1.1 INTRODUCTION

Radar systems have evolved tremendously since their early days when their functions were limited to target detection and target range determination. In fact, the word radar was originally an acronym that stood for radio detection and ranging. Modern radars, however, are sophisticated transducer/computer systems that not only detect targets and determine target range but also track, identify, image, and classify targets while suppressing strong unwanted interference such as echoes from the environment (known as clutter) and countermeasures (jamming). Modern systems apply these major radar functions in an expanding range of applications, from the traditional military and civilian tracking of aircraft and vehicles to two- and three-dimensional mapping, collision avoidance, Earth resources monitoring, and many others.

The goal of Principles of Modern Radar: Basic Principles is to provide both newcomers to radar and current practitioners a comprehensive introduction to the functions of a modern radar system, the elements that comprise it, and the principles of their operation and analysis. This chapter provides an overview of the basic concepts of a radar system. The intent is to give the reader a fundamental understanding of these concepts and to
CHAPTER 1 | Introduction and Radar Overview

identify the major issues in radar system design and analysis. Later chapters then expand on these concepts.

1.2 THE RADAR CONCEPT

A radar is an electrical system that transmits radiofrequency (RF) electromagnetic (EM) waves toward a region of interest and receives and detects these EM waves when reflected from objects in that region. Figure 1-1 shows the major elements involved in the process of transmitting a radar signal, propagation of that signal through the atmosphere, reflection of the signal from the target, and receiving the reflected signals. Although the details of a given radar system vary, the major subsystems must include a transmitter, antenna, receiver, and signal processor. The system may be significantly simpler or more complex than that shown in the figure, but Figure 1-1 is representative. The subsystem that generates the EM waves is the transmitter. The antenna is the subsystem that takes as input these EM waves from the transmitter and introduces them into the propagation medium (normally the atmosphere). The transmitter is connected to the antenna through a transmit/receive (T/R) device (usually a circulator or a switch). The T/R device has the function of providing a connection point so that the transmitter and the receiver can both be attached to the antenna simultaneously and at the same time provide isolation between the transmitter and receiver to protect the sensitive receiver components from the high-powered transmit signal. The transmitted signal propagates through the environment to the target. The EM wave induces currents on the target, which reradiates these currents into the environment. In addition to the desired target, other surfaces on the ground and in the atmosphere reradiate the signal. These unintentional and unwanted but legitimate signals are called clutter. Some of the reradiated signal radiates toward the radar receiver antenna to be captured. Propagation effects of the atmosphere and Earth on the waves may alter the strength of the EM waves both at the target and at the receive antenna.

The radar receive antenna receives the EM waves that are “reflected” from an object. The object may be a target of interest, as depicted in Figure 1-1, or it may be of no interest, such as clutter. The portion of the signal reflected from the object that propagates back to the radar antenna is “captured” by the antenna and applied to the receiver circuits. The components in the receiver amplify the received signal, convert the RF signal to an intermediate frequency (IF), and subsequently apply the signal to an analog-to-digital converter (ADC) and then to the signal/data processor. The detector is the device that removes the carrier from the modulated target return signal so that target data can be sorted and analyzed by the signal processor.\(^1\)

The propagation of EM waves and their interaction with the atmosphere, clutter, and targets are discussed in Part 2 of this text (Chapters 4 through 8), while the major subsystems of a radar are described in Part 3 (Chapters 9 through 13).

The range, \(R\), to a detected target can be determined based on the time, \(\Delta T\), it takes the EM waves to propagate to that target and back at the speed of light. Since distance is speed multiplied by time and the distance the EM wave has to travel to the target and back is \(2R\),

\[
R = \frac{c\Delta T}{2}
\]

\(1.1\)

\(^1\)Not all radar systems employ digital signal and data processing. Some systems apply the analog-detected voltage to a display for the operator to view.
1.3 The Physics of EM Waves

Here \( c \) is the speed of light in meters per second \((c \approx 3 \times 10^8 \text{ m/s})\), \( \Delta T \) is the time in seconds for the round-trip travel, and \( R \) is the distance in meters to the target.\(^2\)

Received target signals exist in the presence of interference. Interference comes in four different forms: (1) internal and external electronic noise; (2) reflected EM waves from objects not of interest, often called clutter; (3) unintentional external EM waves created by other human-made sources, that is, electromagnetic interference (EMI); and (4) intentional jamming from an electronic countermeasures (ECM) system, in the form of noise or false targets. Determining the presence of a target in the presence of noise, clutter and jamming is a primary function of the radar’s signal processor. Detection in noise and clutter will be discussed further in this and subsequent chapters; it is a major concern of a significant portion of this textbook.

EMI is unintentional, as in the case of noise from an engine ignition or electric motor brushes. Jamming signals can take the form of noise, much like internal receiver thermal noise, or false targets, much like a true radar target.

**FIGURE 1-1**
Major elements of the radar transmission/reception process.

---

**1.3 THE PHYSICS OF EM WAVES**

Electromagnetic waves are electric and magnetic field waves, oscillating at the carrier frequency. The nature of electromagnetic fields is described by Maxwell’s equations, presented in the Appendix. The electric, \( E \), field is in one plane, and the magnetic, \( B \), field is orthogonal to the \( E \) field.\(^3\) The direction of propagation of this EM wave through space (at the speed of light, \( c \)) is orthogonal to the plane described by the \( E \) and \( B \) fields, using the right-hand rule. Figure 1-2 depicts the coordinate system. The \( E \) field is aligned

---

\(^2\)The actual value of \( c \) in a vacuum is 299,792,458 m/s, but \( c = 3 \times 10^8 \) is an excellent approximation for almost all radar work. The speed of light in air is nearly the same value.

\(^3\)Sometimes \( B \) is used to denote magnetic induction, in which case \( H \) would denote magnetic field. There are other definitions for \( B \) and \( H \); a description of these is beyond the scope of this chapter.
CHAPTER 1 | Introduction and Radar Overview

FIGURE 1-2
Orientation of the electromagnetic fields and velocity vector.

along the y-axis, the \( B \) field along the x-axis, and the direction of propagation along the z-axis.

The amplitude of the \( x \) or \( y \) component of the electric field of an electromagnetic wave propagating along the z-axis can be represented mathematically as

\[
E = E_0 \cos(kz - \omega t + \phi)
\]  

(1.2)

where \( E_0 \) is the peak amplitude, and \( \phi \) is the initial phase.

The wave number, \( k \), and the angular frequency, \( \omega \) are related by

\[
k = \frac{2\pi}{\lambda} \text{ radians/m, \ } \omega = 2\pi f \text{ radians/sec}
\]

(1.3)

where \( \lambda \) is the wavelength in meters, and \( f \) is the carrier frequency in hertz.

1.3.1 Wavelength, Frequency, and Phase

1.3.1.1 Wavelength

As the EM wave propagates in space, the amplitude of \( E \) for a linearly polarized wave, measured at a single point in time, traces out a sinusoid as shown in Figure 1-3. This corresponds to holding \( t \) constant in equation (1.2) and letting \( z \) vary. The wavelength, \( \lambda \), of the wave is the distance from any point on the sinusoid to the next corresponding point, for example, peak to peak or null (descending) to null (descending).

1.3.1.2 Frequency

If, on the other hand, a fixed location in space was chosen and the amplitude of \( E \) was observed as a function of time at that location, the result would be a sinusoid as a function of time as shown in Figure 1-4. This corresponds to holding \( z \) constant in equation (1.2) and letting \( t \) vary. The period, \( T_0 \), of the wave is the time from any point on the sinusoid to the next corresponding part, for example, peak to peak or null (descending) to null (descending).
1.3 | The Physics of EM Waves

The Physics of EM Waves

Amplitude

Time

Period $T_0$

FIGURE 1-4

The period of a sinusoidal electromagnetic wave.

The period is the time it takes the EM wave to go through one cycle. If the period is expressed in seconds, then the inverse of the period is the number of cycles the wave goes through in 1 second. This quantity is the wave’s frequency, $f$,

$$ f = \frac{1}{T_0} \quad (1.4) $$

Frequency is expressed in hertz; 1 Hz equals one cycle per second.

The wavelength and frequency of an EM wave are not independent; their product is the speed of light ($c$ in free space),

$$ \lambda f = c \quad (1.5) $$

Therefore, if either the frequency or wavelength is known, then the other is known as well. For example, a 3 cm EM wave has a frequency of

$$ f = \frac{c}{\lambda} = \frac{3 \times 10^8 \text{ m/s}}{0.03 \text{ m}} = 10^{10} \text{ Hz or 10 GHz} \quad (1.6) $$

where “G” stands for “giga” or $10^9$.

Shown in Figure 1-5 are the different types of EM waves as a function of frequency, from EM telegraphy to gamma rays. Although they are all EM waves, some of their characteristics are very different depending on their frequency. Radars operate in the range of 3 MHz to 300 GHz, though the large majority operate between about 300 MHz and 35 GHz. This range is divided into a number of RF “bands” [1] as shown in Table 1-1. Shown alongside the radar bands are the International Telecommunications Union (ITU) frequencies authorized for radar use. Note that a given radar system will not operate over the entire range of frequencies within its design band but rather over a limited range within that band. Authorization for use of frequencies as issued by the Federal Communication Commission (FCC) in the United States limits the range of frequencies for a given system. Furthermore, the FCC interacts with the ITU, a worldwide frequency coordination organization. Also, at frequencies above about 16 GHz, the specific frequencies are often chosen to coincide with relative “nulls” in the atmospheric absorption characteristics, as will be discussed shortly. The electronic warfare (EW) community uses a different set of letter band designations. Table 1-2 lists the EW bands.

1.3.1.3 Phase

Note that in equation (1.2) the wave number is in units of radians per meter and so is a kind of “spatial frequency.” The quantity $\phi$ is often called the fixed, or initial, phase. It is arbitrary in that it depends on the electric field’s initial conditions (i.e., the value of $E$) for
FIGURE 1-5
Electromagnetic wave types.

Radar Bands
HF = 3–30 MHz
VHF = 30–300 MHz
UHF = 300–1000 MHz
L-Band = 1–2 GHz
S-Band = 2–4 GHz
C-Band = 4–8 GHz
X-Band = 8–12 GHz
Ku-Band = 12–18 GHz
K-Band = 18–27 GHz
Ka-Band = 27–40 GHz
W-Band = 75–110 GHz

\[ c = \frac{f}{\lambda} \text{(m/sec)} \]

<table>
<thead>
<tr>
<th>Band</th>
<th>Frequency Range</th>
<th>ITU Radar Freq.</th>
</tr>
</thead>
<tbody>
<tr>
<td>High frequency (HF)</td>
<td>3–30 MHz</td>
<td>138–144 MHz</td>
</tr>
<tr>
<td>Very high frequency (VHF)</td>
<td>30–300 MHz</td>
<td>216–255 MHz</td>
</tr>
<tr>
<td>Ultra high frequency (UHF)</td>
<td>300 MHz–1 GHz</td>
<td>420–450 MHz</td>
</tr>
<tr>
<td></td>
<td></td>
<td>890–942 MHz</td>
</tr>
<tr>
<td>L</td>
<td>1–2 GHz</td>
<td>1.215–1.400 GHz</td>
</tr>
<tr>
<td>S</td>
<td>2–4 GHz</td>
<td>2.3–2.5 GHz</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.7–3.7 GHz</td>
</tr>
<tr>
<td>C</td>
<td>4–8 GHz</td>
<td>5.250–5.925 GHz</td>
</tr>
<tr>
<td>X</td>
<td>8–12 GHz</td>
<td>8.500–10.680 GHz</td>
</tr>
<tr>
<td>Ku (“under” K-band)</td>
<td>12–18 GHz</td>
<td>13.4–14.0 GHz</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15.7–17.7 GHz</td>
</tr>
<tr>
<td>K</td>
<td>18–27 GHz</td>
<td>24.05–24.25 GHz</td>
</tr>
<tr>
<td></td>
<td></td>
<td>24.65–24.75 GHz</td>
</tr>
<tr>
<td>Ka (“above” K-band)</td>
<td>27–40 GHz</td>
<td>33.4–36.0 GHz</td>
</tr>
<tr>
<td>V</td>
<td>40–75 GHz</td>
<td>59.0–64.0 GHz</td>
</tr>
<tr>
<td>W</td>
<td>75–110 GHz</td>
<td>76.0–81.0 GHz</td>
</tr>
<tr>
<td></td>
<td></td>
<td>92.0–100.0 GHz</td>
</tr>
<tr>
<td>mm</td>
<td>100–300 GHz</td>
<td>126.0–142.0 GHz</td>
</tr>
<tr>
<td></td>
<td></td>
<td>144.0–149.0 GHz</td>
</tr>
<tr>
<td></td>
<td></td>
<td>231.0–235.0 GHz</td>
</tr>
<tr>
<td></td>
<td></td>
<td>238.0–248.0 GHz</td>
</tr>
</tbody>
</table>
1.3 | The Physics of EM Waves

### TABLE 1-2: EW Bands

<table>
<thead>
<tr>
<th>Band</th>
<th>Frequency Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>30–250 MHz</td>
</tr>
<tr>
<td>B</td>
<td>250–500 MHz</td>
</tr>
<tr>
<td>C</td>
<td>500–1,000 MHz</td>
</tr>
<tr>
<td>D</td>
<td>1–2 GHz</td>
</tr>
<tr>
<td>E</td>
<td>2–3 GHz</td>
</tr>
<tr>
<td>F</td>
<td>3–4 GHz</td>
</tr>
<tr>
<td>G</td>
<td>4–6 GHz</td>
</tr>
<tr>
<td>H</td>
<td>6–8 GHz</td>
</tr>
<tr>
<td>I</td>
<td>8–10 GHz</td>
</tr>
<tr>
<td>J</td>
<td>10–20 GHz</td>
</tr>
<tr>
<td>K</td>
<td>20–40 GHz</td>
</tr>
<tr>
<td>L</td>
<td>40–60 GHz</td>
</tr>
<tr>
<td>M</td>
<td>60–100 GHz</td>
</tr>
</tbody>
</table>

the arbitrarily chosen spatial and temporal positions corresponding to \( z = 0 \) and \( t = 0 \).

For example, if \( E = 0 \) when \( x = t = 0 \), then \( \phi = \pm \pi / 2 \) radians. The phase is the total argument of the cosine function, \( k z - \omega t + \phi \), and depends on position, time, and initial conditions.

The relative phase is the phase difference between two waves. Two waves with a zero relative phase are said to be in phase with one another. They can be made to have a nonzero phase difference (i.e., be out of phase) by changing the wave number (wavelength), frequency, or absolute phase of one (or both). Two waves originally in phase can become out of phase if they travel different path lengths. Figure 1-6 illustrates two waves having the same frequency but out of phase by \( \Delta \phi = 50^\circ \). If the waves are viewed as a function of time at a fixed point in space, as in this figure, then one is offset from the other by \( \Delta \phi / \omega \) seconds.

#### 1.3.1.4 Superposition (Interference)

The principle of superposition states that when two or more waves having the same frequency are present at the same place and the same time, the resultant wave is the complex sum, or superposition, of the waves. This complex sum depends on the amplitudes and phases of the waves. For example, two in-phase waves of the same frequency will produce a resultant wave with an amplitude that is the sum of the two waves’ respective amplitudes (constructive interference), while two out-of-phase waves will produce a resultant wave with an amplitude that is less than the sum of the two amplitudes (destructive interference).

![Two sinusoidal waves with the same frequency but a phase difference \( \Delta \phi \).](image-url)
Two waves of equal amplitude that are $\pi$ radians (180°) out of phase will produce a null result (i.e., no wave). The importance of the concept of superposition is seen in many topics related to radar. Among these are the formation of a defined beam produced by an antenna, the total radar cross section (RCS) of a target as a result of the many scatterers, and the effects of multipath as described in Chapter 4.

### 1.3.2 Intensity

The intensity, $Q$, of the EM wave is defined as the power (time-rate-of-change of energy) per unit area of the propagating wave. Thus, intensity is equivalent to power density (watts per square meter). Consider a single (hypothetical) antenna element emitting an EM wave of power $P$ equally in all directions (isotropic) as shown in Figure 1-7. The locus of all points having the peak amplitude at a given moment in time (wavefront) in this wave will be a sphere; the distance between adjacent concentric spheres will be the wavelength. Since the wave is (ideally) isotropic, the power everywhere on the surface of a given spherical wavefront of radius $R$ will be the same (because energy is conserved in a lossless medium). Thus, the transmitted power density is the total radiated transmitted power, $P_t$, divided by the surface area of the sphere, or

$$Q_t = \frac{P_t}{4\pi R^2}$$  \hspace{1cm} (1.7)

The intensity of the EM wave falls off as $1/R^2$, where $R$ is the distance from the isotropic source.

If the wave is sufficiently far from the source and a limited spatial extent of the wave is considered, then the spherical wavefronts are approximately planar, as shown in the right-hand portion of Figure 1-7. It is somewhat arbitrarily decided but universally accepted that if the wave front curvature is less than $\lambda/16$ over a given “aperture” of dimension $D$, then the wave is considered planar. Using relatively simple geometry, this condition is met if the distance from the source to the aperture is at least $2D^2/\lambda$. This is called the far-field, or plane wave, approximation.

### 1.3.3 Polarization

The EM wave’s polarization is the description of the motion and orientation of the electric field vector. Suppose the wave is traveling in the $+z$ direction in a Cartesian ($x$-$y$-$z$) coordinate system. Then the direction of the electric field $E$ must lie in the $x$-$y$ plane. An electric field oriented along some angle in the $x$-$y$ plane thus has components in both the
1.4 Interaction of EM Waves with Matter

The EM waves that a radar transmits and receives interact with matter, specifically, the radar’s antenna, then the atmosphere, and then with the target. The relevant physical principles governing these interactions are diffraction (antenna); attenuation, refraction and depolarization (atmosphere); and reflection (target).

1.4.1 Diffraction

Diffraction is the bending of EM waves as they propagate through an aperture or around the edge of an object. Diffraction is an example of the interference phenomenon discussed in Section 1.3.1.4. The amount of diffraction present depends on the size of the aperture (antenna), $a$, relative to the wavelength, $\lambda$, of the EM wave. Shown in Figure 1-9 are two extreme cases.

The waves emitting from the aperture (idealized in Figure 1-9 as an opening, or “slit,” in a surface) can be thought of (i.e., modeled) as being produced by many individual radiating elements separated by a wavelength (or less) and all emitting waves isotropically.
CHAPTER 1  | Introduction and Radar Overview

FIGURE 1-9
Extreme cases of diffraction.

In physics, this is known as Huygen’s principle. The EM wave characteristics to the right of the opening in Figure 1-9 will be different from those to the left. Whereas the plane wave to the left of the aperture might be wide compared with the opening, there will be a shaped beam emerging from the opening, toward the right, including a main lobe portion, and lower amplitude, angular sidelobes, to be described later. Superposition of the waves from the individual elements using Huygen’s model predicts that the radiation pattern to the right of the aperture will have a distinct main beam rather than an isotropic pattern, having a half-power beamwidth depending on the aperture size, in wavelengths. If the aperture size is much greater than a wavelength (i.e., \( a \gg \lambda \)), then there will be many radiating elements present and significant destructive interference in all but the forward direction. In this case, there is very little diffraction, and the antenna beamwidth will be small. Conversely, if the aperture size is much smaller than a wavelength, then there is essentially only one radiation element present, and no destructive interference takes place. In this case the EM waves propagate nearly isotropically (over only the right-side hemisphere), producing significant diffraction effects and a large beamwidth.

The angular shape of the wave as it exits the aperture is, in general, a \( \sin(x)/x \) (sinc) function. The main lobe half-power (−3 dB) beamwidth, \( \theta_3 \), of a sinc function is

\[
\theta_3 = \frac{0.89 \lambda}{a} \text{ radians}
\]

In the case of an antenna, the same principles apply. In this case, instead of an opening in a large plate, the individual radiators are across a structure called an antenna.\(^4\) The phenomenon of diffraction is responsible for the formation of the antenna pattern and antenna beam (or main lobe of the antenna pattern) as well as the sidelobes.

Consider a circular (diameter \( D \)) planar antenna made up of many \( (N) \) radiating elements, each of which is emitting EM waves of equal amplitudes over a wide range of angles. Figure 1-10 is the photograph of such an antenna. Assume that all the waves are in phase as they are emitted from the antenna elements. At a point along a line perpendicular (normal) to the plane and far away from the antenna (see Section 1.3.2 and Chapter 9 for discussions of the antenna far field), all the waves will have essentially traveled the same distance and, therefore, will all still be in phase with each other. Constructive interference will occur and, assuming that each element produced the same signal level, the resultant

\(^4\)Often, because of this analogy, an antenna is called an aperture.
wave will have an amplitude $N$ times larger than the individual waves emitted from the elements. This represents the peak of the antenna beam. Figure 1-11 depicts the in-phase waves radiating from a linear array of elements and the resulting main beam pattern. The sidelobe pattern is not shown in the figure.

At any point off this normal, the waves will have traveled different path lengths; thus, destructive interference occurs, and the resultant wave will have an amplitude less than $N$ times larger. As the angular distance from the normal increases, this amplitude decreases, finally reaching a perfect null (complete destructive interference). The angular region between the first null to either side of the antenna normal defines the main beam or main lobe of the antenna. Most of the radiated power is concentrated in this region. Twice the angular distance from the peak of the antenna mainbeam to the point where the EM wave power has dropped to half its peak value, or $-3$ dB, is the $3$ dB beamwidth, $\theta_3$. The exact $3$ dB beamwidth depends on several things, including the shape of the antenna face, the illumination pattern across the antenna, and any structural blockage near the antenna, such as protective radomes and antenna support structures. For typical design parameters for a circular antenna,

$$\theta_3 \approx \frac{1.3\lambda}{D} \text{ radians} \quad (1.9)$$

At angles past the first null, the individual waves partially constructively interfere so that the net amplitude starts to increase, rises to a peak, and then falls again to a
CHAPTER 1 | Introduction and Radar Overview

FIGURE 1-12
Idealized one-dimensional antenna pattern.

second null. This pattern is repeated over and over again, forming an antenna pattern as shown in Figure 1-12. This figure shows a one-dimensional planar “cut” through the two-dimensional pattern of an idealized two-dimensional antenna. The lobes outside the main lobe are called antenna sidelobes.

If the phases of the EM waves have different values when they are emitted from the elements, then they will no longer constructively interfere in the far field in the direction of the antenna normal. If these phase values are adjusted properly, the amplitude of the far-field resultant wave can be made to peak at some angle off the normal. All the waves in this direction traveled different path lengths and, therefore, will have different path-length-induced phases. If the original phases upon emission are selected properly, they can be made to compensate for the path-length-induced phases, and all the waves will be in phase in that direction. Thus, by changing the phases of the emitted waves, the peak of the antenna beam will effectively scan from its normal position without the antenna physically moving. This is the basic concept behind a phased array antenna or electronically scanned antenna (ESA); it is discussed in more detail in Chapter 9.

The antenna can be designed to produce an ideal beamwidth for a given radar application. In fact, if the antenna is not geometrically symmetric the azimuthal and elevation angular beamwidths can be different. A circular or square antenna will produce a symmetric beam, while an elliptical or rectangular antenna will produce an asymmetric beam.

Narrow antenna beamwidths are desired in applications such as tracking, mapping, and others where good angular resolution is desired. Track precision improves as the beamwidth is narrower, as seen in Chapter 18.

Applications in which large antenna beamwidths are advantageous are (1) in the search mode and (2) in strip-map synthetic aperture radars (SARs). In the search mode, where high resolution is normally not required, a given volume can be searched faster with a wide beam. For an SAR, the larger the antenna beamwidth, the larger the synthetic aperture can be, and, thus, the finer the target resolution that can be achieved (see Chapter 21). However, large antenna beamwidths have negative performance effects in many radar applications. For example, the ability to resolve targets in the cross-range dimension decreases with increasing beamwidth when SAR is not used, while in air-to-ground radars, the amount of ground clutter (interfering echoes from terrain) competing with desired target signals increases with increasing antenna beamwidth. In addition, larger beamwidths result in reduced antenna gain, decreasing the signal-to-noise ratio (SNR).
1.4.2 Atmospheric Attenuation

Figure 1-13 shows the one-way attenuation (per unit of distance) of EM waves in the atmosphere as a function of frequency. There is very little clear-air attenuation below 1 GHz (L-band). Above 1 GHz, the attenuation steadily increases, and peaks are seen at 22 GHz (due to water vapor absorption), 60 GHz (due to oxygen absorption), and at higher frequencies. Curves are shown at two different altitudes to demonstrate that the different distribution of water vapor and oxygen with altitude affects the absorption characteristics. Above 10 GHz (X-band), there are troughs, or windows, in the absorption spectrum at 35 GHz (Ka-band), 94 GHz (W-band), and other higher frequencies. These windows are the frequencies of choice for radar systems in these higher-frequency bands that have to operate in the atmosphere. For long-range radars (e.g., surface search radars), frequencies at L-band and S-band are generally required to minimize atmospheric attenuation. Though the attenuation versus range values below 10 GHz are low, most of these systems operate at long ranges, so the loss incurred at these ranges is still significant. Chapter 4 presents more detailed information on atmospheric effects.

Rain, fog, and clouds further attenuate EM waves. One-way rain and cloud attenuation is shown in Figure 1-14. Rain attenuation increases with increasing rain rate and increasing frequency. At radar frequencies, rain and cloud attenuation is small, giving radar systems their famous “all weather capability” not seen in electro-optical and infrared (IR) systems. Detailed descriptions and more specific attenuation values are presented in Chapter 4.

1.4.3 Atmospheric Refraction

Refraction is the bending of EM waves at the interface of two different dielectric materials. This occurs because the speed of the EM wave is a function of the material in which it is propagating; the more “optically dense” the material, the slower the speed. Consider a wave incident on the interface to two different materials as shown in Figure 1-15. Within the denser material (glass), the EM wave slows down due to a decrease in wavelength...
FIGURE 1-14  One-way rain and cloud attenuation as a function of frequency. (a) Rain. (b) Clouds.

FIGURE 1-15  Difference in wavelength for wavefronts in two materials.

\[ v = c = \lambda f \]
\[ v' = \lambda' f \]

Speed decreases in glass, but frequency does not change; therefore, wavelength must decrease.

\( v = \lambda f \). The optical density of a material is quantified by the index of refraction, \( n \), given by \( n = \frac{c}{v} \), where \( v \) is the speed of the EM wave in the material. If this wave were incident on the interface at some angle as shown in Figure 1-16, then, given the reduction of wavelength in the material with a higher index of refraction, the only way the wavefronts can remain continuous across the interface is for them to bend at the interface. This bending is refraction.

In radar technology, refraction is encountered in radar signals directed upward (or downward) through the atmosphere at an angle relative to horizontal. Generally, the atmosphere thins with increasing altitude, causing the index of refraction to reduce. Therefore, the path of the transmitted EM wave will deviate from a straight line and bend back toward the earth. Deviations from straight-line propagation adversely affect target location and tracking accuracy unless refraction effects are accounted for.

Refraction can be beneficial for surface-to-surface radars (e.g., shipboard radars detecting other ships) since it can allow the EM wave to propagate over the horizon and detect ships not detectable if detection were limited by the geometric horizon. An extreme gradient in index of refraction with altitude causes the ray to bend more than for standard atmospheric conditions. Over the surface of the sea, this high value of refractive index with height is common. The severe ray bending is called **ducting**, and surface radar systems can “see” well past the geometric horizon.
1.4 Interaction of EM Waves with Matter

Since wavelength decreases, EM waves must bend to keep wavefronts continuous at the interface.

Material 1
Index of Refraction \( n_1 \)

Material 2
Index of Refraction \( n_2 \)

Over land, long-range propagation can be achieved by using the refractive effect at the earth’s ionosphere. The EM wave propagates upward to the ionosphere; there the refractive bending causes the wave to travel back toward the surface of the earth, where it will intersect the earth’s surface several thousand miles away from the transmitting source. The return path will experience the same effect. This condition (sometimes called skip) is most prominent in the high-frequency (HF) region (3–30 MHz) and is generally not encountered above 150 MHz. Radars that use this phenomenon are called over-the-horizon (OTH) radars. Chapter 4 describes the details associated with atmospheric refraction.

1.4.4 Reflection

Incident EM waves induce an electric charge on natural surfaces or the surface of a man-made object, and that object reradiates the EM wave. The reradiation of the EM wave from the surface matter of an object is called scattering or, more often, reflection of the incident wave. If the matter is a conductor so that the electric charge is free to move in the matter, then essentially all the EM wave energy is reradiated. If the matter is a dielectric material so that its electric charge is bound, some of the energy is reradiated, and some propagates into the matter where some is absorbed and some may come out the other side.

The manner in which the EM wave is reflected from the surface depends on the roughness of the surface relative to the wavelength of the incident wave. Generally speaking, roughness is the variation in surface height. It is usually quantified by the standard deviation of the surface height. If the surface is “smooth” \((\lambda \gg \text{roughness})\), then the EM wave’s angle of reflection, \(\theta_r\), equals its angle of incidence, \(\theta_i\), on the surface (see Figure 1-17). This is called specular scattering. Most scattering from man-made objects in radar technology is specular.

If, on the other hand, the surface is “rough” \((\lambda \ll \text{roughness})\), then the scattering is specular only over small local regions of the surface. Macroscopically, the incident energy appears to be reflected at all angles (see Figure 1-18). This is called diffuse scattering. To
CHAPTER 1  |  Introduction and Radar Overview

FIGURE 1-17  Specular scattering.

Predict the scattering of EM waves from an object, both specular and diffuse scattering must be taken into consideration. Scattering from natural surfaces, especially at shorter wavelengths (higher frequencies), is often diffuse.

In radar technology, scattering phenomenology is quantified by the target parameter radar cross section, \( \sigma \). RCS has the units of area (e.g., m\(^2\)). The RCS of a target is not a single number but is a function of target viewing angle relative to the transmitter and receiver antenna and of the frequency and polarization of the incident EM wave. RCS is a measure of not only how much of the incident EM wave is reflected from the target but also how much of the wave is intercepted by the target and how much is directed back toward the radar’s receiver. Thus, these three mechanisms—interception, reflection, and directivity—all interact to determine the RCS of a target. If a target is to be made “invisible” to a radar (i.e., be a stealth target), then its RCS is made to be as low as possible. To do this, at least one of the three mechanisms must be addressed: (1) the amount of the EM wave energy intercepted by the target must be minimized, which is accomplished by minimizing the physical cross section of the target; (2) the amount of energy reflected by the target must be minimized, which is accomplished by absorbing as much of the EM wave as possible through the use of radar-absorbing material (RAM) on the surface of the target; or (3) the amount of the reflected energy directed toward the radar receiver must be minimized, which is accomplished by shaping the target. The RCS of terrain and of targets (including stealth considerations) are discussed in more detail in Chapters 5 and 6, respectively.

1.5  BASIC RADAR CONFIGURATIONS AND WAVEFORMS

1.5.1 Monostatic versus Bistatic

There are two basic antenna configurations of radar systems: monostatic and bistatic (Figure 1-19). In the monostatic configuration, one antenna serves both the transmitter and receiver. In the bistatic configuration, there are separate antennas for the transmit and receive radar functions.
1.5 Basic Radar Configurations and Waveforms

Use of two antennas alone does not determine whether a system is monostatic or bistatic. If the two antennas are very close together, say, on the same structure, then the system is considered to be monostatic. The system is considered to be bistatic only if there is sufficient separation between the two antennas such that “. . . the angles or ranges to the target are sufficiently different.” [2].

The transmitter is often a high-power device that can transmit EM waves with power levels in the range of hundreds of kilowatts ($10^3$ watts) or even megawatts ($10^6$ watts). The receiver, on the other hand, is a power-sensitive device that can respond to EM waves in the range of milliwatts to nanowatts ($10^{-3}$ to $10^{-9}$ watts) or less. In fact, it is not uncommon for a radar receiver to detect signals as low as $-90$ dBm (dB relative to a milliwatt). High-power EM waves from the transmitter, if introduced directly into the receiver, would prevent the detection of targets (self-jamming) and could severely damage the receiver’s sensitive components. Therefore, the receiver must be isolated from the transmitter to protect it from the transmitter’s high-power EM waves. The bistatic radar configuration can provide significant isolation by physically separating the transmitter and receiver antennas.

There are some applications for which the bistatic system has a significant separation between the transmitter and receiver. For example, a semiactive missile has only the receiver portion on board. The transmitter is on another platform. The transmitter “illuminates” the target while the missile “homes” in on the signal reflected from the target.

The bistatic radar can also be employed to enhance the radar’s capability of detecting stealth targets. Recall that a target’s RCS is a measure of the strength of the EM waves that are reflected from the target back toward the radar receive antenna. Stealthy targets are designed to have a low RCS, thereby reducing the distance at which they can be seen. In addition to other techniques, RCS reduction is achieved by shaping the target in a particular way. This shaping may reduce the RCS when looking at the front of a target using monostatic radar; however, it is often the case that the RF wave will scatter in a different direction, providing a large RCS in some “bistatic” direction. When the bistatic
RCS is greater than the monostatic RCS, the target is no longer “stealthy” to the bistatic radar.

Most modern radars are monostatic—a more practical design since only one antenna is required. It is more difficult to provide isolation between the transmitter and receiver since both subsystems must be attached to the antenna. The isolation is provided by a T/R device, such as a circulator or switch, as previously described. For a radar using a pulsed waveform (see the following discussion), the transmitter and receiver do not operate at exactly the same time. Therefore, additional isolation can be achieved by use of an additional switch in the receiver input path.