11

Radars

11.1 INTRODUCTION

The word "RADAR" is an acronym which was coined in 1942 (II World War) by the U.S. Navy for *Radio Detection and Ranging*. It is basically a means of gathering information about distant objects or targets by sending electromagnetic (EM) waves to them and thereafter analysing reflected waves or the echo signals. Radar actually evolved a few years before World War II. It was radar that gave birth to microwave technology. In fact the early researchers found out that the higher frequencies gave the most accurate results. Higher frequencies produce the best echoes, making it possible to detect smaller targets and permit the use of smaller antennas. A radar can detect static or mobile objects or targets and is the most effective method for guiding a pilot with regard to his location in space and also for warning the approach of an enemy plane for similar purposes (Early warning radars).

We know that if an electromagnetic wave encounters sudden change in conductivity σ, permittivity ε or permeability μ in the medium, a part of the electromagnetic energy gets absorbed by the second medium and is reradiated. This sudden change in the electrical properties of the medium constitutes the target.

The reradiated energy on being received back at the radar station gives information about the location of the target. The location of the target includes range, angle and velocity parameters. The range is the distance of the target from radar station. The angle could be azimuth or elevation angle for static targets and velocity for moving targets.

For satisfactory location of the target, the received power (echo power) must be appreciable. Accordingly, the amount of power (energy) required to be radiated by the radar transmitter must be tremendous, typically few kW to MW. Such high power at high frequencies can be generated using magnetrons.

Advantages

1. Radars can see through darkness, haze, fog, rain, and snow.
2. They can determine the range and angle *i.e.*, the location of the target very accurately.

Limitations

1. Radars cannot resolve in detail like the human eye, especially at short distances.
2. They cannot recognise the colour of the target.

Applications

Civilian Applications

1. Navigational aid on ground and sea (navigation is not affected by poor visibility or darkness).
2. Radar altimeters for determining the height of plane above ground.
3. Radar blind lander for aiding aircraft to land under poor visibility, at night, under adverse weather conditions etc.
4. Airborne radar for satellite surveillance.
5. Police radars for directing and detecting speeding vehicles.
6. Radars for determining the speed of moving targets, (e.g the speed of a cricket ball being bowled) automobiles, shells, guided missiles etc.

Military Applications

1. Detection and ranging of enemy targets even at night.
2. Aiming guns at aircraft and ships.
3. Bombing ships, aircraft or cities even during overcast or at night.
4. Early warning regarding approaching aircraft or ships.
5. Directing guided missiles.
6. Searching for submarines, land masses and buoys.

11.2. BLOCK DIAGRAM OF A SIMPLE RADAR

The most basic form of a radar is shown in Fig. 11.1.

The simple radar system consists of a transmitting antenna and receiving antenna connected to the transmitter (T_x) and receiver (R_x) respectively. Such a radar system is called a *bistatic radar*.

The transmitter radiates or transmits electromagnetic radiations generated by a magnetron oscillator. A portion of this transmitted signal is intercepted, by the target and is reradiated in all directions. The receiver antenna, collects the returned echo signal and delivers it to the receiver where it is processed to detect the presence of the target and to extract its relative velocity with respect to radar station if the target is moving.

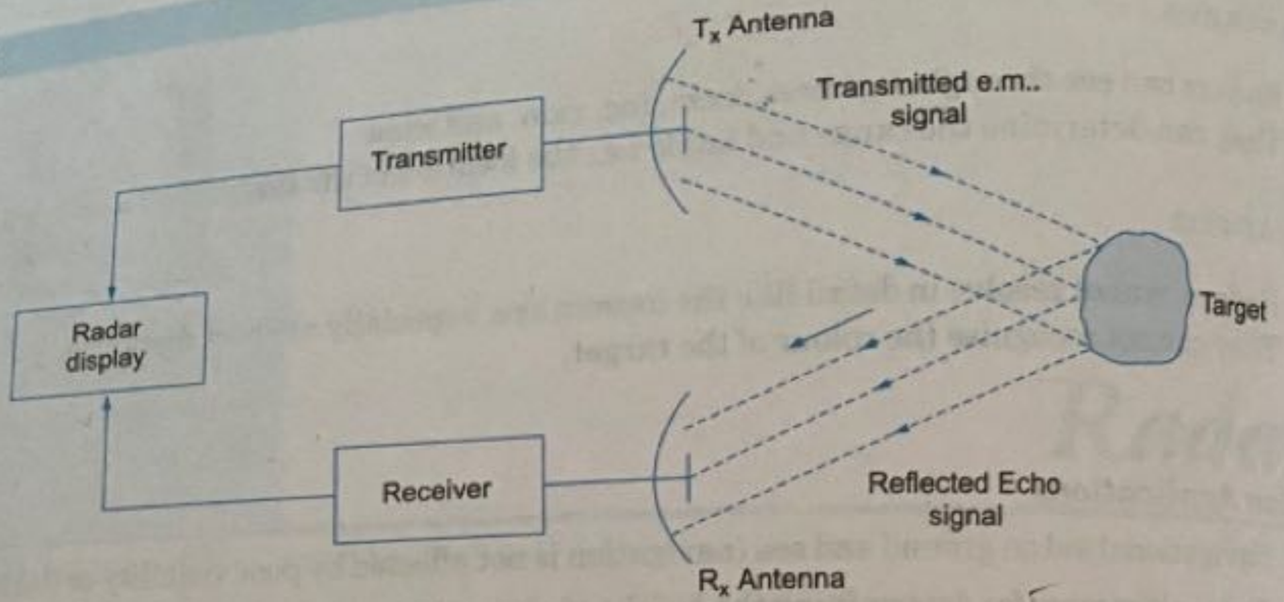

Fig. 11.1 Block diagram of a bistatic radar.

Improved Radar. A modified block diagram is shown in Fig. 11.2 which has another important block called the *duplexer*.

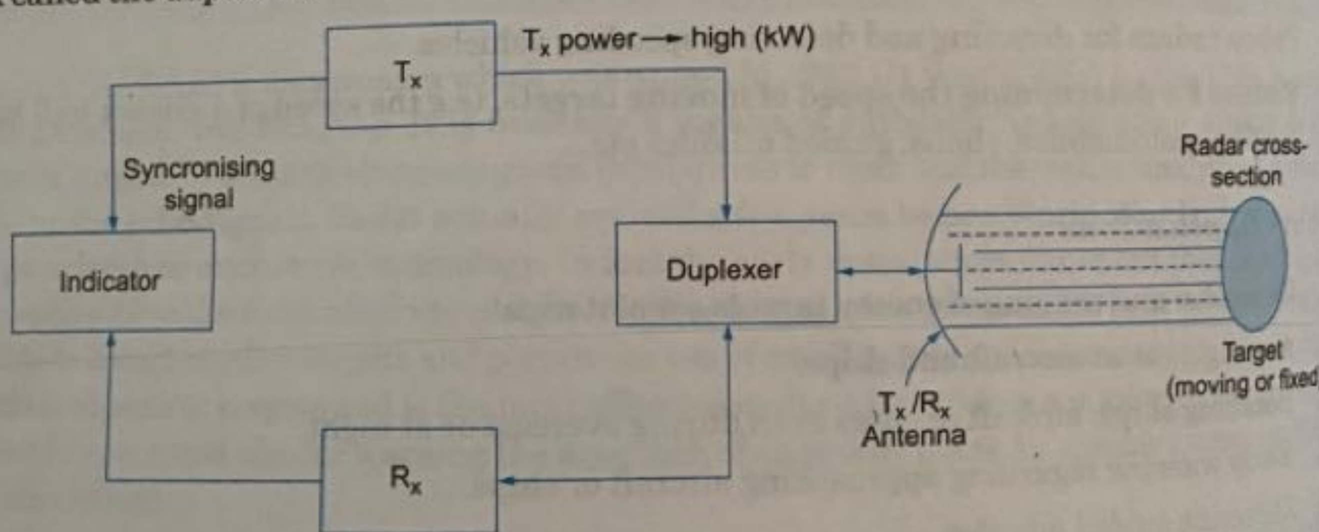

Fig. 11.2 Block diagram of a monostatic radar.

The functions of a duplexer are

1. to isolate the transmitter and receiver during transmission and reception.
2. to protect the receiver from high power transmitter.
3. to help use a single transmitter/receiver antenna.

Such a radar where a single antenna is used for both transmitting and receiving is called a *monostatic radar*, which is the most usual form of radar.

In general, radars consist of a transmitter, a receiver, a display and antennas. The received echo signal after it is processed by the receiver is displayed on the radar screen. It is very much possible to detect the height, speed and direction of travel of the target by space triangulation and by the time taken for the echo to come back after reflection from the target. The display screen can be similarly calibrated to indicate the target data.

The general requirement for any radar system are summarised as below.

1. The duplexer should be automatic in its operation.
2. The radar transmitter should remain silent during the echo period.
3. The transmitted pulse should be quite powerful to counter the attenuation during forward and return journeys.
4. The received echo pulse being weak, the receiver should be extremely sensitive and at the same time immune to noise (clutter) signals. It should have necessary amplification, signal processing circuitry and capability to display the target information on the radar screen.
5. The radar antenna should be highly directive and have a large gain so that it can radiate a strong signal and receive a weak pulse.
6. Pulse repetition frequency (prf) of the radar should be high compared to target scanning period where prf is given by the relation prf = duty cycle/pulse width *i.e.*, A small duty cycle provides the necessary time required for the pulse to go to the target, get reflected and provide echo pulse for the radar receiver. Normally pulse lengths (widths) lie in the range of 0.1 to 10 μsec. The average power depends on the transmitted power P_t and the duty cycle given by

$$P_{av} = P_t \times \text{duty cycle} = P_t \times \text{pulse width} \times \text{prf}.$$

Standard-radar-frequency letter band designations are shown in Table 11.1.

Table 11.1 Standard-Radar-Frequency Band Designations

Band designation	*Nominal frequency range (GHz)*	*Specific radar bands based on ITU assignment (GHz)*
L	1.0–2.0	1.215–1.400
S	2.0–4.0	2.300–2.500
C	4.0–8.0	5.250–5.925
X	8.0–12.5	8.500–10.680
Ku	12.5–18.0	13.40–14.00
		15.70–17.70
K	18.0–26.5	24.05–24.25
Ka	26.5–40.0	33.40–36.00

11.3 CLASSIFICATION

Radar systems can be broadly classified into two basic categories.

1. Continuous wave (CW)/Doppler Radars.
2. Pulsed Radars.

A *Continuous-Wave Radar* transmits a continuous wave signal and is generally useful in Doppler radars which utilises the Doppler effect. If there is any relative motion between the radar and the target, the shift in carrier frequency (Doppler shift) of the reflected wave becomes a measure of the target's relative velocity and may be used to distinguish moving targets from stationary targets. The Doppler effect can be experienced while standing near a train track. A change in frequency (pitch) of the train whistle occurs as the train approaches and then moves away. There are also radars that combine both of these effects.

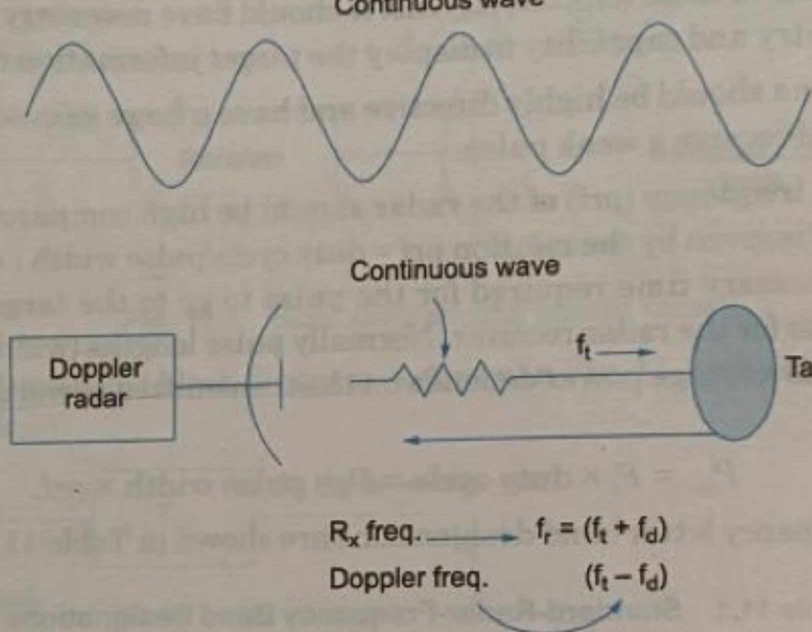

Fig. 11.3 Continuous wave radar.

A radar using the *Doppler effect principle* is known as a Doppler Radar which is useful for navigation over land and sea while navigating through aircraft or ship.

A *Pulsed-Radar* is more useful than CW Radar. Here, a pulse waveform, generally a train of narrow rectangular shaped pulses modulating a sine-wave carrier is transmitted as shown in Fig. 11.4. The range or distance to the target is determined by measuring the time T taken by the pulse to travel to the target and return to the radar station.

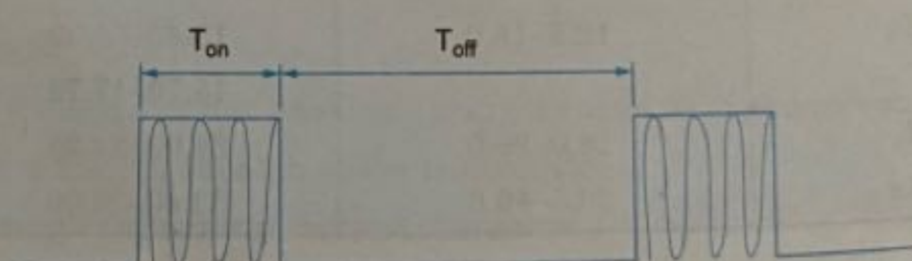

Fig. 11.4 Pulse modulated sine wave.

Since electromagnetic waves travel with the velocity of light c, the range R for *stationary target* is given by $2R = cT$ ...(11.1)

or
$$R = \frac{cT}{2}$$

[factor of 2 is to account for 2-way propagation]

where, $2R$ = total distance (2-way) between radar and target.

T = time taken by em waves to cover a distance '$2R$'.

c = velocity of light.

These two radar systems will be discussed in detail later in the chapter.

11.4 FREE SPACE RADAR RANGE EQUATION

The radar range equation relates the range of a radar to the characteristics of the T_x, R_x, antenna, target and the environment (medium).

Free space actually means that the radar set and the target are isolated in an unbound empty space. It basically indicates that there are no obstacles between radar antenna and the target. Also the free space medium is transparent (no absorption of electromagnetic waves) and homogeneous with respect to the refractive index at the radar frequency.

If the power of radar transmitter is denoted by P_t and if an isotropic antenna (one which radiates power uniformly in all directions is used), then the power density at a distance R from the radar is equal to the transmitter power divided by the surface area of sphere of radius R as shown in Fig. 11.5.

i.e., power density at a distance R from an isotropic source,

$$= \frac{P_t}{4\pi R^2} \text{ watts/m}^2 \qquad \text{...(11.2)}$$

Radars usually employ directive antennas to direct the transmitted 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 target as compared with the power that would have been radiated from an isotropic antenna.

Power density at a distance R from directive antenna of power gain G,

$$= \frac{P_t G}{4\pi R^2} \text{ watts/m}^2 \qquad \text{...(11.3)}$$

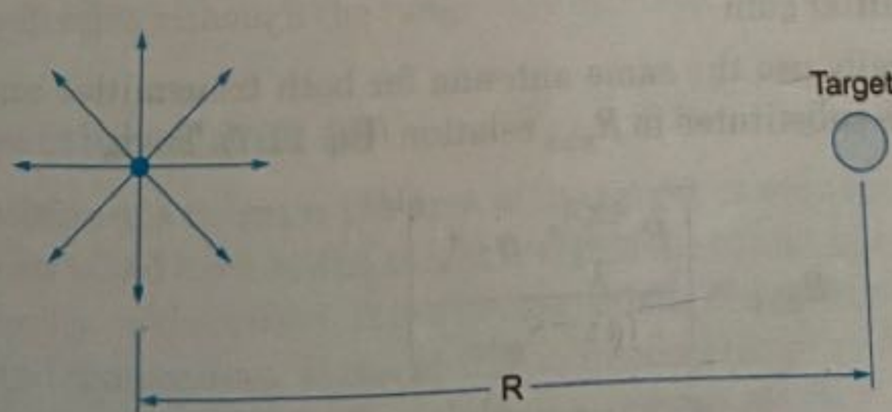

Fig. 11.5

The target intercepts a portion of the incident power and radiates it in various directions. A measure of the amount of incident power intercepted by the target and reradiated back in the direction of radar is denoted as the *radar cross-section of target* (σ).

The total power intercepted by a target having an area 'σ', is,

$$= \frac{P_t G}{4\pi R^2} \cdot \sigma \text{ watts} \quad \text{...(11.4)}$$

where σ is also defined as the area of the target as seen by the radar. It has units of area in m^2. σ is a characteristic of a particular target and is a measure of its size and shape. The power density of echo signal at the radar station is

$$= \frac{P_t G\sigma}{4\pi R^2} \cdot \frac{1}{4\pi R^2} = \frac{P_t G\sigma}{(4\pi R^2)^2} \text{ watts} \quad \text{...(11.5)}$$

The radar antenna captures a portion of the echo power. If the effective area of the receiving antenna is denoted by A_e, the power P_r received by the radar is given by,

$$P_r = \frac{P_t G\sigma A_e}{(4\pi R^2)^2} \text{ watts} \quad \text{...(11.6)}$$

Maximum Radar Range **(R_{max})** is the distance beyond which the target cannot be detected. It occurs when the received echo signal power P_r just equals the minimum detectable signal (S_{min}) i.e., when $P_r = S_{min}$, $R = R_{max}$ and when substituted in Eq. 11.6, we get

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

i.e.,

$$R_{max} = \left[\frac{P_t . G\sigma A_e}{(4\pi)^2 . S_{min}}\right]^{1/4} \quad \text{...(11.7)}$$

From antenna theory, we know that

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

where, λ = wavelength of radiated energy,

A_e = capture (or effective) area of receiving antenna,

G = transmitter gain

Since radars generally use the same antenna for both transmitter and receiver, the above expression for G can be substituted in R_{max} relation (Eq. 11.7). Then,

$$R_{max} = \left[\frac{P_t \dfrac{4\pi A_e}{\lambda^2} \cdot \sigma \cdot A_e}{(4\pi)^2 S_{min}}\right]^{1/4} \quad \text{...(11.8)}$$

i.e.,

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

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

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

$$R_{max} = \left[\frac{P_t G^2 \cdot \lambda^2 \cdot \sigma}{(4\pi)^3 \cdot S_{min}}\right]^{1/4}, \quad ...(11.9)$$

Equation 11.8 and 11.9 are the two alternative forms of *maximum radar range equation*.

11.4.1 Factors affecting Range of a Radar

As seen by the relation for R_{max} (Eq. 11.7, 11.8 and 11.9), it is readily observed that R_{max} depends upon the transmitted power P_t, frequency of the transmitted signal ($\lambda = c/f$), the cross sectional area of the target σ and the minimum receiver signal ($P_{r(min)}$.

Transmitter Power

In case the radar range is to be doubled, we have to increase the transmitter power 16 times since $R_{max} \propto P_t^{1/4}$.

Frequency

We also know that, $R_{max} \propto 1\sqrt{\lambda}$ or $R_{max} \propto \sqrt{f}$. This implies that increase in frequency increases the range. However this requirement is in conflict with the dependance of beam width of the antenna which is directly proportional to the wavelength λ.

For example, in a parabolic antenna the beam width is given by λ/D where D is the diameter of the parabola. If λ is reduced or frequency is increased, the beam width becomes very narrow which reduces the tracking range of the radar. This is particularly so in case of a search radar where the sweep of the antenna that covers a portion of the sky will require a longer time if the lobe beam width is very narrow. In such cases the radar frequency cannot be increased far too much as the radar becomes ineffective although the range may increase.

Target cross sectional area (σ)

The radar cross section of a target is the area of the target as seen by a radar. It is defined as the ratio of the power reflected back by the target towards the source per unit solid angle to the total incident power density on the target. It is a characteristic of a particular target and is a measure of its size, shape and composition. It can also be defined as the area of a perfectly conducting flat plane, facing the source that would reflect the same amount of power. They can be determined for various targets as shown in Table 11.2.

Substituting for this, k (1.38×10^{-23}) and T_o (300 K), we obtain a practical radar range equation given by,

$$R_{\max} = 48 \left[\frac{P_t \cdot D^4 \sigma}{B\lambda^2 (F-1)} \right]^{1/4} \text{ km} \qquad \text{...(11.13)}$$

It may be noted that the radar range cannot be extended indefinitely merely by controlling the parameters in the radar range equation. Radar receiver is exposed to interference and jamming from enemy during war time and the receiver power has to be sufficiently adequate to overcome these interfering signals. Further suitable anti-jamming techniques involving spread spectrum systems like frequency hopping etc. will have to be adopted.

The single most practical method of improving the radar range is to increase the antenna aperture which is proportional to its gain. An improved antenna design is the key to improved radar design.

11.5 MAXIMUM UNAMBIGUOUS RANGE (R_{unamb})

We have already seen that a typical radar waveform is a pulse modulated sine wave. Once a transmitted pulse is emitted by the radar, a sufficient length of time must be allowed so that the echo signals due to this pulse may be received and detected before the next pulse is transmitted. Therefore, the rate at which the pulse may be transmitted is determined by the longest range at which the targets are expected. If *pulse repetition frequency* (prf) is too high, echo signals from targets and ambiguities in the measuring range might result. Echoes that arrive after the transmission of next pulse are called "*Second-Time Around Echoes*".

The range beyond which targets appear as second-time around echoes is called "*Maximum Unambiguous Range*"

$$T = T_R = T_{ON} + T_{OFF} = \frac{1}{\text{prf}} \qquad \text{...(11.14)}$$

But
$$R_{\max} = \frac{cT}{2} = \frac{c(\text{Max value of } T_R)}{2}$$

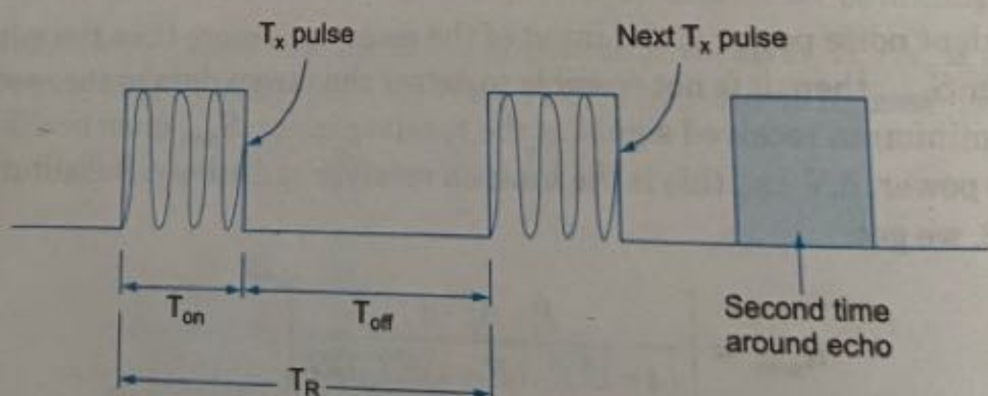

Fig. 11.7

Hence, Maximum unambiguous range is given by,

$$R_{\text{unamb}} = \frac{c(T_{ON} + T_{OFF})}{2} = \frac{c}{2\,\text{prf}} \qquad \text{...(11.15)}$$

Example 11.1

Calculate the maximum range of a radar system which operates at 3 cm with a peak pulse power of 600 kW if its antenna is 5 m^2, minimum detectable signal is 10^{-13} W and the radar cross sectional area of the target is 20 m^2.

Solution. $\lambda = 3$ cm; $P_t = 600$ kW, $S_{\min} = 10^{-13}$ W, $A_e = 5\ m^2$;

$$\sigma = 20\ m^2;\ R_{\max} = ?$$

$$R_{\max} = \left[\frac{P_t \cdot A_e^2 \cdot \sigma}{4\pi\lambda^2 \cdot S_{\min}}\right]^{1/4} = \left[\frac{600 \times 10^3 \times 5^2 \times 20}{4 \times \pi \times (3 \times 10^{-2})^2 \times 10^{-13}}\right]^{1/4} = 717.657\ \text{km}$$

In nautical miles; 1 nm = 1.853 km,

$$R_{\max} = \frac{717.657}{1.853} = 387\ \text{nm}$$

Example 11.2

A 10 GHz radar has the following characteristics, peak transmitted power = 250 kW; power gain of antenna = 2500; minimum detectable peak signal power by receiver = 10^{-14} watts; cross sectional area of the radar antenna = 10 m^2.

If this radar were to be used to detect a target of 2 m^2 equivalent cross section, find the maximum range possible.

Solution. Given

$$P_t = 250\ \text{kW};\ G = 2500;\ S_{\min} = 10^{-14}\ \text{W};\ A_e = 10\ m^2;\ \sigma = 2\ m^2;\ f = 10\ \text{GHz}$$

$$\lambda = c/f = \frac{3 \times 10^8}{10 \times 10^9} = 0.03\ \text{m}$$

$$R_{\max} = \left[\frac{P_t \cdot G A_e \sigma}{(4\pi)^2 S_{\min}}\right]^{1/4} = \left[\frac{250 \times 10^3 \times 2500 \times 10 \times 2}{(4\pi)^2 \times 10^{-14}}\right]^{1/4}$$

$$= 298.28\ \text{km}$$

Example 11.3

A marine radar operating at 10 GHz has a maximum range of 50 km with an antenna gain of 4000. If the transmitter has a power of 250 kW and minimum detectable signal of 10^{-11} W. Determine the cross section of the target thc radar can sight.

Solution. Given

$$f = 10\ \text{GHz};\ P_t = 250\ \text{kW};\ G = 4000;\ R = 50\ \text{km};\ P_r = 10^{-11}\ \text{W}$$

$\therefore$
$$\lambda = c/f = \frac{3\times10^8}{10\times10^9} = \mathbf{0.03\ m}$$

$$P_r = \frac{P_t\cdot G\cdot\sigma A_e}{(4\pi R^2)^2}\ \text{watts.}$$

$$A_e = \frac{G\lambda^2}{4\pi} = \frac{4000\times(0.03)^2}{4\pi} = 0.2865$$

$\therefore$
$$\sigma = \frac{P_r(4\pi R^2)^2}{P_t\cdot G\cdot A_e}$$

$$= \frac{10^{-11}\times(4\pi)^2\times(50\times10^3)^4}{250\times10^3\times4000\times0.2865}$$

$$\sigma = \mathbf{34.45\ m^2}.$$

Example 11.4

A guided missile tracking radar has the following specifications.

Transmitted Power	= 400 kW
Pulse repetition frequency	= 1500 pps
Pulse width	= 0.8 µsec

Determine (*a*) Unambiguous range (*b*) Duty cycle (*c*) Average power (*d*) Suitable bandwidth of the radar.

Solution. Given $P_t = 400$ kW; prf = 1500 pps (pulses per second); $t_w = 0.8\ \mu s$;

(*a*) $R_{\text{unamb}} = \dfrac{c}{2\,\text{prf}} = \dfrac{3\times10^8}{2\times1500} = \mathbf{100\ km}$

(*b*) Duty cycle $= \dfrac{T_{ON}}{T_{ON}+T_{OFF}} = \dfrac{T_{ON}}{(1/\text{prf})} = \dfrac{0.8\times10^{-6}}{1/1500} = \mathbf{0.0012}$

(*c*) $P_{av} = P_t \times$ Duty cycle $= 400\times10^3\times0.0012 = \mathbf{480\ W}$

(*d*) Suitable BW $= \eta/t_w$; $\eta = 1$ or 1.4

$\eta = 1$, $$\text{BW} = \frac{1}{0.8\times10^{-6}} = \mathbf{1.25\ MHz}$$

$\eta = 1.4$, $$\text{BW} = \frac{1.4}{0.8\times10^{-6}} = \mathbf{1.75\ MHz}$$

Example 11.5

A military radar operates at 5 GHz with 2.5 MW power output. If the antenna diameter is 5 m, the receiver band width is 1.6 MHz and has a 12 dB noise figure, what is the maximum detection range for 1 m² target.

Solution. Given

$$P_t = 2.5 \times 10^6 \text{ W}; D = 5 \text{ m}; \sigma = 1 \text{ m}^2; B = 1.6 \times 10^6 \text{ Hz};$$

$$\lambda = c/f = \frac{3 \times 10^8}{5 \times 10^9} = 0.06 \text{ m}:$$

$$F = \text{antilog}_{10}\left(\frac{12}{10}\right) = 15.85$$

R_{max} is given by (Eq. 11.13),

$$R_{max} = 48\left[\frac{P_t D^4 \cdot \sigma}{B\lambda^2(F-1)}\right]^{1/4} \text{ Km}$$

$$= 48\left[\frac{2.5 \times 10^6 \times 5^4 \times 1}{1.6 \times 10^6 \times (0.06)^2(15.85-1)}\right]^{1/4}$$

i.e.,

$$R_{max} \approx \mathbf{556\ km}$$

Example 11.6

A civilian radar has a maximum range of 30 kms. Determine the maximum range with an equivalent echoing area of 50 times and the effect of doubling the transmitter power on the range.

Solution. Given : $R_{max} = 30$ kms

Maximum range with an equivalent echoing area of 50 times

$$= 30\sqrt[4]{50} \approx 80 \text{ kms}$$

Range would be increased if T_x power is doubled by a factor of

$$\sqrt[4]{2} = \mathbf{1.19}$$

11.6 PULSED RADAR SYSTEM

The block diagram of a high-power pulsed radar set is shown above in Fig. 11.8 and various terminologies are defined below.

Trigger source provides pulses for the modulator.

Pulse modulator provides rectangular voltage pulses which act as the supply voltage to the output tube, thus switching it ON and OFF as required.

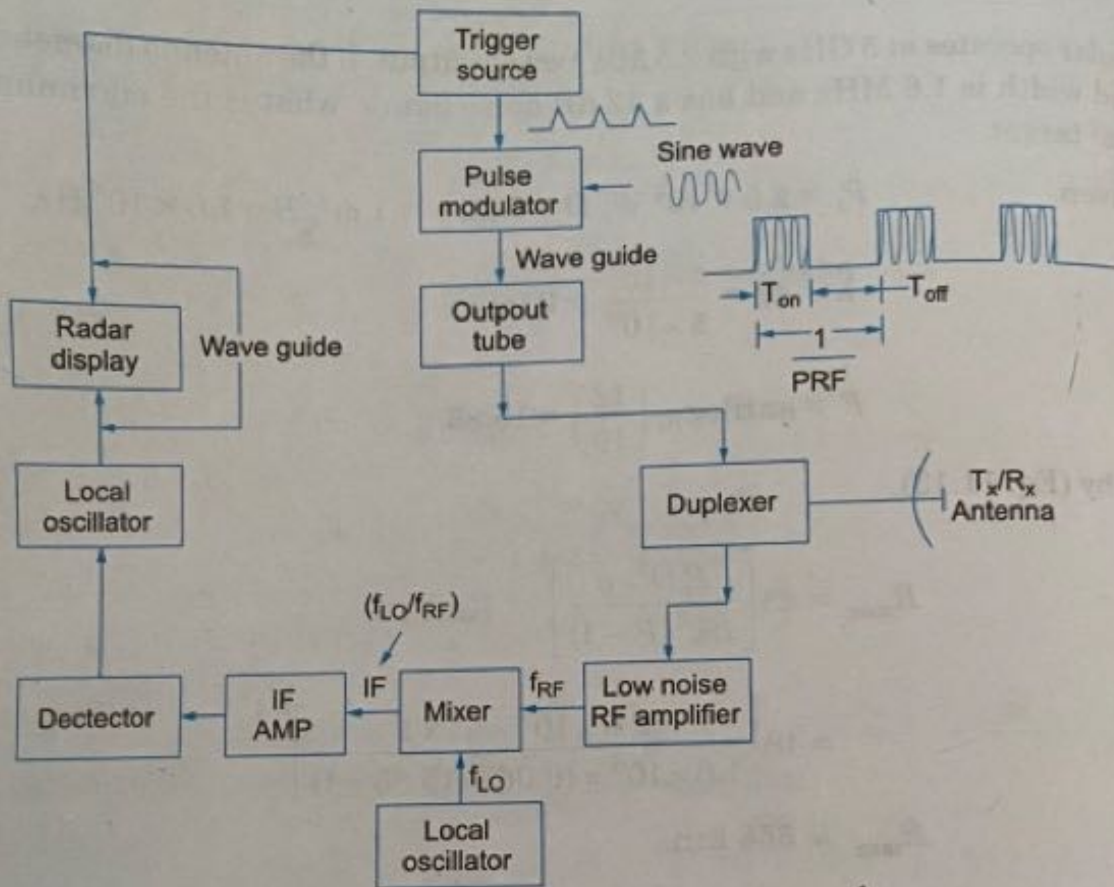

Fig. 11.8 Pulsed radar block diagram.

Output tube may be an oscillator tube such as a magnetron oscillator or an amplifier such as klystron, travelling wave tube or crossed-field amplifier (CFA). If an amplifier is used, a source of microwave is also required. Low power radars use IMPATT or Gunn oscillators or TRAPATT amplifiers. Below C-band (3.9-8.0 GHz), power transistor amplifiers or oscillators may also be used.

The *pulse modulated since-wave carrier* then travels via a *Duplexer* to the *antenna* where it is radiated into space. A single antenna is generally used for both transmission and reception. Usually *parabolic reflectors* with centre feed arrangements is made use of.

Duplexer. The receiver must be protected from damages caused by high power of the transmitter. This is the function of the duplexer. The duplexer also serves to channelize the returned echo signal to the receiver and not to the transmitter. The duplexer consists of gas-discharge tubes, one know as TR (transmitter-receiver) tube and the other as ATR (anti-transmitter-receiver). The TR tube protects the receiver during transmission and the ATR helps in directing the received echo signals to the receiver. The detailed operation of duplexer will be discussed in section 11.7.

Receiver is usually of *supperheterodyne* type whose function is to detect the desired echo-signals in the presence of noise, interference and clutter. The receiver in pulsed radar consists of the RF amplifier, mixer, local oscillator, IF amplifier, detector, video amplifier, and radar display.

Low Noise RF amplifier is the first stage of the receiver. It is a low noise transmitter amplifier or a parametric amplifier or a TWT amplifier. Silicon bipolar transistor is used at lower radar frequencies (below L-band *i.e.,* 1215 to 1400 MHz) and the GaAs FET is preferred at higher frequencies. It raises the strength of the echo signal.

Mixer and Local Oscillator. These convert RF signal output from RF amplifier to comparatively lower frequency levels called intermediate frequency (IF). Thus, in a mixer stage, the carrier frequency is reduced.

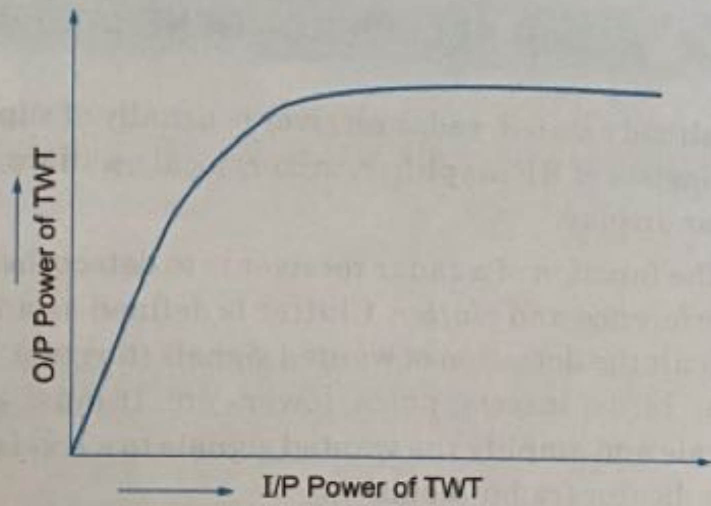

Fig. 11.9

IF amplifier consists of a cascade of tuned amplifiers and provides the main receiver gain. It should be designed as a matched filter to get maximum peak signal-to-mean noise power ratio at the output. A typical IF amplifier for an air surveillance radar might have a *center frequency* of 30 MHz or 60 MHz and a bandwidth of 1 MHz.

Detector is often a Schottky-barrier diode which extracts 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 usually on C.R.T. (Cathode Ray Tube) directly or via computer processing and enhancing. Synchronising pulses are applied by the trigger source to the display devices or the display indicator.

Radar Direction Indication and Data Presentation

For locating the target, we know that it is essential to get the following information. The range information giving the distance of the target from the radar station and the angle information both the azimuth (horizontal direction) and the elevation (vertical direction) are desired. The angle information is obtained from the radar antenna and range information is determined from the time taken by the pulse to travel from the radar to the target and back to the receiver.

This data obtained at the output of the radar receiver can be presented by any of the following ways.

1. Deflection modulation of a CRT screen or A-scope
2. Intensity modulation of a CRT or Plan Position Indicator (PPI)
3. Feeding the data to a computer.

Additional information regarding height, speed or velocity can be displayed on separate displays or integrating them on the above displays.

The detailed description of A-scope and PPI are given in section 11.9.

Synchronising or timing pulses are supplied to the indicator to set [illegible] *reference value* as zero. *Direction indication i.e.,* angle information is obtained from [illegible] tion of the antenna

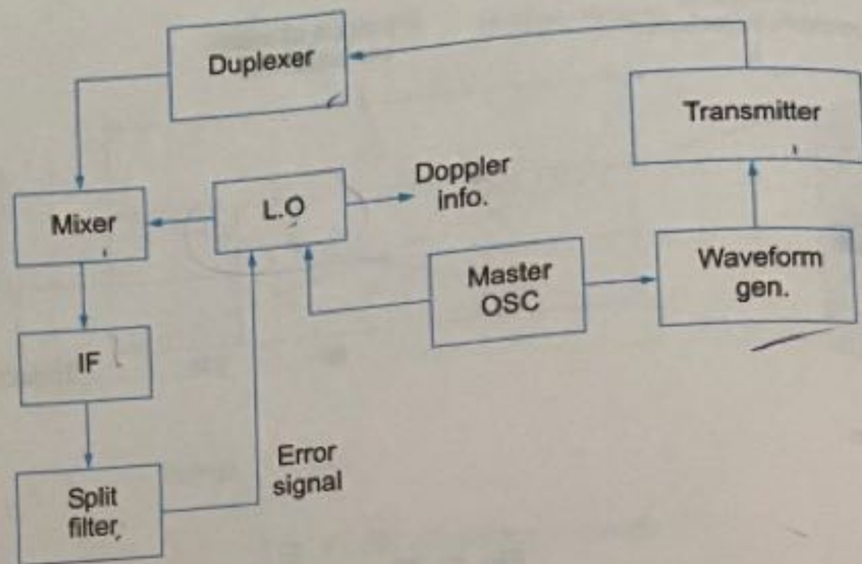

Fig. 11.38

Tracking in Doppler

When the target is moving relative to radar, then there will be a shift in the carrier frequency of the received signal and this effect is called *Doppler Effect*. The shift in frequency is the *Doppler Shift* and this is a measure of the velocity of the target.

Tracking radars can also track the doppler frequency shift generated by a moving target. This may be accomplished with a frequency discriminator and a tunable oscillator to maintain the received signal in the centre of a narrow band filter. The output from the discriminator is a measure of frequency shift and the speed of the target is a measure of this voltage.

A doppler tracker is also called a velocity tracker. Similar to a range tracker except that the tracking gate is now in the frequencuy domain. A simple doppler tracking system consists of a split filter error detection system in the receiver chain. The difference between the target IF and the receiver's normal IF determines the tracking error. the system used for measurement is shown in Fig.11.38. The error generated by the split filter circuit is monitored by the local oscillator until the doppler shifted signal becomes the normal IF.

Since the ability to track targets at varying angles is physically limited, most of the single beam-width radars have one to four tracking channels. A phased array could have hundreds of tracking channels. Radar tracking capabilities vary widely and basically depend upon the mission to be accomplished and the radar design.

11.12 DOPPLER EFFECT

When the target is moving relative to radar it will result in, an apparent shift in the carrier frequency of the received signal. This effect is called the doppler effect and it is the basis of Continuous Wave (CW) radar.

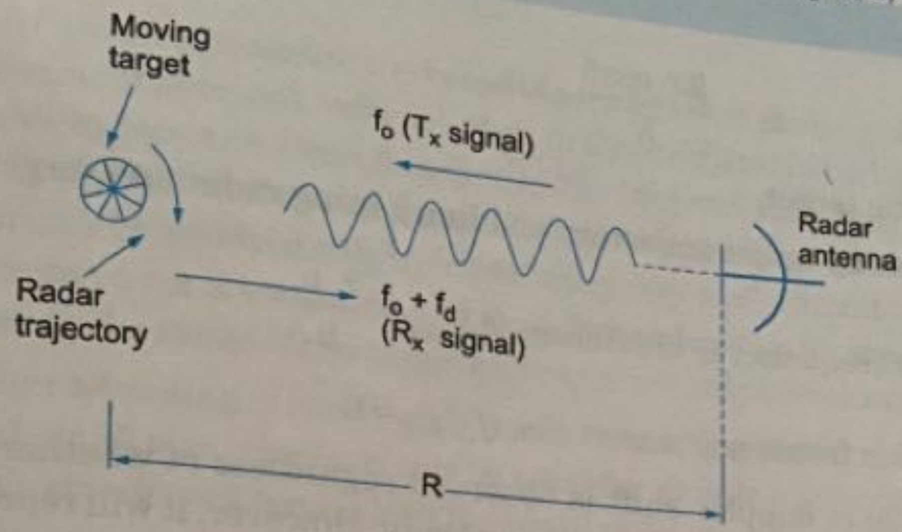

Fig. 11.39

If R is the distance of the target from radar station, the total number of wavelengths contained in the two-way path $= \frac{2R}{\lambda}$ where, λ = wavelength of the transmitted wave. (Refer Fig. 11.39).

Since one wavelength corresponds to a phase shift of 2π rads, the total phase shift

$$\phi = 2\pi \times 2\,R/\lambda \quad i.e. \quad \phi = \frac{4\pi R}{\lambda}\ \text{rad} \qquad \text{...(11.20)}$$

If the target is in motion, R (the range) and ϕ (phase) are continuously changing.

A change in ϕ with respect to time is equal to frequency. The *doppler angular frequency* (ω_d) is given by,

$$\omega_d = 2\pi f_d = \frac{d\phi}{dt} = \frac{d}{dt}\left(\frac{4\pi R}{\lambda}\right) = \frac{4\pi}{\lambda}\cdot\frac{dR}{dt} = \frac{4\pi}{\lambda}\cdot v_r \qquad \text{...(11.21)}$$

where, f_d = doppler frequency shift

v_r = relative velocity of target with respect to radar

$$\therefore \qquad f_d = \frac{2v_r}{\lambda}\ \text{Hz} \qquad \text{...(11.22)}$$

The relative velocity (v_r) may be written as (as per Fig. 11.40)

$$v_r = v\cos\theta$$

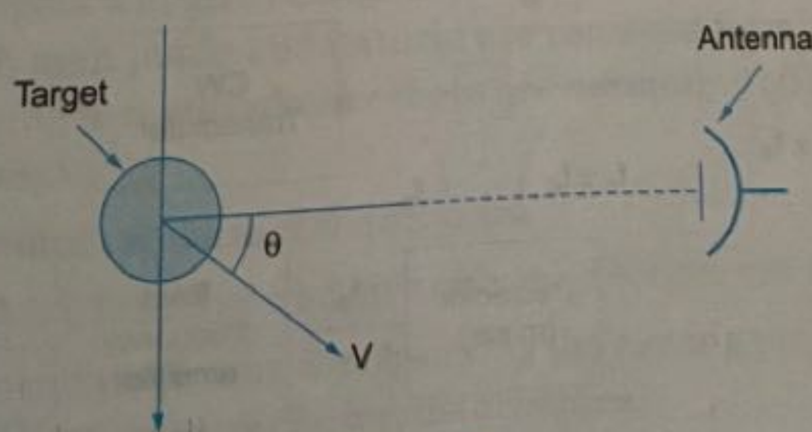

Fig. 11.40

$$\therefore \qquad f_d = \frac{2v \cdot \cos\theta}{\lambda}$$

where, v = speed of the target

θ = angle made by target trajectory and line joining radar and target.

When $\theta = 0$, doppler frequency is maximum $(f_d)_{max} = \frac{2 \cdot v}{\lambda}$

When $\theta = 90°$, doppler frequency is zero. *i.e.*, $(f_d)_{min} = 0$

The same magnitude of doppler shift is observed regardless of whether a target is moving towards the radar or away from it, with a given velocity. However, it will represent an increase in frequency in the former case and reduction in the latter. On the basis of this frequency change, it is possible to determine the relative velocity of target with either pulsed or CW radar. We can also distinguish between stationary and moving targets and eliminate blips due to stationary targets. This is done by pulsed radar with an MTI (Moving Target Indicator).

11.13 CW DOPPLER RADAR

The block diagram of a simple CW Doppler radar is shown in Fig. 11.41.

The transmitter generates a continuous oscillation of frequency 'fo' which is radiated by the antenna. A portion of this radiated energy is intercepted by the target and the reradiated energy is collected by the receiver 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_o' by an amount. The plus sign for an approaching target and minus for a receding target. The received echo signal $(f_o \pm f_d)$ enters the radar via the antenna and is mixed in a detector mixer with a portion of the transmitter signal 'f_o' to produce the doppler frequency f_d. The purpose of using a beat frequency 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 such as a frequency meter.

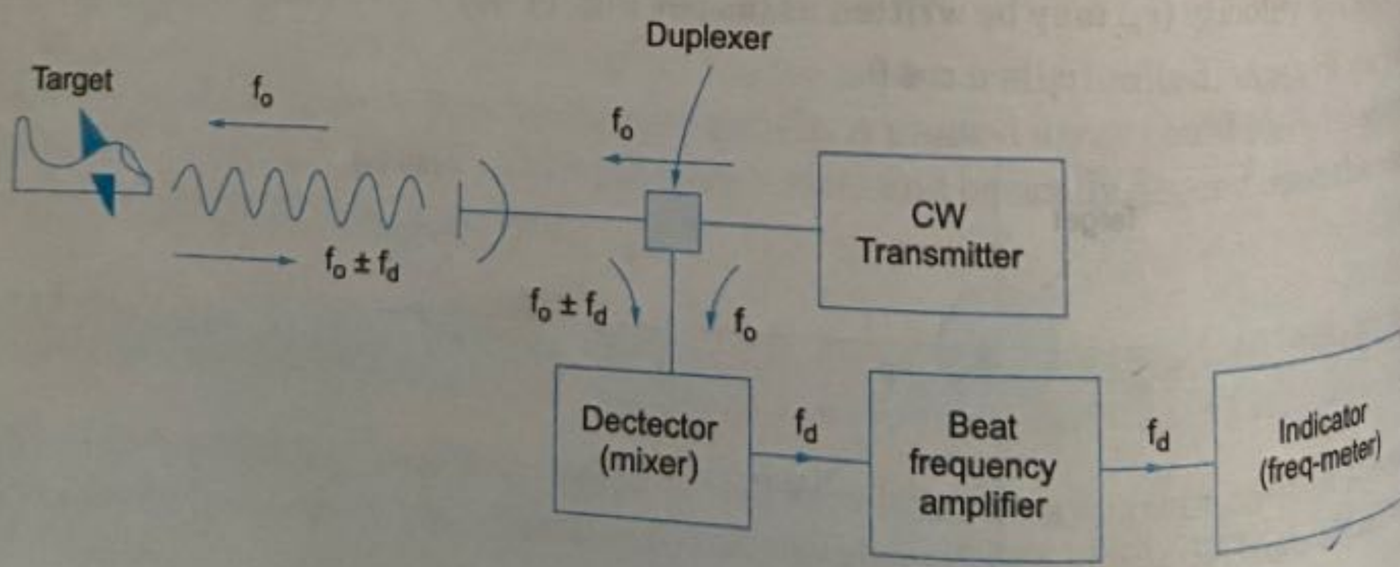

Fig. 11.41

The CW radar can be used to measure the speed of automobiles, shells, guided missiles etc. It can be used to detect movement of troops, vehicles even in the dark and in bad weather. Unlike pulsed radar, CW radar is able to detect an aircraft inspite of fixed objects. However, practical application of CW radar is limited by the fact that several targets at a given bearing tend to cause confusion. Also, range discrimination may be achieved only by introducing very costly circuit complexity. Further it is limited in the maximum power it transmits and this places a limit on its maximum range. Also, it is not capable of indicating the range of the target and can show only its velocity.

CW radar has other advantages like it used low transmitting power, low power consumption, simple circuitry and small size. Hence it can be used for mobile applications. It can be used by police radars and also in aircraft navigation for speed measurement and as rate of climb meter.

The Doppler effect can be utilised in a pulsed radar system by combining special delay line techniques, the system can be made to determine target velocity and to distinguish moving targets from stationary targets. This improved system is called a *moving target indicator* (MTI) radar system.

11.14 MOVING TARGET INDICATOR (MTI) RADAR

This radar uses the doppler effect for its operation. Many a times it is not possible to distinguish a moving target in the presence of static or permanent echoes of comparable appearance on the radar screen.

We have seen that in a PPI display, there is a lot of clutter due to these stationary target echoes. Also, it is quite possible that a moving target has a range and bearing such that the echo from the moving target gets superimposed on the ground clutter. Such a condition can exist in mountainous region or in close vicinity of modern cities cluttered with tall buildings. Another example could be when a moving aeroplane seeks to hide behind other aeroplanes as in war time, when deliberately, pilotless aeroplanes at lower heights provide cover for bombers racing above. This is done so that radar cannot pick up the bombers and to avoid antiaircraft action.

Principle. When it is desired to remove the clutter due to stationary targets, an MTI radar is employed. The basic principle of an MTI radar is to compare a set of received echoes with those received during the previous sweep and cancelling out those whose phase has remained unchanged. Moving targets will give change of phase and are not cancelled. Thus clutter due to stationary targets both man made and natural are removed from the display and this allows easier detection of moving targets (whose echoes are normally 100 times smaller than those of nearby stationary targets).

The effects of dependance on phase of the echo are

1. targets which are too far away and give only mild echoes are netted in the radar.
2. time taken by the radar operator for observing the moving targets is greatly reduced due to elimination of ambiguities and clutter disturbances.
3. stationary or slow moving targets cannot mask the faster ones in the display.

Practical MTI systems are capable of cancelling echoes from fixed targets having amplitude of the order of 40 dB or greater above visibility. At the same time, it is quite possible to observe moving targets that are superimposed on fixed targets and those that are weaker than the fixed targets by as much as 25 dB.

11.14.1 Blind Speeds

If the target has uniform velocity, the successive sweeps will have doppler phase shifts of exactly 2π (or 360°) and the target appears stationary and gives wrong radar indication. The speed corresponding to this condition is called blind speed. However constant velocity is not possible for any target beyond a particular time and the echo will be netted in the third or fourth successive sweeps. Of course ECM techniques have reached such sophistication that a target can fly at a blind speed purposefully so that it is undetected by the radar.

If a target moves a half wavelength between successive pulses, the change in phase shift will be precisely 2π radians. Hence blind speed/velocity can be represented by the relation.

$$v_b = \text{prf} \cdot \frac{n\lambda}{2} \quad \text{...(11.24)}$$

where, v_b = blind speed

λ = Wavelength of transmitted pulse

and n = any integer (1, 2, ...)

The target can travel with blind speed, by analysing the transmitted frequency and pulse repetition frequency and adjust its radial velocity as per the analysis. However a variable pulse repetition frequency decided by a pseudo random generator used by the radar transmitter will solve the problem of blind speed.

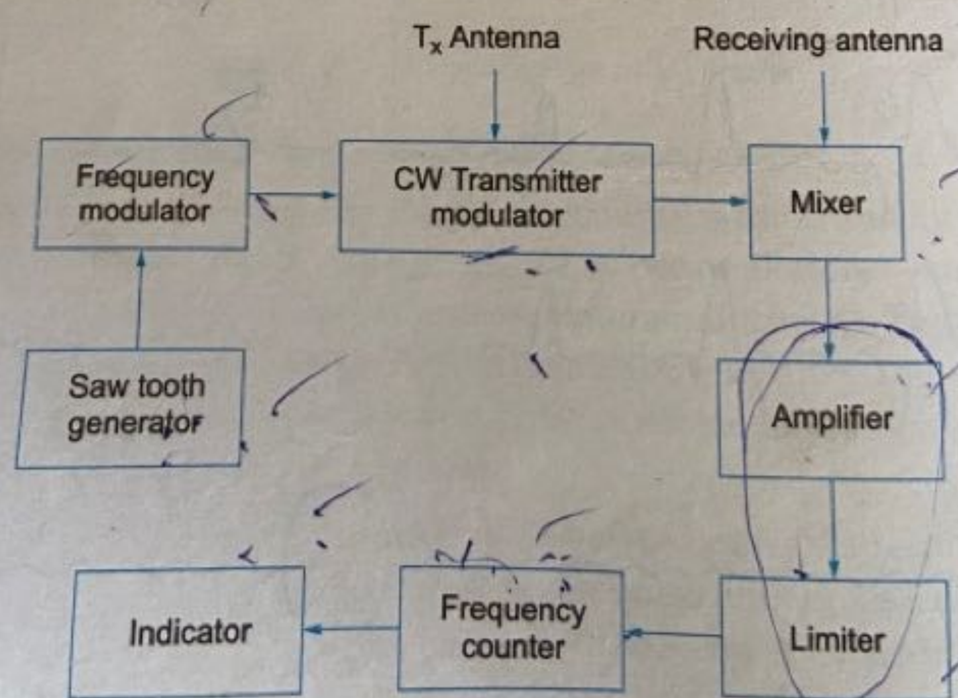

Fig. 11.44 FM-CW radar (block diagram).

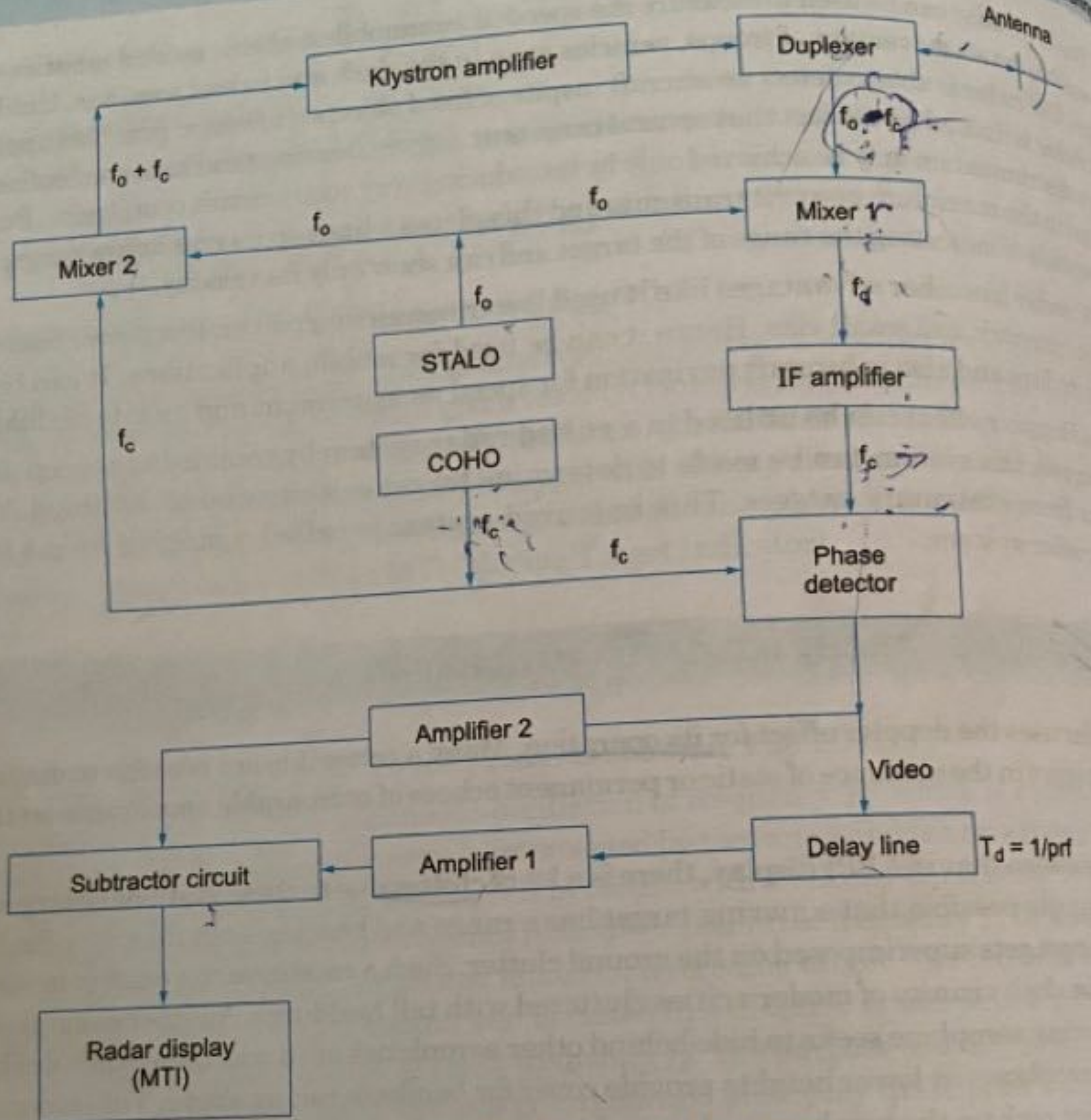

Fig. 11.42 Block diagram of MTI radar.

Block diagram. A block diagram of an MTI radar is shown in Fig. 11.42.

The block diagram shows two mixers. Mixer ② generates the transmitter frequency ($f_o + f_c$) which is obtained by the sum of frequencies produced by two oscillators — the STALO (stable local oscillator producing f_o) and the COHO (Coherent oscillator producing f_c). The transmitted frequency drives a multicavity klystron amplifier, which acts as an output tube. This amplifier provides the desired amplification for providing a high power pulse when modulator switches on this tube. This transmitter pulse is the output via the duplexer.

The echo pulse from the target (due to the transmitted pulse) is received by the MTI radar antenna. If the echo is due to a moving target, the echo pulse undergoes a doppler frequency shift. The received echo pulses then pass through Mixer ① of the receiver which heterodynes the received signal of frequency ($f_o + f_c$) with the output of the STALO at f_o and produces a difference frequency f_c at its output. The two mixers ① and ② are identical in all respects except that Mixer ① produces a difference frequency whereas Mixer ② produces a sum frequency. This difference frequency signal is further amplified by an IF amplifier and is given to the phase sensitive detector or phase discriminator. This detector compares the IF signal with the reference signal from the COHO oscillator. The frequency produced by COHO is the same as the IF frequency and hence called coherent frequency. The detector provides an output depending upon the phase difference between these two signals. Since all received signal pulses will have a phase difference compared with the transmitted pulse, the phase detector gives output for both fixed and also for moving targets. Phase difference is constant for all fixed targets but varies for moving targets. Doppler frequency shift causes this variation in phase difference. A change of half cycle in the doppler frequency shift would cause an output of opposite polarity in the phase detector output. The output of the phase detector therefore will have an output that has different magnitudes and polarities for successive pulses in case of a moving target. However, for fixed targets the magnitude and polarities for successive pulses in case of a moving target. However, for fixed targets the magnitude and polarity of the output will remain the same for all transmitted pulses as shown in Fig. 11.43.

The output of the phase detector is applied to a delay line which has a delay time corresponding to the prf of the transmitted pulse ($T_d = 1/\text{prf}$). The delayed output is amplified by amplifier ① and given to the subtracting circuit. At the same time the undelayed output of the detector is amplified by an identical amplifier ① and given to the subtracting circuit. *i.e.* the outputs of phase detector for successive pulses are subtracted from each other. For a fixed target, signal pulse such as ① in Fig. 11.43*a* the delayed pulse at the subtractor input will be ② of Fig. 11.43*b* and when subtracted these will cancel out as shown in Fig. 11.43*d*. However for moving target pulses such ③ and ⑤ as shown in Fig. 11.43*a*, the delayed pulses ④ and ⑥ at the subtractor input will have different magnitude/phase and would not cancel each other when subtracted. As a result the subtractor output for moving targets (Fig. 11.43*d*) are available for display.

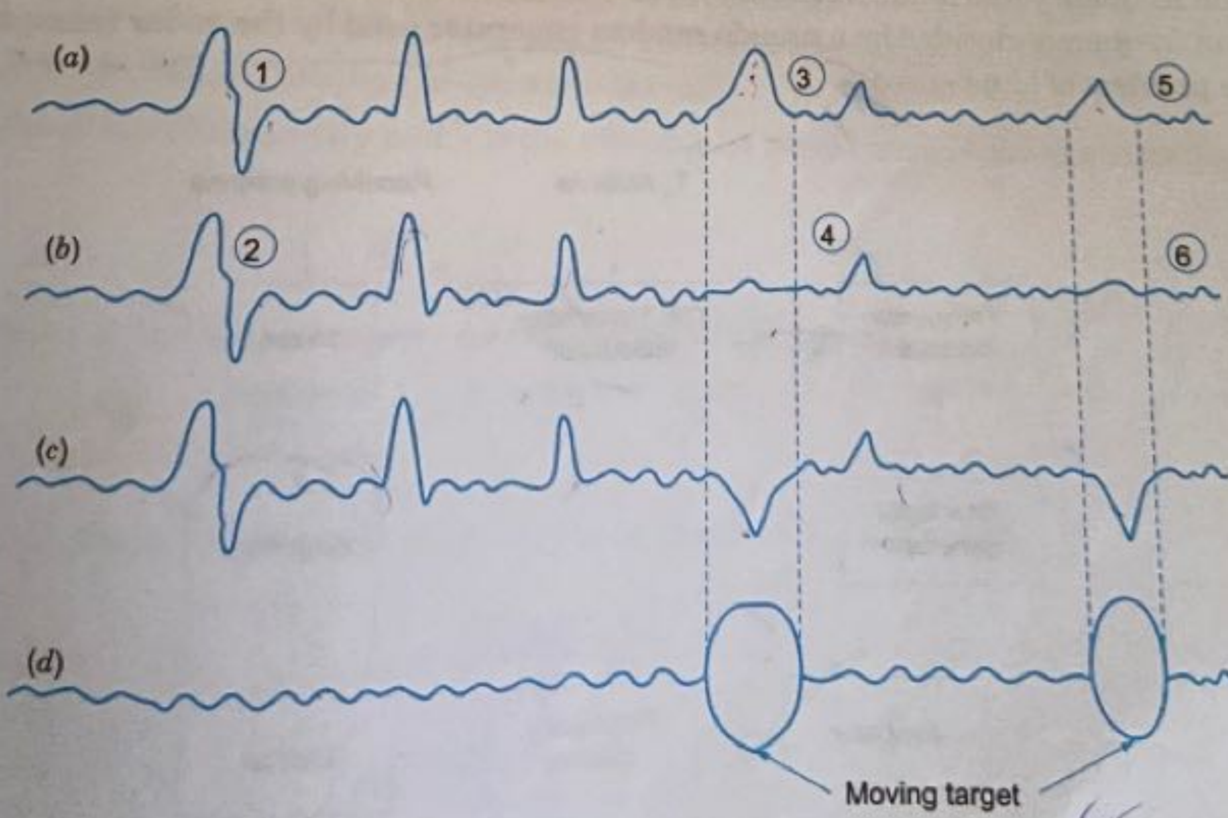

Fig. 11.43 (a) (b) and (c) phase detector output for three successive pulses (d) subtracting circuit output indicating moving targets.