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INDUS UNIVERSITY

Radar and Navigation(EC0607)
Unit-2
B.Tech (Electronics and Communication)
Semester-VI

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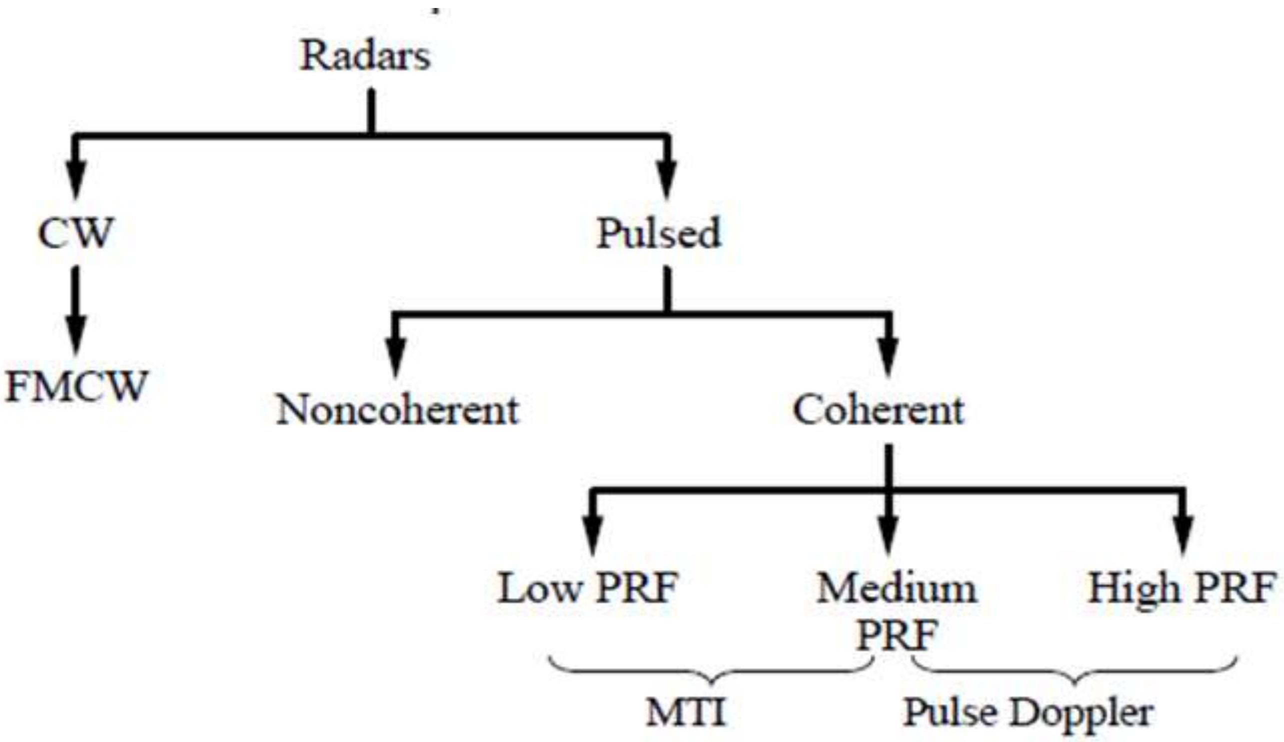
Academic Year 2019-2020

CW & FM CW Radar and
MTI Radar Pulse Doppler Radar

Classification by Waveform



CW- Continuous wave
FMCW- Frequency modulated continuous wave
PRF- Pulse repetition frequency
MTI- Moving target indicator

THE DOPPLER EFFECT

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

- The radar transmitter may be operated continuously rather than pulsed if it is possible to separate the strong transmitted signal from the weak echo

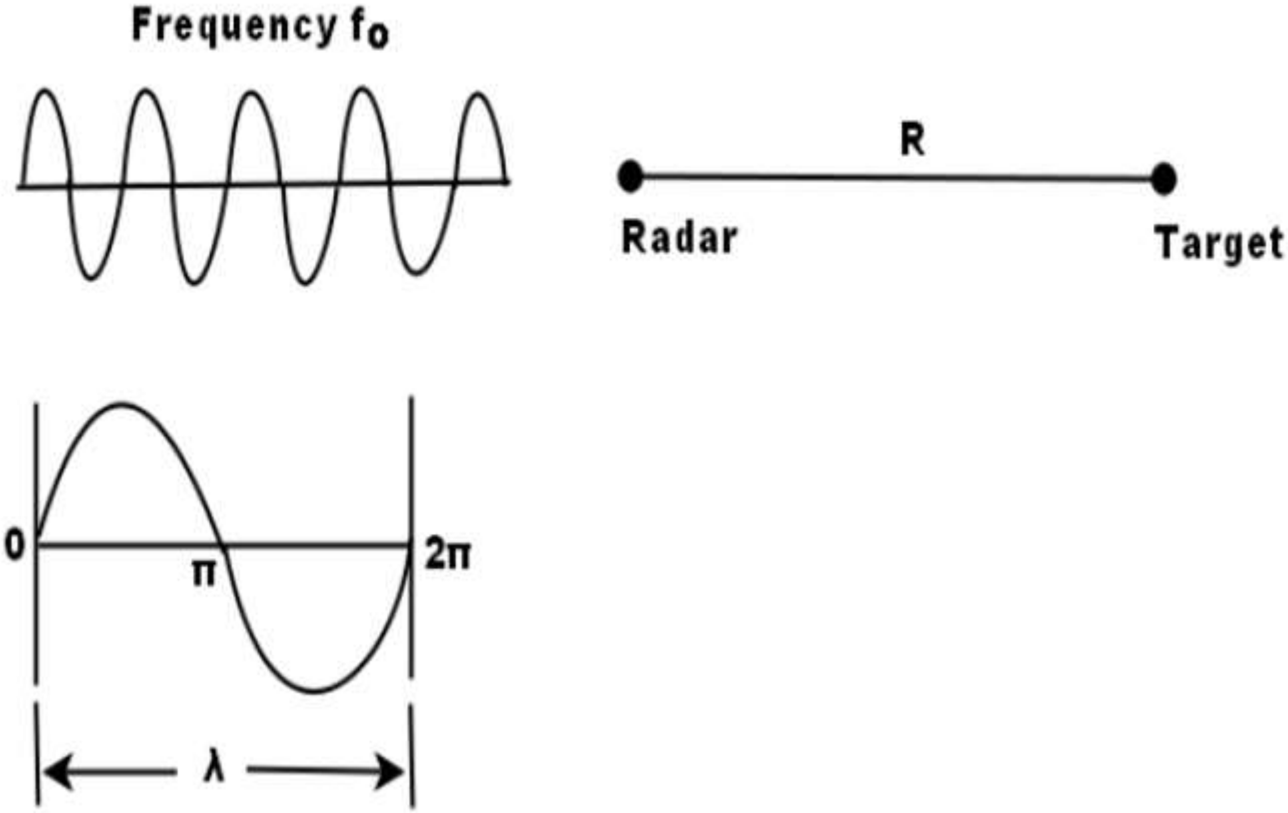
- The received echo-signal power is considerably smaller than the transmitter power (as low as 10−18 times the transmitter power - or sometimes even less).Separate antennas for transmission and reception help isolate the weak echo from the strong leakage signal, but this isolation is usually not sufficient.

- 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 what is known as the Doppler effect.

It is well known in the field of optics and acoustics that if there is relative motion between the source of a signal and the observer of the signal, along the line joining the two, then an apparent shift in frequency will result. This is the Doppler effect and is the basis of CW (Continuous Wave) radars.

Consider Fig. in which a CW radar and a target are placed at a distance of R from each other. The target is moving with a speed *Vr* relative to the radar and along the line joining the radar and the target (also known as the line-of-sight - LOS). Note that the transmitted signal is not in the form of a train of pulses but a continuous wave with frequency *fo*. Let the total number of wavelengths (given by λ) contained in the to-and -fro path between the radar and the target be denoted by n. Then,

$$n = 2R/\lambda$$



The Doppler effect

One wavelength corresponds to an angular excursion of 2π radians. Thus, the total angular excursion φ made by the electromagnetic wave during its transit to the target and back to the radar is

$$\varphi = 2R/\lambda.2\pi = 4\pi R/\lambda$$

When the target is in motion, both R and φ are changing. Now a change in φ with respect to time is equal to an angular frequency. This, in fact, is the Doppler angular frequency *Wd*,

$$W_d = 2\pi f_d = d\varphi/dt = 4\pi/\lambda . dR/dt = 4\pi V_r/\lambda$$

From which we get

$$f_d = 2V_r/\lambda = 2V_r f_o/c$$

Where,

f_d = Doppler frequency shift, in Hz

c = velocity of propagation = 3×10^8 *m/s*

V_r = relative velocity of the target with respect to the radar along the line-of-sight.

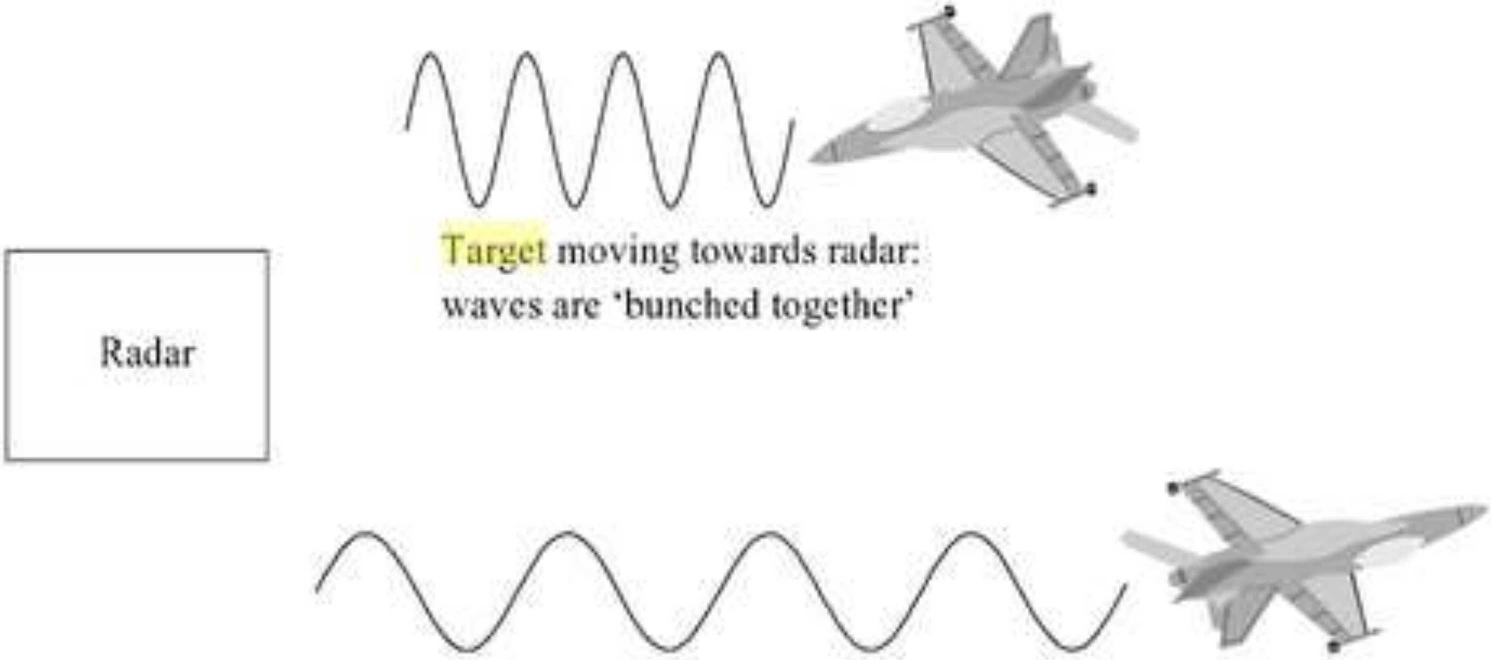
For a stationary radar and a moving target the relative velocity may be written as

$$V_r = V \cos \vartheta$$

Where, V is the target speed and ϑ is the angle made by the target velocity vector with the LOS. When $\vartheta = 0$, the Doppler frequency is a maximum.

The Doppler frequency is zero when the trajectory is perpendicular to the radar-target line-of-sight (that is, $\vartheta = \pi/2 = 90$ degree).

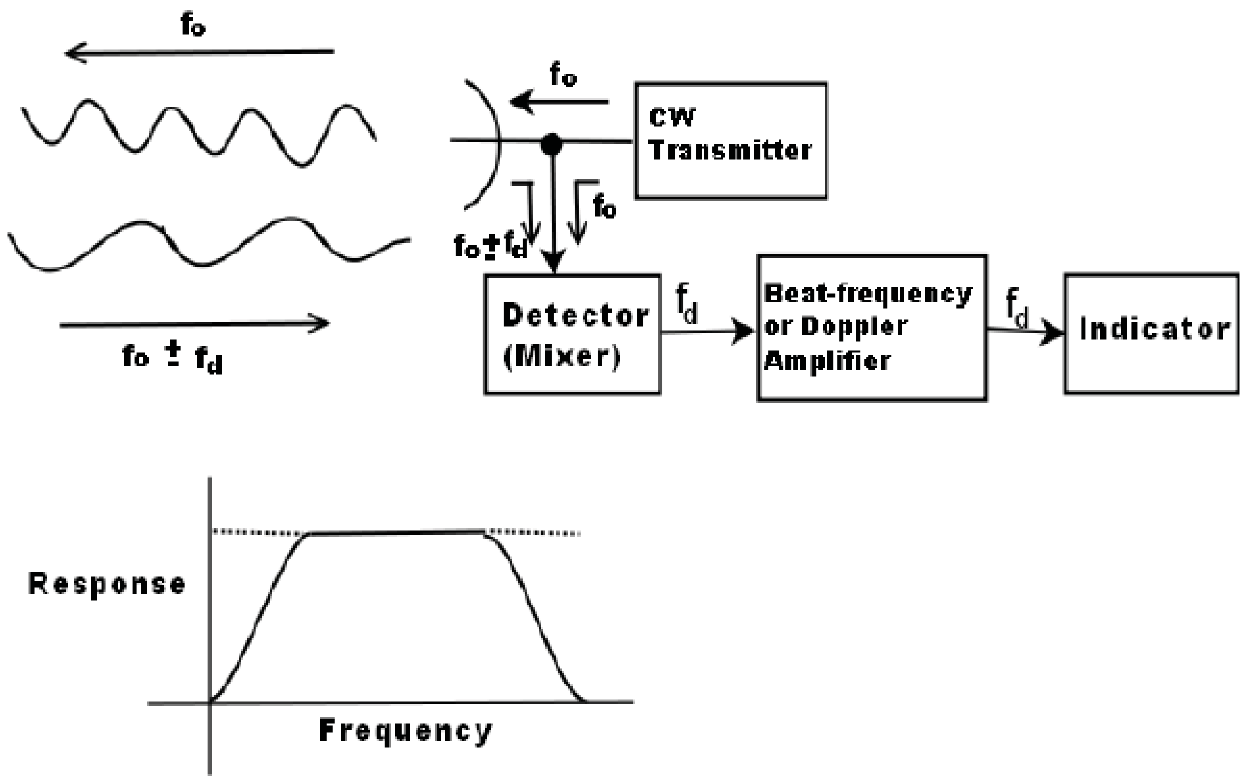
The plus sign applies if the distance between the radar and the target is decreasing (that is, **an approaching target)** and the minus sign applies when this distance is increasing (that is, a **receding target**).



Target moving towards radar:
waves are 'bunched together'

Target moving away from radar:
waves are 'stretched out'

Block diagram of CW radar

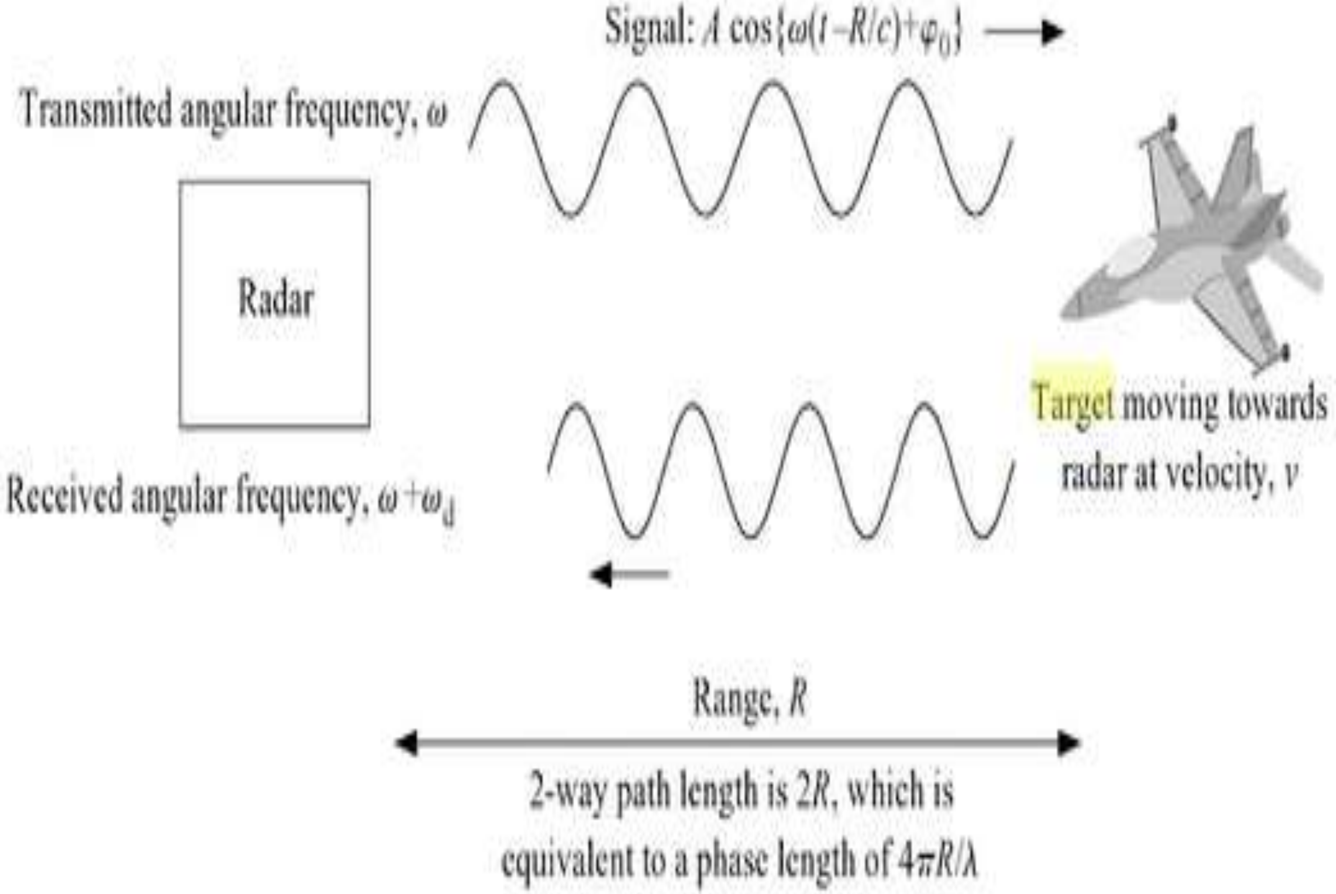


Operation of CW radar

- The transmitter generates a continuous oscillation of frequency f0, which is radiated by the antenna.

- 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.

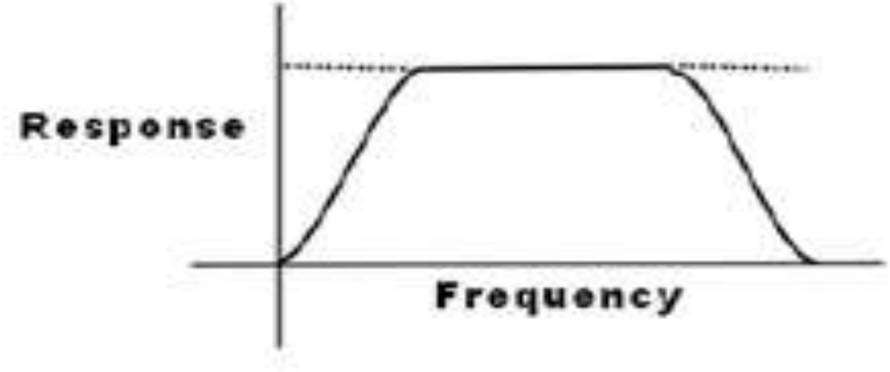
- If the target is in motion with a velocity Vr relative to the radar, the received signal frequency will be shifted from the transmitted signal frequency f0 by an amount ±fd.


Signal: $A\cos\{\omega(t-R/c)+\varphi_0\}$
Transmitted angular frequency, ω
Radar
Target moving towards radar at velocity, v
Received angular frequency, $\omega+\omega_d$
Range, R
2-way path length is $2R$, which is equivalent to a phase length of $4\pi R/\lambda$

The plus sign applies if the distance between the radar and the target is decreasing (that is, **an approaching target)** and the minus sign applies when this distance is increasing (that is, a **receding target**).

- The received echo signal at a frequency *f0 ± fd enters the radar via the antenna and is hetero*dyned in the detector (mixer) with a portion of the transmitted signal *f0 to* produce a doppler beat note of frequency *fd. However, the sign of fd is lost* in this process.

- The purpose of the doppler amplifier (beat frequency amplifier) is to eliminate echoes from stationary targets and to amplify the Doppler echo signal to a level where it can be shown on indicating device.



Its frequency response characteristics is as shown in Fig. The low-frequency cutoff must be high enough to reject the d-c component caused by stationary targets, and yet it must be low enough to pass the smallest doppler frequency expected.

Cont…

- Sometimes both conditions cannot be met simultaneously and a compromise is necessary. The doppler cutoff frequency (on the higher side) is usually selected to pass the highest doppler frequency expected.

- The indicator could be a pair of earphones or a frequency meter. Earphones are used when an exact knowledge of the doppler frequency is not required.

The ear then acts as a selective (narrow) band pass filter with a pass band of the order of 50 Hz centered about the signal frequency.

This is of use for subsonic aircraft targets when the transmitter frequency falls in the middle range of the microwave frequency region. (A *subsonic aircraft* is an *aircraft* with a maximum speed less than the speed of sound .All current civil *aircraft*, including airliners, helicopters and airships, as well as many military types, are *subsonic)*

Cont…

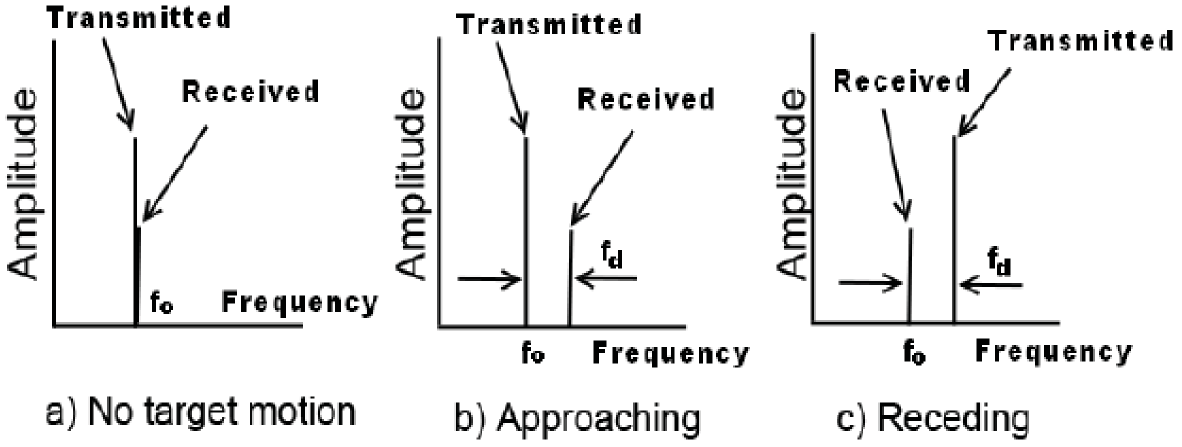
- If audio detection is desired for those combination of target velocity and transmitter frequency which do not result in audible doppler frequencies, the doppler signal could be heterodyned to the audible range.

- The doppler frequency can be detected and measured by conventional frequency meters, usually one that counts cycles.

Sign of Radial velocity

- In many applications of CW radar it is of interest to know if the target is approaching or receding(Away). This might be determined with separate filters located on either side of the intermediate frequency.

- If the echo-signal frequency lies below the transmitted frequency (carrier), then the target is receding; whereas if the echo frequency is greater that the transmitted frequency (carrier), then the target is approaching.



a) No target motion b) Approaching c) Receding

Cont..

- However, the doppler-frequency spectrum "**<u>folds over"</u>** in the video because of the action of the detector, and hence the information about whether the doppler shift is positive or negative is lost.

- But it is possible to determine its sign from a technique borrowed from single-sideband communication.

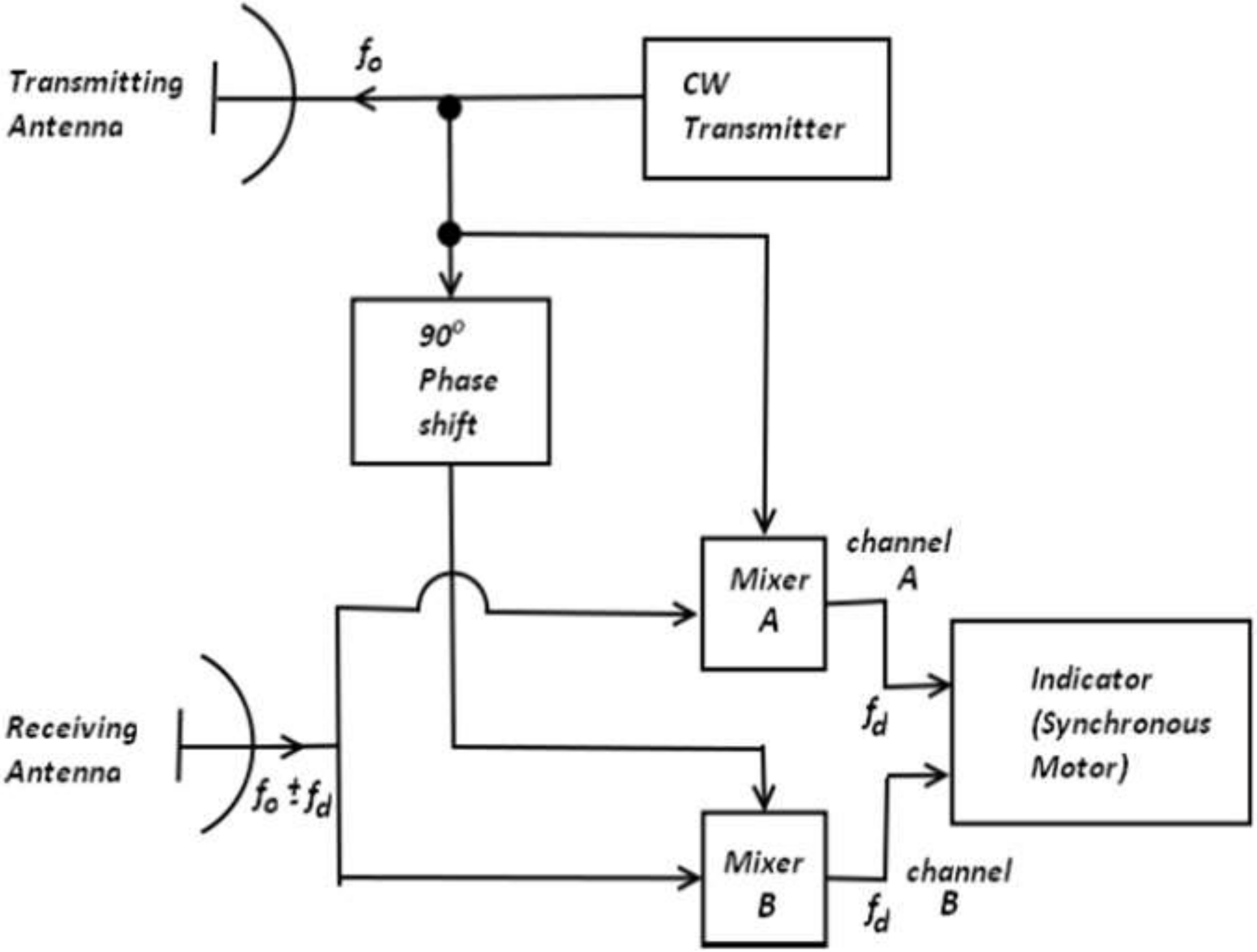
- If the transmitter signal is given by,

$$E_t = E_o cos\ w_o t$$

- The echo signal from the moving target will be,

$$E_r = K_1 E_0 cos\ [(w_o + w_d)t + \phi]$$

- *E_0 = amplitude of the transmitted signal*
- *K_1 = a constant determined from the radar equation* representing the reduction in power of the echo signal
- *w_o = angular frequency of transmitted signal, rad/sec*
- *w_d = Doppler angular frequency shift, rad/sec*
- *φ = a constant phase shift, which depends upon the range* of initial detection (i.e., distance between the radar and the target)



Determination of the sign of the Doppler frequency

- The sign of the doppler frequency, and therefore the direction of target motion, may be found by splitting the received signal into two channels as shown in Fig.

- In channel A the signal is processed as in a simple CW radar. The receiver signal and a portion of the transmitter signal heterodyne in the detector (mixer) to yield a difference signal,

$$E_A = K_2 E_0 cos(\pm w_d t + \phi)$$

- The channel B has *π/2* phase delay introduced in the reference signal. The output of the channel B mixer is,

$$E_B = K_2 E_0 \cos(\pm w_d t + \phi + \frac{\pi}{2})$$

- If the target is approaching (positive Doppler),the outputs from the two channels are,

$$E_A = K_2 E_0 \cos(w_d t + \phi)$$

$$E_B = K_2 E_0 \cos(w_d t + \phi + \frac{\pi}{2})$$

- on the other hand, if the target is receding (negative Doppler),

$$E_A(-) = K_2 E_0 \cos(w_d t + \phi)$$

$$E_B(-) = K_2 E_0 \cos(w_d t + \phi + \frac{\pi}{2})$$

Cont…

- The sign of *wd and the direction of the target's motion may be determined* according to whether the output of channel B leads or lags the output of channel A

- One method of determining the relative phase relationship between the two channels is to apply the outputs of the two channels to a synchronous two-phase motor

- The direction of the motor's rotation is an indication of the direction of the target's motion

Isolation Between Transmitter and Receiver

- A single antenna serves the purpose of both transmission and reception in the simple CW radar described above. Though, in principle, a single antenna is sufficient as the necessary isolation is obtained by the separation in frequency (as a result of Doppler effect), in practice there is considerable transmitter leakage
- But this leakage is beneficial too since it supplies the reference frequency necessary for the detection of the doppler frequency shift. Otherwise a sample of the transmitted signal must be made available at the receiver

- However, there are two reasons why the amount of transmitter leakage power should be kept at a low value

- **The maximum power the receiver input circuitry can withstand, without being physically damaged is quite low**

- ***The transmitter noise which enters the receiver from the transmitter*** **reduces receiver sensitivity**

- The amount of isolation required depends on the transmitter power and the accompanying transmitter noise as well as sensitivity of the receiver
- If the safe value of power which might be applied to a receiver were 10 mw and if the transmitter power were 1 kw, the isolation between transmitter and receiver must be at least 50 dB

CW Radar Disadvantages

- The amplitude of the signal that can be transmitted by a CW radar is dependent on the isolation that can be achieved between the transmitter and the receiver since the transmitter noise that finds its way into the receiver limits the receiver sensitivity

- This limits the maximum range of the radar. The pulse radar has no similar limitations to its maximum range because the transmitter is not operative when the receiver is turned on

- One of the greatest shortcomings of the simple CW radar is its inability to obtain a measurement of range. This limitation can be overcome by modulating the CW carrier, as in the frequency-modulated radar

FM CW Radar

- The primary functions of a radar is to measure the range to an object. This is not possible in a CW radar since there is no way of determining the time after which a particular part of the transmitted waveform comes back in the form of an echo

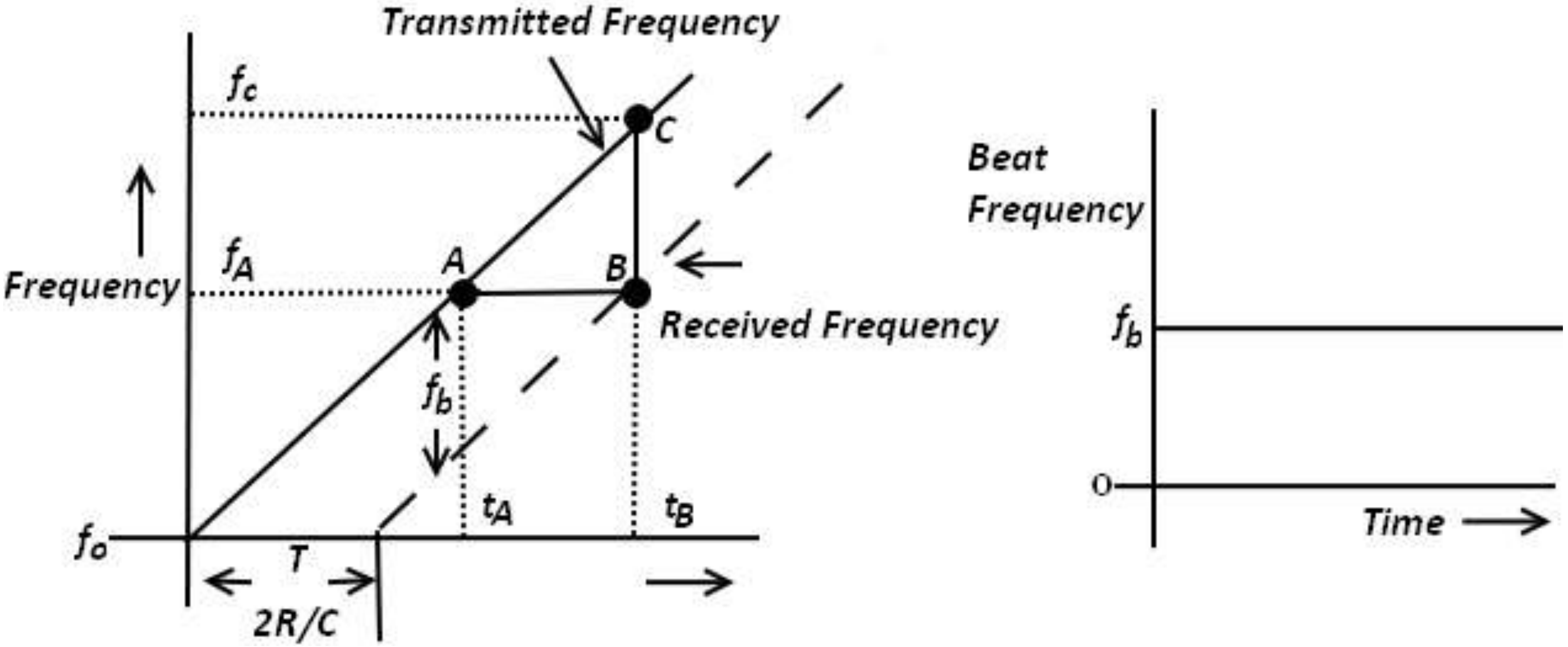
- Because one part of a continuous signal waveform can not be distinguished from another

- In pulse radars there is considerable gap between one pulse and the next and so it was easy to identify a pulse with its echo. Recall that even there this identification became difficult when the gap between pulses was small (or the target was at a large distance), giving rise to second-time-around echoes

- In CW radars an exactly similar effect, though of a more serious nature, occurs thus making it impossible to identify echo waveform with its original transmitted waveform. This is the reason why an ordinary radar is incapable of measuring range to an object

- **<u>A solution to this problem can be obtained by using frequency modulation</u>**
- A simple way to do this is to vary the transmitted frequency over a certain range
- Radars which use this mode of operation are called frequency modulated continuous wave (FM-CW) radars

Figure: Linear frequency modulation in FM-CW radars



- In FM-CW, the transmitted signal frequency is varied as a function of time. Suppose it increases linearly with time, then we will have a variation as shown in Fig
- Here, *fb* is the beat frequency which is defined as the **difference between the transmitted and received frequency.** Since the beat (or difference frequency) is caused only by the target's range (as the target is stationary) it is also denoted by *fr*
- Consider the transmitter CW signal at time *tA*, having frequency *fa*. This signal hits the stationary target and comes back to the radar at time *tB* when the frequency of the transmitted signal would have increased to *fc*
- Hence, the increase in the transmitted frequency during the to-and-fro transit time *T* of a signal is (*fc* − *fa*) and is the beat frequency

- Thus, at any given instant, **time difference between the currently transmitted signal frequency and the currently received signal is a measure of the to-and-fro transit time of the transmitted signal**
- We extract range information from a measurement of *fb* as follows:
- Let the slope of the curve shown Fig. be *f*0, the rate of change of frequency, or the modulation rate. Note that this is a known quantity since the modulation rate is chosen by the designer at the radar end. Then,

$$f_b = f_r = f^0 T = f^0 \frac{2R}{c}$$

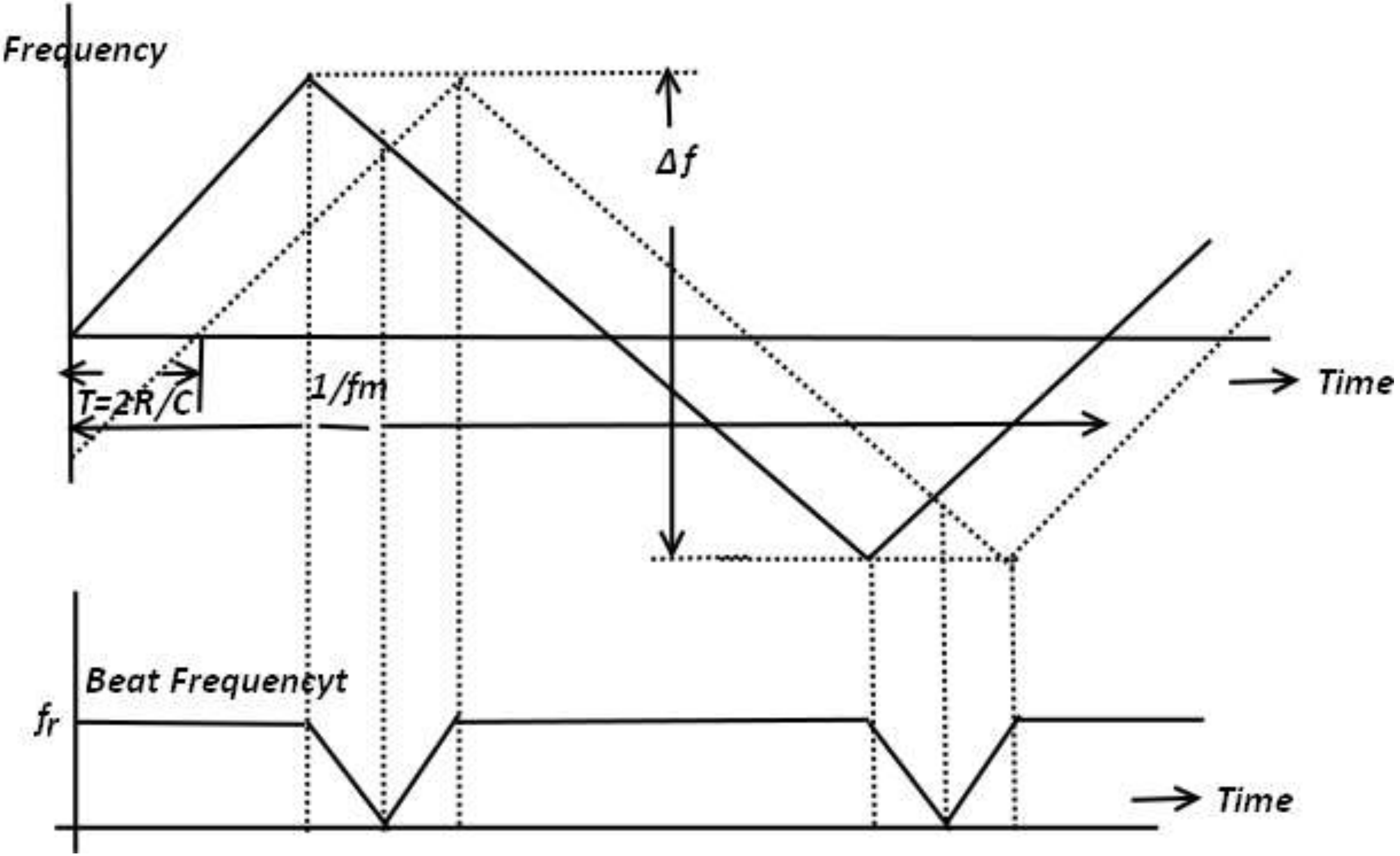
- where, *R* is the distance to the target and so *T* = 2*R/c* .
- The above analysis shows that measurement of *fb* and the knowledge the frequency modulation rate is sufficient to obtain the required range information

- The obvious flaw in the above scheme is that the transmitted frequency cannot go on increasing indefinitely(for an unlimited or unspecified period of time)**. A solution is to use a periodic change in the frequency. A particular case is the triangular-frequency modulation waveform.**

- This is shown in Fig where both the frequency modulation scheme and the resulting beat frequency curve is given. Note that the sign of the beat frequency is not preserved and hence it always appears as a positive frequency.

- Here, the beat frequency is given by *fr (Difference in freq due to range only)* at all points except in the neighborhood of the peaks of the transmitted signal.

Figure: Triangular frequency modulation in FM-CW radars



- Note that the frequency of the triangular modulation waveform is *fm* and hence its time period is given by 1/*fm.*

$$f_r = \frac{2R}{c} f^0 = \frac{2R}{c} \cdot \frac{\triangle f/2}{1/(4f_m)} = \frac{4Rf_m\triangle f}{c}$$

- Hence, the measurement of beat frequency measure the range as,

$$R = \frac{cf_r}{4f_m\triangle f} = \left[\frac{c}{4f_m\triangle f}\right] f_r = kf_r$$

- *Where K* can be used for calibrating the frequency counter.

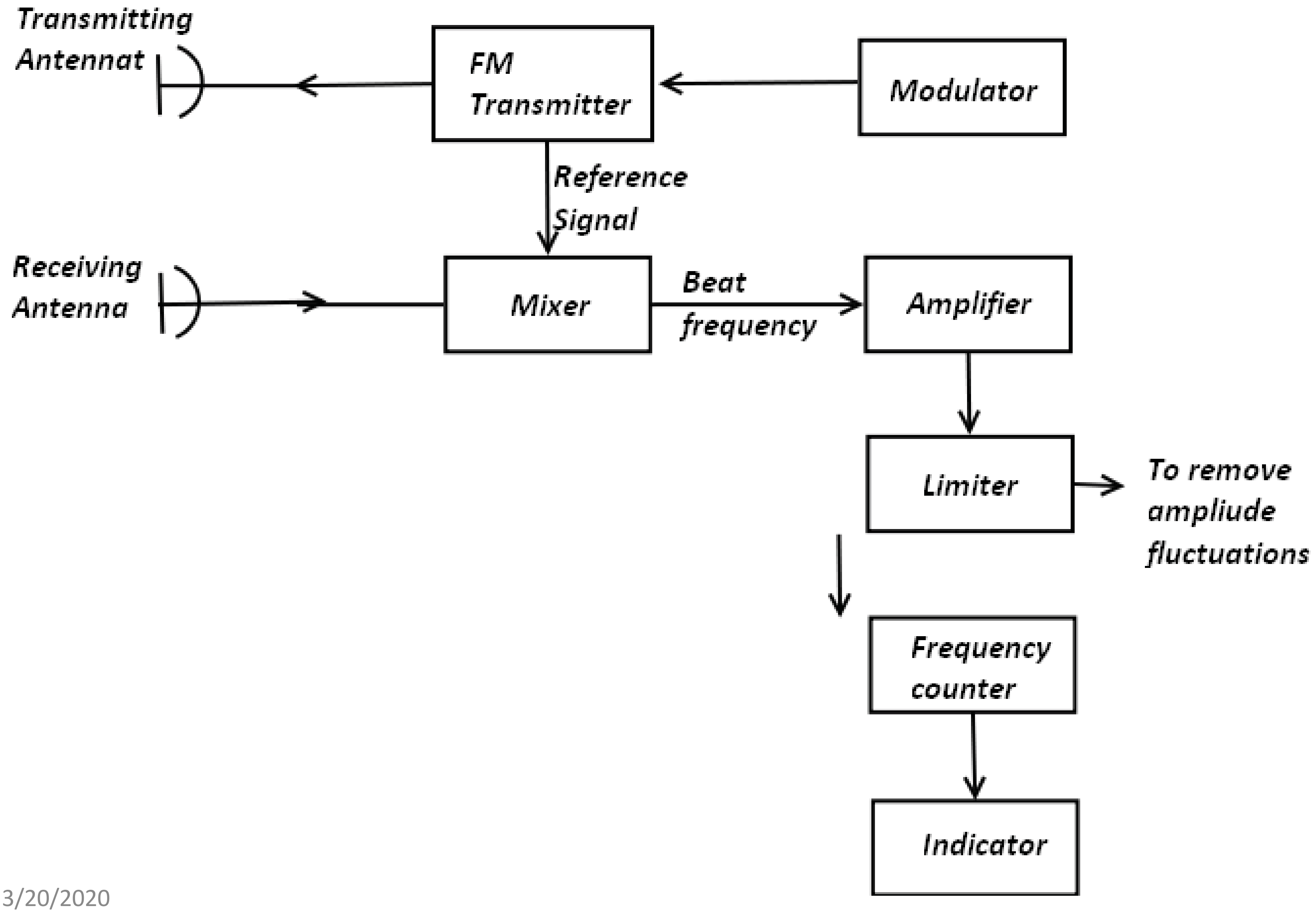
FM CW radar for moving targets

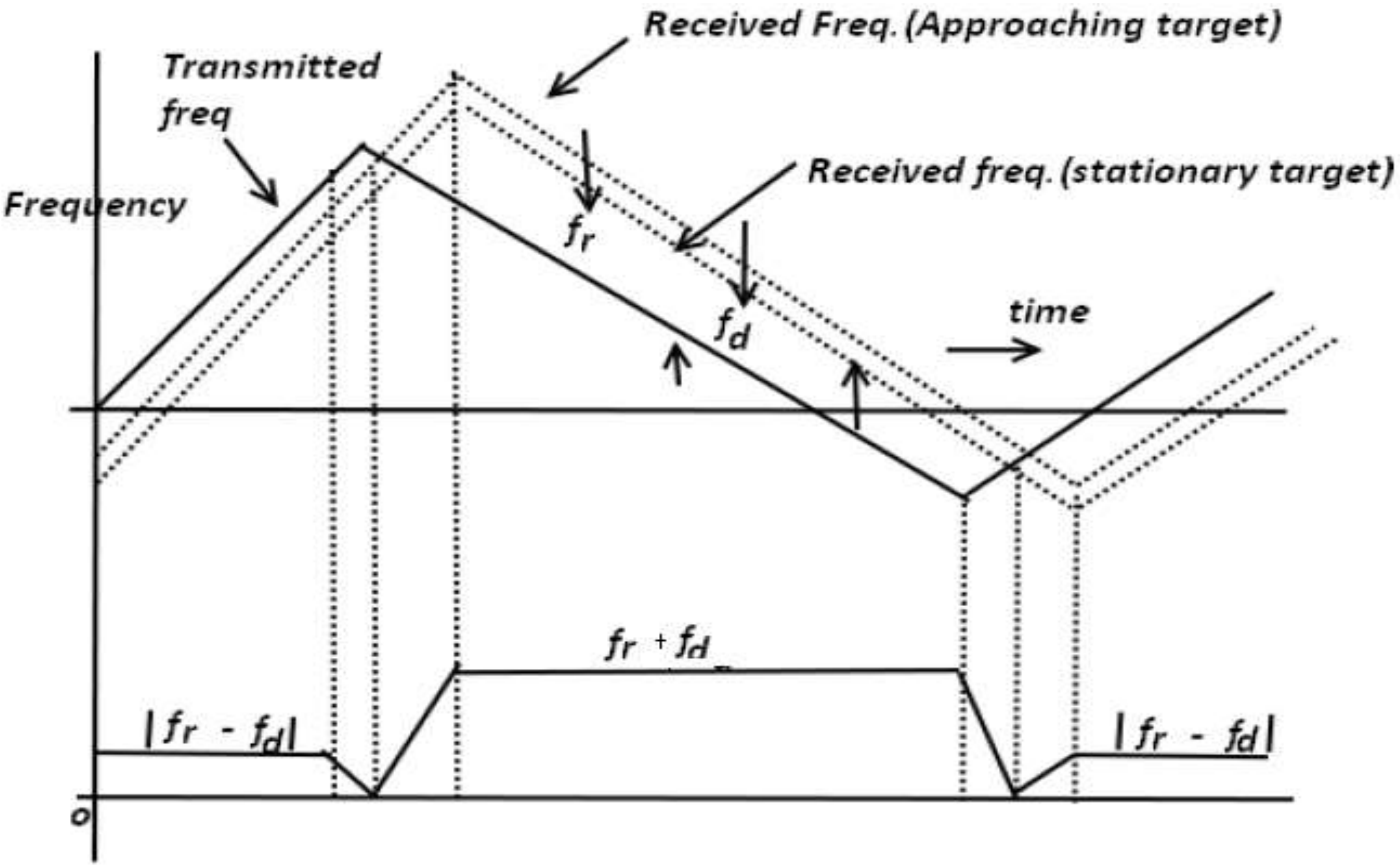
- In the above analysis the target was assumed to be stationary. Suppose it is not, **then there will be another frequency change due to the Doppler frequency shift**. This is denoted by *fd* and the beat (difference) frequency will now be

  fb = |fr ± fd|

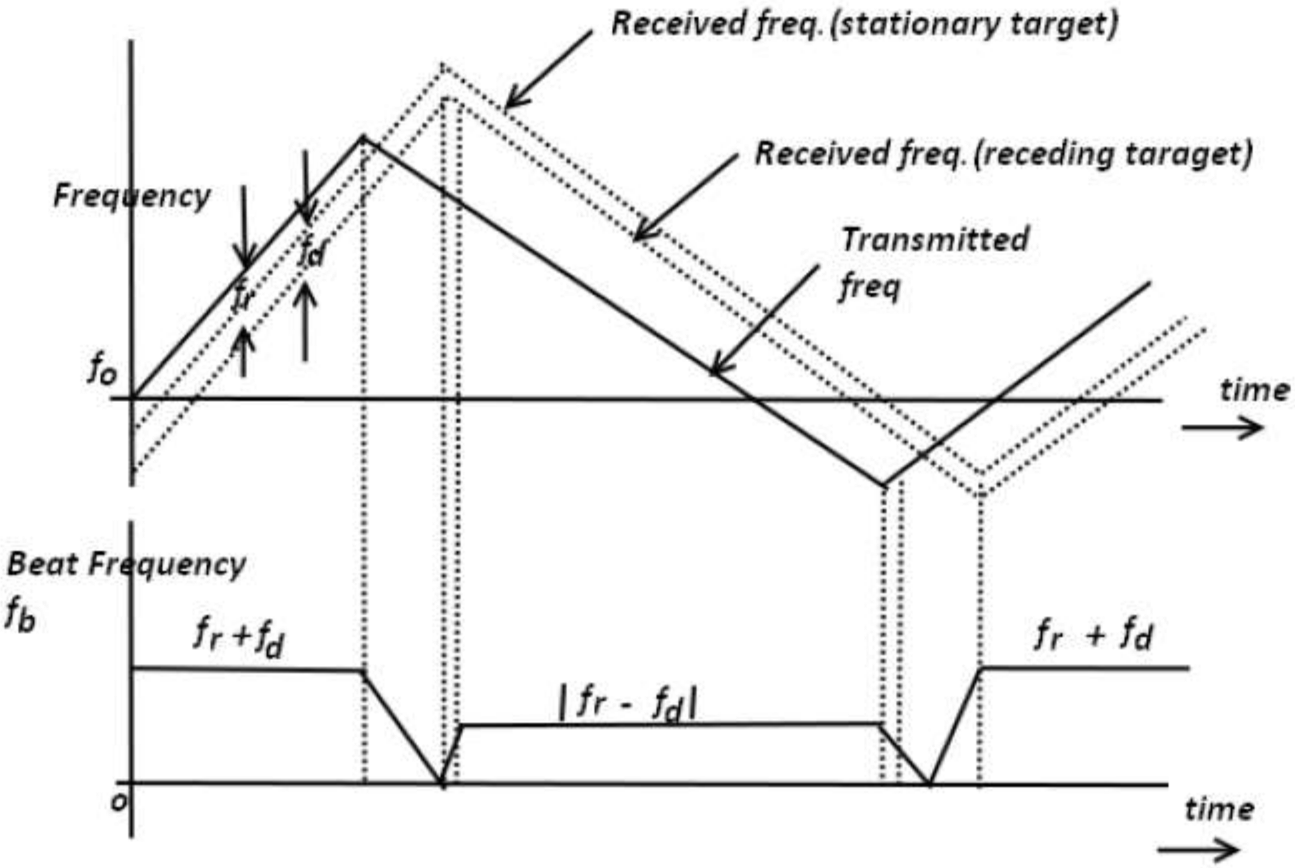
  Where fr is the difference frequency due to range only.
- Here **beat frequency is lower during the increasing portion of the transmitted frequency and higher during the decreasing portion of the transmitted frequency for approaching g target**
- Reverse in case of receding target

Block Diagram of FM CW radar





Approaching Target



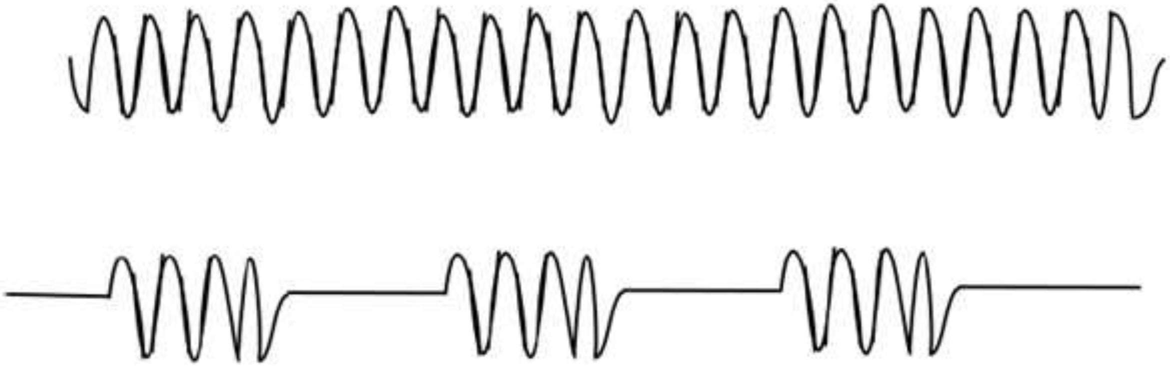
Receding Target

MTI & Pulse Doppler Radar

Definition

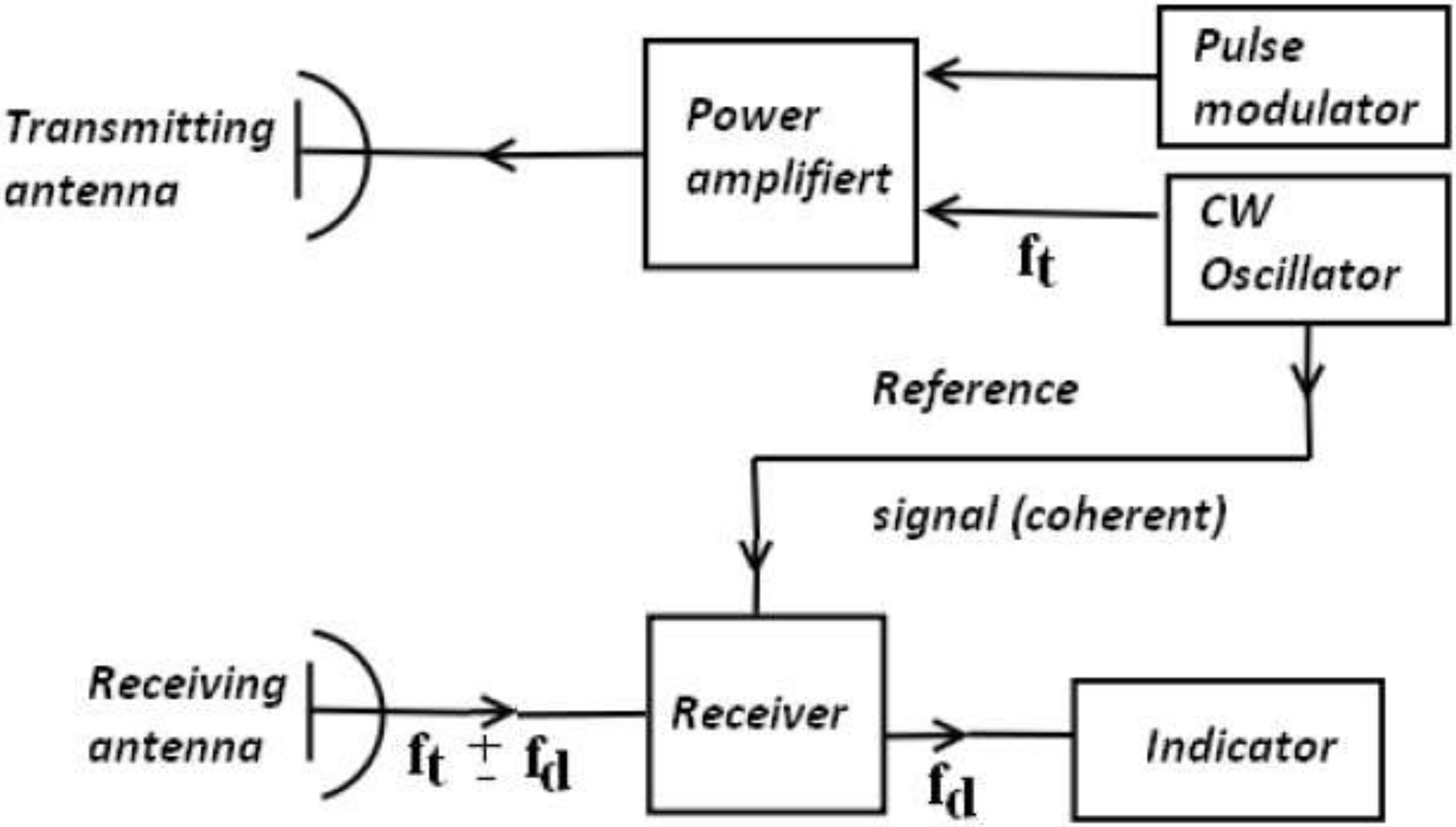
- **Pulse radars which use the doppler frequency shift to distinguish between moving and fixed targets** are called MTI (Moving Target Indicators) and Pulse Doppler Radars.

- In principle the CW radar can be converted to a pulse radar by providing a pulse modulator which turns on and off the power amplifier to generate pulses.



Pulse train generated from a continuous signal

Block diagram of Pulse Doppler Radar



Operation of Pulse Doppler Radar

- CW oscillator supplies a coherent reference needed to detect the Doppler frequency shift. By coherent it means that the phase of the transmitted signal is maintain in the reference signal.
- Let the CW oscillator voltage be

$$V_{osc} = A_1 sin(2\pi f_t t)$$

- The reference signal is

$$V_{ref} = A_2 sin(2\pi f_t t)$$

- The doppler-shifted echo-signal voltage is

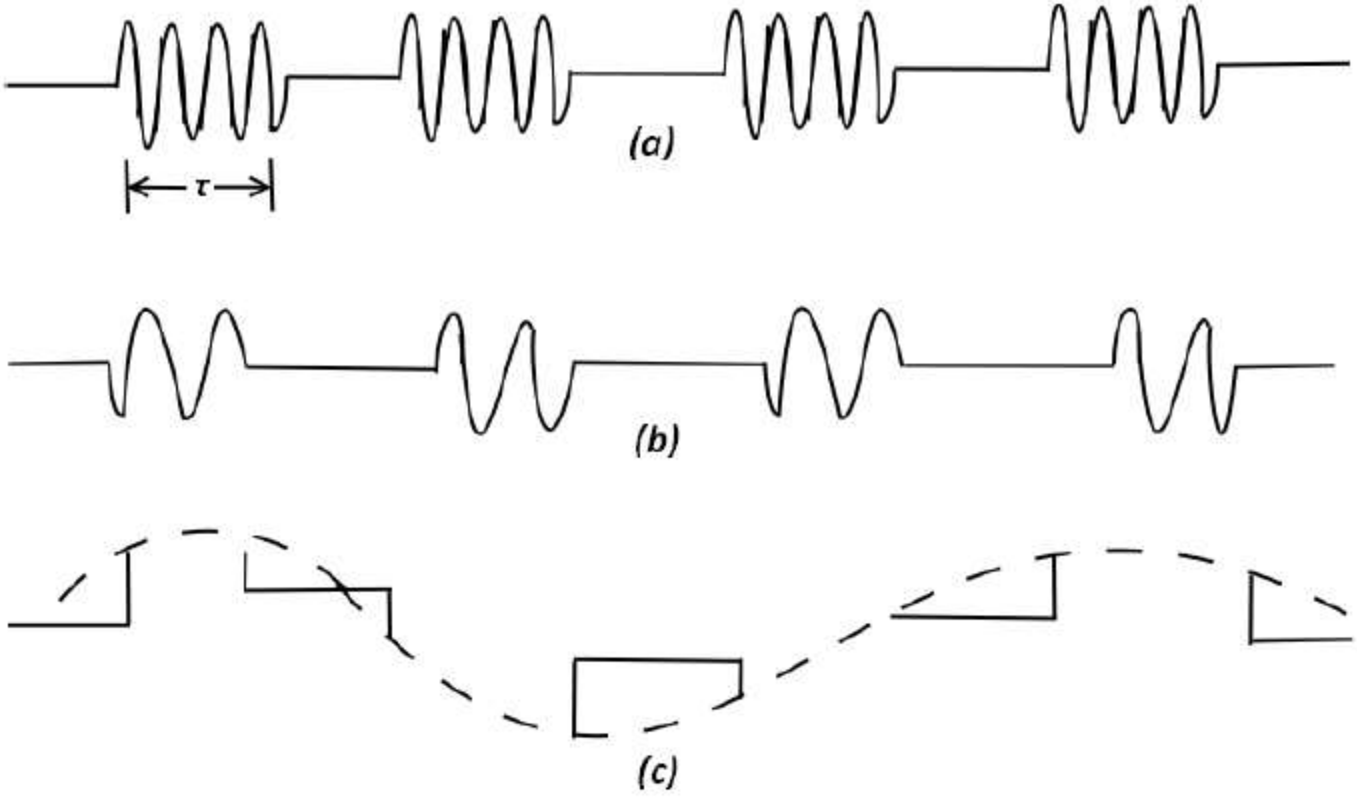
$$V_{echo} = A_3 sin\left[2\pi(f_t \pm f_d)t - \frac{4\pi f_t R_0}{c}\right]$$

- The reference signal and the target echo signal are heterodyned in the mixer stage. The difference frequency component is

$$V_{diff} = A_4 sin\left[2\pi f_d t - \frac{4\pi f_t R_0}{c}\right]$$

- For **stationary targets** the doppler frequency shift fd will be zero; hence **V diff will not vary with time** and may take on any constant value from +A4to −A4, including zero
- But when the target is in motion relative to the radar, fd has a value other than zero and the voltage corresponding to the **difference frequency from the mixer will vary with time for moving targets**
- *Basis for rejecting the stationary clutter echoes from moving target echoes*

Output Waveforms on video display of Pulse Doppler Radar



(a) Reflected Signal (B) Difference signal (fd>1/T) (c) Difference signal (fd<1/T)

- In radar, pulse width τ is long enough and if target’s Doppler frequency is large enough, it is possible **to detect Doppler frequency shift on basis of frequency change in one pulse. (fig. b)**

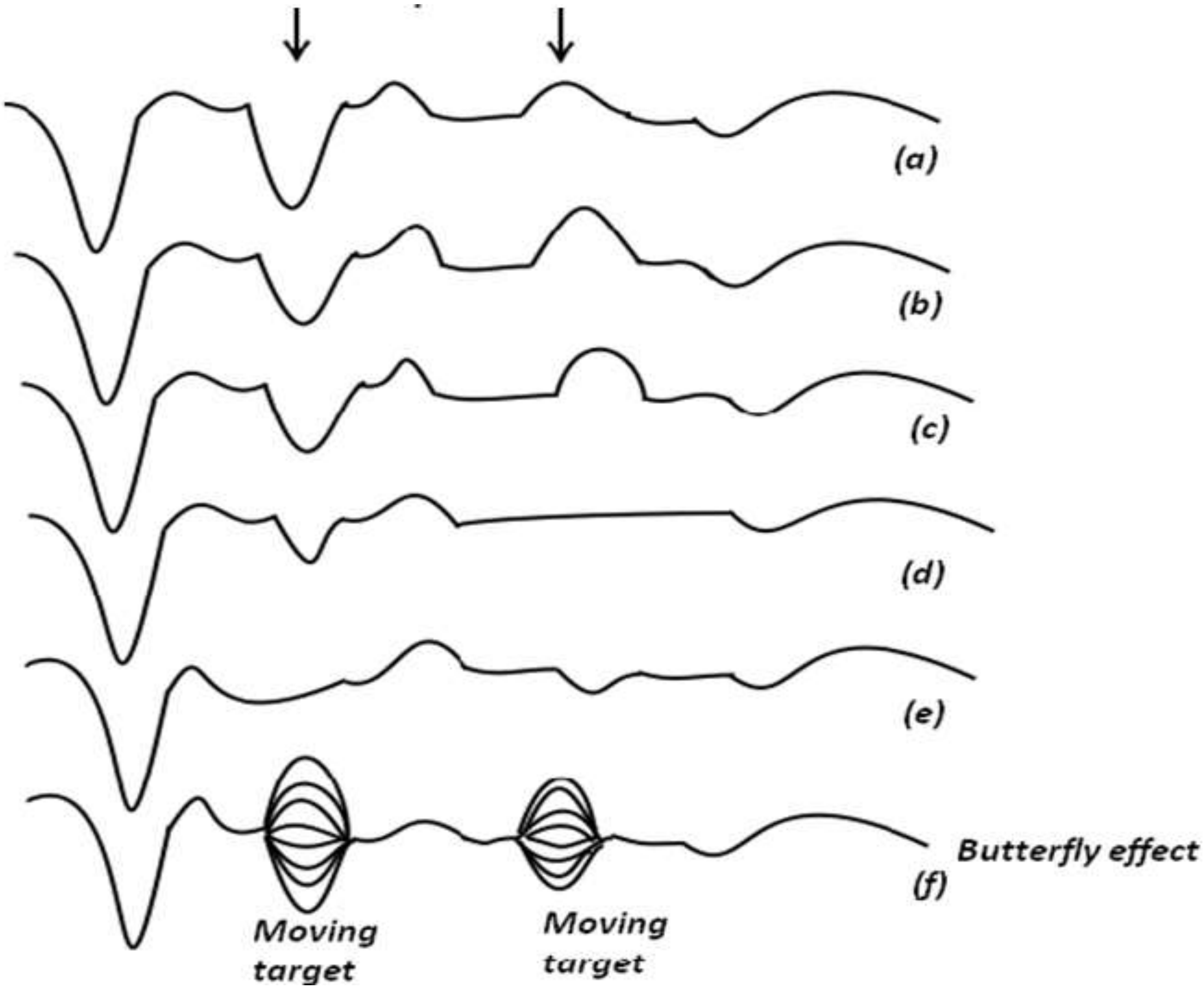
$$f_d > 1/\tau$$

- It requires that there be at least one cycle of fd within the pulse

- This does not meet in detecting Aircrafts since fd is smaller than 1/ τ
- **More than one pulses is needed to detect the Doppler frequency shift when $f_d < 1/\tau$ (fig. c)** where Doppler frequency is shown dashed

Successive Sweeps of MTI Radar

- Difference signal is the output of the mixer and is displayed on an A-scope (amplitude vs. time or range) in successive sweeps
- The amplitude of the signals from stationary targets do not change with the number of sweeps. But the echo signals from moving targets will change in amplitude over successive sweeps
- When these sweeps are superposed over each other due to the **effect of persistence of vision, the moving targets will produce signals which on the A-scope display will look like a butterfly opening and closing its wings**



(a-e) Successive sweeps of an MTI Radar on an A- Scope display (f) Superposition of these signals

Delay line Canceller

- However, Doppler information is required regarding moving targets only. Method to extract this information is to employ **delay-line cancellers**

- If one sweep is subtracted form previous sweep, fixed clutter echoes will cancel and will not be displayed

- Whereas, moving targets change in amplitude from sweep to sweep because of their doppler frequency shift. If one sweep is subtracted from the other, the result will be uncancelled residue as shown in fig

Block diagram of Delay Line Canceller

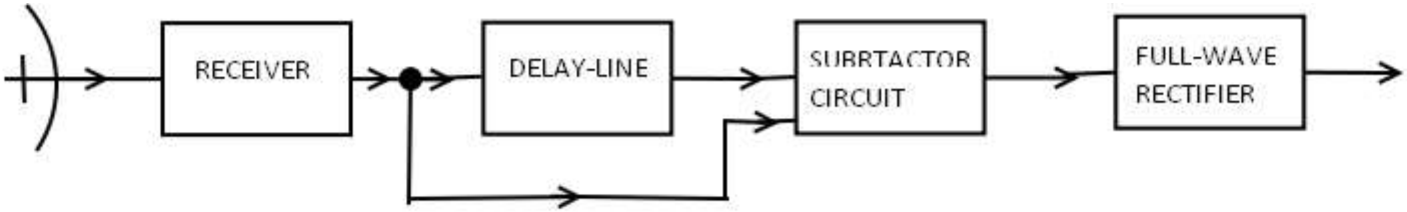
- The output of MTI receiver is digitized and is the input to delay line canceller

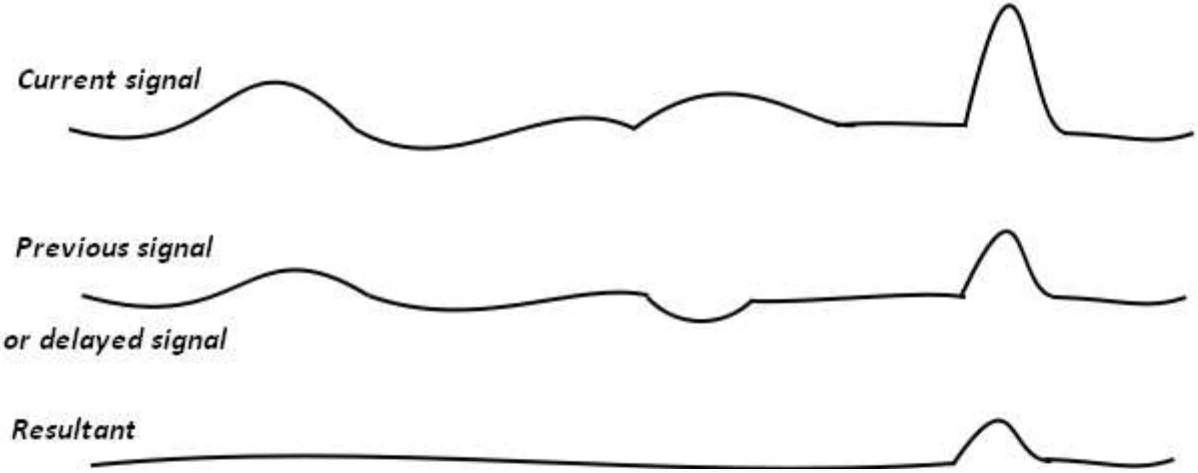
- **Delay T is achieved by storing the radar output from one pulse transmission or sweep in digital memory for a time equal to PRI.** So that T=PRI=1/fp

- The output obtained after subtraction of two successive sweeps is bipolar video, since the clutter echoes contain both +ve and –ve amplitudes

- Absolute value of bipolar video is taken, which is the unipolar video. Unipolar video signal is converted into analog signal by DAC if processed signal is to be displayed on PPI indicator

Block diagram of DLC





Blind Speed due to DLC

- Use of delay line cancellers cause problems of blind speeds. The signal is delayed by one pulse time period and then subtracted from signal coming next

- Suppose the signal from the moving target fluctuates in such a way that the signal after this time delay is the **same** as the signal before this time delay

- **This will happen whenever *fd is a multiple of fp (the pulse repetition frequencv). that* is.**

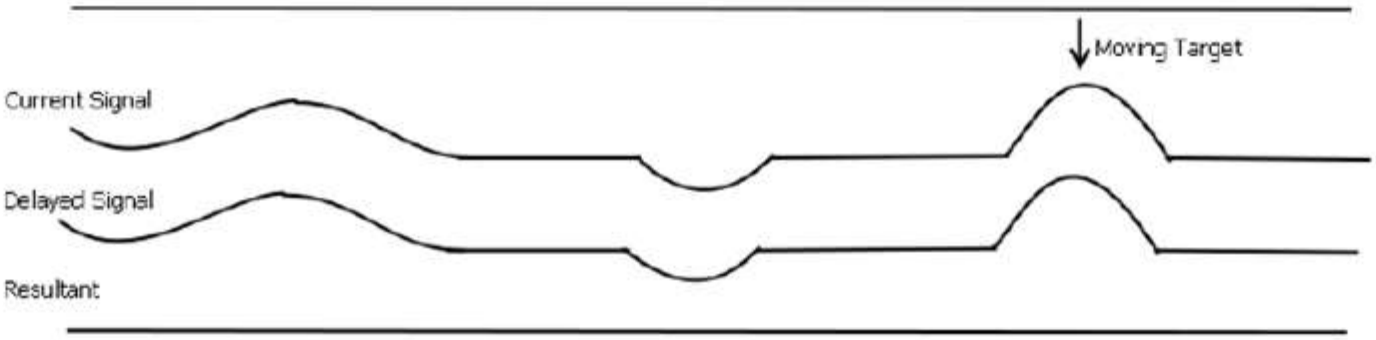
$$f_d = \mathrm{n} f_p, \quad n = 1, 2, \ldots$$

- At this instance, the resultant signal after subtraction is Zero. Thus the **radar fails to detect, or is blind to, the presence of such a moving target**

- Doppler frequency shifts *fd which cause this phenomenon are themselves* caused by certain specific target velocities

$$f_d = nf_p = 2v_r/\lambda$$

$$v_r = \frac{n\lambda f_p}{2} = \frac{n\lambda}{2T}, n = 1, 2, \ldots$$



Effect of Blind speed

- For a specific n this is called the nth blind speed. Whenever the target relative velocity with respect to the radar along the line of sight matches with these speeds, an MTI radar fails to detect the moving target
- Thus to avoid doppler ambiguities (due to blind speeds) the **first blind speed must be larger than the maximum expected relative velocity of the target**
- This can be achieved by either **making fp large or by making λ large**. So MTI radars should operate at long wavelengths (low carrier frequencies) or high pulse repetition frequencies, or both
- But, unfortunately other constraint prevent this kind of choice. Too **low radar frequencies make the beam-width wider and cause deterioration in angular resolution**
- Too **high pulse repetition frequencies cause ambiguous range measurements**

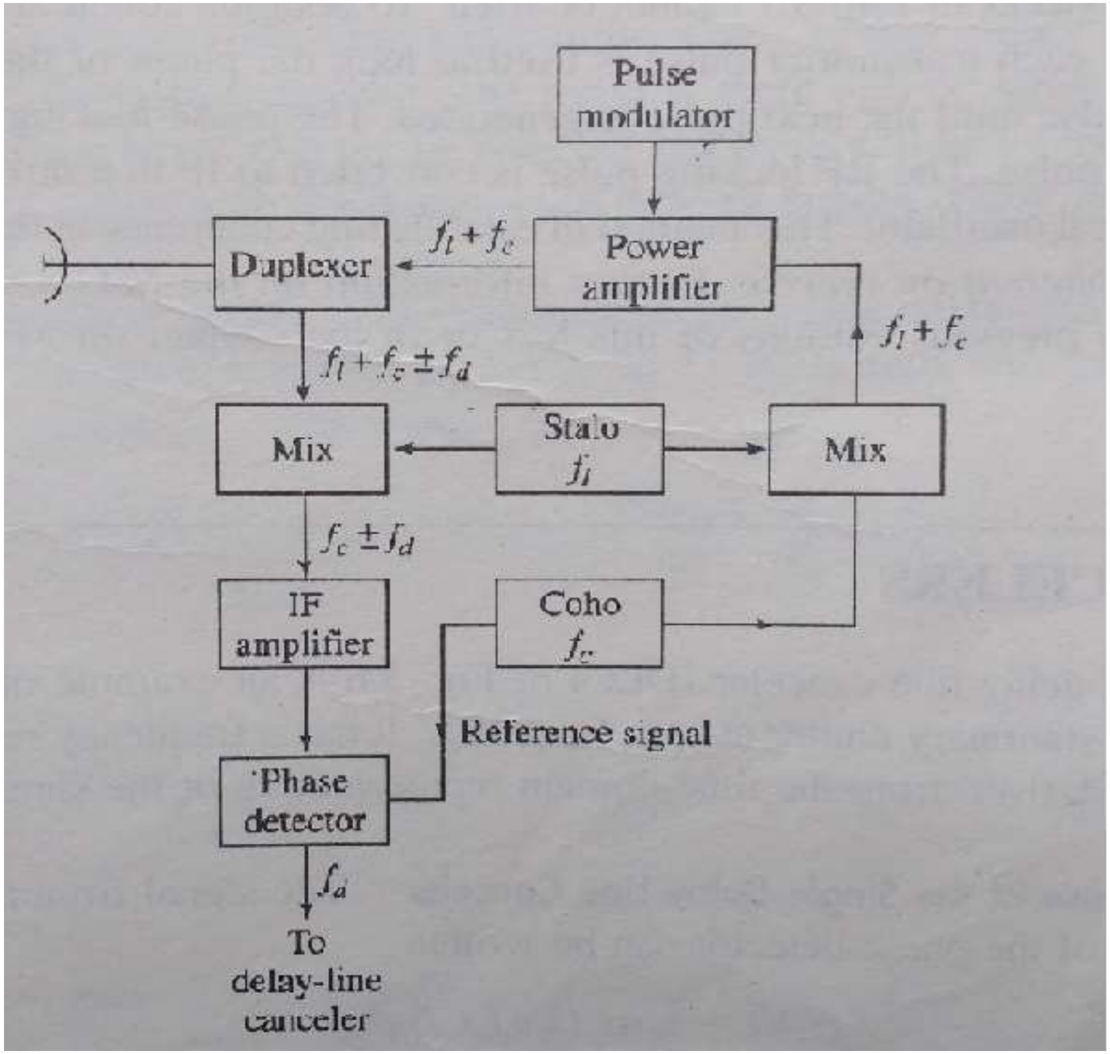
Choice of MTI & Pulse Doppler radar

- MTI radars operate on low pulse repetition frequencies and thus are prone to blind speeds, but they do not have the problems of range ambiguities

- On the other hand, pulse doppler radars operate at high pulse repetition frequencies and thus are affected by ambiguous range measurements. But they do not have the problem of blind speeds

- MTI radars are usually used as high-resolution surveillance radars in airports. Pulse doppler radars are used for detection of high-speed extraterrestrial objects like satellites and astronomical bodies

Coherent MTI Radar



- Stalo is the Stable Local Oscillator which is basically used to identify the need for high stability in MTI receiver

- Coho is the short name of Coherent Local Oscillator which is basically used as reference signal in MTI receiver that has the phase of transmitted signal

Reference

- NPTEL