CW and Frequency Modulated Radar.

Introduction :-

A radar detects the presence of objects & locate their position in space by transmitted EM energy & observing the returned echo. A pulse radar transmits a relatively short burst of EM energy, after which the receiver is turned on to listen for the echo.

The echo not only indicates that a target is present, but the time that elapses between the transmission of the pulse & the receipt of the echo is a measure of the distance to the target. Separation of the echo signal & the transmitted signal is made on the basis of differences in time.

If the strong transmitted signal can be separated from the weak echo the radar transmitter may be operated continuously rather than pulsed. The received echo-signal power is considerably smaller than the transmitted power.

Sometimes seperate antennas are required for txn & reception to segragate the weak echo from the strong leakage signal, but the isolation is usually not sufficient.

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

When there is a relative motion between Radar & target, there is apparent change in the echo-signal freq. This effect is known as Doppler Effect.

→ The radar radiate EM waves towards the targets for detection & also to obtain details of the target.

→ When the target is stationary, the freq of the received echo is same as freq ~~is moving~~, of the txd signal.

→ When target is moving, the freq of the received echo is found to be different from transmitted frequency.

→ If the target approaches the radar, the freq is increased and if the target moves away from the radar, the freq is decreased.

→ Therefore in the moving targets, freq shift exists in the received echo signal.

→ This frequency shift is know as Doppler freq. shift.

→ The presence of frequency shift in the received echo signals in the radar due to moving targets is known as Doppler effect.

Doppler frequency shift (f_d) :-

If R is the distance from Radar to target, the total no. of wavelengths (λ) contained in the two-way path between the Radar & target

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

since one wavelength corresponds to an angular phase of 2π radians.

The total phase angle (ϕ) made by the EM wave during its transmit to and from the target.

$$\phi = 2\pi \times \text{total no. of wavelengths}$$

$$= 2\pi \times \frac{2R}{\lambda} \text{ radians}$$

$$\boxed{\phi = \frac{4\pi R}{\lambda} \text{ radians}} \quad \text{— (1)}$$

→ If the target is in motion, distance R and phase ϕ are continuously changing.

→ The rate of phase is equal to freq.

$\therefore\ \omega_d$ = Doppler angular freq.

$$\boxed{\omega_d = 2\pi f_d = \frac{d\phi}{dt}} \quad \text{— (2)}$$

substitute (1) in (2)

$$\omega_d = \frac{d}{dt}\left(\frac{4\pi R}{\lambda}\right) = \frac{4\pi}{\lambda}\frac{dR}{dt} = \frac{4\pi}{\lambda} V_r$$

we know that $\frac{dR}{dt} = V_r$

V_r = Relative velocity of the target with respect in knots.

$$2\pi f_d = \frac{4\pi}{\lambda} V_r$$

$$f_d = \frac{4\pi}{\lambda}\frac{V_r}{2\pi}$$

$$\boxed{f_d = \frac{2V_r}{\lambda}} \Rightarrow f_d = \frac{2V_r f}{c}$$

If f_d in Hz, V_r in knots, λ in meters

$$\therefore \boxed{f_d = \frac{1.03 V_r}{\lambda}}$$

The relative velocity may be written as

$$\boxed{V_r = V\cos\theta}$$

where V = target Speed

θ = angle made by the target trajectory.

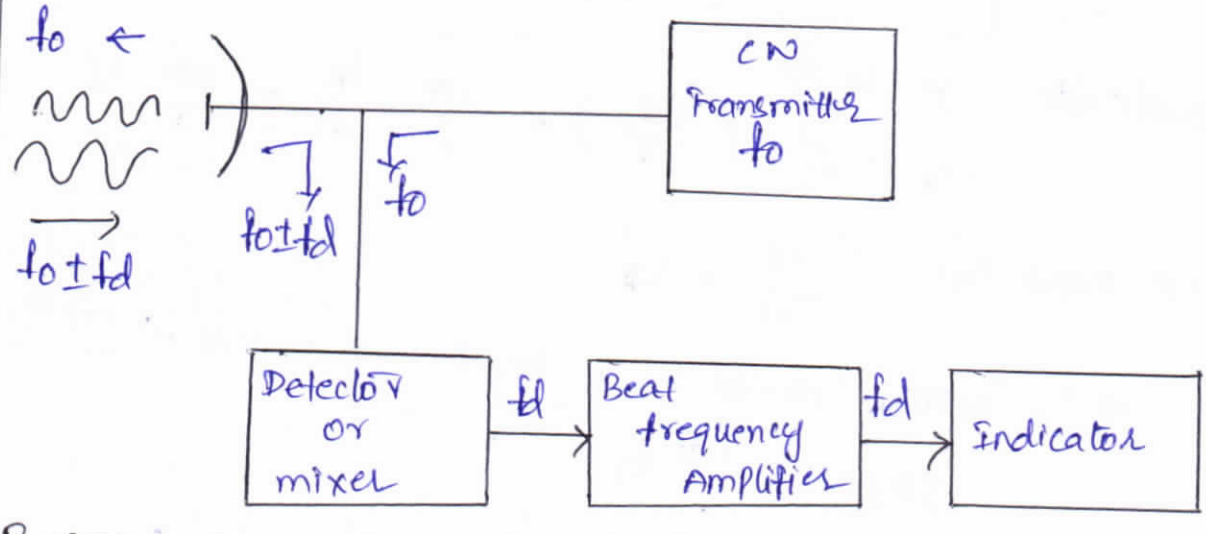
$$\boxed{f_d = 2V\cos\theta/\lambda}$$

when $\theta = 0°$, the doppler freq is maximum, the doppler freq is zero, when the trajectory is $\perp$lar to the Radar line of sight $(\theta = 90°)$.

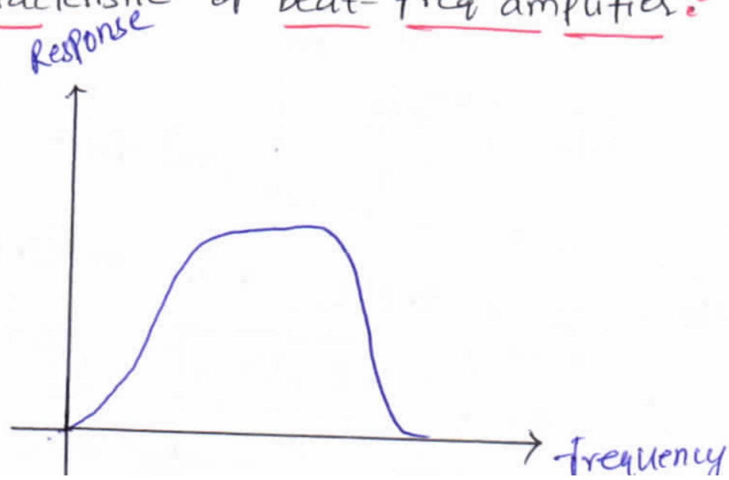
Continuous wave (CW) Radar:-

A simple CW Radar is as shown in figure. This Radar consists of a transmitter, detector, beat freq amplifier & indicator.

Block diagram:-



Response characteristic of beat-freq amplifier:-



The transmitter transmits a ~~cw of~~ frequency oscillation or oscillation of frequency (f_o), which is radiated by the antenna. An amount of radiated energy is intercepted by the ~~antenna~~. ~~An~~ a target and some of this energy is scattered back in the direction of Radar. This energy is collected by the receiving antenna.

If the target is in motion with a relative velocity v_r to the Radar, then the received signal will be shifted by an amount of '$\pm f_d$'

The plus (+) sign associated with the Doppler frequency applies if the distance between target and Radar is decreasing (closing target), i.e. when the received signal freq. is greater than the transmitted signal frequency.

The minus sign (−) associated with the Doppler freq applies if the distance between target and Radar is increasing (receding target), ie., when the received signal frequency is lessthan transmitted signal frequency.

The received echo signal at a frequency ($f_o \pm f_d$) enters the Radar via the antenna and is heterodyne in the detector with a part of the transmitted signal f_o to produce a Doppler beat frequency f_d. The sign is lost in this process.

The Doppler amplifier is used to eliminate the echoes from stationary targets

The upper cut-off frequency is selected to pass the highest Doppler frequency expected. ~~to pass~~ An indicator is used to indicate frequency. Generally indicator consists of a pair of earphones or a frequency meter.

Isolation between transmitter & Receiver:-

→ In the simple CW Radar a single antenna is used for both transmission & reception. Due to this there may be a transmission leakage but separation in frequency due to doppler effect is achieved. In practice, it is not possible to eliminate completely the transmission leakage. So there is a necessity to provide isolation between transmitter & receiver.

→ The main importance of providing isolation between transmitter & receiver is to eliminate the transmitter leakage.

→ If same antenna is used for txn & reception, the reflections produced in the transmission line by the antenna limits the isolation. The antenna can never be perfectly matched to freespace, & there will always be some transmitted signal reflected back towards the receiver.

→ The reflection coefficient from a mismatched antenna with VSWR (σ) is $\rho = \left|\frac{\sigma-1}{\sigma+1}\right|$

→ Therefore if an isolation of 20dB is to be obtained the VSWR must be less than 1.22.

If 40dB of isolation is required, the VSWR must be less than 1.02

→ The largest isolations are obtained with two antennas, one for transmission, the other for reception - physically separated from one another.

→ Isolations of the order of 80dB or more are possible with

→ If directivity of antenna is more, the separation between two antennas is more, the isolation will be high.

→ A common radome enclosing the two antennas should be avoided since it limits the amount of isolation that can be achieved.

→ The transmitter noise that enters the radar receiver via backscatter from the clutter is called transmitter clutter. It can appear at the same frequencies as the doppler shifts from moving targets and can mask desired targets.

Intermediate - frequency receiver:-

→ The receiver of the simple CW Radar is analogous to a superheterodyne receiver.

→ Also called homodyne receivers.

→ This receiver is not as sensitive because of increased noise at the lower intermediate frequencies caused by flicker effect.

→ Flicker-effect noise occurs in semiconductor devices such as diode detectors and cathodes of vaccumtubes.

→ The noise power produced by the flicker effect varies as $\frac{1}{f^{\alpha}}$, where α is approximately unity.

→ The detector of the CW receiver can introduce a considerable amount of flicker noise, which is reduce the receiver sensitivity.

→ For short range low power applications, the decrease in sensitivity might be tolerated. But for maximum efficiency with CW radar, the reduction in sensitivity caused by the simple doppler receiver with zero IF cannot be tolerated.

→ The effects of flicker noise are overcome in the normal superheterodyne receiver by using an Intermediate frequency high enough to render the flicker noise small compared with the normal receiver noise.

Comparison between zero & non-zero If receiver :-

1. zero IF receiver is not as sensitive because of increased noise at lower intermediate freq caused by flicker effect

2. The reduction in sensitivity has greater effect on the maximum efficiency with CW Radar.
3. The improvement in receiver sensitivity with an non-zero IF receiver might be around 30dB over the zero IF receiver

CW Radar with non-zero IF receiver :-

Block diagram :-

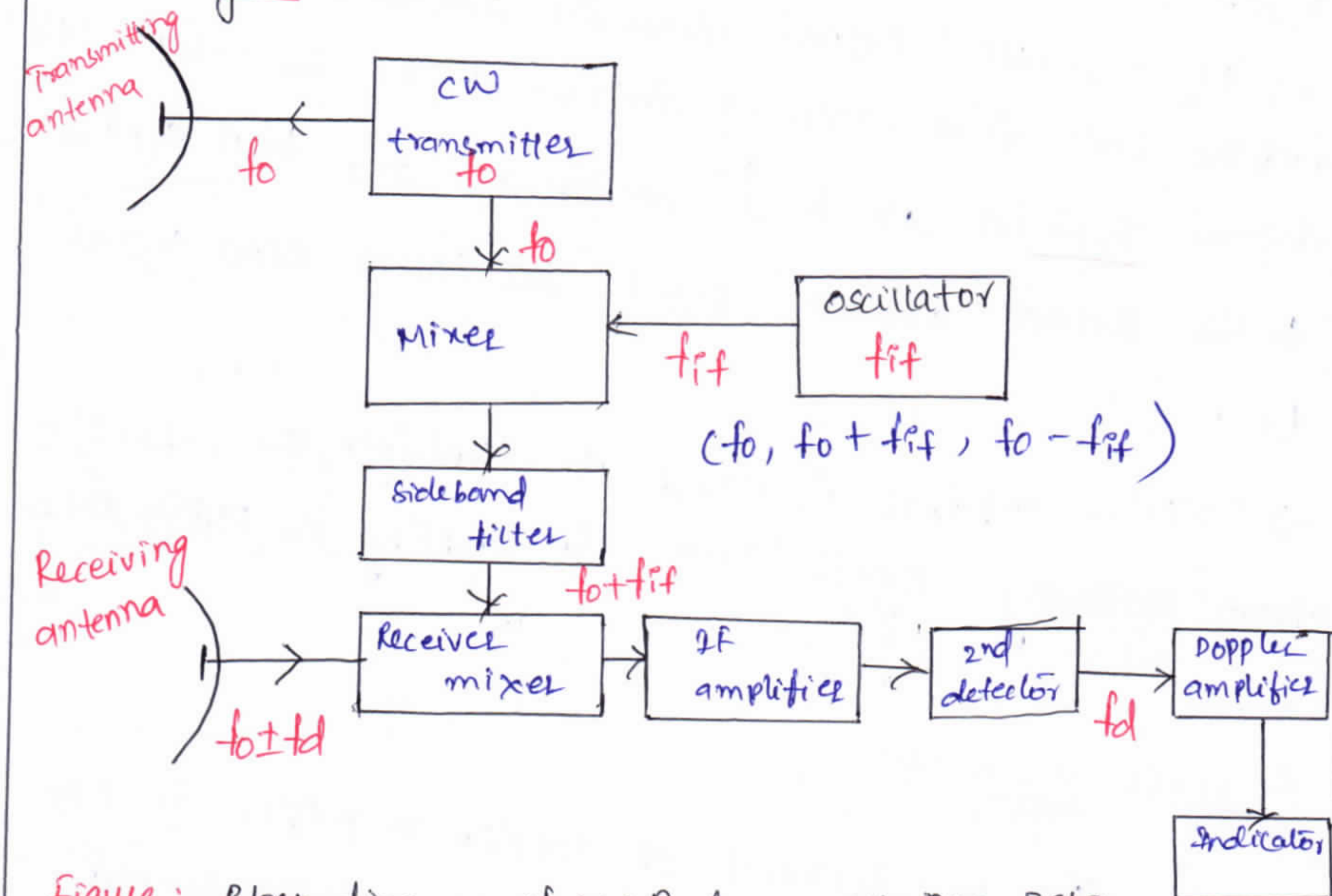


Figure: Block diagram of CW Radar with non-zero IF receiver.

→ CW Radar whose receiver operates with a non-zero IF block diagram is as shown in figure.

→ In this separate antennas are used for both transmission & reception.

→ Instead of the local oscillator determined in the conventional super heterodyne receiver, the local oscillator or reference signal is derived in this receiver from a part of transmitted signal mixed with a locally generated signal of intermediate freq f_{if} to generate the two side bands f_o+f_{if} & f_o-f_{if} along with f_o and higher harmonics.

→ from this signal one of the sideband is selected by passing it through narrowband filter as the reference signal.

→ The reference signal from the sideband filter is mixed with the signal from receiving antenna to get the intermediate signal $f_{if} \pm f_d$ which is amplified and then applied to the second detector to get the Doppler echo signal f_d.

→ Doppler amplifier is used to eliminate the echoes from stationary targets and to amplify the Doppler echo signal

Receiver Bandwidth:-

→ The requirement of Doppler amplifier in CW Radar is bandwidth. The Doppler amplifier should wide enough to receive the signal.

→ The factors which tend to spread to the CW signal energy over a finite band of frequencies are discussed in the following.

→ If the received waveform were a sine finite duration, its frequency spectrum would be a delta function and the receiver bandwidth would be infinitesimal.

→ But a sinewave of infinite duration an infinitesimal BW cannot occur in nature.

→ The echosignal is sinewave of finite duration rather than infinite in practical.

→ The frequency spectrum of a finite - duration sinewave has a shape of the form of $\frac{\sin \pi (f-f_0)\delta}{\pi (f-f_0)}$ f_0: freq. δ: duration of sinewave

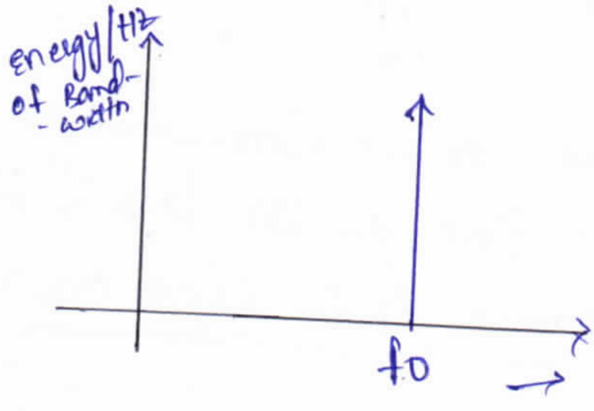


Fig: freq spectrum of CW oscillation of infinite duration

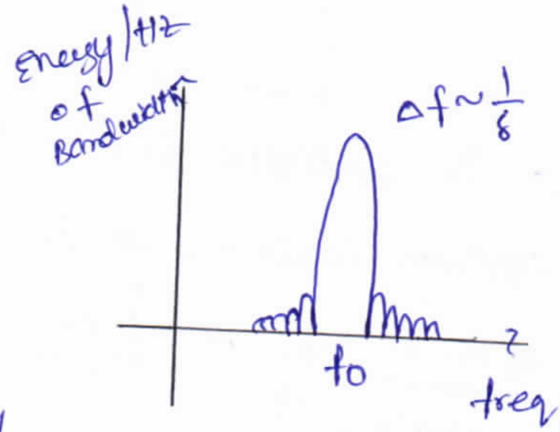


fig: finite duration

→ The above characteristic is approximated by the practical receivers.

→ In practical aspects the echo may not be a pure sine wave, so we need to broaden the bandwidth still further.

→ For CW radar assume that the duration of the received signal is given by $\delta = \theta_B / \theta_s$

where θ_B : antenna Beamwidth in degrees

θ_s : Antenna scanning rate in degree/sec.

Example:- If the antenna beamwidth and antenna scanning rate are 2° and 36°/sec (6 rpm) respectively.

→ Then the spread in spectrum of the received signal due to the finite time on the target is 18 Hz, which is the independent of the transmitted freq.

$$\delta = \theta_B / \theta_S = \frac{2^\circ}{36^\circ} = \frac{1}{18^\circ}$$

$$\boxed{BW = \frac{1}{\delta} = \frac{1}{1/18} = 18^\circ}$$

→ In addition to the spread of the received signal spectrum caused by the finite time on the target, the spectrum may be further wideband, if the target cross section fluctuates.

→ If a_r is the acceleration of the target with respect to the Radar, the signal will occupy a bandwidth

$$\Delta f_d = \left(\frac{2a_r}{\lambda}\right)^{1/2}$$

Ex:- If a_r is twice the accelaration of gravity, the receiver bandwidth $\approx$ 20 Hz.

when Radars wavelength (λ) = 10 cm.

Filter Bank in CW Radar receiver:-

→ A relative wide band of frequencies called as bank of narrow band filters are used to measure the freq of echo signal.

→ These filters are also used to improve the signal to noise ratio of the receiver. 2-

→ The bandwidth of each individual filter is wide enough to accept the signal energy, but not so wide as to introduce more noise than need be.

→ The center frequencies of the filters are staggered to cover the entire range of Doppler freq's.

→ By using the large number of filter's, the maximum loss will be reduced but it increases the probability of false alarm.

→ A bank of narrow band filters may be used after the detector in the video of the simple CW Radar instead of in the IF. The improvement in signal to noise ratio with a video filter bank is not as good as can be obtained with an IF filter bank but the ability to measure the magnitude of Doppler freq is still preserved.

→ The sign of the Doppler shift is lost with a video filter bank and it cannot be directly determined whether the Doppler freq corresponds to an approaching or to a receding target.

→ Because of foldover, a freq which lies to one side of the IF ~~amp~~ carrier appears, after detection at the same video frequency as one which lies an equal amount

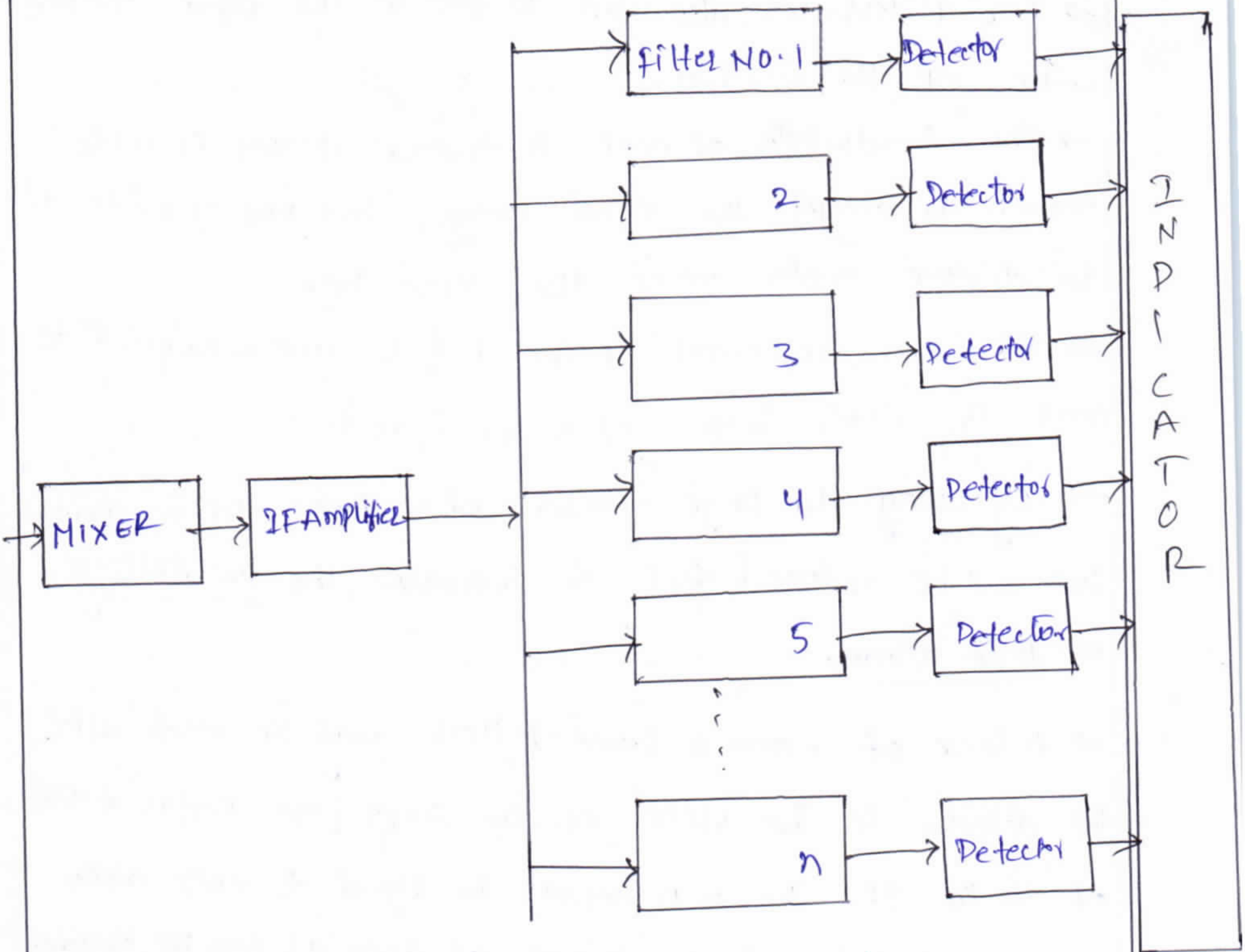


fig: Block diagram of IF Doppler filter bank

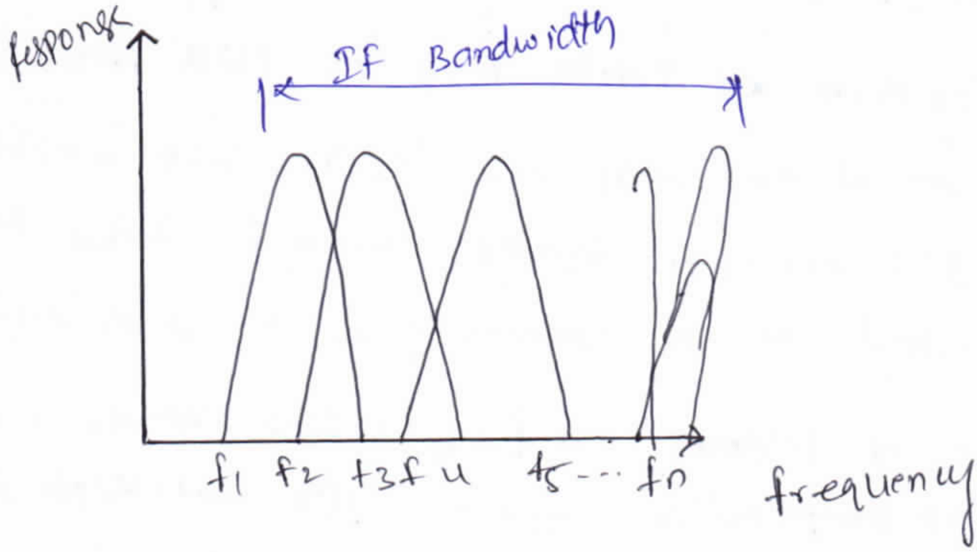


fig: freq-response characteristic of Doppler filter bank.

→ The complexity of the receiver is increased by the bank of overlapping Doppler filter whether in IF or video. The bank of Doppler filters may be replaced by a narrow band tunable filter, when the system requirements permit a time sharing of the Doppler freq range.

Measurement of Doppler direction with CW Radar
(or)
Sign of Radial velocity

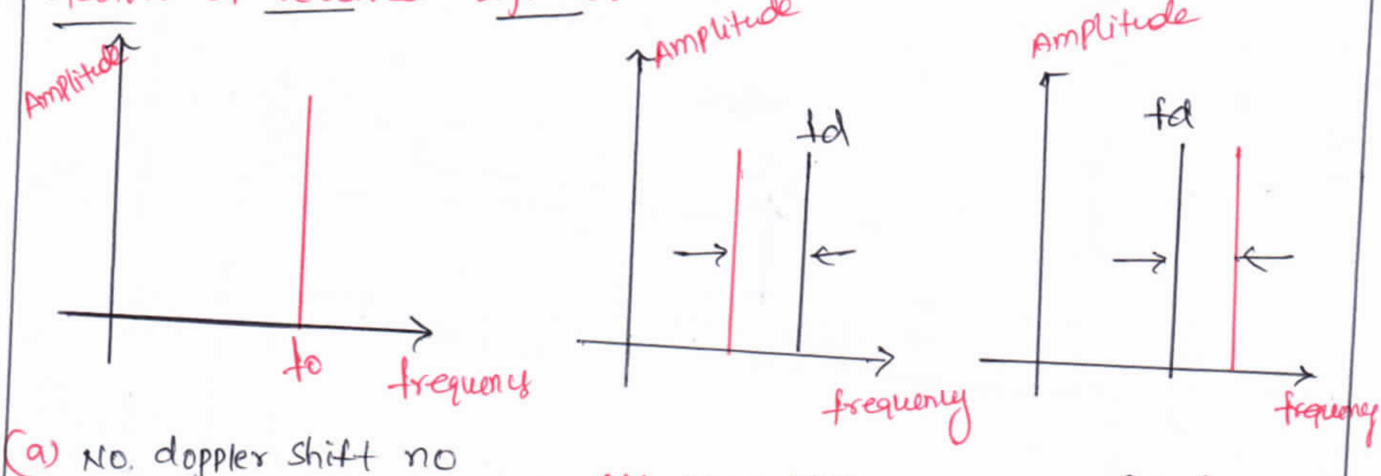
→ In some applications of CW Radar, it is desired to know whether the target is approaching or receding.

→ This might be determined with separate filters located on either side of the intermediate frequency.

→ If the echo signal frequency lies below the carrier, the target is receding.

→ If the echo signal frequency is greater than the carrier, the target is approaching, which is shown in fig below.

Spectra of received signal :-



(a) No doppler shift no relative target motion

(b) Approaching target

(c) Receding target

Applications of CW Radar :-

→ The simple, unmodulated cw radar is used to measure the relative velocity of a moving target.

→ cw radar is used to control the traffic lights.

→ used to regulate the toll booths, to count vehicles.

→ The principal advantage of a cw doppler radar over other methods of measuring speed is that there need not be any physical contact with the object whose speed is being measured.

→ High power cw radars for the detection of aircraft & other targets have been developed.

→ The cw radar is used for short or moderate ranges with simple equipment than a pulse radar.

→ cw radar is used as illuminator to track missiles.

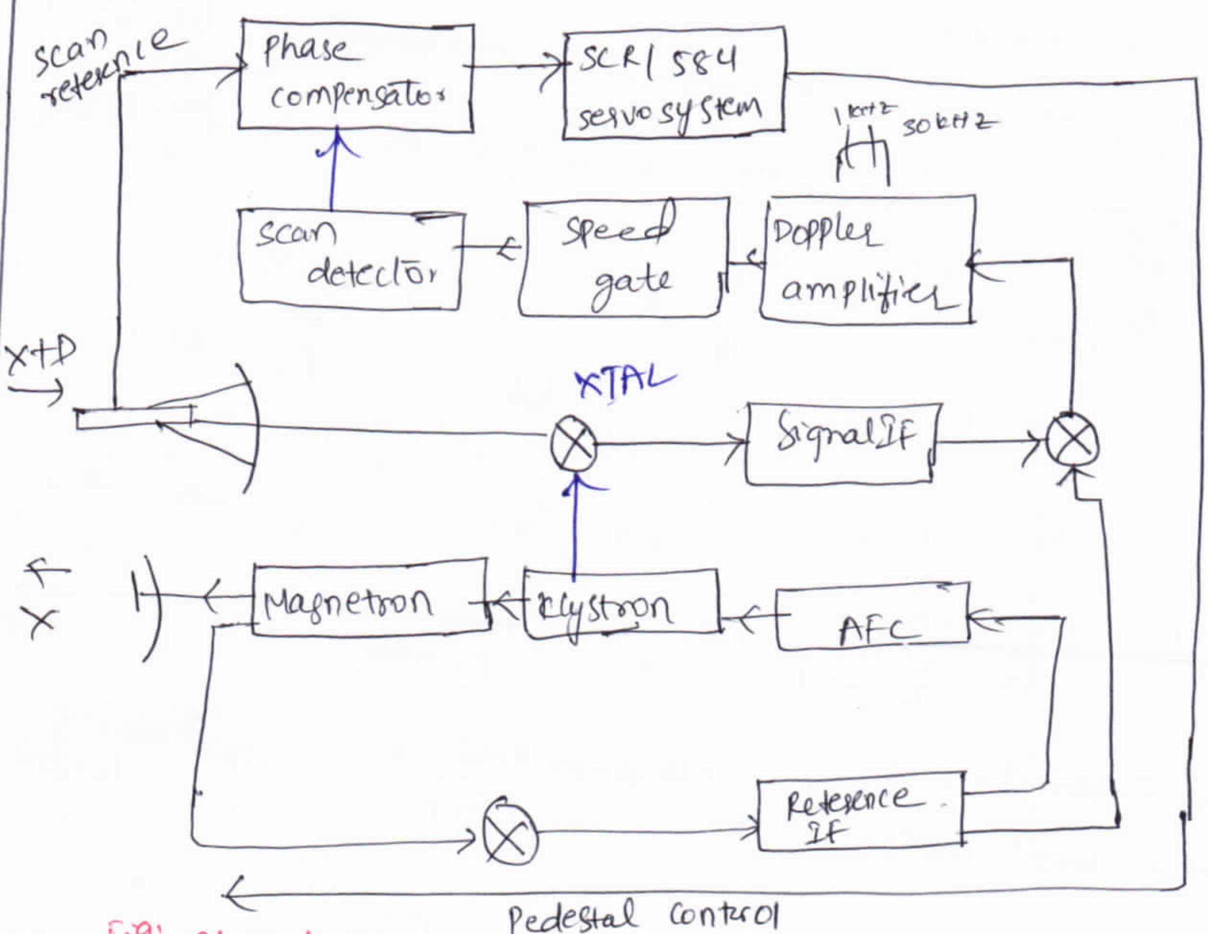


Fig: Block diagram of cw tracking - illuminator

→ CW radar cannot calulate range:-

2-

Unambiguous Range in CW radar:

consider a CW Radar with the following

→ waveform $s(t) = A \sin 2\pi f_0 t$

→ The received signal from moving target at range is $S_r(t) = A_r \sin 2\pi f_0 t - \phi$

where $\phi = 2\pi f_0 t$

But $R = \frac{CT}{2}$; $T = \frac{2R}{C}$ and $\lambda = \frac{c}{f_0}$

$\phi = \frac{2\pi f_0 2R}{c} = \frac{4\pi f_0 R}{c} = \frac{4\pi R}{\lambda}$

$\Rightarrow R = \frac{\lambda\phi}{4\pi} \rightarrow (1)$ where $c = 3\times10^8$ m/s

From the above eqn, it is observed that the maximum unambiguous range occurs when ϕ is max. ie., $\phi = 2\pi$.

∴ Even for relatively large radar wavelength Range is limited to impractical small values.

FREQUENCY MODULATED CW-RADAR

The inability of the simple CW-Radar to measure range is relatively narrow spectrum (bandwidth) of its transmitted waveform. Some sort of timing mark must be applied to a CW carrier if range is to be measured. The timing mark permits the time of transmission & the time of return to be recognised.

→ The sharper or more distinct the mark, the more accurate the measurement of transit time. But the more ~~are~~ distinct the timing mark, the broader will be the transmitted spectrum. This follows the properties of the fourier transform.

→ ∴ A finite of a CW txn can be broadened by the application of modulation, either amplitude, frequency or Phase.

→ A widely used technique to broaden the spectrum of CW radar is to freq-modulate the carrier. The timing mark is the changing frequency. The transit time is proportional to the difference in freq between the echo signal & the transmitter signal.

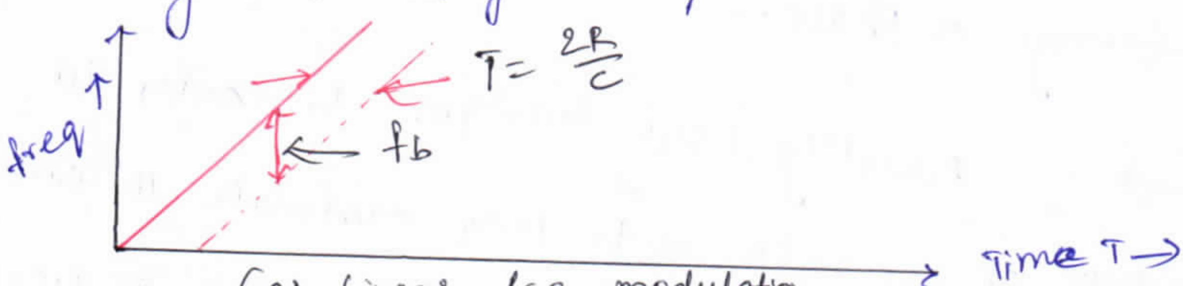
→ The grater the transmitter freq deviation in a given time interval, the more accurate the measurement of the transit time & the greater will be trnl spectrum.

Range and Doppler measurement :-

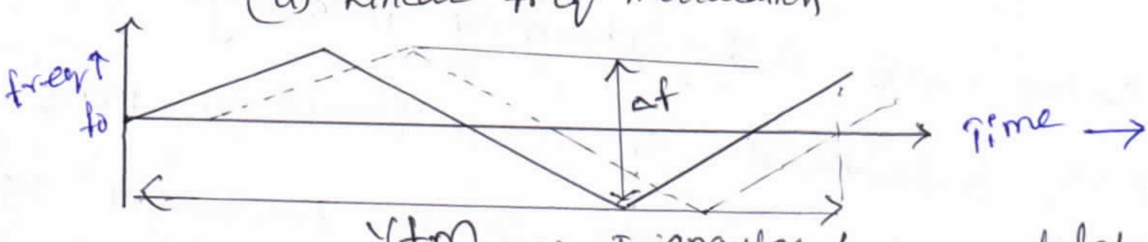
In the freq modulated CW Radar, the txr frequency is changed as a function of time in a known manner. Assume that the txr freq with time as shown by solid line in figure a.

→ If there is a reflecting object at a distance R, an echo signal will return after a time $T = \frac{2R}{c}$. The dashed line in the figure represents the echo signal. If the echo signal is heterodyned with a portion of the transmitter signal in a non-linear element such as a diode, a beat note f_b will be produced.

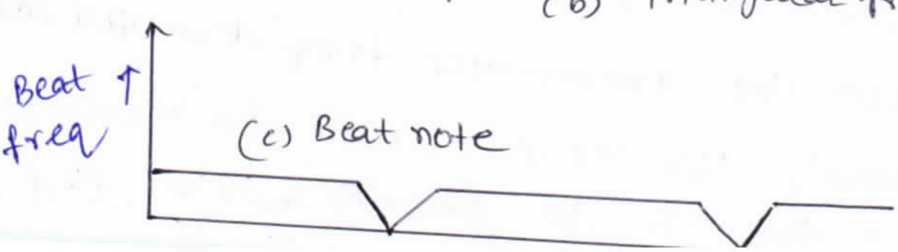
→ If there is no doppler shift, the beat note (difference freq) is a measure of the targets range and $f_b = f_r$, where f_r is the beat freq due only to the targets range.



(a) Linear freq modulation



(b) Triangular freq modulation



(c) Beat note

→ The rate of change of carrier freq is fo, the beat frequency is

$$f_r = f_0 T = \frac{2R}{c} f_0 \rightarrow (1)$$

→ In any Practical cw radar, the frequency cannot be continuously changed in one direction only. periodicity in modulation is necessary, as in triangular frequeny modulation waveform shown in fig b. 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 c for triangular modulation.

→ The beat note is of constant freq except at the turn around region. If the freq is modulated at a rate fm, over a range Δf, the beat frequeny is

$$f_r = \frac{2R}{c} \cdot 2f_m \cdot \Delta f$$

$$f_r = \frac{4Rf_m \Delta f}{c} \quad (2)$$

∴ The measurement of beat frequency determines the range R.

Block diagram of FM-CW RADAR

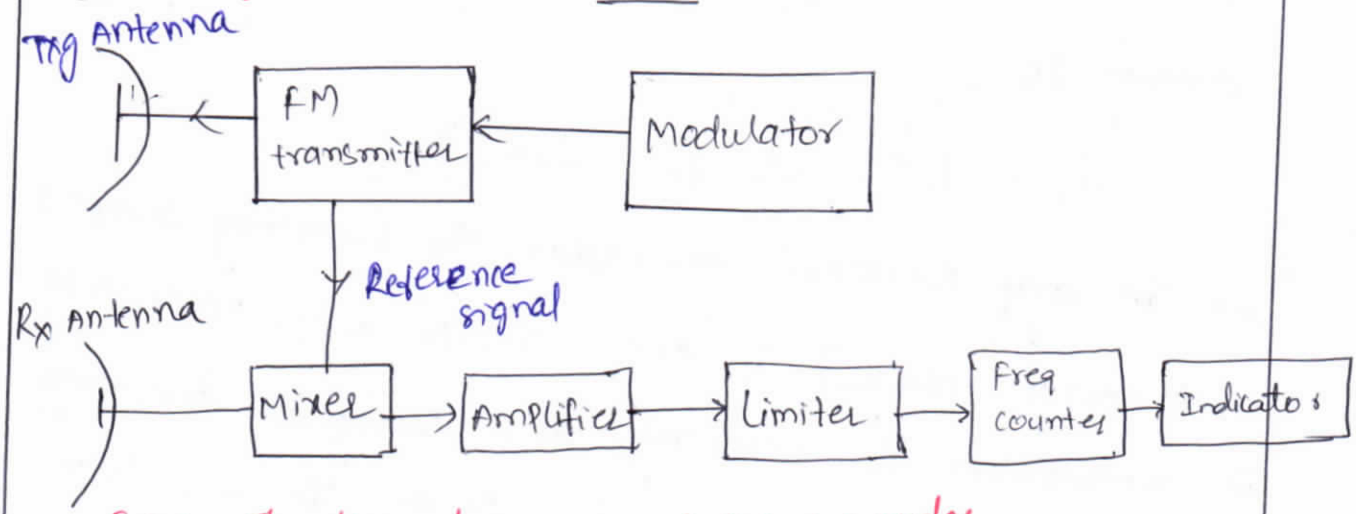


Fig:- The block diagram of FM-CW radar.

Assuming target is stationary:-

A position 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 direct connection.

→ Ideally, the isolation between tx g 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. The beat freq is amplified and limited to remove any amplitude fluctuations. The freq of the amplitude - limited beat note is measured with a cycle - counting frequency meter calibrated in distance.

If the target is not stationary :-

A doppler frequency shift will be superimposed on the FM range beat note and an erroneous range measurement results. The doppler freq shift causes the frequency-time plot of the echo signal to be shifted up or down as shown in fig a.

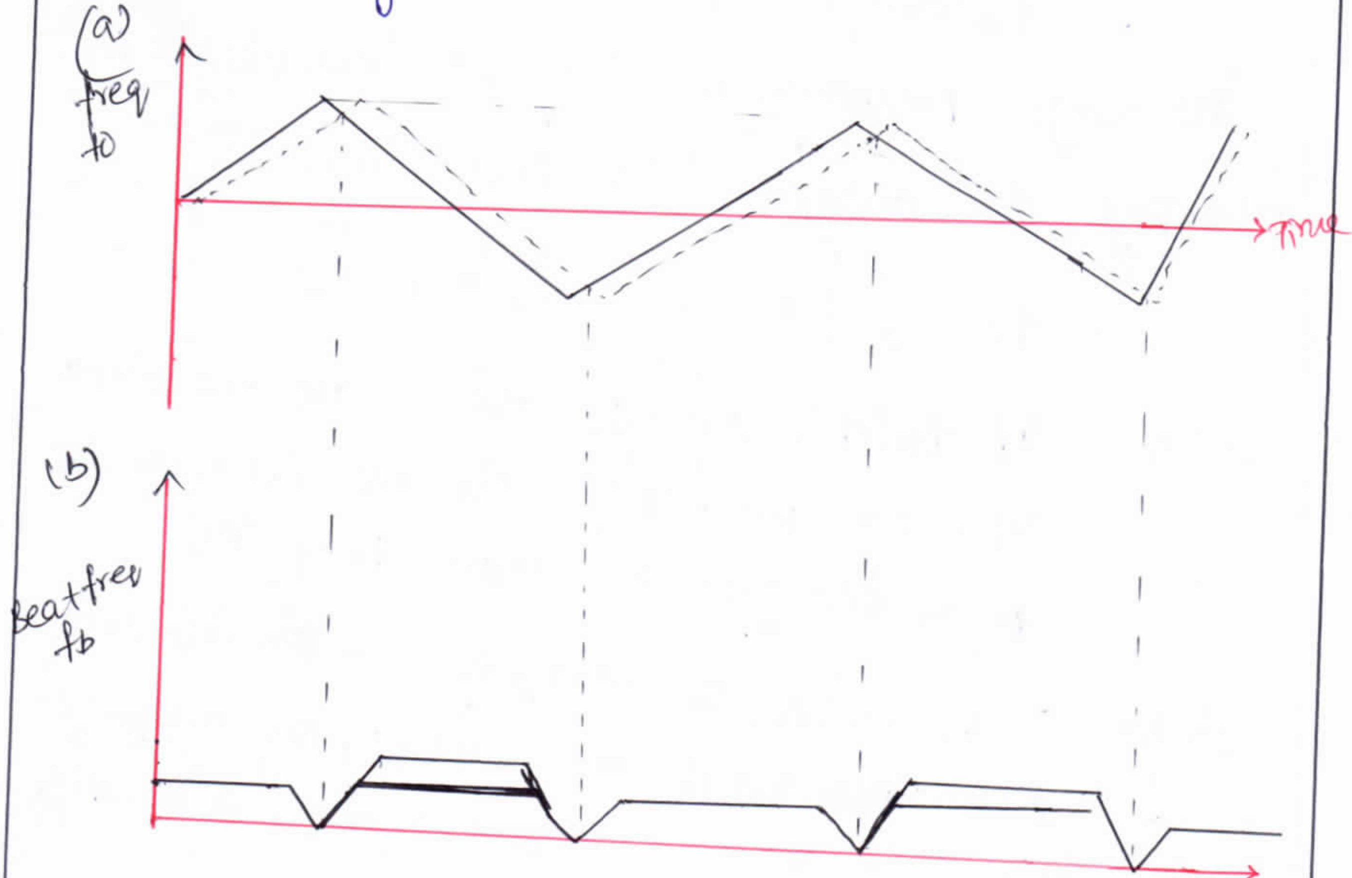


Fig: Freq-time relationships in FMCW radar when the received signal is shifted in frequency by the doppler effect.

On one portion of the frequency modulation cycle the beat freq (fib b) is increased by the doppler shift while on the other portion it is decreased.

If the target is approaching the radar, the beat freq f_b (up) produced during the increasing or up portion of the FM cycle will be the difference between the beat freq due to the range f_r and the

the doppler frequency shift fd

$$f_d(up) = f_r - f_d$$

Similarly on the decreasing portion, the beat frequency f_b(down) is the sum of the two.

$$f_b(down) = f_r + f_d$$

The range frequency f_r may be extracted by measuring the average beat freq i.e.,

$$f_r = \frac{1}{2}\left[f_b(up) + f_b(down)\right]$$

$f_r > f_d$ If $f_b(up)$ and $f_b(down)$ are measured separately, one half the difference between the freq's will yeild the doppler freq ie,

$f_r < f_d$: The roles of the averaging and the difference freq measurements are reversed, the averaging meter will measure doppler velocity, & the diff meter range.

If it is not known that the roles of the meters are reversed because of a change in the inequality sign between f_r & f_d, an incorrect interpretation of the measurement will result.

when morethan one target is present:-

The mixer output will contain morethan one diff freq. If the system is linear, there will be a freq component corresponding to each target.

In principle the range to each target may be determined by measuring the individual frequency the individual frequency components and applying equation

$$f_r = \frac{4Rf_m \Delta f}{c} \text{ to each.}$$

To measure the individual freq's, they must be separated from one another.

FM-CW Altimeter:-

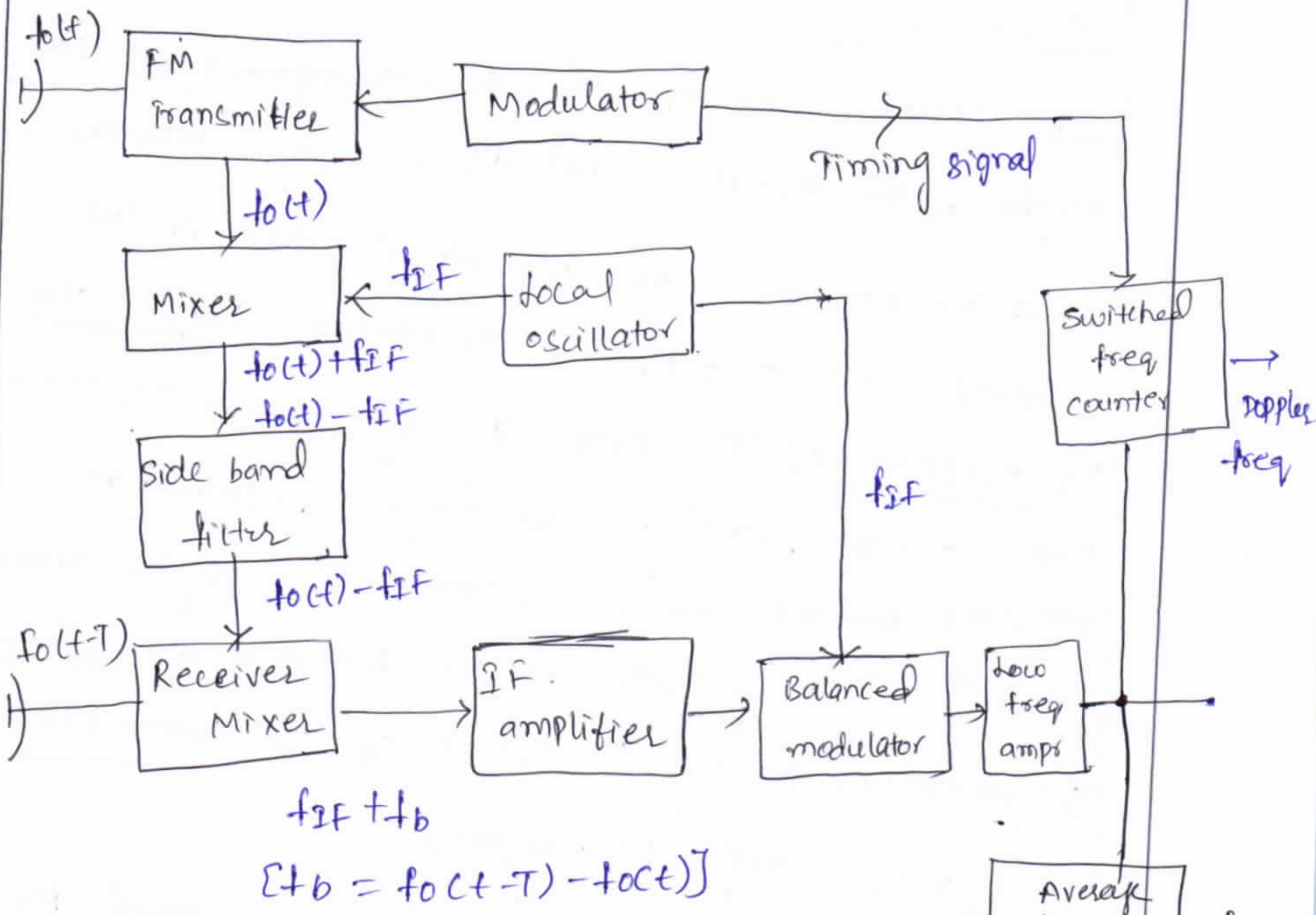
→ FM-CW was applied to measurement of the height of the ionosphere and as an aircraft altimeter.

→ The FM-CW radar principle is used in the aircraft radio altimeter to measure height above the surface of the earth. The large backscatter cross-secton and the relatively short ranges required of altimeters permit low transmitter power & low antenna gain. Since the relative motion between the aircraft & ground is small, the effect of the doppler freq shift may usually be neglected.

The band from 4.2 to 4.4 GHz is reserved for radio altimeters, although they have in the past operated at UHF. The transmitter power is relatively low & can be obtained from a CW magnetron, a back-ward wave oscillator, or a reflex klystron, but these have been replaced by the solid state transmitter.

A block diagram of the FM-CW radar with a side band super heterodyne receiver is shown in figure.

A portion of the freq modulated signal is applied to a mixer along with the oscillator signal. The selection of local oscillator freq is a bit different from that in the usual super heterodyne receiver.



Block diagram of FM-CW Altimeter

The local oscillator frequency f_{IF} should be same as the intermediate freq (IF) used in the receiver, where as in the conventional super heterodyne the local oscillator freq is of the same order of magnitude as the RF signal.

The output of the mixer consists of the varying transmitter frequency $f_0(t)$ plus two side band frequencies, one on either side of $f_0(t)$ and separated from $f_0(t)$ by the local oscillator freq f_{IF}. The filter selects the lower sideband $f_0(t) - f_{IF}$ and rejects the carrier ie the upper side band.

→ The side band that is passed by the filter is modulated in the same fashion as the transmitted signal. The side band filter must have sufficient bandwidth to pass the modulation, but not the carrier or other sideband. The filtered sideband serves the function of the local oscillator.

When an echo signal is present, the output of the receiver mixer is an IF signal of freq $f_{IF} + f_b$ where f_b is composed of the range freq f_r ie the doppler velocity freq f_d. The IF signals is amplified and applied to the balanced detector along with the local oscillator signal f_{IF}.

The o/p of the detector contains the beat frequency which is amplified to a level where it can actuate the freq measuring circuits.

Multiple frequency CW Radar:-

The multiple frequency CW Radar is used to measure the accurate range. The transmitted waveform is assumed to consist of two continuous sinewaves of frequency f_1 & f_2 separated by an amount Δf. Let the amplitudes of all signals are equal to unity.

The voltage waveforms of the two components of the transmitted signal V_{1r} & V_{2r}, may be written as

$$V_{1r} = \sin(2\pi f_1 t + \phi_1)$$

$$V_{2r} = \sin(2\pi f_2 t + \phi_2)$$

where ϕ_1 & ϕ_2 are arbitrary constant phase angles.

The echo signal is shifted in frequency by the doppler effect. The form of the doppler shifted signals at each of the 2 frequencies f_1 & f_2 may be written as

$$V_{1R} = \sin\left(\left|2\pi(f_1 \pm f_{d1})t - \frac{4\pi f_1 R_0}{c} + \phi_1\right|\right)$$

$$V_{2R} = \sin\left|2\pi(f_2 \pm f_{d2})t - \frac{4\pi f_2 R_0}{c} + \phi_2\right|$$

where R_0 = Range to target at a particular time.

t = to (range that would be measured if target were not moving).

f_{d1} = Doppler freq shift associated with freq f_1

f_{d2} = Doppler " " " f_2.

Since the two RF freq's f_1 & f_2 are approximately the same, the doppler freq shifts f_{d1} & f_{d2} are approximately equal to one another.

The receiver separates the two components of the echo signal E_e heterodynes each received signal component with the corresponding transmitted waveform and extracts the two doppler frequency components given below.

$$v_{1D} = \sin\left(\pm 2\pi f_d t - \frac{4\pi f_1 R_0}{c}\right)$$

$$v_{2D} = \sin\left(\pm 2\pi f_d t - \frac{4\pi f_2 R_0}{c}\right)$$

The phase difference between two component is

$$\Delta\phi = \frac{4\pi (f_2 - f_1) R_0}{c} = \frac{4\pi \Delta f R_0}{c}$$

Hence

$$R_0 = \frac{c\Delta\phi}{4\pi\Delta f}$$

A large difference in frequency between the two transmitted signals improves the accuracy of the range measurement since large Δf means a proportionately large change in $\Delta\phi$ for a given range.

However, there is a limit to the value of Δf, since $\Delta\phi$ cannot be greater than 2π radians if the range is to remain unambiguous. The max unambiguous range R_{unamb} is

$$R_{unamb} = \frac{c}{2\Delta f}$$

The two freq CW Radar is essentially single target radar since only one phase diff can be measured at a time.

Advantages of FM-CW Radar:-

→ Range can be measured by simple broadening the simple broadening the spectrum of CW radar i.e. frequency modulating carrier.

→ Sinusoidal freq is easily obtained than linear modulation.

→ Synchronisation is not necessary in FM-CW radar as it is required in multiple FMCW.

→ FM-CW radar requires a single freq for measuring the range where as multiple FCW radar require two different freq's of large difference.

for FM-CW radar

$$R = \frac{c\Delta\phi}{4\pi f_0}$$

For multiple freq CW radar

$$R = \frac{c\Delta\phi}{4\pi\Delta f} \quad ; \Delta f = f_2 - f_1$$

Disadvantages:-

→ The FMCW radar is used for only single targets

→ The accuracy of range measurement of FMCW radar is less compared to multiple freq CW radar it is deals with single freq.

→ when the freq modulated signal is non-uniform or if the mixer is not operating in the linear region measurement of range is more complicated.