UNIT – I

BASICS OF RADAR

1.1 INTRODUCTION:

According to our text, the first attempt to detect targets using electromagnetic radiation took place in 1904 or 1920. In 1904, Hülsmeyer bounced waves off of a ship and in 1922 Taylor and Young observed an interference pattern when a ship passed between transmit and receive antennas. Although these appear to be the first instances of the use of radar, the term *radar* was not applied to them. Again according to our test it appears that the first use of the term radar occurred around 1925 when Briet and Tauve used a pulsed radar to measure the height of the ionosphere.

Radars come in two basic types with variations within the types

- Pulsed, where the radar transmits a sequence of pulses of radio frequency (RF) energy
- CW (Continuous Wave), where the radar transmits a continuous signal.

The first two examples above were CW radars and the third example was a pulsed radar.

Since a CW radar transmits a continuous signal it requires the use of separate transmit and receive antennas because it is not (usually) possible to simultaneously receive while the radar is transmitting. Pulsed radars get around this problem by using what we might think of as time multiplexing. Specifically, during the time the pulse is transmitted the antenna is connected to the transmitter. After the transmit phase is completed the antenna is connected to the receiver. In the radar there is a device that is called a circulator that effectively performs this switching function. Pulsed radars are the most common type of radar because they only require one antenna.

Another variation on radar is type is whether it is *monostatic* or *bistatic*.

- In a monostatic radar the transmitter and receiver, and associated antennas, are collocated. This is the most common type of radar because it is the most compact. If a monostatic radar is pulsed it will usually use the same antenna for transmit and receive. If a monostatic radar is CW it will usually have separate transmit and receive antennas with a shield between them.

- In a biastatic radar the transmitter and receiver are separated. This is the type of radar that might be used in a missile seeker. In this case, the transmitter is located on the ground, or in an aircraft, and the receiver is located in the missile.

The word radar is a contraction of RAdio Detection And Ranging. As implied by this contraction, radars are used to detect the presence of a target and to determine its location. The contraction implies that the quantity measured is range. While this is correct, modern radars are also used to measure range-rate and angle. It turns out that by measuring these parameters one can perform reasonably accurate calculations of the x-y-z location and velocity of a target. In some instances one can also form reasonable estimates of higher derivatives of x, y and z.

Radars operate in the radio frequency band of the energy spectrum between about 100 MHz (VHF) and 100 GHz (Ka or millimeter wave (mmw)). A listing of frequency bands and associated frequencies are shown in your text.

Usually, but not always,

- Search radars operate at VHF to C band
- Track radars operate in X and Ku bands, and sometimes in K band
- Instrumentation radars and short range radars sometimes operate in the Ka band.

Some notes on operating frequency considerations

- Low frequency radars require large antennas or have broader beams (broader distribution of energy in angle space – think of the beam of a flashlight). They are not usually associated with accurate angle measurement.
- Low frequency radars have limitations on range measurement accuracy because fine range measurement implies large instantaneous bandwidth of the transmit signal. This causes problems with transmitter and receiver design because the bandwidth could be a significant percentage of the transmit frequency.
- Doppler measurement is not as accurate because Doppler frequency is related to transmit frequency.
- High power is easier to generate at low frequencies.
- For search, we want high power but we don't necessarily need fine range or angle measurement. Thus, search radars tend to use lower frequencies.

- For track, we need fine range and angle measurement but we don't necessarily need high power. Thus, track radars tend to use higher frequencies
- The above also often leads to assigning the functions of search and track to different radars. However, modern radars tend to be "multi-function" and incorporate both functions in one radar. This can lead to trade offs in operating frequency and in the search and track functions.

1.2 MAXIMUM UNAMBIGUOUS RANGE:

A problem with pulsed radars and range measurement is how to unambiguously determine the range to the target. This problem arises because of the fact that pulsed radars typically transmit a sequence of pulses. The issue is where do we choose $t=0$ in computing range delay? The common method is to choose it at the time of a transmit pulse. Thus, $t=0$ is reset on each transmit pulse.

To define the problem, we consider the situation of *Figure 2*. In this figure the transmit pulses are spaced 400 µs apart. The target range is 90 Km, which means that the range delay to the target is

$$\tau_R = \frac{2R}{c} = \frac{2\times 90\times 10^3}{3\times 10^8} = 60\times 10^{-5} \text{ s} = 600\ \mu\text{s}.$$

This means that the return from pulse 1 would not be received until after pulse 2 is transmitted, the return from pulse 2 would not be received until after pulse 3 is transmitted, etc. Since all of the transmit pulses are the same and all received pulses are the same we have no way of associating received pulse 1 with transmit pulse 1. In fact, since we reset $t=0$ on each transmit pulse, we will associate received pulse k with transmit pulse $k+1$. Further, we would measure the range delay as 200 µs. If we were use this value of range delay to compute range we would get an apparent range of

$$R_A = 150\tau = 150\times 200 = 30{,}000 \text{ m or } 30 \text{ Km}.$$

Because of this we say that we have an *ambiguity*, or uncertainty, in measuring range.

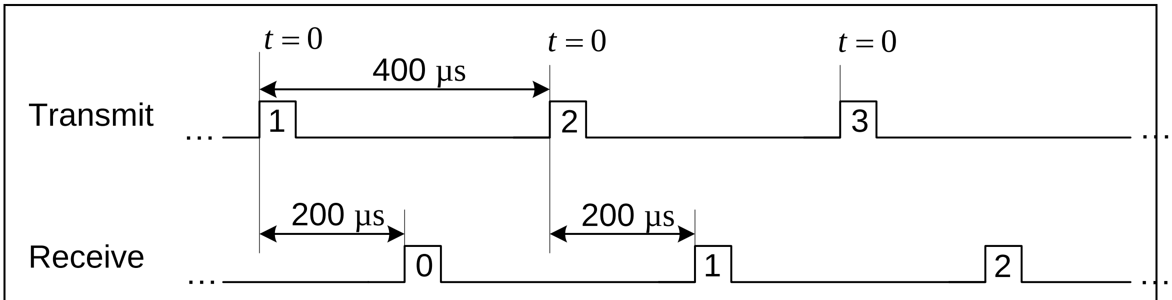

Figure 2 – Illustration of Ambiguous Range

If the spacing between pulses is τ_{PRI} we say that the radar has an *unambiguous range* of

$$R_{amb} = \frac{c\tau_{PRI}}{2} .$$

This tells us that if the target range is less than R_{amb} the radar can measure its range unambiguously. If the target range is greater than R_{amb} we cannot measure its range unambiguously.

In the above notation, PRI stands for *pulse repetition interval* and is defined as the spacing between transmit pulses. A related term is *pulse repetition frequency*, or PRF. PRF is the reciprocal of PRI.

To avoid range ambiguities, radar designers typically choose the PRI to be greater than the range delay associated with the longest range targets of interest. They also limit the power to try to be sure that long range targets will not be detected by the radar.

Ambiguous range is a problem in search, but not track. In track, the radar tracking filters or algorithms have an idea of target range and can "look" in the proper place, even if the returns are ambiguous.

Another way to circumvent the ambiguous range problem is to use waveforms with multiple PRIs. That is, waveforms where the spacing between transmit pulses changes. An example of a multiple PRI transmit waveform, and the appropriate received signal, is shown in *Figure 3*. In this figure, the spacings between the four transmit pulses are 400 μs, 300 μs and 350 μs. The target range delay is 600 μs, as in the previous example. It will be noted that the position of the number 1 received pulse, relative to the number 2 transmit pulse is 200 μs and the location of the number 2 received pulse, relative to the number 3 transmit pulse is 300 μs. The fact that the location of the received pulse relative to the most recently transmitted pulse is changing gives us the indication that the target range is ambiguous. We can use this fact to ignore the returns.

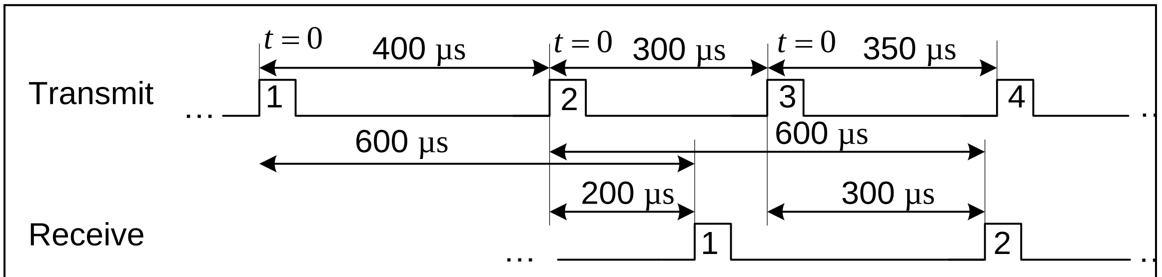

Figure 3 – Staggered PRI Waveform and Ambiguous Range

As an alternative, we could use the measured range delays in a *range resolve* algorithm to compute the true target range. Such an approach is used in pulsed Doppler radars because the PRIs used in these radars almost always result in ambiguous range operation.

1.3 SIMPLE FORM OF RADAR EQUATION:

One of the simpler equations of radar theory is the radar range equation. Although it is one of the simpler equations, ironically, it is an equation that few radar analysts understand and many radar analysts misuse. The problem lies not with the equation itself but with the various terms that make-up the equation. It is my belief that if one really understands the radar range equation one will have a very solid foundation in the fundamentals of radar theory. Because of the difficulties associated with using and understanding the radar range equation we will devote considerable class time to it and to the things it impacts, like detection theory, matched filters and the ambiguity function.

One form of the basic radar range equation is

$$SNR = \frac{P_S}{P_N} = \frac{P_T G_T G_R \lambda^2 \sigma}{(4\pi)^3 R^4 k T_0 B F_n L} \qquad (1)$$

where

- SNR is termed the signal-to-noise ratio and has the units of watts/watt, or w/w.
- P_S is the signal power at some point in the radar receiver – usually at the output of the matched filter or the signal processor. It has the units of watts (w).

- P_N is the noise power at the same point that P_S is specified and has the units of watts.
- P_T is termed the *peak transmit power* and is the average power when the radar is transmitting a signal. P_T can be specified at the output of the transmitter or at some other point like the output of the antenna feed. It has the units of watts
- G_T is the power gain of the transmit antenna and has the units of w/w.
- G_R is the power gain of the receive antenna and has the units of w/w. Usually, $G_T = G_R$ for monostatic radars.
- λ is the radar wavelength (see (21) of the Radar Basics section) and had the units of meters (m).
- σ is the target *radar cross-section or RCS* and has the units of square meters or m^2.
- R is the range from the radar to the target and has the units of meters.
- k is Boltzman's constant and is equal to $1.38 \times 10^{23}\ \text{w}/(\text{Hz}\ ^\circ\text{K})$.
- T_0 denotes room temperature in Kelvins $(^\circ\text{K})$. We take $T_0 = 293\ ^\circ\text{K}$ and usually use the approximation $kT_0 = 4 \times 10^{-21}\ \text{w/Hz}$.
- B is the ***effective*** noise bandwidth of the radar and has the units of Hz. I emphasized the word effective because this point is extremely important and seldom understood by radar analysts.
- F_n is the radar *noise figure* and is dimensionless, or has the units of w/w.
- L is a term included to account for all losses that must be considered when using the radar range equation. It accounts for losses that apply to the signal and not the noise. L has the units of w/w. L accounts for a multitude of factors that degrade radar performance. These factors include those related to the radar itself, the environment in which the radar operates, the radar operators and, often, the ignorance of the radar analyst.

We will spend the next several pages deriving the radar range equation and attempting to carefully explain its various terms and their origins. In the process we will present other forms of the radar range equation that are used in different applications. We will start by deriving P_S, or the signal power component and follow this by a derivation P_N, or the noise component.

DERIVATION OF P_S

We will start at the transmitter output and go through the waveguide and antenna and out into space, see *Figure 4*. For now, we assume that the radar is in free space. We can account for the effects of the atmosphere at a later date. We assume that the transmitter generates a single, rectangular pulse (a standard assumption) at some carrier frequency, f_c. A sketch of the *pulse* (the terminology we use) is contained in *Figure 5*. The average power in the signal *over the duration of the pulse* is termed the *peak* transmit power and is denoted as P_T. The reason we term this power the peak transmit power is that we will later want to consider the transmit power averaged over many pulses.

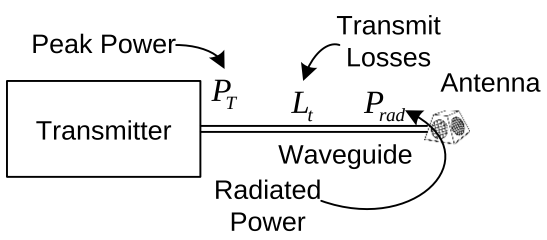

Figure 4 – Transmit Section of a Radar

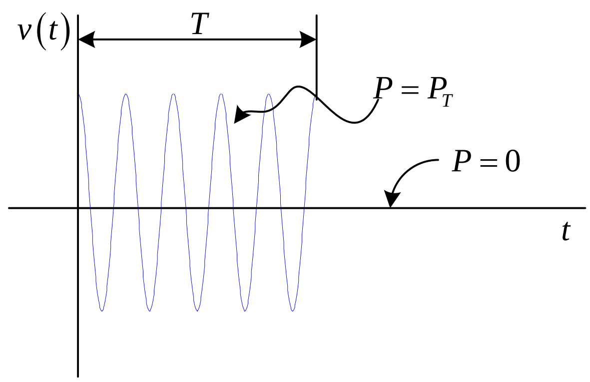

Figure 5 – Depiction of a Transmit Pulse

The waveguide of *Figure 4* carries the signal from the transmitter to the antenna feed. The only feature of the waveguide that is of interest in the radar range equation is the fact that it is a lossy device that attenuates the signal. Although we only refer to the "waveguide" here, in a practical radar there are several devices between the transmitter and antenna feed. We lump all of these into a conceptual waveguide.

Since the waveguide is a lossy device we characterize it in terms of its loss which we denote as L_t and term *transmit loss*. Since L_t is a loss it is greater than unity. With this, the power at the feed is

$$P_{rad} = \frac{P_T}{L_t} \text{ w} \tag{2}$$

and is termed the *radiated power*.

We assume that the feed and the antenna are ideal and thus introduce no additional losses to the radiated power. In actuality, the antenna assembly (antenna and feed) will have losses associated with it. In some instances, the losses are incorporated in L_t and in other cases they are incorporated in the antenna gain, which will be discussed shortly. When using the radar range equation, one must be sure that the antenna losses are accounted for in one place or the other. Because of the above assumption, the power radiated into space is P_{rad}.

The purpose of the radar antenna is to concentrate or focus the radiated power in a small angular sector of space. In this fashion, the radar antenna works much as the reflector in a flashlight. As with a flashlight, a radar antenna doesn't perfectly focus the beam. However, for now we will assume it does. Later, we will account for the fact that the focusing isn't perfect by a scaling term.

With the above, we assume that all of the radiated power is concentrated in an area, A_{beam}, as indicated in *Figure 6*. Therefore, the power density over A_{beam} is

$$S_R = \frac{P_{rad}}{A_{beam}} = \frac{P_T / L_t}{A_{beam}} \text{ w/m}^2 . \tag{3}$$

To carry (3) to the next step we need an equation for A_{beam}. Finding the area of the ellipse of *Figure 6* is not easy. To get around this problem we find the area of the rectangle that contains the elliptical beam of *Figure 3*. We will then include a scaling factor to account for the fact that the area of the rectangle is greater than the area of the ellipse. This scaling factor will also account for losses in the feed and antenna.

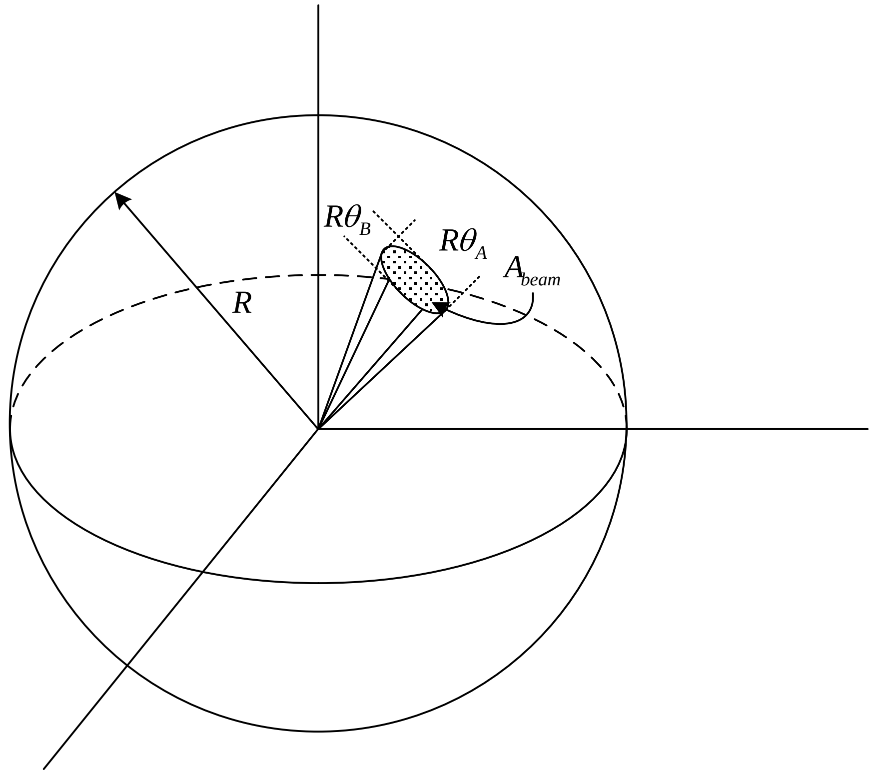

Figure 6 – Radiation Sphere with Antenna Beam

The length of the two sides of a rectangle that contains the ellipse of *Figure 3* are $R\theta_A$ and $R\theta_B$, and the area of the rectangle is

$$A_{rect} = R^2\theta_A\theta_B \text{ m}^2. \tag{4}$$

From this we write A_{beam} as

$$A_{beam} = K_A R^2\theta_A\theta_B \text{ m}^2 \tag{5}$$

where K_A is the aforementioned scaling factor. If we substitute (5) into (3) we get

$$S_R = \frac{P_T/L_t}{K_A R^2\theta_A\theta_B} \text{ w/m}^2. \tag{6}$$

At this point we define a term, G_T, that we call the transmit *antenna gain* as

$$G_T = \frac{4\pi}{K_A\theta_A\theta_B} \text{ w/w} \tag{7}$$

and use it to rewrite (6) as

$$S_R = \frac{G_T P_T}{4\pi R^2 L_t} \text{ w/m}^2 . \tag{8}$$

We now want to discuss a quantity termed *effective radiated power*. To do so we ask the question: What power would we need at the feed of an isotropic radiator to get a power density of S_R at all points on a sphere of radius R? An isotropic radiator is an antenna that does not focus energy. We can think of it as a point source radiator. We note that an isotropic radiator cannot exist in the "real world". However, it is a mathematical and conceptual concept that we often use in radar theory.

If we denote the effective radiated power as P_{eff} and realize that the surface area of a sphere of radius R is $4\pi R^2$ we can write the power density on the surface of the sphere as

$$S_R = \frac{P_{eff}}{4\pi R^2} \text{ w/m}^2 . \tag{9}$$

If we equate (8) and (9) we obtain

$$P_{eff} = \frac{P_T G_T}{L_t} \text{ w} = ERP \tag{10}$$

as the effective radiated power, or ERP. Many radar analysts think that the power at the output of a radar antenna is the ERP. It is not. The power at the output of the antenna is P_T / L_t. All the antenna does if focus this power over a relatively small angular sector.

Another note is that the development above makes the tacit assumption that the antenna is pointed exactly at the target. If the antenna is not pointed at the target, G_T must be modified to account for this. We do this by means of an *antenna pattern* which is a function that gives the value of G_T at all possible angles of the target relative to where the antenna is pointing.

We next want to address the factor K_A in (7). K_A accounts for the properties of the antenna. Specifically:

- It accounts for the fact that the beam area is an ellipse rather than a rectangle.
- It accounts for the fact that not all of the power is concentrated in the antenna beam. Some of it will "spill" out of the beam into what we term the *antenna sidelobes*.
- It accounts for the fact that the antenna causes ohmic power losses.

It has been my experience that a good value for K_A is 1.65. With this we can write the antenna gain as

$$G_T = \frac{4\pi}{1.65\theta_A\theta_B} \text{ w/w}. \qquad (11)$$

In (11) the quantities θ_A and θ_B are termed the *antenna beamwidths* and have the units of radians. In many applications, θ_A and θ_B are specified in degrees. In this case we write the gain as

$$G_T = \frac{25{,}000}{\theta_A^\circ\theta_B^\circ} \text{ w/w} \qquad (12)$$

where the two beamwidths in the denominator are in degrees.

To visualize the concept of beamwidth we consider *Figure 4* which is a plot of $G_T(\theta,\phi)$ vs. θ for $\phi = 0$. The expression $G_T(\theta,\phi)$ is a means of saying that the antenna gain is a function of where the target is located relative to where the antenna is pointing. With some thought, you will realize that two angles are needed to specify any point on the sphere discussed earlier.

The unit of measure on the vertical axis is decibels, or dB, and is the common unit of measure for G_T in radar applications. We define the beamwidth of an antenna as the distance between the *3-dB points*[1] of *Figure 4*. The 3-dB points are the angles where $G_T(\theta,\phi)$ is 3 dB below its maximum value. As a side note, the maximum value of $G_T(\theta,\phi)$ is the antenna gain, or G_T. With this we find that the antenna represented in *Figure 7* has a beamwidth of 2 degrees in the θ direction. We might call this θ_A°. Suppose we were to plot $G_T(\theta,\phi)$ vs. ϕ for $\theta = 0$ and find distance between the 3-dB points was 2.5 degrees. We would then say that the beamwidth was 2.5 degrees in the ϕ direction. We would then call this θ_B°. We would compute the antenna gain as

$$G_T = \frac{25{,}000}{2 \times 2.5} = 5000 \text{ w/w or } 37 \text{ dB}. \qquad (13)$$

[1] The concept of 3-dB points should be familiar from control and signal processing theory in that it is the standard measure used to characterize bandwidth.

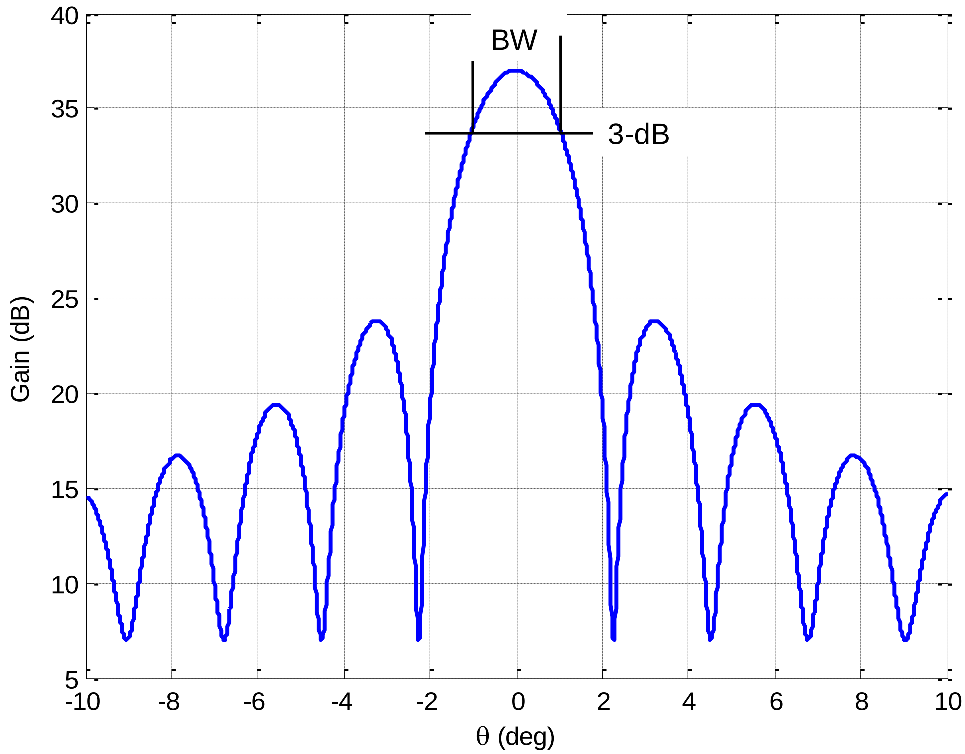

Figure 7 – Sample Antenna Pattern

1.4.RADAR BLOCK DIAGRAM AND OPERATION:

The block diagram given below shows the main components of pulse radar and their operation. The transmitter may be an oscillator, such as a magnetron, which is pulsed (turned on and off) by the modulator to generate a repetitive train of pulses of the kind shown in Figure 8. The waveform generated by the transmitter travels along a transmission line to the antenna, which is generally used for both transmitting and receiving. The duplexer consists of two devices, one known as TR (Transmit-Receive) and the other as ATR (Anti-Transmit-Receive). The TR protects the delicate circuits of the receiver from the high power of the transmitter during transmission and the ATR channels the returned echo signal to the receiver, and not to the transmitter, during reception. The first stage of the receiver is a low-noise RF (radio frequency) amplifier. The mixer and the local oscillator convert the RF signal to an IF (intermediate frequency) signal. This signal is passed through an IF amplifier which is designed to maximize the signal-to-noise ratio at its output. The pulse modulation of the echo signal is extracted by the detector and amplified by the video amplifier to a level at which the signal can be properly displayed on a CRT (Cathode Ray Tube). Timing signals are also supplied for range reference. Angle information is obtained from the pointing direction of the antenna. The most common form of the CRT display is the PPI (Plan Position Indicator), 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 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.

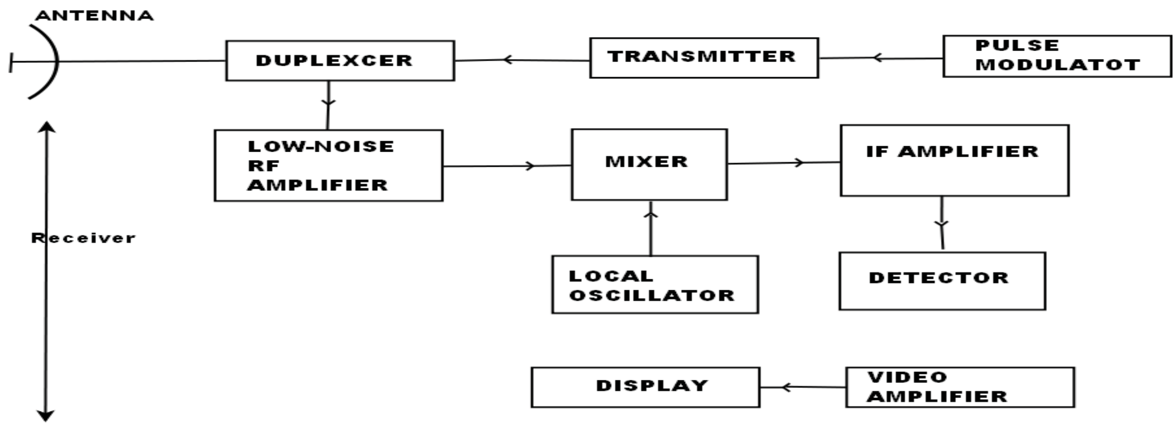

Figure 8. The block Diagram of Basic Pulse Radar System

A B-scope display is similar to the PPI except that it utilizes rectangular,rather than polar, coordinates and displays range vs. angle. Both the B-scopeand the PPI, being intensity modulated, have limited dynamic range. (seefigures in Skolnik's book)

Another form of display is the A-scope display, which plots target amplitudevs. range, for some fixed direction. This is a deflection-modulated display. It is more suited for tracking radar application than for surveillance radars.The block diagram is a simplified version which omits many important details like devices which automatically compensate the receiver for changes in frequency (AFC - Automatic Frequency Controller), gain (AGC - Automatic Gain Controller), 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, and pulse compression for achieving the resolution benefits of a short pulse but with the energy of a large pulse. Similarly, there are many other devices, used according to requirement, which have not been discussed here.

1.5 RADAR FREQUENCIES:

Conventionally, radars are usually operated at frequencies between 220 MHz and 35 GHz, a spread of more than 7 octaves. However, they can also be operated at other frequencies outside this range. For example, skywave HF over-the-horizon (OTH) radars might operate at frequencies as low as 4 to 5 MHz and ground wave F radars as low as 2 MHz. Millimeter wave radars may operate at 94 GHz. Laser radars have been known to operate at even higher frequencies (Refer to Skolnik, pages 7-8, for details).

APPLICATIONS OF RADARS:

- On ground : Detection, location, and tracking of aircraft and space targets.
- In the air : Detection of other aircraft, ships, or land vehicles; mapping of land; storm avoidance, terrain avoidance, and navigation.
- On the sea : Navigation aid and safety device to locate buoys, shore lines, other ships, and for observation of aircraft.
- In space : Guidance of spacecraft; remote sensing of land and sea.

Some specific applications are as follows:

- Air traffic control : Controlling of air traffic in the vicinity of airports; and also for automated landing.
- Aircraft navigation : Weather avoidance to indicate regions of severe precipitation; terrain following/terrain avoidance (TF/TA); radio altimeter and doppler navigator are also radars.
- Ship safety : Collision avoidance; detection of navigation buoys.
- Space : Rendezvous and docking; landing on the moon and other planets; detection and tracking of satellites.
- Remote sensing: Sensing of geophysical object, or the ”environment” like weather, cloud cover, earth resources, water resources, agriculture, forests, geological formation, etc. This is usually done from aircraft or satellites.
- Law enforcement : To monitor speed of vehicles in traffic.
- Military : Surveillance and navigation; control and guidance of weapons. The largest use of radars occurs here.

1.6 RANGE PERFORMANCE OF RADARS:

The simple form of the radar equation expressed the maximum radar range Rmax, in terms of
radar and target parameters:

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

where P_t = transmitted power, watts
G = antenna gain
A_e = antenna effective aperture, m^2
σ = radar cross section, m^2
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 σ. 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. above 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 S_{min} and the target cross section σ 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 IN RADAR:

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 (Figure 9). 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 Figure.9, 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 Figure.9 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 signal 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 $B\tau \approx 1$. 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.)

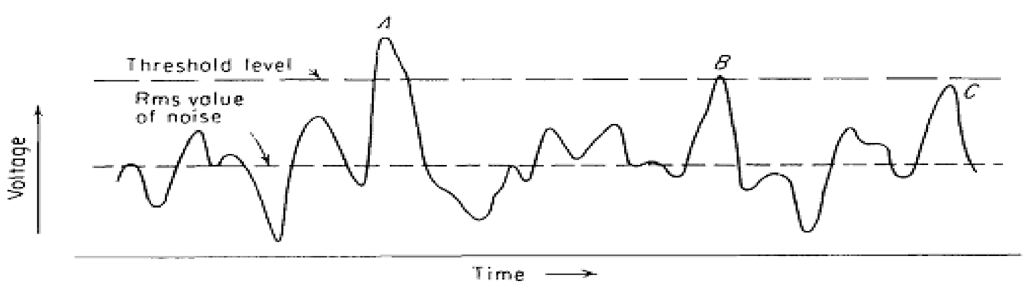

Figure.9 Envelope of radar receiver output as a function of time

1.8 Receiver Noise:

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. If 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 Bn, (in hertz) at a temperature T (degrees Kelvin) is equal to

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

where k = Boltzmann's constant = 1.38 x 10^{-23} J/deg.

If the temperature T is taken to be 290 K, which corresponds approximately to room temperature (62°F), the factor kT is 4 x 10^{-21} W/Hz of bandwidth. If the receiver circuitry were at some other temperature, the thermal-noise power would be correspondingly different.

A receiver with a reactance input such as a parametric amplifier need not have any significant ohmic loss. The limitation in this case is the thermal noise seen by the antenna and the ohmic losses in the transmission line.

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 fo = frequency of maximum response (usually occurs at midband).

When H (f) is normalized to unity at midband (maximum-response frequency), H (fo) = 1. The bandwidth Bn is called the noise bandwidth and is the bandwidth of an equivalent rectangular filter whose noise-power output is the same as the filter with characteristic H (f). The 3-dB bandwidth is defined as the separation in hertz between the points on the frequency-response characteristic where the response is reduced to 0.707 (3 dB) from its maximum value. The 3-dB bandwidth is widely used, since it is easy to measure. The measurement of noise bandwidth however, involves a complete knowledge of the response characteristic H (f). The frequency-response characteristics of many practical radar receivers are such that the 3-dB and the noise bandwidths do not differ appreciably. Therefore the 3-dB bandwidth may be used in many cases as an approximation to the noise bandwidth.

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. 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 Fn of a receiver is defined by the equation

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

Where N_o = noise output from receiver, and G_a = available gain. The standard temperature T is taken to be 290 K, according to the Institute of Electrical and Electronics Engineers definition. The noise N_o is measured over the linear portion of the receiver input-output characteristic, usually at the output of the IF amplifier before the nonlinear second detector. The receiver bandwidth B_n is that of the IF amplifier in most receivers. The available gain G_a is the ratio of the signal out S_o to the signal in S_i, and kT_oB_n is the input noise Ni in an ideal
receiver. Equation above may be rewritten as

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

The noise figure may be interpreted, therefore, as a measure of the degradation of signal-to noise- ratio as the signal passes through the receiver.

Rearranging Eq. above the input signal may be expressed as

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

If the minimum detectable signal Smin, is that value of Si corresponding to the minimum ratio of output (IF) signal-to-noise ratio $(S_o/N_o)_{min}$ necessary for detection, then

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

Substituting Eq. discussed above into Eq. earlier results in the following form of the radar equation:

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

1.9 MODIFIED RADAR RANGE EQUATION:

The essence of radar is the ability to scan three-dimensional space and gather information about detected objects, ranging from simple presence to details such as location, speed, direction, shape, and identity. In most implementations, a pulsed-RF or pulsed-microwave signal is generated by the radar system, beamed toward the target in question, and collected by the same antenna that transmitted the signal. The signal power at the radar receiver is directly proportional to the transmitted power, the antenna gain (or aperture size), and the degree to which a target reflects the radar signal (i.e., its RCS). Perhaps more significantly, it is indirectly proportional to the fourth power of the distance to the target. This entire process is described by the radar range equation. It incorporates the crucial variables and provides a basis for understanding the measurements that are made to verify and ensure optimal performance. Our derivation of the range equation starts with a simple spherical scattering model of propagation for a point-source antenna (i.e., an isotropic radiator). Assume, for simplicity, that the antenna is illuminating the interior of an imaginary sphere with equal power density in each unit of surface area (Figure 1). The surface area of a sphere is a function of its radius

There exist hundreds of versions of the radar range equation. Below is one of the more basic forms for a single antenna system (same antenna for both transmit and receive). The target is assumed to be in the center of the antenna beam. The maximum radar detection range is;

$$R_{max} = \sqrt[4]{\frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 P_{min}}} = \sqrt[4]{\frac{P_t G^2 c^2 \sigma}{f_o^2 (4\pi)^3 P_{min}}}$$

P_t = **Transmit power** (power dimensions)
P_{min} = **minimum detectable signal** (power)
λ = **transmit wavelength** (length)
σ = **Target radar cross section** (area)
f_o = **Frequency** (Hz)
G = **Antenna Gain** (ratio)
c = **speed of light**

The variables in the above equation are constant and radar dependent except target RCS. Transmit power will be on the order of 1 mW (0 dBm) and antenna gain around 100 (20 dB) for an effective radiated power (ERP) of 100 mW (20 dBm). Minimum detectable signals are on the order of picowatts; RCS for an automobile might be on the order of 100 square meters. The accuracy of the radar range equation is only as good as the input data.

Minimum detectable signal (P_{min}) depends on receiver bandwidth (B), noise figure (F), temperature (T), and required signal-to-noise ratio (S/N). A narrow bandwidth receiver will be more sensitive than a wider bandwidth receiver. Noise figure is a measure of how much noise a device (the receiver) contributes to a signal: the smaller the noise figure, the less noise the device contributes. Increasing temperature affects receiver sensitivity by increasing input noise.

$$\mathbf{P_{min} = k\ T\ B\ F\ (S/N)_{min}}$$

P_{min} = Minimum Detectable Signal
k = Blotzmann's Constant = 1.38×10^{-23} (Watt*sec/°Kelvin)
T = Temperature (°Kelvin)
B = Receiver Bandwidth (Hz)
F = Noise Factor (ratio), Noise Figure (dB)
$(S/N)_{min}$ = Minimum Signal to Noise Ratio

The available input thermal noise power (**background noise**) is proportional to the product kTB where k is Boltzmann's constant, T is temperature (degrees Kelvin) and B is receiver noise bandwidth (approximately receiver bandwidth) in hertz.

T = 290°K (62.33°F), B = 1 Hz

kTB = -174 dBm/Hz

The radar range equation above can be written for power received as a function of range for a given transmit power, wavelength, antenna gain, and RCS.

$$P_{rec} = \frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 R_{max}^4} = \frac{P_t G^2 c^2 \sigma}{f_o^2 (4\pi)^3 R^4}$$

$$P_{rec} = P_t G^2 \left(\frac{\lambda}{4\pi R}\right)^2 \frac{\sigma}{4\pi R^2}$$

range loss between transmit antenna & target — loss due to target reflection & range

P_{rec} = Power Received	G = Antenna Gain
P_t = Transmit Power	Sigma = Radar Cross Section
f_o = Transmit Frequency	R = Range
Lamda = Transmit Wavelength	c = Speed of Light

Radar Detector Range

Radar has a range loss inversely proportional to range to the 4th power ($1/R^4$). Radio communications range losses are inversely proportional to range squared (one-way path is $1/R^2$). Signal power received (by a radar detector), where Gdet is detector antenna gain, can be expressed as shown below. By substituting radar detector minimum signal for power received, detector maximum range can be estimated if radar power and antenna gain are known (ERP -- effective radiated power).

$$P_{det} = \frac{P_t\, G\, G_{det}\, \lambda^2}{(4\pi R)^2} = P_t\, G\, G_{det} \left(\frac{\lambda}{4\pi R}\right)^2 = \frac{P_t\, G\, G_{det}\, c^2}{f_o^2\, (4\pi R)^2}$$

$$R = \sqrt{\frac{P_t\, G\, G_{det}\, \lambda^2}{(4\pi)^2\, P_{det}}} = \sqrt{\frac{P_t\, G\, G_{det}\, c^2}{f_o^2 (4\pi)^2\, P_{det}}}$$

P_{det} = Power Received by Detector
G_{det} = Detector Antenna Gain

Radar propagation loss is proportional to $1/R^4$ (2-way signal path), while a radar detector would be picking up the signal on the direct (1-way) path with loss proportional to $1/R^2$(a *hugh* advantage for the detector). Another *hugh* advantage is the radar is receiving a **reflection** (RCS), *most* of the reflective energy is directed **away** from the radar. The radar has the advantage of a much larger antenna (more gain) and more sensitive (to radar signal) receiver. However, good radar detector should be able to detect a radar before the radar detects the vehicle, but *not* always.

1.10 SIGNAL-TO-NOISE (S/N) RATIO:

The Signal-to-Noise Ratio (S/N) (a.k.a. SNR) in a receiver is the signal power in the receiver divided by the mean noise power of the receiver. All receivers require the signal to exceed the noise by some amount. Usually if the signal power is less than or just equals the noise power it is not detectable. For a signal to be detected, the signal energy plus the noise energy must exceed some threshold value. Therefore, just because N is in the denominator doesn't mean it can be increased to lower the MOS. S/N is a required minimum ratio, if N is increased, then S must also be increased to maintain that threshold. The threshold value is chosen high enough above the mean noise level so that the probability of random noise peaks exceeding the threshold, and causing false alarms, is acceptably low. Figure 1 depicts the concept of required S/N. It can be seen that the signal at time A exceeds the S/N ratio and indicates a false alarm or target. The signal at time B is just at the threshold, and the signal at time C is clearly below it. In the sample, if the temperature is taken as room temperature (T = 290EK), the noise power input is -114 dBm for a one o MHz bandwidth. Normally $(S/N)_{min}$ may be set higher than S/N shown in Figure 1 to meet false alarm specifications.

The acceptable minimum Signal-to-Noise ratio (or think of it as Signal above Noise) for a receiver depends on the intended use of the receiver. For instance, a receiver that had to detect a single radar pulse would probably need a higher minimum S/N than a receiver that could integrate a large number of radar pulses (increasing the total signal energy) for detection with the same probability of false alarms. Receivers with human operators using a video display may function satisfactorily with low minimum S/N because a skilled operator can be very proficient at picking signals out of a noise background. As shown in Table 1, the setting of an acceptable minimum S/N is highly dependent on the required characteristics of the receiver and of the signal.

1.11 FALSE ALARM TIME AND PROBABILITY:

Consider an IF amplifier with bandwidth BIF followed by a second detector and a video amplifier with bandwidth Bv. The second detector and video amplifier are assumed to form an envelope detector, that is, one which rejects the carrier frequency but passes the modulation envelope. To extract the modulation envelope, the video bandwidth must be wide enough to pass the low-frequency components generated by the second detector, but not so wide as to pass the high-frequency components at or near the intermediate frequency. The video bandwidth Bv, must be greater than BIF /2 in order to pass all the video modulation. Most radar receivers used in conjunction with an operator viewing a CRT display meet this condition and may be considered envelope detectors. Either a square-law or a linear detector may be assumed since the effect on the detection probability by assuming one instead of the other is usually small.

Figure 10. Part of the Receiver block of Radar system

The noise entering the IF filter (the terms filter and amplifier are used interchangeably) is assumed to be gaussian, with probability-density function given by

$$p(v) = \frac{1}{\sqrt{2\pi\psi_0}} \exp \frac{-v^2}{2\psi_0}$$

where p(v) dv is the probability of finding the noise voltage v between the values of v and v + dv, Ψ_0 is the variance, or mean-square value of the noise voltage, and the mean value of v is taken to be zero. If gaussian noise were passed through a narrowband IF filter-one
whose bandwidth is small compared with the mid frequency-the probability density of the envelope of the noise voltage output is shown by Rice to be

$$p(R) = \frac{R}{\psi_0} \exp\left(-\frac{R^2}{2\psi_0}\right)$$

where R is the amplitude of the envelope of the filter output. Equation above is a form of the Rayleigh probability-density function. The probability that the envelope of the noise voltage will lie between the values of V1 and V2 is

$$\text{Probability } (V_1 < R < V_2) = \int_{V_1}^{V_2} \frac{R}{\psi_0} \exp\left(-\frac{R^2}{2\psi_0}\right) dR$$

The probability that the noise voltage envelope will exceed the voltage threshold VT is

$$\text{Probability } (V_T < R < \infty) = \int_{V_T}^{\infty} \frac{R}{\psi_0} \exp\left(-\frac{R^2}{2\psi_0}\right) dR$$

$$= \exp\left(-\frac{V_T^2}{2\psi_0}\right) = P_{fa}$$

Whenever the voltage envelope exceeds the threshold, target detection is considered to have occurred, by definition. Since the probability of a false alarm is the probability that noise will cross the threshold, Eq. above gives the probability of a false alarm, denoted Pfa The average time interval between crossings of the threshold by noise alone is defined as the false-alarm time Tfa,

$$T_{fa} = \lim_{N \to \infty} \frac{1}{N} \sum_{k=1}^{N} T_k$$

where Tk is the time between crossings of the threshold VT by the noise envelope, when the slope of the crossing is positive. The false-alarm probability may also be defined as the ratio of the duration of time the envelope is actually above the threshold to the total time it could have
been above the threshold, or

$$P_{fa} = \frac{\sum_{k=1}^{N} t_k}{\sum_{k=1}^{N} T_k} = \frac{\langle t_k \rangle_{av}}{\langle T_k \rangle_{av}} = \frac{1}{T_{fa} B}$$

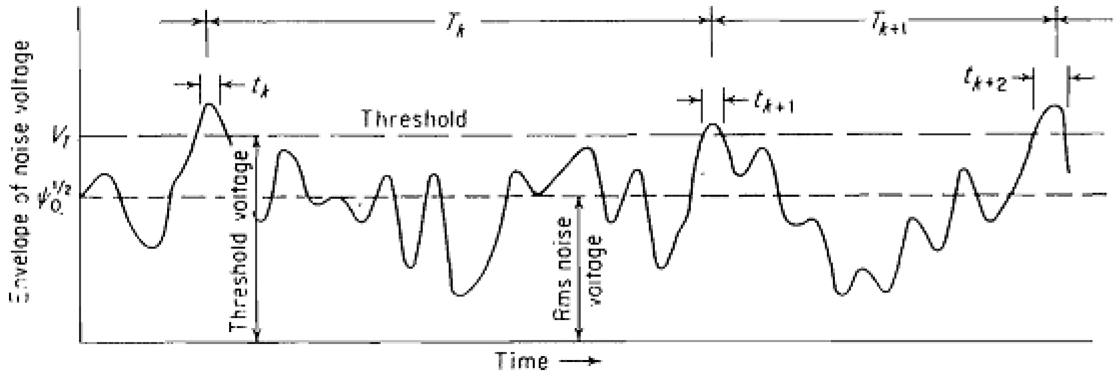

Figure.11 Envelope of receiver output illustrating false alarms due to noise.

where tk and Tk are defined in Fig.The average duration of a noise pulse is approximately the reciprocal of the bandwidth B, which in the case of the envelope detector is BIF. Equating equations discussed above we get with V2 T / 2 Ψo as the abscissa. If, for example, the bandwidth of the IF amplifier were 1 MHz and the average false-alarm time that could be tolerated were 15 min, the probability of a false alarm is 1.11 x 10-9 . From Eq. above the threshold voltage necessary to achieve this false-alarm time is 6.45 times the rms value of the noise voltage.

The false-alarm probabilities of practical radars are quite small. The reason for this is that the false-alarm probability is the probability that a noise pulse will cross the threshold during an interval of time approximately equal to the reciprocal of the bandwidth. For a 1- MHz bandwidth, there are of the order of 106 noise pulses per second. Hence the false alarm probability of any one pulse must be small (< 10-6) if false-alarm times greater than 1 s are to be obtained.

1.12 INTEGRATION OF RADAR PULSES:

Many pulses are usually returned from any particular target on each radar scan and can be used to improve detection. The number of pulses nB returned from a point target as the radar antenna scans through its beamwidth is

$$n_B = \frac{\theta_B f_p}{\dot{\theta}_s} = \frac{\theta_B f_p}{6\omega_m}$$

where θ_B = antenna beamwidth, deg
f_p = pulse repetition frequency, Hz
$\dot{\theta}_s$ = antenna scanning rate, deg/s
ω_m = antenna scan rate, rpm

Typical parameters for a ground-based search radar might be pulse repetition frequency 300 Hz, 1.5° beamwidth, and antenna scan rate 5 rpm (30°/s). These parameters result in 15 hits from a point target on each scan. The process of summing all the radar echo pulses for the purpose of improving detection is called integration. Many techniques might be employed for accomplishing integration. All practical integration techniques employ some sort of storage device. Perhaps the most common radar integration method is the cathode-ray-tube display combined with the integrating properties of the eye and brain of the radar operator.

Integration may be accomplished in the radar receiver either before the second detector (in the IF) or after the second detector (in the video). A definite distinction must be made between these two cases. Integration before the detector is called predetection, or coherent, integration, while integration after the detector is called post detection, or non coherent, integration. Predetection integration requires that the phase of the echo signal be preserved if full benefit is to be obtained from the summing process. On the other hand, phase information is destroyed by the second detector; hence post detection integration is not concerned with preserving RF phase. For this convenience, post detection integration is not as efficient as predetection integration.

If n pulses, all of the same signal-to-noise ratio, were integrated by an ideal predetection integrator, the resultant, or integrated, signal-to-noise (power) ratio would be exactly n times that of a single pulse. If the same n pulses were integrated by an ideal postdetection device, the resultant signal-to-noise ratio would be less than n times that of a single pulse. This loss in integration efficiency is caused by the nonlinear action of the second detector, which converts some of the signal energy to noise energy in the rectification process.

The comparison of predetection and postdetection integration may be briefly summarized by stating that although postdetection integration is not as efficient as predetection integration, it is easier to implement in most applications. Post detection integration is therefore preferred, even though the integrated signal-to-noise ratio may not be as great. An alert, trained operator viewing a properly designed cathode-ray tube display is a close approximation to the theoretical postdetection integrator. The efficiency of postdetection integration relative to ideal predetection integration has been computed by Marcum when all pulses are of equal amplitude. The integration efficiency may be defined as follows:

$$E_i(n) = \frac{(S/N)_1}{n(S/N)_n}$$

where n = number of pulses integrated

$(S/N)_1$ = value of signal-to-noise ratio of a single pulse required to produce given probability of detection (for $n = 1$)

$(S/N)_n$ = value of signal-to-noise ratio per pulse required to produce same probability of detection when n pulses are integrated

1.13 RADAR CROSS SECTION OF TARGETS:

The radar cross section of a target is the (fictional) area intercepting that amount of power which when scattered equally in all directions, produces an echo at the radar equal to that from the target; or in other terms,

$$\sigma = \frac{\text{power reflected toward source/unit solid angle}}{\text{incident power density}/4\pi} = \lim_{R \to \infty} 4\pi R^2 \left| \frac{E_r}{E_i} \right|^2$$

where R = distance between radar and target
E_r = reflected field strength at radar
E_i = strength of incident field at target

This equation is equivalent to the radar range equation. For most common types of radar targets such as aircraft, ships, and terrain, the radar cross section does not necessarily bear a simple relationship to the physical area, except that the larger the target size, the larger the cross section is likely to be. Scattering and diffraction are variations of the same physical process. When an object scatters an electromagnetic wave, the scattered field is defined as the difference between the total field in the presence of the object and the field that would exist if the object were absent (but with the sources unchanged). On the other hand, the diffracted field is the total field in the presence of the object. With radar backscatter, the two fields are the same, and one may talk about scattering and diffraction interchangeably.

In theory, the scattered field, and hence the radar cross section, can be determined by solving Maxwell's equations with the proper boundary conditions applied. Unfortunately, the determination of the radar cross section with Maxwell's equations can be accomplished only for the most simple of shapes, and solutions valid over a large range of frequencies are not easy to obtain. The radar cross section of a simple sphere is shown in Fig as a function of its circumference measured in wavelengths ($2\Pi a/\lambda$, where a is the radius of the sphere and λ is the wavelength). The region where the size of the sphere is small compared with the wavelength ($2\Pi a/\lambda << 1$) is called the Rayleigh region, after Lord Rayleigh who, in the early 1870's first studied scattering by small particles. Lord Rayleigh was interested in the scattering of light by microscopic particles, rather than in radar. His work preceded the original electromagnetic echo experiments of Hertz by about fifteen years.

The Rayleigh scattering region is of interest to the radar engineer because the cross sections of raindrops and other meteorological particles fall within this region at the usual radar frequencies. Since the cross section of objects within the Rayleigh region varies as λ-4, rain and clouds are essentially invisible to radars which operate at relatively long wavelengths (low frequencies). The usual radar targets are much larger than raindrops or cloud particles, and lowering the radar frequency to the point where rain or cloud echoes are negligibly small will not seriously reduce the cross section of the larger desired targets. On the other hand, if it were desired to actually observe, rather than eliminate, raindrop echoes, as in a meteorological or weather-observing radar, the higher radar frequencies would be preferred.

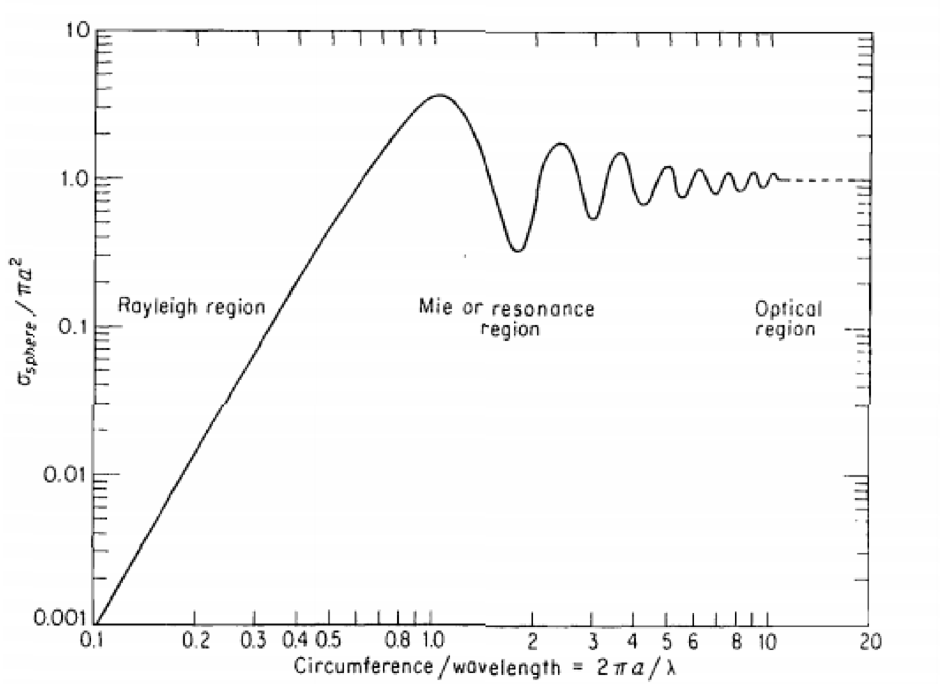

Figure 12 Radar cross section of the sphere. a = radius; λ = wavelength

At the other extreme from the Rayleigh region is the optical region, where the dimensions of the sphere are large compared with the wavelength (2Πa/λ >> 1). For large 2Πa/λ, the radar cross section approaches the optical cross section Πa2. In between the optical and the Rayleigh region is the Mie, or resonance, region. The cross section is oscillatory with frequency within this region. The maximum value is 5.6 dB greater than the optical value, while the value of the first null is 5.5 dB below the optical value. (The theoretical values of the maxima and minima may vary according to the method of calculation employed.) The behavior of the radar cross sections of other simple reflecting objects as a function of frequency is similar to that of the sphere.

1.14 TRANSMITTER POWER, PRF AND RANGE AMBIGUITIES:

Transmitter power:

The power Pt 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 = l/fp, 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 τfp 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 has 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 Eτ = Pav/fp contained in the transmitted waveform:

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

In this form, the range does not depend explicitly on either the wavelength or the pulse repetition frequency. The important parameters affecting range are the total transmitted energy nEτ, the transmitting gain G, the effective receiving aperture Ae, and the receiver noise figure Fn.

Pulse Repetition Frequencies and Range ambiguities:

The pulse repetition frequency (prf) is determined primarily by the maximum range at which targets are expected. If the prf is made too high the likelihood of obtaining target echoes from the wrong pulse transmission is increased. Echo signals received after an interval exceeding the pulse-repetition period are called multiple-time-around echoes. They can result in erroneous or confusing range measurements. Consider the three targets labeled A. B, and C in Figure 13. Target A is located within the maximum unambiguous range Runamb of the radar, target B is at a distance greater than Runamb but less than 2Runamb while target C is greater than 2Runarnh but less than 3Runamb. The appearance of the three targets on an A-scope is sketched in Fig. 9 b. 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 Band 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 C. 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.

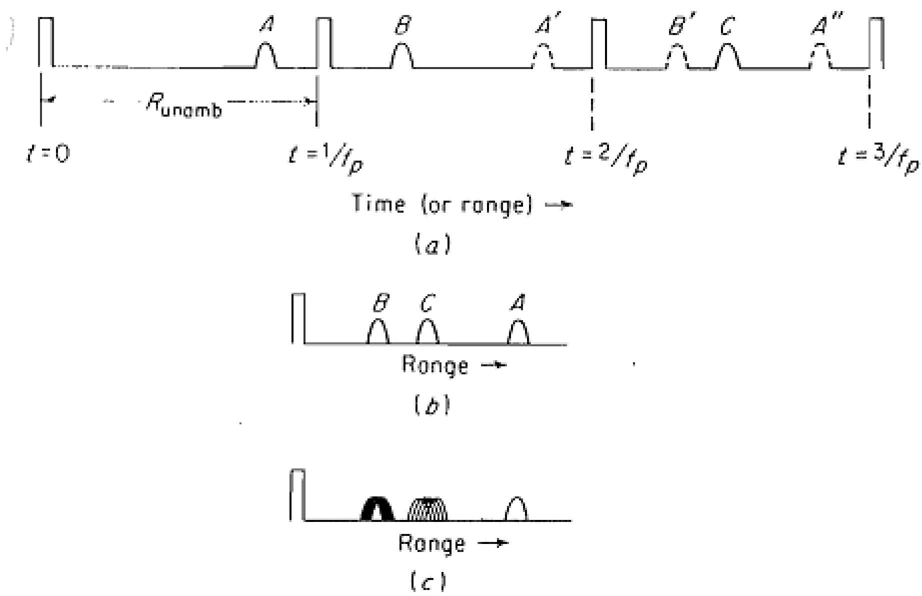

Figure.13 Multiple-time-around echoes that give rise to ambiguities in range
(a) Three targets A, B and C, where A is within R_{unamb}, and B and C are multiple-time-around targets;
(b) the appearance of the three targets on the A-scope;
c) appearance of the three targets on the A-scope with a changing prf.

Instead of modulating the prf, other schemes that might he 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 by the use of the Chinese remainder theorem or other computational algorithms

1.15 SYSTEM LOSSES:

One of the important factors omitted from the simple radar equation was the losses that occur throughout the radar system. The losses reduce the signal-to-noise ratio at the receiver output. They may be of two kinds, depending upon whether or not they can be predicted with any degree of precision before hand. The antenna beam-shape loss, collapsing loss, and losses in the microwave plumbing are examples of losses which can be calculated if the system configuration is known. These losses are very real and cannot be ignored in any serious prediction of radar performance. Losses not readily subject to calculation and which are less predictable include those due to field degradation and to operator fatigue or lack of operator motivation. Estimates of the latter type of loss must be made on the basis of prior experience and experimental observations. They may be subject to considerable variation and uncertainty.

Although the loss associated with any one factor may be small, there are many possible loss mechanisms in a complete radar system, and their sum total can be significant. In this section loss (number greater than unity) and efficiency (number less than unity) are used interchangeably. One is simply the reciprocal of the other.

Plumbing loss:

There is always some finite loss experienced in the transmission lines which connect the output of the transmitter to the antenna. The losses in decibels per 100 ft for radar transmission lines are shown in Fig.10. At the lower radar frequencies the transmission line introduces little loss, unless its length is exceptionally long. At the higher radar frequencies, attenuation may not always be small and may have to be taken into account. In addition to the losses in the transmission line itself, an additional loss can occur at each connection or bend in the line and at the antenna rotary joint if used. Connector losses are usually small, but if the connection is poorly made, it can contribute significant attenuation. Since the same transmission line is generally used for both receiving and transmission, the loss to be inserted in the radar equation is twice the one-way loss. The signal suffers attenuation as it passes through the duplexer.

Generally, the greater the isolation required from the duplexer on transmission, the larger will be the insertion loss. By insertion loss is meant the loss introduced when the component, in this case the duplexer, is inserted into the transmission line. The precise value of the insertion loss depends to a large extent on the particular design. For a typical duplexer it might be of the order of 1 dB. A gas-tube duplexer also introduces loss when in the fired condition (arc loss); approximately 1 dB is typical.

Beam-shape loss:

The antenna gain that appears in the radar equation was assumed to be a constant equal to the maximum value. But in reality the train of pulses returned from a target with a scanning radar is modulated in amplitude by the shape of the antenna beam. To properly take into account the pulse-train modulation caused by the beam shape, the computations of the probability of detection would have to be performed assuming a modulated train of pulses rather than constant-amplitude pulses. Some authors do indeed take account of the beam shape in this manner when computing the probability of detection. Therefore, when using published computations of probability of detection it should be noted whether the effect of the beam shape has been included. This approach is not used. Instead a beam-shape loss is added to the radar equation to account for the fact that the maximum gain is employed in the radar equation rather than a gain that changes pulse to pulse. This is a simpler, albeit less accurate, method. It is based on calculating the reduction in signal power and thus does not depend on the probability of detection. It applies for detection probabilities in the vicinity of 0.50, but it is used as an approximation with other values as a matter of convenience.

Limiting loss:

Limiting in the radar receiver can lower the probability of detection. Although a well-designed and engineered receiver will not limit the received signal under normal circumstances, intensity modulated CRT displays such as the PPI or the B-scope have limited dynamic range and may limit. Some

receivers, however, might employ limiting for some special purpose, as for pulse compression processing for example.
Limiting results in a loss of only a fraction of a decibel for a large number of pulses integrated provided the limiting ratio (ratio of video limit level to rms noise level) is as large as 2 or 3. Other analyses of band pass limiters show that for small signal-to noise ratio, the reduction in the signal-to-noise ratio of a sine-wave imbedded in narrowband gaussian noise is $\Pi/4$ (about 1 dB). However, by appropriately shaping the spectrum of the input noise, it has been suggested that the degradation can be made negligibly small.

Collapsing loss:

If the radar were to integrate additional noise samples along with the wanted signal-to-noise pulses, the added noise results in degradation called the collapsing loss. It can occur in displays which collapse the range information, such as the C-scope which displays elevation vs. azimuth angle. The echo signal from a particular range interval must compete in a collapsed-range C-scope display, not only with the noise energy contained within that range interval but with the noise energy from all other range intervals at the same elevation and azimuth. In some 3D radars (range, azimuth, and elevation) that display the outputs at all elevations on a single PPI (range, azimuth) display, the collapsing of the 3D radar information onto a 2D display results in a loss. A collapsing loss can occur when the output of a high resolution radar is displayed on a device whose resolution is coarser than that inherent in the radar. A collapsing loss also results if the outputs of two (or more) radar receivers are combined and only one contains signal while the other contains noise.