chapter

# 3

# MTI and Pulse Doppler Radar

## ~~3.1~~ INTRODUCTION TO DOPPLER AND MTI RADAR

The radars discussed in the previous chapter were required to detect targets in the presence of noise. In the real world, radars have to deal with more than receiver noise when detecting targets since they can also receive echoes from the natural environment such as land, sea, and weather. These echoes are called *clutter* since they can "clutter" the radar display. Clutter echoes can be many orders of magnitude larger than aircraft echoes. When an aircraft echo and a clutter echo appear in the same radar resolution cell, the aircraft might not be detectable. Chapter 7 describes the characteristics of clutter and discusses methods for reducing these unwanted echoes in order to detect the desired target echoes. However, the most powerful method for detecting moving targets in the midst of large clutter is by taking advantage of the doppler effect, which is the change of frequency of the radar echo signal due to the relative velocity between the radar and the moving target. The use of the doppler frequency shift with a pulse radar for the detection of moving targets in clutter is the subject of this chapter.

Radar deserves much credit for enabling the Allies (chiefly the United Kingdom and the United States) in the first half of World War II to prevail in the crucial air battles and night naval engagements against the Axis powers. Almost all of the radars used in World War II, however, were by today's standards relatively simple pulse systems that did not employ the doppler effect. Fortunately, these pulse radars were able to accomplish their mission without the use of doppler. This would not be possible today. All high-performance military air-defense radars and all civil air-traffic control radars for the detection and tracking of aircraft depend on the doppler frequency shift to separate the large clutter echoes from the much smaller echoes from moving targets. Clutter echoes can be greater than the desired target echoes by as much as 60 or 70 dB, or more, depending on the type of radar and the environment.

**MTI Radar and Pulse Doppler Radar** A pulse radar that employs the doppler shift for detecting moving targets is either an MTI (moving target indication) radar[1] or a pulse doppler radar.[2] The MTI radar has a pulse repetition frequency (prf) low enough to not have any range ambiguities as defined by Eq. (1.2), $R_{un} = c/f_p$. It does, however, have many ambiguities in the doppler domain. The pulse doppler radar, on the other hand, is just the opposite. As we shall see later in this chapter, it has a prf large enough to avoid doppler ambiguities, but it can have numerous range ambiguities. There is also a medium-prf pulse doppler that accepts both range and doppler ambiguities, as discussed in Sec. 3.9.

In addition to detecting moving targets in the midst of large clutter echoes, the doppler frequency shift has other important applications in radar; such as allowing CW (continuous wave) radar to detect moving targets and to measure radial velocity, synthetic aperture radar and inverse synthetic aperture radar for producing images of targets, and meteorological radars concerned with measuring wind shear. These other uses of the doppler frequency shift are not discussed in this chapter.

**Doppler Frequency Shift** The doppler effect used in radar is the same phenomenon that was introduced in high school physics courses to describe the changing pitch of an audible siren from an emergency vehicle as it travels toward or away from the listener. In this chapter we are interested in the doppler effect that changes the frequency of the electromagnetic signal that propagates from the radar to a moving target and back to the radar. If the range to the target is $R$, then the total number of wavelengths $\lambda$ in the two-way path from radar to target and return is $2R/\lambda$. Each wavelength corresponds to a phase change of $2\pi$ radians. The total phase change in the two-way propagation path is then

$$\phi = 2\pi \times \frac{2R}{\lambda} = 4\pi R/\lambda \qquad [3.1]$$

If the target is in motion relative to the radar, $R$ is changing and so will the phase. Differentiating Eq. (3.1) with respect to time gives the rate of change of phase, which is the angular frequency

$$\omega_d = \frac{d\phi}{dt} = \frac{4\pi}{\lambda}\frac{dR}{dt} = \frac{4\pi v_r}{\lambda} = 2\pi f_d \qquad [3.2]$$

where $v_r = dR/dt$ is the radial velocity (meters/second), or rate of change of range with time. If, as in Fig. 3.1, the angle between the target's velocity vector and the radar line of sight to the target is $\theta$, then $v_r = v \cos\theta$, where $v$ is the speed, or magnitude of the vector velocity. The rate of change of $\phi$ with time is the angular frequency $\omega_d = 2\pi f_d$, where $f_d$ is the *doppler frequency shift*. Thus from Eq. (3.2),

$$f_d = \frac{2v_r}{\lambda} = \frac{2f_t v_r}{c} \qquad [3.3]$$

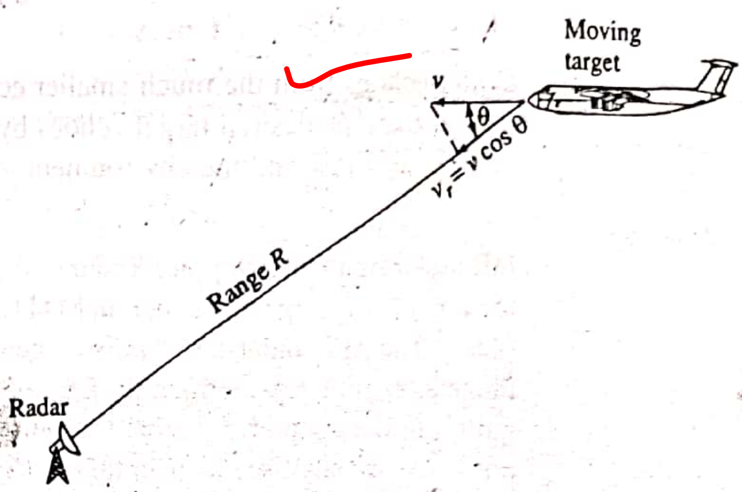


**Figure 3.1** Geometry of radar and target in deriving the doppler frequency shift. Radar, target, and direction of target travel all lie in the same plane in this illustration.

The radar frequency is $f_t = c/\lambda$, and the velocity of propagation $c = 3 \times 10^8$ m/s. If the doppler frequency is in hertz, the radial velocity in knots (abbreviated kt), and the radar wavelength in meters, we can write

$$f_d\,(\text{Hz}) = \frac{1.03 v_r\,(\text{kt})}{\lambda\,(\text{m})} \approx \frac{v_r\,(\text{kt})}{\lambda\,(\text{m})} \qquad [3.4]$$

The doppler frequency in hertz can also be approximately expressed as $3.43 v_r f_t$, where $f_t$ is the radar frequency in GHz and $v_r$ is in knots. A plot of the doppler frequency shift is shown in Fig. 3.2 as a function of the radial velocity and the various radar frequency bands.

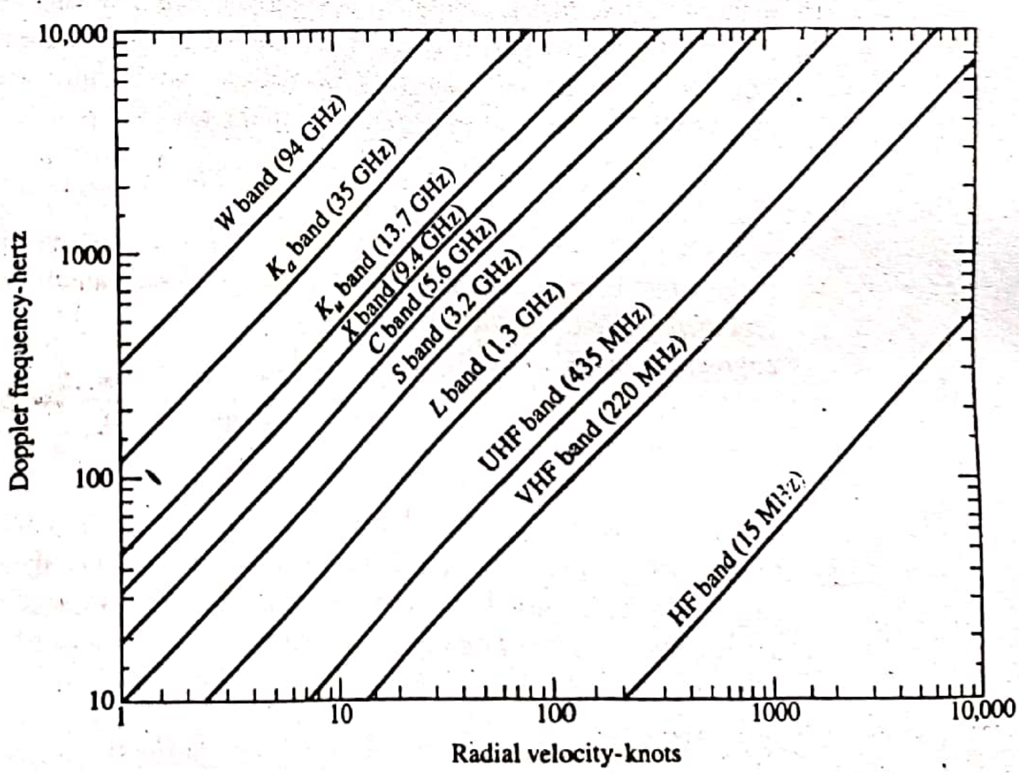


**Figure 3.2** Doppler frequency shift from a moving target as a function of the target's radial velocity and the radar frequency band.

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*Simple CW Doppler Radar* Before discussing the use of doppler in pulse radar, it is instructive to begin by considering the doppler frequency shift experienced with a CW radar. The block diagram of a very simple CW radar that utilizes the doppler frequency shift to detect moving targets is shown in Fig. 3.3a. Unlike a pulse radar, a CW radar transmits while it receives. Without the doppler shift produced by the movement of the target, the weak CW echo signal would not be detected in the presence of the much stronger signal from the transmitter. Filtering in the frequency domain is used to separate the weak doppler-shifted echo signal from the strong transmitter signal in a CW radar.

The transmitter generates a continuous (unmodulated) sinusoidal oscillation at frequency $f_t$, which is then radiated by the antenna. On reflection by a moving target, the transmitted signal is shifted by the doppler effect by an amount $\pm f_d$, as was given by Eq. (3.3). The plus sign applies when the distance between radar and target is decreasing (a closing target); thus, the echo signal from a closing target has a larger frequency than that which was transmitted. The minus sign applies when the distance is increasing (a receding target). To utilize the doppler frequency shift a radar must be able to recognize that the received echo signal has a frequency different from that which was transmitted. This is the function of that portion of the transmitter signal that finds its way (or leaks) into the receiver, as indicated in Fig. 3.3a. The transmitter leakage signal acts as a reference to determine that a frequency change has taken place. The detector, or mixer, multiplies the echo signal at a frequency $f_t \pm f_d$ with the transmitter leakage signal $f_t$. The doppler filter allows the difference frequency from the detector to pass and rejects the higher frequencies. The filter characteristic is shown in Fig. 3.3a just below the doppler-filter block. It has a lower frequency cutoff to remove from the receiver output the transmitter leakage signal and clutter echoes. The upper frequency cutoff is determined by the maximum

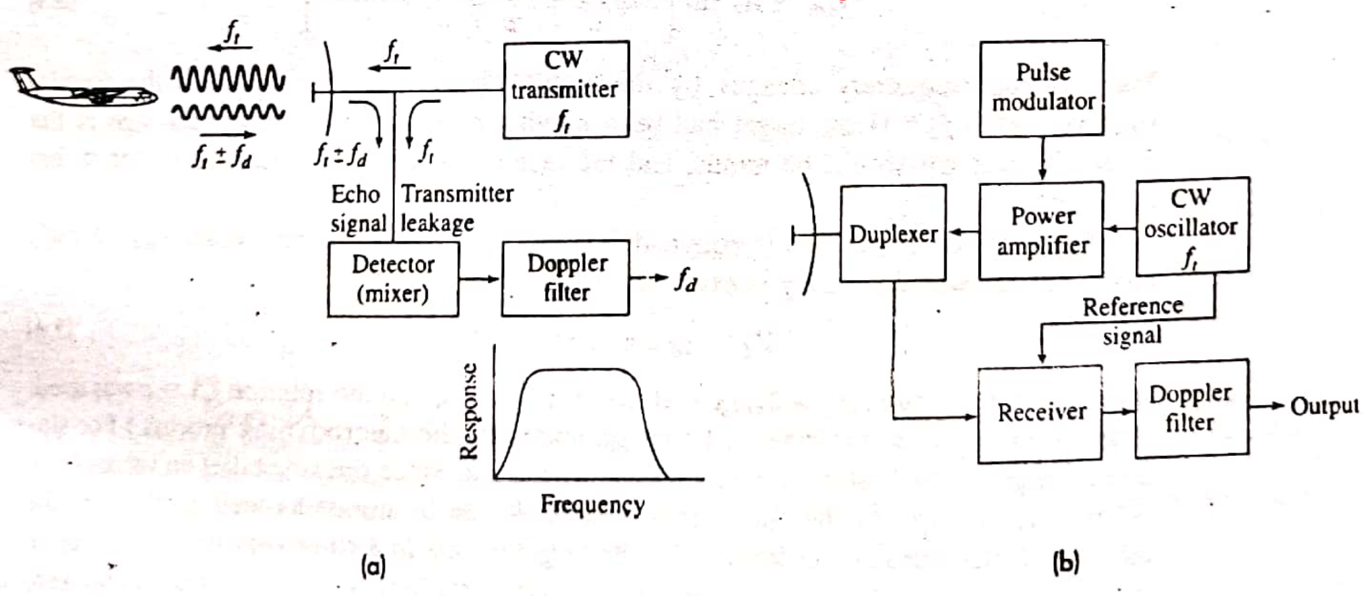


**Figure ~~3.3~~** (a) Simple CW radar block diagram that extracts the doppler frequency shift from a moving target and rejects stationary clutter echoes. The frequency response of the doppler filter is shown at the lower right. (b) Block diagram of a simple pulse radar that extracts the doppler frequency shift of the echo signal from a moving target.

radial velocity expected of moving targets. The doppler filter passes signals with a doppler frequency $f_d$ located within its pass band, but the sign of the doppler is lost along with the direction of the target motion. CW radars can be much more complicated than this simple example, but it is adequate as an introduction to a pulse radar that utilizes the doppler to detect moving targets in clutter.

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*Pulse Radar That Extracts the Doppler Frequency-Shifted Echo Signal* One cannot simply convert the CW radar of Fig. 3.3a to a pulse radar by turning the CW oscillator on and off to generate pluses. Generating pulses in this manner also removes the reference signal at the receiver, which is needed to recognize that a doppler frequency shift has occurred. One way to introduce the reference signal is illustrated in Fig. 3.3b. The output of a stable CW oscillator is amplified by a high-power amplifier. The amplifier is turned on and off (modulated) to generate a series of high-power pulses. The received echo signal is mixed with the output of the CW oscillator which acts as a *coherent reference* to allow recognition of any change in the received echo-signal frequency. By *coherent* is meant that the phase of the transmitted pulse is preserved in the reference signal. The change in frequency is detected (recognized) by the doppler filter.

The doppler frequency shift is derived next in a slightly different manner than was done earlier in this section. If the transmitted signal of frequency $f_t$ is represented as $A_t \sin(2\pi f_t t)$, the received signal is $A_r \sin[2\pi f_t(t - T_R)]$, where $A_t$ = amplitude of transmitted signal and $A_r$ = amplitude of the received echo signal. The round-trip time $T_R$ is equal to $2R/c$, where $R$ = range and $c$ = velocity of propagation. If the target is moving toward the radar, the range is changing and is represented as $R = R_0 - v_r t$, where $v_r$ = radial velocity (assumed constant). The geometry is the same as was shown in Fig. 3.1. With the above substitutions, the received signal is

$$V_{rec} = A_r \sin\left[2\pi f_t\left(1 + \frac{2v_r}{c}\right)t - \frac{4\pi f_t R_0}{c}\right] \qquad [3.5]$$

The received frequency changes by the factor $2f_t v_r/c = 2v_r/\lambda$, which is the doppler frequency shift $f_d$.* If the target had been moving away from the radar, the sign of the doppler frequency would be minus, and the received frequency would be less than that transmitted.

The received signal is heterodyned (mixed) with the reference signal $A_{ref} \sin 2\pi f_t t$ and the difference frequency is extracted, which is given as

$$V_d = A_d \cos(2\pi f_d t - 4\pi R_0/\lambda) \qquad [3.6]$$

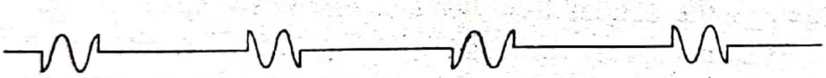
where $A_d$ = amplitude, $f_d = 2v_r/\lambda$ = doppler frequency, and the relation $f_t\lambda = c$ was used. (The cosine replaces the sine in the trigonometry of the heterodyning process.) For stationary targets $f_d = 0$ and the output signal is constant. Since the sine takes on values from +1 to −1, the sign of the clutter echo amplitude can be minus as well as plus. On the other hand, the echo signal from a moving target results in a time-varying output (due to the doppler shift) which is the basis for rejecting stationary clutter echoes (with zero doppler frequency) but allowing moving-target echoes to pass.

*The terms *doppler frequency shift*, *doppler frequency*, and *doppler shift* are used interchangeably in this chapter.

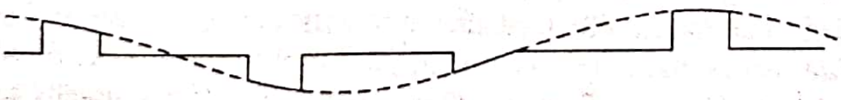
If the radar pulse width is long enough and if the target's doppler frequency is large enough, it may be possible to detect the doppler frequency shift on the basis of the frequency change within a single pulse. If Fig. 3.4a represents the RF (or IF) echo pulse train, Fig. 3.4b is the pulse train when there is a recognizable doppler frequency shift. To detect a doppler shift on the basis of a single pulse of width $\tau$ generally requires that there be at least one cycle of the doppler frequency $f_d$ within the pulse; or that $f_d\tau > 1$. This condition, however, is not usually met when detecting aircraft since the doppler frequency $f_d$ is generally much smaller than $1/\tau$. Thus the doppler effect cannot be utilized with a *single* short pulse in this case. Figure 3.4c is more representative of the doppler frequency for aircraft-detection radars. The doppler is shown sampled at the pulse repetition frequency (prf). More than one pulse is needed to recognize a change in the echo frequency due to the doppler effect. (Figure 3.4c is exaggerated in that the pulse width is usually small compared to the pulse repetition period. For example, $\tau$ might be of the order of 1 $\mu$s, and the pulse repetition period might be of the order of 1 ms.)

**Sweep-to-Sweep Subtraction and the Delay-Line Canceler** Figures 3.5a and b represent (in a very approximate manner) the bipolar video (both positive and negative amplitudes) from two successive sweeps* of an MTI (moving target indication) radar defined at the beginning of this chapter. The fixed clutter echoes in this figure remain the same from sweep to sweep. The output of the MTI radar is called *bipolar video,* since the signal has negative as well as positive values. (*Unipolar video* is rectified bipolar video with


(a)



(b)



(c)

**Figure 3.4** (a) Representation of the echo pulse train at either the RF or IF portion of the receiver; (b) video pulse train after the phase detector when the doppler frequency $f_d > 1/\tau$; (c) video pulse train for the doppler frequency $f_d < 1/\tau$, which is usually the case for aircraft-surveillance radar. The doppler frequency signal is shown dashed in (c), as if it were CW. Note that the pulses in (c) have an exaggerated width compared to the period of the doppler frequency.

**Sweep* as used here is what occurs in the time between two transmitted pulses, or the pulse repetition interval. It is a more convenient term to use than is *pulse repetition period,* but the latter is more descriptive. The term *sweep* originally signified the action of moving the electron beam of a cathode ray tube display across the face of the tube during the time of a pulse repetition.

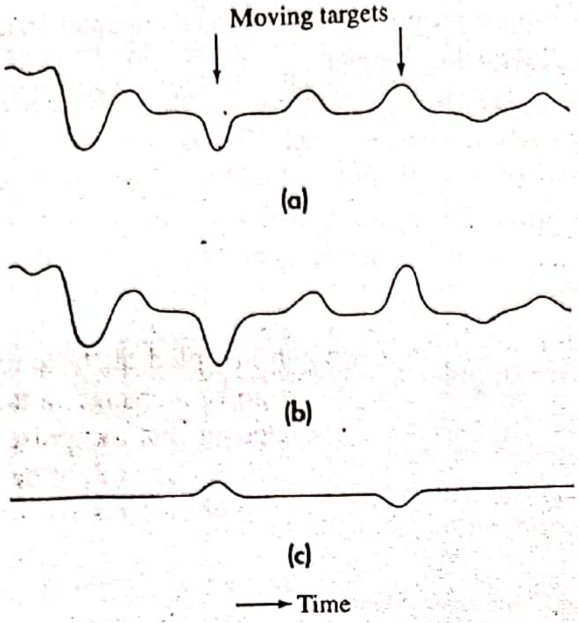
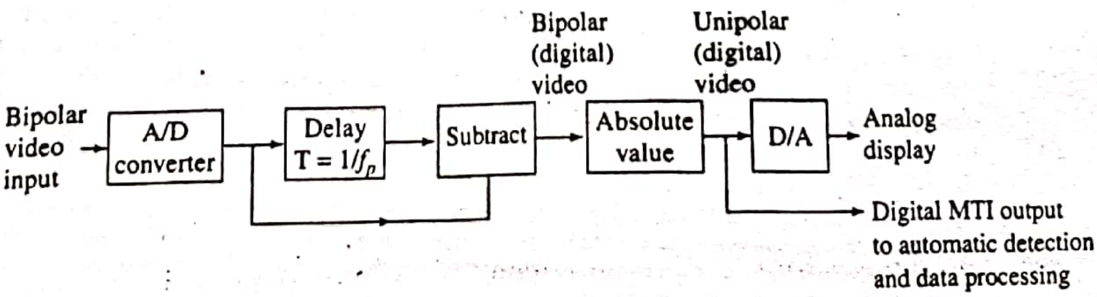



**Figure 3.5** Two successive sweeps, (a) and (b), of an MTI radar A-scope display (amplitude as a function of time, or range). Arrows indicate the positions of moving targets. When (b) is subtracted from (a), the result is (c) and echoes from stationary targets are canceled, leaving only moving targets.

only positive values.) If one sweep is subtracted from the previous sweep, fixed clutter echoes will cancel and will not be detected or displayed. On the other hand, 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 an uncancelled residue, as shown in Fig. 3.5c.

Subtraction of the echoes from two successive sweeps is accomplished in a *delay-line canceler,* as indicated by the diagram of Fig. 3.6. The output of the MTI receiver is digitized and is the input to the delay-line canceler (which performs the role of a doppler filter). The delay $T$ is achieved by storing the radar output from one pulse transmission, or sweep, in a digital memory for a time equal to the pulse repetition period so that $T = T_p = 1/f_p$. The output obtained after subtraction of two successive sweeps is *bipolar (digital) video* since the clutter echoes in the output contain both positive and negative amplitudes [as can be seen from Eq. (3.6) when $f_d = 0$]. It is usually called *video,* even though it is a series of digital words rather than an analog video signal. The absolute value

**Figure 3.6** Block diagram of a single delay-line canceler.



of the bipolar video is taken, which is then ***unipolar video.*** Unipolar video is needed if an analog display is used that requires positive signals only. The unipolar digital video is then converted to an analog signal by the digital-to-analog (D/A) converter if the processed signal is to be displayed on a PPI (plan position indicator). Alternatively, the digital signals may be used for automatically making the detection decision and for further data processing, such as automatic tracking and/or target recognition. The name *delay-line canceler* was originally applied when analog delay lines (usually acoustic) were used in the early MTI radars. Even though analog delay lines have been replaced by digital memories, the name delay-line canceler is still used to describe the operation of Fig. 3.6.

**MTI Radar Block Diagram** The block diagram of Fig. 3.3 illustrated the reference signal necessary for an MTI radar, but it is oversimplified. A slightly more elaborate block diagram of an MTI radar employing a power amplifier as the transmitter is shown in Fig. 3.7. The local oscillator of an MTI radar's superheterodyne receiver must be more stable than the local oscillator for a radar that does not employ doppler. If the phase of the local oscillator were to change significantly between pulses, an uncancelled clutter residue can result at the output of the delay-line canceler which might be mistaken for a moving target even though only clutter were present. To recognize the need for high stability, the local oscillator of an MTI receiver is called the *stalo,* which stands for *stable local oscillator.* The IF stage is designed as a matched filter, as is usually the case in radar. Instead of an amplitude detector, there is a *phase detector* following the IF stage. This is a mixer-like device that combines the received signal (at IF) and the reference signal from the *coho* so as to produce the difference between the received signal and the reference signal frequencies.[3] This difference is the doppler frequency. The name *coho* stands for

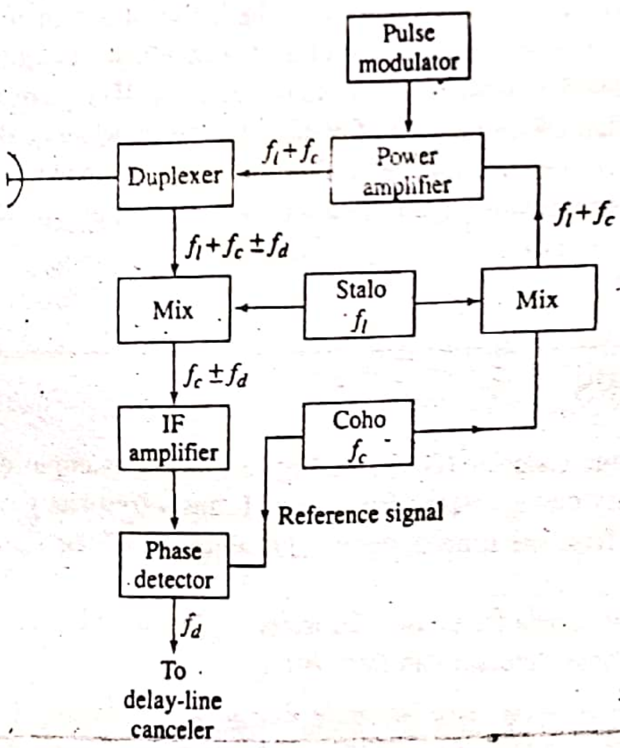



**Figure 3.7** Block diagram of an MTI radar that uses a power amplifier as the transmitter.