Radar Principles for the Non-Specialist

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Elementary Electromagnetics and the Radar Range Equation

HIGHLIGHTS

- Some fundamentals of radio waves from Faraday, Maxwell, and Hertz
- Putting together a simple radar and discussing its principal parts
- Deriving the radar range equation from first principles
- Discovering special features of surveillance and tracking radars

Radar is an acronym for *RAdio Detection And Ranging*. Before we develop the principles of radar, we will review the characteristics of radio waves.

1.1 RADIO WAVES

Radio waves occupy a portion of the electromagnetic spectrum from frequencies of a few kilohertz (that is, a few thousand cycles per second) to a few million megahertz ($>10^{12}$ cycles per second). The total electromagnetic spectrum embraces all the frequencies to cosmic rays, beyond 10^{16} megahertz (MHz). Radio waves represent less than one-billionth of the total spectrum (see Appendix 2).

Although electromagnetic energy can be described either as waves or as quanta, the lower frequencies are much better suited to explanations by wave theory. Radio waves are certainly thought of in those terms.

The definitive experiments in electromagnetism were performed by Michael Faraday in a period of ten days in 1831 [*Encyclopedia Britannica,* 1984, Vol. 7,

p. 174; Williams, 1971, pp. 535–537]. Using Faraday's work as his foundation, James Clerk Maxwell succeeded, by the early 1860s, in synthesizing the properties of electricity and magnetism into a set of equations that achieved a unified theory for electromagnetics [*Encyclopedia Britannica,* 1984, Vol. 11, p. 718; Everitt, 1974, pp. 204–217].

In Maxwell's time, it was only dimly appreciated that light is electromagnetic energy and that all electromagnetic energy propagates with the same velocity in free space. Yet, Maxwell's equations, solved for the speed of light, give the correct result. Maxwell's equations are the foundation for the theory and design of modern radio and radar systems. Faraday and Maxwell noted that time-varying electric currents produced time-varying electric and magnetic fields in free space, that these fields would induce time-varying electric currents in materials they encountered, and that these currents would, in turn, generate electric and magnetic fields of their own. These fields "propagate" in free space at the speed of light.

In 1886, Heinrich Hertz conducted a number of experiments showing that radio waves reflected, refracted, were polarized, interfered with each other, and traveled at high velocity. Hertz is credited with verifying Maxwell's theories [*Encyclopedia Britannica,* 1984, Vol. 6, pp. 647–648; McCormach, 1972, pp. 341–350]. These characteristics—of reradiation and of known velocity—already portended the invention of radar.

The first use of radio waves was for communication, and the means of generating radio waves was with spark gaps generating short, intense pulses of current to achieve the needed electromagnetic radiation. The generation of sinusoidal waves (arising first from the use of alternators and later from oscillators designed using the vacuum tubes invented by Lee DeForest in 1906) revolutionized communications [Susskind, 1971, pp. 6–7]. When radar was invented, the use of sinusoidal oscillators was adopted from communications, but the transmitters sent periodic bursts of these sinusoidal waves, carefully counting time between them. More complex modulation schemes for radar came later.

The increasing use of radio in the early 1900s led to observations that objects passing between the transmitters and receivers produced interference patterns (exactly as aircraft today affect television reception). Bistatic (noncollocated transmitter and receiver) CW "radars" that could detect targets in this manner were explored by many countries at the beginning of the 1930s. Monostatic (collocated transmitter and receiver) radars were developed shortly after. The first successful pulsed radar experiments were conducted by the U.S. Naval Research Laboratory (NRL) in 1934. By 1937, NRL had demonstrated a radar at sea, but deployment was delayed until 1940. In the meantime, Great Britain, which earlier had trailed in radar development, succeeded in deploying the first operational system (the Chain Home radars) by 1938. Concurrently, France, Germany, and the Soviet Union also had substantial radar programs underway [Skolnik, 2001, pp. 14–19].

1.2 A Simple Radar

The principles of a primitive radar are now clear, transmission, propagation, and reflection. A functional diagram of a radar system is shown in Figure 1.1. A pulse of electromagnetic energy, oscillating at a predetermined frequency, f_c, and duration, τ, is generated by the transmitter. The pulse is routed through a transmit-receive switch to an antenna. The transmit-receive switch, or *duplexer*, protects the sensitive receiver from the high-power transmitted pulse. The pulse is radiated into free space through an antenna. The electromagnetic pulse propagates outward at the speed of light, scattering (reradiating) from objects it

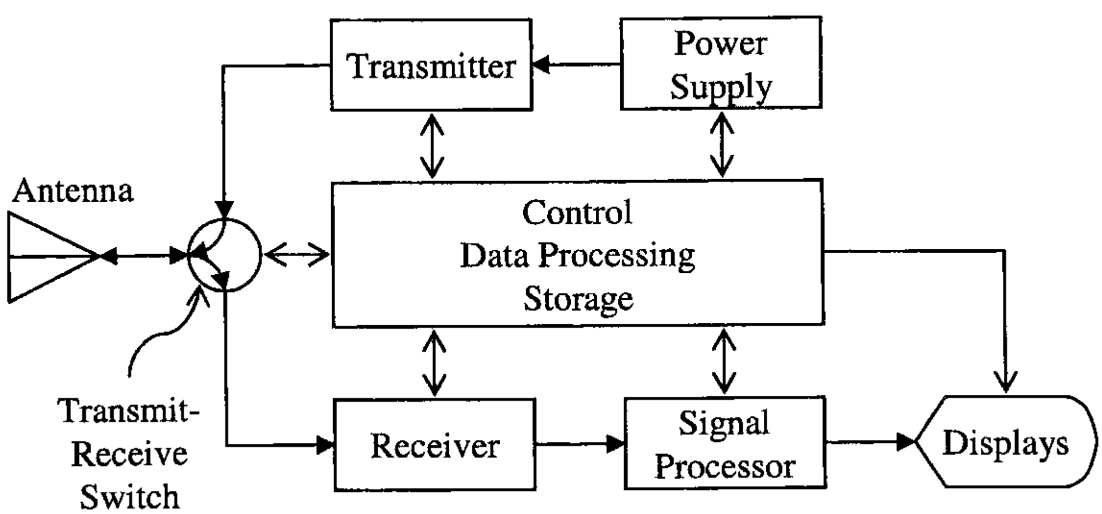

Figure 1.1 Radar block diagram.

encounters along the way. Part of the scattered signal returns to the radar. The scattered signal is collected by the antenna and routed through the transmit-receive switch to the receiver. The presence of the received signal can be detected in the receiver, because it imitates the frequency and the duration of the transmitted pulse. The received signal is enhanced, interfering signals are reduced, and measurements of the object are made by signal processing. The resulting detections of received signals are presented to radar operators on displays.

Detecting the presence of an object is good, but the real value of radar is being able to measure the range between the radar and the object. When a pulse is transmitted, a clock is started. When a received signal is detected, the clock is stopped. Using basic physics—distance equals speed × time—the range to a detected object can be calculated as in Equation (1.1). The distance traveled by the pulse is twice the range—once to the object and once back to the radar.

$$2R = c\,\Delta t \Rightarrow R = \frac{c\,\Delta t}{2} \tag{1.1}$$

where:

R = range from the radar to the object, meters
c = speed of light, 3×10^8 meters/second
Δt = elapsed time, seconds

The transmitted pulsed radar waveform is shown in Figure 1.2. Some other parameters of this basic system for radio detection and ranging are immediately available. The wavelength of the propagated energy is given in Equation (1.2). The angular frequency, ω (radians/sec), is $2\pi f_c$. The time between radar pulses is the interpulse period, or the pulse repetition interval (PRI), and the number of pulses sent per time interval is the pulse repetition frequency (PRF). PRI and PRF are reciprocal, i.e., PRF = 1/PRI. The ratio of the time the pulse is on to the PRI is called the duty cycle [Equation (1.3)]. The average power over one pulse repetition interval is the product of the peak power and duty cycle [Equation (1.4)]. The energy in one pulse is the product of its peak power and duration [Equation (1.5)]. All the previously mentioned transmitted waveform parameters are important in radar design and performance. Most will be discussed in various applications. The impact of these waveform parameters on radar measurements will be discussed in Chapter 5.

$$\lambda = \frac{c}{f_c} \tag{1.2}$$

where:

λ = wavelength, meters
c = speed of light, 3×10^8 meters/second
f_c = radar carrier frequency, hertz

$$d_t = \frac{\tau}{PRI} = \tau\, PRF \tag{1.3}$$

where:

d_t = duty cycle, no units
τ = pulse duration, or pulse width, or pulse length, seconds
PRI = pulse repetition interval, seconds
PRF = pulse repetition frequency, hertz

$$P_{ave} = P\, d_t = P\frac{\tau}{PRI} = P\,\tau\, PRF \tag{1.4}$$

where:

P_{ave} = average transmit power, watts
P = peak transmit power, watts

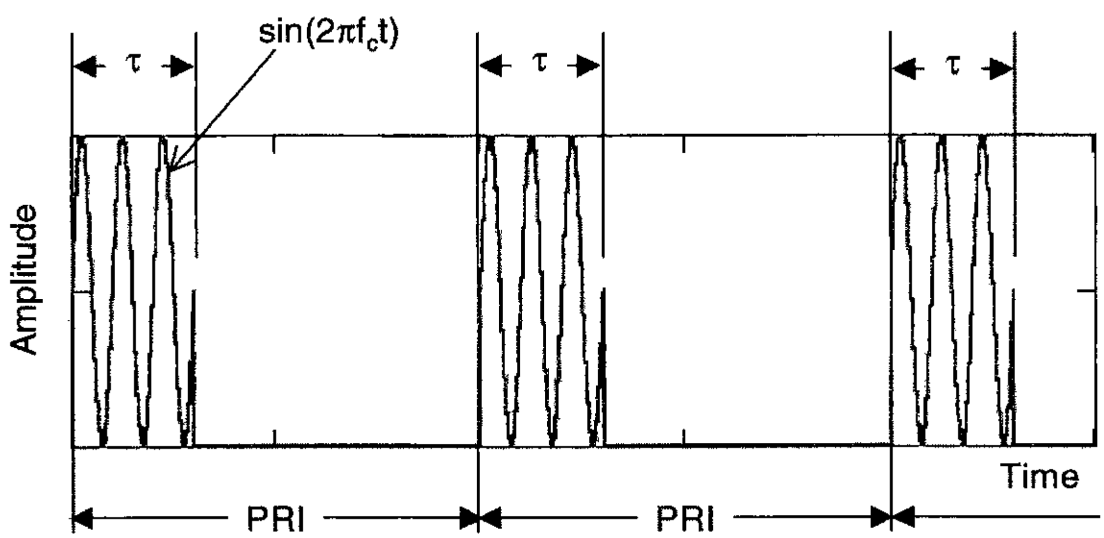

Figure 1.2 Transmitted radar waveform.

$$E = P\tau \tag{1.5}$$

where:

E = energy in one pulse, watt-seconds or joules

Polarized radar waves are equivalent to polarized light waves [Sears, 1948, pp. 167–185], and the singly polarized radar wave is analogous to polarized optical glasses. Polarization is the orientation of the electromagnetic wave relative to the direction of its propagation. An electromagnetic wave consists of two perpendicular components, the electric field (E-field) and the magnetic field (H-field), as shown in Figure 1.3. Polarization is defined by the alignment of the E-field. Linear polarization describes a linear alignment of the E-field, usually ei-

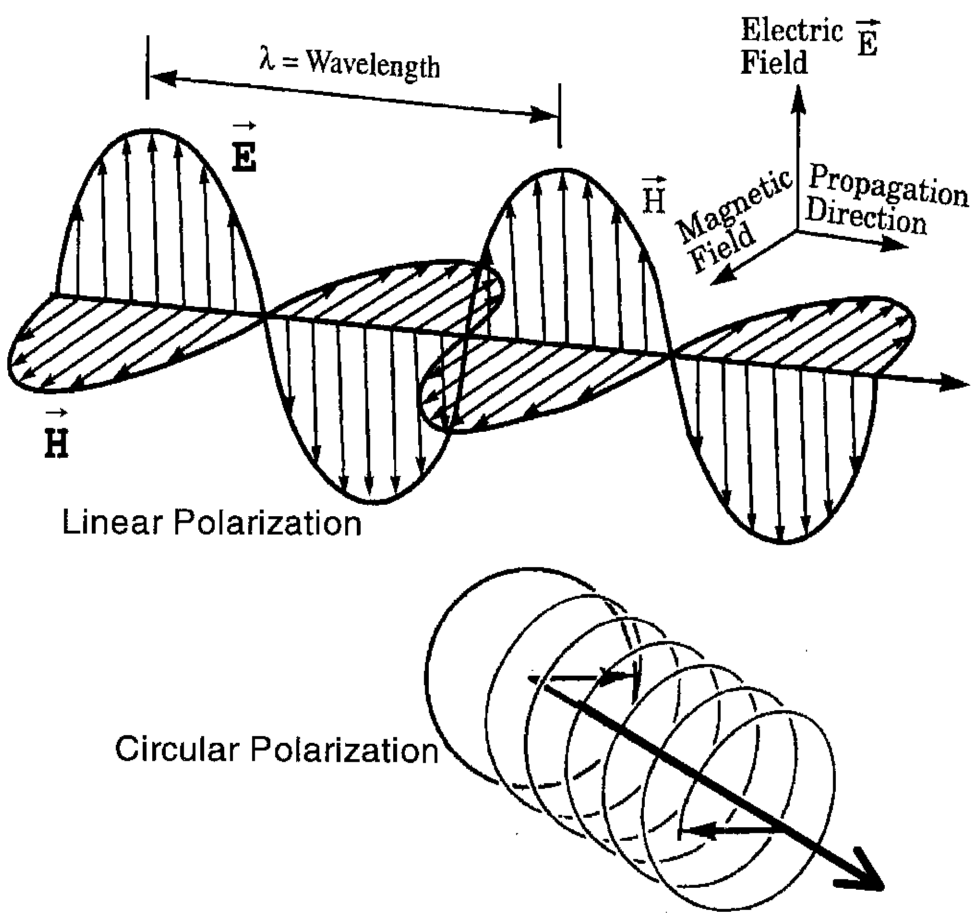

Figure 1.3 Polarization of an electromagnetic wave.

ther horizontal or vertical (as shown in Figure 1.3). Circular polarization describes a rotating vector (one full revolution each radio frequency cycle), either left hand or right hand.

1.3 The Radar Range Equation

The fundamental determinant of radar performance, in any of the missions prescribed for it, is the radar range equation. It can be derived from fundamental principles, as shown in Figure 1.4. Imagine an isotropic source of an electromagnetic pulse of peak power, P, radiating into free space. Provide the source with some focusing device, an antenna that concentrates the power from isotropic to a confined solid angle. Call the ratio of this focusing over isotropic radiation the gain of the transmit antenna, G_T. Antennas will be discussed in detail in Chapter 2. We often represent antenna gain in decibels. Decibels are discussed in detail in Appendix 1. The power density received at range R from the radar is given in Equation (1.6).

$$\frac{P\,\mathrm{G}_T}{4\pi R^2} \tag{1.6}$$

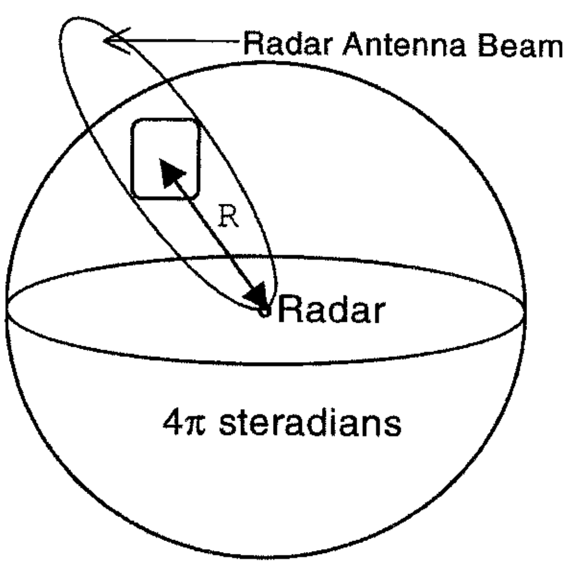

Figure 1.4 Radar spherical geometry.

where:

P = peak transmit power, watts
G_T = transmit antenna gain, no units
R = radar to object range, meters

The power density is intercepted by a target. A portion is reradiated back to the radar, based on the radar cross section, σ, of the target. Radar cross section (RCS) will be discussed in detail in Chapter 4. The power reradiated from the target back to the radar is given in Equation (1.7).

$$\frac{P G_T \sigma}{4\pi R^2} \tag{1.7}$$

where:

σ = target radar cross section, square meters (m^2)

The power density arriving back at the radar from the target is given in Equation (1.8), assuming the transmit and receive antenna are collocated (monostatic). This power density is collected by the effective area of the receive antenna. The received power, now defined as the received signal, *S*, is given in Equation (1.9). We often represent the received signal in decibels relative to one watt (dBW) or relative to one milliwatt (dBm) (see Appendix 1).

$$\frac{P G_T \sigma}{(4\pi)^2 R^4} \tag{1.8}$$

$$S = \frac{P G_T \sigma A_e}{(4\pi)^2 R^4} \tag{1.9}$$

where:

S = received signal power, watts
A_e = effective area of the receive antenna, meters $A_e = \rho A$
ρ = antenna efficiency, $0 < \rho < 1$, no units
A = physical area of the antenna, meters

The gain of an antenna is directly related to its effective area. In Chapter 2, we will derive the relationship given in Equation (1.10).

$$G = \frac{4\pi A_e}{\lambda^2} \Rightarrow A_e = \frac{G\lambda^2}{4\pi} \tag{1.10}$$

where:

G = radar antenna gain, no units

If the radar's transmit and receive antenna are the same, the resulting single-pulse received signal power is given in Equation (1.11).

$$S = \frac{P G^2 \lambda^2 \sigma}{(4\pi)^3 R^4} \tag{1.11}$$

1.3.1 Receiver Noise

Unfortunately, there is always noise power contaminating the signal power that arrives at the receiver. Some of the noise is generated in the transmitter, some of it is added by the cosmos (galactic noise), some of it is contributed by the Earth's atmosphere (spherics), some is added by the Earth itself, and some from manufactured sources (automobiles, power facilities, or other radars). However, for most radar systems, the vast majority of the noise is generated in the front end of the radar receiver, particularly by the first amplifier and mixer stages. The source of the noise generated in the front end of the radar receiver is the thermal heating of its electronic components. Basic chemistry tells us that when atoms are heated, their electrons flow. Flowing electrons produce current flow, resulting in noise. This is better known as thermal noise, as given in Equation (1.12). We often represent the receiver thermal noise in decibels relative to one watt (dBW) or relative to one milliwatt (dBm). This total system noise can be measured at the receiver output in the absence of signal. The noise figure relates theory to what we can practically achieve. We often represent the noise figure in decibels.

$$N = (F_n - 1)kT_0B \tag{1.12}$$

where:

N = receiver thermal noise, watts

F_n = receiver noise figure, no units

k = Boltzmann's constant, 1.38×10^{-23} watt-seconds/kelvins
T_0 = receiver temperature (usually room temperature, 290 K), kelvins
B = receiver filter bandwidth, hertz

The effective noise temperature is another common way of relating receiver thermal noise theory to what can be practically achieved [Equation (1.13)]. The effective noise temperature is essentially the temperature the receiver would have to reach to produce the resultant noise power.

$$T_e = (F_n - 1)T_0 \tag{1.13}$$

where:
T_e = effective noise temperature, kelvins

1.3.2 Signal-to-Noise Ratio

The radar range equation is the ratio of the received target signal power to the receiver noise. If the various losses that exist in the system are lumped together in a single term, the radar range equation is given in Equation (1.14). We often represent the signal-to-noise ratio *(S/N)* in decibels. The same goes for the radar system losses.

$$S/N = \frac{P G^2 \lambda^2 \sigma}{(4\pi)^3 R^4 (F_n - 1)\, k\, T_0\, B\, L_s} \tag{1.14}$$

where:
S/N = single pulse signal-to-noise ratio, no units
L_s = radar system losses, no units

The radar range equation is dominated by the R^4 factor in the denominator. There is no magic way to achieve a high-performance system. If low RCS targets are to be engaged, a combination of high power, high antenna gain, and low noise seems to be dictated. Fortunately, if needed, and it most often is, we can "integrate" multiple return pulses to improve the S/N. Considerable S/N benefits can result from integration of multiple pulses [Brookner, 1977, pp. 81–99]. We will discuss integration in more detail in Chapter 3.

1.3.3 Detection Range

The single pulse radar range equation can be solved for the range at which the radar will detect the presence of a target with a given S/N. The radar detection range is given in Equation (1.15). In Chapter 3, we will discuss how to determine the S/N required for detection.

$$R_d = \sqrt[4]{\frac{P\,G^2\,\lambda^2\,\sigma}{(4\pi)^3\,SNR_d\,(F_n-1)\,k\,T_0\,B\,L_s}} \tag{1.15}$$

where:

R_d = radar detection range, meters

SNR_d = single pulse signal-to-noise ratio required for detection, no units

1.3.4 Other Forms of the Radar Range Equation

There are, however, several ways of manipulating the equation to illustrate various uses. Checking the units of the range equation shows it to be dimensionless. It is pulse power divided by noise power. To emphasize the importance of energy and of matched filters that yield the maximum theoretical signal-to-noise ratio, S/N is often replaced by E/N_0, the maximum ratio of root-mean-square (RMS) signal energy to RMS noise energy [Equation (1.16)]. We will discuss matched filters in more detail in Chapter 3; for now, we will just state that the matched filter bandwidth is the reciprocal of the pulse width. Furthermore, because it facilitates calculations, $2E/N_0$ is also used. The RMS voltage of a sinusoid is equal to the peak voltage divided by the square root of 2, making $2E/N_0$ the peak signal energy divided by the RMS noise energy.

$$\frac{E}{N_0} = \frac{P\,\tau\,G^2\,\lambda^2\,\sigma}{(4\pi)^3\,R^4\,(F_n-1)\,k\,T_0\,L_s} \tag{1.16}$$

where:

E/N_0 = single pulse energy signal-to-noise ratio, no units

E = RMS signal energy in one pulse, watts/hertz or watt-seconds or joules

N_0 = RMS noise energy, watts/hertz or watt-seconds or joules

Obviously, the range equation can be solved for any of its parameters. Often, it is solved for R, necessitating taking the fourth root of the whole right side of the equation. While this practice is rigorous, it destroys the perspective provided by having those variables in the numerator that multiply signal and those in the denominator that divide it. Boltzmann's constant, $(4\pi)^3$, and conversion factors of meters into kilometers are often accumulated as a single number, easing calculations but removing insights. Examples of this loss of insight are the average power, energy, and surveillance versions of the radar range equation. Each one contains one or more assumptions that are too easily overlooked.

1.4 Surveillance

Surveillance radars are designed to scan a solid angle in some time span, and the scan program places the necessary number of pulses into each angle bin. Surveillance radars are often required to detect large numbers of targets (aircraft, ships, missiles, and so on) flying around them. Detection must occur before these targets reach a specified minimum range. The surveillance radar designer will select the frequency of the radar at which the combination of the physical size of the radar aperture and the generation of radar power are least expensive. Because both characteristics favor the use of lower microwave frequencies, the vast majority of surveillance radars are at those frequencies. A survey of such radars around the world, including both U.S. and Russian missile and aircraft warning and surveillance systems, confirms the truism. Virtually all these radars are in the frequency band between 200 and 1500 MHz (VHF to L-band).

Big apertures and high-powered transmitters are characteristic of surveillance radars. Average power of a few hundred kilowatts (kW) (with from 10 to 50 megawatts [MW] of peak power, depending on duty cycle) is possible for these radars. For reflector antenna radars, such power can be generated by several oil-cooled klystrons operated in parallel. For phased array radars, transistor amplifiers may be used behind each element (100 W each behind several thousand elements) or large tubes (traveling wave tubes or klystrons) behind groups of elements.

Apertures may range in diameter from 1 to over 120 m for both reflector antennas and arrays, giving gains of about 40 dB and beamwidths on the order of 1 square degree.

1.5 TRACKING

Tracking radars have different characteristics from those of surveillance radars. We discuss tracking in Chapter 3. Here, we will limit comments to saying that the driving parameter in good tracking is short wavelength. Not surprisingly, tracking radars (including the ground-controlled approach radars at airports and missile trackers of the military) are at the high microwave frequencies (from 3 to 20 GHz). For the designer of a radar requiring a combination mission of both surveillance and tracking, the relative desirability of high frequency for trackers and big apertures for surveyors poses a dilemma. The usual procedure is to write down a cost function and settle the matter of frequency by optimizing costs with respect to wavelength. Specific examples of how many existing radars obey the dictates of the previously listed functions are these: The Lincoln Laboratory ALCOR tracking radar at Kwajalein Atoll in the South Pacific is at C-band ($\lambda \cong 0.08$ m); the Ballistic Missile Early Warning and PAVE PAWS submarine launched ballistic missile (SLBM) warning radars in Canada, Greenland, Scotland, Massachusetts, and California are at UHF, $\lambda \cong 0.6$ m.

1.6 EXERCISES

1. The Anti-Ballistic Missile Defense Treaty of the Strategic Arms Limitations accords with Russia limits radars at ABM sites in the two countries to 3×10^6 watt-meters-squared of power-aperture product. The radar designers want to use a 250-kW peak power transmitter, operating at a frequency $f_c = 6$ GHz. Assuming that such a radar requires a signal-to-noise ratio $S/N = 10$ (10 dB) for detection, a bandwidth $B = 300$ kHz, effective noise temperature $T_e = 1000$ K, and system losses $L_s = 10$ (10 dB), what would be its maximum possible detection range against a 10-m^2 target?

2. If a radar with transmit peak power $P = 1$ MW peak power and antenna gain $G = 1000$ (30 dB) irradiates a target with an RCS $\sigma = 1$ m^2 target at a range $R = 500$ km range, what power density arrives back at the radar antenna?

3. The radar in Exercise 2 is transmitting at $f_c = 1$ GHz. If the receive side of this radar has a noise figure $F_n = 3$ dB, receiver bandwidth $B = 100$ kHz, and system losses $L_s = 10$ (10 dB), what receiver temperature, T_0 (kelvins) is required to give the single pulse signal-to-noise ratio of unity?

4. The cost of a radar is the cost of power plus the cost of aperture plus a constant. The cost of power is the cost/kilowatt multiplied by the number of

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Antennas

HIGHLIGHTS

- Antenna gain and effective area
- Remarkable utility of the paraboloid
- Deriving the antenna far-field antenna gain pattern with calculus
- Design features for mainbeams and sidelobes
- Unique features of arrays
- Several ways to steer the beams of phased arrays, emphasizing phase shifters

An antenna is the mechanism by which the electromagnetic signal is radiated and received. For radars (although not necessarily for antennas in other electromagnetic applications), it is essential that the antenna enhance performance. A radar antenna has three roles: to be a major contributor to the radar's detection performance, to provide the required surveillance, and to allow measurements of angle of sufficient accuracy and precision.

A reasonable place to begin is with the two expressions used in Chapter 1 to derive the radar range equation: *antenna gain* and *effective area.* For a transmitting antenna, antenna gain is simply a measure of how much focusing of the transmitted waveform is being accomplished by the antenna. Focusing is the ability to add up energy preferentially. Energy arriving at the antenna from a given direction is integrated; that arriving from elsewhere is not. It is assumed that energy arriving at the antenna is in the form of plane waves, that is, the phase of the arriving energy is constant over any plane perpendicular to the direction of arrival, as shown in Figure 2.1. Because most sources of electromag-

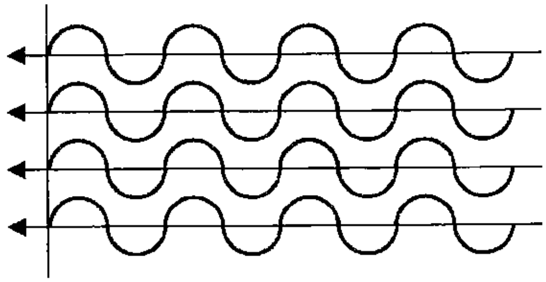


Figure 2.1 A plane wave.

netic energy are small, these wavefronts are really spherical, but at ranges of interest, the approximation to a plane wave is good.

For a receiving antenna, effective area is simply a measure of ability of the antenna to intercept the incident power density. Electromagnetic theory tells us the relationship between antenna gain and the effective area of the antenna [Equation (2.1)]. Effective area is related to the physical area of the antenna by the antenna efficiency. The antenna efficiency term allows us to account for factors such as antenna manufacturing tolerances, illumination function, feed networks, array element characteristics, and so forth.

$$G = \frac{4\pi A_e}{\lambda^2} = \frac{4\pi \rho A}{\lambda^2} \tag{2.1}$$

where:

G = antenna gain, no units
A_e = effective area of the antenna, meters
λ = wavelength, meters
ρ = antenna efficiency, $0 < \rho < 1$, no units
A = physical area of the antenna, meters

2.1 A Parabolic Reflector

The classical shape for focusing electromagnetic energy is the parabolic reflector (often referred to as a *dish*). Recall that a parabola (depicted in Figure 2.2) has interesting characteristics [Gardner, 1981]. Parallel lines, drawn from a line perpendicular to the axis of the parabola to the parabola and thence to its fo-

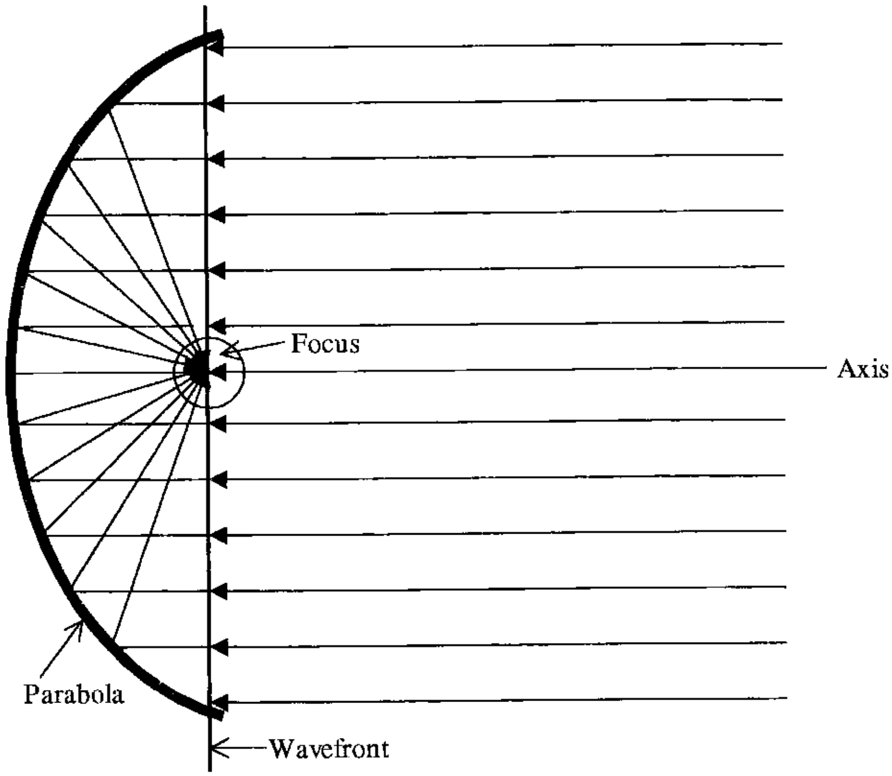


Figure 2.2 A parabolic antenna.

cus, will all be of the same length. Consequently, arriving plane waves will maintain constant phase over this distance. Furthermore, the angle made by the reflected line (with a line tangent to the parabola at that point) is always the same as the angle made by the incident line. If the lines are thought of as rays, then the angle of incidence equals the angle of reflection, which is Snell's law. The application to electromagnetic waves is obvious. All waves arriving parallel to the axis of the parabola and oscillating in phase will add up at the focus; other arriving waves will not add up. In effect, the parabola is focused on infinity. Only waves arriving from a source at infinity (a few miles approximating infinity in practice) will be parallel. The same can be said for radiating waves. Energy leaving the focus and reflecting off the parabola will radiate as a plane wave. When extended to a third dimension, the figure becomes a paraboloid. Put a small antenna, such as a feed horn, at its focus, and we have a parabolic reflector. Mount it on a pedestal that allows it to pivot on two axes, and we have the canonical radar antenna.

Notice that any segment of the parabola has equivalent characteristics. If only the top one-third of the reflector is illuminated, the feed is offset and does not interfere with the incident radiation. Reflectors with offset feeds are commonplace in radar. The feed might also be embedded in the center of the reflector, radiating its energy outward against a plate at the paraboloid's focus, which in turn would reflect it against the reflector. For the geometry to work, the "splash plate" must be a hyperboloid. This arrangement is known as a Cassegrain feed, after the optical telescopes of similar design. Of course, these applications require careful design of the feeds, which are antennas themselves.

Traditionally, reflector antennas have modest antenna efficiencies. Computer-controlled manufacturing has greatly improved the precision of reflector antennas and thus increased their efficiencies.

The plane wave generated by the two-dimensional parabola could also be generated by a line of incremental sources generating sinusoidal waves that are in phase. Being "in phase" means being in the same point of the sinusoidal wave at the same instant in time, as shown in Figure 2.3. we will postulate that these sources radiate semi-isotropically (that is, in a semicircle above a ground plane) and that they are sufficiently close together that they are "indistinguishable" from an extended source of in-phase energy. (How to determine what is "indistinguishable" is described in Chapter 8 under "Far Field of an Antenna," p. 219.) Because there can be a change in these phase relationships as a function of angle, the antenna gain varies with angle as the waves from each source go in and out of phase with respect to each other.

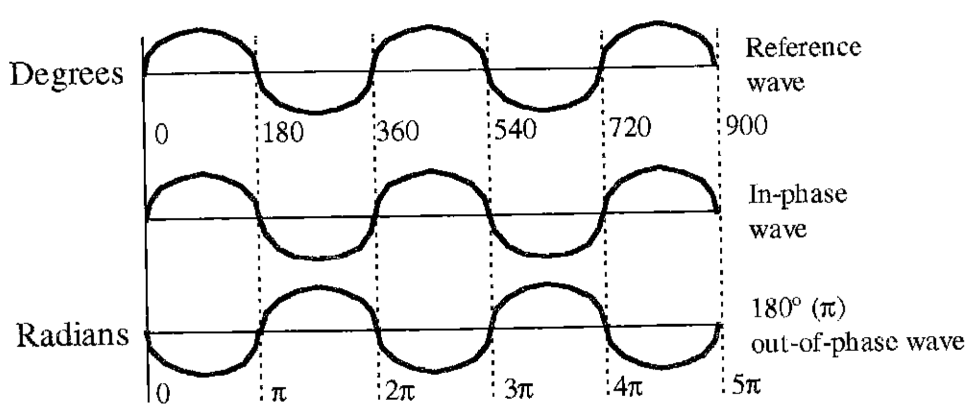


Figure 2.3 Phase relationships.

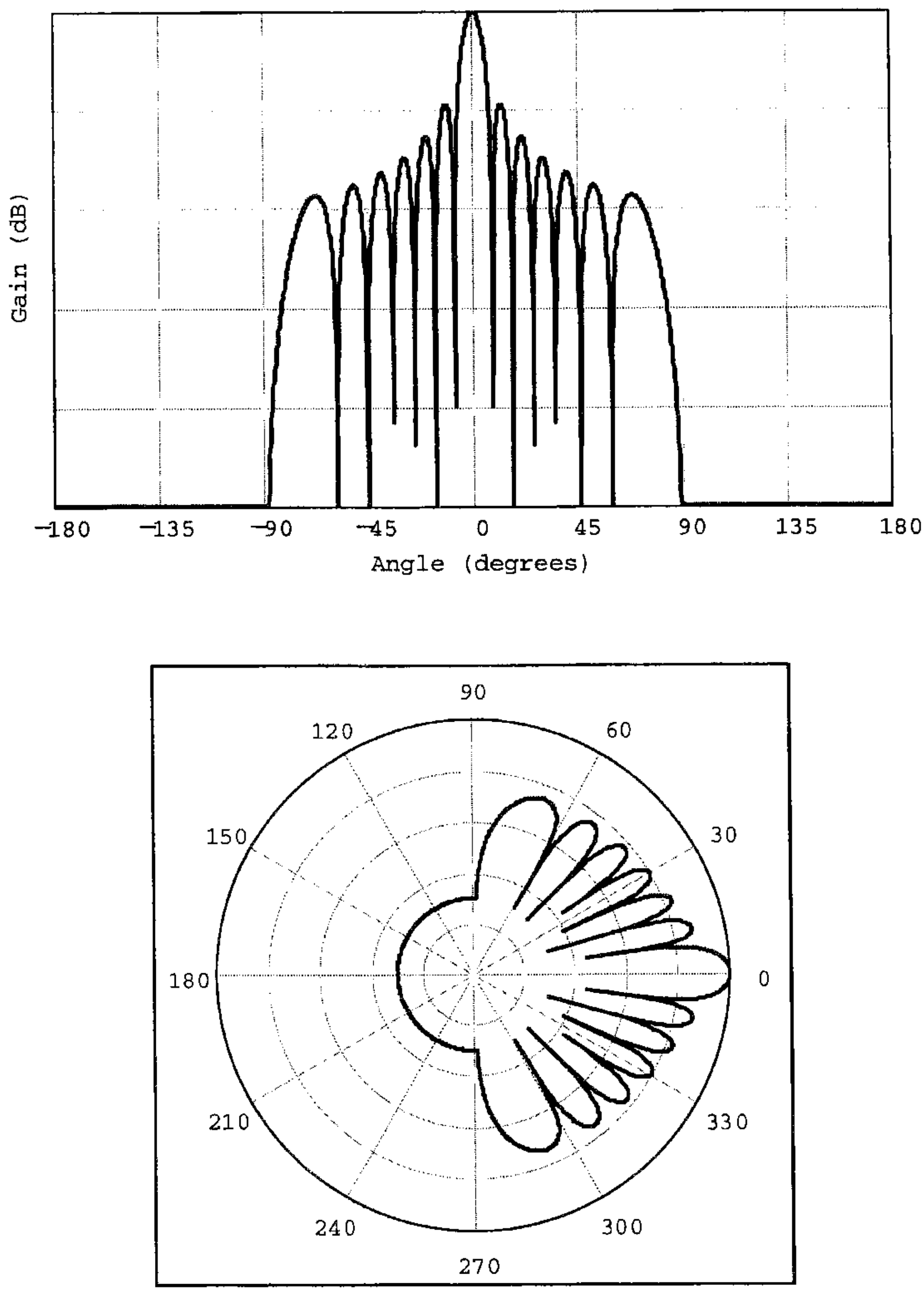


Figure 2.6 Antenna gain pattern, x-y plot and polar plot.

Sometimes an approximation will do, but most times we need an accurate antenna gain value at a specific angle.

2.3 ARRAY RADARS

An important class of radars uses arrays instead of reflectors for its antennas [Allen, 1963; Hansen, 1966; Stark, 1974; Skolnik, 2001; Stimson, 1998]. Array antennas are the distant past, present, and future of radar systems. Some illumination functions that are difficult or impossible to achieve with reflector antennas can be straightforwardly achieved with an array. Array antennas can also electronically steer the antenna beam, so the time and mechanical stresses of moving the antenna beam around the sky are eliminated. An electronically steerable array, whose beam steering is essentially inertialess, is more complex and capable of less precision than the reflector antenna, but it is much more cost effective when the mission requires surveying large solid angles while tracking large numbers of targets and perhaps guiding interceptors as well. Whereas one or more reflector antennas might handle tens of targets simultaneously, if hundreds, or even thousands, of targets are involved, electronic steering is the only practical answer. That is why missions such as space-track, submarine-launched missile warning, multiple target track/engage fire control, and navy battle group defense all use array antennas in various forms.

The big ballistic missile early warning system (BMEWS) array radar in Thule, Greenland, is used for warning of the launch of intercontinental ballistic missiles. The space-track array radar in Florida is used to catalog space objects. The Cobra Dane array radar in Shemya, Alaska, gathers intelligence data. The Navy's Aegis defense system uses array radars, as do some modern airport approach control radar systems.

In somewhat less demanding missions, electronic scanning may be used in one dimension while mechanical scanning is used in the other. Some air traffic control radars have this feature, as do some air-to-air and air-to-ground airborne radars. Generally, these radars electronically scan in the elevation plane and mechanically scan in azimuth.

Although there are many approaches to achieving electronic beam steering, it must be done by time-delay networks, phasing networks, or a combination of the two. Time-delay steering is the simplest to grasp conceptually. A beam can be formed in almost any direction by adjusting the time at which energy is permitted to emerge from each differential source, or element. In Figure 2.11, a wavefront is formed at an arbitrary angle by delaying by progressive time increments the emission of energy across segments of the one-dimensional array. A beam is formed pointing in the desired angular direction by the relationship between elements given in Equation (2.23).

$$\theta_0 = \sin^{-1}\left(\frac{c\,\Delta t}{d}\right) \tag{2.23}$$

where:

θ_0 = desired mainbeam pointing angle relative to the array boresight, radians, or degrees

c = speed of light, 3×10^8 meters/second

Δt = time delay between successive array elements, seconds

d = array element spacing, meters

True time-delay arrays have been built, but consider the complexity: for n beam positions, we have $n\ \Delta t$ time-delay networks at each element. For an N-

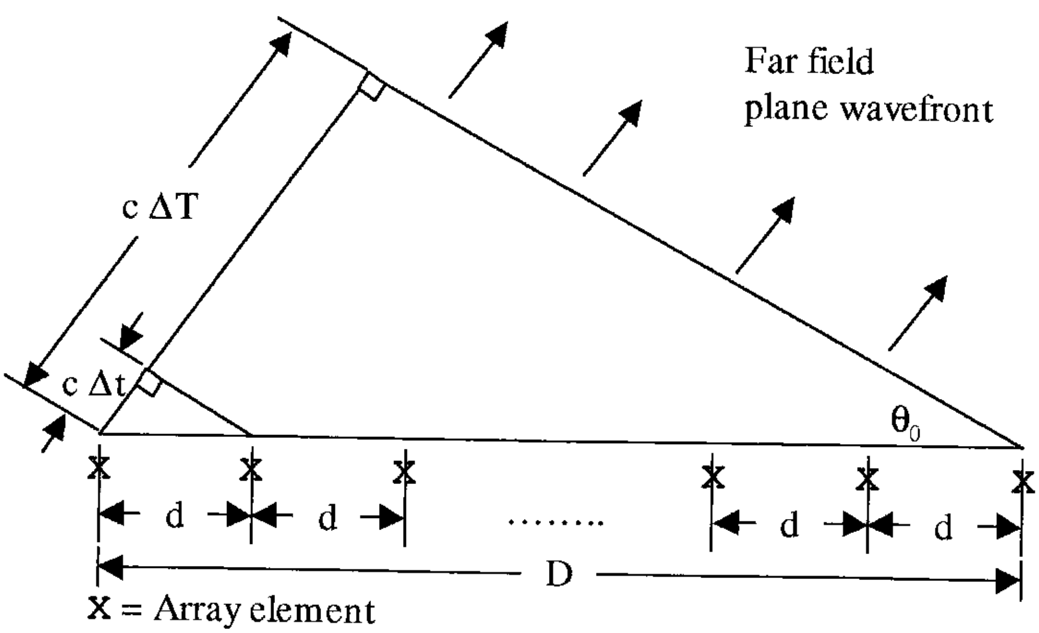


Figure 2.11 Time-delay steering.

element array, we have $N \times n \times \Delta t$ time-delay networks. Because, for practical radar systems, n can be hundreds and N thousands, the result is $>10^5$ time delays. Within any radar pulse, however, only the phase relationships count; so, provided the pulse is long compared to the size of the array (that is, $c\,\tau >> D$), time-delay networks need not be used, and the phase relationship across the elements determines the beam direction. From Figure 2.12, assuming sinusoidal signals, the ith element produces a signal $V_i \cos(\omega t + \beta_i)$. A beam is formed pointing in the desired angular direction by the phase relationship given in Equation (2.24). The entire phase progression across the array is given in Equation (2.25).

$$\beta_i = \frac{2\pi\, d_i}{\lambda} \sin\theta_0 \tag{2.24}$$

$$B = \sum_{i=1}^{N} \beta_i$$

$$B = \frac{2\pi\, D}{\lambda} \sin\theta_0 \tag{2.25}$$

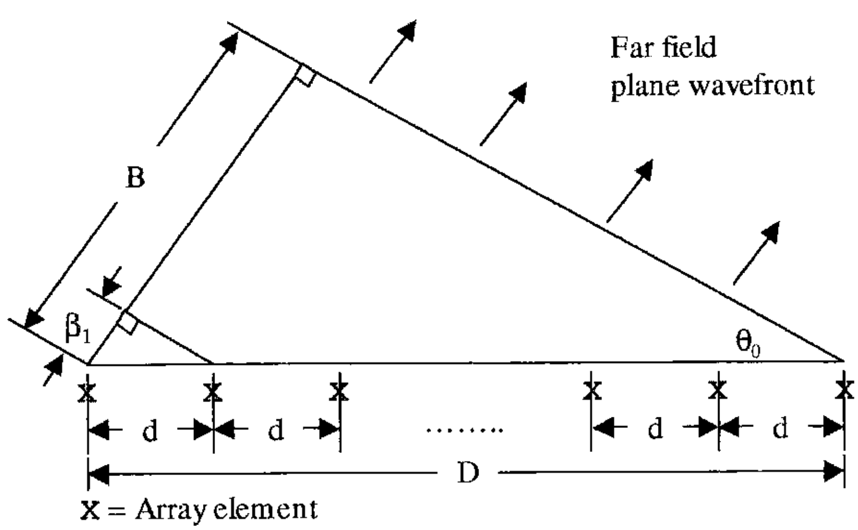


Figure 2.12 A phase-steered array.

where:

β_i = phase shift at the *i*th element, radians
d_i = distance of the *i*th array element from the start of the array, meters
λ = wavelength, meters
B = entire phase progression across the array, radians
N = number of array elements, no units
D = length of the array, meters
θ_0 = desired mainbeam pointing angle relative to the array boresight, radians

Observe that an equivalent β_i may be achieved for any θ_0 by making λ a variable. The array can thus be made to point in an arbitrary direction by changing the frequency. To keep the change in λ to a usable level, say ±5%, it is necessary to have the electrical distance between elements greater than 5λ. The ratio of this electrical distance to the physical distance is called the *wrap-up factor*. Some electronic beam steering is done in just this way and is called *frequency scanning*. For frequency-scan arrays, the direction the mainbeam points is given in Equation (2.26). If the mainbeam is to be steered over the angular limits $\pm\theta_1$, the necessary wavelength (or frequency excursion) is given in Equation (2.27). Several U.S. and Russian radars use this type of beam steering. Its advantage of relative simplicity must be weighed against its disadvantage of extremely narrow signal bandwidth (a wideband signal causes steering of the beam). Consequently, several other ways to steer beams electronically have been found.

$$\sin(\theta_0) = \frac{L}{d}\left(1 - \frac{\lambda}{\lambda_0}\right) = \frac{L}{d}\left(1 - \frac{f_0}{f}\right) \tag{2.26}$$

$$\sin(\theta_1) = \frac{L}{2\,d}\,\frac{\Delta\lambda}{\lambda_0} \cong \frac{L}{2d}\,\frac{\Delta f}{f_0} \tag{2.27}$$

where:

θ_0 = beam steering angle, radians or degrees
L = electrical distance between array elements, meters
d = physical distance between array elements, meters
λ = transmitted wavelength, meters
λ_0 = wavelength corresponding to the beam pointing at broadside, meters
f_0 = frequency corresponding to the beam pointing at broadside, hertz
f = transmitted frequency, hertz

4

Radar Cross Section

HIGHLIGHTS

- Definition of radar cross section (RCS)
- The RCS of a sphere
- RCSs of some simple shapes based on simple theory
- Wavelength dependence of RCS
- Optical, resonance, and Rayleigh regions
- Effect of polarization
- Mitigating polarization effects
- RCS of dipoles and clouds of dipoles (chaff)
- The RCS of various types of clutter
- Clutter fences
- Inferring physical characteristics from RCS (radar signature)

Radar cross section (RCS) is a measure of the electromagnetic energy intercepted and reradiated at the same wavelength by any object. The dimensions are those of an area, usually square meters (m^2) or decibels relative to a square meter (dBsm). The relationship between square meters and dBsm is given in Equation (4.1). The RCS of an object is a complex combination of multiple factors: size, shape, material, edges, wavelength, and polarization. Simple objects tend to have a single, or few, scattering sources. Complex objects (such as airplanes) tend to have multiple scattering sources (e.g., nose, fuselage, inlet, wing root, wing, and so forth). Thus, for complex objects, the RCS is the complex (amplitude and phase) combination of contributions from each scattering source.

The understanding of RCS concepts generally starts with an idealized object that is large with respect to a wavelength, has an intercept area of one square unit, is perfectly conducting, and reradiates isotropically. It is easy to build an object with these characteristics; a copper sphere is an example. Providing it is large with respect to the wavelength of the incident electromagnetic energy, a copper sphere of projected area of 1 m^2 has radar cross section, usually indicated by σ, of 1 m^2 or, for any sphere of radius a, $2\pi a/\lambda > 10$, as given in Equation (4.2).

$$\text{dBsm} = 10\log(\text{m}^2) \qquad \text{m}^2 = 10^{\left(\frac{\text{dBsm}}{10}\right)} \tag{4.1}$$

$$\sigma_s = \pi a^2 \tag{4.2}$$

where:

σ_s = radar cross section of sphere, $2\pi a/\lambda > 10$, square meters
a = radius of the sphere, meters
λ = wavelength, meters

The RCS of an object can be determined by solving Maxwell's equations. The RCS of an object can also be established by measuring it and comparing it to that of the reference object. For complex, many-surfaced objects (such as airplanes), attempts to solve Maxwell's equations for the various boundary conditions have not been very successful. Measurement and comparison then became the only way of obtaining RCS. As the characteristics of the object vary with aspect angle, so does the RCS, often fluctuating rapidly. Computer programs are able to calculate the radar cross section for some rather complicated bodies. Computer programs essentially break down a complicated target into many simple surfaces and superpose their radar cross sections (amplitude and phase) to compute the overall radar cross section.

For several classes of simple objects, RCS can be easily calculated. When the target does not reradiate isotropically, it may have gain in the direction of the radar, as given in Equation (4.3).

$$\sigma = G A_e \tag{4.3}$$

where:

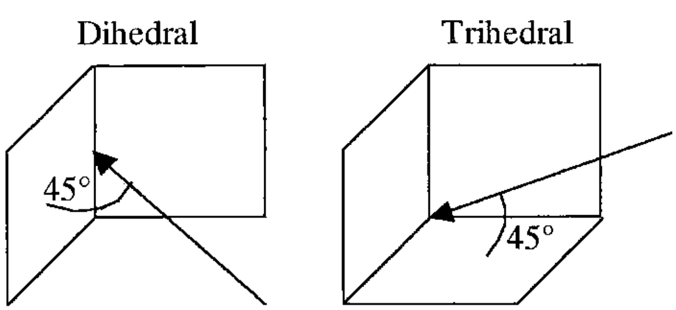
σ = radar cross section for nonisoptropic object, square meters
G = reradiation gain in the direction of the radar, no units
A_e = electromagnetic area of the object as seen by the radar, square meters

In Chapter 2, we showed from first principles that the reradiation gain is a function of the electromagnetic area and wavelength [Equation (4.4)]. It should always be remembered that the area is an electromagnetic area as seen by the radar at the instant in time that radar cross section is being induced. From this, the calculation of the RCS of a flat plate is trivial [Equation (4.5)].

$$G = \frac{4\pi A_e}{\lambda^2} \tag{4.4}$$

$$\sigma = \frac{4\pi A_e^2}{\lambda^2} \tag{4.5}$$

The calculation of such retrodirective targets as corner reflectors where the radar is seeing the equivalent of a flat plate is straightforward. Figure 4.1 is a sketch of a two-face (dihedral) and a three-face (trihedral) corner reflector. The faces are at right angles to each other. Some basic trigonometry reveals that many plane waves arriving at these reflectors are directed back toward the



Note: Arrows indicated entry angle for maximum RCS

Figure 4.1 Two corner reflector designs.

radiating source in phase, making the maximum RCS equal to the projected area of the corner reflector [Knott, Schaeffer, and Tuley, 1985, p. 178]. If all facets of these reflectors are equal sized squares, then the RCS of the dihedral and trihedral are given in Equations (4.6) and (4.7), respectively.

$$\sigma_d = \frac{8\pi a^4}{\lambda^2} \tag{4.6}$$

$$\sigma_t = \frac{12\pi a^4}{\lambda^2} \tag{4.7}$$

where:

σ_d = radar cross section of a dihedral corner reflector, square meters
a = dimension of the square, meters
σ_t = radar cross section of a trihedral corner reflector, square meters

4.1 RCS of a Sphere

A calculation can also be made to determine the amount of a sphere that is sufficiently flat that it scatters back to the radar. From the ratio of its RCS to its physical surface area, we have already established that the RCS is one-fourth the surface area. This can also be derived using the geometry of Figure 4.2, as given

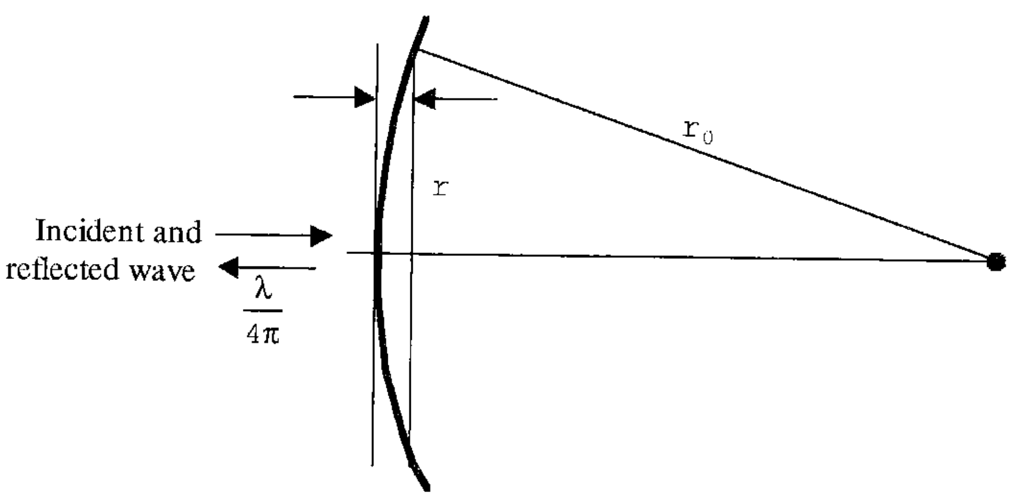


Figure 4.2 Geometry for sphere RCS.

9

Radar Potentials and Limitations

From the previous chapters, you can adequately understand and summarize what radars do and how they do it. However, you need some perspective on whether radar is the system of choice for accomplishing a particular objective in view of some of the alternatives available. Good managers must be able not only to understand the salient technical verities of the work they are managing, but be able to make a judicious choice among the options available for getting the job done.

Allocation of scarce resources is probably a manager's most vital task. Reviewing the key attributes and limitations of radar and knowing how other technologies and other systems compare in capability will assist you greatly. Doing these comparisons with matrices and lists is not as much fun or as illuminating as doing them by missions. The first approach would be similar to preparing a cookbook to satisfy all tastes; the second is to discuss the menu that will satisfy a particular craving. Some of these missions are big, and some are small. The extent of the analytical discussion of them has no relationship to their size, but to the adequacy of radar for meeting the requirement.

9.1 SURVEILLANCE

If the range is neither too long nor too short (less than several thousand kilometers in the first case and a kilometer or so in the second), radar is preeminent in any surveillance mission that requires night and bad-weather operations. This is a very broad mission. It includes vehicle traffic on the highways and at state or national borders, aircraft on runways and in the air, and ships at sea and in harbors. In most cases, it not only includes surveillance of the vehicles, but radars aboard the vehicles themselves (for example, altimeters). Boats maneuvering in harbors in the United States do not usually receive centralized direction; they need onboard radars. Aircraft in airports receive centralized direction; they generally do not have surveillance radars. The mission does not include underwater surveillance. Electromagnetic waves do not propagate well underwater; sound waves do. Sonar is the underwater analog of radar and is used there.

Radar is preeminent in this mission for two reasons: It is active, and it is usually all weather. Being active allows night operations; the radar provides its own illumination. A radar's measuring stick is the speed of light. Nothing in the universe is faster or more efficient. Even if measurements of position could be made by other means (and they can in many cases), the radar measurement is simpler and easier. Imagine a sonar for traffic patrol: bigger, heavier, requiring more power (the medium is lossy), and with a speed of propagation of 330 m/sec rather than 3×10^8.

Wavelength determines a radar's all-weather capability. The longer the wavelength, the less problem there is with weather. Although radar is thought of as all weather, not all radar is all weather. Radars in the infrared or the visible light spectrum (lasers) are not all weather. Radars in the microwave region and below are all weather.

As ranges get longer or the need for better resolution emerges, radar begins to falter. An example of the first condition is deep space surveillance; an example of the second is perimeter security of a plant, base, or other facility.

There are particular radars that can find satellites at geosynchronous altitude (40,766 km above the equator) if they know in general where to look. (The Haystack radar of the Lincoln Laboratory is one. It has a 36.6-m reflector antenna at X-band, a theoretical 70-dB gain, and average power in the hundreds of kilowatts.) However, the task of surveying space for satellites at ranges of more than a few thousand kilometers is too much for radar to undertake. The extent of the problem for space surveillance is not difficult to adumbrate, because geosynchronous satellite orbits are deterministic. By the laws of celestial mechanics, a satellite must pass across the equator twice in each orbit. The Earth turns under each orbit at the rate of 15° per hour. The satellite's inclination angle is the highest latitude over the Earth to which its orbit carries it. A combination of those factors determines at what times, in what directions, and at what ranges satellites in circular orbits will pass over a region on the Earth's surface. Satellites in elliptical orbits add to the difficulty, because the only constraint on the duration of their orbits is that of remaining an Earth satellite.

With them, there is no association of altitude with velocity, although a line from the satellite to the Earth's center will carve out equal areas in equal time.

As a little calculation using the radar range equation of Chapter 1 will show, radars of the kind we have described (power-aperture products of 3×10^9 kW-m^2) do not have time to detect 1-m^2 RCS at 6400 km and scan a substantial segment of the sky as well. Optical telescopes placed at correct locations on the Earth's surface can do well at accounting for these longer-range satellites—not with the same rapidity of response, because they cannot operate in daylight, but with better overall accuracy.

At 6400 km, the segment of the spherical shell of possible satellite orbits eclipsed by the Earth is 1/16 the area of the entire shell, so these satellites will be illuminated by the sun 15/16 of the time. For higher altitude satellites, the eclipsing is less. Therefore, using a passive optical satellite for high-altitude satellite surveillance may be a good idea.

Radar also tends to be less than ideal in a surveillance role when very high resolution is required. For example, a sensor covering the outside perimeter of a security fence would need to differentiate among vehicles, animals, and human beings. How many resolution cells are required for recognition of various classes of target is a matter of intense debate, but it is clear that the resolution (perhaps 1 m) of a very narrow beam, millimeter wave radar at a few hundred yards could not compete with an optical system of the same diameter (which would have several orders of magnitude better angular resolution) or even the human eye (which can resolve at least 0.3 m at 450 m in nonideal conditions).

At these comparatively short ranges, weather and night conditions do not affect passive systems appreciably, so infrared sensors and low-light-level TV are very competitive, even when there is considerable dust, fog, and smoke.

9.2 Navigation

The Earth is literally webbed with long- and short-range navigation systems that use electromagnetic waves but not radar. In many of these, the vehicle is passive, the system itself providing virtually all the energy required. In others, the vehicles have transponders. In addition, the Navstar Global Positioning System (GPS), a net of satellites, provides positive location to anyone in the world to a three-dimensional accuracy of a few meters or better.

Yet, radar has a navigation mission. It can provide essential Doppler information to update an inertial guidance system, and radar maps can provide references by which a vehicle can locate itself. Because commercially available inertial navigators have 0.45-m/sec or so drifts, they need updating. A Doppler radar is one solution. There are others, GPS being the primary example. There are also other means for obtaining map references: optical, IR, and microwave radiometry. If the other forms of navigation are good enough, maps are not required.

Both Doppler radars and radar mapping are essential in military operations. In such an emergency, it is necessary to be self-contained independent of time of day, weather, and the status of outside navigation aids. In that situation, radar shines. Another form of navigation is weapon guidance. Radar has a role in one form of this: active and semiactive homing. Because we can guide these vehicles in several other ways, radar's role could be described as important but not unique.

9.3 Signatures

We have already emphasized that electromagnetic wavelengths that allow radar to penetrate fog, dust, smoke, and rain are effective because they are long compared to infrared and light waves. These same waves are less effective as imagers because their resolution is not fine enough. The physical limit of angle resolution is about λ^2 and, for range resolution, a few RF cycles. If we want details to use in recognition, identification, analysis, targeting, and so forth, there is no substitute for resolution. As has been mentioned in other chapters, the wavelengths at microwave frequencies (C-band) are 5×10^{-2} m. Wavelengths of visible light are 5.5×10^{-7} m, of far infrared, 20×10^{-6} m. A radar image has, say, 10 by 10 resolution cells. The same image in the visible has 1,000,000 by 1,000,000. In the far infrared, it has 25,000 by 25,000.

Of course, we have radars at optical frequencies, and they make high-resolution images (which are not as appealing to the human eye and do not contain as much information as images produced by diffused illumination) in three dimensions. Photography and television are just as convenient and far less expensive. Moreover, infrared images can be obtained at night, using the irradiance of the objects in the scene as the illumination source.

Radar imagery must resort for its utility to the all-weather role. Again, the military applications dominate, although natural disasters have substantial relevance. The military commander needs to know the status of an enemy's deployed forces and cannot wait for daylight or good weather; attacking aircraft must be able to identify enemy targets through snow, rain, fog, smoke, and dust. In these situations, some resolution is urgent, but super-resolution is a luxury. Here, modern radars (all that the technology can provide) are indispensable.

There is a partial way out of the dilemma of all-weather imagery. It is to place the image-gathering sensor so close to its subject that the weather no longer interferes. Although this approach is no help in obtaining high-resolution maps of a battlefront or a hurricane's passage, it is promising for weapon delivery where the weapon can be placed near the target by various means and can then use onboard high-resolution sensors to close with it autonomously. Whether such applications are affordable remains to be seen.

9.4 Science

Speculation on the potential uses of radar in science is for the futurists. Current and past uses are substantial, however. The study of the ionosphere and of our own and neighboring planets are cases in point. Study of the ionosphere, and particularly of the auroral region in the northern hemisphere, has proceeded vigorously for about 30 years. Much knowledge about its characteristics, particularly propagation, has been exploited in system design.

Mapping radars have been flown several times in space by NASA. Because electromagnetic waves have some penetrating power, images of subsurface features in both land and water were obtained, portending new dimensions in Earth resources research.

The Haystack radar was used in the 1960s in a test of relativity by making measurements on the planet Mercury as the radar line of sight to Mercury neared the edge of the sun. The Arecibo system has examined all the planets inside Jupiter. Plans have been made to study the planets further with a new S-band radar system. Planets such as Venus (shrouded in an atmosphere that is impenetrable to many of the higher frequencies) are made to order for radars. We have already seen high-resolution synthetic aperture radar maps of the surface of Venus. Venus is being explored from Earthbound radars and from radars on board the space vehicles sent there. In fact, virtually all explorers of the solar system that expect to land will have at least a radar altimeter on board, barometric altimeters being useless when there is no atmosphere and unsatisfactory when the atmosphere pressure gradients are poorly known.

Although radars have not achieved the eminence of ultrasonic, infrared, and X-ray medical diagnostic techniques, there are conceptual uses of parts of the spectrum for imaging internal tissue and organs. However, the frequencies that penetrate best on the macro scale are too low for imaging, and the higher frequencies, when stopped by tissue, deposit their energy (as with microwave ovens and diathermy). The ultrasound systems used to image the heart and arteries near the heart are "radars of sound" (sonar). X-ray radars have long been discussed, the problems of focusing rays with the energy of X-rays and the problem of controlling the backscattered energy (it does not return as X-rays) being the principal barriers to a useful system. X-rays have high penetration on the micro scale, but their interactions with tissue are atomic rather than electromagnetic.

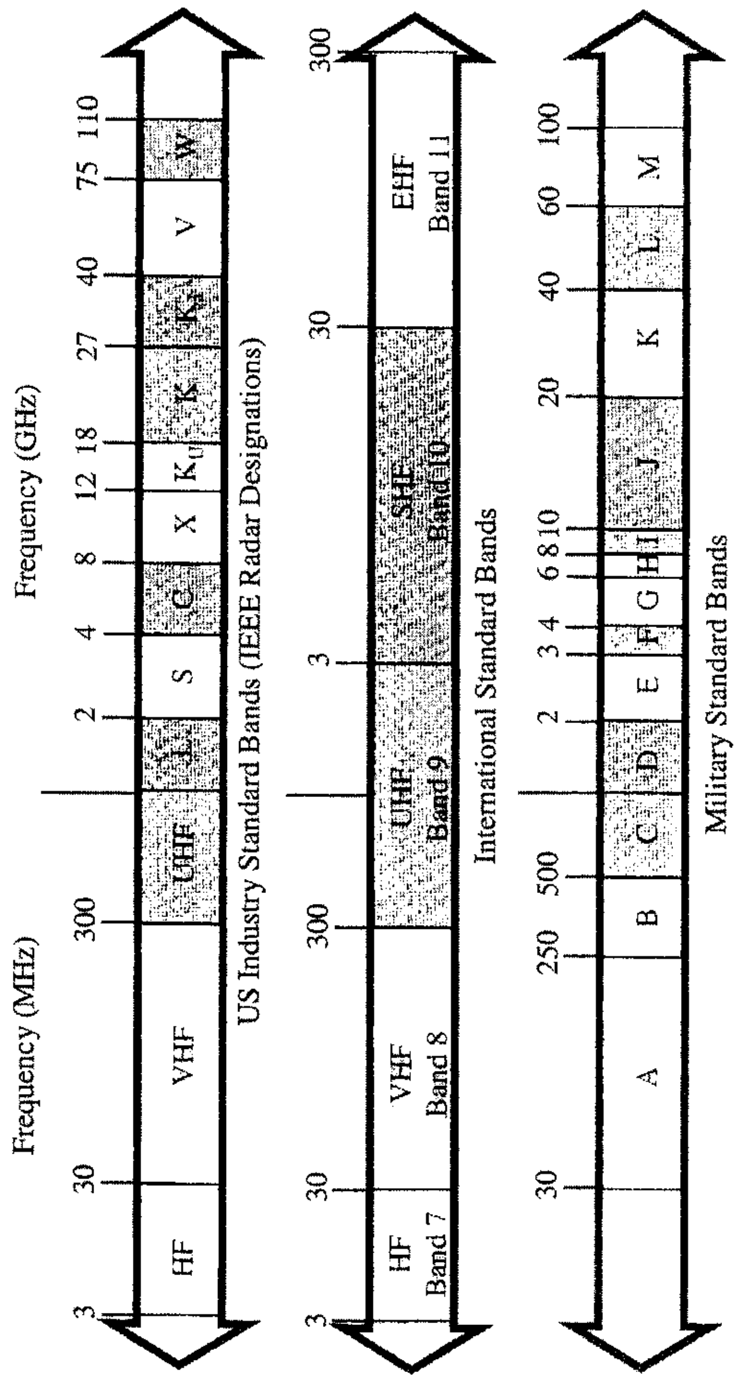
9.5 SUMMARY

To summarize, the qualities that make radar essential to modern life also limit its utility. The fact that it furnishes its own illumination makes it valuable for obtaining almost instantaneous range and range rate data on targets and for night operations against passive or noncooperative targets, but this limits its ultimate range. The fact that the frequencies at which radars operate can penetrate bad weather, smoke, and dust and can see over the Earth's horizon makes them essential to emergency operations, particularly military operations, but prevents them from obtaining the high resolution they need to get fine-grained images.

The vigorous application of new technology and human ingenuity will tend to expand radar's applications and mitigate its shortcomings. However, the natural laws cannot be overcome, inevitably consigning radar to its niche: an interesting and important technology with multifaceted but limited uses.

Appendix 2

The Radar Spectrum



Appendix 5

Glossary

This glossary provides assistance in understanding terms used in this book. There may be more general, more specific, or entirely different meanings for these terms when they are used elsewhere.

Adaptive array: an electronically steerable antenna designed to respond automatically and optimally to a variety of situations

Adaptive receiver: a receiver with circuitry or perhaps programming that enables it to adjust to the characteristics of the incoming signal

AGC: automatic gain control, keeping the excursions of the received signal within bounds with an automatic negative feedback loop

Ambiguous angle: an angle where the characteristics of an antenna pattern are such that there is uncertainty about the angular location of a target (as with an interferometer)

Ambiguous range: the condition that the round-trip time between pulses is insufficient to accommodate all the targets that the radar will see, resulting in uncertainty about target range

Ambiguous range rate: the situation that occurs when the Doppler processing scheme of the radar is such that target range rates fold over, making those range rates uncertain

Ampere's law: current passing through a conductor creates a magnetic field around the conductor; named after the man who discovered the phenomenon

Amplitude: the "height" of a trace on a display or record, usually referring to a measurement of voltage or power

Analog error signals: indicators derived from a continuous process that permits correction while the process is going on, as with a radar beam tracking a target

Analog signal processing: performing various operations on signals while they are still in their received form, that is, continuous rather than quantized or digitized

Analog-to-digital (AD) converter: electronic circuitry that samples an incoming signal and assigns a number (or a computer word) that describes each sample

Angle resolution: the capability of an antenna to separate two objects in angle

Angle tracking: to follow a target in angle, by whatever means

Angular error: the amount by which an antenna or other angle measuring system fails to indicate the exact angle of a target

Angular rate: the rapidity with which a target's position changes in angle

Antenna pattern: the "intensity" of the field at locations around the antenna at long distances from it; usually established by taking a series of measurements

Anti-jam gain or margin: the ratio by which a particular waveform or other technique is able to mitigate the effects of jamming

Aperture: literally an "opening"; its size determines the amount of electromagnetic energy intercepted; thus, any antenna is called an aperture

Arecibo: the location in Puerto Rico of a 1000-ft-aperture ionospheric and astronomic radar

Array factor: the component of an array antenna gain pattern due to the array of individual elements

Aspect angle: the angle made by some arbitrary characteristic of the target, say, its axis, with the axis of the radar antenna beam

Auroral ionosphere: the ionosphere near the Earth's magnetic poles when excited by magnetic storms

Azimuth: the angle from a fixed point, say, due north, in the plane of the Earth's surface (horizontal plane)

Barrage jamming: disrupting and interfering jamming that continuously covers all the radar frequencies being radiated

Beam steering: moving an antenna pattern about the sky, usually by electronic means

Beamwidth: the lateral dimension (in angle) of the principal lobe (main lobe or main beam) of an antenna pattern

Bistatic radar: a radar whose transmit and receive antennas are substantially separated

Blanking circuit: an electronic scheme by which particular range or angle locations in the radar coverage are wiped out

Blass array: an electronically steered array consisting of stacked beams that are turned on and off with a waveguide matrix; named after its inventor

Blind ranges: ranges where a filter that suppresses clutter at one range also suppresses signals at other ranges

Blind speeds: speeds at which a filter that suppresses clutter at one range rate also suppresses signals at other range rates

Boltzmann's constant: the number by which temperature (in kelvins) is related to energy (in joules or watt-seconds) per hertz of bandwidth; it is 1.38×10^{-23} joules/°K, named after the man who developed the phenomenon

Boresight: the forward direction on the axis of an antenna; loosely, the direction a reflector antenna is pointing or the direction perpendicular to the surface of any antenna

Butler array or matrix: an electronically steered array with the characteristics that there are as many beams formed as there are elements, they are orthogonal and the output is the Fourier transform of the input; named after its inventor

Carrier frequency: the rate of oscillation of the radio waves that carry a signal through space

Cassegrain feed: an antenna feed patterned after the optical telescope feed of the same name; the feed is located at the center of a parabolic reflector, reflecting onto the reflector via a hyperboloid at its focus

CFAR: constant false-alarm rate; keeping noise level constant by normalizing to a noise sample taken near the target

Chaff: small, light pieces of material that have high radar cross section

Circular polarization: a characteristic of radio waves whose electric vector rotates 360° during each radio frequency cycle

Clutter: unwanted and interfering radar returns from objects other than targets

Clutter coefficient: the ratio of the return received from clutter to what would have been received from a perfectly conducting isotropic radiator of the same physical area

Clutter fence: a screen around a radar site that prevents low-angle clutter sources from being illuminated

Coherence: the preservation of fixed phase relationships over time in the conduct of radar operations

Collision frequency: the rate at which the free electrons in an ionized medium collide with ions or atoms

Comb filters: an array of filters, arranged like the teeth of a comb, whose response frequencies are close together

Cone sphere: the shape created by a sphere capping a truncated cone; similar in shape to an ice cream cone

Conical scan: a tracking technique in which an antenna feed or the antenna itself makes a small, circular motion, sequentially comparing returns to obtain more accurate angle information about the target

Convolution: multiplying the overlapping portions of two functions continuously as one is moved across the other

Corner reflector (dihedral and trihedral): radar targets designed to have high retrodirective radar cross section. The dihedral has two faces, the trihedral three.

Cross range: a measurement orthogonal to the axis of an antenna, differentiated from arc length derived from an angle measurement

Data link: a communications channel for information, usually digitized and wide bandwidth

Dead zone: the region near a radar from which returns are not received because the receiver is either turned off or not connected to the antenna while the transmitter is radiating

Decibel: ten bels, a bel being the logarithm to the base ten of the ratio of output power to input power

Difference beam: the remainder or residue that results when the voltage from a signal in one beam is subtracted from that in an adjoining beam

Diffraction grating: a matrix of narrow slits that breaks light up into fringes caused by the constructive and destructive interference of light waves

Diffuse: to break up and distribute on reflection, as with an incident electromagnetic wave

Digital signal processing: performing various operations on signals after they have been converted to digital form, as differentiated from analog signal processing

Directional coupler: a switch that connects one electric circuit with another in such a way that energy moves easily in one direction but not in the other

Distributions: various probability density functions of mathematical statistics [exponential, gamma, Gaussian (normal), and Rayleigh] that find applications in radar theory

Doppler ambiguity: a condition in which range rate data folds over so that there is uncertainty about the true Doppler frequency

Doppler sidelobes: the residue of a filter's frequency response that appears in adjacent filters

Doppler spread: the band of frequencies within which Doppler returns might occur

Downrange: away from the radar along the axis of its antenna

EHF: extremely high frequency; frequency band

Electric vector: the direction and magnitude of the voltage measured in an electromagnetic field

Electron density: the number of free electrons per unit volume of an ionized gas or plasma

Electronic countermeasures (ECM): using electronic techniques to disrupt radar or communications

Electronic counter-countermeasures (ECCM): activities to counter ECM

Element factor: the pattern of individual elements of an array antenna

Envelope: the shape, amplitude, or modulation of a signal after the radio frequency carrier has been removed; the post-detection content of the signal

Envelope integration: building up the signal by summing two or more signal envelopes; post-detection integration

Erf(x): a form of the integral of the standard Gaussian distribution in which the standard deviation has been made narrower by the square root of two

ERP: effective radiated power of a radar or jammer (peak power × transmit antenna gain)

Ether: an imagined medium by which, it was thought until the nineteenth century, light waves were able to propagate in space

False-alarm probability: the likelihood that noise alone will cross a threshold and be erroneously accepted as a signal

False-alarm rate: the frequency with which noise alone crosses a threshold and is erroneously accepted as a signal

Fan beams: antenna patterns whose main lobes are in the shape of a fan

Faraday's law: a time-varying magnetic field will induce a voltage in a circuit immersed in that field; also known as the induction law; named after its discoverer

Faraday rotation: the turning of the electric vector of an electromagnetic wave as it passes through an ionized medium, an action that occurs due to Faraday's law

Far field: the region sufficiently far from an antenna that the phases of wavelets arriving from the antenna edges will be negligibly different from those arriving from the center; similar relationship for the radar cross section of a target

Fast Fourier transform (FFT): an algorithm for efficiently calculating the frequency content of a digitized time function

Fat beams: antenna patterns whose main lobes occupy a relatively large solid angle

Feedhorn: the expanding end of a waveguide that acts as a launcher of electromagnetic waves

FM chirp: a frequency-modulated signal that smoothly changes frequency upward or downward during its transmission; if it were a sound wave, it would be heard as a chirp

FM ramp: the ramp-like shape of the plot of a waveform whose frequency is changing either upward or downward during transmission

Fourier transforms: a mathematical operation that changes a function to reveal its characteristics in a different dimension; named after its inventor

Fraunhoffer diffraction: the far-field patterns that appear when light is propagated through a narrow slit or grating

Frequency ambiguity: uncertainty about the true Doppler shift of a target because of fold over in the Doppler processor

Frequency diversify: a characteristic of radars that can radiate at any one of a large number of frequencies; a design to reduce jamming vulnerability

Frequency domain: the dimension in which a function is evaluated for its spectral content

Frequency scanning: a technique by which an array antenna surveys a solid angle by changing its carrier frequency

Gain: the focusing power of an antenna as measured by the ratio of the angular area of a sphere to the angular area of the antenna beam; or the power of a processor to build up the signal-to-noise ratio by applying various techniques

Galactic noise: unwanted and interfering electromagnetic radiation that enters the radar from the cosmos

Gaussian: refers to the normal probability distribution; phenomena whose events are normally distributed are "Gaussian"

Geometric optics region: the region where the scattering of electromagnetic waves is from objects whose characteristic dimension is much larger than a wavelength

Geosynchronous: synchronized with the turning of the Earth; satellites in orbits whose period is 24 hr and whose inclination is zero degrees are geosynchronous

Gigahertz (GHz): billions (10^9) of cycles per second

Grating lobes: patterns in which energy appears at almost equal amplitudes in several locations, as with diffraction through multiple slits or interferometry

Grazing angle: the angle an antenna beam makes with the surface of the Earth

Gun-barrel analogy: the inference that the trajectories of radar targets can be compared with those of bullets emerging from a gun barrel

Half-wave dipole: a radiating or receiving element consisting of a straight conducting wire one-half as long as the wavelength of the associated radio waves

Hamming weighting: tailoring the amplitude of an antenna illumination function to reduce antenna sidelobes, or a waveform to reduce measurement sidelobes, so that it is the shape of a cosine on a pedestal; named after its designer

Haystack radar: a very large, high-precision reflector antenna radar atop Haystack Hill in Massachusetts

HF: high frequency, frequency band

Horizontal polarization: the condition of a radio wave whose electric vector is in the plane of the Earth's surface

Huggins beam steering: a method of moving a radar beam about the sky by adding and then subtracting the correct phases from the carrier frequency; named after its inventor

Hybrid: a device that employs a mixture of two or more electronic technologies, such as mixing tubes and solid state devices, analog and digital processing, and waveguide and electronic circuits

Hypothesis: test a method of decision making in mathematical statistics in which a threshold is set at a predetermined level, fixing the probability of incorrectly accepting or rejecting the hypothesis

Illumination function: the voltage or power pattern with which an antenna is excited

Noncoherent integration: the adding together of the envelopes or modulation of signals without regard for the phase of the carrier frequency; post-detection integration

Incremental sources: imaginary small radiators of electromagnetic energy used as a convenience for developing theory

Inertial guidance: a completely autonomous system of navigation that measures accelerations and deduces other quantities from those measurements and original position

Interferometer: a system that uses phase differences (constructive and destructive interference) to determine angular position to high accuracy

Interpulse period: the interval between radar pulses, pulse repetition interval (PRI), the reciprocal of the pulse repetition frequency (PRF)

Inverse synthetic aperture: the use of the deterministic rotation of an object in a radar beam to derive differential Doppler information and thereby resolve the object in angle; the "inverse" of having the radar beam pass across the target

Ionospheric radars: radars that irradiate the ionosphere so that scientific information can be derived from the noncoherent backscatter received

Ionospheric sounders: systems that probe the ionosphere by transmitting rapidly varying frequencies toward it; returns are evaluated to obtain estimates of electron density as a function of height

Isotropic radiator: an imaginary source of electromagnetic energy that radiates equal amplitudes and phases in all directions

Jitter: small, rapid, perhaps random fluctuations about an intended point or location

Kalman filter: a well known tracking algorithm (named after its creator) that weights measurements according to their quality to optimize results

Keplerian motion: movement dictated only by the forces of gravity, such as the movement of planets and satellites

Kilohertz (kHz): thousands (10^3) of cycles per second

Kilometers (km): thousands (10^3) of meters

Kilowatts (kW): thousands (10^3) of watts

Klystrons: high-power amplifiers of radio frequency energy, capable of coherent operation

Laser radar: a radar at optical, infrared or ultraviolet frequencies

Lidar: for "light detection and ranging"; a laser radar; sometimes, "ladar"

Linear array: an array antenna consisting of radiating elements arranged in a line

Line feed: a feed whose elements are arranged in a line; they may also be phased, as in a line feed that removes spherical aberration

LPI radar: low probability of intercept radar; a radar with waveform and antenna designed to minimize the power radiated in both spatial and spectral domains

Main beam: that part of an antenna pattern that contains the major portion of the energy

Matched filter: a filter in a radar receiver whose spectral response is matched to the spectral content of the transmitted waveform

Megahertz (MHz): millions (10^6) of cycles per second

Megawatt (MW): millions (10^6) of watts

Microseconds (μsec): one one-millionth (10^{-6}) of a second

Microwatt (μW): one one-millionth (10^{-6}) of a watt

Milliradian (mrad): an angle measure of one one-thousandth of a radian, that is, 0.0573°

Millisecond (msec): one one-thousandth (10^{-3}) of a second

Milliwatt (mW): one one-thousandth (10^{-3}) of a watt

MMIC: monolithic microwave integrated circuit; refers to an all solid state array element integrated on a single piece of substrate

Modulation: the impression upon the radio frequency carrier of the signal fluctuations

Monopulse tracking: deriving out of a single pulse all the information necessary to obtain angle measurements

Moving target indication (MTI): the use of the Doppler content of the radar returns to achieve cancellation of clutter at zero range rate (or some other specific range rate)

MTI cancellers: the electronic circuits that accomplish the clutter cancellation for MTI

Newtonian trajectories: flight paths that have no forces acting on them except the forces of gravity

Noise: unwanted, sometimes random, electromagnetic energy that mixes with and interferes with the wanted signal energy

Normalize: to refer data to a convenient or common reference point and apply a standard interval from that point

North filter: a filter that gives an optimum response for signal against Gaussian noise, also called a *matched filter;* named after the person who first analyzed it

Nutate: to nod or wobble slightly

Nutation: a slow or small rotation superimposed on a more rapid or larger one

Orthogonal polarization: orientation of the electric field of electromagnetic radiation (including light) at right angles to a reference electric field

Oscillators: electric circuits that produce sinusoidal waves (waves that rise and fall smoothly and harmonically)

Over-the-horizon radar: radar that uses ionospheric reflection to detect targets beyond the horizon, operating in the frequency band that supports the phenomenon: the HF (high-frequency) band

Parabolic antenna: a device that radiates and focuses electromagnetic energy by use of the shape of the curve of a parabola

Paraboloid: a surface made up by revolving a parabola about its axis; the shape of a parabolic antenna

Parameter: an arbitrary constant that may take on or be assigned various values

Passive ECM: the use of such things as chaff and decoys to defeat radar or communications passively

Pedestal: the structure that supports a radar antenna

Pencil beam: electromagnetic energy focused to a narrow angle in two dimensions as with a searchlight beam

Phase array: an antenna that forms a beam by assigning phases to a number of separate radiating elements

Phase locked: phase held at a constant phase relationship by being tied electrically to a reference oscillator, usually a stable local oscillator

Phase shifter: electronic circuits that shift phase in discrete, predetermined steps

Plan view: the perspective from above

Plasma frequency: the rate of vibration of the electrons in an ionized medium

Polarization: the alignment of the electric field with respect to the propagation vector

Polarize: to align the electric vectors of electromagnetic radiation

Potted: physically fixed in position by being embedded in a resin or other seal

Power-aperture: the product of a radar's power and the physical aperture of its antenna

Power spectral density: the power present in the frequency constituents of a function (usually a plot of these quantities)

Propagation: the outward spreading of electromagnetic waves

Pseudorandom code: a series of random quantities (numbers or levels) whose randomness is unproven; or, random quantities that are replicated when generated for later autocorrelation

Pulse-burst waveform: a train of pulses

Pulse compression: a technique by which more bandwidth is inserted into a pulse than its duration would imply it could contain

Pulse Doppler: a radar or a waveform that uses a series of pulses that are processed for their range rate content

Quanta: small discrete packages of energy

Quantum mechanics: a theory of physics that treats the interactions of radiation and matter; its name derives from the observation that these interactions take place only in discrete packages

Radar: an instrument for radio detection and ranging

Radar altimeter: a radar that measures altitude

Radar cross section: a measure of the amount of electromagnetic energy a radar target intercepts and scatters back toward the radar

Radar signature: identifying features or patterns in a target's radar cross section

Radial velocity: the component of velocity vector on the radial toward or away from a point, for example, along the line of sight from a radar

Radian: form to express an angle in radians

Radian frequency: to express frequency in radians per second rather than in cycles or degrees per second

Random variable: in statistics, a function defined over a sample space; a nondeterministic variable

Range error: the inaccuracy in a range measurement

Range rate: the magnitude of the projection of the radar-to-target velocity vector (including both radar and target velocity vectors) on the radar-to-target range vector

Range rate ambiguities: foldover of range rates in the signal processor, requiring additional processing to determine the actual range rates of the targets

Range rate resolution: the ability to differentiate two targets in range rate

Range rate spectrum: the frequencies generated by a moving target

Range rate tracking: following a target in range rate

Range resolution: the ability to differentiate two targets in range

Range sidelobes: the residues of a pulse compression waveform that spill over into and contaminate adjacent range cells

Range tracking: following a target in range

Rayleigh region: a region where electromagnetic energy is scattering from targets that are smaller than a wavelength; named after Lord Rayleigh, who calculated the magnitude of that scattering

Rectification: processing of electric waves that swing both positive and negative into waves that swing only positive

Refraction: the bending of electromagnetic waves that takes place as the medium varies over the propagation path

Resolution bin or cell: the extent of the region (in angle, range, or range rate) filled by the return from a single-point target

Resonance region: the region where the wavelength of the scattered electromagnetic energy is of the same order as the characteristic dimension of the target

Root-mean-square (RMS): the square root of the average of the sum of the squares of a series of values

Scanning: moving a radar beam around the sky to cover a prescribed region

Scattering: the reflection of electromagnetic energy from a target

Scintillation: rapid variations in the level of scattering from a target

Semi-isotropic radiation: emission from a point source of equal levels of energy in all directions within a hemisphere

Servo drive: the power provided to equipment by a technique that uses system output to determine partially what the input will be

Servo loops: the electric circuits that sample system output and refer it back to the input

Servomechanism: an automatic device that uses feedback to control systems, usually by inserting at the input control signals derived from samples of the output

SHF: super high frequency; frequency band

Sidelobe: the unwanted, out-of-place residue of an antenna pattern or waveform

Sidelobe jamming: the act of sending interfering and disrupting signals into the radar antenna sidelobes

Side-looking radar: a radar that points at an angle substantially off the velocity vector of its carrier, hence, another name for a synthetic aperture radar

Signal-processing gain: the improvement in signal-to-noise ratio that results when various processing techniques are applied

Signal-to-noise ratio: the ratio of the RMS signal power to the RMS noise power at the output of a radar receiver

Sinusoid: sine or cosine plots

Skip distance: the range at which a radio wave propagated from the Earth toward the ionosphere returns to the Earth's surface

Solid angle: an area in angle, a number of square degrees or steradians

Spark gap: a mechanism by which electromagnetic energy is radiated by building up the field intensity across a gap until the intervening medium breaks down and a spark occurs

Specular returns: radar reflections of high amplitude and short duration, like flashes from a mirror

Spherical aberration: distortion in a wave front, resulting when it is reflected off a spherical surface rather than a parabola

Spherics: bursts of electromagnetic interference caused by disturbances in the atmosphere

Squint angle: the angle off the velocity vector of its carrier that a synthetic aperture radar may be pointed

STC: sensitivity time control: attenuating the radar return signal exponentially as a function of time to keep near-in returns from saturating the receiver

Steradian: the solid angle subtended by an area on the surface of a sphere equal to its radius squared

Sub-array factor: the component of an array antenna gain pattern due to a group of elements

Sub-cutter visibility: the capability of a radar processor to suppress clutter

Sum beam: the adding together of two slightly displaced antenna beams single beam that is the sum of the two, as with monopulse tracking

Surveillance: providing coverage of or keeping watch over

Synthetic aperture radar (SAR): a system that uses movement of an antenna beam across an area to synthesize a very large aperture and provide very good angle, and thus cross-range, resolution

Synthetic display: an uncluttered presentation obtained by distilling essential formation from noisy data and rejecting the latter

Tapering: varying the density of the elements in an array or the power by the array elements in order to obtain a tailored aperture illumination control the array far field pattern

Thermal noise: unwanted signals generated by the heat inherent in the of a radar system, a major factor in the first stage of radio frequency amplification

Threshold: a level established for decision-making as to whether or not a desired signal present

Time-delay networks: circuits in array radars that point the antenna various directions by progressively delaying the radiation of the signal array elements

Time domain: viewing a multidimensional function in its time dimension

Time sidelobes: the spreading residues in range of pulse compression forms, also called *range sidelobes*

Tracking: following selected targets over time, whether in range, angle, or range rate

Tracking gate: a region of special attention around a target being tracked with appropriate logic to keep the gate moving with the target

Track-while-scan (TWS): the radar operation in which targets are followed by the routine scanning function, differentiated from an operation where changes its routine to do tracking

Transponders: equipment that generates and radiates energy as a resulting a signal; it may reradiate an enhanced version of the signal received new information

Truncated cone: a conical shape that has been cut off at right angles to the axis of the cone at some arbitrary point

UHF: ultra high frequency; frequency band

Unambiguous range: the range associated with the time between radar pulses, that is, the maximum distance at which the round trip to a target can be completed before the next pulse is sent

Unambiguous range rate: a waveform design feature that provides that the range rates of the targets of interest will not fold over in the signal processor

Variance: a statistical quantity indicating the spread of a distribution about its mean

Vertical polarization: by convention, an electromagnetic wave whose electric vector is perpendicular to the Earth's surface

Vertical return: that part of an airborne radar signal that returns from directly beneath the aircraft where the angle of incidence is 90°

VHF: very high frequency; frequency band

Video integration: adding up signals after they have been through the envelope detector when only the envelope of the original signal remains

Waveforms: various shapes of radar pulses or groups of pulses designed to accomplish particular objectives

Weighting: changing the shapes of pulses or the envelopes of groups of pulses to tailor their sidelobes, usually by rounding the ends with a slowly varying function, such as a cosine

Woodward ambiguity function: the surface that results when responses to waveforms are mapped in both range rate and time; named after the person who led in analyzing ambiguity functions