UNIT-I

THE NATURE OF RADAR AND

1.1. INTRODUCTION

Radar is an electronic device for the detection and location of objects. It operates by transmitting a particular type of waveform, a pulse-modulated sine wave for example, and detects the nature of the echo signal. Radar is used to extend the capability of man's senses for observing his environment, especially the sense of vision. The value of radar lies not in being a substitute for the eye, but in doing what the eye cannot do. Radar cannot resolve detail as well as the eye, nor is it yet capable of recognizing the "color" of objects to the degree of sophistication of which the eye is capable. However, radar can be designed to see through those conditions impervious to normal human vision, such as darkness, haze, fog, rain, and snow. In addition, radar has the advantage of being able to measure the distance or range to the object. This is probably its most important attribute.

An elementary form of radar,consists of a transmitting antenna emitting electromagnetic radiation generated by an oscillator of some sort, a receiving antenna, and an energy-detecting device, or receiver. A portion of the transmitted signal is intercepted by a reflecting object (target) and is reradiated in all directions. It is the energy reradiated in back direction that is of prime interest to the radar. The receiving antenna collects the returned energy and delivers it to a receiver, where it is processed to detect the presence of the target and to extract its location and relative velocity. The **distance** to the target is determined by measuring the time taken for the radar signal to travel to the target and back. The **direction, or angular position**, of the target may be determined from the direction of arrival of the reflected wave front. The usual method of measuring the **direction** of arrival is with narrow antenna beams. If **relative motion** exists between target and radar, the shift in the carrier frequency of the reflected wave (doppler effect) is a measure of the target's relative (radial) velocity and may be used to distinguish moving targets from stationary objects. In radars which continuously track the movement of a target, a continuous indication of the rate of change of target position is also available.

Radar is a contraction of the words **radio detection and ranging**. It was first developed as a detection device to warn of the approach of hostile aircraft and for directing antiaircraft weapons. Although a well-designed modern radar can usually extract more information from the target signal than merely range, the measurement functions. There seem to be no other competitive techniques which can measure range as well or as rapidly as can a radar.

The most common radar waveform is a train of narrow, rectangular-shape pulses modulating a sinewave carrier. The distance, or range, to the target is determined by measuring the time T_R taken by the pulse to travel to the target and return. Since electromagnetic energy propagates at the speed of light $c = 3*10^8$ m/s, the range R is

$$R=\{c\, T_R\}/2 \qquad \textit{Eq. } (1.1)$$

The factor 2 appears in the denominator because of the two-way propagation of radar. With the range in kilometers or nautical miles, and T_R in microseconds, *Eq.* (1.1) becomes

$$R(km)=0.15T_R(\mu s)$$

$$R(nmi)=0.081T_R(\mu s)$$

Each microsecond of round-trip travel time corresponds to a distance of 0.081 nautical mile,0.093 statute mile, 150 meters, 164 yards, or 492. feet.

Once the transmitted pulse is emitted by the radar, a sufficient length of time must elapse to allow any echo signals to return and be detected before the next pulse may be transmitted. Therefore the rate at which the pulses may be transmitted is determined by the longest range at which targets are expected. If the pulse repetition frequency were too high, echo signals from some targets might arrive before the transmission of the next pulse, and ambiguities in measuring range might result. Echoes that arrive after the transmission of the next pulse are called **second-time-around (or multipletime-around) echoes.** Such an echo would appear to be at a much shorter range than the actual and could be misleading if it were not known to be a second-time-around echo. The range beyond which targets appear as second-time-around echoes is called the **maximum unambiguous range** and is

$$R_{\text{unamb}} = \frac{c}{2f_p}$$

Where f_p = pulse repetition frequency, in cycles per second.

1.2 THE SIMPLE FORM OF THE RADAR EQUATION

The radar equation relates the range of a radar to the characteristics of the transmitter, receiver, antenna, target, and the environment in which the radar operates. The radar equation is useful

- in determining the distance of the target from the radar.
- as a tool for understanding radar operation.
- in serving as a basis for radar design.

Consider a radar using a transmitting antenna which radiates power uni-formly in all directions. Such antennas are called isotropic antennas. Let P_t be the power radiated by such an antenna. Then the power density at a distance R is given by,

$$P_d = \frac{P_t}{4\pi R^2}$$

This is apparent from Fig. given below

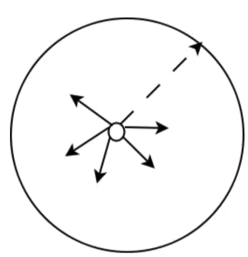

Figure: Power density at distance R from the radar

Note that at a distance R, the power P_t is uniformly distributed over an area given by the surface area of a sphere of radius R. Hence, we get the equation or P_d as above.

However, it is somewhat wasteful to radiate energy in all directions. Thus, radars may employ directive antennas to channelize, or direct, the radiated power in a particular direction (i.e., the direction of the target). The gain in power density so achieved is denoted by G and is a measure of the increased power radiated in the direction of the target as compared to the power that would have been radiated from an isotropic antenna. It may also be defined as the ratio of the maximum radiation intensity from the given antenna to the Radiation intensity from a lossless isotropic antenna with the same power input. Here, radiation intensity is defined as the power radiated per unit solid angle in a given direction. The factor G is also known as the antenna gain. Thus, the power density from a directive antenna at a distance R is given by

$$P_d = \hat{P}_d G = \frac{P_t G}{4\pi R^2}$$

The target, situated at a distance R, intercepts a portion of the power and reflects it in various directions. The measure of the amount of power intercepted by the target is defined as the radar cross-section of the target. It is denoted by σ and has the unit of area. Note that the radar cross-section is the characteristic of a particular target and is a measure of its size as

seen by the radar. Thus, the amount of power intercepted by the target at a distance R from the radar is,

$$\hat{P} = P_d \sigma = \frac{P_t G \sigma}{4\pi R^2}$$

A simple way to understand this equation is to assume that the target has a surface area σ on which radiations of density P_d impinge. However, like all ”simple” explanations, this statement is not precise in the sense that σ is not just the surface area that the target presents to the radar radiations, but σ is a complex function of the target surface area as well as many other factors which depend on the characteristics of the target.

Now we assume that this power p gets radiated in all directions, and therefore, using the same argument, the power density of the reflected signal at the receiving antenna is given by

$$P_d^r = \frac{\hat{P}}{4\pi R^2} = \frac{P_t G \sigma}{\left(4\pi R^2\right)^2}$$

The radar antenna now captures a portion of this reflected power. How much of this power is actually captured depends on what is known as the effective area of the receiving antenna. This is denoted by A_e and has the unit of area. It is also known as the antenna effective aperture. The power P_r received by the radar is,

$$P_r = P_d^r A_e = \frac{P_t G \sigma A_e}{\left(4\pi R^2\right)^2} = \frac{P_t G \sigma A_e}{(4\pi)^2 R^4}$$

The radar receiver must be capable of detecting the power received. Sup-pose the radar receiver can detect only those signals which are greater than a value S_{min} (known as the minimum detectable signal), then the maximum range of the radar can be obtained from

$$S_{\min} = \frac{P_t G \sigma A_e}{(4\pi)^2 R_{\max}^4}$$

From which

$$R_{\max} = \left[\frac{P_t G \sigma A_e}{(4\pi)^2 S_{\min}}\right]^{1/4}$$

This is the fundamental form of the radar equation. Note that the two important antenna parameters used here are the antenna gain G and the effective antenna aperture A_e.

Many radars use the same antenna for both transmission and reception. In such cases, from antenna theory, the relationship between the antenna gain and the receiving effective area of an antenna is given as,

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

where, λ is the wavelength of the transmitted energy. Substituting this relation in (2.13), we obtain another form of the radar equation.

$$R_{\max} = \left[\frac{P_t \sigma A_e^2}{(4\pi)^2 S_{\min}}\right]^{1/4}$$

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

and obtain the radar equation as,

$$R_{\max} = \left[\frac{P_t \sigma G^2 \lambda^2}{(4\pi)^3 S_{\min}} \right]^{1/4}$$

The above radar equation must be interpreted somewhat carefully. Note that in above equation R_{max} appears to be inversely proportional to $\lambda^{1/2}$ whereas in one of equation it appears to be directly proportional to $\lambda^{1/2}$, and in one of equaton it is independent of λ. The reason behind this apparent anomaly is the following: when we speak of the variation of a particular parameter with respect to another, we assume that all other parameters are constants. This is possible only when these parameters are independent. In this case it is not so, since the dependence between G, A_e, and λ is governed by and any variation in one of these parameters has to affect at least only of the other two. Hence, we cannot speak of the variation of R_{max} with respect to λ only (or with respect to G or A_e only.)

1.3 RADAR BLOCK DIAGRAM AND OPERATION

The operation of a typical pulse radar may be described with the aid of the block diagram shown Fig. 1.1. The transmitter may be an oscillator, such as a magnetron, that is " pulsed" (turned on and on) by the modulator to generate a repetitive train of pulses. The magnetron has probably been the most widely used of the various microwave generators for radar. A typical radar for the detection of aircraft at ranges of 100 or 200 nmi might employ a peak power of the order of a megawatt, an average power of several kilowatts, a pulse width of several microseconds, and a pulse repetition frequency of several hundred pulses per second. The waveform generated by the transmitter travels via a transmission line to the antenna, where it is radiated into space. A single antenna is generally used for both transmitting and receiving. The receiver must be protected from damage caused by the high power of the transmitter. This is the function of the duplexer. The duplexer also serves to channel the returned echo signals to the receiver and not to the transmitter. The duplexer might consist of two gas-discharge devices, one known as a TR (transmit-receive) and the other an ATR (anti-transmit-receive). The TR protects the receiver during transmission and the ATR directs the echo signal to the receiver during reception. Solid-state ferrite circulators and receiver protectors with gas-plasma TR devices and/or diode limiters are also employed as duplexers.

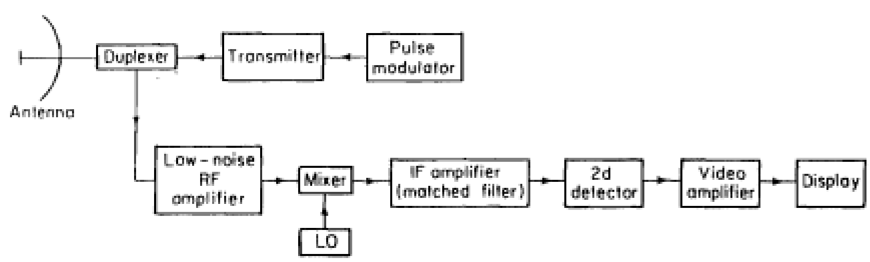

Figure 1.1 Block diagram of a pulse radar.

The receiver is usually of the superheterodyne type. The first stage might be a low-noise RF amplifier, such as a parametric amplifier or a low-noise transistor. However, it is not always desirable to employ a low-noise first stage in radar. The receiver input can simply be the mixer stage, especially in military radars that must operate in a noisy environment. Although a receiver with a low-noise front-end will be more sensitive, the mixer input can have greater dynamic range, less susceptibility to overload, and less vulnerability to electronic interference.

The mixer and local oscillator (LO) convert the RF signal to an intermediate frequency **(IF).** A typical" IF amplifier for an air-surveillance radar might have a center frequency of 30 or 60 MHz and a bandwidth of the order of one megahertz. The IF amplifier should be designed as a matched filter; i.e., its frequency-response function ***H (f)*** should maximize the **signal-to-mean-noise-power** ratio at the output. This occurs when the magnitude of the frequency-response function mod of ***H (f)*** is equal to the magnitude of the echo signal spectrum mod of *S(f')*, and the phase spectrum of the matched filter is the negative of the phase spectrum of the echo signal. In a radar whose signal waveform approximates a rectangular pulse, the conventional IF filter bandpass characteristic approximates a matched filter when the product of the IF bandwidth B and the pulse width τ is of the order of unity, that is, $\boldsymbol{B\tau}$ approxs to1.

After maximizing the signal-to-noise ratio in the IF amplifier, the pulse modulation is extracted by the second detector and amplified by the video amplifier to a level where it can be properly displayed, usually on a cathode-ray tube (CRT). Timing signals are also supplied to the indicator to provide the range zero. Angle information is obtained from the pointing direction of the antenna. The most common form of cathode-ray tube display is the plan position indicator, or **PPI** (Fig. **1.2a),** which maps in polar coordinates the location of the target in azimuth and range. This is an intensity-modulated display in which the amplitude of the receiver output modulates the electron-beam intensity (z axis) as the electron beam is made to sweep outward from the center of the tube. The beam rotates in angle in response to the antenna position. B-scope display is similar to the PPI except that it utilizes rectangular, rather than polar, coordinates to display range vs. angle. Both the B-scope and the PPI, being intensity modulated, have limited dynamic range. Another form of display is the shown in Fig. **1.2b,** which plots target .amplitude axis) vs. range axis), for some fixed direction. This is a deflection-modulated display. It is more suited for tracking-radar application than for surveillance radar.

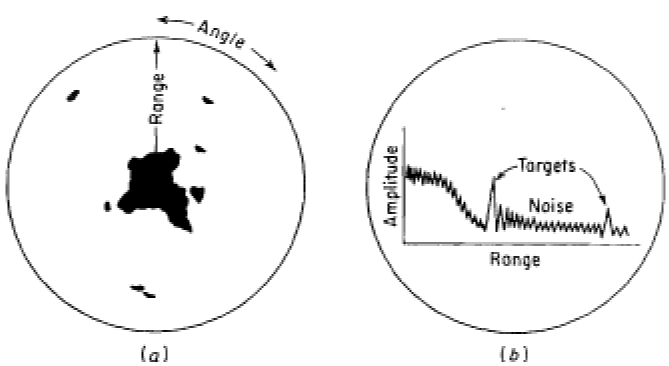

Figure 1.2 (a) PPI presentation displaying range vs. angle (intensity modulation); *(b)* A-scope presentation displaying amplitude vs. range (deflection modulation).

The block diagram of Fig. 1.1 is a simplified version that omits many details. It does not include several devices often found in radar, such as means for automatically compensating the receiver for changes in frequency (AFC) or gain **(AGC),** receiver circuits for reducing interference from other radars and from unwanted signals, rotary joints in the transmission lines to allow movement of the antenna, circuitry for discriminating between moving targets and unwanted stationary objects MTI), and pulse compression for achieving the resolution benefits of a short pulse but with the energy of a 'long pulse. If the radar is used for tracking, some means are necessary for sensing the angular location of a moving target and allowing the antenna automatically to lock-on and to track the target. Monitoring devices are usually included to ensure that the transmitter is delivering the proper shape pulse at the proper power level and that the receiver sensitivity has not degraded. Provisions may also be incorporated in the radar for locating equipment failures so that faulty circuits can be easily found and replaced.

Instead of displaying the " raw-video" output of a surveillance radar directly on the CRT, it might first be processed by an automatic detection and tracking (ADT) device that quantizes the radar coverage into range-azimuth resolution cells, adds (or integrates) all the echo pulses received within each cell, establishes a threshold (on the basis of these integrated pulses) that permits only the strong outputs due to target echoes to pass while rejecting noise, establishes and maintains the tracks (trajectories) of each target, and displays the processed information to the operator. These operations of an ADT are usually implemented with digital computer technology.

A common form of radar antenna is a reflector with a parabolic shape, fed (illuminated) from a point source at its focus. The parabolic reflector focuses the energy into a narrow beam, just as does a searchlight or an automobile headlamp. The beam may be scanned in space by mechanical pointing of the antenna. Phased-array antennas have also been used for radar. In a phased array. the beam is scanned by electronically varying the phase of the currents across the aperture.

1.4 RADAR FREQUENCIES

Conventional radars generally have been operated at frequencies extending from about 220 MHz to 35GHz spread of more than seven octaves. These are not necessarily the limits, since radars can be, and have been, operated at frequencies outside either end of this range. Skywave HF over-the-horizon (OTH) radar might be at frequencies as low as 4 or 5 MHz, and groundwave HF radars as low as 2 MHz. At the other end of the spectrum, millimeter radars have operated at 94 GHz. Laser radars operate at even higher frequencies.

The place of radar frequencies in the electromagnetic spectrum is shown in Fig. 1.3. Some of the nomenclature employed to designate the various frequency regions is also shown. Early in the development of radar, a letter code such as S, X, L, etc., was employed to designate radar frequency bands. Although its original purpose was to guard military secrecy, the designations were maintained, probably out of habit as well as the need for some convenient short nomenclature. This usage has continued and is now an accepted practice of radar engineers. Table 1.1 lists the radar-frequency letter-band nomenclature adopted by the **IEEE.'** These are related to the specific bands assigned by the International Telecommunications Union for radar. For example, although the nominal frequency range for L band is **1000** to 2000 MHz, an L-band radar is thought of as being confined within the region from 1215 to 1400 **MHz** since that is the extent of the assigned band. Letter-band nomenclature is not a substitute for the actual numerical frequency limits of radars. The specific numerical frequency limits should be used whenever appropriate, but the letter designations of Table 1.1 may be used whenever a short notation is desired.

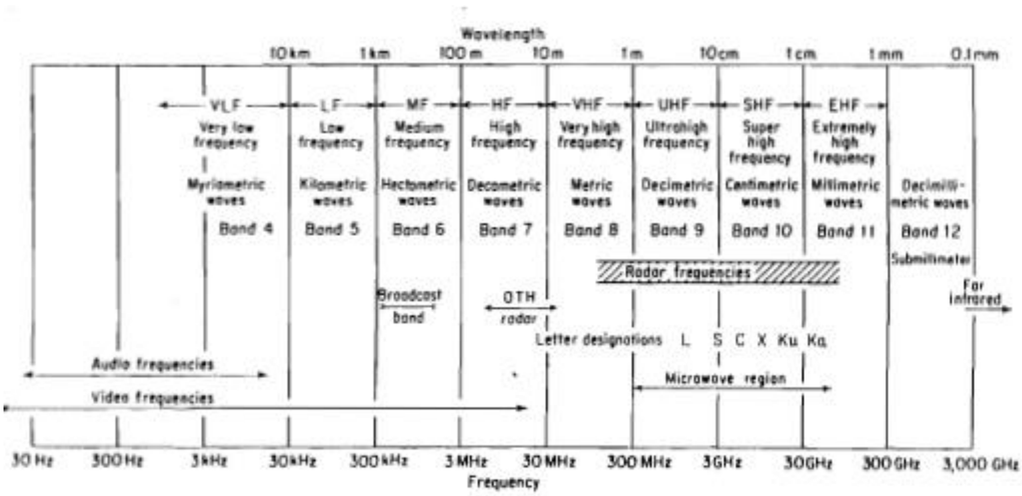

Figure 1.3 Radar frequencies and the electromagnetic spectrum.

Table 1.1 Standard radar-frequency letter-band nomenclature

Band designation	Nominal frequency range	Specific radiolocation (radar) bands based on ITU assignments for region 2
HF	3-30 MHz	
VHF	30-300 MHz	138-144 MHz 216-225
UHF	300-1000 MHz	420-450 MHz 890-942
L	1000-2000 MHz	1215-1400 MHz
S	2000-4000 MHz	2300-2500 MHz 2700-3700
C	4000-8000 MHz	5250-5925 MHz
X	8000-12,000 MHz	8500-10,680 MHz
K_u	12.0-18 GHz	13.4-14.0 GHz 15.7-17.7
K	18-27 GHz	24.05-24.25 GHz
K_a	27-40 GHz	33.4-36.0 GHz
mm	40-300 GHz	

1.5 APPLICATIONS OF RADAR

Radar has been employed on the ground, in the air, on the sea, and in space. Ground-based radar has been applied chiefly to the detection, location, and tracking of aircraft or space targets. Shipboard radar is used as a navigation aid and safety device to locate buoys, shore lines and other ships. as well as for observing aircraft. Airborne radar may be used to detect other aircraft, ships, or land vehicles, or it may be used for mapping of land, storm avoidance, terrain avoidance, and navigation. In space, radar has assisted in the guidance of spacecraft and for the remote sensing of the land and sea.

Tracffic Control (A TC). Radars are employed throughout the world for the purpose of safely controlling air traffic and route and in the vicinity of airports. Aircraft and ground vehicular traffic at large airports are monitored by means of high-resolution radar. Radar has been used with GCA (ground-control approach) systems to guide aircraft to a safe landing in bad weather. In addition, the microwave landing system and the widely used ATC radar-beacon system are based in large part on radar technology.

Aircraft Navigation. The weather-avoidance radar used on aircraft to outline regions of precipitation to the pilot is a classical form of radar. Radar is also used for terrain avoidance and terrain following. Although they may not always be thought of as radars, the radio altimeter (either FM/CW or pulse) and the doppler navigator are also radars. Sometimes ground-mapping radars of moderately high resolution are used for aircraft navigation purposes.

Ship Safety. Radar is used for enhancing the safety of ship travel by warning of potential collision with other ships, and for detecting navigation buoys, especially in poor visibility. In terms of numbers, this is one of the larger applications of radar, but in terms of physical size and cost it is one of the smallest. It has also proven to be one of the most reliable radar systems. Automatic detection and tracking equipments (also called plot extractors) are commercially available for use with such radars for the purpose of collision avoidance. Shore-based radar of moderately high resolution is also used for the surveillance of harbors as an aid to navigation.

Space. Space vehicles have used radar for rendezvous and docking, and for landing on the moon. Some of the largest ground-based radars are for the detection and tracking of satellites. Satellite-borne radars have also been used for remote sensing as mentioned below.

Remote Sensing. A11 radars are remote sensors; however, as this term is used it implies the sensing of geophysical objects, or the "environment." For some time, radar has been used as a remote sensor of the weather. It was also used in the past to probe the moon and the planets (radar astronomy). The ionospheric sounder, an important adjunct for HF (short wave) communications, is a radar. Remote sensing with radar is also concerned with Earth resources, which includes the measurement and mapping of sea conditions, water resources, ice cover, agriculture, forestry conditions, geological formations, and environmental pollution. The platforms for such radars include satellites as well as aircraft.

Law Enforcement. In addition to the wide use of radar to measure the speed of automobile traffic by highway police, radar has also been employed as a means for the detection of intruders.

Military. Many of the civilian applications of radar are also employed by the military. The traditional role of radar for military application has been for surveillance, navigation, and for the control and guidance of weapons. It represents, by far, the largest use of radar.

THE RADAR EQUATION

1.6 PREDICTION OF RANGE PERFORMANCE

The simple form of the radar equation derived in Sec. 1.2 expressed the maximum radar range R_{max} in terms of radar and target parameters:

$$R_{max} = \left[\frac{P_t G \sigma A_e}{(4\pi)^2 S_{min}} \right]^{1/4}$$

where P_t = transmitted power, watts
G= antenna gain
A_e= antenna emective aperture, m^2
σ = radar cross section, m2
S_{min} = minimum detectable signal, watts

All the parameters are to some extent under the control of the radar designer, except for the target cross section a. The radar equation states that if long ranges are desired, the transmitted power must be large, the radiated energy must be concentrated into a narrow beam (high transmitting antenna gain), the received echo energy must be collected with a large antenna aperture (also synonymous with high gain), and the receiver must be sensitive to weak signals.

In practice, however, the simple radar equation does not predict the range performance of actual radar equipments to a satisfactory degree of accuracy. The predicted values of radar range are usually optimistic. In some cases the actual range might be only half that predicted.
Part of this discrepancy is due to the failure of Eq. to explicitly include the various losses that can occur throughout the system or the loss in performance usually experienced when electronic equipment is operated in the field rather than under laboratory-type conditions. Another important factor that must be considered in the radar equation is the statistical or unpredictable nature of several of the parameters. The minimum detectable signal and the target cross section are both statistical in nature and must be expressed in statistical terms.

Other statistical factors which do not appear explicitly in Eq. but which have an effect on the radar performance are the meteorological conditions along the propagation path and the performance of the radar operator, if one is employed. The statistical nature of these several parameters does not allow the maximum radar range to be described by a single number. Its specification must include a statement of the probability that the radar will detect a certain type of target at a particular range.

1.7 MINIMUM DETECTABLE SIGNAL

The ability of a radar receiver to detect a weak echo signal is limited by the noise energy that occupies the same portion of the frequency spectrum as does the signal energy. The weakest signal the receiver can detect is called the ***minimum detectable signal.*** The specification of the minimum detectable signal is sometimes difficult because of its statistical nature and because the criterion for deciding whether a target is present or not may not be too well defined.

Detection is based on establishing a threshold level at the output of the receiver. If the receiver output exceeds the threshold, a signal is assumed to be present. This is called ***threshold detection.*** Consider the output of a typical radar receiver as a function of time (Fig. 1.4). This might represent one sweep of the video output displayed on an A-scope. The envelope has a fluctuating appearance caused by the random nature of noise. If a large signal is present such as at *A* in Fig. 1.4, it is greater than the surrounding noise peaks and can be recognized on the basis of its amplitude. Thus, if the threshold level were set sufficiently high, the envelope would not generally exceed. the threshold if noise alone were present, but would exceed it if a strong signal were present. If the signal were small, however, it would be more difficult to recognize its presence. The threshold level must be low if weak signals are to be detected, but it cannot be so low that noise peaks cross the threshold and give a false indication of the presence of targets.

The voltage envelope of Fig. 1.4 is assumed to be from a matched-filter receiver. A matched filter is one designed to maximize the output peak signal to average noise (power) ratio. It has a frequency-response function which is proportional to the complex conjugate of the signa1,spectrum. (This is not the same as the concept of" impedance match of circuit theory.) The ideal matched-filter receiver cannot always be exactly realized in practice, but it is possible to approach.it with practical receiver circuits. A matched filter for a radar transmitting a rectangular-shaped .pulse is usually characterized by a bandwidth B approximately the reciprocal of the pulse width τ, or $B\tau = 1$. The output of a matched-filter receiver is the cross correlation between the received waveform and a replica of the transmitted waveform. Hence it does not preserve the shape of the input waveform. (There is no reason to wish to preserve the shape of the received waveform so long as the output signal-to-noise ratio is maximized.)

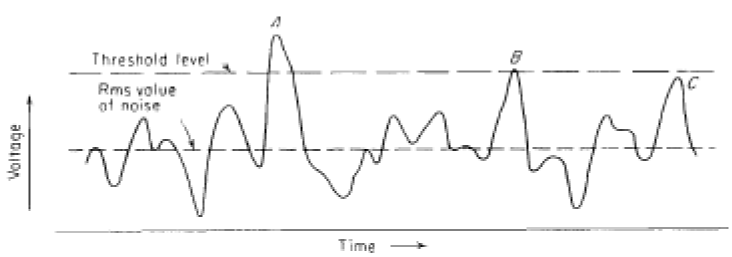

Figure 1.4 Typical envelope of the radar receiver output as a function of time. *A,* and B, and *C* represent signal plus noise. ,A and B would be valid detections, but C is a missed detection.

Let us return to the receiver output as represented in Fig. 1.4. A threshold level is established, as shown by the dashed line. A target is said to be detected if the envelope crosses the threshold. if the signal is large such as at *A,* it is not difficult to decide that a target is present. Let us consider the two signals at B and C, representing target echoes of equal amplitude. The noise voltage accompanying the signal at B is large enough so that the combination of signal plus noise exceeds the threshold. At *C* the noise is not as large and the resultant signal plus noise does not cross the threshold. Thus the presence of noise will sometimes enhance the detection of weak signals but it may also cause the loss of a signal which would otherwise be detected.

Weak signals such as C would riot be lost if the threshold level were lower. But too low a threshold increases the likelihood that noise alone will rise above the threshold and be taken for a real signal. Such an occurrence is called a **false alarm**. Therefore, if the threshold is set too low, false target indications are obtained, but if it is set too high, targets might be missed. The selection of the proper threshold level is a compromise that depends upon how important it is if a mistake is made either by (1) failing to recognize a signal that is present (probability of a miss) or by (2) falsely indicating the presence of a signal when none exists (probability of a false alarm).

When the target-decision process is made by an operator viewing a cathode-ray-tube display, it would seem that the criterion used by the operator for detection ought to be analogous to the setting of a threshold, either consciously or subconsciously. The chief difference between the electronic and the operator thresholds is that the former may be determined with some logic and can be expected to remain constant with time, while the latter's threshold might be difficult to predict and may not remain fixed. The individual's performance as part of the radar detection process depends upon the state of the operator's fatigue and motivation, as well as training.

The capability of the human operator as part of the radar detection process can be determined only by experiment. Needless to say, in experiments of this nature there are likely to be wide variations between different experimenters. Therefore, for the purposes of the present discussion, the operator will be considered the same as an electronic threshold detector, an assumption that is generally valid for an alert, trained operator.

The signal to noise ratio necessary to provide adequate detection is one of the important parameters that must be determined in order to compute the minimum detectable signal, Although the detection decision is usually based on measurements at the video output, it is easier to consider maximizing the signal-to-noise ratio at the output of the IF amplifier rather than in the video.

1.8 RECEIVER NOISE & MODIFIED RANGE EQUATION

Since noise is the chief factor limiting receiver sensitivity, it is necessary to obtain some means of describing it quantitatively. Noise is unwanted electromagnetic energy which interferes with the ability of the receiver to detect the wanted signal. It may originate within the receiver itself, or it may enter via the receiving antenna along with the desired signal. the radar were to operate in a perfectly noise-free environment so that no external sources of noise accompanied the desired signal, and if the receiver itself were so perfect that it did not generate any excess noise, there would still exist an unavoidable component of noise generated by the thermal motion of the conduction electrons in the ohmic portions of the receiver input stages. This is called thermal noise, or Johnson noise, and is directly proportional to the temperature of the ohmic portions of the circuit and the receiver bandwidth .The available thermal-noise power generated by a receiver of bandwidth ***B*,** (in hertz) at a temperature T (degrees Kelvin) is equal to

Available thermal-noise power = $\mathbf{kTB_n}$

where $\boldsymbol{k}$ = Boltzmann's constant = 1.38 x10^{-23} J/deg. If the temperature T is taken to be 290 K, which corresponds approximately to room temperature (62^{θ} F), the factor $\boldsymbol{kT}$ is 4 x $\mathbf{10^{-21}}$ W/Hz of bandwidth. If the receiver circuitry were at some other temperature, the thermal-noise power would be correspondingly different.

For radar receivers of the superheterodyne type (the type of receiver used for most radar applications), the receiver bandwidth is approximately that of the **intermediate-frequency** stages. It should be cautioned that the bandwidth ***B,*** of Eq. is not the 3-dB, or half-power, bandwidth commonly employed by electronic engineers. It is an integrated bandwidth and is given by

$$B_n = \frac{\int_{-\infty}^{\infty} |H(f)|^2 \, df}{|H(f_0)|^2}$$

where H(f) frequency-response characteristic of IF amplifier (filter) and f_0= frequency of maximum response (usually occurs at midband).

The noise power in practical receivers is often greater than can be accounted for by thermal noise alone. The additional noise components are due to mechanisms other than the thermal agitation of the conduction electrons. For purposes of the present discussion, however, the exact origin of the extra noise components is not important except to know that it exists. No matter whether the noise is generated by a thermal mechanism or by some other mechanism. the total noise at the output of the receiver may be considered to be equal to the thermal-noise power obtained from an ideal receiver multiplied by a factor called the noise ***figure.*** The noise figure F_n of a receiver is defined by the equation

$$F_n = \frac{N_o}{kT_0 B_n G_a} = \frac{\text{noise out of practical receiver}}{\text{noise out of ideal receiver at std temp } T_0}$$

where *No* = noise output from receiver, and Go= available gain

$$F_n = \frac{S_i/N_i}{S_o/N_o}$$

The noise figure may be interpreted, therefore, as a measure of the degradation of signal-tonoise-ratio as the signal passes through the receiver.
Rearranging Eq. the input signal may be expressed as

$$S_i = \frac{kT_0 B_n F_n S_o}{N_o}$$

$$S_{min} = kT_0 B_n F_n \left(\frac{S_o}{N_o}\right)_{min}$$

$$R_{max}^4 = \frac{P_t G A_e \sigma}{(4\pi)^2 k T_0 B_n F_n (S_o/N_o)_{min}}$$

1.12 TRANSMITTER POWER

The power P, in the radar equation is called by the radar engineer the peak power. The peak pulse power as used in the radar equation is not the instantaneous peak power of a sine wave. It is defined as the power averaged over that carrier-frequency cycle which occurs at the maximum of the pulse of power. (Peak power is usually equal to one-half the maximum instantaneous power.) The average radar power Pav, is also of interest in radar and is defined as the average transmitter power over the pulse-repetition period. If the transmitted waveform is a train of rectangular pulses of width τ and pulse-repetition period Tp = ***1/ f p*** **,** the average power is related to the peak power by

$$P_{av} = \frac{P_t \tau}{T_p} = P_t \tau f_p$$

The ratio Pav/Pt, τ/TP, or τ fp is called the duty cycle of the radar. **A** pulse radar for detection of aircraft might have typically a duty cycle of 0.001, while a CW radar which transmits continuously as a duty cycle of unity.

Writing the radar equation in terms of the average power rather than the peak power, we get

$$R_{max}^4 = \frac{P_{av} G A_e \sigma n E_i(n)}{(4\pi)^2 k T_0 F_n (B_n \tau)(S/N)_1 \ f_p}$$

The bandwidth and the pulse width are grouped together since the product of the two is usually of the order of unity in most pulse-radar applications.

If the transmitted waveform is not a rectangular pulse, it is sometimes more convenient to express the radar equation in terms of the energy ***E*** τ = Pav/fp

$$R_{max}^4 = \frac{E_\tau G A_e \sigma n E_i(n)}{(4\pi)^2 k T_0 F_n (B_n \tau)(S/N)_1}$$

1.13 PULSE REPETITION FREQUENCY AND RANGE AMBIGUITIES

Consider the three targets labeled A, B and C in Fig. 1.5 Target A is located within the maximum unambiguous range Runamb of the radar, target B is at a distance greater than Runam, but less than 2RUnambw, the target C is greater than 2Runamb but less than 3Runmb. The appearance of the three targets on an A-scope is sketched in Fig. 1.5 The multiple-time-around echoes on the A-scope cannot be distinguished from proper target echoes actually within the maximum unambiguous range. Only the range measured for target A is correct; those for B and C are not.

One method of distinguishing multiple-time-around echoes from unambiguous echoes is to operate with a varying pulse repetition frequency. The echo signal from an unambiguous range target will appear at the same place on the A-scope on each sweep no matter whether the prf is modulated or not. However, echoes from multiple-time-around targets will be spread over a finite range as shown in Fig. *1.5.*The prf may be changed continuously within prescribed limits, or it may be changed discretely among several predetermined values. The number of separate pulse repetition frequencies will depend upon the degree of the multiple time targets. Second-time targets need only two separate repetition frequencies in order to be resolved.

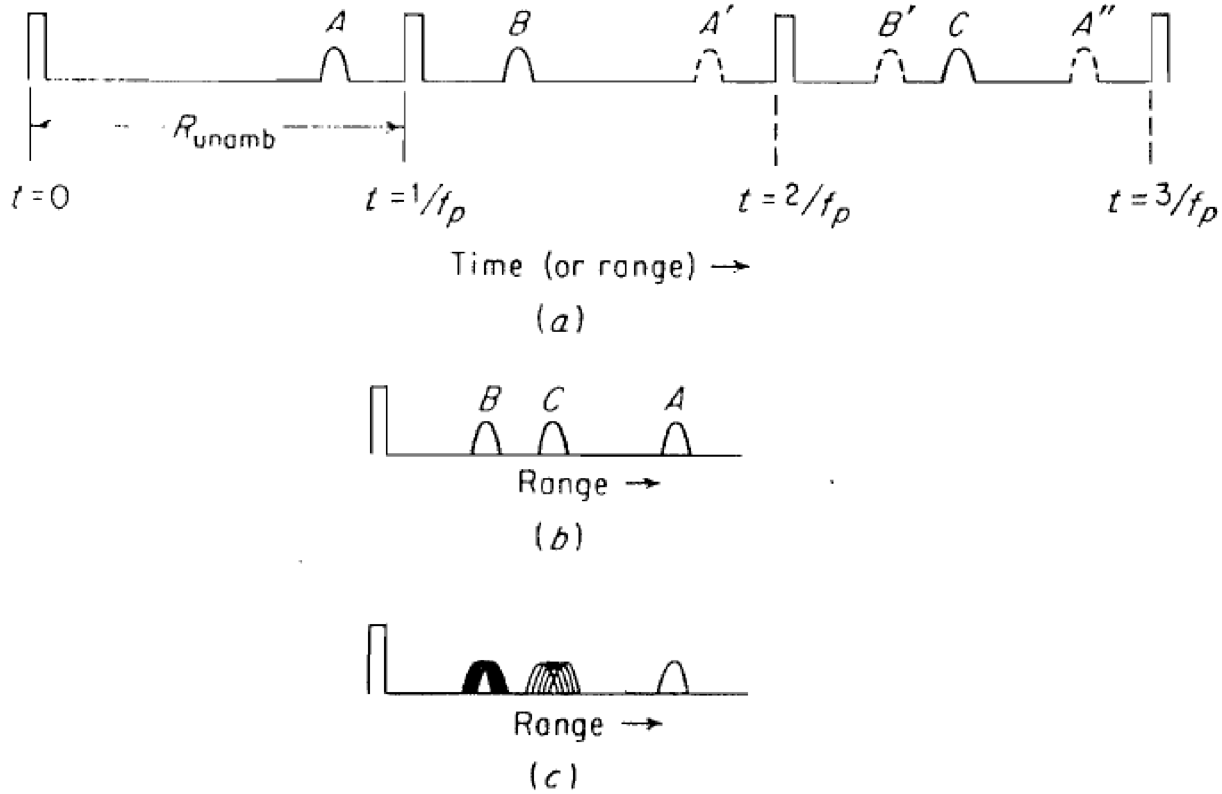

Figure 1.5 Multiple-time-around echoes that give rise to ambiguities in range. (a) Three targets A, B and C, where A is within *Runamb*, and B and *C* are multiple-time-around targets; *(b)* the appearance of the three targets on the A-scope; (c) appearance of the three targets on the A-scope with a changing prf.

Instead of modulating the prf, other schemes that might be employed to "mark" successive pulses so as to identify multiple-time-around echoes include changing the pulse amplitude, pulse width, frequency, phase, or polarization of transmission from pulse to pulse. Generally, such schemes are not so successful in practice as one would like. One of the fundamental limitations is the fold over of nearby targets; that is, nearby strong ground targets (clutter) can be quite large and can mask weak multiple-time-around targets appearing at the same place on the display. Also, more time is required to process the data when resolving ambiguities. Ambiguities may theoretically be resolved by observing the variation of the echo signal with time (range). This is not always a practical technique, however, since the echo-signal amplitude can fluctuate strongly for reasons other than a change in range. Instead, the range ambiguities in a multiple prf radar can be conveniently decoded and the true range found.

1.14 SYSTEM LOSSES

For the last radar range equation-related topic we want to address radar losses. In our previous discussions we have discussed some of the causes of losses, and it future discussions we will discuss more. At this point we will provide a summary of various loss terms. We will not address all possible loss terms since their number can be very large.

- **Transmit Losses** – Typically associated with the feed, waveguides and other components between the power amplifier and the antenna. These are typically 1 to 2 dB in a well designed radar.

- **Receive Losses** – Typically associated with the feed, waveguides and other components between the mouth of the feed and RF amplifier. These are also typically 1 to 2 dB for a well designed radar. If the noise figure is referenced to the antenna terminals, receive losses are included in the noise figure. This is something to be careful of.

- **Atmospheric Losses** – These are losses due to absorption by the atmosphere. They are dependent upon the radar operating frequency, the range to the target and the elevation angle of the target relative to the radar. Both Skolnik's text and Radar Handbook have graph depicting these losses.

- **Scanning or Beamshape Loss** – This loss term accounts for the fact that, as the beam scans across the target, the signal amplitudes of the pulses coherently, or non-coherently, integrated varies. Because of this, the full integration gain of the integrator can't be realized. From the Skolnik Radar Handbook typical values are

  - 1.6 dB for a scanning, fan beam radar

  - 3.2 dB for a thinner beam, scanning radar

  - 3.2 dB for a phased array radar wherein the beams of a search sector overlap at the 3-dB beam positions.

- **Range-Gate Straddling Loss** – If the radar samples in range at a rate of once per range resolution cell the loss is usually taken to be 3 dB.

- **Doppler Straddling Loss** – The loss associated with forming the Doppler dimension of a range-Doppler map. Its particular value depends upon the specific Doppler processor implementation but typical values are 1 to 2 dB.

- **Collapsing Loss** – If the coherent or non-coherent integrator integrates only noise over some if its integration time (due to the fact that the beam has moved fairly far off of the target) the radar will incur a loss that is given by

$$Lc=n+m/m$$

where n is the number of pulses containing signal-plus-noise and m is the number of pulses containing only noise.

- **Signal Processing Loss** – If the radar uses an MTI with a staggered PRF waveform, and a good MTI and PRF stagger design, it will suffer 0 to 1 dB signal processing loss.

- **Miscellaneous Loss** – Radar designers and analysts usually include an additional 1 to 2 dB loss to account for various factors they forgot to consider.