RF and Microwave Wireless Systems. Kai Chang
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CHAPTER SEVEN

Radar and Sensor Systems

7.1 INTRODUCTION AND CLASSIFICATIONS

Radar stands for radio detection and ranging. It operates by radiating electromagnetic waves and detecting the echo returned from the targets. The nature of an echo signal provides information about the target—range, direction, and velocity. Although radar cannot reorganize the color of the object and resolve the detailed features of the target like the human eye, it can see through darkness, fog and rain, and over a much longer range. It can also measure the range, direction, and velocity of the target.

A basic radar consists of a transmitter, a receiver, and a transmitting and receiving antenna. A very small portion of the transmitted energy is intercepted and reflected by the target. A part of the reflection is reradiated back to the radar (this is called back-reradiation), as shown in Fig. 7.1. The back-reradiation is received by the radar, amplified, and processed. The range to the target is found from the time it takes for the transmitted signal to travel to the target and back. The direction or angular position of the target is determined by the arrival angle of the returned signal. A directive antenna with a narrow beamwidth is generally used to find the direction. The relative motion of the target can be determined from the doppler shift in the carrier frequency of the returned signal.

Although the basic concept is fairly simple, the actual implementation of radar could be complicated in order to obtain the information in a complex environment. A sophisticated radar is required to search, detect, and track multiple targets in a hostile environment; to identify the target from land and sea clutter; and to discern the target from its size and shape. To search and track targets would require mechanical or electronic scanning of the antenna beam. For mechanical scanning, a motor or gimbal can be used, but the speed is slow. Phased arrays can be used for electronic scanning, which has the advantages of fast speed and a stationary antenna.

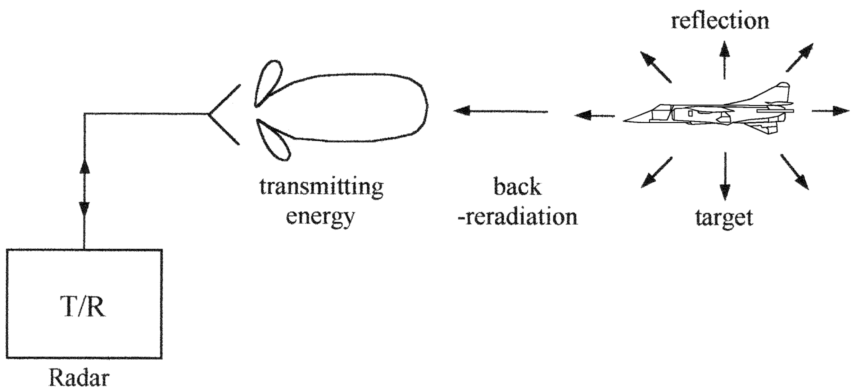

FIGURE 7.1 Radar and back-radiation: T/R is a transmitting and receiving module.

For some military radar, frequency agility is important to avoid lock-in or detection by the enemy.

Radar was originally developed during World War II for military use. Practical radar systems have been built ranging from megahertz to the optical region (laser radar, or ladar). Today, radar is still widely used by the military for surveillance and weapon control. However, increasing civil applications have been seen in the past 20 years for traffic control and navigation of aircraft, ships, and automobiles, security systems, remote sensing, weather forecasting, and industrial applications.

Radar normally operates at a narrow-band, narrow beamwidth (high-gain antenna) and medium to high transmitted power. Some radar systems are also known as sensors, for example, the intruder detection sensor/radar for home or office security. The transmitted power of this type of sensor is generally very low.

Radar can be classified according to locations of deployment, operating functions, applications, and waveforms.

1. *Locations*: airborne, ground-based, ship or marine, space-based, missile or smart weapon, etc.
2. *Functions*: search, track, search and track
3. *Applications*: traffic control, weather, terrain avoidance, collision avoidance, navigation, air defense, remote sensing, imaging or mapping, surveillance, reconnaissance, missile or weapon guidance, weapon fuses, distance measurement (e.g., altimeter), intruder detection, speed measurement (police radar), etc.
4. *Waveforms*: pulsed, pulse compression, continuous wave (CW), frequency-modulated continuous wave (FMCW)

Radar can also be classified as monostatic radar or bistatic radar. Monostatic radar uses a single antenna serving as a transmitting and receiving antenna. The transmitting and receiving signals are separated by a duplexer. Bistatic radar uses a separate transmitting and receiving antenna to improve the isolation between transmitter and receiver. Most radar systems are monostatic types.

Radar and sensor systems are big business. The two major applications of RF and microwave technology are communications and radar/sensor. In the following sections, an introduction and overview of radar systems are given.

7.2 RADAR EQUATION

The radar equation gives the range in terms of the characteristics of the transmitter, receiver, antenna, target, and environment [1, 2]. It is a basic equation for understanding radar operation. The equation has several different forms and will be derived in the following.

Consider a simple system configuration, as shown in Fig. 7.2. The radar consists of a transmitter, a receiver, and an antenna for transmitting and receiving. A duplexer is used to separate the transmitting and receiving signals. A circulator is shown in Fig. 7.2 as a duplexer. A switch can also be used, since transmitting and receiving are operating at different times. The target could be an aircraft, missile, satellite, ship, tank, car, person, mountain, iceberg, cloud, wind, raindrop, and so on. Different targets will have different radar cross sections (σ). The parameter P_t is the transmitted power and P_r is the received power. For a pulse radar, P_t is the peak pulse power. For a CW radar, it is the average power. Since the same antenna is used for transmitting and receiving, we have

$$G = G_t = G_r = \text{gain of antenna} \tag{7.1}$$

$$A_e = A_{\text{et}} = A_{\text{er}} = \text{effective area of antenna} \tag{7.2}$$

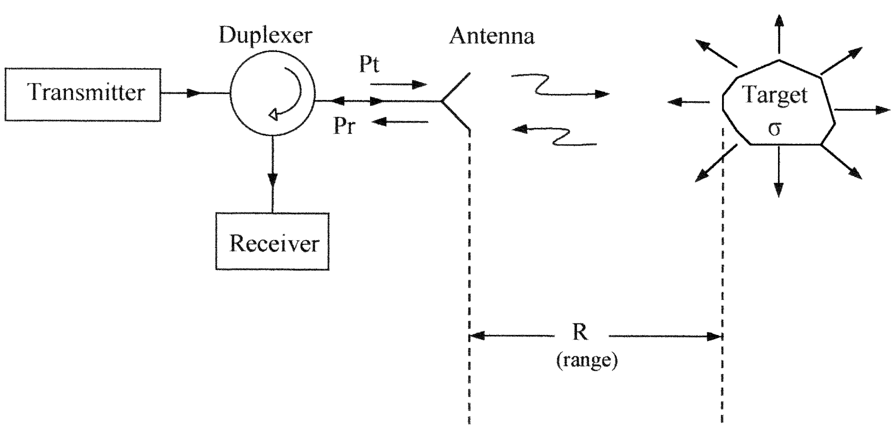

FIGURE 7.2 Basic radar system.

Note that

$$G_t = \frac{4\pi}{\lambda_0^2} A_{\mathrm{et}} \tag{7.3}$$

$$A_{\mathrm{et}} = \eta_a A_t \tag{7.4}$$

where λ_0 is the free-space wavelength, η_a is the antenna efficiency, and A_t is the antenna aperture size.

Let us first assume that there is no misalignment (which means the maximum of the antenna beam is aimed at the target), no polarization mismatch, no loss in the atmosphere, and no impedance mismatch at the antenna feed. Later, a loss term will be incorporated to account for the above losses. The target is assumed to be located in the far-field region of the antenna.

The power density (in watts per square meter) at the target location from an isotropic antenna is given by

$$\text{Power density} = \frac{P_t}{4\pi R^2} \tag{7.5}$$

For a radar using a directive antenna with a gain of G_t, the power density at the target location should be increased by G_t times. We have

$$\text{Power density at target location from a directive antenna} = \frac{P_t}{4\pi R^2} G_t \tag{7.6}$$

The measure of the amount of incident power intercepted by the target and reradiated back in the direction of the radar is denoted by the radar cross section σ, where σ is in square meters and is defined as

$$\sigma = \frac{\text{power backscattered to radar}}{\text{power density at target}} \tag{7.7}$$

Therefore, the backscattered power at the target location is [3]

$$\text{Power backscattered to radar (W)} = \frac{P_t G_t}{4\pi R^2} \sigma \tag{7.8}$$

A detailed description of the radar cross section is given in Section 7.4. The backscattered power decays at a rate of $1/4\pi R^2$ away from the target. The power density (in watts per square meters) of the echo signal back to the radar antenna location is

$$\text{Power density backscattered by target and returned to radar location} = \frac{P_t G_t}{4\pi R^2}\frac{\sigma}{4\pi R^2} \tag{7.9}$$

The radar receiving antenna captures only a small portion of this backscattered power. The captured receiving power is given by

$$P_r = \text{returned power captured by radar (W)} = \frac{P_t G_t}{4\pi R^2}\frac{\sigma}{4\pi R^2}A_{\text{er}} \tag{7.10}$$

Replacing A_{er} with $G_r\lambda_0^2/4\pi$, we have

$$P_r = \frac{P_t G_t}{4\pi R^2}\frac{\sigma}{4\pi R^2}\frac{G_r\lambda_0^2}{4\pi} \tag{7.11}$$

For monostatic radar, $G_r = G_t$, and Eq. (7.11) becomes

$$P_r = \frac{P_t G^2 \sigma \lambda_0^2}{(4\pi)^3 R^4} \tag{7.12}$$

This is the radar equation.

If the minimum allowable signal power is S_{min}, then we have the maximum allowable range when the received signal is $S_{i,\text{min}}$. Let $P_r = S_{i,\text{min}}$:

$$R = R_{\text{max}} = \left(\frac{P_t G^2 \sigma \lambda_0^2}{(4\pi)^3 S_{i,\text{min}}}\right)^{1/4} \tag{7.13}$$

where P_t = transmitting power (W)
G = antenna gain (linear ratio, unitless)
σ = radar cross section (m^2)
λ_0 = free-space wavelength (m)
$S_{i,\text{min}}$ = minimum receiving signal (W)
R_{max} = maximum range (m)

This is another form of the radar equation. The maximum radar range (R_{max}) is the distance beyond which the required signal is too small for the required system operation. The parameters $S_{i,\min}$ is the minimum input signal level to the radar receiver. The noise factor of a receiver is defined as

$$F = \frac{S_i/N_i}{S_o/N_o}$$

where S_i and N_i are input signal and noise levels, respectively, and S_o and N_o are output signal and noise levels, respectively, as shown in Fig. 7.3. Since $N_i = kTB$, as shown in Chapter 5, we have

$$S_i = kTBF\frac{S_o}{N_o} \tag{7.14}$$

where k is the Boltzmann factor, T is the absolute temperature, and B is the bandwidth. When $S_i = S_{i,\min}$, then $S_o/N_o = (S_o/N_o)_{\min}$. The minimum receiving signal is thus given by

$$S_{i,\min} = kTBF\left(\frac{S_o}{N_o}\right)_{\min} \tag{7.15}$$

Substituting this into Eq. (7.13) gives

$$R_{\max} = \left[\frac{P_t G^2 \sigma \lambda_0^2}{(4\pi)^3 kTBF\left(\frac{S_o}{N_o}\right)_{\min}}\right]^{\frac{1}{4}} \tag{7.16}$$

where $k = 1.38 \times 10^{-23}$ J/K, T is temperature in kelvin, B is bandwidth in hertz, F is the noise figure in ratio, $(S_o/N_o)_{\min}$ is minimum output signal-to-noise ratio in ratio. Here $(S_o/N_o)_{\min}$ is determined by the system performance requirements. For good probability of detection and low false-alarm rate, $(S_o/N_o)_{\min}$ needs to be high. Figure 7.4 shows the probability of detection and false-alarm rate as a function of (S_o/N_o). An S_o/N_o of 10 dB corresponds to a probability of detection of 76% and a false alarm probability of 0.1% (or 10^{-3}). An S_o/N_o of 16 dB will give a probability of detection of 99.99% and a false-alarm rate of 10^{-4}% (or 10^{-6}).

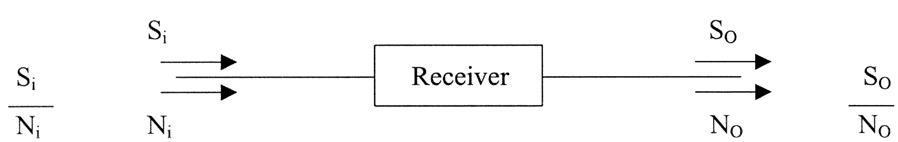

FIGURE 7.3 The SNR ratio of a receiver.

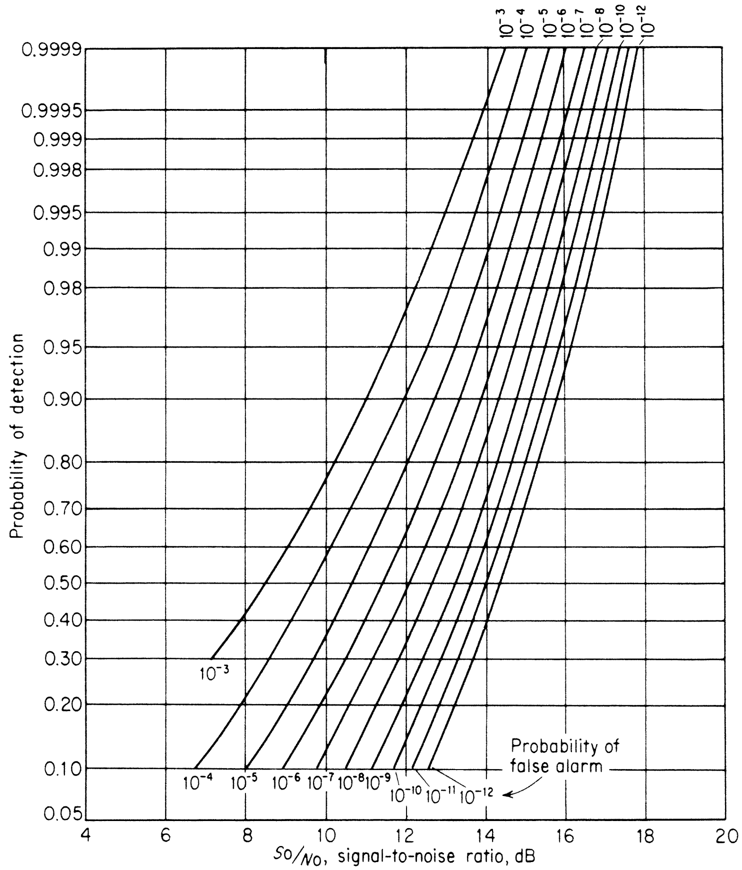

FIGURE 7.4 Probability of detection for a sine wave in noise as a function of the signal-to-noise (power) ratio and the probability of false alarm. (From reference [1], with permission from McGraw-Hill.)

7.3 RADAR EQUATION INCLUDING PULSE INTEGRATION AND SYSTEM LOSSES

The results given in Fig. 7.4 are for a single pulse only. However, many pulses are generally returned from a target on each radar scan. The integration of these pulses can be used to improve the detection and radar range. The number of pulses (n) on the target as the radar antenna scans through its beamwidth is

$$n = \frac{\theta_B}{\dot{\theta}_s} \times \text{PRF} = \frac{\theta_B}{\dot{\theta}_s} \frac{1}{T_p} \tag{7.17}$$

where θ_B is the radar antenna 3-dB beamwidth in degrees, $\dot{\theta}_s$ is the scan rate in degrees per second, PRF is the pulse repetition frequency in pulses per second, T_p is the period, and $\theta_B/\dot{\theta}_s$ gives the time that the target is within the 3-dB beamwidth of the radar antenna. At long distances, the target is assumed to be a point as shown in Fig. 7.5.

Example 7.1 A pulse radar system has a PRF = 300 Hz, an antenna with a 3-dB beamwidth of 1.5°, and an antenna scanning rate of 5 rpm. How many pulses will hit the target and return for integration?

Solution Use Eq. (7.17):

$$n = \frac{\theta_B}{\dot{\theta}_s} \times \text{PRF}$$

Now

$$\theta_B = 1.5^\circ \qquad \dot{\theta}_s = 5 \text{ rpm} = 5 \times 360^\circ/60 \text{ sec} = 30^\circ/\text{sec}$$
$$\text{PRF} = 300 \text{ cycles/sec}$$
$$n = \frac{1.5^\circ}{30^\circ/\text{sec}} \times 300/\text{sec} = 15 \text{ pulses}$$

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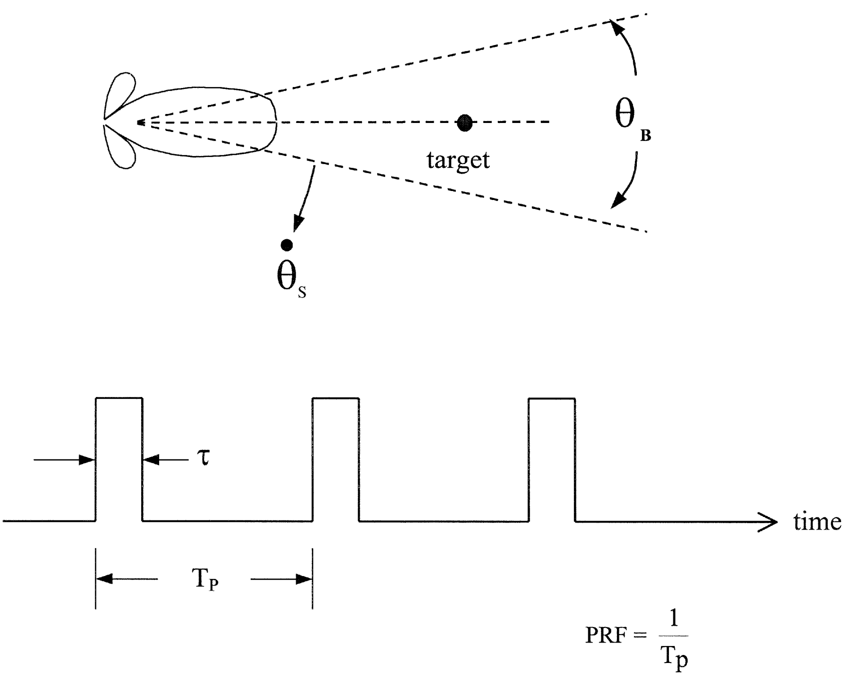

FIGURE 7.5 Concept for pulse integration.

Another system consideration is the losses involved due to pointing or misalignment, polarization mismatch, antenna feed or plumbing losses, antenna beam-shape loss, atmospheric loss, and so on [1]. These losses can be combined and represented by a total loss of L_{sys}. The radar equation [i.e., Eq. (7.16)] is modified to include the effects of system losses and pulse integration and becomes

$$R_{max} = \left[\frac{P_t G^2 \sigma \lambda_0^2 n}{(4\pi)^3 kTBF(S_o/N_o)_{min} L_{sys}} \right]^{1/4} \tag{7.18}$$

where P_t = transmitting power, W
G = antenna gain in ratio (unitless)
σ = radar cross section of target, m^2
λ_0 = free-space wavelength, m
n = number of hits integrated (unitless)
$k = 1.38 \times 10^{-23}$ J/K (Boltzmann constant) (J = W/sec)
T = temperature, K
B = bandwidth, Hz
F = noise factor in ratio (unitless)
$(S_o/N_o)_{min}$ = minimum receiver output signal-to-noise ratio (unitless)
L_{sys} = system loss in ratio (unitless)
R_{max} = radar range, m

For any distance R, we have

$$R = \left[\frac{P_t G^2 \sigma \lambda_0^2 n}{(4\pi)^3 kTBF(S_o/N_o) L_{sys}} \right]^{1/4} \tag{7.19}$$

As expected, the S_o/N_o is increased as the distance is reduced.

Example 7.2 A 35-GHz pulse radar is used to detect and track space debris with a diameter of 1 cm [radar cross section (RCS) = 4.45×10^{-5} m^2]. Calculate the maximum range using the following parameters:

P_t = 2000 kW (peaks)	T = 290 K
G = 66 dB	$(S_o/N_o)_{min}$ = 10 dB
B = 250 MHz	L_{sys} = 10 dB
F = 5 dB	n = 10

Solution Substitute the following values into Eq. (7.18):

$$
\begin{aligned}
P_t &= 2000 \text{ kW} = 2 \times 10^6 \text{ W} & k &= 1.38 \times 10^{-23} \text{ J/K} \\
G &= 66 \text{ dB} = 3.98 \times 10^6 & T &= 290 \text{ K} \\
B &= 250 \text{ MHz} = 2.5 \times 10^8 \text{ Hz} & \sigma &= 4.45 \times 10^{-5} \text{ m}^2 \\
F &= 5 \text{ dB} = 3.16 & \lambda_0 &= c/f_0 = 0.00857 \text{ m} \\
(S_o/N_o)_{\min} &= 10 \text{ dB} = 10 & L_{\text{sys}} &= 10 \text{ dB} = 10 \\
n &= 10
\end{aligned}
$$

Then we have

$$
\begin{aligned}
R_{\max} &= \left[\frac{P_t G^2 \sigma \lambda_0^2 n}{(4\pi)^3 kTBF(S_o/N_o)_{\min} L_{\text{sys}}} \right]^{1/4} \\
&= \left[\frac{2 \times 10^6 \text{ W} \times (3.98 \times 10^6)^2 \times 4.45 \times 10^{-5} \text{ m}^2 \times (0.00857 \text{ m})^2 \times 10}{(4\pi)^3 \times 1.38 \times 10^{-23} \text{ J/K} \times 290 \text{ K} \times 2.5 \times 10^8/\text{sec} \times 3.16 \times 10 \times 10} \right]^{1/4} \\
&= 3.58 \times 10^4 \text{ m} = 35.8 \text{ km}
\end{aligned}
$$

■

From Eq. (7.19), it is interesting to note that the strength of a target's echo is inversely proportional to the range to the fourth power ($1/R^4$). Consequently, as a distant target approaches, its echoes rapidly grow strong. The range at which they become strong enough to be detected depends on a number of factors such as the transmitted power, size or gain of the antenna, reflection characteristics of the target, wavelength of radio waves, length of time the target is in the antenna beam during each search scan, number of search scans in which the target appears, noise figure and bandwidth of the receiver, system losses, and strength of background noise and clutter. To double the range would require an increase in transmitting power by 16 times, or an increase of antenna gain by 4 times, or the reduction of the receiver noise figure by 16 times.

7.4 RADAR CROSS SECTION

The RCS of a target is the effective (or fictional) area defined as the ratio of backscattered power to the incident power density. The larger the RCS, the higher the power backscattered to the radar.

The RCS depends on the actual size of the target, the shape of the target, the materials of the target, the frequency and polarization of the incident wave, and the incident and reflected angles relative to the target. The RCS can be considered as the effective area of the target. It does not necessarily have a simple relationship to the physical area, but the larger the target size, the larger the cross section is likely to be. The shape of the target is also important in determining the RCS. As an example, a corner reflector reflects most incident waves to the incoming direction, as shown in Fig. 7.6, but a stealth bomber will deflect the incident wave. The building material of

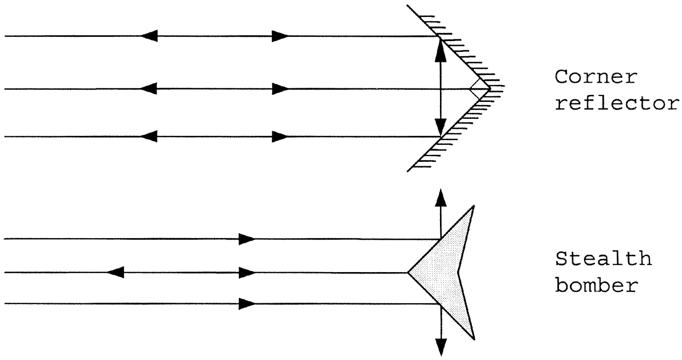

FIGURE 7.6 Incident and reflected waves.

the target is obviously an influence on the RCS. If the target is made of wood or plastics, the reflection is small. As a matter of fact, Howard Hughes tried to build a wooden aircraft (*Spruce Goose*) during World War II to avoid radar detection. For a metal body, one can coat the surface with absorbing materials (lossy dielectrics) to reduce the reflection. This is part of the reason that stealth fighters/bombers are invisible to radar.

The RCS is a strong function of frequency. In general, the higher the frequency, the larger the RCS. Table 7.1, comparing radar cross sections for a person [4] and various aircrafts, shows the necessity of using a higher frequency to detect small targets. The RCS also depends on the direction as viewed by the radar or the angles of the incident and reflected waves. Figure 7.7 shows the experimental RCS of a B-26 bomber as a function of the azimuth angle [5]. It can be seen that the RCS of an aircraft is difficult to specify accurately because of the dependence on the viewing angles. An average value is usually taken for use in computing the radar equation.

TABLE 7.1 Radar Cross Sections as a Function of Frequency

	Frequency (GHz)		σ, m^2
		(a) *For a Person*	
	0.410		0.033–2.33
	1.120		0.098–0.997
	2.890		0.140–1.05
	4.800		0.368–1.88
	9.375		0.495–1.22
Aircraft	UHF	*S*-band, 2–4 GHz	*X*-band, 8–12 GHz
		(b) *For Aircraft*	
Boeing 707	10 m^2	40 m^2	60 m^2
Boeing 747	15 m^2	60 m^2	100 m^2
Fighter	—	—	1 m^2

FIGURE 7.7 Experimental RCS of the B-26 bomber at 3 GHz as a function of azimuth angle [5].

For simple shapes of targets, the RCS can be calculated by solving Maxwell's equations meeting the proper boundary conditions. The determination of the RCS for more complicated targets would require the use of numerical methods or measurements. The RCS of a conducting sphere or a long thin rod can be calculated exactly. Figure 7.8 shows the RCS of a simple sphere as a function of its circumference measured in wavelength. It can be seen that at low frequency or when the sphere is small, the RCS varies as λ^{-4}. This is called the Rayleigh region, after Lord Rayleigh. From this figure, one can see that to observe a small raindrop would require high radar frequencies. For electrically large spheres (i.e., $a/\lambda \gg 1$), the RCS of the sphere is close to πa^2. This is the optical region where geometrical optics are valid. Between the optical region and the Rayleigh region is the Mie or resonance region. In this region, the RCS oscillates with frequency due to phase cancellation and the addition of various scattered field components.

Table 7.2 lists the approximate radar cross sections for various targets at microwave frequencies [1]. For accurate system design, more precise values

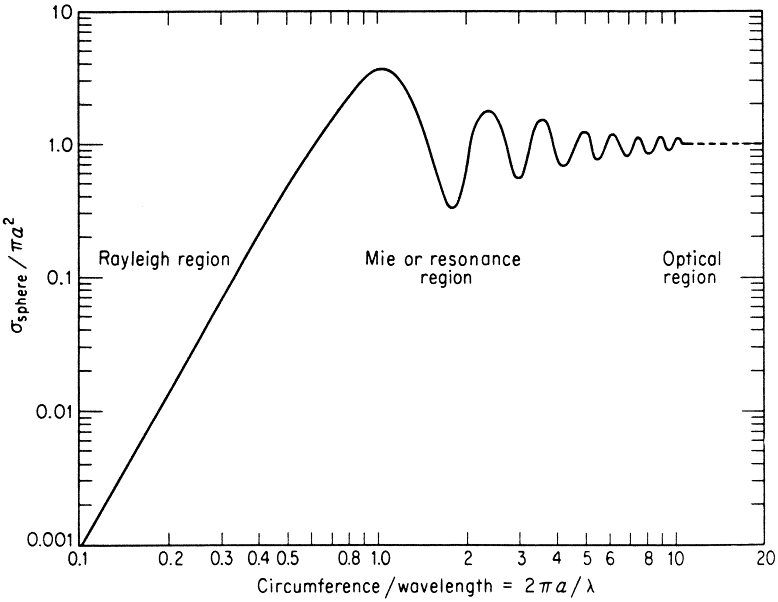

FIGURE 7.8 Radar cross section of the sphere: a = radius; λ = wavelength.

TABLE 7.2 Examples of Radar Cross Sections at Microwave Frequencies

	Cross Section (m^3)
Conventional, unmanned winged missile	0.5
Small, single engine aircraft	1
Small fighter, or four-passenger jet	2
Large fighter	6
Medium bomber or medium jet airliner	20
Large bomber or large jet airliner	40
Jumbo jet	100
Small open boat	0.02
Small pleasure boat	2
Cabin cruiser	10
Pickup truck	200
Automobile	100
Bicycle	2
Man	1
Bird	0.01
Insect	10^{-5}

Source: From reference [1], with permission from McGraw-Hill.

should be obtained from measurements or numerical methods for radar range calculation. The RCS can also be expressed as dBSm, which is decibels relative to 1 m^2. An RCS of 10 m^2 is 10 dBSm, for example.

7.5 PULSE RADAR

A pulse radar transmits a train of rectangular pulses, each pulse consisting of a short burst of microwave signals, as shown in Fig. 7.9. The pulse has a width τ and a pulse repetition period $T_p = 1/f_p$, where f_p is the pulse repetition frequency (PRF) or pulse repetition rate. The duty cycle is defined as

$$\text{Duty cycle} = \frac{\tau}{T_p} \times 100\% \tag{7.20a}$$

The average power is related to the peak power by

$$P_{\text{av}} = \frac{P_t \tau}{T_p} \tag{7.20b}$$

where P_t is the peak pulse power.

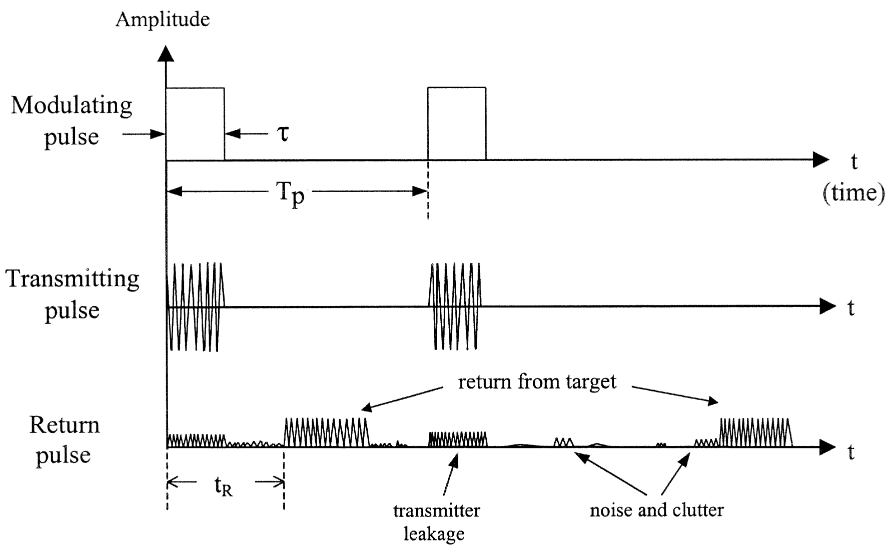

FIGURE 7.9 Modulating, transmitting, and return pulses.

The transmitting pulse hits the target and returns to the radar at some time t_R later depending on the distance, where t_R is the round-trip time of a pulsed microwave signal. The target range can be determined by

$$R = \tfrac{1}{2} c t_R \tag{7.21}$$

where c is the speed of light, $c = 3 \times 10^8$ m/sec in free space.

To avoid range ambiguities, the maximum t_R should be less than T_p. The maximum range without ambiguity requires

$$R'_{\max} = \frac{cT_p}{2} = \frac{c}{2f_p} \tag{7.22}$$

Here, $R'_{\max}$ can be increased by increasing T_p or reducing f_p, where f_p is normally ranged from 100 to 100 kHz to avoid the range ambiguity.

A matched filter is normally designed to maximize the output peak signal to average noise power ratio. The ideal matched-filter receiver cannot always be exactly realized in practice but can be approximated with practical receiver circuits. For optimal performance, the pulse width is designed such that [1]

$$B\tau \approx 1 \tag{7.23}$$

where B is the bandwidth.

Example 7.3 A pulse radar transmits a train of pulses with $\tau = 10\ \mu\text{s}$ and $T_p = 1$ msec. Determine the PRF, duty cycle, and optimum bandwidth.

Solution The pulse repetition frequency is given as

$$\text{PRF} = \frac{1}{T_p} = \frac{1}{1\ \text{msec}} = 10^3\ \text{Hz}$$

$$\text{Duty cycle} = \frac{\tau}{T_p} \times 100\% = \frac{10\ \mu\text{sec}}{1\ \text{msec}} \times 100\% = 1\%$$

$$B = \frac{1}{\tau} = 0.1\ \text{MHz}$$

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Figure 7.10 shows an example block diagram for a pulse radar system. A pulse modulator is used to control the output power of a high-power amplifier. The modulation can be accomplished either by bias to the active device or by an external $p{-}i{-}n$ or ferrite switch placed after the amplifier output port. A small part of the CW oscillator output is coupled to the mixer and serves as the LO to the mixer. The majority of output power from the oscillator is fed into an upconverter where it mixes with an IF signal f_{IF} to generate a signal of $f_0 + f_{IF}$. This signal is amplified by multiple-stage power amplifiers (solid-state devices or tubes) and passed through a duplexer to the antenna for transmission to free space. The duplexer could be a circulator or a transmit/receive (T/R) switch. The circulator diverts the signal moving from the power amplifier to the antenna. The receiving signal will be directed to the mixer. If it is a single-pole, double-throw (SPDT) T/R switch, it will be connected to the antenna and to the power amplifier in the transmitting mode and to the mixer in the receiving mode. The transmitting signal hits the target and returns to the radar antenna. The return signal will be delayed by t_R, which depends on the target range. The return signal frequency will be shifted by a doppler frequency (to be discussed in the next section) f_d if there is a relative speed between the radar and target. The return signal is mixed with f_0 to generate the IF signal of $f_{IF} \pm f_d$. The speed of the target can be determined from f_d. The IF signal is amplified, detected, and processed to obtain the range and speed. For a search radar, the display shows a polar plot of target range versus angle while the antenna beam is rotated for 360° azimuthal coverage.

To separate the transmitting and receiving ports, the duplexer should provide good isolation between the two ports. Otherwise, the leakage from the transmitter to the receiver is too high, which could drown the target return or damage the receiver. To protect the receiver, the mixer could be biased off during the transmitting mode, or a limiter could be added before the mixer. Another point worth mentioning is that the same oscillator is used for both the transmitter and receiver in this example. This greatly simplifies the system and avoids the frequency instability and drift problem. Any frequency drift in f_0 in the transmitting signal will be canceled out in the mixer. For short-pulse operation, the power amplifier can generate considerably higher

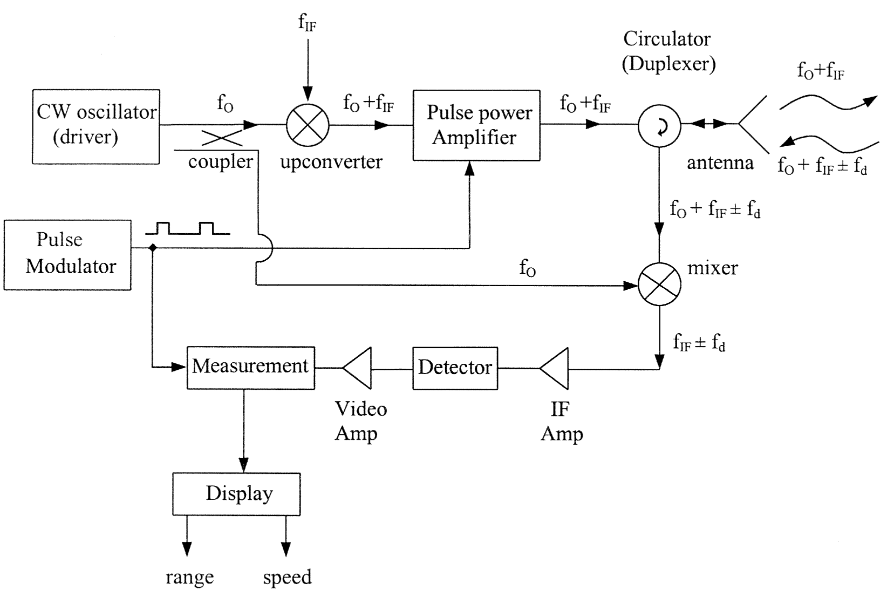

FIGURE 7.10 Typical pulse radar block diagram.

peak power than the CW amplifier. Using tubes, hundreds of kilowatts or megawatts of peak power are available. The power is much lower for solid-state devices in the range from tens of watts to kilowatts.

7.6 CONTINUOUS-WAVE OR DOPPLER RADAR

Continuous-wave or doppler radar is a simple type of radar. It can be used to detect a moving target and determine the velocity of the target. It is well known in acoustics and optics that if there is a relative movement between the source (oscillator) and the observer, an apparent shift in frequency will result. The phenomenon is called the doppler effect, and the frequency shift is the doppler shift. Doppler shift is the basis of CW or doppler radar.

Consider that a radar transmitter has a frequency f_0 and the relative target velocity is v_r. If R is the distance from the radar to the target, the total number of wavelengths contained in the two-way round trip between the target and radar is $2R/\lambda_0$. The total angular excursion or phase ϕ made by the electromagnetic wave during its transit to and from the target is

$$\phi = 2\pi \frac{2R}{\lambda_0} \tag{7.24}$$

The multiplication by 2π is from the fact that each wavelength corresponds to a 2π phase excursion. If the target is in relative motion with the radar, R and ϕ are continuously changing. The change in ϕ with respect to time gives a frequency shift ω_d. The doppler angular frequency shift ω_d is given by

$$\omega_d = 2\pi f_d = \frac{d\phi}{dt} = \frac{4\pi}{\lambda_0}\frac{dR}{dt} = \frac{4\pi}{\lambda_0} v_r \tag{7.25}$$

Therefore

$$f_d = \frac{2}{\lambda_0} v_r = \frac{2v_r}{c} f_0 \tag{7.26}$$

where f_0 is the transmitting signal frequency, c is the speed of light, and v_r is the relative velocity of the target. Since v_r is normally much smaller than c, f_d is very small unless f_0 is at a high (microwave) frequency. The received signal frequency is $f_0 \pm f_d$. The plus sign is for an approaching target and the minus sign for a receding target.

For a target that is not directly moving toward or away from a radar as shown in Fig. 7.11, the relative velocity v_r may be written as

$$v_r = v \cos\theta \tag{7.27}$$

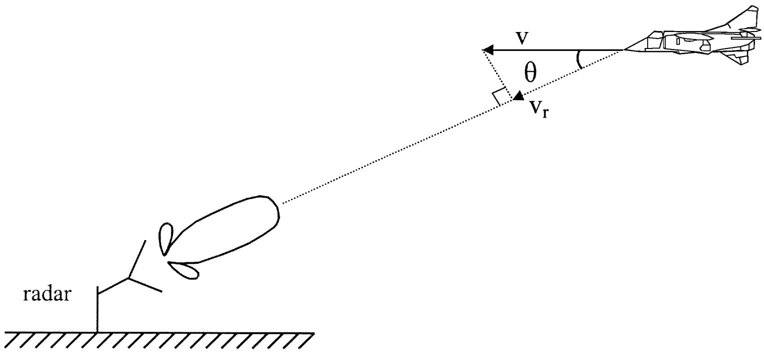

FIGURE 7.11 Relative speed calculation.

where v is the target speed and θ is the angle between the target trajectory and the line joining the target and radar. It can be seen that

$$v_r = \begin{cases} v & \text{if } \theta = 0 \\ 0 & \text{if } \theta = 90^\circ \end{cases}$$

Therefore, the doppler shift is zero when the trajectory is perpendicular to the radar line of sight.

Example 7.4 A police radar operating at 10.5 GHz is used to track a car's speed. If a car is moving at a speed of 100 km/h and is directly aproaching the police radar, what is the doppler shift frequency in hertz?

Solution Use the following parameters:

$$f_0 = 10.5 \text{ GHz}$$
$$\theta = 0^\circ$$
$$v_r = v = 100 \text{ km/h} = 100 \times 1000 \text{ m/3600 sec} = 27.78 \text{ m/sec}$$

Using Eq. (7.26), we have

$$f_d = \frac{2v_r}{c} f_0 = \frac{2 \times 27.78 \text{ m/sec}}{3 \times 10^8 \text{ m/sec}} \times 10.5 \times 10^9 \text{ Hz}$$
$$= 1944 \text{ Hz}$$ ■

Continuous-wave radar is relatively simple as compared to pulse radar, since no pulse modulation is needed. Figure 7.12 shows an example block diagram. A CW source/oscillator with a frequency f_0 is used as a transmitter. Similar to the pulse case, part of the CW oscillator power can be used as the LO for the mixer. Any frequency drift will be canceled out in the mixing action. The transmitting signal will

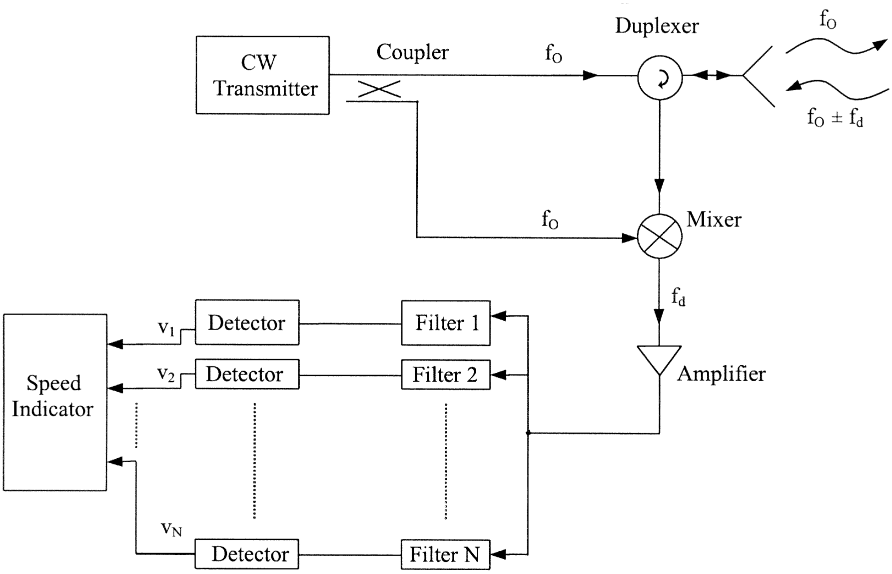

FIGURE 7.12 Doppler or CW radar block diagram.

pass through a duplexer (which is a circulator in Fig. 7.12) and be transmitted to free space by an antenna. The signal returned from the target has a frequency $f_0 \pm f_d$. This returned signal is mixed with the transmitting signal f_0 to generate an IF signal of f_d. The doppler shift frequency f_d is then amplified and filtered through the filter bank for frequency identification. The filter bank consists of many narrow-band filters that can be used to identify the frequency range of f_d and thus the range of target speed. The narrow-band nature of the filter also improves the SNR of the system. Figure 7.13 shows the frequency responses of these filters.

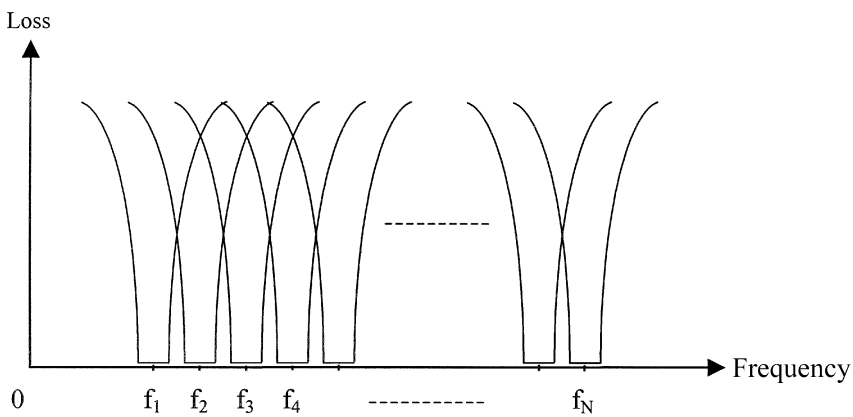

FIGURE 7.13 Frequency response characteristics of the filter bank.

Isolation between the transmitter and receiver for a single antenna system can be accomplished by using a circulator, hybrid junction, or separate polarization. If better isolation is required, separate antennas for transmitting and receiving can be used.

Since f_d is generally less than 1 MHz, the system suffers from the flicker noise ($1/f$ noise). To improve the sensitivity, an intermediate-frequency receiver system can be used. Figure 7.14 shows two different types of such a system. One uses a single antenna and the other uses two antennas.

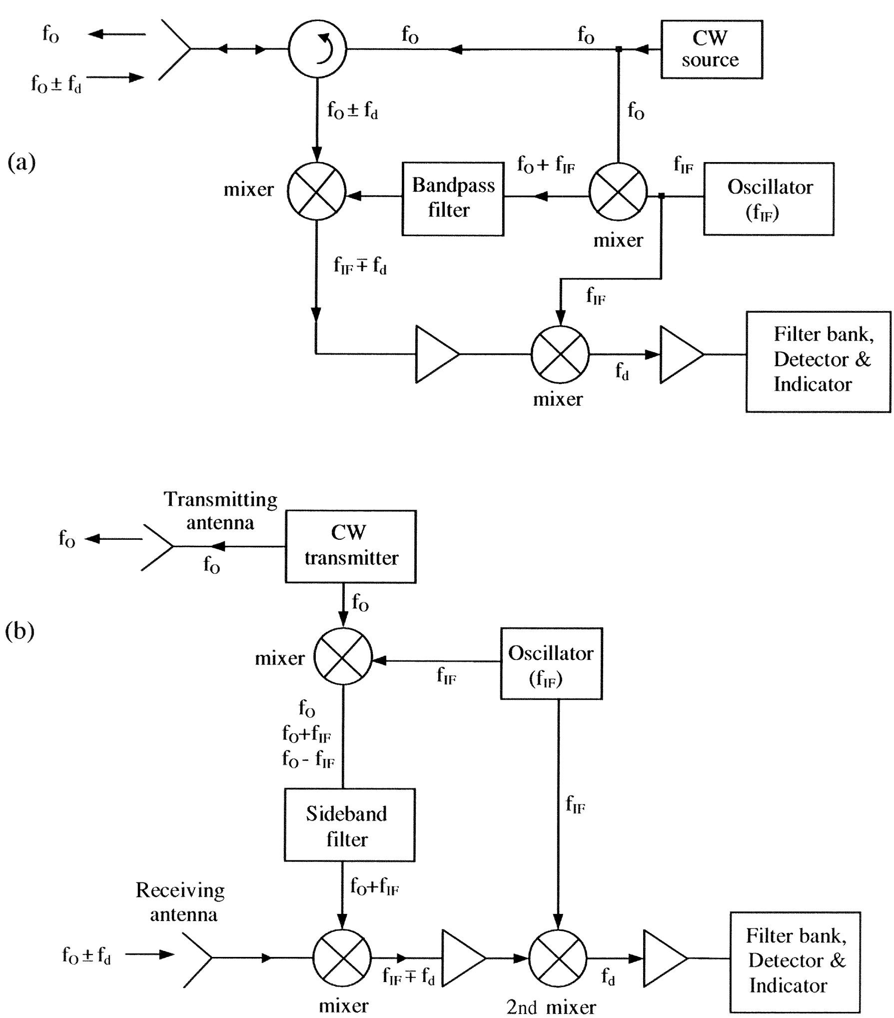

FIGURE 7.14 CW radar using superheterodyne technique to improve sensitivity: (*a*) single-antenna system; (*b*) two-antenna system.

The CW radar is simple and does not require modulation. It can be built at a low cost and has found many commercial applications for detecting moving targets and measuring their relative velocities. It has been used for police speed-monitoring radar, rate-of-climb meters for aircraft, traffic control, vehicle speedometers, vehicle brake sensors, flow meters, docking speed sensors for ships, and speed measurement for missiles, aircraft, and sports.

The output power of a CW radar is limited by the isolation that can be achieved between the transmitter and receiver. Unlike the pulse radar, the CW radar transmitter is on when the returned signal is received by the receiver. The transmitter signal noise leaked to the receiver limits the receiver sensitivity and the range performance. For these reasons, the CW radar is used only for short or moderate ranges. A two-antenna system can improve the transmitter-to-receiver isolation, but the system is more complicated.

Although the CW radar can be used to measure the target velocity, it does not provide any range information because there is no timing mark involved in the transmitted waveform. To overcome this problem, a frequency-modulated CW (FMCW) radar is described in the next section.

7.7 FREQUENCY-MODULATED CONTINUOUS-WAVE RADAR

The shortcomings of the simple CW radar led to the development of FMCW radar. For range measurement, some kind of timing information or timing mark is needed to recognize the time of transmission and the time of return. The CW radar transmits a single frequency signal and has a very narrow frequency spectrum. The timing mark would require some finite broader spectrum by the application of amplitude, frequency, or phase modulation.

A pulse radar uses an amplitude-modulated waveform for a timing mark. Frequency modulation is commonly used for CW radar for range measurement. The timing mark is the changing frequency. The transmitting time is determined from the difference in frequency between the transmitting signal and the returned signal.

Figure 7.15 shows a block diagram of an FMCW radar. A voltage-controlled oscillator is used to generate an FM signal. A two-antenna system is shown here for transmitter–receiver isolation improvement. The returned signal is $f_1 \pm f_d$. The plus sign stands for the target moving toward the radar and the minus sign for the target moving away from the radar. Let us consider the following two cases: The target is stationary, and the target is moving.

7.7.1 Stationary-Target Case

For simplicity, a stationary target is first considered. In this case, the doppler frequency shift (f_d) is equal to zero. The transmitter frequency is changed as a function of time in a known manner. There are many different forms of frequency–time variations. If the transmitter frequency varies linearly with time, as shown by the solid line in Fig. 7.16, a return signal (dotted line) will be received at t_R or $t_2 - t_1$ time later with $t_R = 2R/c$. At the time t_1, the transmitter radiates a signal with frequency f_1. When this signal is received at t_2, the transmitting frequency has been changed to f_2. The beat signal generated by the mixer by mixing f_2 and f_1 has a frequency of $f_2 - f_1$. Since the target is stationary, the beat signal (f_b) is due to the range only. We have

$$f_R = f_b = f_2 - f_1 \tag{7.28}$$

From the small triangle shown in Fig. 7.16, the frequency variation rate is equal to the slope of the triangle:

$$\dot{f} = \frac{\Delta f}{\Delta t} = \frac{f_2 - f_1}{t_2 - t_1} = \frac{f_b}{t_R} \tag{7.29}$$

The frequency variation rate can also be calculated from the modulation rate (frequency). As shown in Fig. 7.16, the frequency varies by $2\,\Delta f$ in a period of T_m, which is equal to $1/f_m$, where f_m is the modulating rate and T_m is the period. One can write

$$\dot{f} = \frac{2\,\Delta f}{T_m} = 2f_m\,\Delta f \tag{7.30}$$

Combining Eqs. (7.29) and (7.30) gives

$$f_b = f_R = t_R\dot{f} = 2f_m t_R\,\Delta f \tag{7.31}$$

Substituting $t_R = 2R/c$ into (7.31), we have

$$R = \frac{cf_R}{4f_m\,\Delta f} \tag{7.32}$$

The variation of frequency as a function of time is known, since it is set up by the system design. The modulation rate (f_m) and modulation range (Δf) are known. From Eq. (7.32), the range can be determined by measuring f_R, which is the IF beat frequency at the receiving time (i.e., t_2).

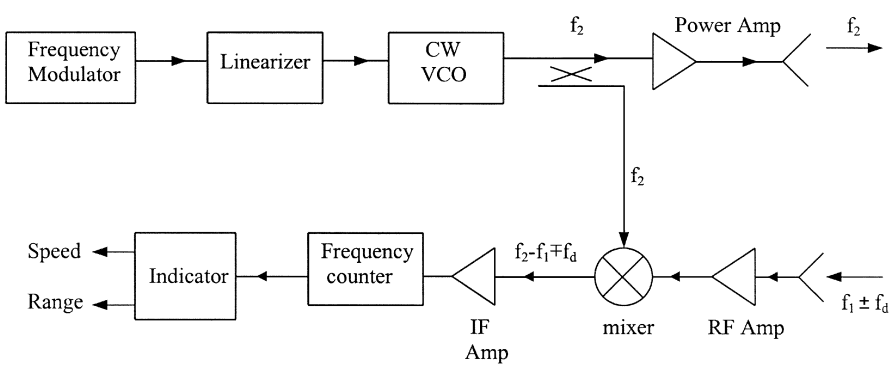

FIGURE 7.15 Block diagram of an FMCW radar.

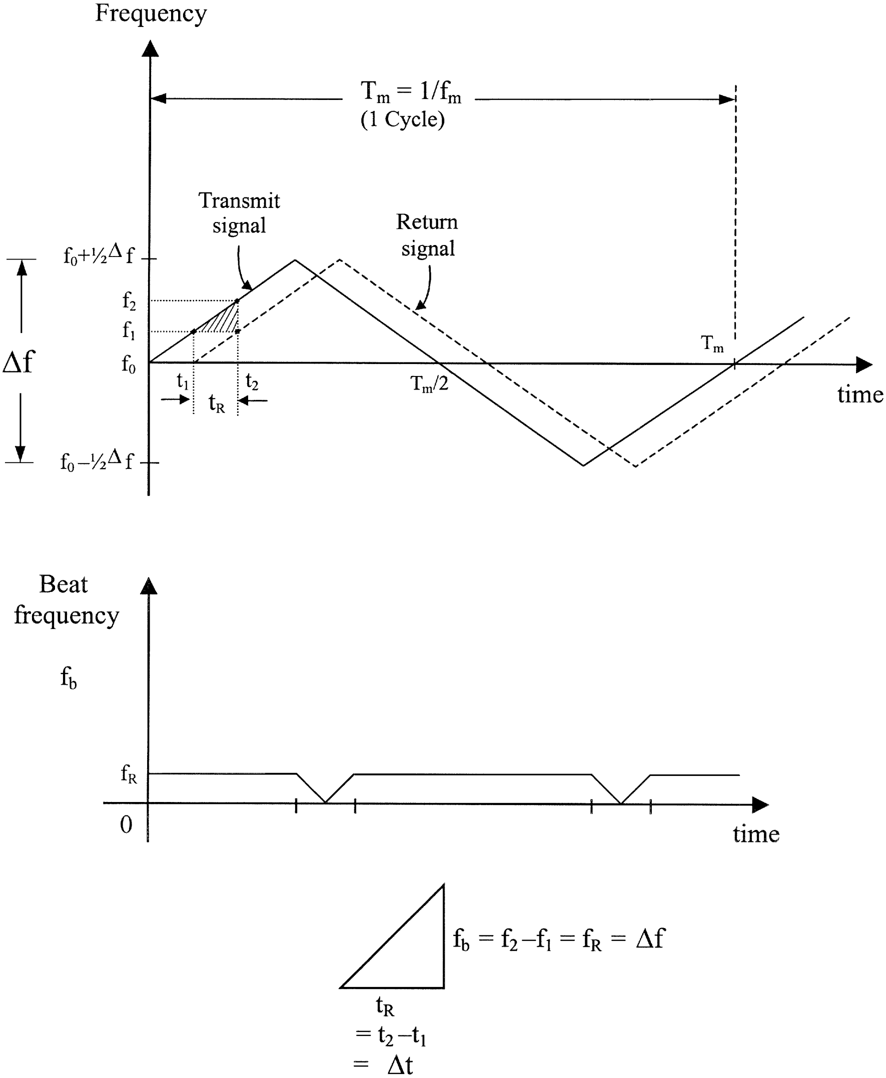

FIGURE 7.16 An FMCW radar with a triangular frequency modulation waveform for a stationary target case.

7.7.2 Moving-Target Case

If the target is moving, a doppler frequency shift will be superimposed on the range beat signal. It would be necessary to separate the doppler shift and the range information. In this case, f_d is not equal to zero, and the output frequency from the mixer is $f_2 - f_1 \mp f_d$, as shown in Fig. 7.15. The minus sign is for the target moving toward the radar, and the plus sign is for the target moving away from the radar.

Figure 7.17(*b*) shows the waveform for a target moving toward radar. For comparison, the waveform for a stationary target is also shown in Fig. 7.17(*a*). During the period when the frequency is increased, the beat frequency is

$$f_b\ (\text{up}) = f_R - f_d \tag{7.33}$$

During the period when the frequency is decreased, the beat frequency is

$$f_b\ (\text{down}) = f_R + f_d \tag{7.34}$$

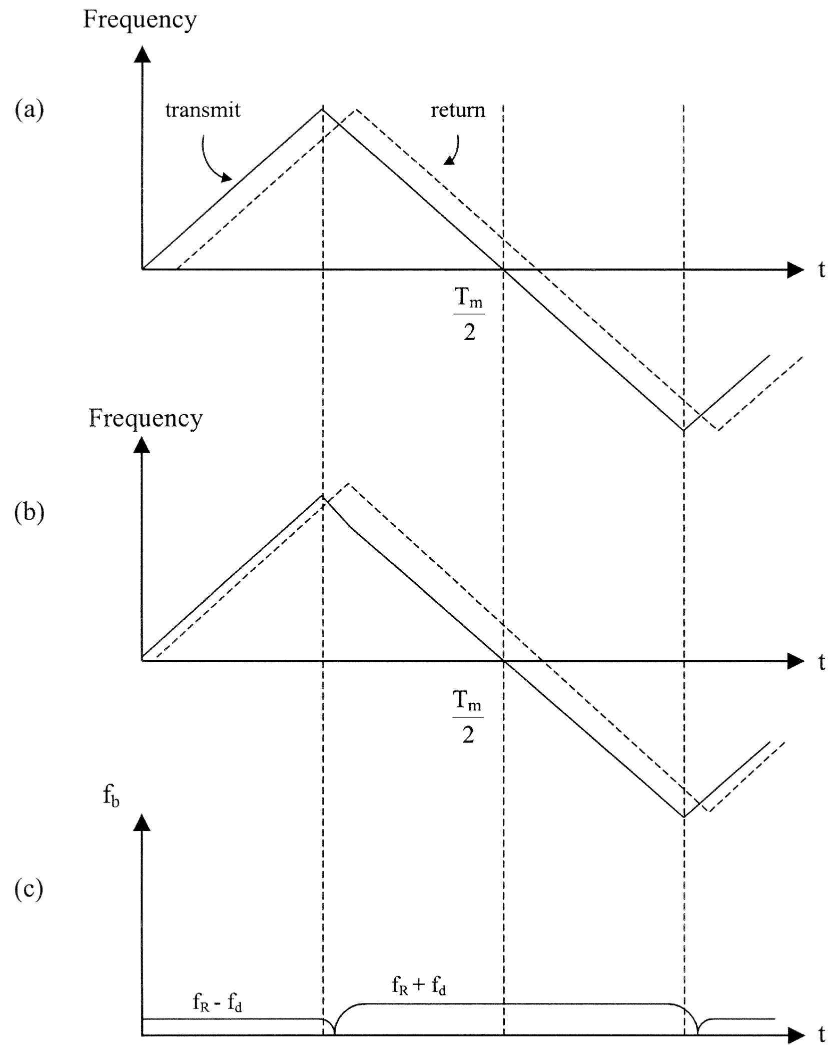

FIGURE 7.17 Waveform for a moving target: (*a*) stationary target waveform for comparison; (*b*) waveform for a target moving toward radar; (*c*) beat signal from a target moving toward radar.

The range information is in f_R, which can be obtained by

$$f_R = \tfrac{1}{2}[f_b\ (\text{up}) + f_b\ (\text{down})] \tag{7.35}$$

The speed information is given by

$$f_d = \tfrac{1}{2}[f_b\ (\text{down}) - f_b\ (\text{up})] \tag{7.36}$$

From f_R, one can find the range

$$R = \frac{cf_R}{4f_m\ \Delta f} \tag{7.37}$$

From f_d, one can find the relative speed

$$v_r = \frac{cf_d}{2f_0} \tag{7.38}$$

Similarly, for a target moving away from radar, one can find f_R and f_d from f_b (up) and f_b (down).

In this case, f_b (up) and f_b (down) are given by

$$f_b\ (\text{up}) = f_R + f_d \tag{7.39}$$

$$f_b\ (\text{down}) = f_R - f_d \tag{7.40}$$

Example 7.5 An FMCW altimeter uses a sideband superheterodyne receiver, as shown in Fig. 7.18. The transmitting frequency is modulated from 4.2 to 4.4 GHz linearly, as shown. The modulating frequency is 10 kHz. If a returned beat signal of 20 MHz is detected, what is the range in meters?

Solution Assuming that the radar is pointing directly to the ground with $\theta = 90^\circ$, we have

$$v_r = v \cos\theta = 0$$

From the waveform, $f_m = 10$ kHz and $\Delta f = 200$ MHz.

The beat signal $f_b = 20$ MHz $= f_R$. The range can be calculated from Eq. (7.32):

$$\begin{aligned} R &= \frac{cf_R}{4f_m\ \Delta f} = \frac{3 \times 10^8\ \text{m/sec} \times 20 \times 10^6\ \text{Hz}}{4 \times 10 \times 10^3\ \text{Hz} \times 200 \times 10^6\ \text{Hz}} \\ &= 750\ \text{m} \end{aligned}$$

Note that both the range and doppler shift can be obtained if the radar antenna is tilted with $\theta \neq 90^\circ$. ■

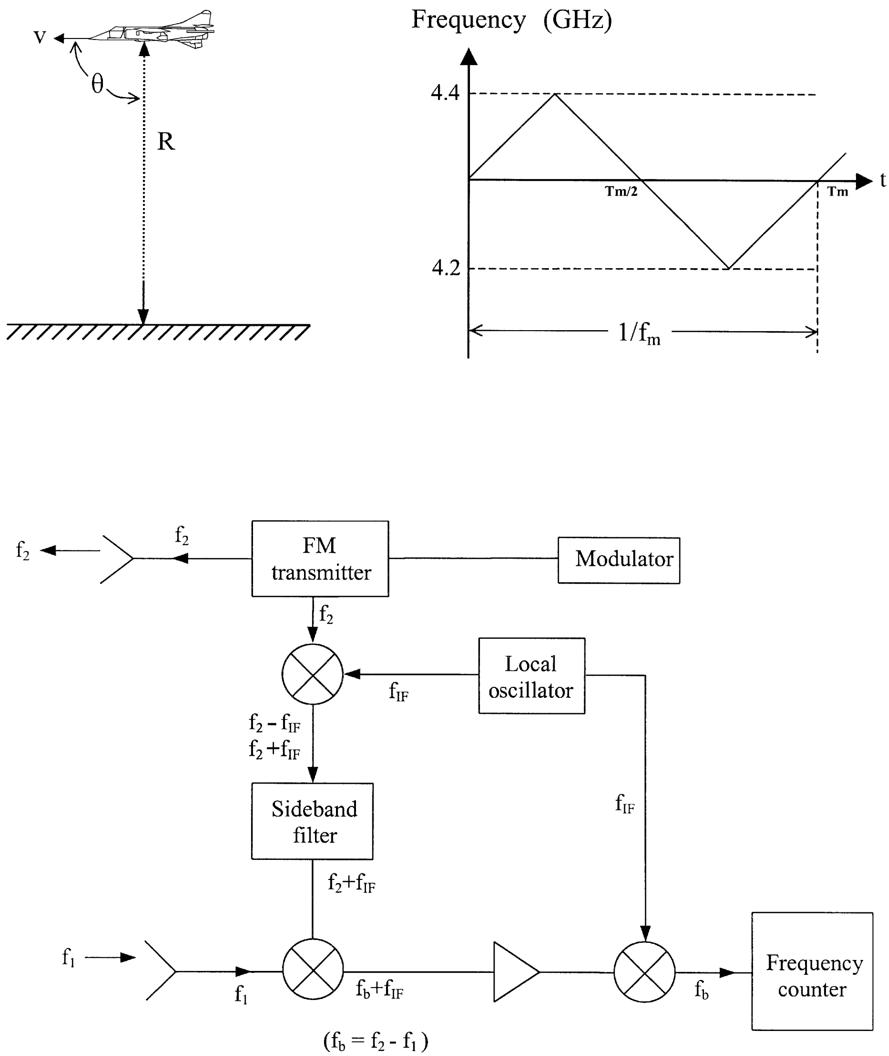

FIGURE 7.18 An FMCW altimeter and its waveform.

For an FMCW radar with a linear waveform, as shown in Fig. 7.16, a perfect linear curve is assumed in the calculation of the range. Any deviation from the linear curve will affect the accuracy and resolution in the range calculation. A linearizer can be used between the voltage-controlled oscillator and the varactor bias supply to produce a linear frequency tuning.

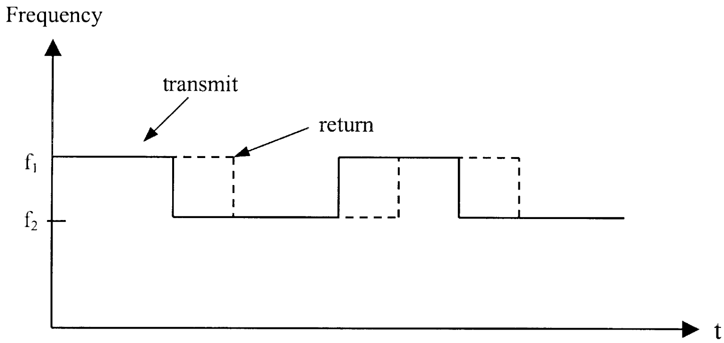

FIGURE 7.19 Two-step frequency modulation waveform.

Other frequency waveforms can also be used. Figure 7.19 shows a two-step frequency modulation as a function of time. The beat signal will occur when the frequency of the returning signal differs from the transmitting signal.

7.8 DIRECTION FINDING AND TRACKING

A tracking radar needs to find its target before it can track. The radar first searches for the target. This is normally done by scanning the antenna beam over a wide angle in one- or two-dimensional space. The beam scanning can be accomplished mechanically or electronically or both. After the target is detected, the tracking radar will track the target by measuring the coordinates of a target and providing data that may be used to determine the target path and to predict its future position. To predict future positions, all or part of the following data are required: range, speed, elevation angle, and azimuth angle. The elevation and azimuth angles give the direction of the target. A radar might track the target in range, in angle, in doppler shift, or any combination of the three. But in general, a tracking radar refers to angle tracking.

It is difficult to optimize a radar to operate in both search and tracking modes. Therefore, many radar systems employ a separate search radar and tracking radar. The search radar or acquisition radar provides the target coordinates for the tracking radar. The tracking radar acquires the target by performing a limited search in the area of the designated target coordinates provided by the search radar.

There are two major types of tracking radar: continuous-tracking radar and track-while-scan radar. The continuous-tracking radar provides continuous-tracking data on a particular target, while the track-while-scan radar supplies sampled data on one or more targets.

The ability of a radar to find the direction of a target is due to a directive antenna with a narrow beamwidth. An error signal will be generated if the antenna beam is not exactly on the target. This error signal will be used to control a servomotor to align the antenna to the target. There are three methods for generating the error signal for tracking:

1. Sequential lobing
2. Conical scan
3. Monopulse

A brief description of each method is given below.

7.8.1 Sequential Lobing

In sequential lobing, the antenna beam is switched between two positions, as shown in Fig. 7.20. The difference in amplitude between the received signal voltages obtained in the two switched positions is a measure of the angular displacement of the target from the switching axis.

The sign of the difference determines the direction that the antenna must be moved in order to align the switching axis with the direction of the target. When the

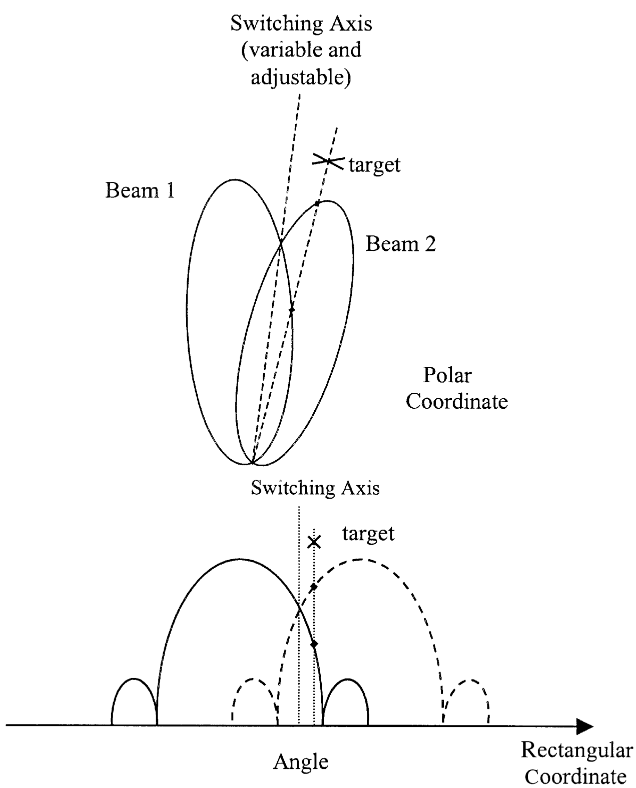

FIGURE 7.20 Sequential lobing.

voltages in the two switched positions are equal, the target is tracked in the direction of the switching axis.

7.8.2 Conical Scan

As shown in Fig. 7.21, this method is an extension of sequential lobing. The antenna rotates continuously instead of switching to two discrete positions. If the rotation axis is not aligned with the target, the echo signal will be amplitude modulated at a frequency equal to the rotation frequency of the beam. The demodulated signal is applied to the servocontrol system to continuously adjust the antenna position. When the line of sight to the target and rotation axis are aligned, there is no amplitude modulation output (i.e., returning signal has the same amplitude during rotation).

7.8.3 Monopulse Tracking

The above two methods require a minimum number of pulses to extract the angle error signal. In the time interval during which a measurement is made, the train of echo pulses must contain no amplitude modulation components other than the modulation produced by scanning. The above two methods could be severely limited in applications due to the fluctuating target RCS. Monopulse tracking uses a *single* pulse rather than many pulses and avoids the effects of pulse-to-pulse amplitude fluctuation.

For simplicity, let us consider the one-dimensional monopulse tracking first. Example applications are surface-to-surface or ship-to-ship tracking radar. The amplitude comparison monopulse radar uses two overlapping antenna patterns to obtain the azimuth angular error in one coordinate, as shown in Fig. 7.22. The sum

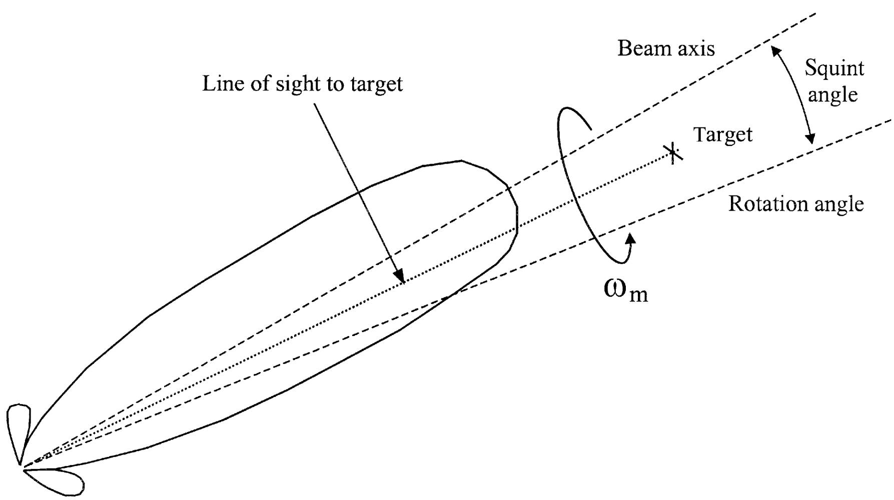

FIGURE 7.21 Conical scan.

and difference of the antenna patterns and error signal are shown in Fig. 7.23. If the target is aligned with the antenna axis, $A = B$ and the angle error signal is zero. The target is tracked. Otherwise, $A \neq B$, resulting in an error signal. The one-dimensional monopulse system consists of two antenna feeds located side by side, a transmitter, two receivers (one for the sum channel and the other for the difference channel), and a monopulse comparator. A block diagram is shown in Fig. 7.24. The comparator generates the sum-and-difference signals. Microwave hybrid couplers, magic-Ts, or rat-race ring circuits can be used as comparators. Shown in Fig. 7.24 is a rat-race ring circuit. The transmitting signal at port 1 will split equally into ports 2 and 3 in phase and radiate out through the two feeds. The received signals at ports 2 and 3 will arrive at port 1 in phase, resulting in a sum ($\sum$) signal, and arrive at port 4 with 180° out of phase, resulting in a difference (Δ) signal. The different phases are due to the different signal traveling paths, as shown in Fig. 7.24. The antenna beams are used for direction finding and tracking. They can also be used in homing and navigation applications.

Mathematically, one can derive $A + B$ and $A - B$ if the target is located at an angle θ from the broad side, as shown for Fig. 7.25. The phase difference between the two paths is

$$\phi = \frac{2\pi}{\lambda_0} d \sin\theta = 2\pi \frac{d \sin\theta}{\lambda_0} \tag{7.41}$$

where d is the separation of the two antenna feeds and λ_0 is the free-space wavelength:

$$\begin{aligned} |A + B| &= |V_0 e^{j\phi} + V_0| = |V_0(1 + e^{j\phi})| \\ &= |V_0|\sqrt{(1 + \cos\phi)^2 + \sin^2\phi} \\ &= 2|V_0| \cos(\tfrac{1}{2}\phi) \end{aligned} \tag{7.42}$$

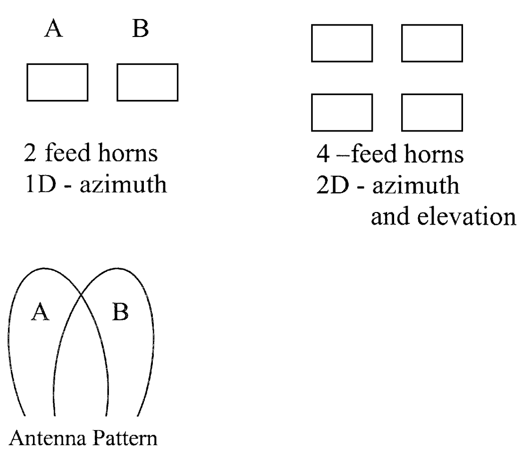

FIGURE 7.22 Feed arrangements of monopulse systems.

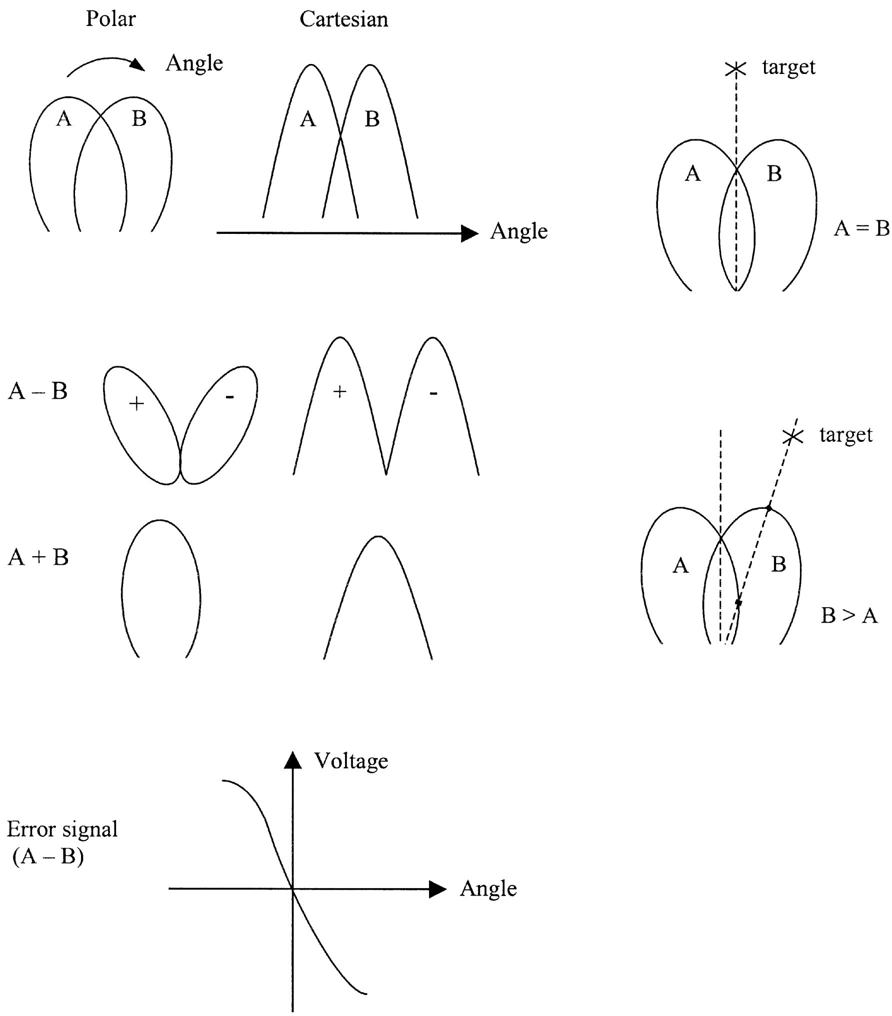

FIGURE 7.23 The sum $(A + B)$ and differences $(A - B)$ patterns and error signal.

When $\theta = 0$, the target is tracked. We have $\phi = 0$ and $|A + B| = 2|V_0| =$ maximum.

$$|A - B| = |V_0 - V_0 e^{j\phi}| = |V_0|\sqrt{(1 - \cos\phi)^2 + \sin^2\phi}$$
$$= 2|V_0| \sin\tfrac{1}{2}\phi \tag{7.43}$$

When $\theta = 0$, we have $\phi = 0$ and $|A - B| = 0$. As shown in Fig. 7.25, $|A + B|$ and $|A - B|$ can be plotted as a function of ϕ.

If both the azimuth and elevation tracking are needed, a two-dimensional monopulse system is required. Figure 7.26 shows a block diagram for the

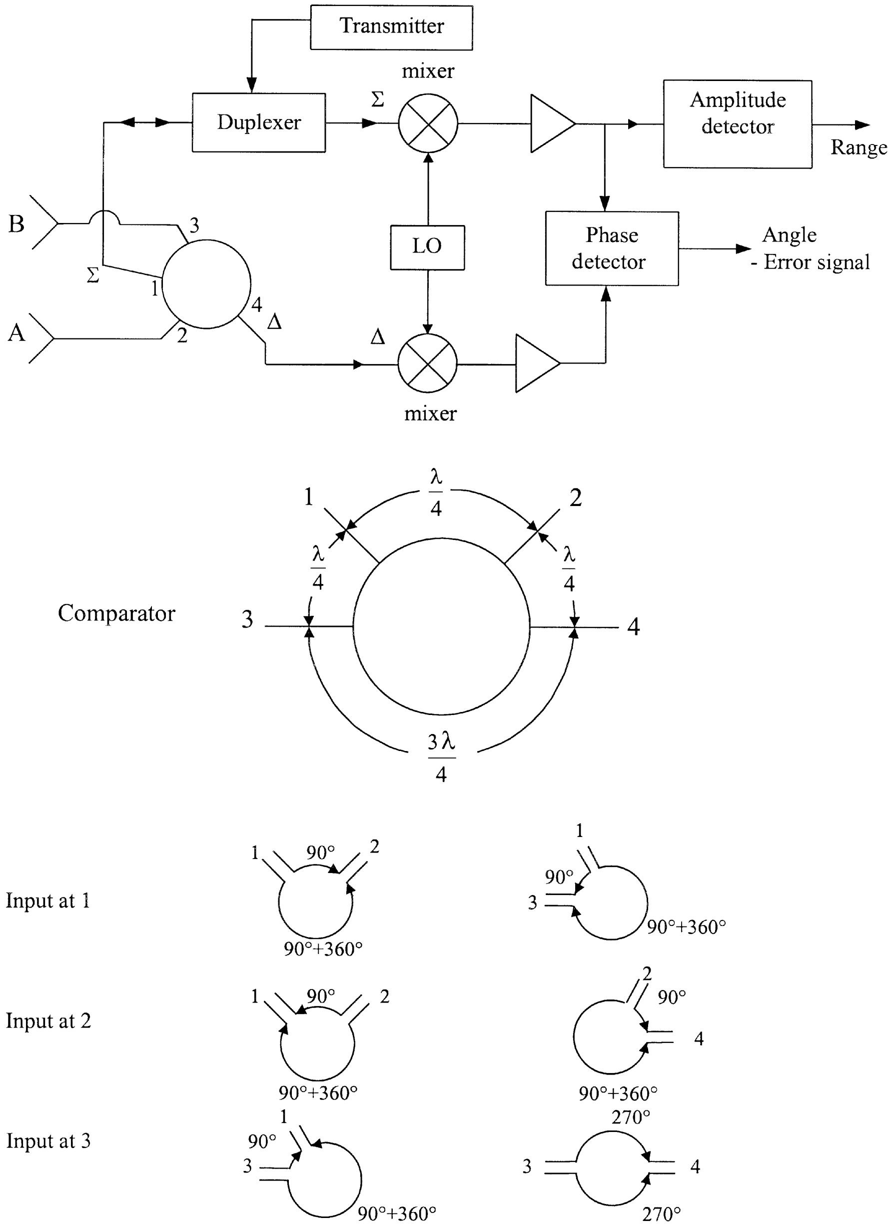

FIGURE 7.24 Block diagram and comparator for an amplitude comparison monopulse radar with one angular coordinate.

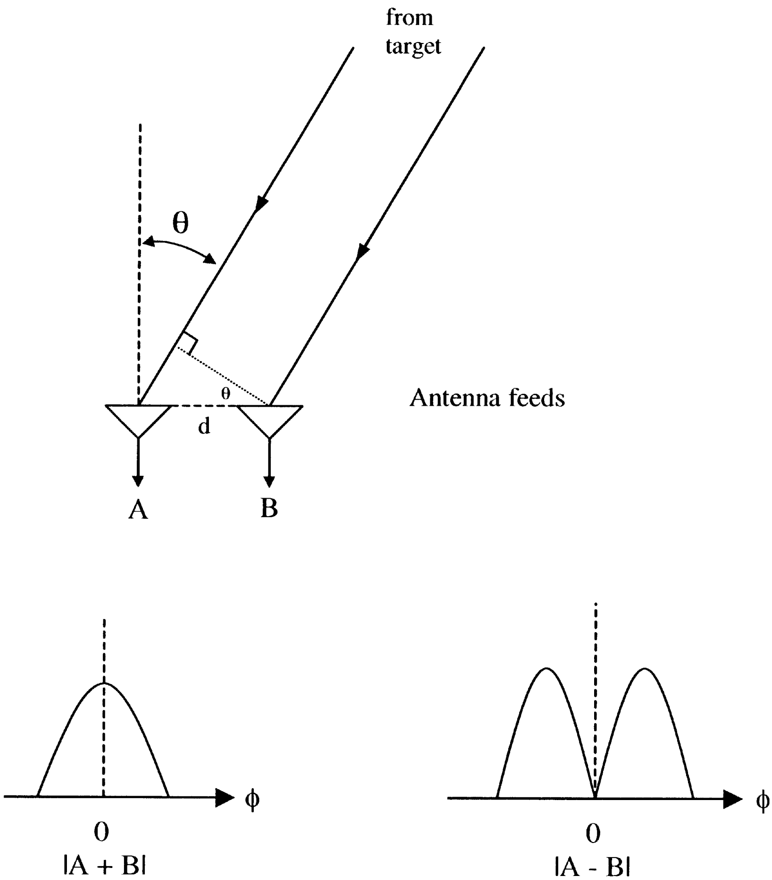

FIGURE 7.25 Calculation of $|A + B|$ and $|A - B|$.

comparator and Fig. 7.27 for the receiver. Three separate receivers are used to process the sum $(A + B + C + D)$, the elevation error $[(B + D) - (A + C)]$, and the azimuth error $[(A + B) - (C + D)]$ signals. The sum signal is used as a reference for the phase detector and also to extract the range information. The signal $[(A + D) - (B + C)]$ is not useful and dumped to a load.

7.9 MOVING-TARGET INDICATION AND PULSE DOPPLER RADAR

The doppler shift in the returning pulse produced by a moving target can be used by a pulse radar to determine the relative velocity of the target. This application is similar to the CW radar described earlier. The doppler shift can also be used to separate the moving target from undesired stationary fixed background (clutter). This application allows the detection of a small moving target in the presence of large

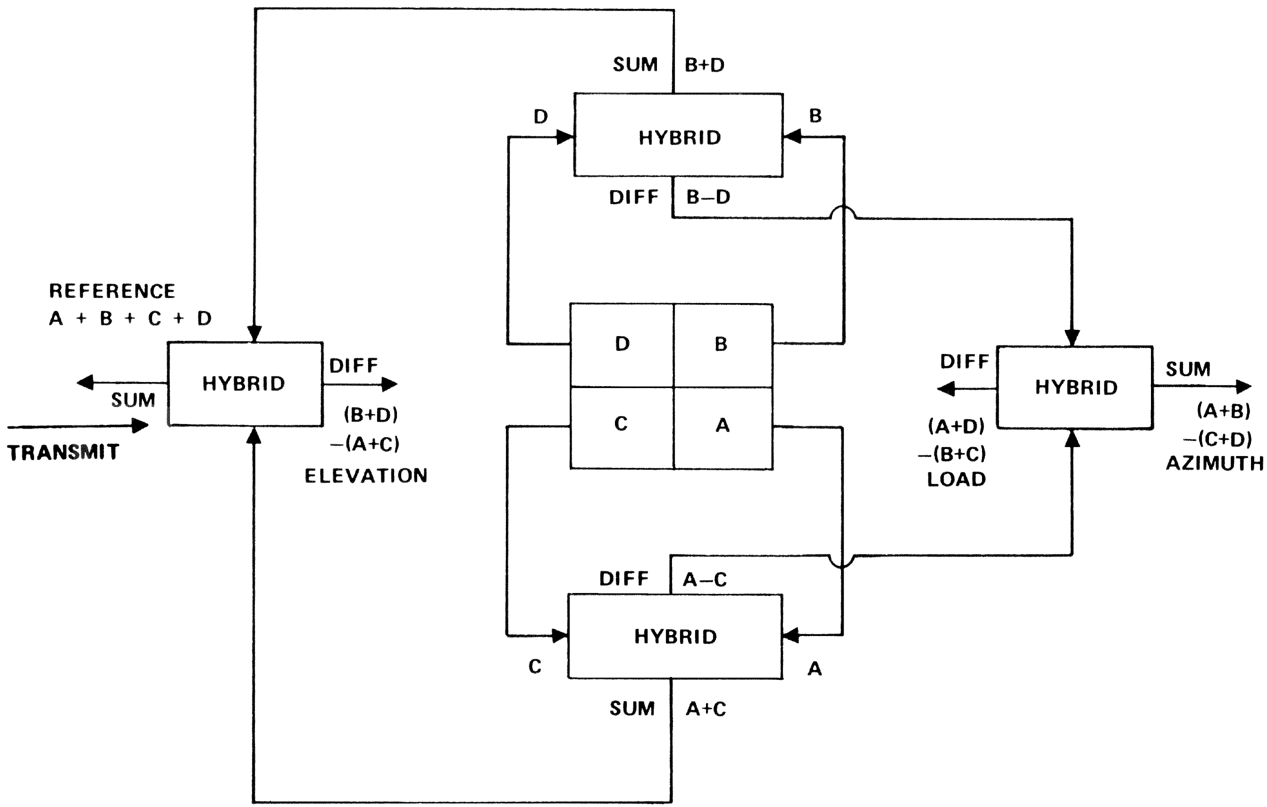

FIGURE 7.26 Configuration of amplitude comparison monopulse system.

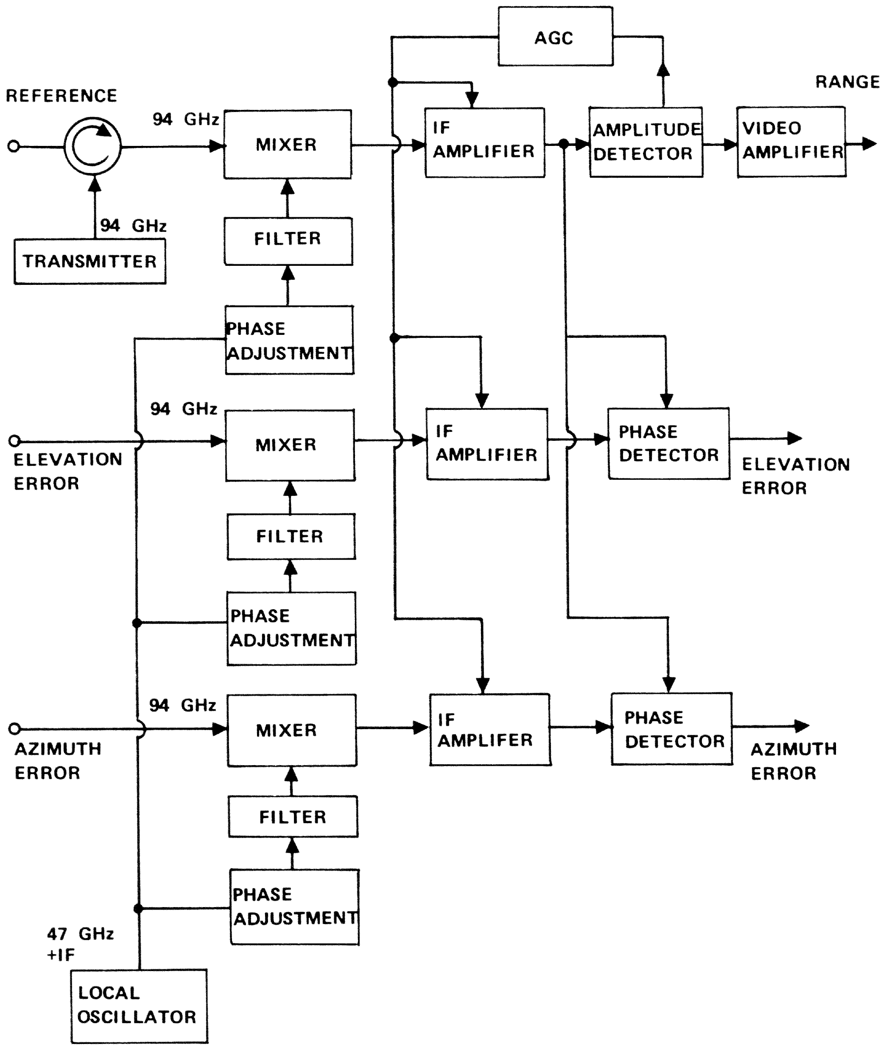

FIGURE 7.27 Amplitude comparison monopulse receiver operating at 94 GHz.

clutter. Such a pulse radar that utilizes the doppler frequency shift as a means for discriminating the moving target from the fixed clutter is called an MTI (moving target indicator), or pulse doppler radar. For example, a small moving car in the presence of land clutter and a moving ship in sea clutter can be detected by an MTI radar.

Figure 7.28 shows a simple block diagram for an MTI radar. The transmitting pulse has a carrier frequency f_0. The returning pulse frequency is $f_0 \pm f_d$. The

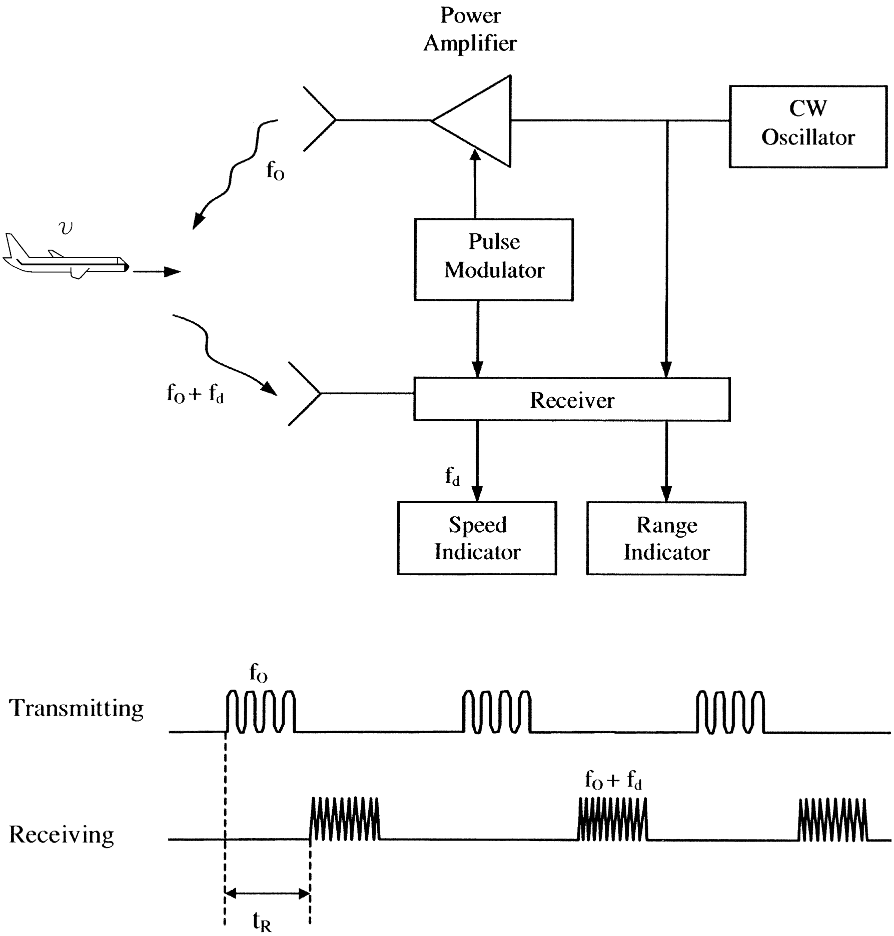

FIGURE 7.28 Pulse doppler radar.

returning pulse is also delayed by t_R, which is the time for the signal to travel to the target and return. The range and relative velocity can be found by

$$R = \tfrac{1}{2} c t_R \tag{7.44}$$

$$v_r = \frac{c f_d}{2 f_0} \tag{7.45}$$

The delay line cancelers, range-gated doppler filters, and digital signal processing are used to extract the doppler information [1].

7.10 SYNTHETIC APERTURE RADAR

A synthetic aperture radar (SAR) achieves high resolution in the cross-range dimension by taking advantage of the motion of the aircraft or satellite carrying the radar to synthesize the effect of a large antenna aperture. The use of SAR can generate high-resolution maps for military reconnaissance, geological and mineral exploration, and remote sensing applications [1, 6].

Figure 7.29 shows an aircraft traveling at a constant speed v along a straight line. The radar emits a pulse every pulse repetition period (T_p). During this time, the airplane travels a distance vT_p. The crosses in the figure indicate the position of the radar antenna when a pulse is transmitted. This is equivalent to a linear synthesized antenna array with the element separation of a distance vT_p.

Conventional aperture resolution on the cross-range dimension is given by [1]

$$\delta = R\theta_B \tag{7.46}$$

where R is the range and θ_B is the half-power beamwidth of the antenna. For an SAR, the resolution becomes

$$\delta_s = R\theta_s = \tfrac{1}{2}D \tag{7.47}$$

where θ_s is the beamwidth of a synthetic aperture antenna and D is the diameter of the antenna. It is interesting to note that δ_s is independent of the range.

As an example, for a conventional antenna with $\theta_B = 0.2^\circ$ (this is a very narrow beamwidth) at a range of 100 km, we have, from Eq. (7.46),

$$\delta = 350 \text{ m}$$

For an SAR at X-band with an antenna diameter of 3 m, the resolution is

$$\delta_s = 1.5 \text{ m}$$

which is much better than δ.

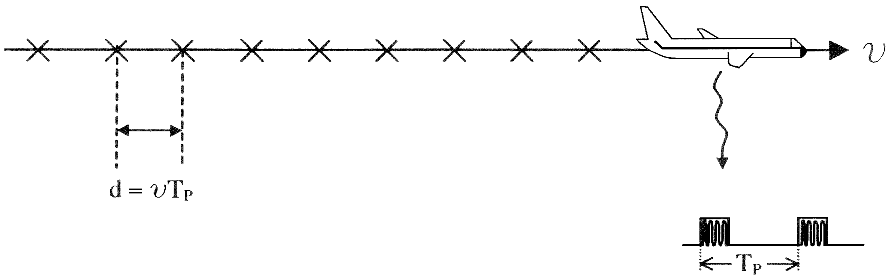

FIGURE 7.29 Synthetic aperture radar traveling at a constant speed v.

7.11 PRACTICAL RADAR EXAMPLES

There are many considerations in radar system design. The user requirements have a direct impact on the microwave subsystem design as summarized in Table 7.3 [7].

Table 7.4 shows the system parameters for a commercial air route surveillance radar. The *L*-band frequency was selected for all-weather operations with a range of

TABLE 7.3 Impact of User Requirements on Microwave Design

User Requirement	Impact on Microwave Subsystems
Type of target (scattering cross section) and maximum/minimum range	Antenna size and operating frequency; transmitter power; transmitter types: solid state or tube; waveform
Ability to observe close-in targets	Sensitivity time control (STC) provided by $p-i-n$ diode attenuator in RF or IF
Coverage	Antenna rotation (azimuth and/or elevation); mechanically versus electronically scanned antenna
Number of targets observed simultaneously	Mechanically versus electronically scanned antenna
Minimum spacing of targets	Antenna size; operating frequency (higher frequencies yield more spatial resolution); pulse width (modulation frequency)
Operating weather conditions	Operating frequency; increase transmitter power to overcome attenuation due to weather
Site restrictions	Transmitter and antenna size; transmitter efficiency (affects size of power conditioning circuitry); blank sector (turn off transmitter at specified azimuth angles); reduce ground clutter (use phase stable transmitter, higher operating frequency)
Reliability/availability	Redundant transmitters, power supplies, receivers; switchover box
Maintainability	Replacable subsystems (consider interface specification tolerances to eliminate retuning circuits); connectors positioned for ease of operation
Electromagnetic compatibility	Receiver has high dynamic range to minimize spurious signals; transmitter pulse shaping to restrict bandwidth; transmitter filtering to avoid spurious signals
Weight	Efficient transmitter reduces supply weight; lightweight antenna affects performance
Cost/delivery schedule	Use known, proven designs; introduce new technologies where needed; begin development/testing of “untried” components early

Source: From reference [7].

TABLE 7.4 Parameters of ARSR-3 Radar System[a]

Minimum target size	2 m^2
Maximum range	370 km (200 nautical miles)
Operating frequency range	1.25–1.35 GHz
Probability of detection	80% (one scan)
Probability of false alarm	10^{-6}
Pulse width	2 sec
Resolution	500 m
Pulse repetition frequency	310–365 Hz
Lowest blind speed	600 m/sec (1200 knots)
Peak power	5 MW
Average power	3600 W
Receiver noise figure	4 dB
Moving-target indicator (MTI) improvement	39 dB (3-pulse canceler, 50 dB with 4-pulse canceler)
Antenna size	12.8 m (42 ft) × 6.9 m (22 ft)
Beamwidth (azimuth/elevation)	1.25/40°
Polarization	Horizontal, vertical, and circular
Antenna gain	34 dB (34.5 dB lower beam, 33.5 dB upper beam)
Antenna scan time	12 sec
EIRP (on-axis effective isotropic radiate power)	101 dBW (12,500 MW)
Average power/effective aperture/scan time product (antenna efficiency = 60%)	2300 kW m^2 sec

[a]Courtesy of Westinghouse Electric Corp.
Source: From reference [7].

370 km, a probability of detection of 80% for one scan, and a false-alarm rate of 10^{-6} (i.e., one false report per a million pulses) for a target size of 2 m^2. The high peak power is generated by a Klystron tube. Figure 7.30 shows the radar installation. The antenna is a truncated reflector. A radome is used to protect the antenna. Dual systems operate simultaneously on opposite polarizations at slightly different frequencies. This allows operation with one system shut down for repairs.

Table 7.5 shows the system parameters and performance of a USSR Cosmos 1500 side-looking radar [2]. The oceanographic satellite was launched on September 28, 1983, into a nominal 650-km polar orbit to provide continuous world ocean observations for civil and military users. The radar serves as a radiometer to monitor oceans and ice zones, using a slotted waveguide array antenna. The system operates at 9.5 GHz with a peak output power of 100 kW generated by a magnetron tube.

Space-based radars in satellites can be used to monitor global air traffic. A rosette constellation of three satellites at an orbital altitude of 10,371 km provides continuous worldwide visibility by at least two satellites simultaneously [8]. Table 7.6 shows the system parameters. The radar antenna is a phased array with a maximum scan angle of 22.4°. Distributed solid-state T/R modules are used as transmitters. Each module provides 155 mW peak power with a total of 144,020 modules.

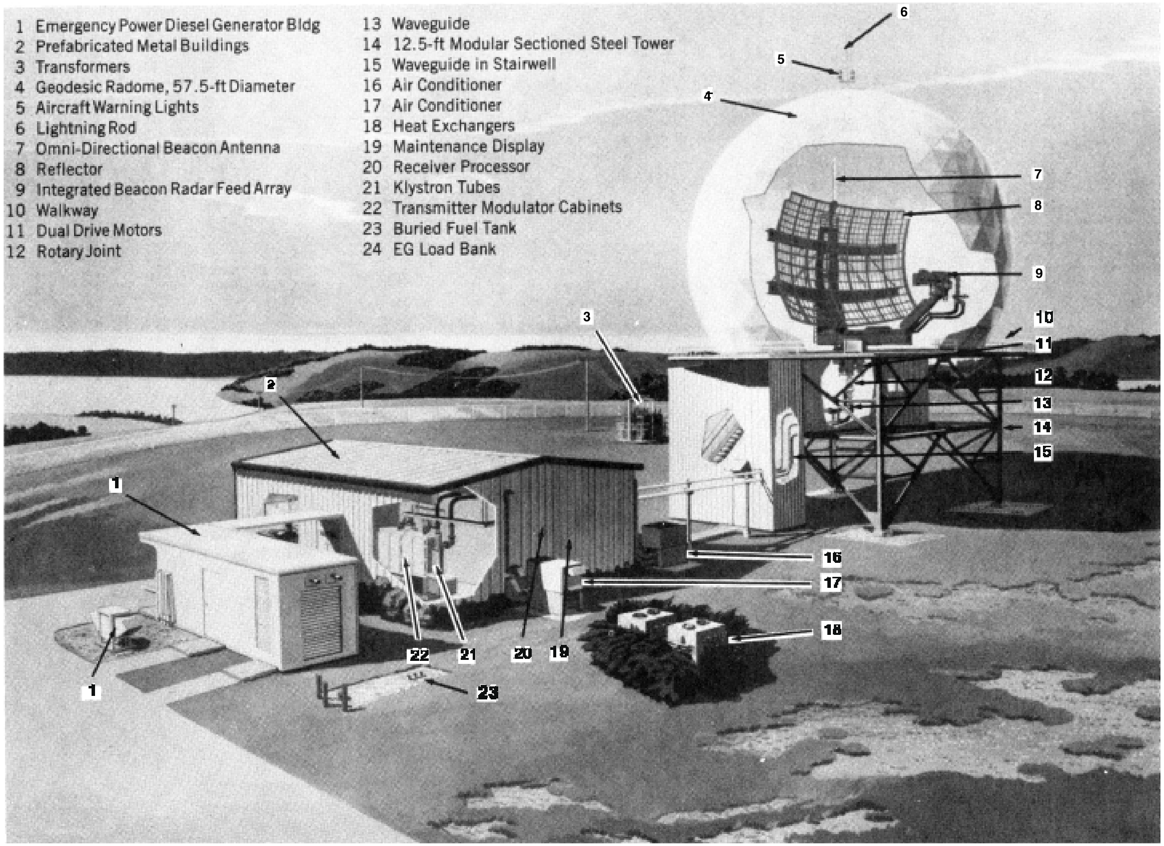

FIGURE 7.30 ARSR-3 radar station diagram. (Courtesy of Westinghouse Electric Corp.)

TABLE 7.5 Cosmos 1500 SLR Parameters and Performance

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chapter.

Source: From reference [2].

PROBLEMS

7.1 A radar transmits a peak power of 20 kW at 10 GHz. The radar uses a dish antenna with a gain of 40 dB. The receiver has a bandwidth of 25 MHz and a noise figure of 10 dB operating at room temperature (290 K). The overall system loss is estimated to be 6 dB. The radar is used to detect an airplane with a radar cross section of 10 m^2 at a distance of 1 km. (a) What is the return signal level (P_r) (in watts)? (b) What is the SNR (in decibels) at the receiver output? (Assume only one pulse integration.)

TABLE 7.6 Radar Parameters for Global Air Traffic Surveillance

Antenna	
Type	Corporate-fed active phased array
Diameter	100 m
Frequency	2 GHz
Wavelength	0.15 m
Polarization	Circular
Number of elements	576,078
Number of modules	144,020
Element spacing	0.7244 wavelength
Beamwidth	1.83 mrad
Directive gain	66.42 dB
Maximum scan angle	22.4°
Receiver	
Type	Distributed solid-state monolithic T/R module
Bandwidth	500 kHz
System noise temperature	490 K
Compressed pulse width	2 μsec
Transmitter	
Type	Distributed solidd-state monolithic T/R module
Peak power	22.33 kW
Pulse width	200 μsec
Maximum duty	0.20
Frequency	2 GHz
Signal Processor	
Type	Digital
Input speed	50 million words per second

Source: From reference [8], with permission from IEEE.

7.2 A high-power radar uses a dish antenna with a diameter of 4 m operating at 3 GHz. The transmitter produces 100 kW CW power. What is the minimum safe distance for someone accidentally getting into the main beam? (The U.S. standard requires a power density of <10 mW/cm^2 for safety.) Assume that the dish antenna has a 55% efficiency.

7.3 A pulse radar has the following parameters:

$$\begin{aligned} P_t &= 16\text{ kW (peak)} & \text{Frequency} &= 35\text{ GHz}, & T &= 290\text{ K} \\ B &= 20\text{ MHz} & \text{PRF} &= 100\text{ kHz}, & F &= 6\text{ dB} \\ \text{Pulse with } \tau &= 0.05\ \mu\text{sec} & \text{Scan rate} &= 60^\circ/\text{sec} & L_{\text{sys}} &= 10\text{ dB} \end{aligned}$$

$$\text{Antenna} = \text{2-m dish (i.e., diameter} = 2\text{ m)}$$

$$\text{Target (airplane) RCS} = 30\text{ m}^2 \qquad \text{Antenna efficiency} = 55\%$$

$$\text{Probability of detection} = 0.998 \qquad \text{False-alarm rate} = 10^{-8}$$

Calculate (a) the maximum range in kilometers, (b) the receiver output SNR when the target is 140 km from the radar, and (c) the maximum range in kilometers if the peak power is increased to 160 kW.

7.4 A pulse radar has the following parameters: $P_t = 100$ kW, PRF $= 10$ kHz, pulse width $= 2$ μsec. What are the duty cycle in percent, the average transmit power in watts, and the maximum range (in meters) without ambiguity?

7.5 A pulse radar has the following parameters:

$P_t = 1000$ W (peak)	Frequency $= 35$ GHz,	$T = 290$ K
PRF $= 100$ kHz	$B = 20$ MHz,	Pulse width $\tau = 0.05$ μsec
$F = 6$ dB	Scan rate $= 60^\circ/\text{sec}$	$L_{\text{sys}} = 10$ dB

Antenna = 2-m dish (i.e., diameter = 2 m)

Airplane (target) RCS $= 30\ \text{m}^2$ Antenna efficiency $= 55\%$

Probability of detection $= 0.998$ False-alarm rate $= 10^{-8}$

Calculate (a) the maximum range in kilometers and (b) the maximum range without ambiguity in kilometers. (c) Determine which one is the limiting maximum range.

7.6 A pulse radar is used for air traffic control. The radar uses a 55% efficiency dish antenna with a diameter of 3 m operating at 10 GHz. The airplane has a radar cross section of 60 m^2 and is located 180 km away from the radar. Assume that $P_t = 100$ kW, $T = 290$ K, $B = 10$ MHz, $F = 6$ dB, $L_{\text{sys}} = 10$ dB, PRF $= 1$ kHz, and $n = 10$. Calculate (a) the SNR at the output of the radar receiver, (b) the SNR at the input of the radar receiver, (c) the probability of detection if the false-alarm rate is 10^{-12}, and (d) the scan rate in degrees per second.

7.7 A pulse radar is used for surveillance. The radar is operating at 20 GHz with a dish antenna. The dish antenna has a diameter of 2 m and an efficiency of 55%. An airplane has a radar cross section of 50 m^2 located at a distance of 500 km away from the radar. Other system parameters are $P_t = 100$ kW, temperature $= 290$ K, $B = 20$ MHz, $F = 6$ dB, $L_{\text{sys}} = 10$ dB, PRF $= 1$ kHz, and $n = 10$. Calculate (a) the SNR at the output of the radar receiver, (b) the SNR at the input of the radar receiver, (c) the false-alarm rate if the probability of detection is 95%, and (d) the scan rate in degrees per second.

7.8 A pulse radar has the following specifications:

Pulse width = 1 μsec

Pulse repetition frequency = 1 kHz

Peak power = 100 kW

Calculate (a) the duty cycle in percent, (b) the maximum range in kilometers without ambiguity, and (c) the average power in watts.

7.9 A radar is used for air defense surveillance to detect a fighter with a radar cross section of 1 m^2. The radar transmits a peak power of 100 kW at 10 GHz. The antenna gain is 50 dB. The system has a bandwidth of 10 MHz and operates at room temperature. The receiver has a noise figure of 6 dB. The overall system loss is 6 dB. If we want to have a probability of detection of 90% and a false-alarm rate of 0.01% (i.e., 10^{-4}), what is the maximum range of this radar assuming only one pulse integration?

7.10 A pulsed radar for air defense uses a dish antenna with a diameter of 6 m operating at 3 GHz. The output peak power is 100 kW. The radar repetition rate is 1 kHz and the pulse width is 1 μsec. The scan rate of the antenna beam is 3 rpm. Calculate (a) the duty cycle in percent, (b) the average transmit power in watts, (c) the time (in seconds) that the target is within the 3-dB beamwidth of the radar antenna, (d) the number of pulses returned to radar, (e) the maximum range without ambiguity in meters, and (f) the optimum system bandwidth.

7.11 A car travels at a speed of 120 km/h. A police radar is positioned at the location shown in Fig. P7.11. The radar is operating at 24.5 GHz. Calculate the doppler shift frequency that appears as the IF frequency at the output of the radar mixer.

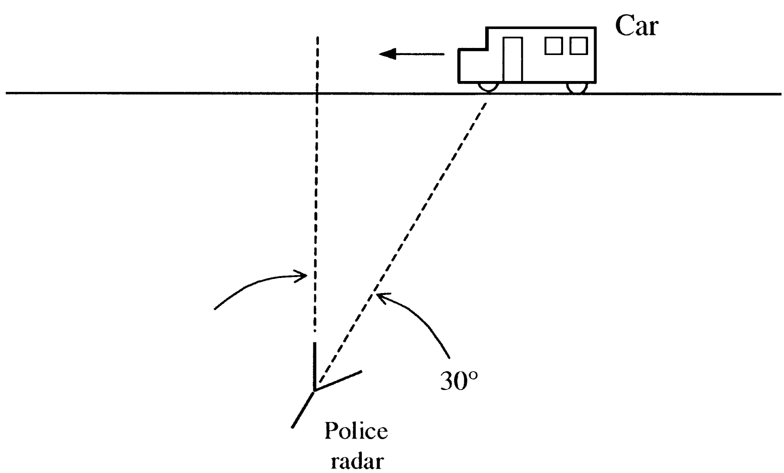

FIGURE P7.11

7.12 A CW radar is used to track an airplane, as shown in Fig. P7.12. If the radar transmits a 10-GHz signal and the airplane travels at a speed of 800 km/h, what is the returned signal frequency?

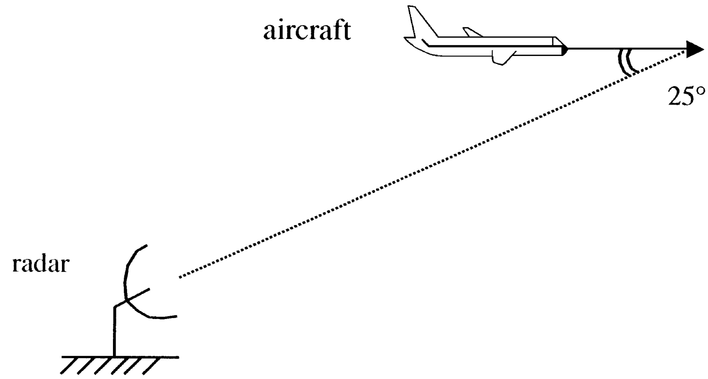

FIGURE P7.12

7.13 A CW radar is used to track the speed of an aircraft, as shown in Fig. P7.13. If the aircraft travels at a speed of 1000 km/h and the radar transmits a signal of 10 GHz, what is the returned signal frequency?

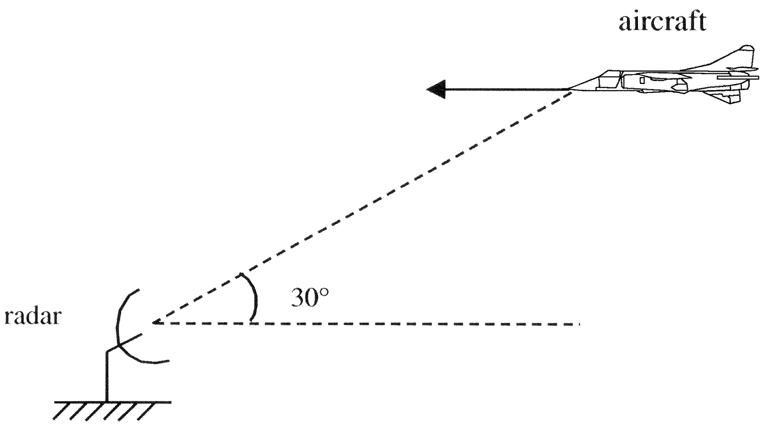

FIGURE P7.13

7.14 The transmitting and receiving signal frequencies as a function of time of an FMCW radar are shown in Fig. P7.14. The target is stationary. Determine the range (in kilometers) of the target if the output IF beat signal is (a) 25 MHz and (b) 10 MHz.

7.15 An FMCW radar has the returned beat signal (f_b) as a function of time, as shown in Fig. P7.15. Calculate the range and the speed of the target.

7.16 An FMCW radar has the return beat signal frequency shown in Fig. P7.16. The operating center frequency is 20 GHz and the frequency is varied in the range of 20 GHz ± 10 MHz. Calculate the range in kilometers and the relative velocity in kilometers per second for the target.

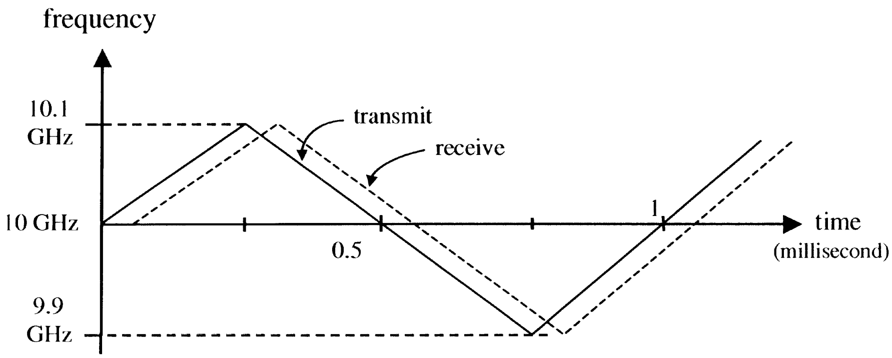

FIGURE P7.14

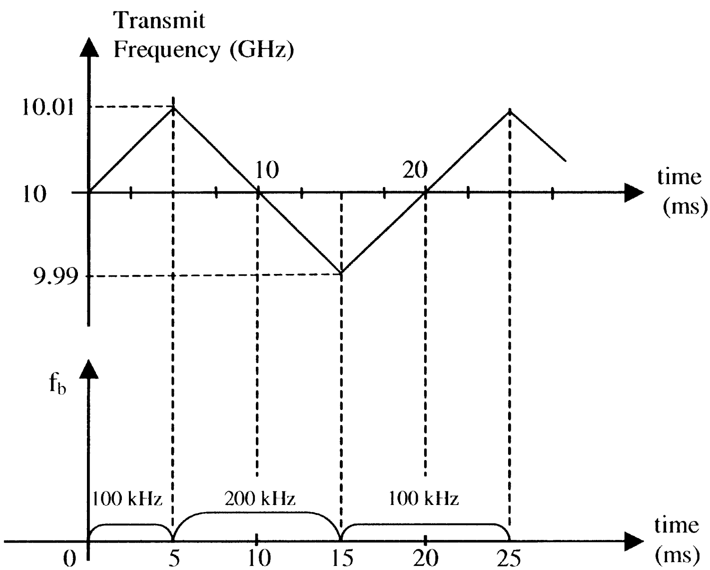

FIGURE P7.15

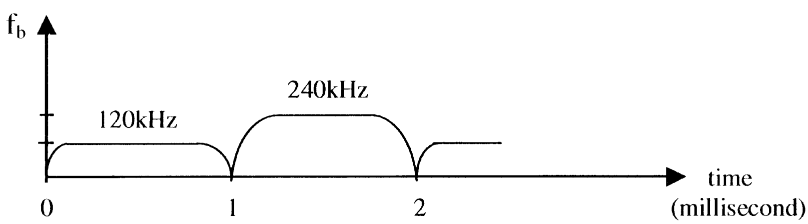

FIGURE P7.16

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