UNIT-II

CW RADAR

2.1 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 receipt of the echo is a measure of the distance to the target. Separation of the echo signal and the transmitted signal is made on the basis of differences in time.

The radar transmitter may be operated continuously rather than pulsed if the strong transmitted signal can be separated from the weak echo. The received-echo-signal power is considerably smaller than the transmitter power; it might be as little as 10^{-18} that of the transmitted power-sometimes even less. Separate antennas for transmission and reception help segregate the weak echo from the strong leakage signal, but the isolation is usually not sufficient. A feasible technique for separating the received signal from the transmitted signal when there is relative motion between radar and target is based on recognizing the change in the echo-signal frequency caused by the doppler effect.

It is well known in the fields of optics and acoustics that if either the source of oscillation or the observer of the oscillation is in motion, an apparent shift in frequency will result. This is the ***doppler effect*** and is the basis of CW radar. If R is the distance from the radar to target, the total number of wavelengths contained in the two-way path between the radar and the target is ***2R/* λ**. The distance R and the wavelength λ are assumed to be measured in the same units. Since one wavelength corresponds to an angular excursion of 2π radians, the total angular excursion ϕ made by the electromagnetic wave during its transit to and from the target is **4πR/ λ** radians. If the target is in motion, R and the phase 4 are continually changing. A change in ϕ, with respect to time is equal to a frequency. This is the doppler angular frequency ω_d, given by

$$W_d = 2\pi f_d = \frac{d\phi}{dt} = \frac{4\pi}{\lambda}.\frac{dR}{dt} = \frac{4\pi V_r}{\lambda}$$

Where

f_d= doppler frequency shift

υ_r=relative(radial) velocity of target with respect to radar

The doppler frequency shift is

$$f_d = \frac{2V_r}{\lambda} = \frac{2V_r f_o}{c}$$

Where

f=transmitted frequency

c=velocity of light

The relative velocity may be written , $\upsilon_r = \upsilon \cos\theta$, where v is the target speed and θ is the angle made by the target trajectory and the line joining radar and target. When $\theta = 0$, the doppler frequency is maximum. The doppler is zero when the trajectory is perpendicular to the radar line of sight $(\theta = 90°)$.

2.2 CW RADAR

Consider the simple CW radar as illustrated by the block diagram of Fig2.1. The transmitter generates a continuous (unmodulated) oscillation of frequency f_o, 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 v_r relative to the radar, the received signal will be shifted in frequency from the transmitted frequency f_o by an amount $\pm$ fd as given by Eq. The plus sign associated with the doppler frequency applies if the distance between target and radar is decreasing (closing target), that is, when the received signal frequency is greater than the transmitted signal frequency. The minus sign applies if the distance is increasing (receding target). The received echo signal at a frequency $f \pm f_d$ enters the radar via the antenna and is heterodyned in the detector (mixer) with a portion of the transmitter signal f_o to produce a doppler beat note of frequency f_d. The sign f_d is lost in this process.

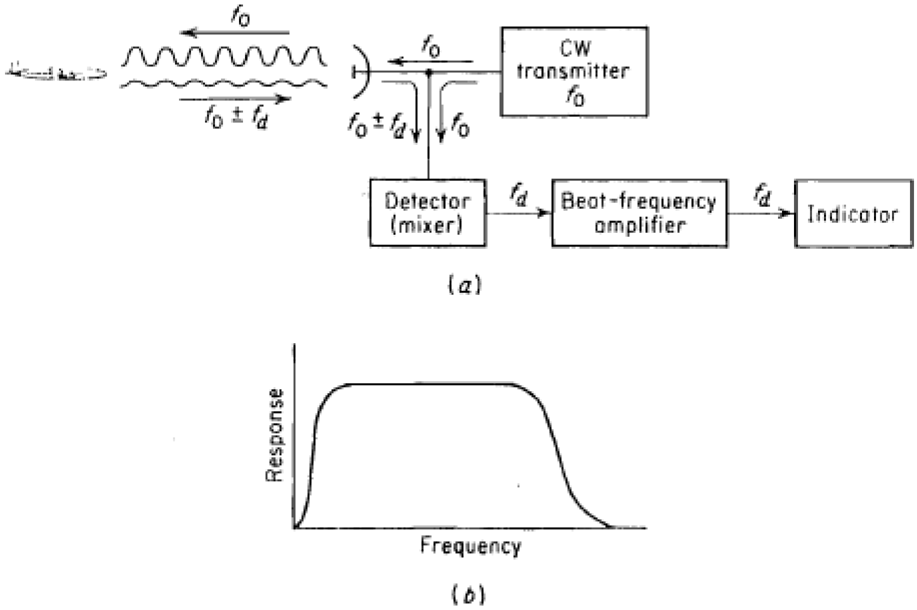


Figure2.1 (a) Simple CW radar block diagram; *(b)* response characteristic beat-frequency ampilfier.

The purpose of the doppler amplifier is to eliminate echoes from stationary targets and to amplify the doppler echo signal to a level where it can operate an indicating device. It might have a frequency-response characteristic similar to that Fig.2.1(b). The low-frequency cut off must be high enough to reject the d-c component caused by stationary targets, but yet it must be low enough to pass the smallest doppler frequency expected. Sometimes both conditions cannot be met simultaneously and compromise is necessary. The upper cut off frequency is selected to pass the highest doppler frequency expected.

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

2.3 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 or having its sensitivity reduced, 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 the ruggedness and sensitivity of the receiver. If the safe value of power which might be applied to a receiver were 10mw and if the transmitter power were 1 kw, the isolation between transmitter and receiver must be at least 50 dB. In long range CW applications, it is the level of the noise accompanying the transmitter leakage signal, rather than the damage this leakage might cause to the receiver circuitry, which determines the amount of isolation required. For example, suppose the isolation between the transmitter and receiver were such that 10mw of leakage signal appeared at the receiver. If the minimum detectable signal were 10^{-13} watt, the transmitter noise must be at least 110 dB below the transmitted carrier.

The receiver of a pulsed radar is isolated and protected from the damaging effects of the transmitted pulse by the duplexer, which short-circuits the receiver input during the transmission period. Turning off the receiver during transmission with a duplexer is not possible in a CW radar since the transmitter is operated continuously. Isolation between transmitter and receiver might be obtained with a **single antenna** by using a **hybrid junction, circulator, turnstile junction, or with separate polarizations**. **Separate antennas** for transmitting and receiving might also be used.

The amount of isolation which can be readily achieved between the arms of practical hybrid junctions such as the magic-T, rat race, or short-slot coupler is of the order of 20 to 30 dB. In some instances, when extreme precision is exercised, an isolation of perhaps 60 dB or more might be achieved. One limitation of the hybrid junction is the 6-dB loss in overall performance which results from the inherent waste of half the transmitted power and half the received signal power. Both the loss in performance and the difficulty in obtaining large isolations have limited the application of the hybrid junction to short-range radars.

Ferrite isolation devices such as the circulator do not suffer the 6-dB loss inherent in the hybrid junction. Practical devices have isolation of the order of 20 to 50 dB.

Turnstile junctions achieve isolations as high as 40 to 60 dB.

The use of orthogonal polarizations for transmitting and receiving is limited to short range radars because of the relatively small amount of isolation that can be obtained.

An important factor which limits the use of isolation devices with a common antenna is the reflections produced in the transmission line by the antenna. The antenna can never be perfectly matched to free space, and there will always be some transmitted signal reflected back toward the receiver. The reflection coefficient from a mismatched antenna with a voltage standing wave ratio σ is $|\rho| = (\sigma-1)/(\sigma+1)$. Therefore, if an isolation of 20 dB is to be obtained, the VSWR must be less than 1.22. If 40 dB 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 80 dB or more are possible with high-gain antennas. The more directive the antenna beam and the greater the spacing between antennas, the greater will be the isolation. When the antenna designer is restricted by the nature of the application, large isolations may not be possible. For example, typical isolations between transmitting and receiving antennas on missiles might be about 50 dB at X band, 70 dB at *K* band and as low as 20 dB at L band. Metallic baffles, as well as absorbing material, placed between the antennas can provide additional isolation.

It has been reported that the isolation between two X-band horn antennas of 22 dB gain can be increased from a normal value of 70 dB to about 120 dB by separating the two with a smooth surface covered by a sheet of radar-absorbing material and providing screening ridges at the edges of the horns. A common radome enclosing the two antennas should be avoided since it limits the amount of isolation that can be achieved.

Additional isolation can be obtained by properly introducing a controlled sample of the transmitted signal directly into the receiver. The phase and amplitude of this " **buck-off**" signal are adjusted to cancel the portion of the transmitter signal that leaks into the receiver. An additional 10 dB of isolation might be obtained. The phase and amplitude of the leakage signal, however, can vary as the antenna scans, which results in varying cancellation.

2.4 INTERMEDIATE-FREQUENCY RECEIVER

The receiver of the simple CW radar of Fig 2.1. is in some respects analogous to a superheterodyne receiver. Receivers of this type are called homodyne receivers, or superheterodyne receivers with zero IF. The function of the local oscillator is replaced by the leakage signal from the transmitter. Such a receiver is simpler than one with a more conventional intermediate frequency since no IF amplifier or local oscillator is required. However, the simpler 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 vacuum tubes. The noise power produced by the flicker effect varies as $1/f^{\alpha}$ where α is approximately unity. This is in contrast to shot noise or thermal noise, which is independent of frequency. Thus, at the lower range of frequencies (audio or video region), where the doppler frequencies usually are found, the detector of the CW receiver can introduce a considerable amount of flicker noise, resulting in reduced receiver sensitivity. For short-range, low-power, applications this decrease in sensitivity might be tolerated since it can be compensated by a modest increase in antenna aperture and/or additional transmitter power. 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. This results from the inverse frequency dependence of flicker noise. Figure shows a block diagram of the CW radar whose receiver operates with a nonzero IF. Separate antennas are shown for transmission and reception. Instead of the usual local oscillator found in the conventional superheterodyne receiver, the local oscillator (or reference signal)

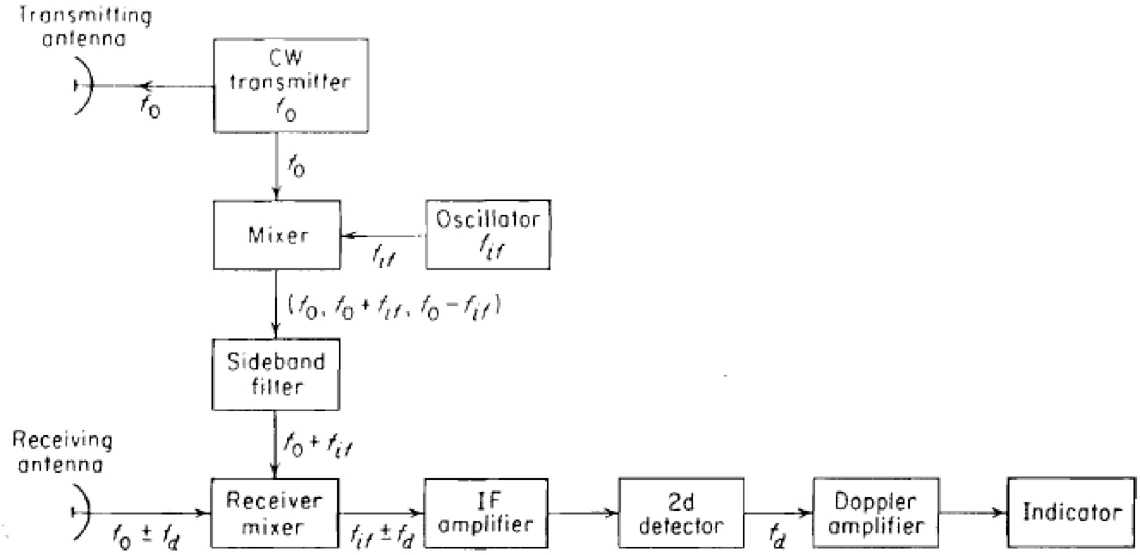


Figure 2.2:Block diagram of CW doppler radar with nonzero IF receiver, sometimes called *sideband superheterodyne***.**

is derived in the receiver from a portion of the transmitted signal mixed with a locally generated signal of frequency equal to that of the receiver IF. Since the output of the mixer consists of two sidebands on either side of the carrier plus higher harmonics, a narrowband filter selects one of the sidebands as the reference signal. The improvement in receiver sensitivity with an intermediate-frequency superheterodyne might be as much as 30 dB over the simple receiver of Fig2.1.

2.5 RECEIVER BANDWIDTH

One of the requirements of the doppler-frequency amplifier in the simple CW radar (Fig.2.1)or the IF amplifier of the sideband superheterodyne (Fig.2.2) is that it be wide enough to pass the expected range of doppler frequencies. In most cases of practical interest the expected range of doppler frequencies will be much wider than the frequency spectrum occupied by the signal energy. Consequently, the use of a wideband amplifier covering the expected doppler range will result in an increase in noise and a lowering of the receiver sensitivity. If the frequency of the doppler-shifted echo signal were known beforehand, a narrowband filter-one just wide enough to reduce the excess noise without eliminating a significant amount of signal energy-might be used. If the waveform of the echo signal were known, as well as its carrier frequency, the matched filter could be specified.

Several factors tend to spread the CW signal energy over a finite frequency band. These must be known if an approximation to the bandwidth required for the narrowband doppler filter is to be obtained.

If the received waveform were a sine wave of infinite duration, its frequency spectrum would be a delta function (Fig. 2.3a) and the receiver bandwidth would be infinitesimal. But a sine wave of infinite duration and an infinitesimal bandwidth cannot occur in nature. The more normal situation is an echo signal which is a sine wave of finite rather than infinite duration. The frequency spectrum of a finite-duration sine wave has a shape of the form [sin $\pi(f-f_o)\delta$]/

$\pi(f-f_o)$, where f, and δ are the frequency and duration of the sine wave respectively, and f is the frequency variable over which the spectrum is plotted (Fig. 3.b).

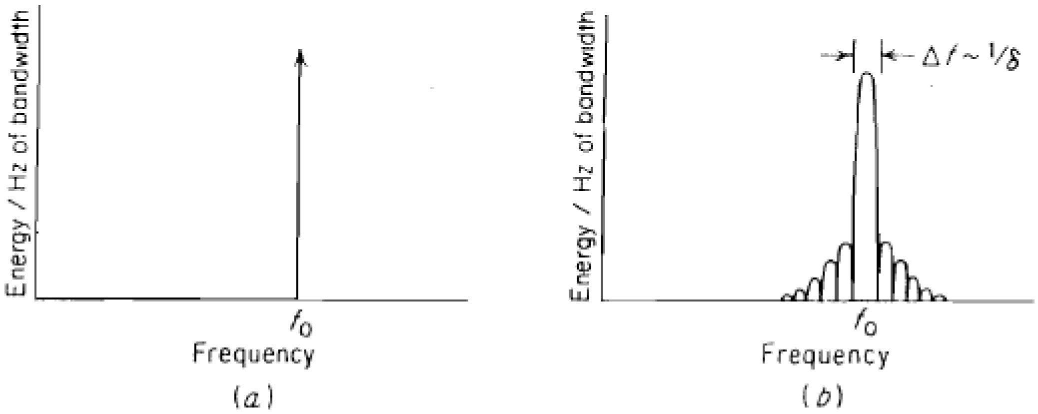


Figure 2.3 Frequency spectrum of CW oscillation of (a infinite duration and *(b)* finite duration.

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

Assume a CW radar with an antenna beamwidth of θ_B deg scanning at the rate of θ_S deg/s. The time on target (duration of the received signal) is $\delta = \theta_B / \theta_S$ sec. Thus the signal is of finite duration and the bandwidth of the receiver must be of the order of the reciprocal of the time on target θ_S / θ_B. Although this is not an exact relation, it is a good enough approximation for purposes of the present discussion.

If the target's relative velocity is not constant, a further widening of the received signal spectrum can occur. If a_r, is the acceleration of the target with respect to the radar, the signal will occupy a bandwidth

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

When the doppler-shifted echo signal is known to lie somewhere within relatively wide band of frequencies, a bank of narrowband filters (Fig. 2.4) spaced throughout the frequency range permits a measurement of frequency and improves the signal-to-noise ratio. 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 frequencies. If the filters are spaced with their half-power points overlapped, the maximum reduction in signal-to-noise ratio of a signal which lies midway between adjacent channels compared with the signal-to-noise ratio at midband is 3 dB. The more filters used to cover the band, the less will be the maximum loss experienced, but the greater the probability of false alarm.

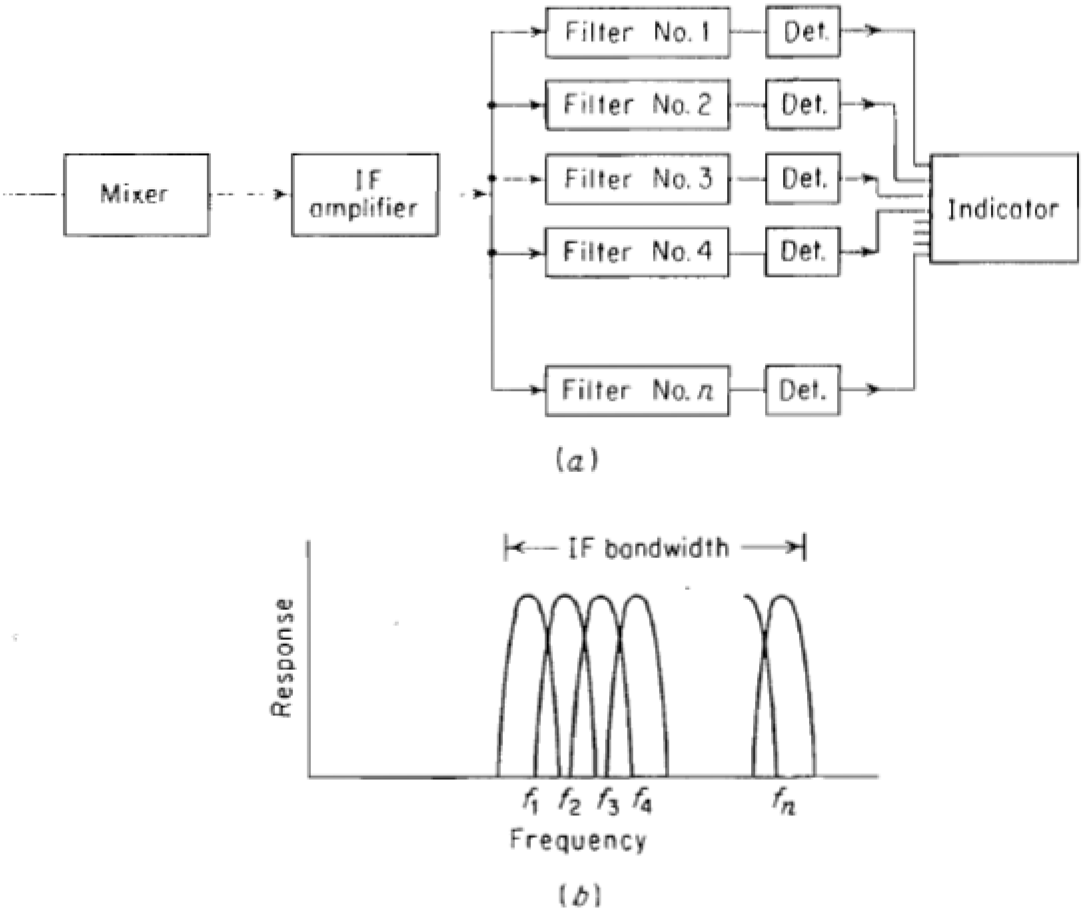


Figure 2.4 (a) Block diagram of IF doppler filter bank; (b) frequency-response characteristic of doppler filter bank.

2.6 SIGN OF THE RADIAL VELOCITY

In many applications of CW radar it is of interest to know if 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, then the target is receding; whereas if the echo frequency is greater that the carrier, then the target is approaching. This is shown in Fig.2.5 given below. However, the doppler-frequency spectrum ”folds over” 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,

$$E_t = E_0 \cos \omega_o t$$

The echo signal from the moving target will be,

$$E_r = K_1 E_0 \cos [(\omega_0 + \omega_d)t + \phi]$$

where, E_0 = amplitude of the transmitted signal

K_1 = a constant determined from the radar equationrepresenting the reduction in power of the echo signal

ω_0 = angular frequency of transmitted signal, rad/sec

ω_d = dopper 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)

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.2.6.

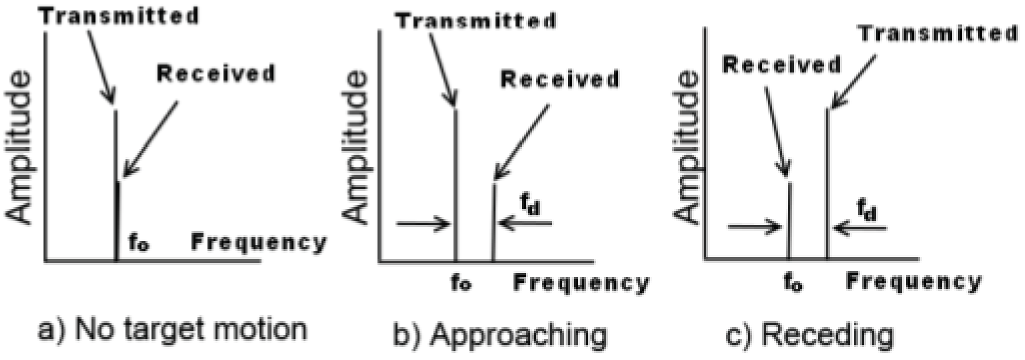


Figure 2.5 Transmitted and received signal frequency.

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,

$$E_A = K_2E_0\cos(\pm\omega_d t + \varphi)$$

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

$$E_B = K_2E_0\cos(\pm\omega_d t + \varphi + \pi/2)$$

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

$$E_A(+) = K_2E_0\cos(\omega_d t + \varphi)$$

$$E_B(+) = K_2E_0\cos(\omega_d t + \varphi + \pi/2)$$

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

$$E_A(-) = K_2E_0\cos(\omega_d t - \varphi)$$

$$E_B(-) = K_2E_0\cos(\omega_d t - \varphi - \pi/2)$$

the sign of wd and the direction of the target's motion may be determined according to hether 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.

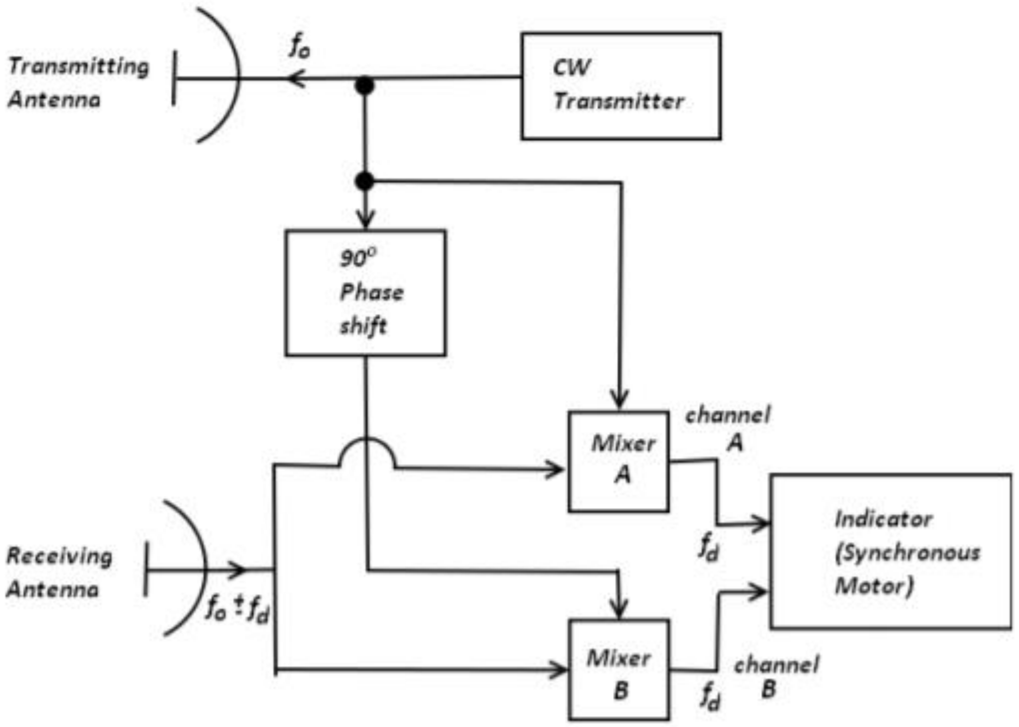


Figure 2.6: Determination of the sign of the Doppler frequency

Electronic methods may be used instead of a synchronous motor to sense the relative phase of the two channels. One application of this technique has been described for a rate-of climb meter for vertical take-off aircraft to determine the velocity of the aircraft with respect to the ground during take-off and landing. It has also been applied to the detection of moving targets in the presence of heavy foliage.

2.7 THE DOPPLER FREQUENCY SHIFT

The expression for the doppler frequency shift given previously is an approximation that is valid for most radar applications. The correct expression for the frequency f* from a target moving with a relative velocity ***v*,** when the frequency f is transmitted is

$$f^* = f\,\frac{(1 + v/c)}{(1 - v/c)}$$

where c is the velocity of propagation. When, as is usually the case, v<<c, Eq. above reduces to approximate form.

2.8 APPLICATIONS OF CW RADAR

The chief use of the simple, unmodulated CW radar is for the measurement of the relative velocity of a moving target, as in the police speed monitor or in the rate-of-climb meter for vertical-take-off aircraft. In support of automobile traffic, CW radar has been suggested for the control of traffic lights, regulation of toll booths, vehicle counting, as a replacement for the " fifth-wheel" speedometer in vehicle testing, as a sensor in antilock braking systems, and for collision avoidance. For railways, CW radar can be used as a speedometer to replace the conventional axle-driven tachometer. In such an application it would be unaffected by errors caused by wheelslip on accelerating or wheelslide when braking. It has been used for the measurement of railroad freight car velocity during humping operations in marshalling yards, and as a detection device to give track maintenance personnel advance warning of approaching trains. CW radar is also employed for monitoring the docking speed of large ships. It has also seen application for intruder alarms and for the measurement of the velocity of missiles, ammunition, and baseballs.

The principal advantage of a CW doppler radar over other non-radar methods of measurement of speed is that there need not be any physical contact between the measuring device and the object whose speed is being measured. Another advantage is that the CW radar, when used for short or moderate ranges, is characterized by simpler equipment than a pulse radar.

Among its disadvantages is the fact that 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.

FREQUENCY MODULATED CW RADAR

The inability of the simple CW radar to measure range is related to the 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 and the time of return to be recognized. The sharper or more distinct the mark, the more accurate the measurement of the transit time. But the more distinct the timing mark, the broader will be the transmitted spectrum. This follows from the properties of the Fourier transform. Therefore a finite spectrum must of necessity be transmitted if transit time or range is to be measured.

The spectrum of a CW transmission can be broadened by the application of modulation, either amplitude. frequency, or phase. An example of an amplitude modulation is the pulse radar. The narrower the pulse, the more accurate the measurement of range and the broader the transmitted spectrum. A widely used technique to broaden the spectrum of CW radar is to frequency-modulate the carrier. The timing mark is the changing frequency. The transit time is proportional to the difference in frequency between the echo signal and the transmitter signal. The greater the transmitter frequency deviation in a given time interval, the more accurate the measurement of the transit time and the greater will be the transmitted spectrum.

2.10 Range and doppler measurement.

In the frequency-modulated CW radar (abbreviated FM-CW), the transmitter frequency is changed as a function of time in a known manner. Assume that the transmitter frequency increases linearly with time, as shown by the solid line in Fig. 2.7a. If there is a reflecting object at a distance R, an echo signal will return after a time T = 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 nonlinear element such as a diode, a beat note f_b will be produced. If there is no doppler frequency shift, the beat note (difference frequency) is a measure of the target's range and $f_b = f_r$ where f_r is the beat frequency due only to the target's range. If the rate of change of the carrier frequency is f_0 , the beat frequency is

$$f_r = \dot{f}_0 T = \frac{2R}{c} \dot{f}_0$$

In any practical CW radar, the frequency cannot be continually changed in one direction only. Periodicity in the modulation is necessary, as in the triangular frequency-modulation waveform sllown in Fig. **2.7b.** The modulation need not necessarily be triangular; **it** can sawtooth, sinusoidal, or some other shape. The resulting beat frequency as a function of **time** shown in Fig. **2.7c** for triangular modulation. The beat note is of constant frequency except at the turn-around region. If the frequency is modulated at a rate f_m over a range **Δf** the beat frequency is

$$f_r = \frac{2R}{c} 2f_m \qquad \Delta f = \frac{4Rf_m \, \Delta f}{c}$$

Thus the measurement of the beat frequency determines the range R.

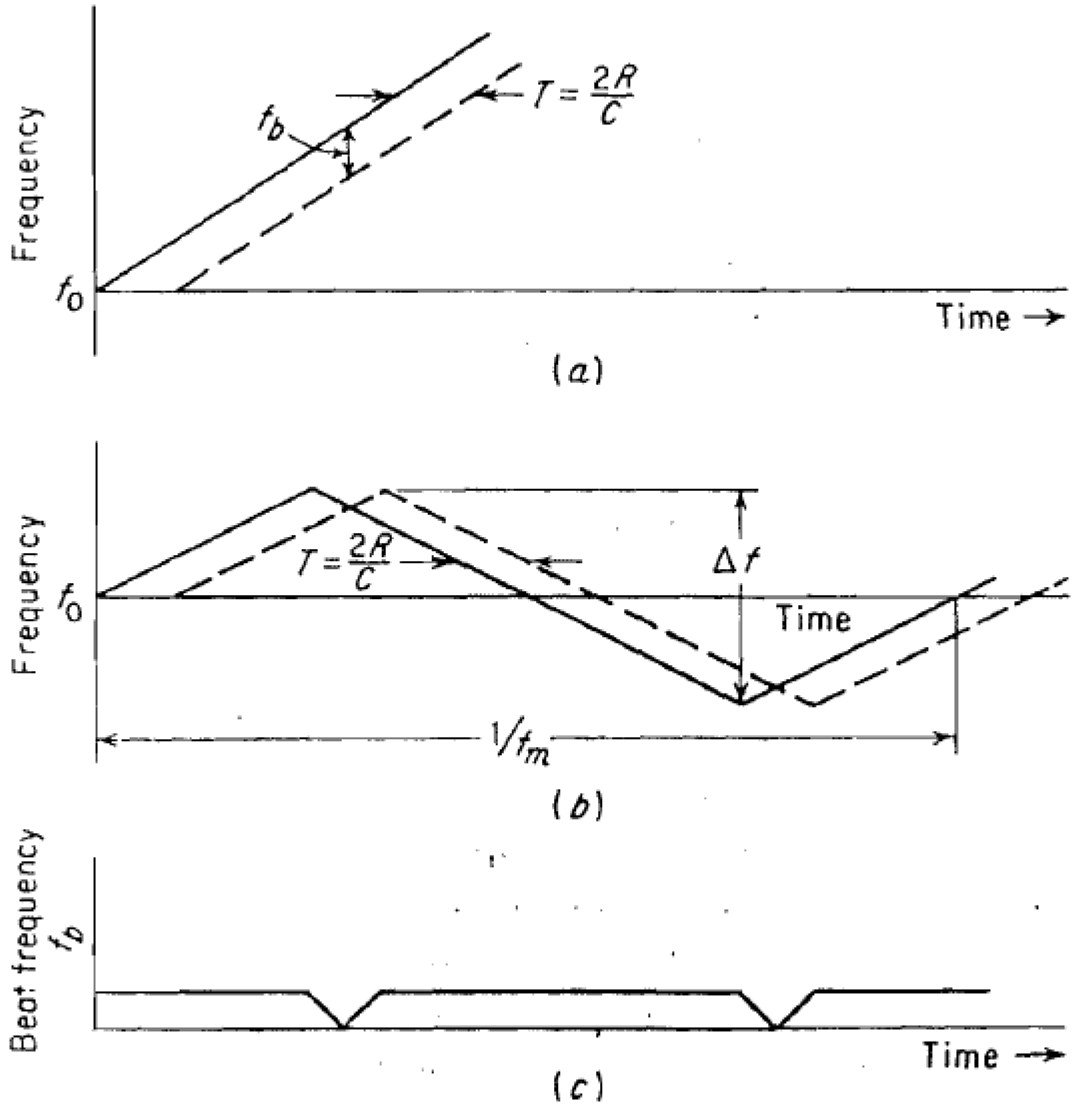
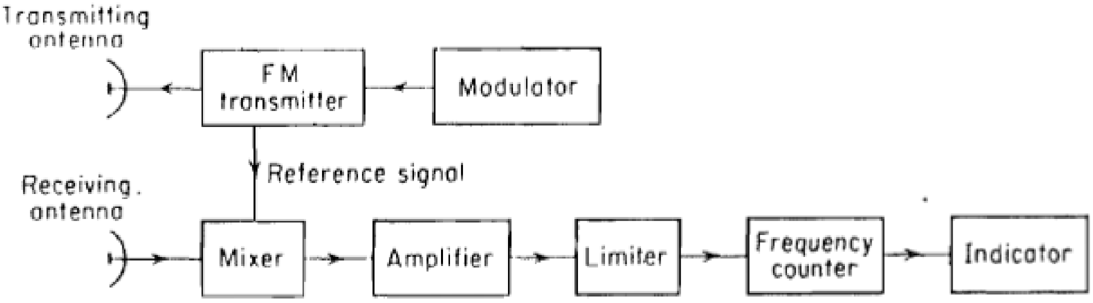


Figure 3.10 Frequency-time relationships in FM-CW radar. Solid curve represents transmitted signal; dashed curve represents echo. (a) Linear frequency modulation; ***(b)*** triangular frequency modulation; (c) beat note of (b)

2.11 BLOCK DIAGRAM AND CHARACTERISTICS

A block diagram illustrating the principle of the FM-CW radar is shown in Fig. 2.8. A portion of the transmitter signal acts as the reference signal required to produce the beat frequency. It is introduced directly into the receiver via a cable or other direct connection.



Ideally the isolation between transmitting and receiving antennas is made sufficiently large so as to reduce to a negligible level the transmitter leakage signal which arrives at the receiver via the coupling between antennas. The beat frequency is amplified and limited to remove any amplitude fluctuations. The frequency of the amplitude-limited beat note is measured with a cycle-counting frequency meter calibrated in distance.

In the above, the target was assumed to be stationary. If this assumption is not applicable, a doppler frequency shift will be superimposed on the FM range beat note and an erroneous range measurement results. The doppler frequency shift causes the frequency-time plot of the echo signal to be shifted up or down (Fig. 2.9a). On one portion of the frequency-modulation cycle the beat frequency (Fig. 2.9b) is increased by the doppler shift, while on the other portion, it is decreased. If for example, the target is approaching the radar, the beat frequency f_b(up) produced during the increasing, or up, portion of the FM cycle will be the difference between the beat frequency due to the range f_r and the doppler frequency shift f_d. Similarly, on the decreasing portion, the beat frequency &(down) is the sum of the two

$$f_b(\text{up}) = f_r - f_d$$

$$f_b(\text{down}) = f_r + f_d$$

The range frequency f_r may be extracted by measuring the average beat frequency; that is, $1/2[f_{b(up)} + f_{b(down)}] = f_r$. If fb(up) and fb(down) are measured separately, for example, by switching a frequency counter every half modulation cycle, one-half the difference between the frequencies will yield the doppler frequency. This assumes.fr > fd . If, on the other hand, fr < *fd*,such as might occur with a high-speed target at short range, the roles of the averaging and the difference-frequency measurements are reversed; the averaging meter will measure doppler velocity, and the difference meter, range. If it is not known that the roles of the meters are reversed because of a change in the inequality sign between *fr* and fd, an incorrect interpretation of the measurements may result.

When more than one target is present within the view of the radar, the mixer output will contain more than one difference frequency. If the system is linear, there will be a frequency component corresponding to each target. In principle, the range to each target may be determined by measuring the individual frequency components and applying Eq.to each. To measure the individual frequencies, they must be separated from one another. This might he accomplished with a bank of narrowband filters, or alternatively, a single frequency corresponding to a single target may be singled out and continuously observed with a narrow band tunable filter. But if the motion of the targets were to produce a doppler frequency shift,
or if the frequency-modulation waveform were nonlinear, or if the mixer were not operated in its linear region, the problem of resolving targets and measuring the range of each becomes more complicated.

If the FM-CW radar is used for single targets only, such as in the radio altimeter, it is not necessary to employ a linear modulation waveform. This is certainly advantageous since a sinusoidal or almost sinusoidal frequency modulation is easier to obtain with practical equipments than are linear modulations. The beat frequency obtained with sinusoidal modulation is not constant over the modulation cycle as it is with linear modulation. However, it may be shown that the ***average*** beat frequency measured over a modulation cycle, when substituted into Eq. yields the correct value of target range. Any reasonable-shape modulation waveform can be used to measure the range, provided the average beat frequency is measured .If the target is in motion and the beat signal contains a component due to the doppler frequency shift, the range frequency can be extracted, as before, if the average frequency is measured. To extract the doppler frequency, the modulation waveform must have equal upsweep and downsweep time intervals.

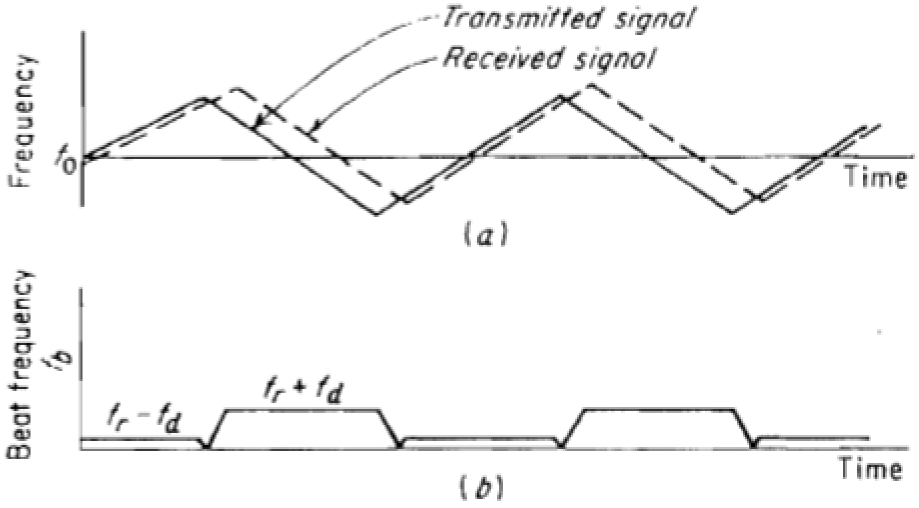


Figure 2.9 Frequency-time relationships in **FM-CW** radar when the received signal is shifted in frequency by the doppler effect (a) Transmitted (solid curve) and echo (dashed curve) frequencies; (b) beat frequency.

2.12 FM CW 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 section and the relatively short ranges required of altimeters permit low transmitter power and low antenna gain. Since the relative motion between the aircraft and ground is small, the effect of the doppler frequency shift may usually be neglected.

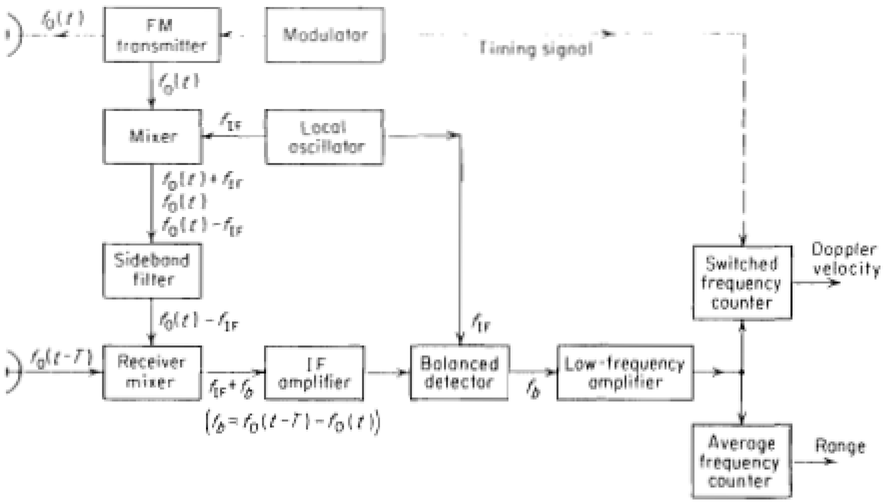
The band from 4.2 to 4.4 **GHz** is reserved for radio altimeters, although they have in the past operated at UHF. The transmitter power is relatively low and can be obtained from a CW magnetron, a backward-wave oscillator, or a reflex klystron, but these have been replaced by the solid state transmitter.

The altimeter can employ a simple homodyne receiver, but for better sensitivity and stability the superheterodyne is to be preferred whenever its more complex construction can be tolerated. A block diagram of the FM-CW radar with a sideband superheterodyne receiver is shown in Fig. 3.13. A portion of the frequency-modulated transmitted signal is applied to a mixer along with the oscillator signal. The selection of the local-oscillator frequency is a bit different from that in the usual superheterodyne receiver. The local-oscillator frequency should be the same as the intermediate frequency used in the receiver, whereas in the conventional superheterodyne the LO frequency is of the same order of magnitude as the RF signal. The output of the mixer consists of the varying transmitter frequency fo(t) plus two sideband frequencies, one on either side of fo(t) and separated from fo(t) by the local-oscillator frequency. The filter selects the lower sideband *fo(t)* - fiF and rejects the carrier and the upper sidehand. The sidehand that is passed by the filter is modulated in the same fashion as the transmitted signal. The sideband 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 frequency Fif+fb where *fb* is composed of the range frequency fr and the doppler velocity frequency fd. The IF signal is amplified and applied to the balanced detector along with the local-oscillator signal fIF. The output of the detector contains the beat frequency (range frequency and the doppler velocity frequency), which is amplified to a level where it can actuate the frequency-measuring circuits.

In Fig. 2.10, the output of the low-frequency amplifier is divided into two channels: one feeds an average-frequency counter to determine range, the other feeds a switched frequency counter to determine the doppler velocity (assuming *fr > fd)'* Only the averaging frequency counter need be used in an altimeter application, since the rate of change of altitude is usually small.

A target at short range will generally result in a strong signal at low frequency, while one at long range will result in a weak signal at high frequency. Therefore the frequency characteristic of the low-frequency amplifier in the FM-CW radar may be shaped to provide attenuation at the low frequencies corresponding to short ranges and large echo signals. Less attenuation is applied to the higher frequencies, where the echo signals are weaker.



The echo signal from an isolated target varies inversely as the fourth power of the range, as is well known from the radar equation. With this as a criterion, the gain of the low frequency amplifier should be made to increase at the rate of 12 dB/octave. The output of the amplifier would then be independent of the range, for constant target cross section. Amplifier response shaping is similar in function to sensitivity time control (STC) employed in conventional pulse radar. However, in the altimeter, the echo signal from an extended target such as the ground varies inversely as the square (rather than the fourth power) of the range, since the greater the range, the greater the echo area illuminated by the beam For extended targets, therefore, the low-frequency amplifier gain should increase 6 dB/octave. **A** compromise between the isolated (12-dB slope) and extended (6-dB slope) target echoes might be a characteristic with a slope of 9dBloctave. The constant output produced by shaping the doppler-amplifier frequency-response characteristic is not only helpful in lowering the dynamic range requirements of the frequency-measuring device, but the attenuation of the low frequencies effects a reduction of low-frequency interfering noise. Lowered gain at low altitudes also helps to reduce interference from unwanted reflections. The response at the upper end of the frequency characteristic is rapidly reduced for frequencies beyond that corresponding to maximum range. If there is a minimum target range, the response is also cut off at the low-frequency end, to further reduce the extraneous noise entering the receiver.

Another method of processing the range or height information from an altimeter so as to reduce the noise output from the receiver and improve the sensitivity uses a narrow bandwidth low-frequency amplifier with a feedback loop to maintain the beat frequency constant. When a fixed-frequency excursion (or deviation) is used, as in the usual altimeter, the beat frequency can vary over a considerable range of values. The low-frequency-amplifier bandwidth must be sufficiently wide to encompass the expected range of beat frequencies. Since the bandwidth is broader than need be to pass the signal energy, the signal-to-noise ratio is reduced and the receiver sensitivity degraded. Instead of maintaining the frequency excursion Δf constant and obtaining a varying beat frequency, Δf can be varied to maintain the beat frequency constant. The beat-frequency amplifier need only be wide enough to pass the received signal energy, thus reducing the amount of noise with which the signal must compete. The frequency excursion is maintained by a servomechanism to that value which permits the beat frequency to fall within the passband of the narrow filter. The value of the frequency excursion is then a measure of the altitude and may be substituted into Eq.

When used in the FM altimeter, the technique of servo-controlling the frequency excursion is usually applied at all altitudes above a predetermined minimum. Since the frequency excursion Δf is inversely proportional to range, the radar is better operated at very low altitudes in the more normal manner with a fixed Δf and hence a varying beat frequency.

2.13 MULTIPLE-FREQUENCY CW RADAR

Though the CW radar does not measure range, it is possible under some circumstances to do so by measuring the phase of the echo signal relative to the phase of the transmitted signal. Consider a CW radar radiating a single-frequency sine wave of the form sin $2\pi f0t$. (The amplitude of the signal is taken to be unity since it does not influence the result).The signal travels to the target at a range R and returns to the radar after a time T= $2R/c$. The echo signal received at the radar is sin $[2\pi f0(t - T)]$. If the transmitted and received signals are compared in a phase detector, the output **is proportional** to the phase difference between the two and is **A4** = $2\pi f0$ **T** $=4\pi foR/c$. *The* phase difference may therefore be used as a measure of the range, or

However, the measurement of the phase difference ***A4*** is unambiguous only if ***A4*** does not exceed ***2n*** radians. Substituting **A4** = ***2n*** into Eq. (3.17) gives the maximum unambiguous

range as ***112.*** At radar frequencies this unambiguous tange is much too small to be of practical
interest.