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INTRODUCTION

1.1 DEFINITION OF PROPAGATION

Information can be transmitted in many ways. The use of electromagnetic waves for this purpose is attractive, in part, because direct physical connections such as wires or cables are not required. This advantage gave rise to the terms “wireless telegraphy” and “wireless telephony” that were commonly used for radio in the early part of the past century and have returned to popular usage with the widespread development of “wireless” systems for personal communications in recent decades. Electromagnetic waves are utilized in many engineering systems: long-range point-to-point communications, cellular communications, radio and television broadcasting, radar, global navigation satellite systems such as the Global Positioning System (GPS), and so on. The same considerations make electromagnetic energy useful in “sensors”, that is, systems that obtain information about regions from which transmitted energy is reflected. Electromagnetic sensors can be used for detecting hidden objects and people, oil and gas exploration, aircraft control, anticollision detection and warning systems, for measuring electron concentrations in the Earth’s upper atmosphere (and in planetary atmospheres in general), the wave state of the sea, the moisture content of the lower atmosphere, soils, and vegetation, and in many other applications.

In most cases, it is possible to divide the complete system, at least conceptually, into three parts. The first is the transmitter, which generates the electromagnetic wave in an appropriate frequency range and launches it toward the receiver(s) or the region

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Radiowave Propagation: Physics and Applications. By Curt A. Levis, Joel T. Johnson, and Fernando L. Teixeira

to be sensed. The last is the receiver, which captures some fraction of the energy that has been transmitted (or scattered from the medium being sensed) for extracting the desired information. Propagation is the intervening process whereby the information-bearing wave, or signal, is conveyed from one location to another. In communications, propagation is the link between the transmitter and the receiver, while for sensors, propagation occurs between the transmitter and the target to be sensed and between the target and the receiver.

1.2 PROPAGATION AND SYSTEMS DESIGN

Propagation considerations can, and usually do, have a profound influence on communication systems design. They are therefore of great importance to the system engineer as well as to the propagation specialist. For example, consider the case of the "White Alice" system, a communication system implemented in Alaska and northern Canada during the late 1950s, before the advent of satellite communications. It was designed partly for general communications needs and partly to convey information from the Distant Early Warning (DEW) Line to Command Centers of the U.S. Defense forces. The establishment and maintenance of communications centers in an inhospitable environment in the Arctic was a difficult and expensive task. In the high-frequency (HF) band (3–30 MHz), it is possible to transmit signals for very great distances with very modest equipment and antennas—a fact well known to radio amateurs. Thus, an HF system might seem to have been the best solution in this case. There are, however, several drawbacks to this solution. The ready propagation of HF signals would make an HF system very susceptible to interference from signals arriving from other parts of the Earth. Also, HF propagation strongly depends on the ionosphere, an ionized atmospheric region that is significantly influenced by the Sun. At times, the Sun ejects huge streams of charged particles that severely upset the ionosphere and make HF communication in the Arctic and sub-Arctic regions particularly difficult. Thus, an HF system might have been cheap, but it would have been unreliable, and unreliability was unacceptable for this application.

The method chosen was based on the "tropospheric scatter" mechanism, using a frequency of operation of about 900 MHz. This propagation mechanism uses the reflection of signals by minor irregularities that are always present in the lower atmosphere. In contrast with HF propagation links, the ranges that can be achieved by tropospheric scatter links are only on the order of 200 miles, necessitating intermediate communications (repeater) stations between the DEW Line and the more populated areas. Also, very large antennas and high-powered transmitters are required. Figure 1.1 is a picture of a typical "White Alice" site—it should be apparent that its establishment and maintenance in the far North was neither easy nor cheap. Nevertheless, the high reliability and relative freedom from interference associated with tropospheric scatter propagation outweighed the cost and other considerations, so this system was implemented. The White Alice system was eventually superseded by satellite-based systems. This is, however, an interesting historical example that illustrates how propagation considerations can play a dominant role in communication systems design.

FIGURE 1.1 "White Alice" tropospheric communications site. (Courtesy of Western Electric.)

1.3 HISTORICAL PERSPECTIVE

The idea that electromagnetic signals might propagate over considerable distances at the velocity of light was first proposed in 1865 by James Clerk Maxwell. Having added the "displacement current" term to the set of equations governing electromagnetic events (now termed Maxwell's equations), he deduced that among their possible solutions wave solutions would exist. This prediction was verified experimentally by Heinrich Hertz in a series of experiments conducted in the late 1880s. Many of his experiments utilized waves of approximately 1 m wavelength, in what is now termed the ultra high frequency (UHF) range, and transmission distances were usually on the order of only a few feet.

Such an orderly progression from theory to experimental verification has by no means been characteristic of the field of radiowave propagation in general, however. When Guglielmo Marconi attempted his first trans-Atlantic transmissions in 1901, using waves of approximately 300 m length in what is now called the medium-frequency (MF) band, there was no clear theoretical understanding of whether signal transmission over such great distances might be possible. After the experiment was a success, there remained considerable controversy about the actual propagation mechanism until the now accepted explanation—ionospheric propagation—was sufficiently well understood to be generally accepted. Such a lag of theory behind experiment was quite characteristic of the early days of radio propagation. As more powerful transmitters and more sensitive receivers became available over increasing frequency ranges, the body of knowledge regarding electromagnetic wave propagation has grown enormously and has become increasingly complex.

1.4 THE INFLUENCE OF SIGNAL FREQUENCY AND ENVIRONMENT

In part, this complexity is due to the extraordinary range of frequencies (or wavelengths) that are useful for signal propagation. The lowest of these are in the vicinity of 10 kHz (30 km wavelength), although even lower frequencies (longer wavelengths) are useful for underwater communications and for observing some geomagnetic phenomena. For optical systems, the highest frequencies of interest for communicating information over considerable distances are on the order of 10^{15} Hz, corresponding to a wavelength of a few tenths of a micron. Thus, a frequency (or wavelength) range of 11 orders of magnitude is spanned! A corresponding range in the case of material structures would span from the lengths of the largest bridges to those of the smallest viruses!

The variety and complexity of the observed electromagnetic signal propagation phenomena are further increased by the variety of intervening environments. For example, the depth to which an electromagnetic wave penetrates in seawater varies by a factor of more than 50 over the frequency range 100 kHz to 300 MHz. There are also geographic variations, since salinity varies geographically. In the very low frequency (VLF) band, all wave structures in the ocean are small compared to the wavelength of the signal, and the ocean can be approximated as a smooth conducting surface. At higher frequencies, the signal wavelength decreases until it may be of the same order of magnitude as the large ocean swells. The ocean thus behaves as a rough lossy dielectric in the very high frequency (VHF) range; but in this frequency range, the small capillary wavelets due to wind can still be ignored. As the frequency is increased further, so that the signal wavelength becomes a few millimeters or less, the swells represent randomly tilted flat plates; it is now the capillary wavelets that represent roughness. Clearly, the sea surface is a complicated propagation medium boundary. Land exhibits similar variations except that in most cases there are no important short temporal scale changes.[1] The atmosphere, like the sea, is highly variable both temporally and geographically since its lower levels are strongly influenced by the weather, and its upper ones by solar activity.

It is not surprising, then, that different propagation calculation techniques are appropriate to the various frequency and environmental regimes, and that in many cases the resulting predictions are only of an approximate and statistical nature. This book does not attempt to develop any of these techniques exhaustively, but rather gives a survey of the most common calculations and phenomena.

Since signal frequency is such a very important parameter, a rough indication of which range is being considered is often necessary. The frequency band designations recommended by the IEEE as given in Table 1.1 will be used for this purpose. These are frequently used in the literature as well. They are generally not meant to be taken too literally, as propagation phenomena do not fall so neatly into decade frequency regions. Nevertheless, this nomenclature is useful for giving a quick, rough indication of the frequency range under discussion. The UHF and SHF bands, commonly used in radar applications, have an additional set of frequency band designations used for radar systems, as indicated in Table 1.2.

[1] An exception would be those produced by some land vegetation under strong winds.

TABLE 1.1 IEEE Frequency Band Designations

Band Name	Abbreviation	Frequencies	Wavelengths
Very low frequency	VLF	3–30 kHz	10–100 km
Low frequency	LF	30–300 kHz	1–10 km
Medium frequency	MF	300 kHz to 3 MHz	100 m to 1 km
High frequency	HF	3–30 MHz	10–100 m
Very high frequency	VHF	30–300 MHz	1–10 m
Ultra high frequency	UHF	300 MHz to 3 GHz	0.1–1 m
Super high frequency	SHF	3–30 GHz	1–10 cm
Extremely high frequency	EHF	30–300 GHz	1–10 mm

The wide frequency range employed and the variety of natural environments give rise to a surprising number of propagation mechanisms for electromagnetic signals. By "propagation mechanism" we mean a physically distinct process by which the signal may travel from the transmitter to the receiver or to and from the region being sensed. Depending both on frequency and on the environmental conditions, one or only a few mechanisms usually produce much higher signal strengths at the receiver than the others. The former are said to be the dominant mechanisms for the conditions considered (some authors use the word "modes"), and the others can often be neglected. One of the aims of this book is to develop an understanding of which mechanisms are likely to be dominant for particular frequency ranges and environmental conditions.

As an example, consider ordinary ionospheric reflection. Under many conditions, the ionosphere is very effective in guiding signals in the range VLF to HF. Signals propagated by this mechanism are likely to be much stronger than those received in any other way over the same distance, and other mechanisms may be neglected when this is true. But this is not always true. For example, the ionospheric reflection process is not useful when distances between the transmitter and the receiver are relatively short. In that case, signals arriving at the ionosphere at steep angles pass right through it, while those going up at shallow angles end up at too great distances; the ionospheric signals are then said to "skip" over the receiver. Also, in the LF range during the

TABLE 1.2 Microwave Frequency Band Designations

Band Name	Frequencies (GHz)	Wavelengths (cm)
L	1.0–2.0	15–30
S	2.0–4.0	7.5–15
C	4.0–8.0	3.75–7.5
X	8.0–12.0	2.5–3.75
K_u	12.0–18.0	1.67–2.5
K	18.0–27.0	1.11–1.67
K_a	27.0–40.0	0.75–1.11
V	40.0–75.0	0.40–0.75
W	75.0–110	0.27–0.40

daytime, certain regions of the ionosphere absorb signals very effectively so that the signal strength is attenuated. The same is true of HF at medium and high latitudes when the Sun is highly disturbed. Under any of these conditions, other propagation mechanisms may become dominant—otherwise, no *efficient* propagation mechanism may exist, so that terrestrial communications in certain frequency ranges becomes very difficult or impossible.

One example of this variability of propagation mechanisms is easy to observe: the daytime/nighttime effect in U. S. standard (AM) radio broadcasts, which fall into the MF band. During the daytime, only stations within a 200 or 300 mile radius are received, and the reception is likely to be interference free. At sunset, the picture changes, sometimes with dramatic abruptness. Now distant stations can be received with ease. Unfortunately, on those frequencies that are shared by several stations, many are likely to be received simultaneously, much to the dissatisfaction of the listener! The nighttime propagation mechanism is dominated by ionospheric reflection, the so-called “skywave" mode, but since (as noted above) the ionosphere absorbs signals well in this frequency range in the daytime, the daytime mechanism is a different one, namely, the so-called “groundwave" mode. Thus, a change in the dominant propagation mechanism is responsible for the difference in reception conditions. Note that the groundwave mode is present at night as well, but its effect is not noticed then at large distances from the transmitter because of the much higher signal strength of the skywave ionospheric signal.

1.5 PROPAGATION MECHANISMS

Before proceeding further, it will be useful to first develop some cursory acquaintance with the propagation modes or mechanisms to be discussed later in this book in more detail. Propagation mechanisms are separated below into “typical” and “unusual” categories, depending on the degree to which they are used in practice. We begin with the “typical” mechanisms, which are treated in later chapters.

Direct Propagation The simplest mechanism is perhaps *direct propagation*, involving the travel of the signal directly from the transmitter to the receiver quite unaffected by the intervening medium. It assumes the form of a spherical wave emanating from the transmitter. Since the receiver is often sufficiently far away from the transmitter, this wave can be approximated as a plane wave at the receiver location. Direct propagation may seem to be a highly idealized situation, but it has important applications. For frequencies in the UHF and higher frequency bands, the ionosphere has little influence, essentially because the electrons responsible for its conductivity at lower frequencies are unable to follow the rapid variations at such high frequencies. Also, at higher frequencies it is possible to build very directive antennas, so that the signal beam may be kept isolated from ground effects (except perhaps at the end point of its intended path, if this is very close to the ground). Under these conditions, the signal propagation is mostly unaffected by ground or sky effects: propagation is essentially direct. Since most radars and satellite communications systems operate in this fashion, and because a narrow beam is also advantageous for separating a particular radar target from its surroundings, direct propagation is the dominant mechanism, and sometimes the only one to be considered, for many microwave radar and satellite communications calculations. The frequency spectrum for direct propagation is not open ended at the higher frequency end, however, because then a band of frequencies (in the upper SHF range and above) is reached in which atmospheric constituents are able to absorb energy efficiently. In this range, the direct propagation assumption must be modified to account for this absorption by the inclusion of an additional attenuation term. As frequency is increased even further, the wavelength decreases until it becomes of the order of magnitude of atmospheric dust and water droplet particles. As a result, these particles can scatter or absorb the signal quite strongly, which requires further modification of the propagation model. In short, direct propagation is the appropriate mechanism to consider only when all other mechanisms are inoperative, a situation most frequently encountered in the atmosphere at UHF and SHF with systems utilizing highly directive antennas and when the transmitter and receiver are in plain view (line of sight) with respect to one another at elevation angles that preclude ground effects.

The effect of gravity causes the atmosphere to be generally more dense and moist at lower altitudes than at higher ones. Though the effect is small, it causes a significant bending of the propagated signal path under many conditions. For example, in the design of microwave links that are sometimes used for long-distance telephone voice and data communications, care must be taken that the link will perform adequately for a variety of atmospheric conditions that may cause the beam to bend upward or downward. This bending is known as *tropospheric refraction.* The atmospheric effects that cause tropospheric refraction also cause time delays as signals propagate through the atmosphere; such time delays have a significant impact on systems used for global navigation such as the Global Positioning System (GPS).

Ducting The bending effect of tropospheric refraction may be strong enough to cause signals to follow closely along the curvature of the Earth, so that they are in effect guided along the Earth. Such behavior is called ducting. Ducts are most frequently observed at VHF and UHF; they also exist at higher frequencies but the more directive antennas employed at these frequencies are less likely to couple efficiently into a duct. Ducting is much more common at some localities than others since it is closely related to meteorological phenomena. In most areas of the world, it is a source of potential interference rather than a means of reliable communication.

Earth Reflections If the antennas used are not very directional, or if they are located near the ground, signals may travel from the transmitter to the receiver by reflection from the ground. In this case, both the directly propagated signal and the ground-reflected signal must be considered in evaluating the propagation performance of a system. A typical case is ground-to-air or air-to-air communication at UHF. The size limitation of aircraft antennas makes it impossible to use highly directive antennas in this frequency regime, so it is not possible to keep signals from reaching the ground. The ground reflected signals can be added to or subtracted from the directly propagated

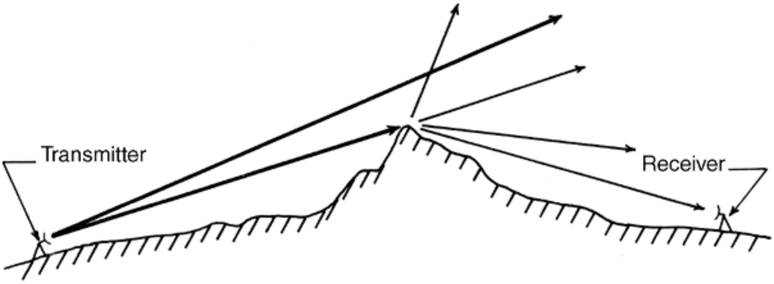

FIGURE 1.2 Diffraction by terrain.

signal (constructive or destructive interference, respectively), so both terms must be considered.

Terrain Diffraction All the mechanisms considered thus far can be described using the concept of rays, that is energy traveling along straight or nearly straight paths. Therefore, these propagation mechanisms would allow no signal transmission when the transmitter and receiver are not within the line of sight. However, such transmission is still possible, and the reason becomes apparent when diffraction is taken into account. Diffraction by the Earth's curvature itself is important, but even more pronounced is the effect of sharper obstacles, such as mountains. These obstacles scatter energy out of the incident beam, some of it toward the receiver as shown in Figure 1.2.

Multipath Environments In many cases, it is possible for transmitted signals to reach a receiver by multiple reflection or diffraction paths instead of a single reflection from the Earth's surface or a single diffraction point from the terrain. When many time-delayed and/or distorted copies of a transmitted signal are received, the term "multipath environment" is used to describe the propagation mechanism. Multipath is usually an important factor for ground-based point-to-point links, especially in urban environments, and must be considered, for example, in the design of wireless cellular communications and data networks. Because the consideration of multiple paths between the source and the receiver can become very complex, it is common to use a statistical methodology (in terms of statistical "fading models") to describe the average properties and variability of propagation links in multipath environments. Recent years have seen extensive efforts in developing communications modulation and signal processing strategies to combat the impact of multipath fading effects. Our discussion will focus on empirical models and fading statistics used to model such propagation channels.

Groundwave When both the transmitting and receiving antennas operate near or on the ground, it is found that the direct and reflected waves cancel almost completely. In this case, however, one also finds that a wave can be excited that travels along the ground surface, one of several types of waves denoted as "surface waves." Since efficient transmitting antennas at MF and lower frequencies are necessarily large in size (since the wavelength is long), they are generally positioned close to the ground, and groundwave propagation becomes important at these lower frequencies. Groundwave propagation is the dominant mechanism for standard daytime (AM) radio broadcast transmissions in the United States; it is usually not an important mechanism at frequencies above the HF band.

Ionospheric Reflections In the MF and HF bands, electromagnetic signals can be well described in terms of rays that are reflected by the ionosphere and the ground—actually the rays are bent rather than sharply reflected in the ionosphere, but the net effect is essentially the same as shown in Figure 1.3. Signal transmission by this means can be very efficient, and great distances can be spanned with modest power and equipment. For this reason, "short-wave" bands, as these frequencies are often called popularly, are utilized for broadcasting, point-to-point communications, and amateur (ham) radio. Depending on the signal frequency, the reflection can occur in different regions (also called layers) of the ionosphere.

In the VLF and LF parts of the spectrum, the ionosphere and the Earth may be considered, respectively, as the top and bottom of a waveguide that guides energy around the Earth. This point of view is particularly useful at the lower end of these frequencies, because then the wavelength is so long that the spacing of the "waveguide walls", that is, the Earth's surface and the effective ionospheric region, is on

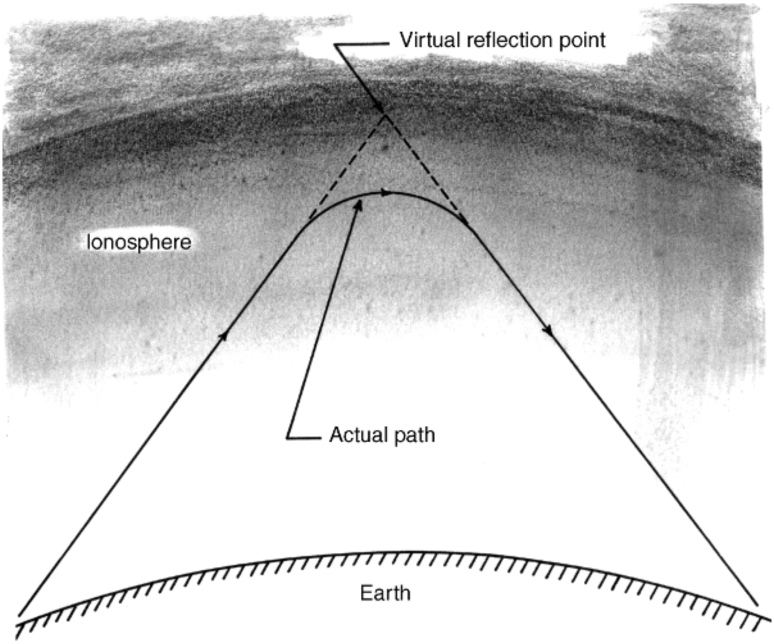

FIGURE 1.3 Ionospheric "reflection."

the order of a wavelength, and the mode description becomes relatively simple for calculation. Strictly speaking, it is not quite correct to distinguish between ionospheric reflection and waveguide modes as different physical mechanisms: in both cases, the signal is guided between the Earth and the ionosphere. However, if the wavelength is sufficiently long, it is more convenient to treat the problem in terms of waveguide modes. If the wavelength is very short compared to the Earth–ionosphere spacing, the ray picture becomes more convenient, and one treats the problem as a series of reflections. In between, in the LF region, computations by either technique become difficult. The distinction between ionospheric hops and waveguide modes is based more on the mathematical description employed than on the actual physical process itself. This book focuses on the ray model of ionospheric propagation.

In addition to apparent reflections or guiding of signals, the ionosphere can also cause important effects on higher frequency systems (up to about 3 GHz) on Earth-to-space paths. Electromagnetic waves propagating through the ionosphere can experience time delays (as in tropospheric propagation), polarization rotation, and scintillation effects.

Unusual Propagation Mechanisms More "unusual" mechanisms that can still be quite effective methods for communication in certain circumstances (as in the "White Alice" example) are discussed below. Brief summaries of some of these mechanisms are provided in Chapter 12.

Tropospheric Scatter: The troposphere is never truly homogeneous, as common experience with wind gusts and other meteorological phenomena suggests. Tropospheric irregularities may be used to advantage when communications are needed over a path of several hundred miles, so that the transmitter and receiver are not within the line of sight of each other. If very strong signals are beamed at a region of the atmosphere that is within the line of sight of both stations as in Figure 1.4, the relatively small signal scattered out of the beam may

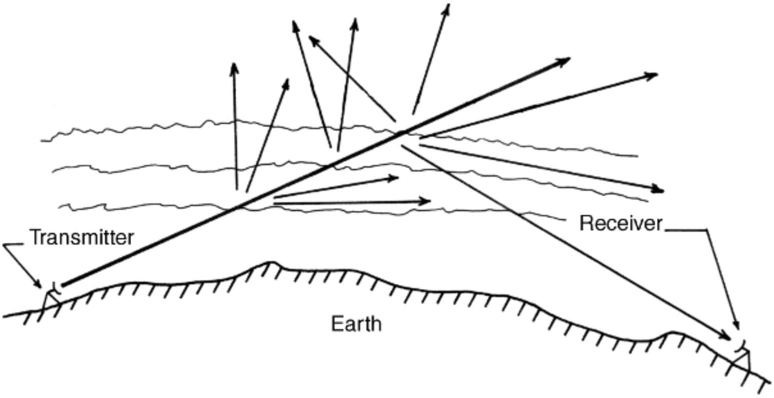

FIGURE 1.4 Tropospheric scatter communications.

be sufficient to allow significant information transfer between the terminals. This is the mechanism employed in the "White Alice" system mentioned at the beginning of this chapter.

Ionospheric Scatter: Signals of a frequency too high to be reflected from the ionosphere may nevertheless still be slightly affected by it. One of these effects is the scattering out of the beam of a small amount of the energy by ionospheric irregularities, quite analogously to the scattering by tropospheric irregularities discussed above. Ionospheric scattering is most noticeable in the frequency regime immediately above the end point of ionospheric reflection. Ionospheric scatter communication systems have been operated successfully in the VHF band.

Meteor Scatter: Many persons think of meteors as rare phenomena, perhaps because our daytime habits and increasingly urban existence lead us to see them rarely. Actually, visually observable meteors are not rare by any means. Most importantly, those too small to be observed visually are even vastly more abundant. As meteors enter the atmosphere, trails of ionized gas are formed that are capable of reflecting electromagnetic signals. Since the ionization is more intense than that of the ionosphere, signals of a high enough frequency to be relatively unaffected by the ionosphere may be returned from meteor trails. Systems in the VHF band have been built based on this mechanism and operated successfully.

Whistlers: Electromagnetic signals in the audio range of frequencies can propagate through the ionosphere in a peculiar mode, in which they follow closely the lines of the Earth's magnetic field. It is not easy to launch man-made signals of such very long wavelengths, but lightning strokes generate and launch energy in this frequency range quite effectively. The lightning-generated signals travel along the Earth's magnetic field lines, often going out a distance of several Earth radii, and are guided by the line to the point on the opposite hemisphere where the field line terminates. This point is called the antipode; at the antipode, the signal may be detected. Part of the signal may be reflected at the antipode to travel back along the same magnetic field line to the point of origin, and so on, back and forth. The peculiar sound of the signals has led to the name "whistlers". This mode of propagation has not been utilized for information transmission because of the very small bandwidth available at such low frequencies and the very restricted area of reception, but it has been a means of obtaining information about the upper ionosphere.

Non-Atmospheric Propagation The propagation phenomena discussed so far have dealt with electromagnetic signal propagation through space or through the Earth's atmosphere over considerable distances. Of course, a totally different environment prevails when electromagnetic signals are propagated through the ocean, the Earth's crust, or other planetary atmospheres, and this can have many applications. Electromagnetic wave propagation into the Earth's crust, for example, can aid in the detection of underground objects and tunnels and in the search for oil and gas fields. In this book, we will be concerned only with propagation in the Earth's atmosphere.

1.6 SUMMARY

Propagation is the process whereby a signal is conveyed between the transmitter and the receiver. An advantage of signal transmission based on electromagnetic waves is that no material link, such as a wire or a cable, is required between the transmitter and the receiver. Propagation considerations can have profound influence on systems design. The signal frequency and the environment determine which propagation mechanisms are dominant. Although these mechanisms generally appear to involve distinct physical processes, in some cases what is different is not the physical process but the mathematical model used to represent it.

A pictorial summary of many of these mechanisms is provided in Figure 1.5. The use of natural and artificial satellites to reflect or retransmit signals is also indicated in this figure.

Table 1.3 lists the most common mechanisms with some applications to which they are most appropriate. The list of applications is, of course, far from inclusive. The notation used for the ionosphere (D-layer, E-layer, and F-layer) is standard, the D-layer being the lowest region useful for reflecting signals back to the Earth, and the F region being the highest (see Chapter 10, section 10.4).

TABLE 1.3 Examples of the Application of Various Propagation Mechanisms

Propagation Mechanism	Applications
Direct	Most radar systems. SHF ground-to-satellite links.
Direct plus Earth reflections	UHF broadcast TV with high-gain antennas. Ground-to-air and air-to-air communications.
Multipath environments	VHF and higher ground-based point-to-point links (especially in urban areas).
Groundwave	Local standard broadcast (AM). Local HF links.
Ionospheric waveguide (D layer)	VLF and LF systems for long-range communications and navigation.
Ionospheric skywave (E and F layers)	MF and HF broadcast and communications (including long-range amateur radio).
Tropospheric scatter	UHF medium-range communications.
Ionospheric scatter	Experimental medium-range communications in lower VHF band.
Meteor scatter	VHF narrow-band long-range communications.

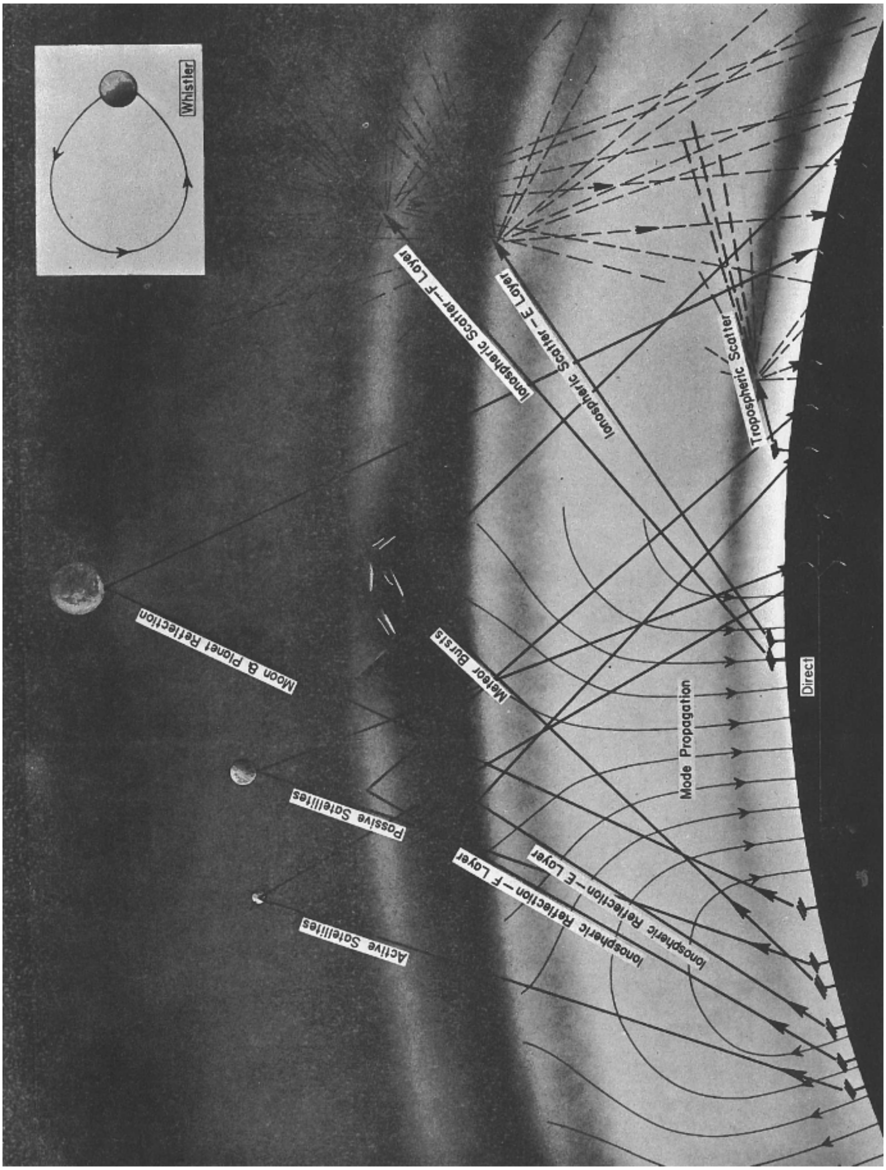

FIGURE 1.5 Summary of propagation mechanisms. (*Source*: R. C. Kirby, “Introduction,” Lecture 1 in *NBS Course in Radio Propagation,* Ionospheric Propagation, Central Radio Propagation Laboratory, National Bureau of Standards, U.S. Deptartment of Commerce, Boulder, CO, 1961.)

TABLE 1.4 The Most Likely Propagation Mechanisms for Each Frequency Band

Frequency Band	Propagation Mechanism
VLF to LF (10–200 kHz)	Waveguide mode between Earth and D-layer. Groundwave at short distances.
LF to MF (200 kHz to 2 MHz)	Transition between groundwave and waveguide mode predominance to skywave (ionospheric hops). Skywave especially pronounced at night.
HF (2–30 MHz)	Ionospheric hops. Very long-range communications with low power and simple antennas. The "short-wave" band.
VHF (30–100 MHz)	Low power and small antennas. Primarily for short range using direct or direct-plus-Earth-reflected propagation (ducting can greatly increase the propagation range).
UHF (80–500 MHz)	Direct: early-warning radars, air-to-satellite and satellite-to-satellite communications. Direct-plus-Earth-reflected: air-to-ground communications, local television. Tropospheric scatter: when large highly directional antennas and high power are used.
SHF (500 MHz to 10 GHz)	Direct: most radars, satellite communications. Tropospheric refraction, terrain diffraction, and multipath become important in ground-to-ground links and in satellite communications at low elevation angles.

In Table 1.4, much of the same information is displayed by frequency bands. The frequency ranges given in parentheses emphasize that the propagation phenomena do not group themselves neatly by the frequency bands as defined by the IEEE and ITU. Of course, the frequency limits in the table are only approximate, since the status of the ionosphere exerts a strong influence for HF and lower frequencies.

It should be emphasized again that the information in this introductory chapter is only cursory and that the tables are meant only to convey a general sense of the importance of both the frequency (wavelength) and the environment in determining the dominant propagation mechanism(s). For example, the entry for "waveguide mode" VLF and LF in Table 1.4 would clearly be inappropriate to a radio-astronomy satellite stationed in space to receive LF signals from distant stars!

1.7 SOURCES OF FURTHER INFORMATION

This book is intended only as an introduction to the vast subject of radiowave propagation. Several organizations, both nationally and internationally, support research in the area, and readers are encouraged to become familiar with the publications of these organizations for more detailed information. Probably the most used source for propagation information is the International Telecommunication Union (ITU), based in

Geneva, Switzerland, which regulates telecommunications internationally and compiles international research that affects these regulations. The Radio Communication sector of the ITU, called the ITU-R, issues a set of reports and recommendations that often serve as useful guidelines for propagation predictions. ITU-R publications can be downloaded via the Internet for a modest charge. Radio regulations of the ITU are also available, but consist mostly of frequency assignments with little propagation information per se. It is interesting to note that these regulations have the force of U.S. law when ratified by the Senate.

Within the United States, the National Telecommunications and Information Administration, Institute for Telecommunications Sciences (NTIA/ITS) of the U.S. Department of Commerce provides reports and expert advice. Computer programs for propagation predictions are also available, usually for a fee. Several Department of Defense agencies, particularly the U.S. Navy, also maintain propagation-focused divisions that often produce computer codes that are publicly available. The U.S. Federal Communications Commission (FCC) is responsible in the United States for regulating electromagnetic communications and can provide publications of its rules and regulations. Information about atmospheric conditions is provided by the National Oceanic and Atmospheric Administration (NOAA) of the U.S. Department of Commerce and also by the National Aeronautics and Space Administration (NASA). Many of these U.S. agencies have counterparts in other countries.

Of course, the convenience of the Internet for obtaining up-to-date information is of note. Many of the organizations listed above maintain web sites that undergo regular updates.

1.8 OVERVIEW OF TEXT

The remaining book is divided into 11 chapters, each of which discusses a different aspect or mechanism of radiowave propagation. The next three chapters serve primarily as a review and introduction to the basic electromagnetic theory that underlies propagation studies, with discussions of propagation media properties, plane wave propagation, and antenna and noise concepts. Chapter 5 then begins the study of direct line-of-sight propagation through the atmosphere, with consideration of atmospheric absorption, rain attenuation, and site diversity improvements. Chapter 6 reviews the basic theory of reflection and refraction at material interfaces such as the ground and discusses the effective Earth radius model for refraction in an inhomogeneous atmosphere along with the ducting effects that can result. Chapter 7 introduces procedures for analysis of reflection, refraction, and diffraction in microwave link design for a given (known) terrain profile. Chapter 8 extends this discussion to include empirical path loss models for point-to-point ground links, as well as a discussion of statistical models that are commonly used to describe fading effects in multipath environments prevalent, for example, in wireless cellular communications. Chapter 9 discusses standard techniques for prediction of surface or ground wave propagation.

Chapter 10 discusses the basic physical properties of the ionosphere, while Chapter 11 considers ionospheric propagation with emphasis on the skywave mechanism at MF and HF and on ionospheric perturbations for Earth–space links at VHF and higher frequencies. Finally, Chapter 12 provides a brief description of other more unusual propagation mechanisms, including tropospheric scatter, as well as other applications, such as radar, involving propagation effects.