PART I

Overview

CHAPTER 1

Introduction and Radar Overview

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Chapter Outline

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

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, ΔT, 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 $2R$,

$$R = \frac{c\Delta T}{2} \tag{1.1}$$

[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.

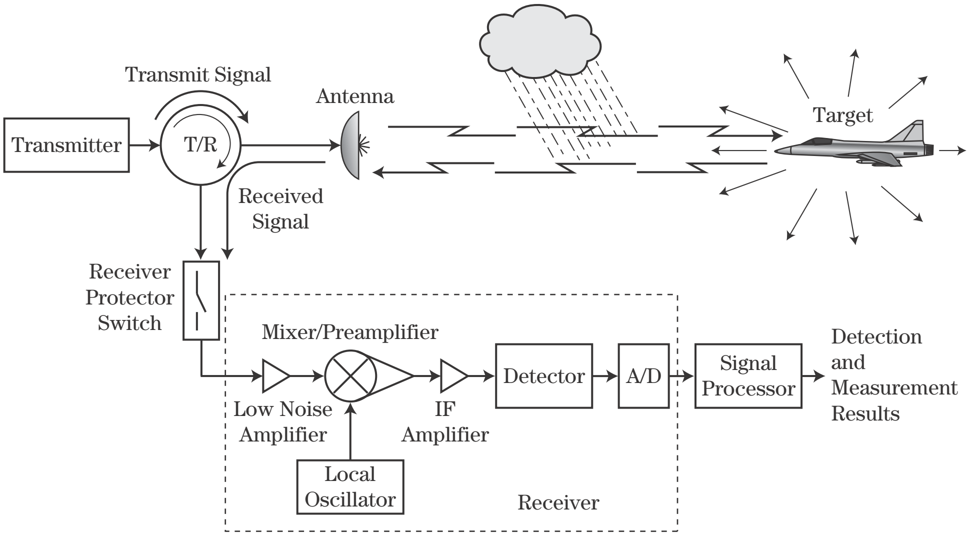


FIGURE 1-1 Major elements of the radar transmission/reception process.

Here c is the speed of light in meters per second ($c \approx 3 \times 10^8$ m/s), ΔT 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.

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, $\boldsymbol{E}$, field is in one plane, and the magnetic, $\boldsymbol{B}$, field is orthogonal to the $\boldsymbol{E}$ 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 $\boldsymbol{E}$ and $\boldsymbol{B}$ fields, using the right-hand rule. Figure 1-2 depicts the coordinate system. The $\boldsymbol{E}$ 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 $\boldsymbol{B}$ is used to denote magnetic induction, in which case $\boldsymbol{H}$ would denote magnetic field. There are other definitions for $\boldsymbol{B}$ and $\boldsymbol{H}$; a description of these is beyond the scope of this chapter.

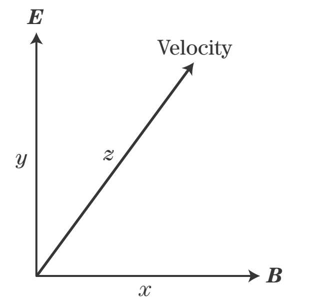


FIGURE 1-2 ■ Orientation of the electromagnetic fields and velocity vector.

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

$$E = E_0 \cos(kz - \omega t + \phi) \tag{1.2}$$

where E_0 is the peak amplitude, and ϕ is the *initial phase*.

The *wave number, k,* and the *angular frequency*, ω are related by

$$k = \frac{2\pi}{\lambda} \text{ radians/m}, \quad \omega = 2\pi f \text{ radians/sec} \tag{1.3}$$

where λ 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*, λ, 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

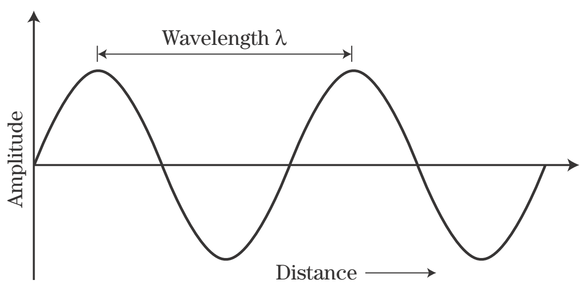


FIGURE 1-3 ■ The wavelength of a sinusoidal electromagnetic wave.

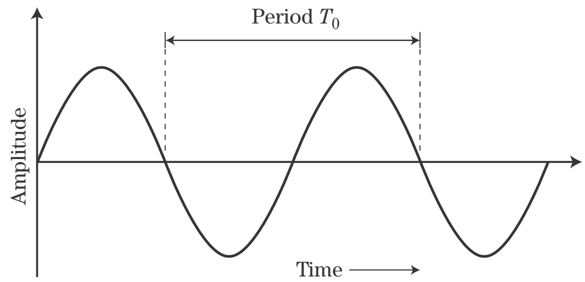


FIGURE 1-4 ■ The period of a sinusoidal electromagnetic wave.

(descending). That is, 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,*

$$f = \frac{1}{T_0} \tag{1.4}$$

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),

$$\lambda f = c \tag{1.5}$$

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

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

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 ϕ 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

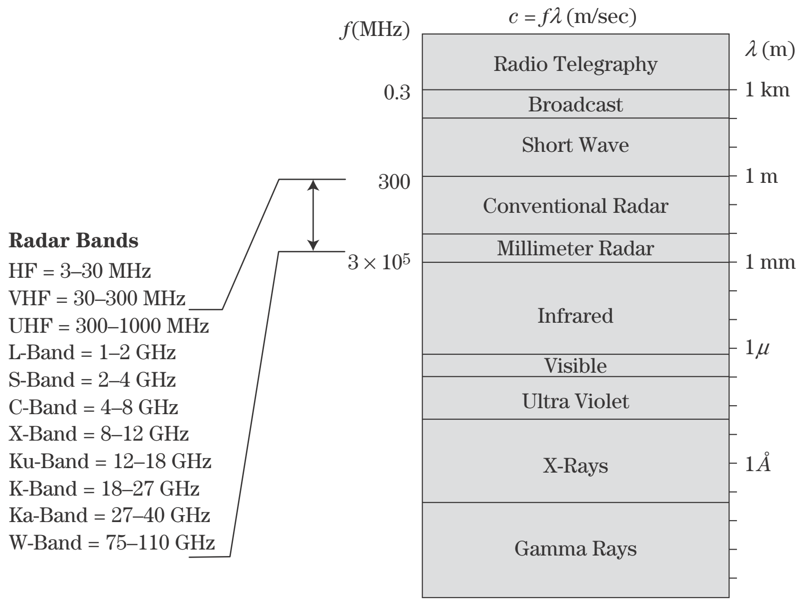


FIGURE 1-5 Electromagnetic wave types.

TABLE 1-1 RF and Radar Bands

Band	Frequency Range	ITU Radar Freq.
High frequency (HF)	3–30 MHz	
Very high frequency (VHF)	30–300 MHz	138–144 MHz 216–225 MHz
Ultra high frequency (UHF)	300 MHz–1 GHz	420–450 MHz 890–942 MHz
L	1–2 GHz	1.215–1.400 GHz
S	2–4 GHz	2.3–2.5 GHz 2.7–3.7 GHz
C	4–8 GHz	5.250–5.925 GHz
X	8–12 GHz	8.500–10.680 GHz
Ku (“under” K-band)	12–18 GHz	13.4–14.0 GHz 15.7–17.7 GHz
K	18–27 GHz	24.05–24.25 GHz 24.65–24.75 GHz
Ka (“above” K-band)	27–40 GHz	33.4–36.0 GHz
V	40–75 GHz	59.0–64.0 GHz
W	75–110 GHz	76.0–81.0 GHz 92.0–100.0 GHz
mm	100–300 GHz	126.0–142.0 GHz 144.0–149.0 GHz 231.0–235.0 GHz 238.0–248.0 GHz

TABLE 1-2 ■ EW Bands

Band	Frequency Range
A	30–250 MHz
B	250–500 MHz
C	500–1,000 MHz
D	1–2 GHz
E	2–3 GHz
F	3–4 GHz
G	4–6 GHz
H	6–8 GHz
I	8–10 GHz
J	10–20 GHz
K	20–40 GHz
L	40–60 GHz
M	60–100 GHz

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, $kz - \omega t + \phi$, 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 $\Delta\phi = 50°$. 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*).

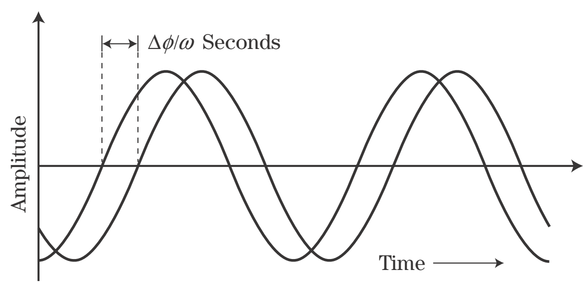


FIGURE 1-6 ■ Two sinusoidal waves with the same frequency but a phase difference $\Delta\phi$.

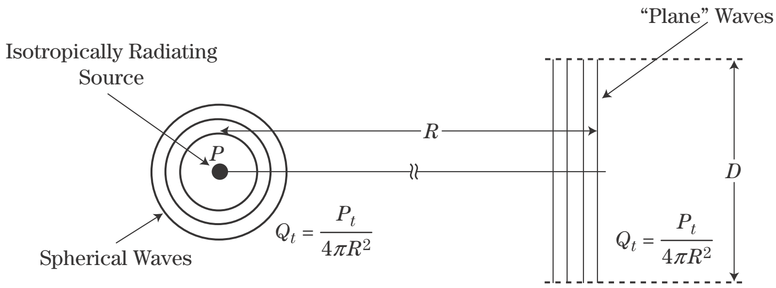


FIGURE 1-7 Intensity of spherical waves.

Two waves of equal amplitude that are π 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

$$Q_t = \frac{P_t}{4\pi R^2} \tag{1.7}$$

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 $\boldsymbol{E}$ 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

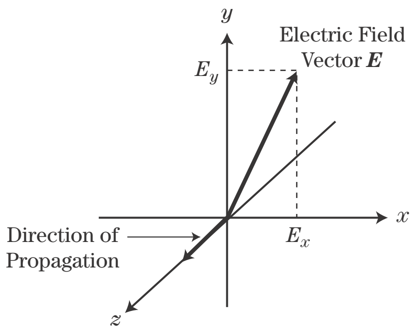


FIGURE 1-8 ■ Polarization components of a transverse EM wave propagating in the $+z$ direction.

x and y directions, say E_x and E_y, as shown in Figure 1-8, which shows the directional components of only the $\boldsymbol{E}$ field. The amplitudes of these two components will each vary sinusoidally as in equation (1.2). The relative peak amplitudes and phases of E_x and E_y determine how the orientation of the resultant vector $\boldsymbol{E}$ varies with time, and thus the *polarization* of the EM wave. For example, if the y component of the electric field is zero, then $\boldsymbol{E}$ oscillates along the x-axis and the EM wave is said to be *linearly polarized* in the x direction. If x represents a horizontally oriented axis, the wave is *horizontally polarized.* Similarly, the wave would be vertically linearly polarized if the x component is zero but the y component is not. If E_x and E_y have the same magnitude and oscillate in phase with one another ($\phi_x = \phi_y$), the field will oscillate linearly along a 45° line in the x-y-plane. In general, the polarization is linear if the x and y components differ in phase by any integer multiple of π radians; the angle of the polarization depends on the relative magnitudes of E_x and E_y.

If $E_x = E_y$ and the phases differ by an odd multiple of $\pi/2$, the tip of $\boldsymbol{E}$ traces out a circle as the wave propagates and the EM wave is said to be *circularly polarized*; one rotation sense is called "right-hand" or "right circular" polarization and the other, "left-hand" or "left circular" polarization. The polarization state is elliptical, when the tip of $\boldsymbol{E}$ traces out an ellipse as the wave propagates. This occurs when $E_x \neq E_y$.

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, λ, 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.

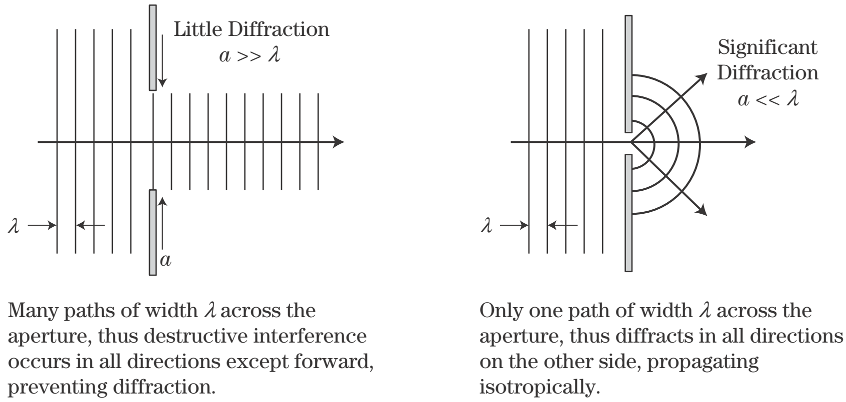


FIGURE 1-9 ■ Extreme cases of diffraction.

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, θ_3, of a sinc function is

$$\theta_3 = \frac{0.89\,\lambda}{a} \text{ radians} \tag{1.8}$$

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*.

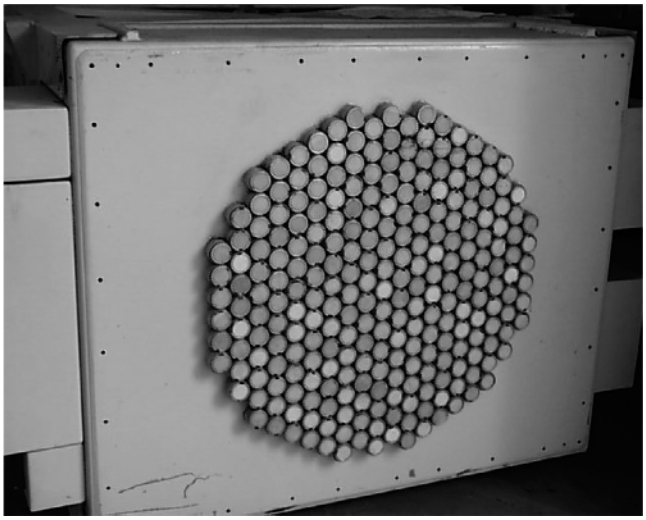


FIGURE 1-10 ■ A multi-element antenna. (Courtesy GTRI. With permission.)

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*, θ_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,

$$\theta_3 \approx \frac{1.3\lambda}{D} \text{ radians} \tag{1.9}$$

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

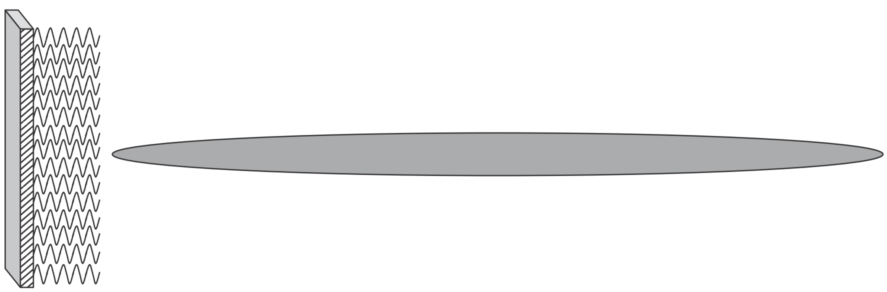


FIGURE 1-11 ■ A multi-element linear array of radiating elements with in-phase signals and resulting main beam pattern.

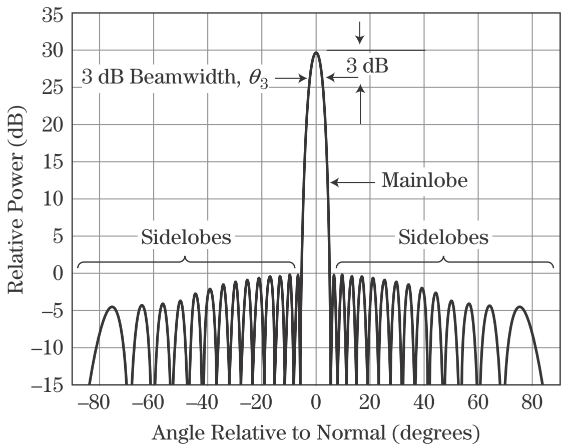


FIGURE 1-12 ■ Idealized one-dimensional antenna pattern.

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.

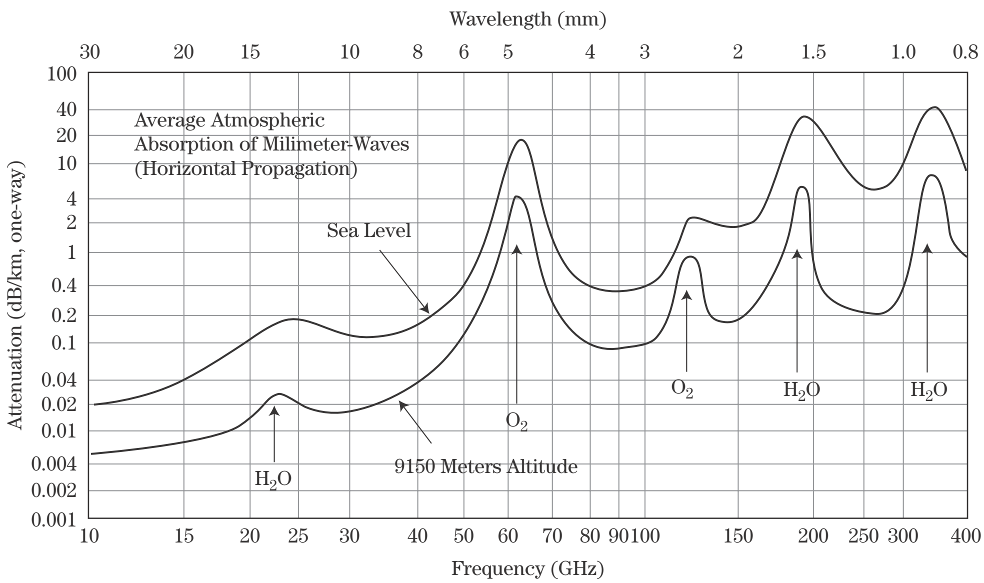


FIGURE 1-13 ■ One-way atmospheric attenuation as a function of frequency at sea level and at 9150 meters altitude. (From U. S. Government work.)

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 difference materials as shown in Figure 1-15. Within the denser material (glass), the EM wave slows down due to a decrease in wavelength

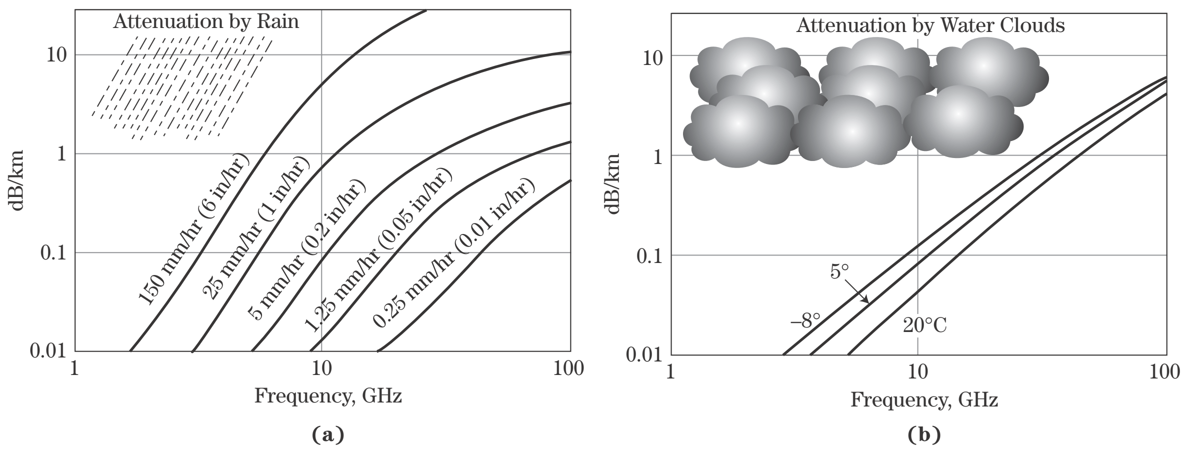
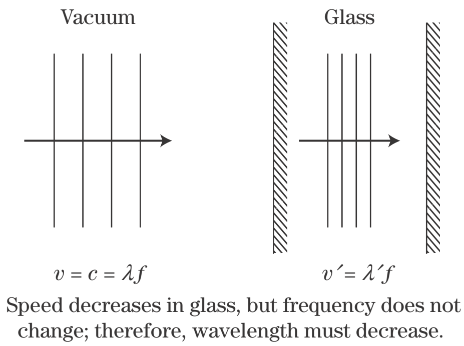


FIGURE 1-14 ■ One-way rain and cloud attenuation as a function of frequency. (a) Rain. (b) Clouds.

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



($v = \lambda f$). The optical density of a material is quantified by the index of refraction, n, given by $n = c/v$, 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.

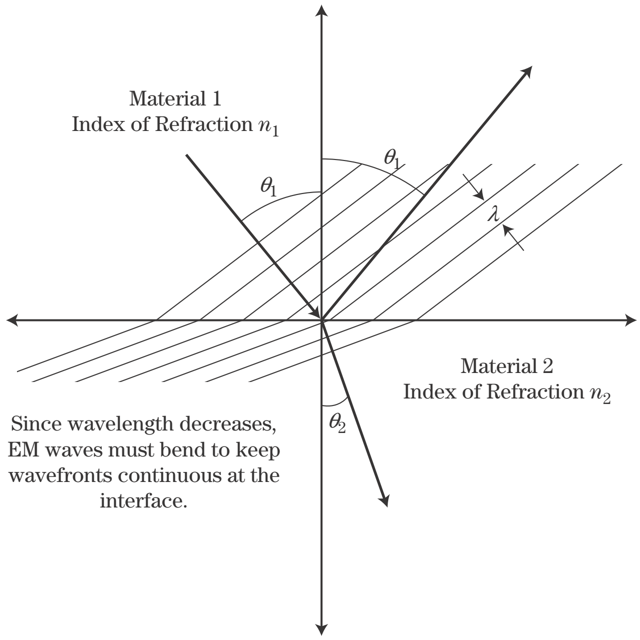


FIGURE 1-16 ■ Bending of wavefronts incident at an angle on the interface of two materials.

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" ($\lambda \gg$ roughness), then the EM wave's angle of reflection, θ_r, equals its angle of incidence, θ_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" ($\lambda \ll$ 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

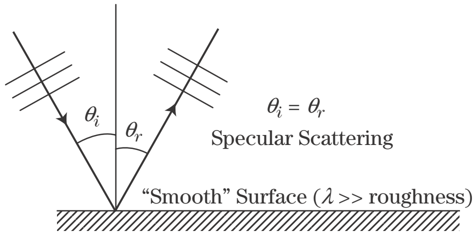


FIGURE 1-17 Specular scattering.

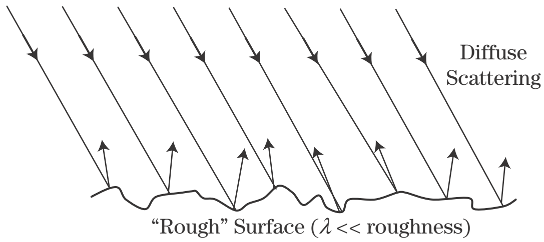


FIGURE 1-18 Diffuse scattering.

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*, σ. 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.

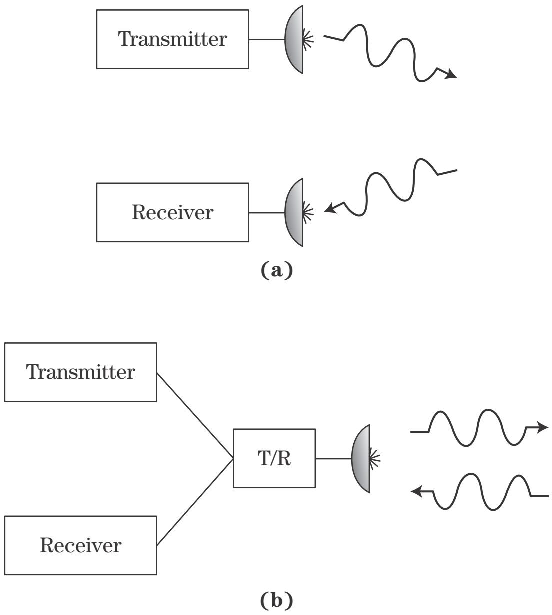


FIGURE 1-19 Basic radar configurations: (a) Bistatic. (b) Monostatic.

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.

1.5.2 Continuous Wave versus Pulsed

1.5.2.1 CW Waveform

Radar waveforms can be divided into two general classes: *continuous wave* (CW) and pulsed. With the CW waveform the transmitter is continually transmitting a signal, usually without interruption, all the time the radar transmitter is operating. The receiver continuously operates also. The pulsed waveform transmitter, on the other hand, emits a sequence of finite duration pulses, separated by times during which the transmitter is "off." While the transmitter is off, the receiver is on so that target signals can be detected.

Continuous wave radars often employ the bistatic configuration to effect transmitter/receiver isolation. Since the isolation between the transmitter and receiver is not perfect, there is some competing signal due to the leakage, relegating CW systems to relatively low power and hence short-range applications. Since a CW radar is continuously transmitting, determination of the transmitted EM wave's round-trip time and, thus, target range, must be accomplished by changing the characteristics of the wave (e.g., changing the wave's *frequency* over time). This frequency modulated (FM) technique effectively puts a timing mark on the EM wave, thus allowing for target range determination. Though there are relatively complex CW systems employed as illuminators in fire control systems, semi-active missiles, and trackers, CW radars tend to be simple radars and are used for such applications as police speed-timing radars, altimeters, and proximity fuses.

1.5.2.2 Pulsed Waveform

Pulsed radars transmit EM waves during a very short time duration, or *pulse width* τ, typically 0.1 to 10 microseconds (μs), but sometimes as little as a few nanoseconds (10^{-9} seconds) or as long as a millsecond. During this time, the receiver is isolated from the antenna, or *blanked*, thus protecting its sensitive components from the transmitter's high-power EM waves. No received signals can be detected during this time. In addition to the isolation provided by the T/R device (shown in Figure 1-1), further protection is offered by the receiver protection switch, not shown in the figure. During the time between transmitted pulses, typically from 1 microsecond to tens of milliseconds, the receiver is connected to the antenna, allowing it to receive any EM waves (echoes) that may have been reflected from objects in the environment. This "listening" time plus the pulse width represents one pulsed radar cycle time, normally called the *interpulse period* (IPP) or *pulse repetition interval* (*PRI*). The pulsed waveform is depicted in Figure 1-20.

Pulse Repetition Frequency (PRF) The number of transmit/receive cycles the radar completes per second is called the *pulse repetition frequency* (PRF), which is properly

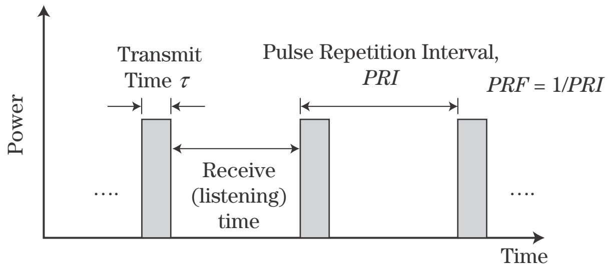


FIGURE 1-20 ■ Pulsed radar waveform.

measured in pulses per second (PPS) but is often expressed in hertz (cycles per second). The PRF and PRI are related according to

$$PRF = \frac{1}{PRI} \tag{1.10}$$

Pulse Width and Duty Cycle The fraction of time the transmitter is transmitting during one radar cycle is called the transmit *duty factor* (or *duty cycle*), d_t, and from Figure 1-20 is given by

$$d_t = \frac{\tau}{PRI} = \tau \cdot PRF \tag{1.11}$$

The average power, P_{avg}, of the transmitted EM wave is given by the product of the peak transmitted power, P_t, and the transmit duty factor:

$$P_{avg} = P_t \cdot d_t = P_t \cdot \tau \cdot PRF \tag{1.12}$$

Range Sampling Figure 1-21 depicts a sequence of two transmit pulses and adds a hypothetical target echo signal. Because the time scale is continuous, a target signal can arrive at the radar receiver at any arbitrary time, with infinitesimal time resolution. In a modern radar system, the received signal is normally sampled at discrete time intervals, using an ADC, which quantizes the signal in time and amplitude. The time quantization corresponds to the ADC sample times, and the amplitude quantization depends on the number of ADC "bits" and the full-scale voltage. To achieve detection, the time between samples must be no more than a pulse width; for example, for a 1 μs transmit pulse, the received signal must be sampled at intervals of no more than a microsecond. Usually, to achieve improved detection, oversampling is used; for example, there would be two samples for a given pulse width. A 1 μs pulse width would suggest a 0.5 μs sample period,

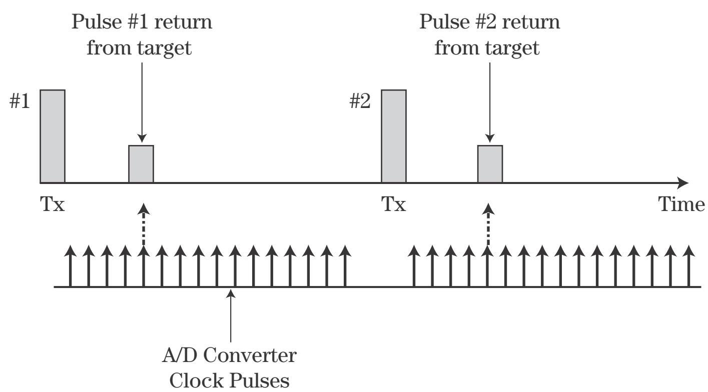


FIGURE 1-21 ■ Pulsed radar waveform showing ADC clock pulses.

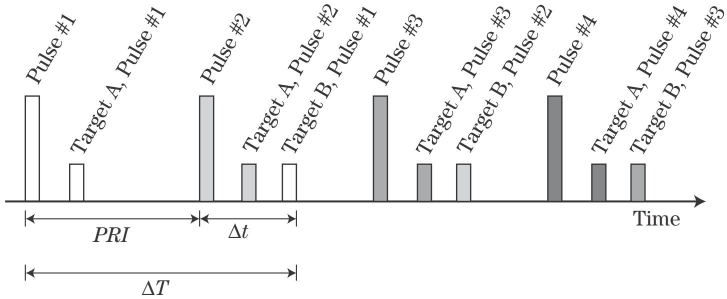


FIGURE 1-22 ■ Pulsed radar range ambiguity.

or a 2 megasample per second (Msps) sample rate. Each of these time samples represents a different range increment, often termed a *range bin*, at a range found from Equation (1.1). The target shown in the figure is at a range corresponding to sample number five.

Unambiguous Range Measurement Recall that target range is determined by measuring the delay time from transmission of a pulse to reception of the reflected signal. Problems can occur in a pulsed radar when determining the range to targets if the pulse round-trip travel time, ΔT, between the radar and the distant target is greater than the interpulse period, *IPP*. In this case, the EM wave in a given pulse will not return to the radar's receiver before the next pulse is transmitted, resulting in a time ambiguity and related *range ambiguity*. The received pulse could be a reflection of the pulse that was just transmitted and, thus, a reflection from a close-in target, or it could be a reflection resulting from a previously transmitted pulse and, thus, a reflection from a distant target.

This situation is illustrated in Figure 1-22. The tall rectangles represent transmitted pulses; the shorter rectangles represent the received echoes from two targets. The shading of the target echoes matches the shading of the pulse from which they originated. The time delay to target A and back is less than the interpulse period, so the echo from target A from a given pulse is received before the next pulse is transmitted. The time delay ΔT to target B is greater than the *PRI*; specifically, suppose $\Delta T = PRI + \Delta t$. Then the reflection from target B due to pulse #1 occurs Δt seconds after pulse #2, as shown in the figure. Consequently, it is unclear if this echo is from a short-range target Δt seconds away or a longer-range target ΔT seconds away[5].

Range ambiguities can be avoided by ensuring that the interpulse period, *PRI*, is long enough or, equivalently, the pulse repetition frequency *PRF* is low enough, such that all echoes of interest from a given pulse return to the radar receiver before the next pulse is transmitted. The round-trip time for the radar wave from equation (1.1) is given by

$$\Delta T = \frac{2R}{c} \tag{1.13}$$

Thus, to prevent range ambiguities, the following condition must be satisfied:

$$PRI \geq \Delta T_{\max} = \frac{2R_{\max}}{c} \quad \text{or} \quad R_{\max} \leq \frac{c \cdot PRI}{2} = \frac{c}{2PRF} \tag{1.14}$$

[5]It appears that the ambiguous range condition could be revealed because the target signal does not appear in the first range interval. In fact, radar systems do not usually detect a target on the basis of any single pulse; several pulses are transmitted and processed. In this case, it is not known that the target signal is "missing" for one (or more) intervals.

where R_{max} is the maximum target range of interest. Conversely, the *unambiguous range,* R_{ua}, is the maximum range at which the range to a target can be measured unambiguously by the radar. It is given by

$$R_{ua} = \frac{c}{2PRF} \tag{1.15}$$

It should be noted that not all radars satisfy this condition. Some systems cannot avoid an ambiguous range condition, due to other conflicting requirements, as is seen in the following section.

1.5.3 Noncoherent versus Coherent

Radar systems can be configured to be noncoherent or coherent. Whereas a noncoherent system detects only the amplitude of the received signal, the coherent system detects the amplitude and the phase, treating the received signal as a vector. Noncoherent systems are often used to provide a two-dimensional display of target location in a ground map background. The amplitude of the signal at any instant in time will determine the brightness of the corresponding area of the display face. Noncoherent radars can be used in cases in which it is known that the desired target signal will exceed any competing clutter signal. All early radars were noncoherent; target detection depended on operator skill in discerning targets from the surrounding environment.

For a coherent system, measurement of the phase of the received signal provides the ability to determine if the phase is changing, which can provide target motion characteristics and the ability to image a target. Though there are still applications for which noncoherent radar technology is appropriate, most modern radar systems are coherent.

A pulsed coherent system measures the phase of the received signal on a pulse-to-pulse basis. This reference sinusoid is usually implemented in the form of a local oscillator (LO) signal used to produce the transmit signal that also serves as the reference for the received signal. This process is depicted in Figure 1-23. The top line is the local oscillator signal; the solid segments represent the transmit pulse times, and the dashed segments represent “listening” times between transmit pulses. If the local oscillator signal is a fixed frequency, it can serve as a reference for measuring the phase of the received signal. The expanded “balloon” shows the phase relationship for a single transmit/receive pulse pair. The ability to measure the phase of the received signal depends on the stability of the LOs, as described in Chapter 12.

1.5.3.1 The Doppler Shift

If there is relative motion between the radar and the target, then the frequency of the EM wave reflected from the target and received by the radar will be different from the frequency of the wave transmitted from the radar. This is the *Doppler effect*, common to all wave phenomena and originally identified as an acoustic (sound wave) phenomenon. The Doppler frequency shift, f_d, or “Doppler” for short, is the difference between the frequency of the received wave and that of the transmitted wave and is approximately given by

$$f_d \approx \frac{2v_r}{\lambda} \tag{1.16}$$

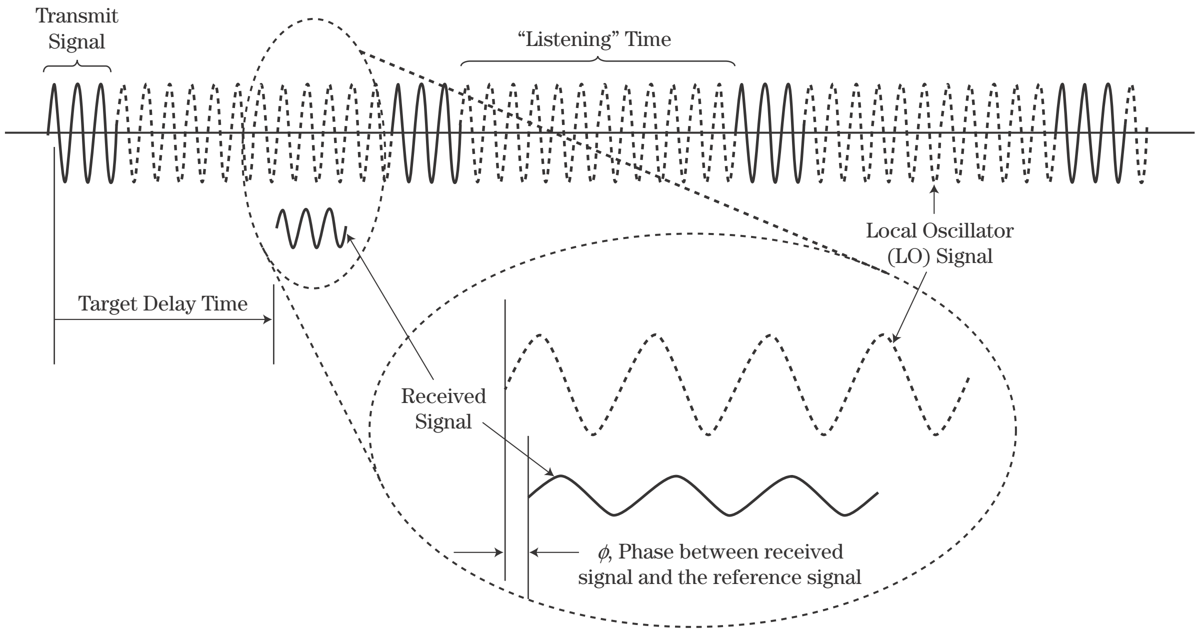


FIGURE 1-23 ■ Coherent system local oscillator, transmit, and received signals.

where v_r is the radial component[6] of the target's velocity vector toward the radar, and λ is the wavelength of the transmitted EM wave. The approximation is excellent as long as the radial component of velocity of the target is much less than the speed of light. The negative of the radial velocity is often called the *range rate*. This radial velocity component, v_r, is positive (and, thus, f_d is positive) for targets approaching the radar and negative (f_d negative) for targets receding from the radar.[7]

1.5.3.2 Unambiguous Doppler Shift Measurement

Clearly from equation (1.15), lowering the PRF of the radar will increase the radar's unambiguous range. However, lowering the radar's PRF also has a negative consequence. Most modern radars measure the Doppler frequency shift of the received EM wave. A pulsed radar samples the Doppler frequency shift at the pulse repetition frequency. This can lead to Doppler frequency ambiguities if the sampling rate (PRF) is not high enough, as discussed in Chapter 14.

One statement of the Nyquist sampling criterion or theorem is that "the maximum frequency that can be unambiguously measured is half the sampling rate." A similar statement holds for measuring negative frequencies. In a radar, Doppler shift is being

[6]The radial component is the component of velocity along the range dimension (i.e., a straight line between the radar and the target).

[7]There is often a point of confusion regarding whether the radial component of velocity is positive or negative. The Doppler frequency shift will be positive for a closing target, so a closing target represents a positive velocity. But since *range rate* is positive for a receding target (one for which the range is increasing) the sign of *range rate* will be opposite from the sign for radial component of velocity.

sampled at the radar's PRF; thus, the maximum range of Doppler shift frequencies that can be unambiguously measured is

$$f_{d_{\max}} = \pm PRF/2 \quad \text{or} \quad PRF_{\min} = 2f_{d_{\max}} = \frac{4v_{r_{\max}}}{\lambda} \tag{1.17}$$

While maximizing unambiguous range leads to lower PRFs, maximizing unambiguous Doppler shift leads to higher PRFs. In many systems, no single PRF can meet both of these opposing requirements. Fortunately, as discussed in Chapter 17, some signal processing techniques such as staggered PRFs allow radars to unambiguously measure range and Doppler shift at almost any PRF.

This conflict leads to the definition of three different *PRF regimes*: low PRF, medium PRF, and high PRF. A *low PRF* system is one that is unambiguous in range, for all target ranges of interest. Though there is no specific range of PRF values that define such a system, the PRF ranges from as low as 100 Hz to as high as 4 kHz. Of course, there may be lower or higher PRFs for low PRF systems, but a large majority of low PRF systems fall into these limits.

At the other extreme, a *high PRF* system is defined as one for which the Doppler shift measurement is always unambiguous. That is, the Nyquist sampling criterion is satisfied for the fastest target of interest. Typical values of PRF for these systems are from 10 kHz to 100 kHz (or sometimes much more).

In between these two conditions lies the *medium PRF* regime, for which both range ambiguities and Doppler ambiguities will exist. Typical values for medium PRF waveforms are from 8 kHz to 30 kHz or so.

For radar systems operating in the HF, VHF, and UHF regions, a different set of conditions apply to the definition for medium PRF. If the radar system operates in these regions it is possible that the PRF required to satisfy the Nyquist sampling criterion will be also sufficient to measure the range to the farthest target of interest unambiguously. In this case, a medium PRF system will be unambiguous in both range and Doppler.

1.6 | NOISE, SIGNAL-TO-NOISE RATIO, AND DETECTION

Because of random thermal motion of charged particles, all objects in the universe with a temperature above absolute zero will be radiating EM waves at, collectively, almost all frequencies. These EM waves, called *thermal noise*, are always present at the radar's receiving antenna and compete with the reflected EM waves from the target. In addition, the radar's receiver, being an electrical device with randomly moving electrons, generates its own internal thermal noise that also competes with the received target signal. In microwave radars, the internally generated noise usually dominates over the noise from the environment.

The noise voltage is always present in the radar receiver circuits. If the radar antenna beam is pointed in the direction of a target when the transmitter generates the transmitted signal, then the signal will illuminate the target, and the signal reflected from that target will propagate toward the receiver antenna, will be captured by the antenna, and will also produce a voltage in the receiver. At the instant in time at which the target signal is present

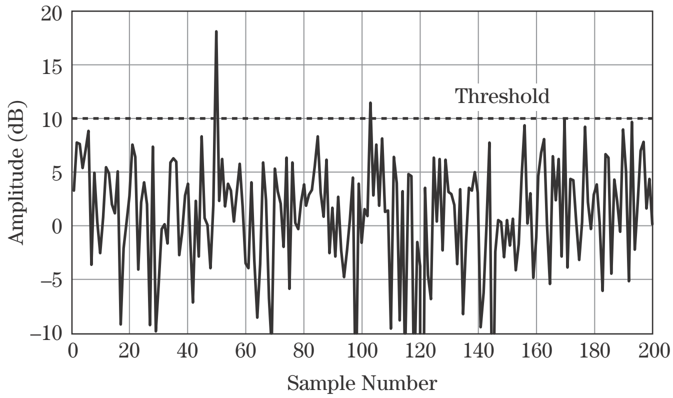


FIGURE 1-24 ■ Threshold detection of a noisy signal.

in the receiver, there will be a combination of the noise and target signal. The voltages add, but because the noise is uncorrelated with the target signal, the total power is just the sum of the target signal power S and the noise power N.

Suppose the signal power of the reflected EM wave from the target is much greater than the noise power due to environmental and receiver noise. If this is the case, the presence of a target echo signal can be revealed by setting an *amplitude threshold* above the noise level (but below the target level). Any received signals (plus noise) that are above this amplitude threshold are assumed to be returns from targets, while signals below this threshold are ignored. This is the basic concept of threshold detection. In the example of Figure 1-24 the receiver output contains 200 samples of noise with a target signal added at sample 50. The target signal is 17 dB larger than the root mean square (rms) noise power. If the threshold is set at a value of 10 dB above the noise power, the signal + noise sample easily exceeds the threshold and so will be detected, while all but one of the noise-only samples does not cross the threshold. Thus, the target signal is revealed in the presence of the noise.

Because it is a random variable, at any given time the noise alone can "spike up" and cross the amplitude threshold, giving rise to some probability that there will be a *false alarm*. In Figure 1-24, a single false alarm occurs at sample 103. In addition, the target-plus-noise signal is a random variable, so at any given time it can drop below the amplitude threshold, resulting in some probability that the target-plus-noise signal will not be detected. Because of this random nature of the signals, the detection performance of a radar must be given in terms of probabilities, usually the probability of detection, P_D, and the probability of false alarm, P_{FA}. P_D is the probability that a target-plus-noise signal will exceed the threshold and P_{FA} is the probability that the noise alone will spike above threshold. Perfect radar detection performance would correspond to $P_D = 1$ (or 100%) and $P_{FA} = 0$ (or 0%). Either P_D or P_{FA} can be arbitrarily set (but not both at the same time) by changing the amplitude threshold. When the threshold is raised, P_{FA} goes down, but unfortunately, so does P_D. When the threshold is lowered, the P_D goes up, but, unfortunately, so does P_{FA}. Thus, when the threshold is changed, P_{FA} and P_D both rise or fall together. To increase P_D while at the same time lowering P_{FA}, the target signal power must be increased relative to the noise power. The ratio of the target signal power to noise power is referred to as the *signal-to-noise ratio*. Chapter 2 develops an equation to predict the SNR called the *radar range equation* (RRE); Chapters 3 and 15 discuss the methods for relating P_D and P_{FA} to SNR; and Chapter 16 presents a description of the processing implemented to automatically establish the threshold voltage.

1.7 BASIC RADAR MEASUREMENTS

1.7.1 Target Position

Target position must be specified in three-dimensional space. Since a radar transmits a beam in some azimuthal and elevation angular direction, and determines range along that angular line to a target, a radar naturally measures target position in a spherical coordinate system (see Figure 1-25).

Modern radars can determine several target parameters simultaneously:

- Azimuthal angle, θ
- Elevation angle, ϕ
- Range, R (by measuring delay time, ΔT)
- Range rate, $\dot{R}$ (by measuring Doppler frequency, f_d)
- Polarization (up to five parameters)

Measurements in each of these dimensions are discussed in the next section.

1.7.1.1 Azimuth Angle, Elevation Angle

The target's angular position, here denoted by the azimuth and elevation angles θ and ϕ, is determined by the pointing angle of the antenna main beam when the target detection occurs. This antenna pointing angle can either be the actual physical pointing angle of a mechanically scanned antenna or the electronic pointing angle of an electronically scanned (phased array) antenna. (See Chapter 9 for more on antenna-scanning mechanisms.) The *monopulse* technique, also described in Chapter 9, can provide a significantly more precise angle measurement than that based on the main beam beamwidth alone.

1.7.1.2 Range

The target's range, R, is determined by the round-trip time of the EM wave as discussed in Section 1.2. The range to the target is determined by measuring the time delay. Repeating equation (1.1) for convenience,

$$R = \frac{c\Delta T}{2}$$

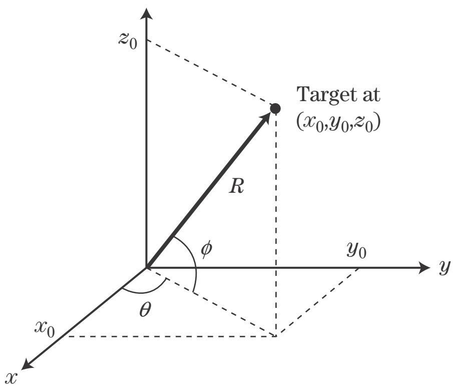


FIGURE 1-25 ■ Spherical coordinate system depicting radar-target geometry.

In most modern radar systems, the delay time, ΔT, is determined by "counting" the number of ADC clock pulses that occur between the transmit time and the target time, assuming that the first clock pulse coincides with the transmit pulse. Chapter 18 presents the details associated with range measurement results and shows that the precision of a range measurement can be much better than the resolution of the measurement.

1.7.2 Range Rate and Doppler Frequency Shift

As described in Section 1.5.4, if there is relative motion between the radar and the target, then the frequency of the EM wave reflected from the target and received by the radar will be different from the frequency of the wave transmitted from the radar. This is the Doppler effect.

The Doppler shift is measured by performing a spectral analysis of the received signal in every range increment. The spectral analysis is usually performed in modern radar systems by transmitting a sequence of several pulses, (often on the order of 30 pulses) and performing a K-point discrete Fourier transform (DFT) on this sequence of received signals for each range increment. The DFT is usually implemented in the form of the fast Fourier transform (FFT), described in Chapter 17.

Doppler shift is a very important quantity in modern radars. Measurement of the Doppler characteristics is used to suppress returns from clutter, to determine the presence of multiple targets at the same range, and to classify and identify moving targets and targets with moving components (e.g., aircraft, helicopters, trucks, tanks). In a synthetic aperture radar, the measurement of Doppler shift is used to improve the cross-range resolution of the radar.

For example, consider a stationary radar designed to detect moving targets on the ground. The EM wave return from a moving target will have a nonzero Doppler shift, whereas the return from stationary clutter (e.g., trees, rocks, buildings) will essentially have a zero Doppler shift. Thus, Doppler shift can be used to sort (discriminate) returns from targets and clutter by employing a high-pass filter in the radar's signal processor. This is the essence of *moving target indication* (MTI) radars discussed in Chapter 17.

1.7.3 Polarization

Because a typical target comprises a multitude of individual scatterers, each at a slightly different distance from the radar, the RCS of an object changes with viewing angle and wavelength, as explained in Chapter 7. It is also sensitive to the transmit and receive polarization of the EM wave. Polarization refers to the vector nature of the EM wave transmitted and received by the radar antenna. The EM wave's polarization is sensitive to the geometry of the object from which it reflects; different objects will change the polarization of the incident EM wave differently. Therefore, the change in polarization of the EM wave when it reflects from an object carries some information regarding the geometrical shape of that object. This information can be used to discriminate unwanted reflected waves (e.g., returns from rain) from those reflected from targets. Also, polarization can be used to discriminate targets from clutter and even to facilitate identifying different targets of interest.

Maximum polarization information is obtained when the *polarization scattering matrix* (PSM) **S** of a target is measured. Equation (1.18) describes the four components of the PSM. Each of the four terms is a vector quantity, having an amplitude and a phase. The subscripts refer to the transmit and receive polarization. Polarizations 1 and 2 are

orthogonal; that is, if polarization 1 is horizontal, the polarization 2 is vertical. If polarization 1 is right-hand-circular, then polarization 2 is left-hand-circular.

$$\mathbf{S} = \begin{bmatrix} \sqrt{\sigma_{11}}e^{j\phi_{11}} & \sqrt{\sigma_{12}}e^{j\phi_{12}} \\ \sqrt{\sigma_{21}}e^{j\phi_{21}} & \sqrt{\sigma_{22}}e^{j\phi_{22}} \end{bmatrix} \tag{1.18}$$

Measuring the PSM requires the radar to be polarization-agile on transmit and to have a dual-polarized receiver. An EM wave of a given polarization (e.g., horizontal polarization) is transmitted and the polarization of the resulting reflecting wave is measured in the dual-polarized receiver. This measurement requires, at a minimum, the measurement of the *amplitude* of the wave in two orthogonal polarization receiver channels (e.g., horizontal and vertical polarizations) and the *relative phase* between the waves in these two channels. The transmit polarization is then changed to an orthogonal state (e.g., vertical polarization) and the polarization of the resulting reflecting wave is measured again. For a monostatic radar, this process results in five unique measured data: three amplitudes and two relative phases.[8] These data constitute the elements of the PSM. Ideally, the two transmit polarizations should be transmitted simultaneously, but in practice they are transmitted at different, but closely spaced times (typically on successive pulses). This time lag creates some uncertainty in the integrity of the PSM; however, if the two transmit times are closely spaced, the uncertainty is minor. A more detailed discussion of the PSM is in Chapter 5.

1.7.4 Resolution

The concept of *resolution* describes a radar's ability to distinguish two or more targets that are closely spaced, whether in range, angle, or Doppler frequency. The idea is illustrated in Figure 1-26, which imagines the receiver output for a single transmitted pulse echoed from two equal-strength point scatterers separated by a distance ΔR. If ΔR is large enough, two distinct echoes would be observed at the receiver output as in Figure 1-26b. In this case, the two scatterers are considered to be *resolved* in range. In Figure 1-26c, the scatterers are close enough that the two echoes overlap, forming a composite echo. In this case the two scatterers are not resolved in range. Depending on the exact spacing of the two scatterers, the two pulses may combine constructively, destructively, or in some intermediate fashion. The result is very sensitive to small spacing changes, so the two scatterers cannot be considered to be reliably resolved when their echoes overlap.

The dividing line between these two cases is shown in Figure 1-26d, where the two pulses abut one another. This occurs when

$$\Delta R = \frac{c\tau}{2} \tag{1.19}$$

The quantity ΔR is called the *range resolution* of the radar. Two targets spaced by more than ΔR will be resolved in range; targets spaced by less than ΔR will not. This equation represents the range resolution achieved using a simple, unmodulated pulse of length τ.

Note that in the discussions so far, the range resolution is proportional to the pulse width τ. A pulse width of 1 μs results in a range resolution of $(3 \times 10^8)(10^{-6})/2 = 150$ m.

[8]Though there are eight values in the matrix, only five are unique. σ_{12} and σ_{21} will be equal, $\angle_{11}$ is the reference angle, and $\angle_{21}$ will equal $\angle_{12}$, so the unique values are σ_{11}, σ_{12}, σ_{22}, $\angle_{12}$, and $\angle_{22}$.

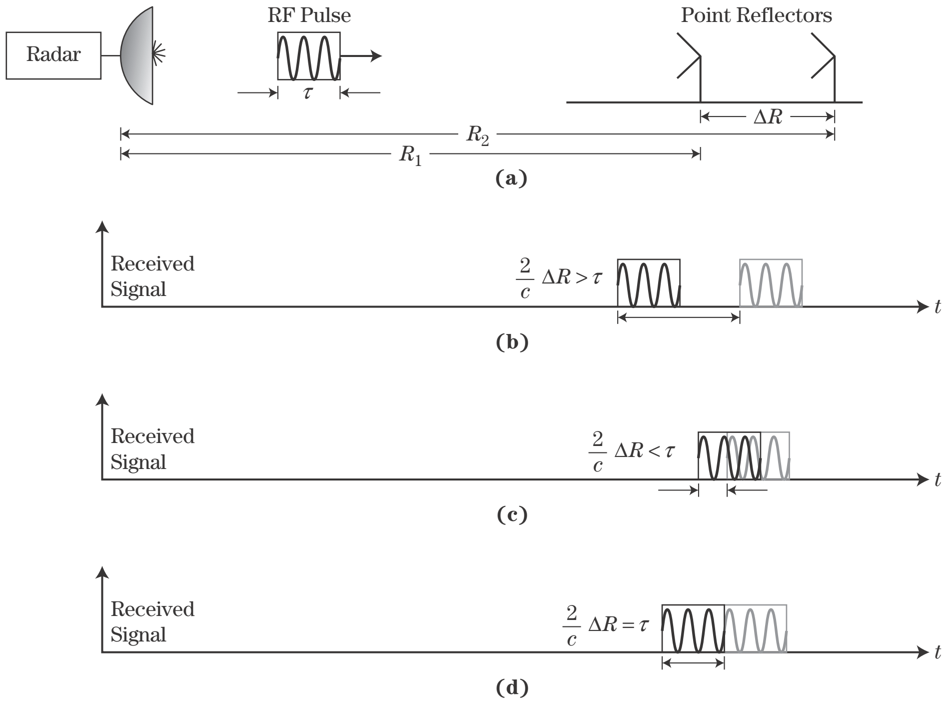


FIGURE 1-26 ■ Concept of resolution in range. (a) Transmitted pulse and two targets. (b) Receiver output for resolved targets. (c) Receiver output for unresolved targets. (d) Receiver output for defining range resolution.

This is the minimum separation at which two targets can be reliably resolved with a 1 μs simple, unmodulated pulse. If finer resolution is needed, shorter pulses can be used. It will be seen later that shorter pulses have less energy and make detection more difficult. Chapter 20 will introduce *pulse compression,* a technique that provides the ability to maintain the energy desired in the pulse while at the same time providing better range resolution by modulating the signal within the pulse.

Figure 1-20 showed the timing of a pulsed radar waveform. A number of choices are available for the actual shape of the waveform comprising each pulse. Figure 1-27 illustrates three of the most common. Part (a) of the figure is a simple unmodulated pulse, oscillating at the radar's RF. This is the most basic radar waveform. Also very common is the *linear frequency modulation* (LFM) or *chirp* pulse (Figure 1-27b). This waveform sweeps the oscillations across a range of frequencies during the pulse transmission time. For example, a chirp pulse might sweep from 8.9 to 9.1 GHz within a single pulse, a swept bandwidth of 200 MHz. Part (c) of the figure illustrates a *phase-coded* pulse. This pulse has a constant frequency but changes its relative phase between one of two values, either zero or π radians, at several points within the pulse. These phase changes cause an abrupt change between a sine function and a negative sine function. Because there are only two values of the relative phase used, this example is a *biphase-coded* pulse. More general versions exist that use many possible phase values.

The choice of pulse waveform affects a number of trade-offs among target detection, measurement, ambiguities, and other aspects of radar performance. These waveforms and their design implications are discussed in Chapter 20.

A radar also resolves a target in azimuth angle, elevation angle, and Doppler frequency. The only difference is the characteristic signal shape that determines achievable resolution. Figure 1-28a shows the Fourier spectrum of a signal consisting of the sum of two sinusoids. This could arise as the Doppler spectrum of a radar viewing two targets at the same range

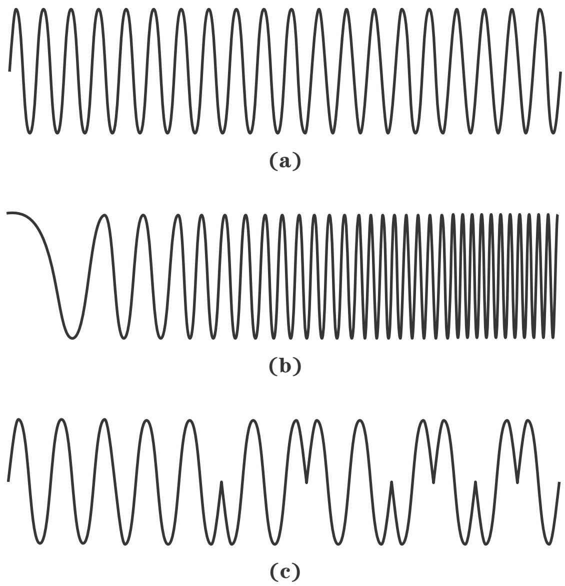


FIGURE 1-27 ■ Three common choices for a single pulse in a pulsed radar waveform. (a) Simple pulse. (b) Linear FM or chirp pulse. (c) Biphase coded pulse.

but different range rates. Each sinusoid contributes a characteristic "sinc" function shape (see Chapter 17) to the Doppler spectrum, centered at the appropriate Doppler shift. The width of the main lobe in the spectrum is proportional to the reciprocal of the time during which the input data were collected. For a "sinc" function, the main lobe 3 dB width is

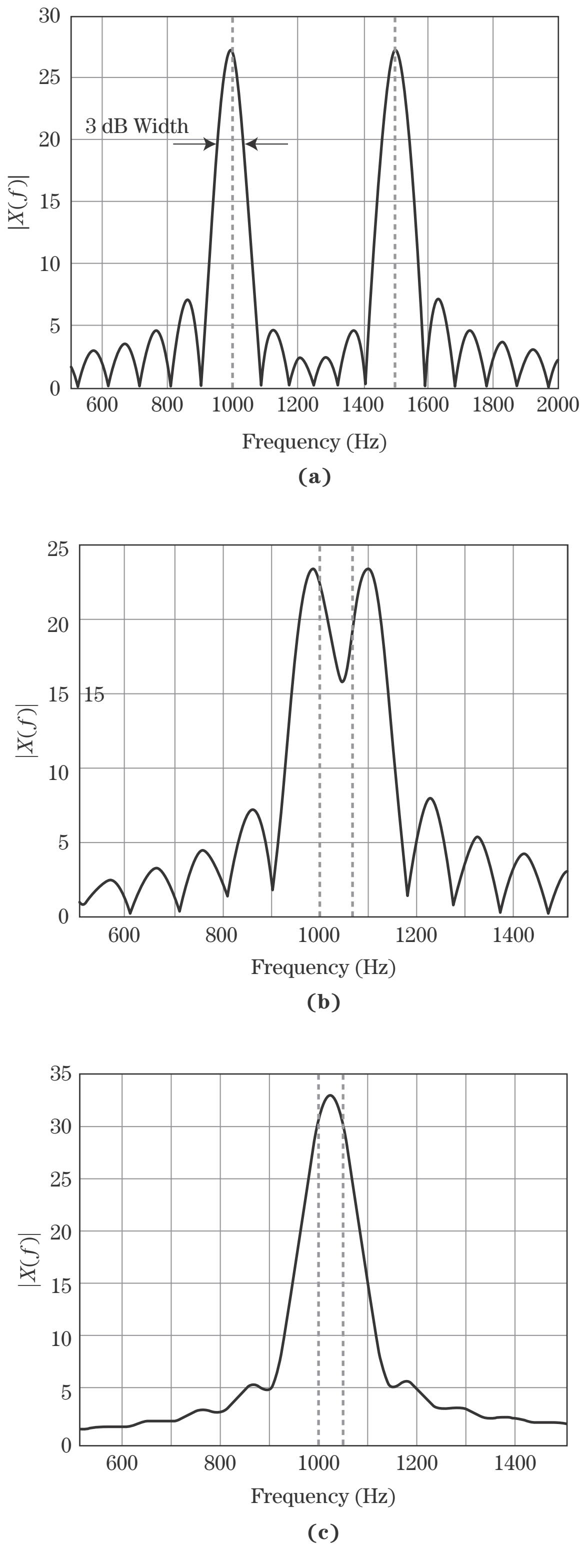
$$3\,\text{dB width} = \frac{0.89}{\text{dwell time}} \tag{1.20}$$

The dwell time is the time duration associated with transmitting the sequence of pulses for performing the FFT, as described in Section 1.7.2. The dwell time for this example is 0.01 seconds, so the width of the central lobe of the sinc function measured 3 dB below its peak (about 71% of the peak amplitude) is 89 Hz in this example. When the two Doppler shifts are separated by more than 89 Hz, they are clearly resolved. When the separation becomes less than 89 Hz, as in Figure 1-28b, the two peaks start to blend together. While two peaks are visible here, the dip between them is shallow. If noise were added to the signals, the ability to resolve these two frequencies reliably would degrade. At a separation of 50 Hz (Figure 1-28c), the two signals are clearly not resolved.

In this Doppler frequency example, the resolution capability is determined by the width of the sinc function main lobe, which in turn is determined by the total pulse burst waveform duration. Also, as will be seen in Chapter 17, when a weighting function is used in the Doppler processing to reduce the sidelobes, the main lobe will be further spread, beyond 89 Hz in this example, further degrading the Doppler resolution. Thus, as with range resolution, Doppler resolution is determined by the transmitted waveform and processing properties.

The signals shown in Figure 1-28 could just as easily represent the receiver output versus scan angle for two scatterers in the same range bin but separated in angle. The "sinc" response would then be the model of a (not very good) antenna pattern. Given a more realistic antenna pattern, as described in Section 1.4.1 and equation (1.9), the angular resolution would be determined by the antenna size. Two targets can be resolved in angle if they are separated by the antenna beamwidth or more.

FIGURE 1-28 ■ Example of frequency resolution. (a) Spectrum of two sinusoids separated by 500 Hz. The 3 dB width of the response is 89 Hz. (b) Spectrum for separation of 75 Hz. (c) Spectrum for separation of 50 Hz. The two dashed lines show the actual sinusoid frequencies in each case.



1.8 BASIC RADAR FUNCTIONS

While there are hundreds of different types of radars in use, the large majority have three basic functions: (1) search/detect; (2) track; and (3) image. These functions are briefly discussed now, followed by a discussion of some of the many types of radar systems and how they apply these functions.

1.8.1 Search/Detect

Almost all radars have to search a given volume and detect targets without a priori information regarding the targets' presence or position. A radar searches a given volume by pointing its antenna in a succession of beam positions that collectively cover the volume of interest. A mechanically scanned antenna moves through the volume continuously. Rotating antennas are an example of this approach. An ESA is pointed to a series of discrete beam positions, as suggested in Figure 1-29.

At each position, one or more pulses are transmitted, and the received data are examined to detect any targets present using the threshold techniques described earlier. For example, 10 pulses might be transmitted in one beam position of an ESA. The detected data from each pulse might then be noncoherently integrated (summed) in each range bin to improve the SNR. This integrated data would then be compared with an appropriately set threshold to make a detection decision for each range bin. The antenna is then steered to the next beam position, and the process is repeated. This procedure is continued until the entire search volume has been tested, at which point the cycle is repeated.

A major issue in search is the amount of time required to search the desired volume once. The search time is a function of the total search volume, the antenna beamwidths, and the *dwell time* spent at each beam position. The latter in turn depends on the number of pulses to be integrated and the desired range coverage (which affects the PRF). Optimization of the search process involves detailed trade-offs among antenna size (which affects beamwidths and thus number of beam positions needed), dwell time (which affects number of pulses available for integration), and overall radar timeline. The search and detection process and these trade-offs are discussed in more detail in Chapter 3.

1.8.2 Track

Once a target is detected in a given search volume, a measurement is made of the target *state*, that is, its position in range, azimuth angle, and elevation angle, and, often, its radial component of velocity. Tracking radars measure target states as a function of time. Individual position measurements are then combined and smoothed to estimate a target *track*.

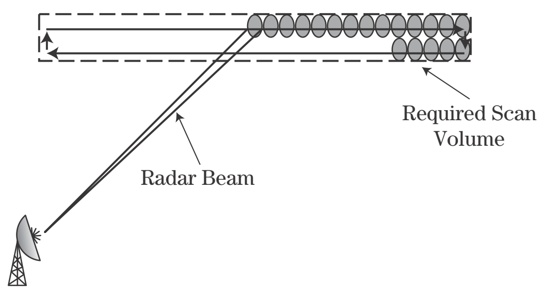


FIGURE 1-29 ■ Coverage of a search volume using a series of discrete beam positions.

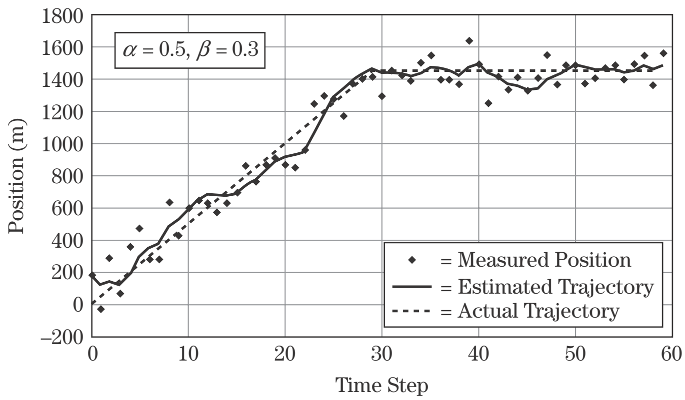


FIGURE 1-30 Example of track filtering for smoothing a series of individual position measurements.

Tracking implies measuring the position and velocity of a target to an accuracy better than the radar's resolution. A variety of techniques are used to do this. For instance, the azimuth position can be estimated to a fraction of the antenna azimuth beamwidth in a mechanically scanned radar by measuring the detected target strength on several successive pulses as the antenna scans and then computing the centroid of the resulting measurements. Similar concepts can be applied in range and Doppler. These and other measurement techniques are described in Chapter 18. Individual measurements are invariably contaminated by measurement noise and other error sources. An improved estimate of the target position over time is obtained by *track filtering*, which combines multiple measurements with a model of the target dynamics to smooth the measurements. For example, the dotted line in Figure 1-30 shows the actual position of a target that is initially moving away from the radar in some coordinate at constant velocity and then at time step 30 stops moving (constant position). The small triangles represent individual noisy measurements of the position, and the solid line shows the estimated position using a particular track filtering algorithm called the *alpha-beta filter* or *alpha-beta tracker*. Advanced systems use various forms of the Kalman filter and other techniques. Track filtering is discussed in Chapter 19.

The optimum radar configurations for tracking and searching are different. Consequently, these search and track functions are sometimes performed by two different radars. This is common in situations where radar weight and volume are not severely limited (i.e., land-based and ship-based operations). When radar weight and volume are limited, as in airborne operations, the search and track functions must be performed by one radar that must then compromise between optimizing search and track functions. For example, a wide antenna beamwidth is desirable for the search mode and a narrow antenna beamwidth is desirable for the track mode, resulting in a medium antenna beamwidth compromise solution.

1.8.3 Imaging

In radar, *imaging* is a general term that refers to several methods for obtaining detailed information on discrete targets or broad-area scenes. The imaging process involves two steps: (1) developing a high-resolution range profile of the target; and (2) developing a high-resolution cross-range (angular) profile. As suggested in equation (1.19) the range resolution is proportional to the pulse width. A shorter transmitted pulse width will lead to better (smaller is better) range resolution. Improved range resolution can also be achieved

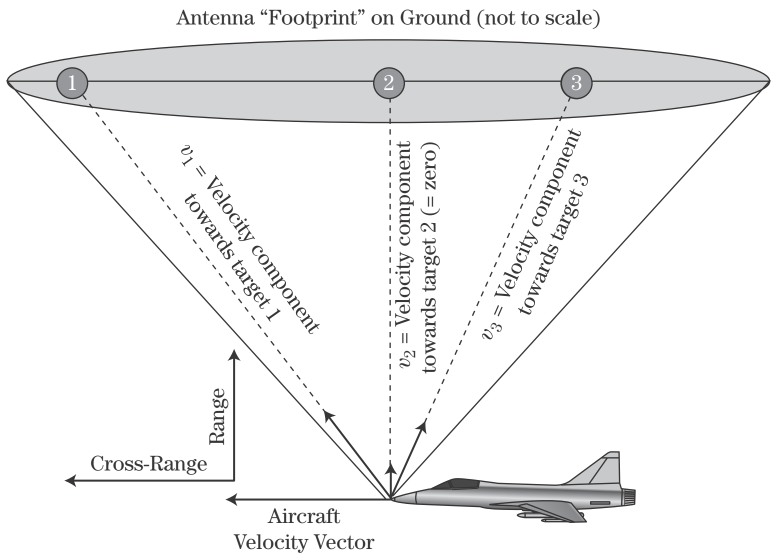


FIGURE 1-31 Synthetic aperture radar geometry.

by modulating the signal within the pulse as described in Section 1.7.4 and shown in Figure 1-27. As presented in Chapter 20, there are other techniques for developing good range resolution.

With the few basics given in Section 1.7.2, one can easily understand how Doppler shift can be used to improve the resolution in an SAR. Consider an aircraft with a radar on board pointing out of the side of the aircraft down to the ground (i.e., a *sidelooking* radar). If the radar's antenna has a 1 degree beamwidth and the ground is 1,000 meters from the radar, then the antenna beam will be approximately 21 meters wide in the cross-range dimension (the direction of aircraft motion, which is also perpendicular to the range dimension) on the ground. This means that two objects on the ground at the same range and closer than 21 meters in the cross-range dimension essentially appear as one object to the radar; that is, they are not resolved. Doppler shift can be used to resolve objects within the antenna's beam in cross-range. As shown in Figure 1-31, objects in the front, middle, and back of the beam will have a positive, zero, and negative Doppler shift, respectively. In fact, each object in the beam with a different cross-range spatial location will have a different Doppler shift. Therefore, if the radar's signal processor is capable of sorting (filtering) the EM wave returns according to Doppler shift, this is tantamount to sorting the objects in the cross-range dimension, thus resolving objects at different positions. Doppler processing is discussed further in Chapters 8 and 17 and synthetic aperture radar in Chapter 21.

Synthetic aperture radars form two-dimensional images of an area at resolutions ranging from 100 m or more to well under 1 m. The first case would typically be used in wide-area imaging from a satellite, while the latter would be used in finely detailed imaging from an airborne (aircraft or *unmanned autonomous vehicle* [UAV] platform). Figure 1-32 is an example of a 1 m resolution airborne SAR image of the Washington, D.C., mall area. Two-dimensional SAR imagery is used for a variety of Earth resources and defense applications, including surveillance, terrain following, mapping, and resource monitoring (discussed in more detail in Chapter 21). In recent years, *interferometric SAR* (IFSAR or InSAR) techniques have been developed for generating three-dimensional SAR imagery.

FIGURE 1-32 ■ 1 m resolution SAR image of the Washington, D.C., mall area. (Courtesy of Sandia National Laboratories. With permission.)

To accomplish their mission, many radars must not only detect but also identify the target before further action (e.g., defensive, offensive, traffic control) is initiated. One common way to attempt identification is for the radar to measure a one-dimensional high-range-resolution "image" (often called a *high-range resolution* [HRR] *profile*) or two-dimensional range/cross-range image of the target, a high-resolution Doppler spectrum, or to determine target polarization characteristics. The radar will employ specific waveforms and processing techniques, such as pulse compression SAR processing or polarization scattering matrix estimates, to measure these properties. *Automatic target recognition* (ATR) techniques are then used to analyze the resulting "imagery" and make identification decisions.

1.9 RADAR APPLICATIONS

Given that the fundamental radar functions are search/detect, track, and image, numerous remote sensing applications can be satisfied by the use of radar technology. The uses for radar are as diverse as ground-penetrating applications, for which the maximum range is a few meters, to long-range over-the-horizon search systems, for which targets are detected at thousands of kilometers range. Transmit peak power levels from a few milliwatts to several megawatts are seen. Antenna beamwidths from as narrow as less than a degree for precision tracking systems to as wide as nearly isotropic for intrusion detection systems are also seen. Some examples are now given. The grouping into "military" and "commercial" applications is somewhat arbitrary; in many cases the same basic functions are used in both arenas. The radar applications represented here are some of the most common, but there are many more.

1.9.1 Military Applications

In about 1945, the U.S. military developed a system of identifying designations for military equipment. The designations are of the form AN/xxx-nn. The x's are replaced with a sequence of three letters, the first of which indicates the installation, or platform (e.g., A for airborne), the second of which designates the type of equipment (e.g., P for radar), and the third of which designates the specific application (e.g., G for fire control). Table 1-3 lists a subset of this "AN nomenclature" that is pertinent to radar. The n's following the

TABLE 1-3 ■ Subset of the AN Nomenclature System for U.S. Military Equipment Applicable to Radar Systems

First Letter (Type of Installation)		Second Letter (Type of Equipment)		Third Letter (Purpose)	
A	Piloted aircraft	L	Countermeasures	D	Direction finger, reconnaissance, or surveillance
F	Fixed ground	P	Radar	G	Fire control or searchlight directing
M	Ground, mobile (installed as operating unit in a vehicle which has no function other than transporting the equipment	Y	Signal/data processing	K	Computing
P	Pack or portable (animal or man)			N	Navigational aids (including altimeter, beacons, compasses, racons, depth sounding, approach, and landing)
S	Water surface craft			Q	Special, or combination of purposes
T	Ground, transportable			R	Receiving, passive detecting
U	Ground utility			S	Detecting or range and bearing, search
V	Ground, vehicular (installed in vehicle designed for functions other than carrying electronic equipment, etc., such as tanks			Y	Surveillance (search, detect, and multiple target tracking) and control (both fire control and air control)

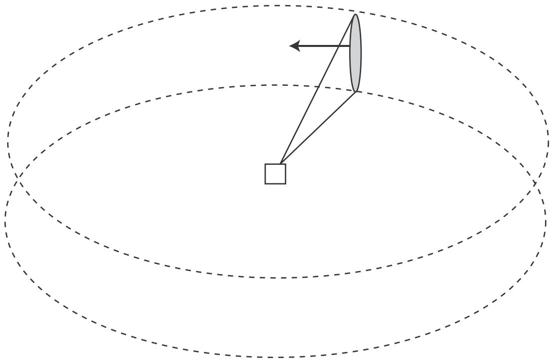
designation are a numerical sequence. For example, the AN/TPQ-36 is a ground-based transportable special purpose radar, in this case for locating the source of incoming mortars. Another example is the AN/SPY-1, a shipboard surveillance and fire control radar (FCR) system.

1.9.1.1 Search Radars

Often, the primary functions associated with the search and track requirements are performed by two independent radar systems. One system performs the search function, and another performs the track function. This is common, though not always the case, for ground-based or surface ship systems. Some applications prohibit the use of more than one radar or more than one aperture. For example, platforms that have limited prime power or space for electronics force the search and track requirements to be performed by one system. This is common in an airborne application and for many electronically scanned antenna systems.

Two-Dimensional Search Some volume search systems employ a “fan”-shaped antenna pattern to perform the search, usually in the range and azimuth dimensions. The antenna aperture will be quite wide horizontally and somewhat narrower vertically. This leads to a narrow azimuth beamwidth and a wide elevation beamwidth. The elevation extent of the search volume is covered by the wide elevation beamwidth, while the azimuth extent is covered by mechanically scanning the antenna in azimuth. Figure 1-33 depicts a fan beam pattern searching a volume. This configuration is common in air traffic control or airport surveillance systems. A system with this beam pattern can provide accurate range and azimuth position but provides poor elevation or height information due to the wide elevation beamwidth. Consequently, it is termed a two-dimensional (2-D) system, providing position information in only two dimensions.

FIGURE 1-33 ■ Fan beam searching a volume providing 2-D target position.



An example of a 2-D radar is the AN/SPS-49 shipboard radar, shown in Figure 1-34. The SPS-49 is a very long-range, two-dimensional air search radar that operates in the UHF band (850–942 MHz). Nominal maximum range of the radar is approximately 250 nmi. The AN/SPS-49 provides automatic detection and reporting of targets supporting the antiair warfare (AAW) mission in Navy surface ships. The AN/SPS-49 uses a large truncated parabolic mechanically stabilized antenna to provide acquisition of air targets in all sea states. Originally produced in 1975 by the Raytheon Company, the SPS-49 is a key part of the combat system on many surface combatants of several navies of the world. It has been extensively modified to provide better detection capabilities of both sea-skimming and high-diving antiship missiles.

The SPS-49 performs accurate centroiding of target range, azimuth, amplitude, ECM level background, and radial velocity with an associated confidence factor to produce accurate target data for the shipboard command and control system. Additionally, processed and raw target data are provided for display consoles.

The AN/SPS-49 has several operational features to optimize radar performance, including an automatic target detection capability with pulse-Doppler processing and clutter maps. This helps ensure reliable detection in both normal and severe clutter. A key feature of the most recent version of the radar, the SPS-49A (V)1, is single-scan radial velocity

FIGURE 1-34 ■ AN/SPS-49 2-D search radar antenna. (Courtesy of U.S. Navy.)

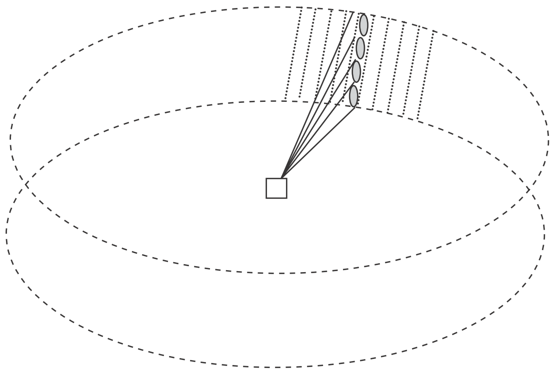


FIGURE 1-35 ■ Pencil beam searching a volume providing 3-D target position.

estimation of all targets, allowing faster promotion to firm track and improved maneuver detection.

The SPS-49 beamwidths are 3.3° in azimuth and 11° in elevation. The narrow azimuth beamwidth provides good resistance to jamming. The antenna rotates at either 6 or 12 rpm. The radar operates in a long-range or short-range mode. In the long-range mode, the radar antenna rotates at 6 rpm. The radar can detect small fighter aircraft at ranges in excess of 225 nautical miles. In the short-range mode, the antenna rotates at 12 rpm to maximize the probability of detection of hostile low-flying aircraft and missiles and "pop-up" targets. The MTI capability incorporated in the AN/SPS-49(V) radar enhances target detection of low-flying, high-speed targets through the cancellation of ground/sea return (clutter), weather, and similar stationary targets.

Three-Dimensional Search Figure 1-35 depicts a pencil beam antenna that provides accurate range, azimuth, and elevation information. A system using this approach is termed a three-dimensional (3-D) search radar.

An example of 3-D search radar used by the U.S. Navy on surface ships, including large amphibious ships and aircraft carriers, is the AN/SPS-48 produced by ITT Gilfillan and shown in Figure 1-36. The antenna is the square planar array consisting of slotted

FIGURE 1-36 ■ AN/SPS-48 3-D search radar antenna. (Courtesy of U.S. Navy.)

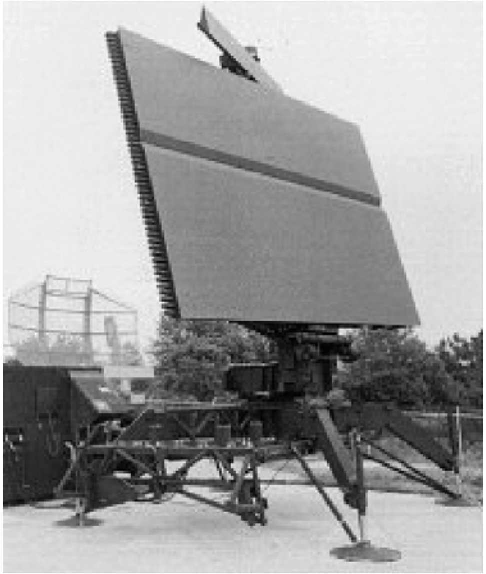


FIGURE 1-37 ■ AN/TPS-75 air defense radar. (Courtesy of U.S. Air Force.)

waveguide. The antenna is fed at the lower left into the serpentine structure attached to the planar array. This serpentine provides frequency sensitivity for scanning in elevation.

The SPS-48 scans in the azimuth plane at 15 rpm by mechanical scanning and in the elevation plane by electronic (frequency) scanning. The large rectangular antenna on top of the main antenna is for the Identification, Friend, or Foe (IFF) system.

The SPS-48 operates in the S-band (2–4 GHz) at an average rated power of 35 kW. The radar scans in elevation (by frequency shifting,) up to 65° from the horizontal. It can detect and automatically track targets from the radar horizon to 100,000 ft. Maximum instrumented range of the SPS-48 is 220 nmi.

The SPS-48 is typically controlled by the shipboard combat system. It provides track data including range, azimuth, elevation, and speed to the combat system and to the display system for action by the ships automated defense system and by the operators.

1.9.1.2 Air Defense Systems

The AN/TPS-75 air defense system used by the U.S. Air Force is shown in Figure 1-37. It has functionality similar to a multifunction 3-D search radar. It scans mechanically in the azimuth direction and electronically in the elevation dimension by means of frequency scanning. The long, narrow antenna shown at the top of the square array is an antenna that interrogates the detected targets for an IFF response. The IFF antenna angle is set back somewhat in azimuth angle so that the IFF interrogation can occur shortly after target detection as the antenna rotates in azimuth.

The AN/MPQ-64 Sentinel shown in Figure 1-38 is an air defense radar used by the U.S. Army and U.S. Marine Corps with similar functionality. This is an X-band coherent (pulse-Doppler) system, using phase scanning in one plane and frequency scanning in the other plane. The system detects, tracks, and identifies airborne threats.

1.9.1.3 Over-the-Horizon Search Radars

During the cold war, the United States wanted to detect ballistic missile activity at very long ranges. Whereas many radar applications are limited to "line-of-sight" performance, ranges

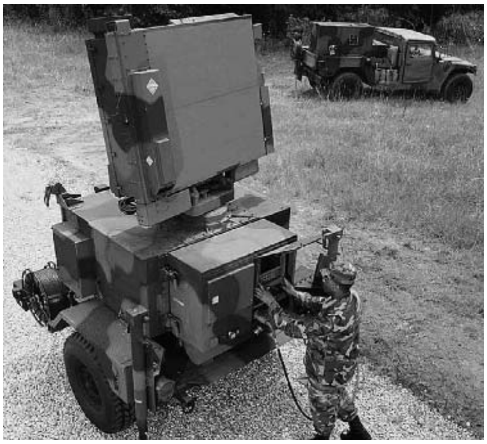


FIGURE 1-38 ■ Photo of an AN/MPQ-64 Sentinel air defense radar. (Courtesy of U.S. Army.)

of several thousand miles were desired. OTH radars were developed for this application. These radars take advantage of the refractive effect in the ionosphere to detect targets at extremely long ranges, sometimes thousands of miles, around the earth. The ionospheric refraction has the effect of reflecting the EM signal. The frequency dependence of this effect is such that it is most effective in the HF band (3–30 MHz). Given the desire for a reasonably narrow beamwidth, the antenna must be very large at such low frequencies, typically thousands of feet long. Consequently, OTH antennas are often made up from separate transmit and receive arrays of elements located on the ground. Figure 1-39 shows an example of such a transmit array. Figure 1-40 depicts the operation of an over-the-horizon system, showing the ray paths for two targets.

1.9.1.4 Ballistic Missile Defense (BMD) Radars

Radar systems can detect the presence of incoming intercontinental ballistic missiles (ICBMs) thousands of kilometers away. These systems must search a large angular volume (approaching a hemisphere) and detect and track very low-RCS, fast-moving targets. Once detected, the incoming missile must be monitored to discriminate it from any debris and

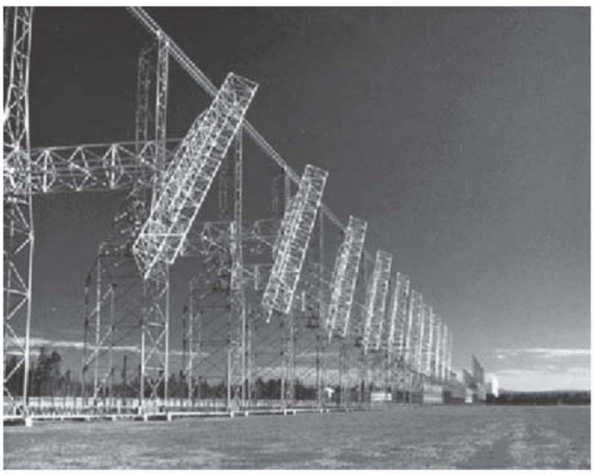


FIGURE 1-39 ■ Over-the-horizon radar system—Transmit array. (Courtesy of U.S. Air Force.)

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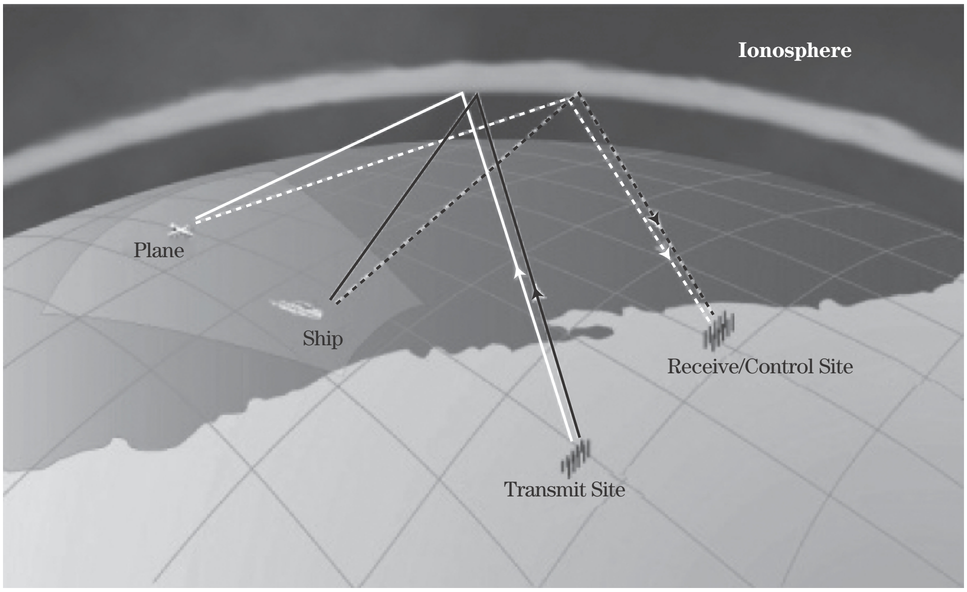

FIGURE 1-40 Over-the-horizon radar concept. (Courtesy of U.S. Air Force.)

decoys from the warhead. This is accomplished with high-range resolution and Doppler processing techniques that are well suited to radar. Examples of BMD radar systems are the sea-based Cobra Judy system and X-Band (SBX) radar and the land-based Pave Paws and Terminal High Altitude Air Defense (THAAD) AN/TPY-2 systems. Figure 1-41 shows the Pave Paws (AN/FPS-115) system, featuring its two extremely large pencil beam phased array antennas.

A newer system is the THAAD radar shown in Figure 1-42. It is an X-band coherent active phased array system, with over 25,000 active array elements. As opposed to fixed-location systems such as the AN/FPS-115, it is transportable so that it can be redeployed as needed.

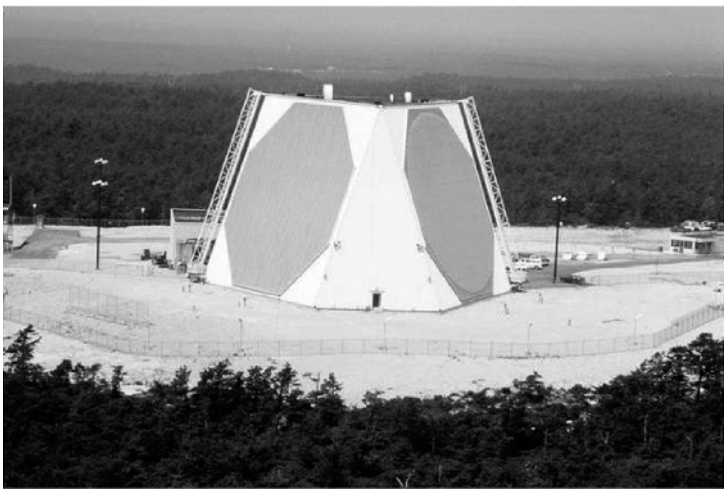

FIGURE 1-41 Pave Paws (AN/FPS-115) ballistic missile defense radar. (Courtesy of Missile Defense Agency.)