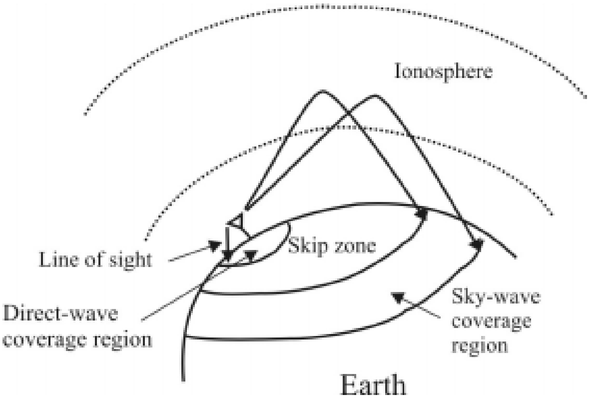

Figure 2.21 Ionospheric propagation creates a skip zone, beyond which the signal returns to the Earth.

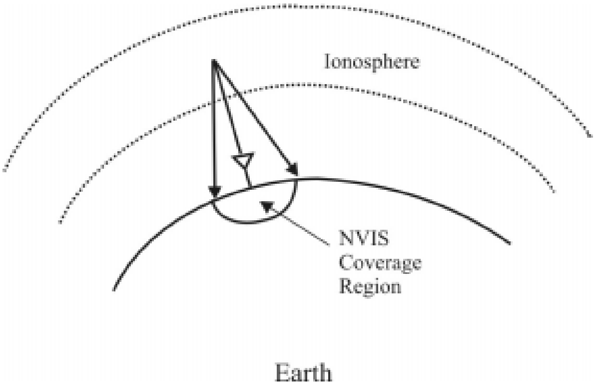

Figure 2.22 NVIS propagation in the HF is for close range. The signal goes straight up and essentially straight back down.

Figure 2.21. In between these ranges no reception is possible. This area is called the *skip zone*.

2.15.3 Near-Vertical Incidence Sky Wave

HF signals can be radiated essentially straight up toward the ionosphere by a properly oriented antenna. Under the right conditions these signals will come virtually straight back down, forming a cone, allowing communication within a range of several hundreds of kilometers from the transmit antenna. This mode of communication is referred to as *near-vertical incident sky wave* (NVIS). The geometry of this mode is illustrated in Figure 2.22, where only half of the ground footprint is shown. To facilitate NVIS communications, the signal must be radiated straight up. This is accomplished by having the antenna arranged horizontally so that the boresight of the antenna is pointed straight up. It must also be at the proper height to maximize the signal component radiated straight up.

2.15.4 HF Fading

Fading of EM waves occurs in the HF range as well. Such fading can be severe, ranging up to 20–30 dB or more. In HF propagation with refraction and reflection via the ionosphere, fading can occur due to changing ionospheric conditions, whether the communication nodes are moving or not. Fading also occurs because of multiple paths taken through the atmosphere by a signal, adding sometimes destructively and sometimes constructively to the signal at the receiver.

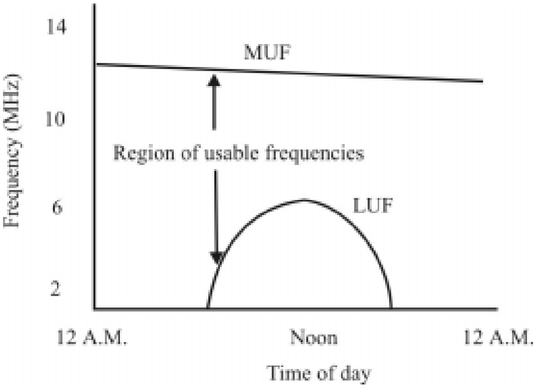

Figure 2.23 Maximum frequency and minimum frequency of ionospheric propagation.

An ionospheric-refracted wave actually is refracted over a region as opposed to a specific point in space. The index of refraction is different over this region, thereby changing the polarization of the wave and giving the effect of making the signal fade at the receiver.

2.15.5 Maximum Usable Frequency and Lowest Usable Frequency

The frequencies supported by the ionosphere at any given time form a band. The lowest frequency is termed the *lowest usable frequency* (LUF), and the highest usable frequency is termed the *maximum usable frequency* (MUF). The lower frequency is determined by the ionization caused by the Sun during the day. Typical characteristics of the MUF and LUF are shown in Figure 2.23.

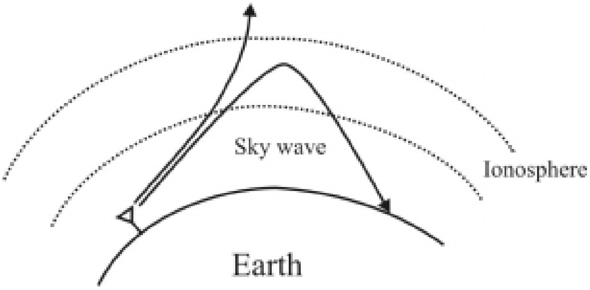

Figure 2.24 An HF signal at the wrong frequency will traverse through the ionosphere without coming back to Earth.

Depending on frequency and incidence angle, a signal impinging on the ionosphere from the bottom will either be refracted or will pass through, not returning to Earth at all, as illustrated in Figure 2.24.

Ionization of the atmosphere on Earth is caused by solar radiation. The solar radiation is not constant, however, and varies on an approximate 10.7-year cycle. The sunspots are dark areas on the Sun, adjacent to which are typically flares of intense radiation. These flares affect the Earth’s ionosphere by increasing the degree of ionization. The result is higher critical frequencies, especially in the highest layer, the F2 layer. This, in turn, facilitates longer range communications during peaks of solar activity. In addition, the Sun rotates on an axis, and the radiation activity around the Sun is not constant. A region of high radiation facing the Earth will cause additional ionization, which rotates away. This period of rotation is approximately 27 days.

2.15.6 Automatic Link Establishment

The aforementioned anomalies of communicating in the HF range illustrate some of the difficulties of using the high-frequency range for communication purposes. This is determining the proper frequency to use, which, as just mentioned, depends on the state of the ionosphere. In the past, it has required skilled technicians to make this determination, thus relegating usage of the HF frequency range to technical experts. With *automatic link establishment* (ALE) techniques, the selection of the proper frequency is performed by the radio equipment itself, precluding the requirement for the operator to have extensive technical experience of such propagation and equipment operation.

The equipment does this by probing the ionosphere with signals of varying frequency and determining the frequency that works the best. It determines this by measuring the quality of the signals received at each frequency. Each end of the link performs the signal quality measurement.

2.16 CONCLUDING REMARKS

Propagation of radio waves is facilitated by different mechanisms depending largely on the frequency of the signal. Lower frequencies tend to propagate further than higher frequencies, all else being equal. The propagation characteristics of signals that are normally of interest to military communication were presented in this chapter. These characteristics are of similar importance to designers of communication systems as well as communication EW systems—the propagation effects are on the signals themselves, irrespective of what the signals are being used for.

Some characteristics, however, perturb the operation of communication systems other than communication EW systems. An example of this is meteor burst communications. One of the more important measurable parameters of communication signals of interest to EW systems is the location of the target. This is unobtainable in meteor burst systems since the transmitter sends the signal toward the meteors, not the receiver.

The ionosphere will reflect (refract) HF waves so very long-distance communications are possible. Although there are exceptions, this form of communication is not possible much above the HF range, however. For the higher-frequency range, propagation is normally limited to RLOS (4/3 Earth model), which significantly limits the distance over which two nodes can communicate close to the Earth. For communication EW systems, this normally means that to intercept such signals, it is more efficient to elevate the receiving antenna. Such elevation typically means putting the receiving antenna on some form of aircraft.

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