LECTURE NOTES
ON
RADAR SYSTEMS
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SYLLABUS

UNIT I

RADAR EQUATION: SNR, Envelope Detector, False Alarm Time and Probability, Integration of Radar Pulses, Radar Cross Section of Targets (simple targets - sphere, cone-sphere), Transmitter Power, PRF and Range Ambiguities, System Losses (qualitative treatment), Illustrative Problems.

UNIT II


UNIT III

UNIT IV
TRACKING RADAR: Tracking with Radar, Sequential Lobing, Conical Scan, Monopulse Tracking Radar – Amplitude Comparison Monopulse (one- and two coordinates), Phase Comparison Monopulse, Tracking in Range, Acquisition and Scanning Patterns, Comparison of Trackers.

UNIT V

RADAR RECEIVERS: Noise Figure and Noise Temperature, Displays – types. Duplexers – Branch type and Balanced type, Circulators as Duplexers. Phased Array Antennas – Basic Concepts, Radiation Pattern, Beam Steering and Beam Width changes, Series versus Parallel Feeds, Applications, Advantages and Limitations.
UNIT I
UNIT I

BASICS OF RADAR & RADAR EQUATION

INTRODUCTION

1. Radar is an acronym for Radio Detection and Ranging.
2. The term “radio” refers to the use of electromagnetic waves with wavelength in so-called radio wave portion of the spectrum, which covers a wide range from $10^4$ Km to 1 cm.
3. It is a system used to detect, range (determine the distance) and map objects such as aircraft and rain. Strong radio waves are transmitted, and a receiver listens for reflected echoes.
4. By analyzing the reflected signal, the reflector can be located, and sometimes identified. Although the amount of returned is tiny, radio signal can easily be detected and amplified. It can operate in darkness, haze, fog, rain and snow, it has ability to measure distance with high accuracy in all-weather conditions.
5. The electronics principal on which radar operates is very similar to the principle of sound wave reflection. If you shout in the direction of sound-reflecting object (like a rocky canon or cave), you will hear an echo.
6. If you know the speed of sound in air, you can estimate the distance and general direction of the object. The time required for a return echo can roughly converted in to distance if the speed of sound is known.
7. The radio frequency energy is transmitted to and reflects from the reflecting object. A small portion of the energy is reflected and return to the radar set. This returned energy is called ECHO.
8. Radar uses electromagnetic energy pulses in the same way, as shown in figure 1.
RANGE TO A TARGET

1. The most common radar waveform is a train of narrow, rectangular-shape pulses modulating a sine wave 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 $c = 3 \times 10^8$ m/s, the range $R$ is

$$ R = \frac{cT_R}{2} $$

2. $R = \frac{cT_R}{2}$

3. 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. above becomes

$$ 1. \quad R \text{ (Km)} = 0.15 \ T_R \text{ (us)} \quad \text{or} \quad R \text{ (nmi)} = 0.081 \ T_R \text{ (us)} $$

MAXIMUM UNAMBIGUOUS RANGE

1. 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.

2. Therefore the rate at which the pulses may be transmitted is determined by the longest range at which targets are expect

3. If the pulse repetition frequency is too high, echo signals from some targets might arrive after the transmission of the next pulse, and ambiguities in measuring range might result.

4. Echoes that arrive after the transmission of the next pulse are called second-time-around or multiple-time-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.

5. The range beyond which targets appear as second-time-around echoes is called the **maximum unambiguous range** and is given by

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

where $f_p =$ pulse repetition frequency, in Hz.

RADAR RANGE EQUATION

1. The radar equation relates the range of a radar to the characteristics of the transmitter, receiver, antenna, target, and environment. It is useful not just as a means for
determining the maximum distance from the radar to the target, but it can serve both as
a tool for understanding radar operation and as a basis for radar design.

2. If the power of the radar transmitter is denoted by $P_t$, and if an isotropic antenna is used
(one which radiates uniformly in all directions), the power density (Watts per unit area)
at a distance $R$ from the radar is equal to the transmitter power divided by the surface
area $4\pi R^2$ of an imaginary sphere of radius $R$, or

$$\text{Power density at range } R \text{ from an isotropic antenna} = \frac{P_t}{4\pi R^2}$$

3. Radars employ directive antennas to channel, or direct, the radiated power $P_t$ into some
particular direction. The gain $G$ of an antenna is a measure of the increased power
radiated in the direction of the target as compared with the power that would have been
radiated from an isotropic antenna.

4. It may be defined as the ratio of the maximum radiation intensity from the subject
antenna to the radiation intensity from a lossless, isotropic antenna with the same power
input. (The radiation intensity is the power radiated per unit solid angle in a given
direction.) The power density at the target from an antenna with a transmitting gain $G$ is

$$\text{Power density at range } R \text{ from a directive antenna} = \frac{P_tG}{4\pi R^2}$$

5. The target intercepts a portion of the incident power and reradiates it in various
directions.

6. The measure of the amount of incident power intercepted by the target and reradiated
back in the direction of the radar is denoted as the radar cross section $\sigma$, and is defined
by the relation

$$\text{Reradiated power density back at the radar} = \left( \frac{P_tG}{4\pi R^2} \right) \frac{\sigma}{4\pi R^2}$$

7. The radar cross section $\sigma$ has units of area. It is a characteristic of the particular target
and is a measure of its size as seen by the radar. The radar antenna captures a portion of
the echo power. If the effective area of the receiving antenna is denoted $A_e$, the power
$P_r$, received by the radar is;

$$P_r = \left( \frac{P_tG}{4\pi R^2} \right) \frac{\sigma}{4\pi R^2} A_e$$

8. The maximum radar range $R_{\text{max}}$ is the distance beyond which the target cannot be
detected. It occurs when the received echo signal power $P$, just equals the minimum
detectable signal $S_{\text{min}}$,

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

9. This is the fundamental form of the radar equation. Note that the important antenna
parameters are the transmitting gain and the receiving effective area.
10. Antenna theory gives the relationship between the transmitting gain and the receiving effective area of an antenna as:

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

11. Since radars generally use the same antenna for both transmission and reception, Eq. can be substituted into Eq. above, first for \( A_e \), then for \( G \), to give two other forms of the radar equation:

\[ R_{\text{max}} = \left[ \frac{P_t G_2 \sigma}{(4\pi)^3 S_{\text{min}}} \right]^{1/4} \]

12. Similarly

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

Then

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

13. The Radar range is proportional to \( \lambda^{1/2} \) in Case 1 & it is proportional to \( \lambda^{-1/2} \) Case 2.

So we can conclude that the Radar range is independent of wavelength.

**RADAR BLOCK DIAGRAM**

1. The operation of a typical pulse radar may be described with the aid of the block diagram shown in Fig

![Block diagram of simple pulse radar](image)

2. **Transmitter:**

   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.
3. **Pulse Modulator**
   The radar modulator is a device, which provides the high power to the transmitter tube to transmit during transmission period. It makes the transmitting tube ON and OFF to generate the desired waveform. Modulator allows the storing the energy in a capacitor bank during rest time.

4. The stored energy then can be put into the pulse when transmitted. It provides rectangular voltage pulses which act as the supply voltage to the output tube such as magnetron, thus switching it ON and OFF as required.

5. **Duplexer**
   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.

6. **Antenna:-**
   The antenna takes the radar pulse from the transmitter and puts it into the air. Furthermore, the antenna must focus the energy into a well-defined beam which increase the power and permits a determination of the direction of the target.

7. **Receiver:-**
   The receiver is usually of the super-heterodyne type whose function is to detect the desired signal in the presence of noise, interference and clutter. The receiver in pulsed radar consists of low noise RF amplifier, mixer, local oscillator, IF amplifier, detector, video amplifier and radar display.

8. **Low Noise RF Amplifier:-**
   Low noise amplifier is the first stage of the receiver. It is low noise transistor amplifier or a parametric amplifier or a TWT amplifier. Silicon bipolar transistor is used at lower radar frequencies (below L-band 1215 to 1400 MHz) and the GaAs FET is preferred at higher frequencies. It amplifies the received weak echo signal.

9. **Mixer and Local Oscillator:-**
   These convert RF signal output from RF amplifier to comparatively lower frequency level called Intermediate Frequency (IF). The typical value for pulse radar is 30 MHz or 60MHz.
10. **IF Amplifier:**

IF Amplifier consist of a cascade of tuned amplifier, these can be synchronous, that is all tuned to the same frequency and having identical band pass characteristics. If a really large bandwidth is needed, the individual IF may be staggered tuned. The typical value for pulse radar is 30 MHz or 60MHz.

11. **Detector:**

Detector is often a schottky-barrier diode which extract the pulse modulation from the IF amplifier output. The detector output is then amplified by the video amplifier to a level where it can be properly displayed on screen directly or via DSP.

12. **Display Unit:**

The received video signal are display on the CRT for further observation and actions. Different types of display system which are used in radar

**RADAR FREQUENCIES**

<table>
<thead>
<tr>
<th>Band designation</th>
<th>Nominal frequency range</th>
<th>Specific radiolocation (radar) bands based on ITU assignments for region 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>HF</td>
<td>3–30 MHz</td>
<td>138–144 MHz</td>
</tr>
<tr>
<td>VHF</td>
<td>30–300 MHz</td>
<td>216–225</td>
</tr>
<tr>
<td>UHF</td>
<td>300–1000 MHz</td>
<td>420–450 MHz</td>
</tr>
<tr>
<td>L</td>
<td>1000–2000 MHz</td>
<td>1215–1400 MHz</td>
</tr>
<tr>
<td>S</td>
<td>2000–4000 MHz</td>
<td>2300–2500 MHz</td>
</tr>
<tr>
<td>C</td>
<td>4000–8000 MHz</td>
<td>5250–5925 MHz</td>
</tr>
<tr>
<td>X</td>
<td>8000–12,000 MHz</td>
<td>8500–10,680 MHz</td>
</tr>
<tr>
<td>K&lt;sub&gt;u&lt;/sub&gt;</td>
<td>12.0–18 GHz</td>
<td>13.4–14.0 GHz</td>
</tr>
<tr>
<td>K</td>
<td>18–27 GHz</td>
<td>24.05–24.25 GHz</td>
</tr>
<tr>
<td>K&lt;sub&gt;u&lt;/sub&gt;</td>
<td>27–40 GHz</td>
<td>33.4–36.0 GHz</td>
</tr>
<tr>
<td>mm</td>
<td>40–300 GHz</td>
<td></td>
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</tbody>
</table>

Figure. IEEE standard radar frequencies

**APPLICATIONS OF RADAR**

1. Radar has been employed on the ground, in the air, on the sea, and in space.
2. Ground-based radar has been applied chiefly to the detection, location, and tracking of aircraft or space targets.
3. 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.
4. 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.

5. In space, radar has assisted in the guidance of spacecraft and for the remote sensing of the land and sea.

6. **Air Traffic Control (ATC):**

   Radars are employed throughout the world for the purpose of safely controlling air traffic en 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.

7. **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.

8. **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 equipment’s (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.

9. **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.

10. **Remote Sensing:**

    All 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.

11. 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.

12. 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.

PREDICTION OF RANGE PERFORMANCE
1. The simple form of the radar equation expressed the maximum radar range $R_{max}$, in terms of radar and target parameters

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

2. where $P_r = \text{transmitted power, watts}$
   $G = \text{antenna gain}$
   $A_e = \text{antenna effective aperture, m}^2$
   $\sigma = \text{radar cross section, m}^2$
   $S_{min} = \text{minimum detectable signal, watts}$

3. All the parameters are to some extent under the control of the radar designer, except for the target cross section $\sigma$.
4. 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.
5. In practice, however, the simple radar equation does not predict the range performance of actual radar equipment’s to a satisfactory degree of accuracy.
6. 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.

7. 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 $S_{\text{min}}$ and the target cross section $\sigma$ are both statistical in nature and must be expressed in statistical terms.

8. 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.

9. 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.

**MINIMUM DETECTABLE SIGNAL**

1. 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.

2. The weakest signal the receiver can detect is called the **minimum detectable signal**.

3. 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.

![Typical envelope of the radar receiver output as a function of time](image)

A & B would be valid detections, but C is a missed detection.
4. 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.

5. Consider the output of a typical radar receiver as a function of time Fig. This might represent one sweep of the video output displayed on an A-scope.

6. 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. it is greater than the surrounding noise peaks and can be recognized on the basis of its amplitude.

7. 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.

8. 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.

9. The voltage envelope of Fig. 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).

10. 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.

11. 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.)

**RECEIVER NOISE AND SIGNAL TO NISE RATIO**

1. Since noise is the chief factor limiting receiver sensitivity, it is necessary to obtain some means of describing it quantitatively.
2. 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.

3. 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.

4. 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.

5. The available thermal-noise power generated by a receiver of bandwidth \(B_n\), (in hertz) at a temperature \(T\) (degrees Kelvin) is equal to,

\[
\text{Available thermal-noise power} = kTB_n
\]

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

7. 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.

8. 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.

9. 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

\[
B_n = \frac{\int_{-\infty}^{\infty} |H(f)|^2 \, df}{\left| H(f_b) \right|^2}
\]

10. Where \(H(f) = \text{frequency-response characteristic of IF amplifier (filter)}\) and \(f_b = \text{frequency of maximum response (usually occurs at mid band)}\). When \(H(f)\) is normalized to unity at mid band (maximum-response frequency), \(H(f_b) = 1\).
12. The bandwidth $B_n$ 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 $H(f)$.

13. 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.

14. 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:

$$F_n = \frac{N_o}{kT_0B_nG_a} = \frac{\text{noise out of practical receiver}}{\text{noise out of ideal receiver at std temp } T_0}$$

15. Where $N_o$ = noise output from receiver, and $G_a$ = available gain. The standard temperature $T$ is taken to be 290 K.

16. 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 $kT_0B_n$ is the input noise $N_i$ in an ideal receiver. Equation above may be rewritten as

$$F_n = \frac{S_i}{S_o}$$

17. If the minimum detectable signal $S_{\text{min}}$, is that value of $S_i$ corresponding to the minimum ratio output (IF) signal-to-noise ratio $(S_o/N_o)_{\text{min}}$ necessary for detection, then

$$S_{\text{min}} = kT_0B_nF_n\left(\frac{S_o}{N_o}\right)_{\text{min}}$$

18. Substituting Eq. discussed above into Eq. earlier results in the following form of the

$$R_{\text{max}} = \frac{P_iG_A\sigma}{(4\pi)^2kT_0B_nF_n(S_o/N_o)_{\text{min}}}$$

**INTEGRATION OF RADAR PULSES**

1. Many pulses are usually returned from any particular target on each radar scan and can be used to improve detection. The number of pulses $n_B$ returned from a point target as the radar antenna scans through its beam width is;
2. Typical parameters for a ground-based search radar might be pulse repetition frequency, 1.5° beam width, and antenna scan rate 5 rpm (30°/s). These parameters result in 15 hits from a point target on each scan.

3. The process of summing all the radar echo pulses for the purpose of improving detection is called integration.

4. 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.

5. 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.

6. Integration before the detector is called pre-detection, or coherent, integration, while integration after the detector is called post-detection, or non-coherent, integration. Pre-detection integration requires that the phase of the echo signal be preserved if full benefit is to be obtained from the summing process.

7. On the other hand, phase information is destroyed by the second detector; hence post-detection integration is no concerned with preserving RF phase. For this convenience, post-detection integration is not as efficient as pre-detection integration.

8. If n pulses, all of the same signal-to-noise ratio, were integrated by an ideal pre-detection integrator, the resultant, or integrated, signal-to-noise (power) ratio would be exactly n times that of a single pulse.

9. If the same n pulses were integrated by an ideal post-detection device, the resultant signal-to-noise ratio would be less than n times that of a single pulse.

10. 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.

11. The comparison of pre-detection and post-detection integration may be briefly summarized by stating that although post-detection integration is not as efficient as pre-detection integration, it is easier to implement in most applications.

12. 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 post-detection integrator.

13. The efficiency of post-detection integration relative to ideal pre-detection integration has been computed by Marcum when all pulses are of equal amplitude. The integration efficiency may be defined as follows:

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

14. The improvement in the signal-to-noise ratio when $n$ pulses are integrated post detection is $nE_i(n)$ and is the integration-improvement factor. The radar equation with $n$ pulses integrated can be written as:

$$R^4_{\text{max}} = \frac{P_t G A_e \sigma}{(4\pi)^2 k T_0 B_n F_n (S/N)_n}$$

RADAR CROSS SECTION OF TARGET

1. Radar cross section is a property of a scattering object or target that is included in the radar eq. to represent the echo signal returned to the radar by target.

   Power density of echo signal at radar = \( \frac{P_t G}{4\pi R^2} \frac{\sigma}{4\pi R^2} \)

   in other terms,

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

   where $R$ = distance between radar and target

   $E_r$ = reflected field strength at radar

   $E_i$ = strength of incident field at target

2. The radar cross section of a target is the (fictional) area intercepting that amount of power which, when scattered equally in all directions.

3. Scattering and diffraction are variations of the same physical process.
4. 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.

5. With radar backscatter, the two fields are the same, and one may talk about scattering and diffraction interchangeably.

6. The scattered field, and hence the radar cross section, can be determined by solving Maxwell's equations with the proper boundary conditions applied.

7. 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.

8. The region where the size of the sphere is small compared with the wavelength \(2\pi a/\lambda \ll 1\) is called the Rayleigh region, after Lord Rayleigh who, in the early 1870 first studied scattering by small particles.

9. Lord Rayleigh was interested in the scattering of light by microscopic particles, rather than in radar. The cross section of objects within the Rayleigh region varies as \(\lambda^{-4}\).

![Fig. Radar cross section of the sphere. \(a = \text{radius}; \lambda = \text{wavelength}\)](image)

10. 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.

11. 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.

12. At the other extreme from the Rayleigh region is the optical region, where the dimensions of the sphere are large compared with the wavelength $2\pi a/\lambda >> 1$. For large $2\pi a/\lambda$, the radar cross section approaches the optical cross section $\pi a^2$. In between the optical and the Rayleigh region is the Mie or resonance, region.

13. 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.

**TRANSMITTER POWER**

1. The power $P_t$ in radar range eq. is called peak power

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

2. The peak pulse power as used in the radar equation is not the instantaneous peak power of a sine wave.

3. It is defined as the power averaged over that carrier-frequency cycle which occurs at the maximum of the pulse of power.

4. If the transmitted waveform is a train of rectangular pulses of width $\tau$ and pulse-repetition period $T_p = 1/f_p$, 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 $P_{av}/P_t$, $\tau/T_p$, or $\tau f_p$ is called the duty cycle of the radar.

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

$$E_t = \frac{P_{av}}{f_p}$$
\[
R_{\text{max}}^4 = \frac{E_t G A_\epsilon \sigma n E_i(n)}{(4\pi)^2 k T_0 F_n(B_n \tau)(S/N)}
\]

Where \( E_i = \) Total energy of the \( n \) pulses which is equals to \( nE_p \).

PULSE REPETITION FREQUENCY AND RANGE AMBIGUITIES

1. The pulse repetition freq.(prf) is determined primarily by the maximum range at which targets are expected.
2. If the prf is made too high, the likelihood of obtaining target echoes from the wrong pulse transmission is increased.
3. Echo signal received after an interval exceeding the pulse-repetition period are called \textit{multiple time around echoes}.
4. Now consider the three targets labeled \( A, B, \) and \( C \) in Fig.

5. Target \( A \) is located within the maximum unambiguous range \( R_{\text{unamb}} \) of the radar, target \( B \) is at a distance greater than \( R_{\text{unamb}} \) but less than 2\( R_{\text{unamb}} \) while
target C is greater than \(2R_{\text{unamb}}\) but less than \(3R_{\text{unamb}}\). The appearance of the three targets on an A-scope is sketched in Fig. c

6. 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.

7. One method of distinguishing multiple-time-around echoes from unambiguous echoes is to operate with a varying pulse repetition frequency.

\[
R_{\text{true}} = f_1 \text{ or } (f_1 + R_{\text{un}1}) \text{ or } (f_1 + R_{\text{un}2}) \text{ or } \ldots
\]

8. The correct range is that value which is the same with the two PRF, generally three PRF are often use to resolve range ambiguities.

**SYSTEM LOSSES**

1. The important factors omitted from the simple radar equation was the losses that occurs throughout the radar system.

   System losses defined by \(L_s\).

2. Loss (number greater than unity) and efficiency (number less than unity) are used interchangeably. One is simply the reciprocal of the other.

**Losses occurs due to,**

- Loss due to integration.
- Loss due to fluctuating cross section.
- Loss due to change in radar cross section of target.
- Losses due to transmission line.
- Losses due to various mechanical part of radar system

**Types of losses:-**

1. **Microwave plumbing loss:** There is always loss in transmission line that connect Transmitter and Reciever In addition there can be loss in the various microwave components such as duplexer, receiver protector, directional coupler, transmission line connector, bend in transmission line, etc.

2. **Duplexer loss:** The loss due to duplexer that is protect Transmitter and Reciever Eg. Gas duplexer, solid state duplexer.

3. **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.
4. **Scanning loss**: When the antenna scan rapidly enough, relative to the round trip time of the echo signal, the antenna gain in the direction of target on transmit might not be the same as that on receive. This results in an additional loss called scanning loss.

5. **Phased array losses**: Some phased array radar have additional transmission losses due to the distribution n/w that connects RX and Transmitter to each of the many elements of array.

6. **Signal processing loss**: Sophisticated signal processing is prevalent in modern radars and is very important for detecting target in clutter and in extracting information from radar echo signals.

**The factor described below can also introduced significant loss:**

1. Matched & Non-matched filter
2. Constant false alarm
3. Automatic integrator
4. Threshold level
5. Limiting loss
6. Sampling loss

**Losses in Doppler processing radar**: This kind of loss occur due to Doppler frequency.

1. **Collapsing loss**: If the radar were to integrate additional noise sample along with signal-pulse-noise pulses, the added noise would result in a degradation called collapsing loss.

2. **Operator loss**: An alert, motivated, and well-trained operator should perform as well as described by theory. However, when distracted, tired, overloaded, or not properly trained, operator performance will decrease. There is little guidance available on how to account for the performance of an operator. Based on both empirical and experimental results, one gives the operator efficiency factor as

3. **Equipment degradation**: It is common for radar operated under field conditions to have performance than when they left the factory. This loss of performance can be recognized by regular testing the radar, especially with built in test equipment that automatically indicating when equipment deviates from specifications.

4. **Transmission loss**: The theoretical one way loss in db per 100 feet for standard transmission line. Since the same transmission line generally is used for transmission and reception, so the loss to be inserted in the radar eq. is twice the one-way loss. Flexible waveguide and coaxial line can have higher loss compare to conventional waveguide. At lower freq. transmission line introduce less loss.
UNIT II
UNIT II
CW AND FREQUENCY MODULATED RADAR

DOPPLER EFFECT

1. A radar detects the presence of objects and locates their position in space by transmitting electromagnetic energy and observing the returned echo. A pulse radar transmits a relatively short burst of electromagnetic energy, after which the receiver is turned on to listen for the echo.

2. The echo not only indicates that a target is present, but the time that elapses between the transmission of the pulse and the receipt of the echo is a measure of the distance to the target.

3. Separation of the echo signal and the transmitted signal is made on the basis of differences in time. The radar transmitter may be operated continuously rather than pulsed if the strong transmitted signal can be separated from the weak echo.

4. The received-echo-signal power is considerably smaller than the transmitter power; it might be as little as $10^{-18}$ that of the transmitted power-sometimes even less. Separate antennas for transmission and reception help segregate the weak echo from the strong leakage signal, but the isolation is usually not sufficient.

5. A feasible technique for separating the received signal from the transmitted signal when there is relative motion between radar and target is based on recognizing the change in the echo-signal frequency caused by the Doppler effect.

6. It is well known in the fields of optics and acoustics that if either the source of oscillation or the observer of the oscillation is in motion, an apparent shift in frequency will result. This is the Doppler Effect and is the basis of CW radar.

7. If $R$ is the distance from the radar to target, tile total number of wavelengths $\lambda$ contained in the two-way path between the radar and the target is $2R / \lambda$.

8. The distance $R$ and the wavelength $\lambda$ are assumed to be measured in the same units. Since one wavelength corresponds to an angular excursion of $2\pi$ radians, the total angular excursion $\nu$ made by the electromagnetic wave during its transit to and from the target is $4\pi R / \lambda$ radians.

9. If the target is in motion, $R$ and the phase $\nu$ are continually changing. A change in $\nu$ with respect to time is equal to a frequency.

10. This is the Doppler angular frequency $\omega_d$ given by;
\[ \omega_d = 2\pi f_d = \frac{\mathrm{dv}}{\mathrm{dt}} \]

\[ \frac{4\pi dR}{\lambda} \frac{\mathrm{d}t}{\mathrm{d}t} = \frac{4\pi v_r}{\lambda} \]

\( f_d \) = Doppler frequency shift
\( v_r \) = relative (or radial) velocity of target with to radar.

**CW RADAR**

Fig. (a) Simple CW radar block diagram; (b) response characteristic of beat-frequency amplifier

1. Consider the simple CW radar as illustrated by the block diagram of Fig. The transmitter generates a continuous (unmodulated) oscillation of frequency \( f_0 \), which is radiated by the antenna.

2. A portion of the radiated energy is intercepted by the target and is scattered, some of it in the direction of the radar, where it is collected by the receiving antenna. If the target is in motion with a velocity \( v_r \), relative to the radar, the received signal will be shifted in frequency from the transmitted frequency \( f_0 \) by an amount \( \pm f_d \) as given by

\[ f_d = 2\pi v_r / \lambda. \]

3. The plus sign associated with the doppler frequency applies if the distance between target and radar is decreasing (closing target), that is, when the received signal frequency is greater than the transmitted signal frequency.
4. The minus sign applies if the distance is increasing (receding target). The received echo signal at a frequency $f_0 \pm f_d$ enters the radar via the antenna and is heterodyned in the detector (mixer) with a portion of the transmitter signal $f_0$ to produce a doppler beat note of frequency $f_d$. The sign of $f_d$ is lost in this process.

5. The purpose of the doppler amplifier is to eliminate echoes from stationary targets and to amplify the doppler echo signal to a level where it can operate an indicating device. It might have a frequency-response characteristic similar to that of Fig.

6. The low-frequency cutoff must be high enough to reject the d-c component caused by stationary targets, but yet it might be low enough to pass the smallest doppler frequency expected. Sometimes both conditions cannot be met simultaneously and a compromise is necessary. The upper cutoff frequency is selected to pass the highest doppler frequency expected.

7. The indicator might be a pair of earphones or a frequency meter. If exact knowledge of the doppler frequency is not necessary, earphones are especially attractive provided the doppler frequencies lie within the audio-frequency response of the ear. Earphones are not only simple devices, but the ear acts as a selective bandpass filter with a passband of the order of 50 Hz centered about the signal frequency.

**ISOLATION BETWEEN TRANSMITTER AND RECEIVER:-**

1. Isolation between the transmitted and the received signals is achieved via separation in frequency as a result of the doppler effect.

2. In practice, it is not possible to eliminate completely the transmitter leakage. However, transmitter leakage is not always undesirable.

3. A moderate amount of leakage entering the receiver along with the echo signal supplies the reference necessary for the detection of the doppler frequency shift.

4. There are two practical effects which limit the amount of transmitter leakage power which can be tolerated at the receiver. These are 1) The maximum amount of power the receiver input circuitry can withstand before it is physically damaged or its sensitivity reduced (burnout) and 2) The amount of transmitter noise due to hum, micro phonics, stray pick-up, and instability which enters the receiver from the transmitter.

5. The additional noise introduced by the transmitter reduces the receiver sensitivity. The amount of isolation required depends on the transmitter power and the accompanying Transmitter noise as well as the ruggedness and the sensitivity of the receiver.
6. The transmitter noise that enters the radar receiver via backscatter from the clutter is sometimes called **transmitted clutter**.

**INTERMEDIATE FREQUENCY RECEIVER**

Fig. Block diagram of Doppler radar with IF receiver (sideband superheterodyne)

1. CW type receivers are called homodyne receivers, or super heterodyne receivers with zero IF. The function of the local oscillator is replaced by the leakage signal from the transmitter.

2. The simpler receiver is not as sensitive because of increased noise at the lower intermediate frequencies caused by **flicker effect**.

3. Flicker-effect noise occurs in **semiconductor devices such as diode detectors and cathodes of vacuum tubes**.

4. The noise power produced by the flicker effect varies as $1/f^\alpha$ where alpha is approximately unity. This is in contrast to shot noise or thermal noise, which is independent of frequency.

5. Generally flicker noise would be high at lower freq. Due to flicker noise receiver sensitivity decreases. The effects of **flicker noise overcome** in the normal super heterodyne receiver by using an **intermediate frequency high enough, increase Transmitter power, or increase antenna aperture**.

6. Instead of the usual local oscillator found in the conventional super heterodyne receiver, the local oscillator (or reference signal) is derived in the receiver from a
portion of the transmitted signal mixed with a locally generated signal of frequency equal to that of the receiver IF.

7. Since the output of the mixer consists of two sidebands on either side of the carrier plus higher harmonics, a narrowband filter selects one of the sidebands as the reference signal.

8. The improvement in receiver sensitivity with an intermediate-frequency super heterodyne might be as much as 30 dB over the simple receiver.

RECEIVER BANDWIDTH

1. One of the requirements of the doppler-frequency amplifier in the simple CW radar or the IF amplifier of the sideband super heterodyne is that it be **wide enough to pass the expected range of doppler frequencies**.

2. In most cases of practical interest the expected range of doppler frequencies will be much wider than the frequency spectrum occupied by the signal energy.

3. The use of a wideband amplifier covering the expected doppler range will result in an increase in noise and a lowering of the receiver sensitivity.

4. If the frequency of the doppler-shifted echo signal were known beforehand,

   A narrowband filter-one just wide enough to reduce the excess noise without eliminating a significant amount of signal energy-might be used.

   Also matched filter could be specified as per requirement.

Fig. Frequency spectrum
5. If the received waveform were a sine wave of infinite duration, its frequency spectrum would be a delta function and the receiver bandwidth would be infinitesimal.

6. But a sine wave of infinite duration and an infinitesimal bandwidth cannot occur in nature.

7. The more normal situation is an echo signal which is a sine wave of finite rather than infinite duration.

8. The frequency spectrum of a finite-duration sine wave has a shape of the form

$$\sin \pi(f - f_0)\Delta / \pi (f - f_0)$$

where, $f_0$ and $\Delta$ are the frequency and duration of the sine wave, respectively, and $f$ is the frequency variable over which the spectrum is plotted.

9. In many instances, the echo is not a pure sine wave of finite duration but is perturbed by fluctuations in cross section, target accelerations, scanning fluctuations, etc., which tend to broaden the bandwidth still further. Some of these spectrum-broadening effects are considered below.

10. Assume a CW radar with an antenna beamwidth of $\Theta_B$ deg. scanning at the rate of $\Theta_s$ deg/s.

11. The time on target (duration of the received signal) is $\Theta_B / \Theta_s$ sec. Thus the signal is of finite duration and the bandwidth of the receiver must be of the order of the reciprocal of the time on target $\Theta_B / \Theta_s$.

12. Although this is not an exact relation, it is a good enough approximation for purposes of the present discussion.

13. If the antenna beamwidth were 20 and if the scanning rate were 360/s (6 rpm), the spread in the spectrum of the received signal due to the finite time on target would be equal to 18 Hz, independent of the transmitted frequency.

**APPLICATION OF CW RADAR**

1. Measurement of the relative velocity of a moving target, as in the police speed monitor or in the rate-of-climb meter for vertical-take-off aircraft.

2. Suggested for the control of traffic lights, regulation of toll booths, vehicle counting, as a replacement for the “fifth-wheel” speedometer in vehicle testing, as a sensor in antilock braking systems, and for collision avoidance.

3. For railways, CW radar can be used as a speedometer

4. CW radar is also employed for monitoring the docking speed of large ships.
5. It has also seen application for intruder alarms and for the measurement of the velocity of missiles, ammunition, and baseballs.
6. In industry this has been applied to the measurement of turbine-blade vibration, the peripheral speed of grinding wheels, and the monitoring of vibrations in the cables of suspension bridges.
7. High-power CW radars for the detection of aircraft and other targets have been developed and have been used in such systems as the Hawk missile systems.

**FREQUENCY MODULATED CW RADAR (FMCW)**

![Block diagram of FMCW radar](image)

1. A portion of the transmitter signal acts as the reference signal required to produce the beat frequency. It is introduced directly into the receiver via a cable or other direct connection.
2. Ideally the isolation between transmitting and receiving antennas is made sufficiently large so as to reduce to a negligible level the transmitter leakage signal which arrives at the receiver via the coupling between antennas.
3. The beat frequency is amplified and limited to remove any amplitude fluctuations. The frequency of the amplitude-limited beat note is measured with a cycle-counting frequency meter calibrated in distance.
4. The target was assumed to be stationary. If this assumption is not applicable, a doppler frequency shift will be superimposed on the FM range beat note and an erroneous range measurement results.
5. The doppler frequency shift causes the frequency-time plot of the echo signal to be shifted up or down. On one portion of the frequency-modulation cycle the heat frequency is increased by the doppler shift, while on the other portion it is decreased.
6. If for example, the target is approaching the radar, the beat frequency $fb(up)$ produced during the increasing, or up, portion of the FM cycle will be the difference between the beat frequency due to the range $fr$, and the doppler frequency shift $fd$. Similarly, on the decreasing portion, the beat frequency, $fb(down)$ is the sum of the two.

$$fb(up) = fr - fd$$

$$fb(down) = fr + fd$$

$$fr = \frac{fb(up) + fb(down)}{2}$$

7. The target was assumed to be stationary. If this assumption is not applicable, a doppler frequency shift will be superimposed on the FM range beat note and an erroneous range measurement results.

8. The doppler frequency shift causes the frequency-time plot of the echo signal to be shifted up or down. On one portion of the frequency-modulation cycle the heat frequency is increased by the doppler shift, while on the other portion it is decreased.

9. If for example, the target is approaching the radar, the beat frequency $fb(up)$ produced during the increasing, or up, portion of the FM cycle will be the difference between the beat frequency due to the range $fr$, and the doppler frequency shift $fd$. Similarly, on the decreasing portion, the beat frequency, $fb(down)$ is the sum of the two.

10. If $fb(up)$ and $fb(down)$ are measured separately, for example, by switching a frequency counter every half modulation cycle, one-half the difference between the frequencies will yield the doppler frequency. This assumes $fr > fd$.

11. If, on the other hand, $fr < fd$ such as might occur with a high-speed target at short range, the roles of the averaging and the difference-frequency measurements are reversed; the averaging meter will measure Doppler velocity, and the difference meter, range.

12. If it is not known that the roles of the meters are reversed because of a change in the inequality sign between $fr$ and $fd$ an incorrect interpretation of the measurements may result.

**RANGE AND DOPPLER MEASUREMENT**

1. The frequency-modulated CW radar (abbreviated as FM-CW), the transmitter frequency is changed as a function of time in a known manner. Assume that the transmitter frequency increases linearly with time, as shown by the solid line in Fig.
Fig. Frequency-time relationships in FM-CW radar. Solid curve represents transmitted signal, dashed curve represents echo. (a) Linear frequency modulation; (b) triangular frequency modulation; (c) beat note of (b)

2. If there is no doppler frequency shift, the beat note (difference frequency) is a measure of the target’s range and \( f_b = f_r \) where \( f_r \) is the beat frequency due only to the target’s range.

3. If the rate of change of the carrier frequency is \( f_0 \), the beat frequency is

\[
    f_r = f_0 T = 2 \frac{R f_0}{c}
\]

4. In any practical CW radar, the frequency cannot be continually changed in one direction only. Periodicity in the modulation is necessary, as in the triangular frequency-modulation waveform shown in Fig.

5. The modulation need not necessarily be triangular; it can be sawtooth, sinusoidal, or some other shape. The resulting beat frequency as a function of time is shown in Fig. for triangular modulation.

6. The beat note is of constant frequency except at the turn-around region. If the frequency is modulated at a rate \( f_m \) over a range \( f \), the beat frequency is

\[
    f_r = 2 * 2 \frac{R f_m}{c} = 4 \frac{R f_m f}{c}
\]
7. Thus the measurement of the beat frequency determines the range $R$.

**FMCW ALTIMETER**

1. The FM-CW radar principle is used in the aircraft radio altimeter to measure height above the surface of the earth.
2. The large backscatter cross section and the relatively short ranges required of altimeters permit low transmitter power and low antenna gain.
3. Since the relative motion between the aircraft and ground is small, the effect of the Doppler frequency shift may usually be neglected.
4. The band from 4.2 to 4.4 G Hz is reserved for radio altimeters, although they have in the past operated at UHF.
5. The transmitter power is relatively low and can be obtained from a CW magnetron, a backward-wave oscillator, or a reflex klystron, but these have been replaced by the solid state transmitter.
6. The altimeter can employ a simple homodyne receiver, but for better sensitivity and stability the superheterodyne is to be preferred whenever its more complex construction can be tolerated.
7. A block diagram of the FM-CW radar with a sideband superheterodyne receiver shown in Fig. A portion of the frequency-modulated transmitted signal is applied to a mixer along with the oscillator signal.
8. The selection of the local-oscillator frequency is a bit different from that in the usual superheterodyne receiver. The local-oscillator frequency $f_{\text{IF}}$ should be the same as the intermediate frequency used in the receiver, whereas in the conventional superheterodyne the LO frequency is of the same order of magnitude as the RF signal.
9. The output of the mixer consists of the varying transmitter frequency $f_0(t)$ plus two sideband frequencies, one on either side of $f_0(t)$ and separated from $f_0(t)$ by the local-oscillator frequency $f_{\text{IF}}$.
10. The filter selects the lower sideband $f_0(t) - f_{\text{IF}}$ and rejects the carrier and the upper sideband.
11. The sideband that is passed by the filter is modulated in the same fashion as the transmitted signal.
MULTIPLE FREQUENCY CW RADAR (MFCW)

1. CW radar does not measure range, it is possible under some circumstances to do so by measuring the phase of the echo signal relative to the phase of the transmitted signal.

2. The variation of phase with freq. is the fundamental basis of radar measurement of time delay or range measurement. It is easier to analysis the pulse radar and FMCW radar in term of time domain.

3. The principal used in multiple freq. CW radar is the measurement of range by computing the phase difference. A measurement of range R of stationary target by employing continuous wave radar transmitting sine waves (2πft). The time taken by the sine wave is t = 2R/c

4. The o/p given by the phase detector, which will compare the transmitted signal on the received signal is written as,

\[ \Delta \nu = \frac{4\pi f R}{c} \]

\[ R = \frac{\lambda \Delta \nu}{4\pi} \]

5. The maximum error occurs in measure net of phase difference is 2π radians. If we put the value \( \Delta \nu = 2\pi \) the maximum ambiguity, in range is.

6. Block diagram of multiple freq. CW radar is almost as CW radar except it has got one more channel and measuring device. The better accuracy in range measurement may be provided by the large freq. diff. between the two transmitted signals. Transmitting three or four freq. instead of just two can make more accurate measurement.

7. The transmitted waveform is assumed to consist of two continuous sine waves of frequency \( f_1 \) and \( f_2 \) separated by an amount \( \Delta f \). The voltage waveforms of the two components of the transmitted signal \( v_{1r} \) and \( v_{2r} \), may be written as

\[ v_{1r} = \sin (2\pi f_1 t + \nu_1) \]

\[ v_{2r} = \sin (2\pi f_2 t + \nu_2) \]

Where \( \nu_1 \) and \( \nu_2 \) are arbitrary (constant) phase angles.

8. The echo signal is shifted in frequency by the doppler effect. The form of the Doppler shifted signals at each of the two frequencies \( f_1 \) and \( f_2 \) may be written as
UNIT III
UNIT III

MTI AND PULSE DOPPLER RADAR

INTRODUCTION

1. The radars discussed till now were required to detect target in the presence of noise. But in practical radar have to deal with more than receiver noise when detecting target while they can also receive echoes from the natural environment such as land, sea, weather etc.
2. These echoes are called clutter, since they tend to clutter the radar display with unwanted information’s.
3. Clutter echoes signal has greater magnitude then echo signal receives from the aircraft.
4. When an aircraft echo and a clutter echo appear in the same radar resolution cell, the aircraft might not be detected.
5. But the Doppler effect permits the radar to distinguish moving target in the presence of fixed target even the echoes signal from fixed has comparatively than the moving target such as aircraft.

MTI RADAR (PRINCIPLE)

1. The radar which uses the concept of desired moving targets from stationary (Moving Target Indicator). Doppler frequency shift for distinguishing objects i.e., clutter is called as MTI radar.
2. The block diagram of MTI radar employing a power amplifier is shown in Fig. The significant difference between this MTI configuration and that of Pulse Doppler radar is the manner in which the reference signal is generated. In Fig., the coherent reference is supplied by an oscillator called the coho, which stands for coherent oscillator. The coho is a stable oscillator whose frequency is the same as the intermediate frequency used in the receiver.
3. In addition to providing the reference signal, the output of the coho fc is also mixed with the local-oscillator frequency fl. The local oscillator must also be a stable oscillator and is called stalo, for stable local oscillator.
4. The RF echo signal is heterodyned with the stalo signal to produce the IF signal, just as in the conventional super heterodyne receiver.
5. The stalo, coho, and the mixer in which they are combined plus any low-level amplification are called the receiver exciter because of the dual role they serve in both the receiver and the transmitter.

6. The characteristic feature of coherent MTI radar is that the transmitted signal must be coherent (in phase) with the reference signal in the receiver. The function of the stalo is to provide the necessary frequency translation from the IF to the transmitted (RF) frequency.

7. Although the phase of the stalo influences the phase of the transmitted signal, any stalo phase shift is canceled on reception because the stalo that generates the transmitted signal also acts as the local oscillator in the receiver.

8. The reference signal from the coho and the IF echo signal are both fed into a mixer called the pulse detector. The phase detector differs from the normal amplitude detector since its output is proportional to the phase difference between the two input signals.

9. Any one of a number of transmitting-tube types might be used as the power amplifier. These include the triode, tetrode, klystron, traveling-wave tube, and the crossed-field amplifier.

Figure: Block diagram of MTI radar with power amplifier transmitter
MTI RADAR WITH POWER OSCILLATOR TRANSMITTER

1. A block diagram of MTI radar using a power oscillator is shown in Fig. 21.2. A portion of the transmitted signal mixed with the STALO output to produce an IF beat signal whose phase is directly related to the phase of the transmitter.
2. This IF pulse is applied to the coherent (COHO) and cause the phase of the COHO CW oscillation to “lock” in step with the phase of the IF reference pulse.
3. The phase of the COHO is then related to the phase of the transmitted pulse and may be used as the reference signal for echoes received from the particular transmitted pulse.
4. Upon the next transmission another IF locking pulse is generated relocks the phase of CW COHO until the next locking pulse comes along.

“BUTTERFLY” EFFECT IN MTI RADAR

1. Moving targets may be distinguished from stationary targets by observing the video output on an A-scope (amplitude vs. range). A single sweep on an A-scope might appear as in Fig. (a).
2. This sweep shows several fixed targets and two moving targets indicated by the two arrows. On the basis of a single sweep, moving targets cannot be distinguished from
fixed targets. (It may be possible to distinguish extended ground targets from point targets by the stretching of the echo pulse. However, this is not a reliable means of discriminating moving from fixed targets since some fixed targets can look like point targets, e.g., a water tower. Also, some moving targets such as aircraft flying in formation can look like extended targets.)

3. Successive A scope sweeps (pulse-repetition intervals) are shown in Fig. (b) to(e). Echoes from fixed targets remain constant throughout but echoes from moving targets vary in amplitude from sweep to sweep at a rate corresponding to the doppler frequency.

4. The superposition of the successive A-scope sweeps is shown in Fig. (J). The moving targets produce, with time, a butterfly effect on the A-scope.

Figure (a-e) Successive sweeps of an MTI radar A-scope display (echo amplitude as a function of time); (f) superposition of many sweeps; arrows indicate position of moving targets
DELAY LINE CANCELLERS

1. It act as a filter to eliminate the DC component of fixed target and pass the ac components of moving target.
2. Two types of delay line cancellers;
   1. Time domain filter / cancellers.
   2. Freq. domain filter / cancellers

![Block diagram of delay line cancellers](image)

FIG. Block diagram of delay line cancellers

1. The simple MTI delay-line canceller shown in Fig is an example of a time-domain filter. The capability of this device depends on the quality of the medium used is the delay line.
2. The Pulse modulator delay line must introduce a time delay equal to the pulse repetition interval. For typical ground-based air-surveillance radars this might be several milliseconds.
3. Delay times of this magnitude cannot be achieved with practical electromagnetic transmission lines. By converting the electromagnetic signal to an acoustic signal it is possible to utilize delay lines of a reasonable physical length since the velocity of propagation of acoustic waves is about 10^-5 that of electromagnetic waves.
4. After the necessary delay is introduced by the acoustic line, the signal is converted back to an electromagnetic signal for further processing.
5. The use of digital delay lines requires that the output of the MTI receiver phase-detector be quantized into a sequence of digital words.
6. The compactness and convenience of digital processing allows the implementation of more complex delay-line cancellers with filter characteristics not practical with analog methods.
7. **One of the advantages of a time-domain delay-line canceller** as compared to the more conventional frequency-domain filter is that a single network operates at all ranges and does not require a separate filter for each range resolution cell.

8. Frequency-domain doppler filter- banks are of interest in some forms of MTI and pulse-doppler radar.

**BLOCK DIAGRAM OF DELAY LINE CANCELLERS**

1. A block diagram of delay line canceller is shown as fig. The bipolar video from the phase detector modulates a carrier before being applied to the delay lines.

![Block diagram of delay line cancellers](image)

2. The radar output is not directly applied to the delay lines as a video since it would be differentiated by the crystal transducer that convert the EM energy into acoustic energy, and vice-versa. The modulated bipolar video is divided between two channels. In one channel the signal is delayed by a PRF, while in the other channel it reaches directly i.e. undelayed.

3. There is considerable attenuation in the signal introduced by the delay line and must be amplified in order to bring it back to its original level.

4. Since the introduction of an amplifier into the delay channel can alter the phase of the delayed waveforms and introduce a line delay, an amplifier with the same delay characteristics is also used in the direct channel.

5. An attenuator might also be interested in the direct channel to make equalizing voltage residue of the order of 1% or 40db.

6. The output from the delayed and undelayed channels are detected to remove the carrier and then subtracted. The uncancelled bipolar video from the subtractor is rectified in a full wave rectifier to obtain unipolar video signal for displaying on the PPI. The purpose of automatic balancing to detect any amplitude timing differences and generate AGC error voltage to adjust the amplifier gain and timing control error voltage to adjust the repetition frequency of the trigger generator.
Types of Delay Line Cancellers

Acoustic Delay Line

Elements of an acoustic delay line
The basic elements of an acoustic delay line outlined in fig. The EM energy is converted into acoustic energy by piezoelectric transmitting crystal.(like transducer) and at the o/p side acoustic energy converted back into EM energy.

2. Quartz Crystal

It has a high Q device with an inherently small bandwidth. However, when transducer is coupled to a delay medium, the medium has a damping effect, which broadens the bandwidth. Consequently, acoustic delay lines are relatively broadband device.

3. Liquid Mercury

1. One of simplest acoustic delay lines consist of a straight cylindrical tube filled with liquid mercury. The transit time of acoustic waves in mercury at room temperature is approximately 17.5 us./inch.

2. To produce a delay of 1000 us the line must be 57 inch in length exclusively of end cells. This is manageable size in ground-based radar.

3. A more compact configuration may be had by folding the line back itself one or more times. Another method of obtaining a more compact delay line is of make use of multiple reflection in a tank filled with liquid.

4. The alignment of the reflecting surface is a problem, and it has been difficult to obtain a leak proof construction. One of the disadvantages of either solid or liquid delay is the large insertion loss.
Response of the Delay Line Canceller (Filter Characteristics)

1. Filter characteristics of the delay-line canceller. The delay-line canceller acts as a filter which rejects the d-c component of clutter. Because of its periodic nature, the filter also rejects energy in the vicinity of the pulse repetition frequency and its harmonics.

2. The video signal received from a particular target at a range $R_0$ is

$$V_1 = k \sin (2 \pi f d t - \phi_0)$$

Where, $\phi_0$ = phase shift
$k$ = amplitude of video signal.

3. The signal from the previous transmission, which is delayed by a time $T = \text{pulse repetition interval}$, is

$$V_2 = k \sin (2 \pi f d (t - T) - \phi_0)$$

4. Everything else is assumed to remain essentially constant over the interval $T$ so that $k$ is the same for both pulses. The output from the sub tractor is

$$V = V_1 - V_2 = 2k \sin \pi f d T \cos [2 \pi f d (t - T / 2) - \phi_0]$$

5. It is assumed that the gain through the delay-line canceller is unity. The output from the canceller $V$ consists of a cosine wave at the doppler frequency $f d$ with an amplitude $2k \sin \pi f d T$.

6. Thus the amplitude of the canceled video output is a function of the Doppler frequency shift and the pulse-repetition interval, or PRF.

7. The magnitude of the relative frequency-response of the delay-line canceller [ratio of the amplitude of the output from the delay-line canceller, $2k \sin \pi f d T$, to the amplitude of the normal radar video $k_0$ is shown in Fig.1.

![Figure. Frequency response of single delay line canceller](image-url)
DOUBLE DELAY LINE CANCELLER

1. The frequency response of a single-delay-line canceller does not always have as broad clutter-rejection null as might be desired in the vicinity of d-c. The clutter-rejection notches may be widened by passing the output of the delay-line canceller through a second delay-line canceller as shown in Fig. The output of the two single-delay-line cancellers in cascade is the square of that from a single canceller.

2. Thus the frequency response is \( \sin^2 \pi f d T \). The configuration of Fig 2 is called a double-delay-line canceller, or simply a double canceller. The relative response of the double canceller compared with that of a single delay line canceller is shown in Fig. 3.

3. The finite width of the clutter spectrum is also shown in this figure so as to illustrate the additional cancellation of clutter offered by the double canceller.

4. The two-delay-line configuration of Fig..2 has the same frequency-response characteristic as the double-delay-line canceller. The operation of the device is as follows. Signal \( f(t) \) is inserted into the adder along with the signal from the preceding pulse period, with its amplitude weighted by the factor - 2, plus the signal from two pulse periods previous. The output of the adder is therefore

\[ f(t) - 2f(t + T) + f(t + 2T) \]

Which is the same as the output from the double-delay-line canceller \( f(t) - f(t + T) - f(t + T) + f(t + 2T) \)

---

Figure 2. (a) Double delay line canceller (b) Three pulse canceller
Figure 3. Frequency response of single & double delay line canceller

BLIND SPEED
1. The response of the single-delay-line canceller will be zero whenever the argument $\pi f_d T$ in the amplitude factor of $V = V_1 - V_2 = 2k \sin \pi f_d T \cos [2\pi f_d (t - T/2) - \nu_0]$ is 0, $\pi$, $2\pi$, etc., or when $f_d = n/T = n f_p$
   a. Where,
   b. $n = 0, 1, 2, \ldots$
   c. $f_p = $ pulse repetition frequency.

2. The delay-line canceller not only eliminates the d-c component caused by clutter ($n = 0$), but unfortunately it also rejects any moving target whose doppler frequency happens to be the same as the PRF or a multiple thereof. Those relative target velocities which result in zero MTI response are called blind speeds and are given by;
   a. $V_n = n \lambda / 2T = n \lambda f_p / 2$
   b. Where,
   c. $v_n$ is the $n$th blind speed.

3. If $\lambda$ is measured in meters, $f_p$ in Hz, and the relative velocity in knots, the blind speeds are;
   a. $V_n = n \lambda f_p / 1.02$

4. The blind speeds are one of the limitations of pulse MTI radar which do not occur with CW radar. They are present in pulse radar because doppler is measured by discrete samples (pulses) at the PRF rather than continuously. If the first blind speed is to be greater than the maximum radial velocity expected from the target, the product $\lambda f_p$ must be large.
MULTIPLE OR STAGGERED PULSE REPETITION FREQUENCIES

1. If radar is operating at multiples PRFs or its PRF is changed either pulse to pulse or scan to scan, than the effect of blind speed can be eliminated from the radar. If two radar operating at same frequencies but having its different PRF then if one radar is blind to moving target.

2. So, if we use single radar but having different PRF than the same affect can be achieved. When the PRF is changing pulse to pulse than it may be called as staggered PRF. Staggering of PRF is generally employed in Air Traffic Control Radar such as Surveillance Radar Element (SRE).

![Frequency response of two PRF](image)

3. In the Fig. 24.1 above the frequency response of two PRF is shown. Suppose the first PRF is $F_1$ shown in bold line and the speed of second PRF is $F_2$ shown in dotted lines. If we observed the figure, it is clear that at particular position when $2F_1=3F_2$, both the PRFs have the same blind speed.

4. The multiples PRFs can be obtained by using several methods. Using the following techniques may vary the PRFs:
   1. Pulse to pulse (known as staggered PRF)
   2. Scan to scan
   3. Dwell to dwell.

5. The problems occur in using staggered PRF is that residual of unconcealed echoes of clutters, which are due to second time around echoes. So to minimize the second time around echoes affect, if we use unstaggered PRF in the sector where second time around are expected more and rest of the sector used staggered PRFs.
RANGE GATED DOPPLER FILTERS

1. In order to separate moving targets from stationary clutter, the delay line canceller has been widely used in MTI radar. Quantizing the time into small intervals can eliminate the loss of range information and collapsing loss. This process is known as range gating where width depends on range accuracy desired. After quantizing the radar return interval, the output from each gate is applied to a narrow band filter.

2. A block diagram of the video of an MTI radar using multiple range gates followed by clutter rejection filter is shown in Fig. Here the range gates sample the output of the phase detector sequentially range interval.

3. Each range open in sequence long enough to sample the voltage of the video waveform corresponding to a different range interval in space or it acts as a switch/gate which open and close at a proper time.

4. The output of the range gate is given to a circuit known as box car generator. Its function is to aid in the filtering and detection process enhancing the fundamental of the modulation frequency and eliminating harmonics of the PRF.

5. The clutter rejection filter is nothing but a band pass filter whose bandwidth depends on the extent of the expected clutter spectrum. The filtered output from the Doppler filter is further fed to a full wave linear detector which converts the bipolar video.
6. A low pass filter or integrator passes these unipolar video to the threshold detection circuit. Any signal crosses the threshold level is treated as a target. The outputs from each range channels are combined for display on the PPI or any other display unit.

![Diagram of Frequency response characteristics of range gated filter](image)

**Figure 24.3. Frequency response characteristics of range gated filter**

7. The presentation of this type of MTI radar is far better than the display from normal MTI radar.

8. The frequency response characteristics of an MTI radar using range gates and filter is shown in fig. the shape of the rejection band is mainly determined by the shape of the band pass filter.

9. It must be pointed out that the MTI radar using range gates and filters is more complex than an MTI with single delay line canceller a better MTI performance is achieved from a better match between clutter filter characteristics and clutter spectrum.
UNIT IV
UNIT IV

TRACKING WITH RADAR

INTRODUCTION

1. A tracking-radar system
   1. Measures the coordinates of a target and
   2. Provides data which may be used to determine the target path and to predict its future position.

2. All or only part of the available radar data—range, elevation angle, azimuth angle, and Doppler frequency shift may be used in predicting future position; that is, a radar might track in range, in angle, in Doppler, or with any combination.

3. Almost any radar can be considered a tracking radar provided its output information is processed properly. But, in general, it is the method by which angle tracking is accomplished that distinguishes what is normal normally considered a tracking radar from any other radar.

4. It is also necessary to distinguish between a continuous tracking radar and a track-while-scan (TWS) radar.

5. The continuous tracking radar supplies continuous tracking data on a particular target, while the track-while-scan supplies sampled data on one or more targets. In general, the continuous tracking radar and the TWS radar employ different types of equipment.

6. The antenna beam in the continuous tracking radar is positioned in angle by a servomechanism actuated by an error signal.

7. The various methods for generating the error signal may be classified as sequential lobbing, conical scan, and simultaneous lobbing or monopulse.

8. The range and Doppler frequency shift can also be continuously tracked, if desired, by a servo control loop actuated by an error signal generated in the radar receiver.

CONICAL SCAN

1. The logical extension of the sequential lobbing technique is to rotate continuously an offset antenna beam rather than discontinuously step the beam between four discrete positions. This is known as conical scanning (Fig. ). The angle between the axis of rotation (which is usually, but not always, the axis of the antenna reflector) and the axis of the antenna beam is called the squint angle.
2. Consider a target at position A. The echo signal will be modulated at a frequency equal to the rotation frequency of the beam. The amplitude of the echo-signal modulation will depend upon the shape of the antenna pattern, the squint angle and the angle between the target line of sight and the rotation axis.

3. The phase of the modulation depends on the angle between the target and the rotation axis. The conical scan modulation is extracted from the echo signal and applied to a servo-control system which continually positions the antenna on the target. When the antenna is on target, as in B of Fig., the line of sight to the target and the rotation axis coincide, and the conical-scan modulation is zero.

![Figure. Conical scan track](image)

4. The logical extension of the sequential lobbing technique is to rotate continuously an offset antenna beam rather than discontinuously step the beam between four discrete positions. This is known as conical scanning (Fig.). The angle between the axis of rotation (which is usually, but not always, the axis of the antenna reflector) and the axis of the antenna beam is called the **squint angle**.

5. Consider a target at position A. The echo signal will be modulated at a frequency equal to the rotation frequency of the beam. The amplitude of the echo-signal modulation will depend upon the shape of the antenna pattern, the squint angle and the angle between the target line of sight and the rotation axis.

6. The phase of the modulation depends on the angle between the target and the rotation axis. The conical scan modulation is extracted from the echo signal and applied to a servo-control system which continually positions the antenna on the target. When the
antenna is on target, as in B of Fig. , the line of sight to the target and the rotation axis coincide, and the conical-scan modulation is zero.

7. A block diagram of the angle-tracking portion of a typical conical-scan tracking radar is shown in Fig.. The antenna is mounted so that it can be positioned in both azimuth and elevation by separate motors, which might be either electric- or hydraulic-driven. The antenna beam is offset by tilting either the feed or the reflector with respect to one another.

8. One of the simplest conical-scan antennas is a parabola with an offset rear feed rotated about the axis of the reflector. If the feed maintains the plane of polarization fixed as it rotates, it is called a nutating feed.

9. A rotating feed causes the polarization to rotate. The latter type of feed requires a rotary joint. The nutating feed requires a flexible joint. If the antenna is small, it may be easier to rotate the dish, which is offset, rather than the feed, thus avoiding the problem of a rotary or flexible RF joint in the feed.

10. A typical conical-scan rotation speed might be 30 r/s. The same motor that provides the conical-scan rotation of the antenna beam also drives a two phase reference generator with two outputs 90° apart in phase. These two outputs serve as a reference to extract the elevation and azimuth errors.
11. The received echo signal is fed to the receiver from the antenna via two rotary joints (not shown in the block diagram). One rotary joint permits motion in azimuth, the other, in elevation.

12. The receiver is a conventional super heterodyne except for features peculiar to the conical scan tracking radar. One feature not found in other radar receivers is a means of extracting the conical-scan modulation, or error signal. This is accomplished after the second detector in the video portion of the receiver.

13. The error signal is compared with the elevation and azimuth reference signals in the angle-error detectors, which are phase-sensitive detectors. A phase sensitive detector is a nonlinear device in which the input signal (in this case the angle-error signal) is mixed with the reference signal.

14. The input and reference signals are of the same frequency. The output d-c voltage reverses polarity as the phase of the input signal changes through 180°. The magnitude of the d-c output from the angle-error detector is proportional to the error, and the sign (polarity) is an indication of the direction of the error. The angle-error detector outputs are amplified and drive the antenna elevation and azimuth servo motors.

15. The angular position of the target may be determined from the elevation and azimuth of the antenna axis. The position can be read out by means of standard angle transducers such as synchronous, potentiometers, or analog-to-digital-data converters.

16. **Advantages:**
   1. It requires a minimum no. of hardware so inexpensive.
   2. It is used in mobile system AAA or a mobile SAM sites.

17. **Disadvantages:**
   It is not able to see target outside their narrow scan patterns.

**SEQUENTIAL LOBBING**

1. A simple pencil-beam antenna is not suitable for tracking radars unless means are provided for determining the magnitude and direction of the target's angular position with respect to some reference direction, usually the axis of the antenna.

2. The difference between the target position and the reference direction is the **angular error.**
3. When the angular error is zero, the target is located along the reference direction. One method of obtaining the direction and the magnitude of the angular error in one coordinate is by alternately switching the antenna beam between two positions is called **lobe switching, sequential switching, or sequential lobbing.**

![Dual beam polar pattern in sequential lobbing](image)

4. There are total four switching position (up-down, right-left) are needed (two additional) to obtain angular error in orthogonal coordinate.

5. The difference in amplitude between the voltages obtained in the two switched positions is a measure of the angular displacement of the target from the switching axis.

6. The sign of the difference determines the direction the antenna must be moved in order to align the switching axis with the direction of the target. When the voltages in the two switched positions are equal, the target is on axis and, its position may be determined from the axis direction.

7. **Advantage:-**
   
   Target position accuracy can be better than the size of antenna beam width.

8. **Applications:**
   
   1. They were used in airborne-interception radar.
   
   2. They were used in ground-based antiaircraft fire-control radars.
MONO-PULSE TRACKING

1. There are two disadvantages in conical scanning and sequential lobbing.
   1. The motion of the antenna is more complex in both.
   2. In conical scan a min. of four pulse is required.
2. Due to the effect of target cross section and the effect of fluctuating echo sometimes need of no. of pulses to extracting error. This problem Can be overcome by using only one pulse.
3. The tracking technique which derives angle error information on the basis of single pulse is known as a mono pulse tracking or simultaneous lobbing more than one antenna beam is used simultaneously where as in conical scanning and sequential lobbing one antenna beam is used on the time shared base.

AMPLITUDE COMPARISON MONO-PULSE

1. In this four feeds are used with one parabolic reflector. There are four horn antennas are used.
2. The receiver received three types of signal
   Sum signal \((A+B+C+D)\)
   Azimuth error signal\(=(A+C)-(B+D)\)
   Elevation error signal\(=(A+B)-(C+D)\)

Figure. Mono-Pulse radar beam pattern
3. In this technique it is important that the signal arriving at various feeds are in phase. In case of array where the antenna surface is very large signals arriving from different off-axis angles present different phases.

4. So their phases need to be equalized before error signal are developed. Sum signal is used for transmission and difference signals are used in reception.

Fig. Block diagram of amplitude comparison mono-pulse tracking radar
5. The receiver has three separate input channel consisting of three mixers, common local oscillator, three IF amplifiers and three detector.

6. The elevation and azimuth error signals are used to drive a servo amplifier and a motor in order to position the antenna in the direction of target.

7. The o/p of sum channel is used to provide the data generally obtain from a radar receiver so that it can be used to provide the data generally obtain from a radar receiver so that it can be used for application like automatic control of the firing weapon.

8. **Advantages:-**
   a. Only one pulse is require to obtain all the information regarding the target and able to locate target in less time comparing other methods.
   b. In this generally error is not occur due to the variation in target cross section.

9. **Disadvantage:-**
   Two extra Rx channel is required and more complex duplexer feeding arrangement, which makes system bulky and more complex and also expensive.

10. **Application:-**
    Automatic control of the firing weapon

**PHASE COMPARISON MONO-PULSE TRACKING**

![Wave front phase relationship for phase comparison monopulse radar](image)
1. The measurement of angle of arrival by comparison of the phase relationships in the signals from the separated antennas of a radio interferometer has been widely used by the radio astronomers for precise measurements of the positions of radio stars.

2. The interferometer as used by the radio astronomer is a passive instrument, the source of energy being radiated by the target itself. A tracking radar which operates with phase information is similar to an active interferometer and might be called an interferometer radar. It has also been called Simultaneous phase comparison radar, or phase-comparison monopulse.

3. In Fig two antennas are shown separated by a distance \( d \). The distance to the target is \( R \) and is assumed large compared with the antenna separation \( d \). The line of sight to the target makes an angle \( \theta \) to the perpendicular bisector of the line joining the two antennas. The distance from antenna 1 to the target is

\[
R_1 = R + \frac{d \sin \theta}{2}
\]

4. The phase difference between the echo signals in the two antennas is approximately

\[
\Delta \phi = \frac{2\pi d \sin \theta}{\lambda}
\]

5. For small angles where \( \sin \theta = 0 \), the phase difference is a linear function of the angular error and may be used to position the antenna via a servo-control loop.

6. In the early versions of the phase-comparison monopulse radar, the angular error was determined by measuring the phase difference between the outputs of receivers connected to each antenna.

7. The output from one of the antennas was used for transmission and for providing the range information. With such an arrangement it was difficult to obtain the desired aperture illuminations and to maintain a stable bore sight.

8. A more satisfactory method of operation is to form the sum and difference patterns in the RF and to process the signals as in conventional amplitude-comparison monopulse radar

**ACQUISITION**

1. Most tracking radars employ a narrow pencil-beam antenna. Examples of the common types of scanning patterns employed with pencil-beam antennas are illustrated in Fig.
2. In the **Helical scan**, the antenna is continuously rotated in azimuth while it is simultaneously raised or lowered in elevation. It traces a helix in space.

3. Helical scanning was employed for the search mode of the SCR-584 fire-control radar, developed during World War II for the aiming of antiaircraft-gun batteries.

4. The SCR-584 antenna was rotated at the rate of 6 rpm and covered a 20" elevation angle in 1 min. The **Palmer scan** derives its name from the familiar penmanship exercises of grammar school days.

5. It consists of a rapid circular scan (conical scan) about the axis of the antenna, combined with a linear movement of the axis of rotation. When the axis of rotation is held stationary, the Palmer scan reduces to the conical scan.

6. The Palmer scan is suited to a search area which is larger in one dimension than another.

7. The **Spiral scan** covers an angular search volume with circular symmetry. Both the spiral scan and the Palmer scan suffer from the disadvantage that all parts of the scan volume do not receive the same energy unless the scanning speed is varied during the scan cycle.

8. The **Raster, or TV, scan**, unlike the Palmer or the spiral scan, paints the search area in a uniform manner.

9. The raster scan is a simple and convenient means for searching a limited sector, rectangular in shape.

10. The nodding scan produced by oscillating the antenna beam rapidly in elevation and slowly in azimuth. Although it may be employed to cover a limited sector - as does the raster scan - nodding scan may also be used to obtain hemispherical coverage, that is, elevation angle extending to 90° and the azimuth scan angle to 360°.

![Fig: Examples of acquisition search patterns. (a) Trace of helical scanning beam; (b) Palmer scan; (c) spiral scan; (d) raster, or TV, scan; (e) nodding scan.](image-url)
11. The helical scan and the nodding scan can both be used to obtain hemispheric coverage with a pencil beam. The nodding scan is also used with height-finding radars.

12. The Palmer, spiral, and raster scans are employed in fire-control tracking radars to assist in the acquisition of the target when the search sector is of limited extent.
UNIT V
RADAR RECEIVERS

INTRODUCTION:
1. Originally the radar display had the important purpose of visually presenting the output of the radar receiver in a form such that an operator could readily and accurately detect the presence of a target and extract information about its location.
2. The display had to be designed so as not to degrade the radar information and to make it easy for the operator to perform with effectiveness the detection and information extraction function.
3. When the display is connected directly to the output of the radar receiver without further processing, the output is called raw video. When the receiver output is first processed by an automatic detector or an automatic detector and tracker before display, it is called synthetic video or processed video.
4. The requirements for the display differ somewhat depending whether raw or processed video is displayed. Some radar operators prefer to see on a display the raw video lightly superimposed on the processed video.
5. The radar display is now more like the familiar television monitor or computer display that shows the entire scene continuously rather than just indicates the echoes from the region currently illuminated by the narrow antenna beam. Thus the role of the display has changed as the need for operator interpretation has decreased.

TYPES OF DISPLAYS
1. Given below are some of the more popular formats that have been employed by IEEE uses the term "display" in its definitions but here we use either "scope" or "display" depending on what is perceived to be the more common usage.
2. A-scope. A deflection-modulated rectangular display in which the vertical deflection is proportional to the amplitude of the receiver output and the horizontal coordinate is proportional to range (or time delay). This display is well suited to a staring or manually tracking radar, but it is not appropriate for continually scanning surveillance radar since the ever-changing background scene makes it difficult to detect targets and interpret what the display is seeing.
3. B-scope. An intensity-modulated rectangular display with azimuth angle indicated by one coordinate (usually horizontal) and range by the orthogonal coordinate (usually...
vertical). It has been used in airborne military radar where the range and angle to the
target are more important than concern about distortion in the angle dimension.

4. **C-scope.** A two-angle intensity-modulated rectangular display with azimuth angle
indicated by the horizontal coordinate and elevation angle by the vertical coordinate.
One application is for airborne intercept radar since the display is similar to what a
pilot might see when looking through the windshield. It is sometimes projected on the
windshield as a heads-up display. The range coordinate is collapsed on this display so
a collapsing loss might occur, depending how the radar information is processed.

5. **D-scope.** A C-scope in which the blips extend vertically to give a rough estimate of
distance.

6. **E Scope** An intensity-modulated rectangular display with range indicated by the
horizontal coordinate and elevation angle by the vertical coordinate. The E-scope
provides a vertical profile of the radar coverage at a particular azimuth. It is of interest
with 3D radars and in military airborne terrain-following radar systems in which the
radar antenna is scanned in elevation to obtain vertical profiles of the terrain ahead of
the aircraft. The E-scope is related to the RHI display.

**DUPLEXERS**

1. Pulsed radar can time share a single antenna between the transmitter and receiver by
employing a fast-acting switching device called a duplexer. On transmission the
duplexer must protect the receiver from damage or burnout, and on reception it must
channel the echo signal to the receiver and not to the transmitter. Furthermore it must
accomplish the switching rapidly, in microseconds or nanoseconds, and it should be
of low loss.

2. For high power applications, the duplexer is a gas-discharge device called a TR.

**BRANCH-TYPE DUPLEXERS:**

1. The branch-type duplexer, diagrammed in Fig. 1 was one of the earliest duplexer
configurations employed. It consists of a TR (transmit-receive) switch and an ATR
(anti-transmit receive) switch, both of which are gas-discharge tubes. When the
transmitter is turned on, the TR and the ATR tubes ionize; that is, they break down, or
fire.

2. The TK in the fired condition acts as a short circuit to prevent transmitter power from
entering the receiver. Since the TR is located a quarter wavelength from the main
transmission line, it appears as a short circuit at the receiver but as an open circuit at
the transmission line so that it does not impede the flow of transmitter power. Since the ATR is displaced a quarter wavelength from the main transmission line, the short circuit it produces during the fired condition appears as an open circuit on the transmission line and thus has no effect on transmission.

3. During reception, the transmitter is off and neither the TR nor the ATR is fired. The open circuit of the ATR, being a quarter wave from the transmission line, appears as a short circuit across the line. Since this short circuit is located a quarter wave from the receiver branch-line, the transmitter is effectively disconnected from the line and the echo signal power is directed to the receiver. The diagram is a parallel configuration. Series or series-parallel configurations are possible.

4. The branch-type duplexer is of limited bandwidth and power-handling capability, and has generally been replaced by the balanced duplexer and other protection devices. It is used, in spite of these limitations, in some low-cost radars.

**Fig. Branch type duplexer**

**BALANCED DUPLEXER:**

1. The balanced duplexer shown in Fig.2a, is based on the short slot hybrid junction which consists of two sections of waveguides joined along one of their narrow walls with a slot cut in the common wall to provide coupling between the two (The short-slot hybrid junction may be thought of as a broadband directional coupler with a coupling ratio of 3 dB.) Two TR tubes are used, one in each section of waveguide.

2. In the transmit condition, Fig.2a, power is divided equally into each waveguide by the first hybrid junction (on the left). Both gas-discharge TR tubes break down and reflect
the incident power out the antenna arm as shown. The short-slot hybrid junction has the property that each time power passes through the slot in either direction, its phase is advanced by 90°.

3. The power travels as indicated by the solid lines. Any power that leaks through the TR tubes (shown by the dashed lines) is directed to the arm with the matched dummy load and not to the receiver. In addition to the attenuation provided by the TR tubes, the hybrid junctions provide an additional 20 to 30 dB of isolation.

4. On reception the TR tubes do not fire and the echo signals pass through the duplexer and into the receiver as shown. The power splits equally at the first junction and because of the 90° phase advance on passing through the slot, the signal recombines in the receiving arm and not in the arm with the dummy load.

5. The balanced duplexer is a popular form of duplexer with good power handling capability and wide bandwidth.

Balanced duplexer using dual TR tubes and two short-slot hybrid junctions. (a) Transmit condition and (b) receive condition.
CIRCULATOR AS DUPLEXER

1. The ferrite circulator is a three- or four-port device that can, in principle, offer separation of the transmitter and receiver without the need for the conventional duplexer configurations. The circulator does not provide sufficient protection by itself and requires a receiver protector as in Fig.

![Circulator and receiver protector diagram](image)

**FIG.** Circulator and receiver protector. A four-port circulator is shown with the fourth port terminated in a matched load to provide greater isolation between the transmitter and the receiver than provided by a three-port circulator.

2. The isolation between the transmitter and receiver ports of a circulator is seldom sufficient to protect the receiver from damage. However, it is not the isolation between transmitter and receiver ports that usually determines the amount of transmitter power at the receiver, but the impedance mismatch at the antenna which reflects transmitter power back into the receiver.

3. The VSWR is a measure of the amount of power reflected by the antenna. For example, a VSWR of 1.5 means that about 4 percent of the transmitter power will be reflected by the antenna mismatch in the direction of the receiver, which corresponds to an isolation of only 14 dB. About 11 percent of the power is reflected when the VSWR is 2.0, corresponding to less than 10 dB of isolation.

4. Thus, a receiver protector is almost always required. It also reduces to a safe level radiations from nearby transmitters. The receiver protector might use solid-state diodes for an all solid-state configuration or it might be a passive TR-limiter consisting of a radioactive primed TR-tube followed by a diode limiter.

5. The ferrite circulator with receiver protector is attractive for radar applications because of its long life, wide bandwidth, and compact design.
PHASED ARRAY ANTENNAS

INTRODUCTION

1. The phased array is a directive antenna made up of individual radiating antennas, or elements, which generate a radiation pattern whose shape and direction is determined by the relative phases and amplitudes of the currents at the individual elements.

2. By properly varying the relative phases, it is possible to steer the direction of the radiation. The radiating elements might be dipoles open-ended waveguides, slots cut in waveguide, any other type of antenna.

3. The inherent flexibility offered by the phased-array antenna in steering the beam by means of electronic control is what has made it of interest for radar. It has been considered in those radar applications where it is necessary to shift the beam rapidly from one position in space to another, or where it is required to obtain information about many targets at a flexible, rapid data rate.

BASIC CONCEPTS

1. An array antenna consists of a number of individual radiating elements suitably spaced with respect to one another. The relative amplitude and phase of the signals applied to each of the elements are controlled to obtain the desired radiation pattern from the combined action of all the elements.

2. Two common geometrical forms of array antennas of interest in radar are the linear array and the planar array. A linear array consists of elements arranged in a straight line in one dimension. A planar array is a two-dimensional configuration of elements arranged to lie in a plane.

3. The planar array may be thought of as a linear array of linear arrays. A broadside array is one in which the direction of maximum radiation is perpendicular, or almost perpendicular to the line (or plane) of the array. An end fire array has its maximum radiation parallel to the array.

4. The linear array generates a fan beam when the phase relationships are such that the radiation is perpendicular to the array. When the radiation is at some angle other than broadside, the radiation pattern is a conical-shaped beam.

5. The broadside linear-array antenna may be used where broad coverage in one plane and narrow beam width in the orthogonal plane are desired. The linear array can also act as a feed for a parabolic-cylinder antenna.
6. The combination of the linear-array feed and the parabolic cylinder generates a more controlled fan beam than is possible with either a simple linear array or with a section of a parabola. The combination of a linear array and parabolic cylinder can also generate a pencil beam.

7. The endfire array is a special case of the linear or the planar array when the beam is directed along the array. Endfire linear arrays have not been widely used in radar applications. They are usually limited to a low or medium gains since an endfire linear antenna of high gain require excessively long array. Small endfire arrays are sometimes used as the radiating element of a broadside array.

8. The two-dimensional planar array is probably the array of most interest in radar applications since it is fundamentally the most versatile of all radar antennas. A rectangular aperture can produce a fan-shaped beam. A square or a circular aperture produces a pencil beam. The array can be made to simultaneously generate many search and/or tracking beams with the same aperture.

9. An array in which the relative phase shift between elements is controlled by electronic devices is called an electronically scanned array. In an electronically scanned array the antenna elements, the transmitters, the receivers, and the data-processing portions of the radar are often designed as a unit.

10. A given radar might work equally well with a mechanically positioned array, a lens, or a reflector antenna if they each had the same radiation pattern, but such a radar could not be converted efficiently to an electronically scanned array by simple replacement of the antenna alone because of the interdependence of the array and the other portions of the radar.

**RADIATION PATTERN**

1. Consider a linear array made up of elements equally spaced a distance apart (Shown in Fig-1 below). The elements are assumed to be isotropic point sources radiating uniformly in all directions with equal amplitude and phase. The outputs of all the elements are summed via lines of equal length to give a sum output voltage, Element 1 will be taken as the reference signal with zero phase.

2. The difference in the phase of the signals in adjacent elements is, where the direction of the incoming radiation is. It is further assumed that the amplitudes and phases of the signals at each element are weighted uniformly.
3. Therefore the amplitudes of the voltages in each element are the same and, for convenience, will be taken to be unity. The sum of all the voltages from the individual elements, when the phase difference between adjacent elements is, can be written

\[ E_a = \sin \omega t + \sin(\omega t + \psi) + \ldots \ldots + \sin[\omega t + (N-1)\psi] \] \hspace{1cm} (1)

Where is the angular frequency of the signal. The sum can be written as,

\[ E_a = \sin[\omega t + (N-1)\psi] \frac{\sin(N\psi)}{2} \frac{\sin(\psi/2)}{\sin(\psi/2)} \] \hspace{1cm} (2)

Fig: N-Element linear array

The magnitude of field intensity pattern is given by,

\[ |E_a| = \left| \frac{\sin[N\pi(\frac{d}{\lambda})\sin \theta]}{\sin[\pi(\frac{d}{\lambda})\sin \theta]} \right| \] \hspace{1cm} (3)

4. Therefore an antenna of isotropic elements has a similar pattern in the rear of the antenna as in the front. The same would be true for an array of dipoles. To avoid ambiguities, the backward radiation is usually eliminated by placing a reflecting
screen behind the array. Thus only the radiation over the forward half of the antenna need be considered.

**BEAM STEERING:**

1. The beam of an array antenna may be steered rapidly in space without moving large mechanical masses by properly varying the phase of the signals applied to each element.
2. Consider an array of equally spaced elements. The spacing between adjacent elements is \( d \), and the signals at each element are assumed of equal amplitude. If the same phase is applied to all elements, the relative phase difference between adjacent elements is zero and the position of the main beam will be broadside to the array at an angle \( \theta \).
3. The main beam will point in a direction other than broadside if the relative phase difference between elements is other than zero. The direction of the main beam is at an angle when the phase difference is \( \pi \). The phase at each element is therefore \( \phi = 0, 1, 2, \ldots \ldots \; (N-1) \), and is any constant phase applied to all elements.

\[
G(\theta) = \frac{\sin^2\left[N\pi(d/\lambda)(\sin \theta - \sin \theta_0)\right]}{N^2 \sin^2\left[\pi(d/\lambda)(\sin \theta - \sin \theta_0)\right]}
\]

4. Above Equation states that the main beam of the antenna pattern may be positioned to an angle \( \theta \), by the insertion of the proper phase shift \( \phi \) at each element of the array. If variable, rather than fixed, phase shifters are used, the beam may be steered as the relative phase between elements is changed.

![Steering of an antenna beam with variable phase shifters (parallel fed array)](image)

Fig.-: Steering of an antenna beam with variable phase shifters (parallel fed array)
CHANGE OF BEAM-WIDTH WITH STEERING ANGLE

1. The half-power beamwidth in the plane of scan increases as the beam is scanned off the broadside direction. The beamwidth is approximately inversely proportional to 
   \[ \text{Where is the angle measured from the normal to the antenna.} \]

2. This may be proved by assuming that the sine in the denominator of Eq.(4) can be replaced by its argument, so that the radiation pattern is of the form, where, where The antenna pattern is reduced to half its maximum value. Denote by the angle corresponding to the half power point when , and , the angle corresponding to the half-power point when ;
   \[ \sin \theta - \sin \theta_0 = \sin(\theta - \theta_0) \cos \theta_0 - [1 - \cos(\theta - \theta_0)] \sin \theta_0 \]

3. The second term on the right hand side of above equation can be neglected when it is small, so that
   \[ \sin \theta - \sin \theta_0 \approx \sin(\theta - \theta_0) \cos \theta_0 \]

4. Using the above approximation, the two angles corresponding to the 3-dB points of the antenna pattern are
   \[ \theta_+ - \theta_0 = \sin^{-1} \frac{0.443 \lambda}{Nd \cos \theta_0} \approx \frac{0.443 \lambda}{Nd \cos \theta_0} \]
   \[ \theta_- - \theta_0 = \sin^{-1} \frac{-0.443 \lambda}{Nd \cos \theta_0} \approx \frac{-0.443 \lambda}{Nd \cos \theta_0} \]

5. The half power beam width is
   \[ \theta_B = \theta_+ - \theta_- \approx \frac{0.886 \lambda}{Nd \cos \theta_0} \]

6. Therefore, when the beam is positioned an angle off broadside, the beam width in the plane of scan increases. The change in beam width with angle, as derived above is not valid when the antenna beam is too far removed from broadside. It certainly does not apply when the energy is radiated in the end fire direction.
SERIES VS PARALLEL FEEDS

1. The relative phase shift between adjacent elements of the array must be in order to position the main beam of the radiation pattern at an angle. The necessary phase relationships between the elements may be obtained with either a series-fed or a parallel fed arrangement. In the series-fed arrangement, the energy may be transmitted from one end of the line (Fig.a), or it may be fed from the center out to each end (Fig.b). The adjacent elements are connected by a phase shifter with phase shift.

2. All the phase shifters are identical and introduce the same amount of phase shift, which is less than radians. In the series arrangement of (Fig.a) where the signal is fed from one end, the position of the beam will vary with frequency. Thus it will be more limited in bandwidth than most array feeds.

3. The center-fed feed of (Fig.b) does not have this problem. In the parallel-fed array of Fig., the energy to be radiated is divided between the elements by a power splitter. When a series of power splitters are used to create a tree-like structure, as in Fig., it is called a corporate feed, since it resembles (when turned upside down) the organization chart of a corporation.

Fig: Series fed array a) From one end b) From center fed
4. Equal lengths of line transmit the energy to each element so that no unwanted phase
differences are introduced by the lines themselves. (If the lines are not of equal
length, compensation in the phase shift must be made.) The proper phase change for
beam steering is introduced by the phase shifters in each of the lines feeding the
elements. When the phase of the first element is taken as the reference, the phase
shifts required in the succeeding elements are.

5. The maximum phase change required of each phase shifter in the parallel-fed array is
many times radians. Since phase shift is periodic with period \( \pi \), it is possible in many
applications to use a phase shifter with a maximum of radians.

6. However, if the pulse width is short compared with the antenna response time (if the
signal bandwidth is large compared with the antenna bandwidth), the system response
may be degraded. For example, if the energy were to arrive in a direction other than
broadside, the entire array would not be excited simultaneously.

7. The combined outputs from the parallel-fed elements will fail to coincide or overlap,
and the received pulse will be smeared. This situation may be relieved by replacing
the modulo phase shifters with delay lines.

APPLICATIONS OF ARRAY IN RADAR

1. The array antenna has several unique characteristics that make it a candidate for
consideration in radar application. However, the attractive features of the array
antenna are sometimes nullified by several serious disadvantages. The array antenna
has the following desirable characteristics not generally enjoyed by other antenna
types. Inertia less rapid beam steering: The beam from an array can be scanned, or
switched from one position to another, in a time limited only by the switching speed
of the phase shifters. Typically, the beam can be switched in several microseconds,
but it can be considerably shorter if desired.

2. **Multiple, independent beams:** A single aperture can generate many simultaneous
independent beams. Alternatively, the same effect can be obtained by rapidly
switching a single beam through a sequence of positions

3. **Potential for large peak and/or average power:** If necessary, each element of the
array can be fed by a separate high-power transmitter with the combining of the
outputs made in “space” to obtain a total power greater than can be obtained from a
single transmitter.
4. **Control of the radiation pattern**: A particular radiation pattern may be more readily obtained with the array than with other microwave antennas since the amplitude and phase of each array element may be individually controlled. Thus, radiation patterns with extremely low sidelobes or with a shaped main beam may be achieved. Separate monopulse sum and difference patterns, each with its own optimum shape, are also possible.

5. **Graceful degradation**: The distributed nature of the array means that it can fail gradually rather than all at once (catastrophically).

6. **Convenient aperture shape**: The shape of the array permits flush mounting and it can be hardened to resist blast.

7. **Electronic beam stabilization**: The ability to steer the beam electronically can be used to stabilize the beam direction when the radar is on a platform, such as a ship or aircraft, that is subject to roll, pitch, or yaw.

**LIMITATIONS:**

1. However, the major limitation that has limited the widespread use of the conventional phased array in radar is its high cost, which is due in large part to its complexity.

2. The software for the computer system that is needed to utilize the inherent flexibility of the array radar also contributes significantly to the system cost and complexity.