CHAPTER 1
AN INTRODUCTION TO RADAR

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1.1 DESCRIPTION OF RADAR

The basic concept of radar is relatively simple even though in many instances its practical implementation is not. A radar operates by radiating electromagnetic energy and detecting the echo returned from reflecting objects (targets). The nature of the echo signal provides information about the target. The range, or distance, to the target is found from the time it takes for the radiated energy to travel to the target and back. The angular location of the target is found with a directive antenna (one with a narrow beamwidth) to sense the angle of arrival of the echo signal. If the target is moving, a radar can derive its track, or trajectory, and predict the future location. The shift in frequency of the received echo signal due to the doppler effect caused by a moving target allows a radar to separate desired moving targets (such as aircraft) from undesired stationary targets (such as land and sea clutter) even though the stationary echo signal may be many orders of magnitude greater than the moving target. With sufficiently high resolution, a radar can discern something about the nature of a target's size and shape. Radar resolution may be obtained in range or angle, or both. Range resolution requires large bandwidth. Angle resolution requires (electrically) large antennas. Resolution in the cross-range dimension is usually not as good as the resolution that can be obtained in range. However, when there is relative motion between the individual parts of a target and the radar, it is possible to use the inherent resolution in doppler frequency to resolve in the cross-range dimension. The cross-range resolution of a synthetic aperture radar (SAR) for imaging a scene such as terrain can be explained as being due to resolution in doppler, although a SAR is usually thought of as generating a large "synthetic" antenna by storing received signals in a memory. The two views—doppler resolution and synthetic antenna—are equivalent. Resolution in the doppler domain is a natural way to envision the cross-range resolution achieved by the inverse synthetic aperture radar (ISAR) used for the imaging of a target.

Radar is an active device in that it carries its own transmitter and does not depend on ambient radiation, as do most optical and infrared sensors. Radar can detect relatively small targets at near or far distances and can measure their range with precision in all weather, which is its chief advantage when compared with other sensors.

The principle of radar has been applied from frequencies of a few megahertz

(HF, or high-frequency region of the electromagnetic spectrum) to well beyond the optical region (laser radar). This is a frequency extent of about 1 billion to 1. The particular techniques for implementing a radar differ greatly over this range of frequencies, but the basic principles remain the same.

Radar was originally developed to satisfy the needs of the military for surveillance and weapon control. Military applications have funded much of the development of its technology. However, radar has seen significant civil applications for the safe travel of aircraft, ships, and spacecraft; the remote sensing of the environment, especially the weather; and law enforcement and many other applications.

Radar Block Diagram. The basic parts of a radar system are illustrated in the simple block diagram of Fig. 1.1. (Other examples of radar block diagrams can be found throughout the handbook.) The radar signal, usually a repetitive train of short pulses, is generated by the transmitter and radiated into space by the antenna. The duplexer permits a single antenna to be time-shared for both transmission and reception. Reflecting objects (targets) intercept and reradiate a portion of the radar signal, a small amount of which is returned in the direction of the radar. The returned echo signal is collected by the radar antenna and amplified by the receiver. If the output of the radar receiver is sufficiently large, detection of a target is said to occur. A radar generally determines the location of a target in range and angle, but the echo signal also can provide information about the nature of the target. The output of the receiver may be presented on a display to an operator who makes the decision as to whether or not a target is present, or the receiver output can be processed by electronic means to automatically recognize the presence of a target and to establish a track of the target from detections made over a period of time. With automatic detection and track (ADT) the operator usually is presented with the processed target track rather than the raw radar detections. In some applications, the processed radar output might be used to directly control a system (such as a guided missile) without any operator intervention.

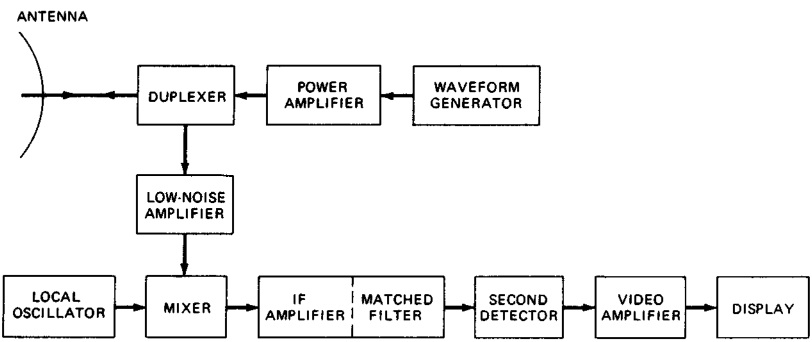

FIG. 1.1 Simple block diagram of a radar employing a power amplifier transmitter and a superheterodyne receiver.

The operation of the radar is described in more detail, starting with the transmitter.

Transmitter. The transmitter (Chap. 4) in Fig. 1.1 is shown as a power amplifier, such as a klystron, traveling-wave tube, crossed-field amplifier, or solid-state device (Chap. 5). A power oscillator such as a magnetron also can be used as the transmitter; but the magnetron usually is of limited average power compared with power amplifiers, especially the klystron, which can produce much larger average power than can a magnetron and is more stable. (It is the *average* power, rather than the *peak* power, which is the measure of the capability of a radar.) Since the basic waveform is generated at low power before being delivered to the power amplifier, it is far easier to achieve the special waveforms needed for pulse compression and for coherent systems such as moving-target indication (MTI) radar and pulse doppler radar. Although the magnetron oscillator can be used for pulse compression and for MTI, better performance can be obtained with a power amplifier configuration. The magnetron oscillator might be found in systems where simplicity and mobility are important and where high average power, good MTI performance, or pulse compression is not required.

The transmitter of a typical ground-based air surveillance radar might have an average power of several kilowatts. Short-range radars might have powers measured in milliwatts. Radars for the detection of space objects (Chap. 22) and HF over-the-horizon radars (Chap. 24) might have average powers of the order of a megawatt.

The radar equation (Sec. 1.2 and Chap. 2) shows that the range of a radar is proportional to the fourth root of the transmitter power. Thus, to double the range requires that the power be increased by 16. This means that there often is a practical, economical limit to the amount of power that should be employed to increase the range of a radar.

Transmitters not only must be able to generate high power with stable waveforms, but they must often operate over a wide bandwidth, with high efficiency and with long, trouble-free life.

Duplexer. The duplexer acts as a rapid switch to protect the receiver from damage when the high-power transmitter is on. On reception, with the transmitter off, the duplexer directs the weak received signal to the receiver rather than to the transmitter. Duplexers generally are some form of gas-discharge device and may be used with solid-state or gas-discharge receiver protectors. A solid-state circulator is sometimes used to provide further isolation between the transmitter and the receiver.

Antenna. The transmitter power is radiated into space by a directive antenna which concentrates the energy into a narrow beam. Mechanically steered parabolic reflector antennas (Chap. 6) and planar phased arrays (Chap. 7) both find wide application in radar. Electronically steered phased array antennas (Chap. 7) are also used. The narrow, directive beam that is characteristic of most radar antennas not only concentrates the energy on target but also permits a measurement of the direction to the target. A typical antenna beamwidth for the detection or tracking of aircraft might be about 1 or 2°. A dedicated tracking radar (Chap. 18) generally has a symmetrical antenna which radiates a pencil-beam pattern. The usual ground-based air surveillance radar that provides the range and azimuth of a target generally uses a mechanically rotated reflector antenna with a fan-shaped beam, narrow in azimuth and broad in elevation. Airborne radars and surface-based 3D air surveillance radars (those that rotate mechanically in azimuth to measure the azimuth angle but use some form of electronic steering or beamforming to obtain the elevation angle, as discussed in Chap. 20) often employ planar array apertures. Mechanical scanning of the radar antenna is usually quite acceptable for the vast majority of radar applications. When it is necessary to scan the beam more quickly than can be achieved with mechanical scanning and when high cost can be tolerated, the electronically steered phased array antenna can be employed. (Beam steering with electronically steered phased arrays can be accomplished in microseconds or less if necessary.)

The size of a radar antenna depends in part on the frequency, whether the radar is located on the ground or on a moving vehicle, and the environment in which it must operate. The lower the frequency, the easier it is to produce a physically large antenna since the mechanical (and electrical) tolerances are proportional to the wavelength. In the ultrahigh-frequency (UHF) band, a *large* antenna (either reflector or phased array) might have a dimension of 100 ft or more. At the upper microwave frequencies (such as X band), radar antennas greater than 10 or 20 ft in dimension can be considered large. (Larger antennas than the above examples have been built, but they are not the norm.) Although there have been microwave antennas with beamwidths as small as 0.05°, radar antennas rarely have beamwidths less than about 0.2°. This corresponds to an aperture of approximately 300 wavelengths (about 31 ft at X band and about 700 ft at UHF).

Receiver. The signal collected by the antenna is sent to the receiver, which is almost always of the superheterodyne type (Chap. 3). The receiver serves to (1) separate the desired signal from the ever-present noise and other interfering signals and (2) amplify the signal sufficiently to actuate a display, such as a cathode-ray tube, or to allow automatic processing by some form of digital device. At microwave frequencies, the noise at the receiver output is usually that generated by the receiver itself rather than external noise which enters via the antenna. The input stage of the receiver must not introduce excessive noise which would interfere with the signal to be detected. A transistor amplifier as the first stage offers acceptably low noise for many radar applications. A first-stage receiver noise figure (defined in Sec. 1.2) might be, typically, 1 or 2 dB. A low-noise receiver front end (the first stage) is desirable for many civil applications, but in military radars the lowest noise figure attainable might not always be appropriate. In a high-noise environment, whether due to unintentional interference or to hostile jamming, a radar with a low-noise receiver is more susceptible than one with higher noise figure. Also, a low-noise amplifier as the front end generally will result in the receiver having less dynamic range—something not desirable when faced with hostile electronic countermeasures (ECM) or when the doppler effect is used to detect small targets in the presence of large clutter. When the disadvantages of a low-noise-figure receiver are to be avoided, the RF amplifier stage is omitted and the mixer stage is employed as the receiver front end. The higher noise figure of the mixer can then be compensated by an equivalent increase in the transmitter power.

The mixer of the superheterodyne receiver translates the receiver RF signal to an intermediate frequency. The gain of the intermediate-frequency (IF) amplifier results in an increase of the receiver signal level. The IF amplifier also includes the function of the matched filter: one which maximizes the output signal-to-noise ratio. Maximizing the signal-to-noise ratio at the output of the IF maximizes the detectability of the signal. Almost all radars have a receiver which closely approximates the matched filter.

The second detector in the receiver is an envelope detector which eliminates the IF carrier and passes the modulation envelope. When doppler processing is employed, as it is in CW (continuous-wave), MTI, and pulse doppler radars, the envelope detector is replaced by a phase detector which extracts the doppler frequency by comparison with a reference signal at the transmitted frequency.

There must also be included filters for rejecting the stationary clutter and passing the doppler-frequency-shifted signals from moving targets.

The video amplifier raises the signal power to a level where it is convenient to display the information it contains. As long as the video bandwidth is not less than half of the IF bandwidth, there is no adverse effect on signal detectability.

A threshold is established at the output of the video amplifier to allow the detection decision to be made. If the receiver output crosses the threshold, a target is said to be present. The decision may be made by an operator, or it might be done with an automatic detector without operator intervention.

Signal Processing. There has not always been general agreement as to what constitutes the signal-processing portion of the radar, but it is usually considered to be the processing whose purpose is to reject undesired signals (such as clutter) and pass desired signals due to targets. It is performed prior to the threshold detector where the detection decision is made. Signal processing includes the matched filter and the doppler filters in MTI and pulse doppler radar. Pulse compression, which is performed before the detection decision is made, is sometimes considered to be signal processing, although it does not fit the definition precisely.

Data Processing. This is the processing done after the detection decision has been made. Automatic tracking (Chap. 8) is the chief example of data processing. Target recognition is another example. It is best to use automatic tracking with a good radar that eliminates most of the unwanted signals so that the automatic tracker only has to deal with desired target detections and not undesired clutter. When a radar cannot eliminate all nuisance echoes, a means to maintain a constant false-alarm rate (CFAR) at the input to the tracker is necessary.

The CFAR portion of the receiver is usually found just before the detection decision is made. It is required to maintain the false-alarm rate constant as the clutter and/or noise background varies. Its purpose is to prevent the automatic tracker from being overloaded with extraneous echoes. It senses the magnitude of the radar echoes from noise or clutter in the near vicinity of the target and uses this information to establish a threshold so that the noise or clutter echoes are rejected at the threshold and not confused as targets by the automatic tracker.

Unfortunately, CFAR reduces the probability of detection. It also results in a loss in signal-to-noise ratio, and it degrades the range resolution. CFAR or its equivalent is necessary when automatic tracking computers cannot handle large numbers of echo signals, but it should be avoided if possible. When an operator is used to make the threshold decision, CFAR is not a necessity as in limited-capacity automatic systems because the operator can usually recognize echoes due to clutter or to increased noise (such as jamming) and not confuse them with desired targets.

Displays. The display for a surveillance radar is usually a cathode-ray tube with a PPI (plan position indicator) format. A PPI is an intensity-modulated, maplike presentation that provides the target's location in polar coordinates (range and angle). Older radars presented the video output of the receiver (called *raw video*) directly to the display, but more modern radars generally display *processed* video, that is, after processing by the automatic detector or the automatic detector and tracker (ADT). These are sometimes called *cleaned-up displays* since the noise and background clutter are removed.

Radar Control. A modern radar can operate at different frequencies within its band, with different waveforms and different signal processing, and with different polarizations so as to maximize its performance under different environmental conditions. These radar parameters might need to be changed according to the local weather, the clutter environment (which is seldom uniform in azimuth and range), interference to or from other electronic equipment, and (if a military radar) the nature of the hostile ECM environment. The different parameters, optimized for each particular situation, can be programmed into the radar ahead of time in anticipation of the environment, or they can be chosen by an operator in real time according to the observed environmental conditions. On the other hand, a *radar control* can be made to automatically recognize when environmental conditions have changed and automatically select, without the aid of an operator, the proper radar operating parameters to maximize performance.

Waveform. The most common radar waveform is a repetitive train of short pulses. Other waveforms are used in radar when particular objectives need to be achieved that cannot be accomplished with a pulse train. CW (a continuous sine wave) is employed on some specialized radars for the measurement of radial velocity from the doppler frequency shift. FM/CW (frequency-modulated CW) is used when range is to be measured with a CW waveform (Chap. 14). Pulse compression waveforms (Chap. 10) are used when the resolution of a short pulse but the energy of a long pulse is desired. MTI radars (Chaps. 15 and 16) with low pulse repetition frequencies (PRFs) and pulse doppler radars (Chap. 17) with high PRFs often use waveforms with multiple pulse repetition intervals in order to avoid range and/or doppler ambiguities.

1.2 RADAR EQUATION

Perhaps the single most useful description of the factors influencing radar performance is the radar equation which gives the range of a radar in terms of the radar characteristics. One form of this equation gives the received signal power P_r as

$$P_r = \frac{P_t G_t}{4\pi R^2} \times \frac{\sigma}{4\pi R^2} \times A_e \tag{1.1}$$

The right-hand side has been written as the product of three factors to represent the physical processes taking place. The first factor is the power density at a distance R meters from a radar that radiates a power of P_t watts from an antenna of gain G_t. The numerator of the second factor is the target cross section σ in square meters. The denominator accounts for the divergence on the return path of the electromagnetic radiation with range and is the same as the denominator of the first factor, which accounts for the divergence on the outward path. The product of the first two terms represents the power per square meter returned to the radar. The antenna of effective aperture area A_e intercepts a portion of this power in an amount given by the product of the three factors. If the maximum radar range R_{max} is defined as that which results in the received power P_r being equal to the receiver minimum detectable signal S_{min}, the radar equation may be written

$$R^4{}_{max} = \frac{P_t G_t A_e \sigma}{(4\pi)^2 S_{min}} \tag{1.2}$$

When the same antenna is used for both transmitting and receiving, the transmitting gain G_t and the effective receiving aperture A_e are related by $G_t = 4\pi A_e/\lambda^2$, where λ is the wavelength of the radar electromagnetic energy. Substituting into Eq. (1.2) gives two other forms of the radar equation:

$$R^4_{max} = \frac{P_t G_t^2 \lambda^2 \sigma}{(4\pi)^3 S_{min}} \tag{1.3a}$$

$$R^4_{max} = \frac{P_t A_e^2 \sigma}{4\pi \lambda^2 S_{min}} \tag{1.3b}$$

The examples of the radar equation given above are useful for rough computations of range performance but they are overly simplified and do not give realistic results. The predicted ranges are generally overly optimistic. There are at least two major reasons why the simple form of the radar equation does not predict with any accuracy the range of actual radars. First, it does not include the various losses that can occur in a radar. Second, the target cross section and the minimum detectable signal are statistical in nature. Thus the specification of the range must be made in statistical terms. The elaboration of the simple range equation to yield meaningful range predictions is the subject of Chap. 2. Although the range enters as the fourth power in Eq. (1.3), it can appear as the cube, as the square, or as the first power in specific situations, some of which are described later in this section and in other chapters.

In addition to its use for range prediction, the radar equation forms a good basis for preliminary system design by providing a guide to the possible tradeoffs among the various parameters that enter into radar performance.

The minimum detectable signal S_{min}, which appears in the radar equation, is a statistical quantity and must be described in terms of the probability of detection and the probability of a false alarm. This is discussed in more detail in Chap. 2; for present purposes it suffices to state that for a signal to be reliably detected it must be larger than noise (generally by 10 to 20 dB) at the point in the receiver where the detection decision is made. The minimum detectable signal can be expressed as the signal-to-noise ratio (S/N) required for reliable detection times the receiver noise. The receiver noise is expressed relative to the thermal noise that would be produced by an ideal receiver. The thermal noise is equal to kTB, where k is Boltzmann's constant, T is the temperature, and B is the receiver bandwidth. The receiver noise is the thermal noise multiplied by the factor F_n, the receiver noise figure. The receiver noise figure is measured relative to a reference temperature T_0 = 290 K (approximately room temperature), and the factor kT_0 becomes 4×10^{-21} W/Hz. The minimum detectable signal in the radar equation can be written

$$S_{min} = kT_0 B F_n \frac{S}{N} \tag{1.4}$$

Sometimes the factor $T_0 F_n$ is replaced with T_s, the system noise temperature.

The above discussion of the radar equation was in terms of the signal power. Although power is a well-understood characteristic of the usual radar waveform consisting of a rectangular pulse, with more complicated waveforms the total signal energy is often a more convenient measure of waveform detectability. It also is more appropriate for theoretical reasons. The ratio of signal energy to noise energy, denoted E/N_0, is a more fundamental parameter than the signal-to-noise (power) ratio in theoretical analyses based on statistical detection theory. No matter what the shape of the received waveform, if the receiver is designed as a matched filter the peak signal-to-noise (power) ratio at the output of the matched filter is $2E/N_0$.

For a rectangular pulse of width τ the signal power is E/τ and the noise power is N_0B, where E = signal energy, N_0 = noise energy, or noise power per unit bandwidth (provided the noise is uniform with frequency), and B = receiver bandwidth. With these substitutions, S_{min} becomes $kT_0F_n(E/N_0)/\tau$. Substituting into Eq. (1.2) gives

$$R^4_{max} = \frac{E_tG_t\,A_e\sigma}{(4\pi)^2kT_0F_n(E/N_0)} \tag{1.5}$$

where $E_t = P_t\tau$ is the energy contained in the transmitted waveform. Although Eq. (1.5) assumes a rectangular pulse, it can be applied to any waveform provided that E_t is interpreted as the energy contained in the transmitted waveform and that the receiver of noise figure F_n is designed as a matched filter. Some of the published results of radar detection theory give the probability of detection and probability of false alarm in terms of S/N rather than E/N_0. When these results assume optimum (matched-filter) processing, the required values of E/N_0 for use in the radar equation can be obtained from the published results for S/N or the visibility factor as described in Chap. 2.

The radar equation can be manipulated into various forms, depending on the particular application. Several examples are given below.

Tracking. In this situation the radar is assumed to track continuously or "searchlight" a target for an interval of time t_0. Equation (1.5) applies, so that the tracking-, or searchlighting-, radar equation is

$$R^4_{max} = \frac{P_{av}t_0G_t\,A_e\sigma}{4\pi kT_0F_n(E/N_0)} \tag{1.6}$$

where $P_{av}t_0 = E_t$. Thus, in a tracking radar that must "see" to a long range, the average power must be high, the time on target must be long, and the antenna must be of large electrical size (G_t) and large physical size (A_e). The frequency does not enter explicitly. Since it is easier mechanically to move a small antenna than a large one, tracking radars are usually found at the higher frequencies, where small apertures can have high gain and thus an adequate $G_t\,A_e$ product.

The radar equation is based on detectability. A tracking radar must also be designed for good angular accuracy. Good angle accuracy is achieved with narrow beamwidths (large G_t) and with high E/N_0 (large A_e). Thus a large $G_t\,A_e$ product is consistent with good tracking accuracy as well as good detectability.

Volume Search. Assume that the radar must search an angular volume of Ω steradians in the time t_s. If the antenna beam subtends an angle of Ω_b steradians, the antenna gain G_t is approximately $4\pi/\Omega_b$. If the antenna beam dwells a time t_0 in each direction subtended by the beam, the total scan time is $t_s = t_0\Omega/\Omega_b$. Substituting these expressions into Eq. (1.5) and noting that $E_t = P_{av}t_0$,

$$R^4_{\max} = \frac{P_{av} A_e \sigma}{4\pi k T_0 F_n (E/N_0)} \frac{t_s}{\Omega} \tag{1.7}$$

Thus for a volume search radar the two important parameters for maximizing range are the average transmitter power and the antenna aperture. Any decrease in time to scan the volume or any increase in the volume searched must be accompanied by a corresponding increase in the product $P_{av} A_e$. Note that the frequency does not enter explicitly.

Jamming. When the detection of the radar signal is limited by an external noise source, such as a deliberate noise jammer rather than by receiver noise, the parameters of importance in determining range performance are slightly different from those presented above (Chap. 9). The receiver noise power per unit bandwidth is now that determined by the jammer rather than the receiver noise figure. When a radar is performing volume search and jamming power enters from a particular direction via the sidelobes, the maximum range can be written

$$R^4_{\max} = \frac{P_{av}}{g_s} \frac{t_s}{\Omega} \frac{\sigma}{E/N_0} \frac{R_J{}^2 B_J}{P_J G_J} \tag{1.8}$$

where g_s = sidelobe level relative to main beam (number less than unity)
R_J = jammer range
B_J = jammer bandwidth
P_J = jammer power
G_J = jammer antenna gain

and E/N_0 is the ratio of signal energy to noise power per unit bandwidth necessary for reliable detection. The parameter of importance is the average power. The antenna sidelobes are also important. This equation was derived by substituting for kT_0F_n in Eq. (1.7) the jamming noise power per unit bandwidth that would enter the radar receiving-antenna sidelobes. It applies only when the normal receiver noise is negligible compared with the jamming noise.

When the radar is searchlighting a target with a jammer, a mode of operation sometimes called *burnthrough*, the range becomes

$$R^2_{\max} = \frac{P_{av} t_0 G_t}{4\pi} \frac{\sigma}{E/N_0} \frac{B_J}{P_J G_J} \tag{1.9}$$

The important radar parameters are the average power, the time of observation, and the transmitting-antenna gain. The maximum range is squared rather than raised to the fourth power as in other forms of the radar equation. Note that in neither jamming example does the antenna aperture area enter explicitly. A large aperture collects more signal, but it also collects more jamming noise. The receiver noise figure does not enter because it is assumed that the jamming noise is considerably larger than the receiver noise. Thus in a noisy environment one might not benefit from the effort to design a receiver with the ultimate in sensitivity. The above two examples of jamming radar equations are simplifications. Other variations are possible.

Clutter. When the radar must detect a small target located on the surface of the sea or land, the interfering unwanted clutter echoes can severely limit the detectability of the target. When clutter power dominates receiver noise power, the range equation simply reduces to an expression for the signal-to-clutter ratio. This ratio is equal to the ratio of the target cross section to the clutter cross section. If clutter is distributed more or less uniformly, the clutter echo will depend on the area illuminated by the radar resolution cell. Surface (ground or sea) clutter is described by the ratio of the clutter echo to the area illuminated by the radar. This normalized clutter coefficient is denoted σ^0.

Consider a pulse radar viewing the target and the clutter at low grazing angles. If single-pulse detection is assumed, the signal-to-clutter ratio is

$$\frac{S}{C} = \frac{\sigma}{\sigma^0 R \theta_b (c\tau/2) \sec \phi} \tag{1.10}$$

or

$$R_{\max} = \frac{\sigma}{(S/C)_{\min} \sigma^0 \theta_b (c\tau/2) \sec \phi}$$

where R = range to clutter patch
θ_b = azimuth beamwidth
c = velocity of propagation
τ = pulse width
ϕ = grazing angle

The clutter patch is assumed to be determined in azimuth by the width of the antenna beam and in the range coordinate by the pulse width. The ratio S/C takes a role similar to the ratio E/N_0 for thermal noise. It must be of sufficient magnitude to achieve reliable detection. The clutter statistics generally differ from the statistics of thermal noise but, as a first guess when no other information is available, the required values of S/C might be taken to be those of E/N_0. It is significant that the range dependence enters linearly rather than as the fourth power. Thus for detection of a target in clutter the radar beam should be narrow and the pulse width should be short. With assumptions other than those above, the important radar parameters for detection of targets in clutter might be different. If n hits are received per scan and if the clutter is correlated from pulse to pulse, no improvement in S/C is obtained as it would be if thermal noise, rather than clutter, were the limitation.

1.3 INFORMATION AVAILABLE FROM THE RADAR ECHO

Although the name *radar* is derived from *ra*dio *d*etection *a*nd *r*anging, a radar is capable of providing more information about the target than is implied by its name. *Detection* of a target signifies the discovery of its presence. It is possible to consider *detection* independently of the process of information extraction, but it is not often that one is interested in knowing only that a target is present without knowing something about its location in space and its nature. The extraction of useful target information is therefore an important part of radar operation.

The ability to consider *detection* independent of *information* extraction does not mean that there is no relation between the two. The extraction of information generally requires a matched filter, or its equivalent, for optimum processing. The more information that is known about the target a priori, the more efficient will be the detection. For example, if the target location were known, the antenna could be pointed in the proper direction and energy or time need not be wasted searching empty space. Or, if the relative velocity were known, the receiver could be pretuned to the correct received frequency, negating the need to search the frequency band over which the doppler shift might occur.

The usual radar provides the location of a target in range and angle. The rate of change of target location can also be measured from the change in range and angle with time, from which the track can be established. In many radar applications a *detection* is not said to occur until its track has been established.

A radar with sufficient resolution in one or more coordinates can determine a target's size and shape. Polarization allows a measure of the symmetry of a target. In principle, a radar can also measure the surface roughness of a target and determine something about its dielectric properties.

Range. The ability to determine range by measuring the time for the radar signal to propagate to the target and back is probably the distinguishing and most important characteristic of conventional radar. No other sensor can measure range to the accuracy possible with radar, at such long ranges, and under adverse weather conditions. Surface-based radars can be made to determine the range of an aircraft to an accuracy of a few tens of meters at distances limited only by the line of sight, generally 200 to 250 nmi. Radar has demonstrated its ability to measure interplanetary distances to an accuracy limited only by the accuracy to which the velocity of propagation is known. At more modest distances, the measurement of range can be made with a precision of a few centimeters.

The usual radar waveform for determining range is the short pulse. The shorter the pulse, the more precise can be the range measurement. A short pulse has a wide spectral width (bandwidth). The effect of a short pulse can be obtained with a long pulse whose spectral width has been increased by phase or frequency modulation. When passed through a *matched filter*, the output is a compressed pulse whose duration is approximately the reciprocal of the spectral width of the modulated long pulse. This is called *pulse compression* and allows the resolution of a short (wide-bandwidth) pulse with the energy of a long pulse. A CW waveform with frequency or phase modulation can also provide an accurate range measurement. It is also possible to measure the range of a single target by comparing the phase difference between two or more CW frequencies. Range measurement with CW waveforms has been widely employed, as in aircraft radar altimeters and surveying instruments.

Radial Velocity. From successive measurements of range the rate of change of range, or radial velocity, can be obtained. The doppler frequency shift of the echo signal from a moving target also provides a measure of radial velocity. However, the doppler frequency measurement in many pulse radars is highly ambiguous, thus reducing its utility as a direct measurement of radial velocity.

When it can be used, it is often preferred to successive range measurements since it can achieve a more accurate measurement in a shorter time.

Any measurement of velocity, whether by the rate of change of range or by the doppler frequency shift, requires time. The longer the time of observation, the more accurate can be the measurement of velocity. (A longer observation time also can increase the signal-to-noise ratio, another factor that results in increased accuracy.) Although the doppler frequency shift is used in some applications to measure radial velocity (as, for example, in such diverse applications as the police speed meter and satellite surveillance radars), it is more widely employed as the basis for sorting moving targets from unwanted stationary clutter echoes, as in MTI, AMTI (airborne MTI), pulse doppler, and CW radars.

Angular Direction. The direction of a target is determined by sensing the angle at which the returning wavefront arrives at the radar. This is usually accomplished with a directive antenna, i.e., one with a narrow radiation pattern. The direction in which the antenna points when the received signal is a maximum indicates the direction of the target. This, as well as other methods for measuring angle, assumes that the atmosphere does not perturb the straight-line propagation of the electromagnetic waves.

The direction of the incident waveform can also be determined by measuring the phase difference between two separated receiving antennas, as with an interferometer. Phase-comparison monopulse also is based on the phase measurement of signals in two separated antennas. The amplitude-comparison monopulse determines the angle of arrival by comparing the amplitudes of the signals received in two squinted beams generated by a single antenna.

The accuracy of the angle of arrival depends on the extent of the antenna aperture. The wider the antenna, the narrower the beamwidth and the better the accuracy.

The angle of arrival, or target direction, is not strictly a radar measurement (as are the range and radial velocity) if a radar measurement is defined as one obtained by comparing the reflected echo signal with the transmitted signal. The determination of angle basically involves only the one-way path. Nevertheless, the angle measurement is an integral part of most surveillance and tracking radars.

Size. If the radar has sufficient resolution, it can provide a measurement of the target's extent, or size. Since many targets of interest have dimensions of several tens of meters, resolution must be several meters or less. Resolutions of this order can be readily obtained in the range coordinate. With conventional antennas and the usual radar ranges, the angular resolution is considerably poorer than what can be achieved in range. However, target resolution in the cross-range (angle) dimension can be obtained comparable with that obtained in range by the use of resolution in the doppler frequency domain. This requires that there be relative motion between the various parts of the target and the radar. It is the basis for the excellent cross-range resolution obtained in a SAR in which the relative motion between target and radar occurs because of the travel of the aircraft or spacecraft on which the radar is mounted. In an ISAR (inverse synthetic aperature radar) the relative motion is provided by the movement of the target.

Shape. The size of a target is seldom of interest in itself, but its shape and its size are important for recognizing one type of target from another. A high-resolution radar that obtains the profile of a target in both range and cross range (as do SAR and ISAR) provides the size and shape of the target. The shape of an object can also be obtained by tomography, in which a two-dimensional image of a three-dimensional object is reconstructed from the measurement of phase and amplitude, at different angles of observation. (The radar might rotate around the fixed object, or the radar can be fixed and the object rotated about its own axis.) Range resolution is not necessary with the coherent tomographic radar method.

As mentioned earlier, comparison of the scattered fields for different polarizations provides a measure of target asymmetry. It should be possible to distinguish targets with different aspect ratios (shapes), as for example, rods from spheres and spheres from aircraft. The complete exploitation of polarization requires the measurement of phase, as well as amplitude of the echo signal at two orthogonal polarizations and a cross-polarization component. Such measurements (which define the polarization matrix) should allow in principle the recognition of one class of target from another, but in practice it is not easy to do.

One characteristic of target *shape* is its surface roughness. This measurement can be of particular interest for echoes from the ground and the sea. Rough targets scatter the incident electromagnetic energy diffusely; smooth targets scatter specularly. By observing the nature of the backscatter as a function of the incident angle it should be possible to determine whether a surface is smooth or rough. Surface roughness is a relative measure and depends on the wavelength of the illuminating signal. A surface that appears rough at one wavelength might appear smooth when illuminated with longer-wavelength radiation. Thus another method for determining surface roughness is by varying the frequency of the illuminating radiation and observing the transition from specular to diffuse scatter. A direct method for determining roughness is to observe the scatter from the object with a resolution that can resolve the roughness scale.

Other Target Measurements. Just as the radial velocity can be determined from the *temporal* doppler frequency shift, it is possible to measure the tangential (cross-range) component of velocity. This can be obtained from the analogous *spatial* doppler frequency shift that expands or compresses the apparent antenna radiation pattern (just as the radial component of velocity can expand or compress the time waveform of a radar signal reflected from a moving target to produce a temporal doppler frequency shift). A measurement of tangential velocity requires a wide-baseline antenna, such as an interferometer. The measurement of tangential velocity has not seen application because the required baseline is often too wide for practical purposes.

It is also possible to note the change of a complex target's radial projection from the change of the received-signal amplitude with time. (A change in the radial projection of a target usually results in a change of the radar cross section.)

Vibrations of the target, rotation of the propellers of an aircraft, or the rotation of a jet engine can induce distinctive modulation on the radar echo which can be detected by a spectral analysis of the radar echo signal.

1.4 RADAR FREQUENCIES

There are no fundamental bounds on radar frequency. Any device that detects and locates a target by radiating electromagnetic energy and utilizes the echo scattered from a target can be classed as a radar, no matter what its frequency.

Radars have been operated at frequencies from a few megahertz to the ultraviolet region of the spectrum. The basic principles are the same at any frequency, but the practical implementation is widely different. In practice, most radars operate at microwave frequencies, but there are notable exceptions.

Radar engineers use letter designations, as shown in Table 1.1, to denote the general frequency band at which a radar operates. These letter bands are universally used in radar. They have been officially accepted as a standard by the Institute of Electrical and Electronics Engineers (IEEE) and have been recognized by the U.S. Department of Defense. Attempts have been made in the past to subdivide the spectrum into other letter bands (as for waveguides and for ECM operations), but the letter bands in Table 1.1 are the only ones that should be used for radar.

The original code letters (P, L, S, X, and K) were introduced during World War II for purposes of secrecy. After the need for secrecy no longer existed, these designations remained. Others were later added as new regions of the spectrum were utilized for radar application. (The nomenclature *P band* is no longer in use. It has been replaced with *UHF*.)

Letter bands are a convenient way to designate the general frequency range of a radar. They serve an important purpose for military applications since they can describe the frequency band of operation without using the exact frequencies at which the radar operates. The exact frequencies over which a radar operates should be used in addition to or instead of the letter bands whenever proper to do so.

TABLE 1.1 Standard Radar-Frequency Letter-Band Nomenclature*

Band designation	Nominal frequency range	Specific frequency ranges for radar based on ITU assignments for Region 2
HF	3 MHz–30 MHz	
VHF	30 MHz–300 MHz	138 MHz–144 MHz 216 MHz–225 MHz
UHF	300 MHz–1000 MHz	420 MHz–450 MHz 890 MHz–942 MHz
L	1000 MHz–2000 MHz	1215 MHz–1400 MHz
S	2000 MHz–4000 MHz	2300 MHz–2500 MHz 2700 MHz–3700 MHz
C	4000 MHz–8000 MHz	5250 MHz–5925 MHz
X	8000 MHz–12,000 MHz	8500 MHz–10,680 MHz
K_u	12.0 GHz–18 GHz	13.4 GHz–14.0 GHz 15.7 GHz–17.7 GHz
K	18 GHz–27 GHz	24.05 GHz–24.25 GHz
K_a	27 GHz–40 GHz	33.4 GHz–36.0 GHz
V	40 GHz–75 GHz	59 GHz–64 GHz
W	75 GHz–110 GHz	76 GHz–81 GHz 92 GHz–100 GHz
mm	110 GHz–300 GHz	126 GHz–142 GHz 144 GHz–149 GHz 231 GHz–235 GHz 238 GHz–248 GHz

*From IEEE Standard 521-1984.

The International Telecommunications Union (ITU) assigns specific frequency bands for radiolocation (radar) use. These are listed in the third column of Table 1.1. They apply to ITU Region 2, which encompasses North and South America. Slight differences exist in the other two ITU regions. Although L band, for example, is shown in the second column of the table as extending from 1000 to 2000 MHz, in practice an L-band radar would be expected to be found somewhere between 1215 and 1400 MHz, the frequency band actually assigned by the ITU.

Each frequency band has its own particular characteristics that make it better for certain applications than for others. In the following, the characteristics of the various portions of the electromagnetic spectrum at which radars have been or could be operated are described. The divisions between the frequency regions are not as sharp in practice as the precise nature of the nomenclature.

HF (3 to 30 MHz). Although the first operational radars installed by the British just prior to World War II were in this frequency band, it has many disadvantages for radar applications. Large antennas are required to achieve narrow beamwidths, the natural ambient noise level is high, the available bandwidths are narrow, and this portion of the electromagnetic spectrum is widely used and restrictively narrow. In addition, the long wavelength means that many targets of interest might be in the Rayleigh region, where the dimensions of the target are small compared with the wavelength; hence, the radar cross section of targets small in size compared with the (HF) wavelength might be lower than the cross section at microwave frequencies.

The British used this frequency band, even though it had disadvantages, because it was the highest frequency at which reliable, readily available high-power components were then available. Ranges of 200 mi were obtained against aircraft. These were the radars that provided detection of hostile aircraft during the battle of Britain and were credited with allowing the limited British fighter resources to be effectively used against the attacking bomber aircraft. They did the job that was required.

Electromagnetic waves at HF have the important property of being refracted by the ionosphere so as to return to the earth at ranges from about 500 to 2000 nmi, depending on the actual condition of the ionosphere. This allows the over-the-horizon detection of aircraft and other targets. The long over-the-horizon ranges that are possible make the HF region of the spectrum quite attractive for the radar observation of areas (such as the ocean) not practical with conventional microwave radar.

VHF (30 to 300 MHz). Most of the early radars developed in the 1930s were in this frequency band. Radar technology at these frequencies represented a daring venture that pushed to the edge of technology known in the thirties. These early radars served quite well the needs of the time and firmly established the utility of radar.

Like the HF region, the VHF (very high frequency) region is crowded, bandwidths are narrow, external noise can be high, and beamwidths are broad. However, the necessary technology is easier and cheaper to achieve than at microwave frequencies. High power and large antennas are readily practical. The stable transmitters and oscillators required for good MTI are easier to achieve than at higher frequencies, and there is relative freedom from the blind speeds that limit the effectiveness of MTI as the frequency is increased. Reflections from rain are not a problem. With horizontal polarization over a good reflecting surface (such as the sea), the constructive interference between the direct wave and the wave reflected from the surface can result in a substantial increase in the maximum range against aircraft (almost twice the free-space range). However, a consequence of this increase in range due to constructive interference is that the accompanying destructive interference results in nulls in the coverage at other elevation angles and less energy at low angles. It is a good frequency for lower-cost radars and for long-range radars such as those for the detection of satellites. It is also the frequency region where it is theoretically difficult to reduce the radar cross section of most types of airborne targets.

In spite of its many attractive features, there have not been many applications of radar in this frequency range because its limitations do not always counterbalance its advantages.

UHF (300 to 1000 MHz). Much of what has been said regarding VHF applies to UHF. However, natural external noise is much less of a problem, and beamwidths are narrower than at VHF. Weather effects usually are not a bother. With a suitably large antenna, it is a good frequency for reliable long-range surveillance radar, especially for extraterrestrial targets such as spacecraft and ballistic missiles. It is well suited for AEW (airborne early warning), e.g., airborne radar that uses AMTI for the detection of aircraft. Solid-state transmitters can generate high power at UHF as well as offer the advantages of maintainability and wide bandwidth.

L Band (1.0 to 2.0 GHz). This is the preferred frequency band for land-based long-range air surveillance radars, such as the 200-nmi radars used for en route air traffic control [designated ARSR by the U.S. Federal Aviation Administration (FAA)]. It is possible to achieve good MTI performance at these frequencies and to obtain high power with narrow-beamwidth antennas. External noise is low. Military 3D radars can be found at L band, but they also are at S band. L band is also suitable for large radars that must detect extraterrestrial targets at long range.

S Band (2.0 to 4.0 GHz). Air surveillance radars can be of long range at S band, but long range usually is more difficult to achieve than at lower frequencies. The blind speeds that occur with MTI radar are more numerous as the frequency increases, thus making MTI less capable. The echo from rain can significantly reduce the range of S-band radars. However, it is the preferred frequency band for long-range weather radars that must make accurate estimates of rainfall rate. It is also a good frequency for medium-range air surveillance applications such as the airport surveillance radar (ASR) found at air terminals. The narrower beamwidths at this frequency can provide good angular accuracy and resolution and make it easier to reduce the effects of hostile main-beam jamming that might be encountered by military radars. Military 3D radars and height finding radars are also found at this frequency because of the narrower elevation beamwidths that can be obtained at the higher frequencies. Long-range airborne air surveillance pulse doppler radars, such as AWACS (Airborne Warning and Control System) also operate in this band.

Generally, frequencies lower than S band are well suited for air surveillance (detection and low-data-rate tracking of many aircraft within a large volume). Frequencies above S band are better for information gathering, such as high-data-rate precision tracking and the recognition of individual targets. If a single frequency must be used for both air surveillance and precision tracking, as in military air defense systems based on phased array multifunction radar, a suitable compromise might be S band.

C Band (4.0 to 8.0 GHz). This band lies between the S and X bands and can be described as a compromise between the two. It is difficult, however, to achieve long-range air surveillance radars at this or higher frequencies. It is the frequency where one can find long-range precision instrumentation radars used for the accurate tracking of missiles. This frequency band has also been used for multifunction phased array air defense radars and for medium-range weather radars.

X Band (8 to 12.5 GHz). This is a popular frequency band for military weapon control (tracking) radar and for civil applications. Shipboard navigation and piloting, weather avoidance, doppler navigation, and the police speed meter are all found at X band. Radars at this frequency are generally of convenient size and are thus of interest for applications where mobility and light weight are important and long range is not. It is advantageous for information gathering as in high-resolution radar because of the wide bandwidth that makes it possible to generate short pulses (or wideband pulse compression) and the narrow beamwidths that can be obtained with relatively small-size antennas. An X-band radar may be small enough to hold in one's hand or as large as the MIT Lincoln Laboratory Haystack Hill radar with its 120-ft-diameter antenna and average radiated power of about 500 kW. Rain, however, can be debilitating to X-band radar.

K_u, K, and K_a Bands (12.5 to 40 GHz). The original K-band radars developed during World War II were centered at a wavelength of 1.25 cm (24 GHz). This proved to be a poor choice since it is too close to the resonance wavelength of water vapor (22.2 GHz), where absorption can reduce the range of a radar. Later this band was subdivided into two bands on either side of the water-vapor absorption frequency. The lower frequency band was designated K_u, and the upper band was designated K_a. These frequencies are of interest because of the wide bandwidths and the narrow beamwidths that can be achieved with small apertures. However, it is difficult to generate and radiate high power. Limitations due to rain clutter and attenuation are increasingly difficult at the higher frequencies. Thus not many radar applications are found at these frequencies. However, the airport surface detection radar for the location and control of ground traffic at airports is at K_u band because of the need for high resolution. The disadvantages that characterize this band are not important in this particular application because of the short range.

Millimeter Wavelengths (above 40 GHz). Although the wavelength of K_a band is about 8.5 millimeters (a frequency of 35 GHz), the technology of K_a-band radar is more like that of microwaves than that of millimeter waves and is seldom considered to be representative of the millimeter-wave region. Millimeter-wave radar, therefore, is taken to be the frequency region from 40 to 300 GHz. The exceptionally high attenuation caused by the atmospheric oxygen absorption line at 60 GHz precludes serious applications in the vicinity of this frequency within the atmosphere. Therefore, the 94-GHz-frequency region (3-mm wavelength) is generally what is thought of as a "typical" frequency representative of millimeter radar.

The millimeter-wave region above 40 GHz has been further subdivided into letter bands in the IEEE Standard, as shown in Table 1.1. Although there has been much interest in the millimeter portion of the electromagnetic spectrum, there have been no operational radars above K_a band. High-power sensitive receivers and low-loss transmission lines are difficult to obtain at millimeter wavelengths, but such problems are not basic. The major reason for the limited utility of this frequency region is the high attenuation that occurs even in the "clear" atmosphere. The so-called propagation window at 94 GHz is actually of greater attenuation than the attenuation at the water-vapor absorption line at 22.2 GHz. The millimeter-wave region is more likely to be of interest for operation in space, where there is no atmospheric attenuation. It might also be considered for short-range applications within the atmosphere where the total attenuation is not large and can be tolerated.

Laser Frequencies. Coherent power of reasonable magnitude and efficiency, along with narrow directive beams, can be obtained from lasers in the infrared, optical, and ultraviolet region of the spectrum. The good angular resolution and range resolution possible with lasers make them attractive for target information-gathering applications, such as precision ranging and imaging. They have had application in military range finders and in distance measurement for surveying. They have been considered for use from space for measuring profiles of atmospheric temperature, water vapor, and ozone, as well as measuring cloud height and tropospheric winds. Lasers are not suitable for wide-area surveillance because of their relatively small physical aperture area. A serious limitation of the laser is its inability to operate effectively in rain, clouds, or fog.

1.5 RADAR NOMENCLATURE

Military electronic equipment, including radar, is designated by the Joint Electronics Type Designation System (JETDS), formerly known as the Joint Army-Navy Nomenclature System (AN System), as described in Military Standard MIL-STD-196D. The letter portion of the designation consists of the letters AN, a slant bar, and three additional letters appropriately selected to indicate where the equipment is installed, the type of equipment, and the purpose of the equipment. Table 1.2 lists the equipment indicator letters. Following the three letters are a dash and a numeral. The numeral is assigned in sequence for that particular combination of letters. Thus the designation AN/SPS-49 is for a shipboard surveillance radar. The number 49 identifies the particular equipment and indicates it is the forty-ninth in the SPS category to which a JETDS designation has been assigned. A suffix letter (A, B, C, etc.) follows the original designation for each modification where interchangeability has been maintained. A change in the power input voltage, phase, or frequency is identified by the addition of the letters X, Y, or Z to the basic nomenclature. When the designation is followed by a dash, the letter T, and a number, the equipment is designed for training. The letter V in parentheses added to the designation indicates variable systems (those whose functions may be varied through the addition or deletion of sets, groups, units, or combinations thereof). Experimental and developmental systems sometimes are assigned special indicators enclosed in parentheses, immediately following the regular designation, to identify the development organization; for example, (XB) indicates the Naval Research Laboratory, and (XW) indicates the

Rome Air Development Center. Empty parentheses, commonly called "bowlegs," are used for a developmental or series "generic" assignment.

TABLE 1.2 JETDS Equipment Indicators*

Installation (first letter)	Type of equipment (second letter)	Purpose (third letter)
A Piloted aircraft	A Invisible light, heat radiation	A Auxiliary assembly
B Underwater mobile, submarine	C Carrier	B Bombing
D Pilotless carrier	D Radiac (radioactive detection, indication, and computation devices)	C Communications (receiving and transmitting)
F Fixed ground	E Laser	D Direction finder reconnaissance and/or surveillance
G General ground use	G Telegraph or teletype	E Ejection and/or release
K Amphibious	I Interphone and public address	G Fire control or searchlight directing
M Ground, mobile	J Electromechanical or inertial wire-covered	H Recording and/or reproducing (graphic meteorological)
P Portable	K Telemetering	K Computing
S Water	L Countermeasures	M Maintenance and/or test assemblies (including tools)
T Ground, transportable	M Meteorological	N Navigational aids (including altimeters, beacons, compasses, racons, depth sounding, approach and landing)
U General utility	N Sound in air	Q Special or combination of purposes
V Ground, vehicular	P Radar	R Receiving, passive detecting
W Water surface and underwater combination	Q Sonar and underwater sound	S Detecting and/or range and bearing, search
Z Piloted and pilotless airborne vehicle combination	R Radio	T Transmitting
	S Special types, magnetic, etc., or combinations of types	W Automatic flight or remote control
	T Telephone (wire)	X Identification and recognition
	V Visual and visible light	Y Surveillance (search, detect, and multiple-target tracking) and control (both fire control and air control)
	W Armament (peculiar to armament, not otherwise covered)	
	X Facsimile or television	
	Y Data processing	

*From Military Standard Joint Electronics Type Designation System, MIL-STD-196D, Jan. 19, 1985.

In the first column of Table 1.2, the installation letter M is used for equipment installed and operated from a vehicle whose sole function is to house and transport the equipment. The letter T is used for ground equipment that is normally moved from place to place and is not capable of operation while being transported. The letter V is used for equipment installed in a vehicle designed for functions other than carrying electronic equipment (such as a tank). The letter G is used for equipment capable of being used in two or more different types of ground installations. Equipment specifically designed to operate while being carried by a person is designated by the installation letter P. The letter U implies use in a combination of two or more general installation classes, such as ground, aircraft, and ship. The letter Z is for equipment in a combination of airborne installations, such as aircraft, drones, and guided missiles.

The equipment indicator letter (second column of Table 1.2) that designates radar is the letter P; but it is also used for beacons which function with a radar, electronic recognition and identification systems, and pulse-type navigation equipment.

Canadian, Australian, New Zealand, and United Kingdom electronic equipment can also be covered by the JETDS designations. For example, a block of numbers from 500 to 599 and 2500 to 2599 is reserved for Canadian use.

The radars used in the air traffic control system of the FAA utilize the following nomenclature:

ASR	airport surveillance radar
ARSR	air route surveillance radar
ASDE	airport surface detection equipment
TDWR	terminal doppler weather radar

The numeral following the letter designation indicates the particular radar model of that type.

Weather radars in use by the U.S. National Weather Service employ the designation WSR, which is not associated with the JETDS nomenclature. The number following the designation indicates the year in which the radar was put into service. When a letter follows the number, it indicates the letter-band designation. Thus, the WSR-74C is a C-band weather radar introduced in 1974.

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