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

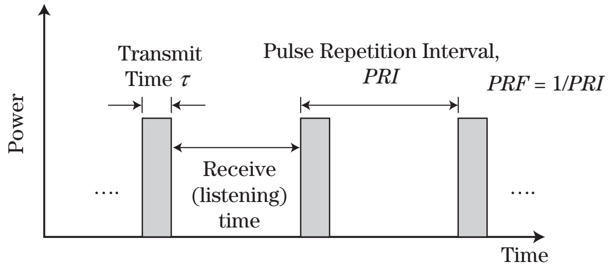

FIGURE 1-20 Pulsed radar waveform.

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,

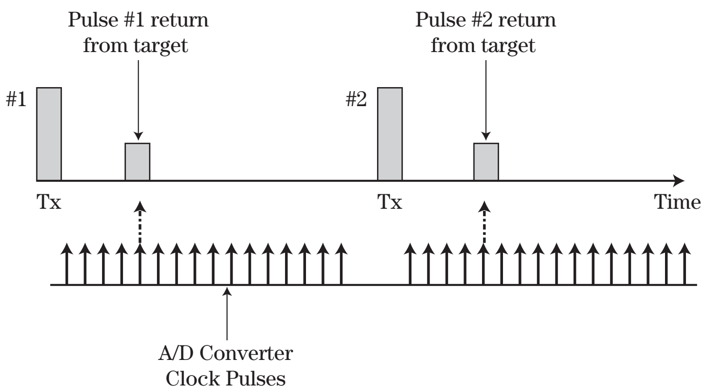

FIGURE 1-21 Pulsed radar waveform showing ADC clock pulses.

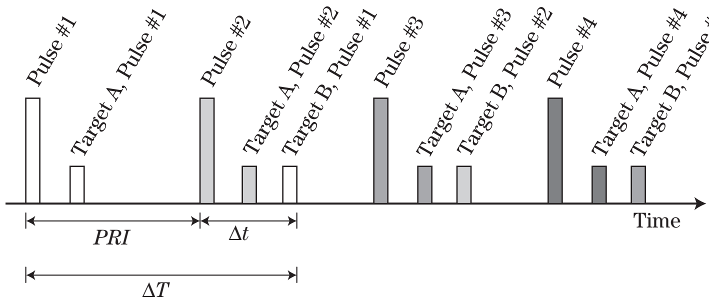

FIGURE 1-22 ■ Pulsed radar range ambiguity.

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

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

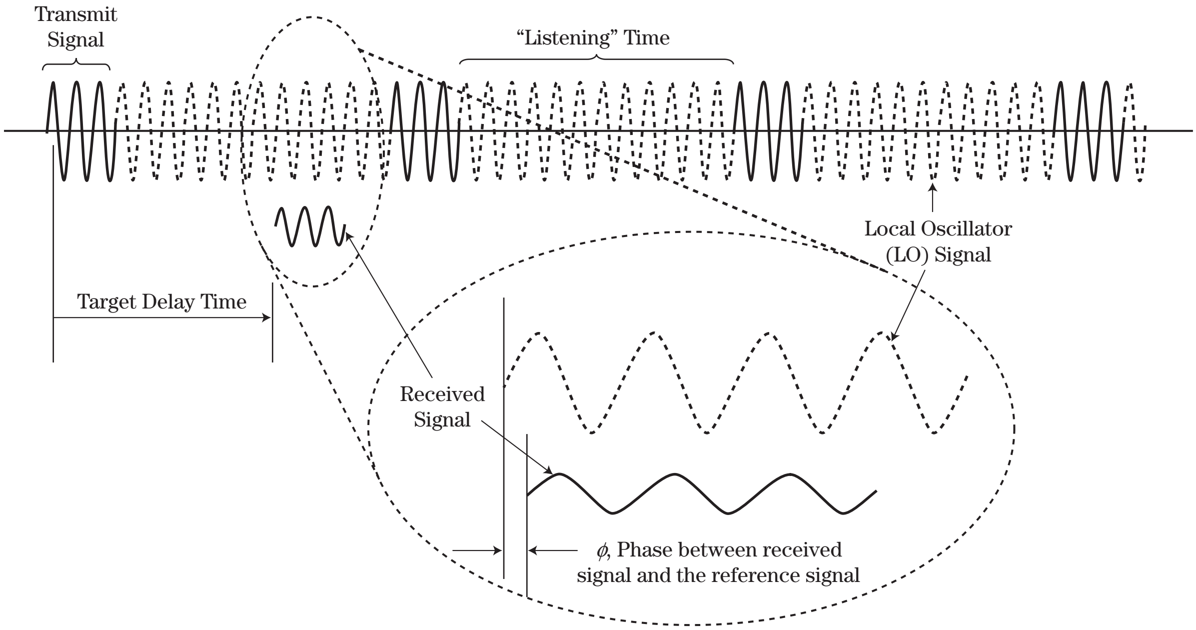

FIGURE 1-23 ■ Coherent system local oscillator, transmit, and received signals.

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

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

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

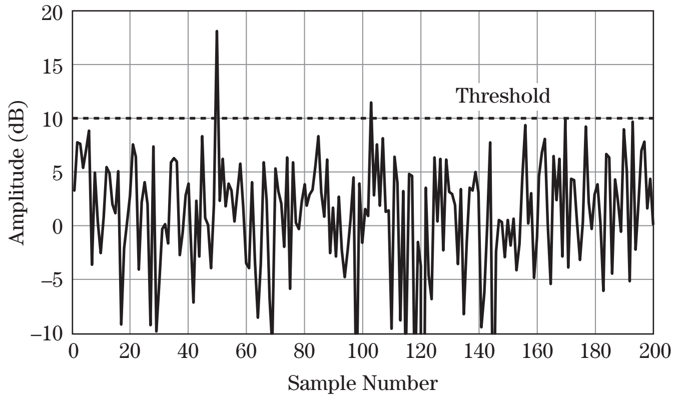

FIGURE 1-24 ■ Threshold detection of a noisy signal.

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,

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

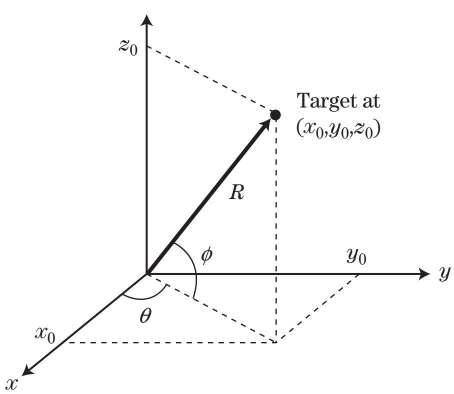

FIGURE 1-25 Spherical coordinate system depicting radar-target geometry.

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 $\sigma_{11}, \sigma_{12}, \sigma_{22}, \angle_{12}$, and $\angle_{22}$.

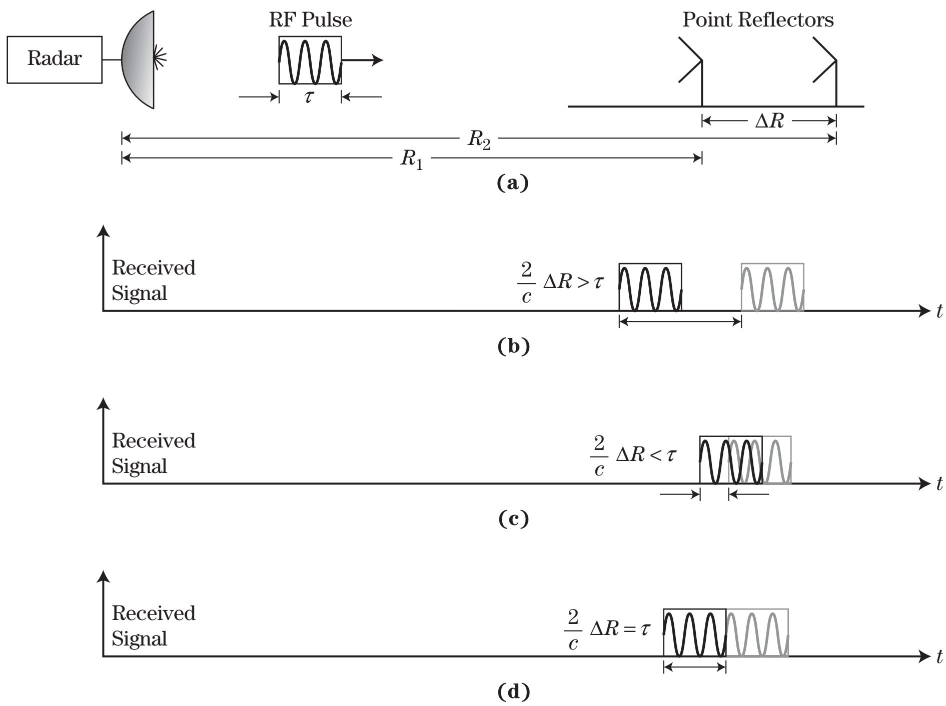

FIGURE 1-26 ■ Concept of resolution in range. (a) Transmitted pulse and two targets. (b) Receiver output for resolved targets. (c) Receiver output for unresolved targets. (d) Receiver output for defining range resolution.

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

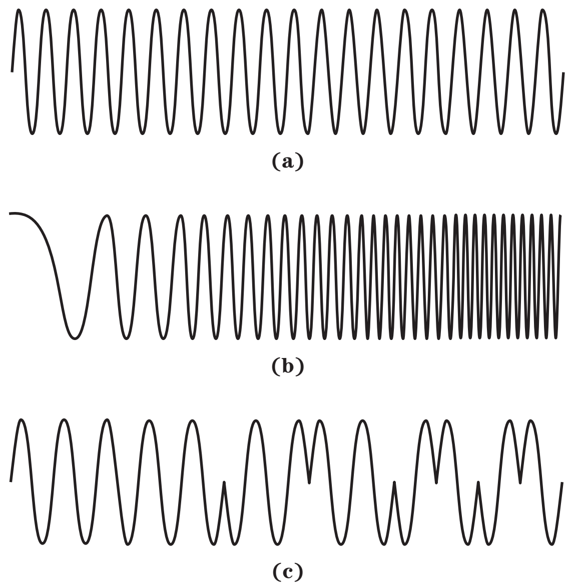

FIGURE 1-27 Three common choices for a single pulse in a pulsed radar waveform. (a) Simple pulse. (b) Linear FM or chirp pulse. (c) Biphase coded pulse.

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.

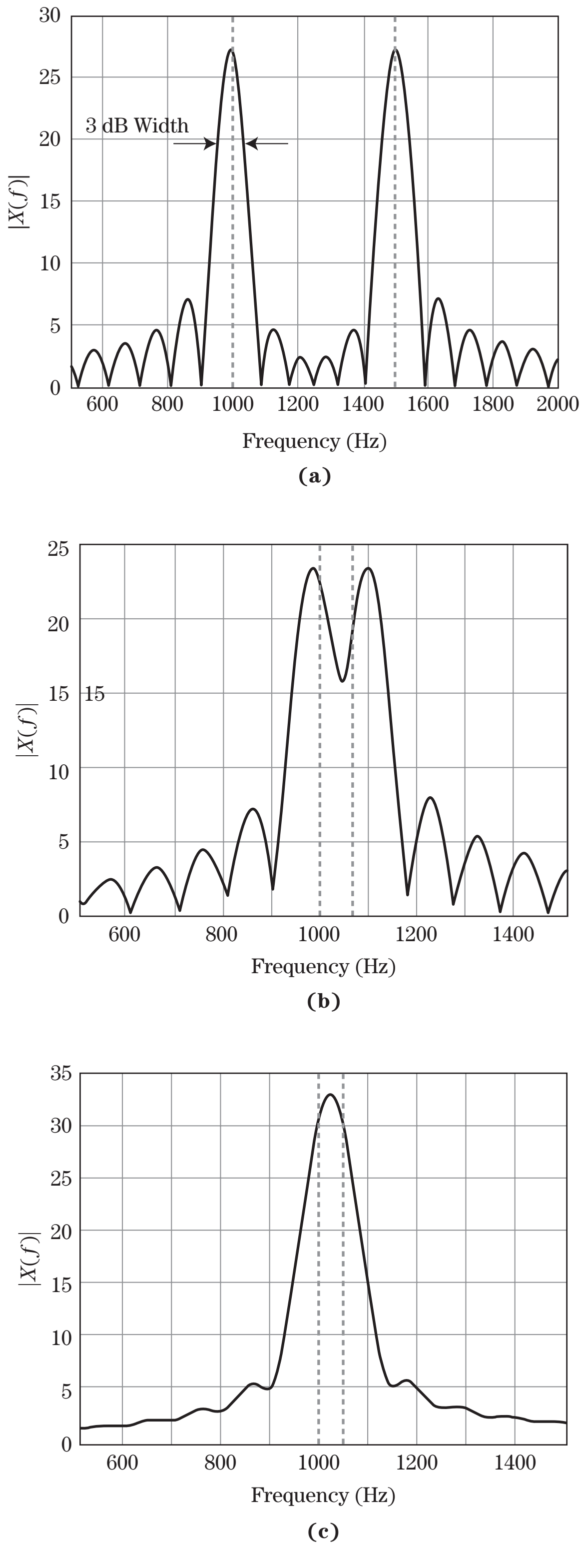

FIGURE 1-28 ■ Example of frequency resolution. (a) Spectrum of two sinusoids separated by 500 Hz. The 3 dB width of the response is 89 Hz. (b) Spectrum for separation of 75 Hz. (c) Spectrum for separation of 50 Hz. The two dashed lines show the actual sinusoid frequencies in each case.

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*.

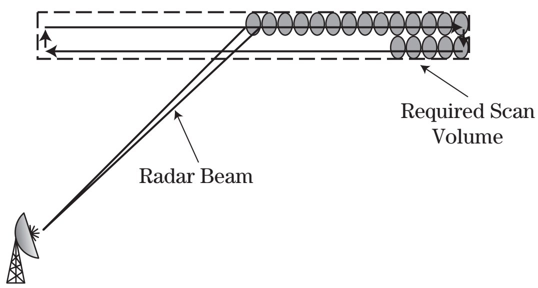

FIGURE 1-29 ■ Coverage of a search volume using a series of discrete beam positions.

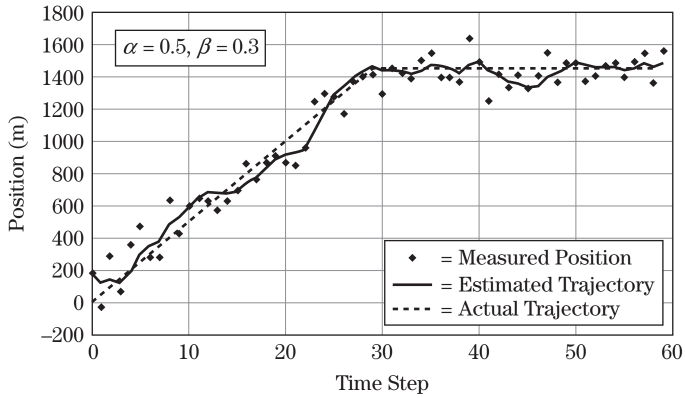

FIGURE 1-30 ■ Example of track filtering for smoothing a series of individual position measurements.

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

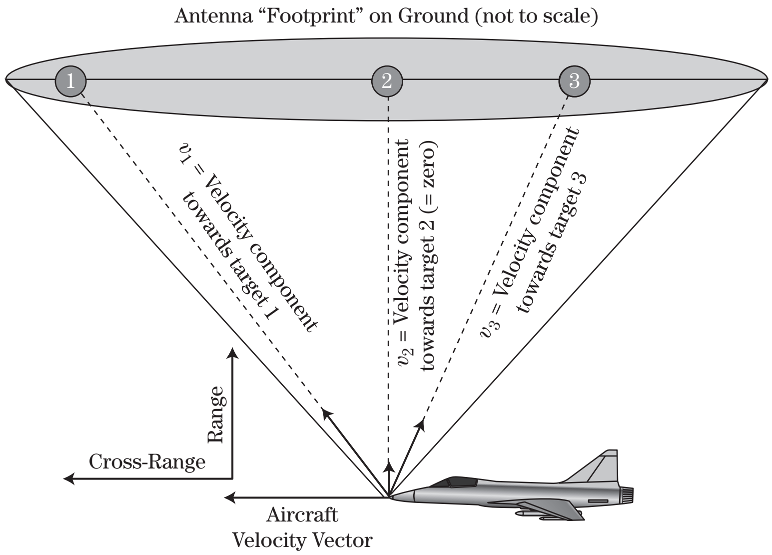

FIGURE 1-31 ■ Synthetic aperture radar geometry.

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.