chapter

4

Tracking Radar

4.1 TRACKING WITH RADAR

Types of Tracking Radar Systems Thus far we have considered radar mainly as a surveillance sensor that detects targets over a region of space. A radar not only recognizes the presence of a target, but it determines the target's location in range and in one or two angle coordinates. As it continues to observe a target over time, the radar can provide the target's trajectory, or *track,* and predict where it will be in the future. There are at least four types of radars that can provide the tracks of targets:

- *Single-target tracker* (STT). This tracker is designed to continuously track a single target at a relatively rapid data rate. The data rate, of course, depends on the application, but 10 observations per second might be "typical" of a military guided-missile weapon-control radar. The antenna beam of a single-target tracker follows the target by obtaining an angle-error signal and employing a closed-loop servo system to keep the error signal small. (A small angle-error signal means that the radar is accurately tracking the target.) Most of this chapter will be concerned with this type of tracker. The *C*-band AN/FPQ-6, shown in Fig. 4.1a is an example of a long-range precision tracking radar that was used at missile instrumentation ranges. The major application for continuous tracking radars has been for the tracking of aircraft and/or missile targets in support of a military weapon-control system.

Figure 4.1 Two examples of missile-range precision instrumentation radars that use monopulse angle-tracking. Both operate at *C* band. (Top) Fixed-site AN/FPQ-6 Precision Tracking Radar with a 29-ft diameter Cassegrain reflector antenna capable of 0.1 mil tracking accuracy. (Bottom) Mobile AN/MPS-39 Multiple Object Tracking Radar (MOTR), a trainable space-fed 12-ft diameter electronically steerable lens array radar for simultaneously tracking up to 10 objects to a range accuracy of several feet and 0.2 mil angle accuracy.

(Courtesy of U.S. Army White Sands Missile Range). Both radars were manufactured by Lockheed-Martin Government Electronic Systems, Moorestown, New Jersey (formerly known as RCA Moorestown).

- *Automatic detection and track* (ADT). This performs tracking as part of an air-surveillance radar. It is found in almost all modern civil air-traffic control radars as well as military air-surveillance radars. The rate at which observations are made depends on the time for the antenna to make one rotation (which might vary from a few seconds to as much as 12 seconds). The ADT, therefore, has a lower data rate than that of the STT, but its advantage is that it can simultaneously track a large number of targets (which might be many hundreds or a few thousands of aircraft). Tracking is done open loop in that the antenna position is not controlled by the processed tracking data as it is in the STT. This type of tracking is discussed in Sec. 4.9.
- *Phased array radar tracking.* A large number of targets can be held in track with a high data rate by an electronically steered phased array radar. Multiple targets are tracked on a time-shared basis under computer control since the beam of an electronically scanned array can be rapidly switched from one angular direction to another, sometimes in a few microseconds. It combines the rapid update rate of a single-target tracker with the ability of the ADT to hold many targets in track. This is the basis for such air-defense weapon systems as Aegis and Patriot. An example of a phased array for multiple-target tracking is the *C*-band multiple-target tracking range instrumentation radar called MOTR which is shown in Fig. 4.1b.
- *Track while scan* (TWS). This radar rapidly scans a limited angular sector to maintain tracks, with a moderate data rate, on more than one target within the coverage of the antenna. It has been used in the past for air-defense radars, aircraft landing radars, and in some airborne intercept radars to hold multiple targets in track. It is briefly mentioned in Sec. 4.7. Unfortunately, the same name *track while scan* was also applied in the past to what is now usually called ADT.

A radar can track targets in range as well as angle. Sometimes tracking of the doppler frequency shift, or the radial velocity, is also performed. Most of the discussion in this chapter, however, will be on angle tracking.

Angle-Tracking In a simple pencil-beam radar the detection of a target provides its location in angle as being somewhere within the antenna beamwidth; but more information is needed to determine the direction the antenna should be moved to maintain the target within its beam. Consider the angle measurement in a single angular coordinate. In order to determine the direction in which the antenna beam needs to be moved, a measurement has to be made at two different beam positions. Figure 4.2 shows two beam positions A and B at two different angles. The two beams are said to be *squinted,* with a squint angle $\pm\theta_q$ relative to the boresight direction. These may be two simultaneous beams, or one beam that is rapidly switched between the two angular positions. The crossover of the two beams determines the *boresight* direction. The tracking radar has to position the two beams so that the boresight is always maintained in the direction of the target; that is, the angle θ_0 is in the direction of the target angle θ_T. In this example, the relative amplitudes a_A and a_B of the echo signals received from a target measured in the two positions determine how far the target is from boresight and in what direction the two beams have to be repositioned to maintain the target on boresight. This applies for one angle coordinate. Two additional beam positions are needed in the orthogonal plane to obtain angle

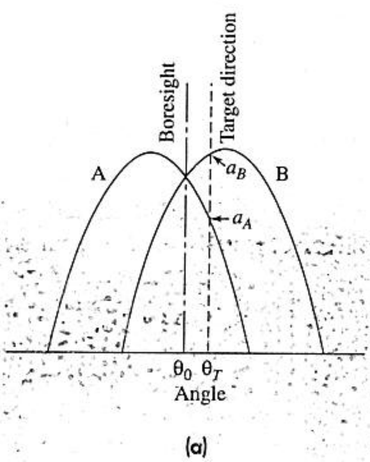

Figure 4.2 Basic principle of continuous angl
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4.2 MONOPULSE TRACKING[1,2]

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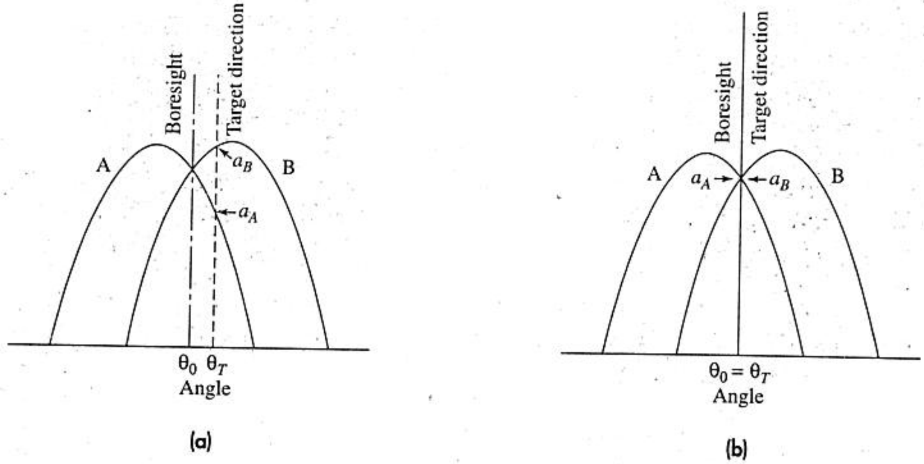

Figure 4.2 Basic principle of continuous angle tracking. (a) Two overlapping antenna patterns that cross over at the boresight direction θ_0. A target is located in this example to the right of the boresight at the angle θ_T. The amplitude a_B of the target echo in beam B is larger than the amplitude a_A in beam A, which indicates that the two beams should be moved to the right to bring the target to the boresight position. (b) Boresight position θ_0 is shown located in the direction of the target θ_T when $a_A = a_B$.

tracking in the orthogonal angle coordinate. Three beam positions are the minimum needed to obtain an angle measurement in two coordinates; but, almost always, four beams have to be used.

Early tracking radars used a single time-shared beam to track in two angles. These trackers which time share a single beam are known as either *conical scan* or *sequential lobing* trackers. (Both will be discussed later in this chapter.) Modern, high-precision tracking radars, however, use the equivalent of four simultaneous beams to perform two-dimensional tracking. They are called *simultaneous lobing* trackers, of which the most popular is *monopulse,* which is described next.

4.2 MONOPULSE TRACKING[1,2]

A monopulse tracker is defined as one in which information concerning the angular location of a target is obtained by comparison of signals received in two or more simultaneous beams.[3] A measurement of angle may be made on the basis of a single pulse; hence, the name *monopulse.* In practice, however, multiple pulses are usually employed to increase the probability of detection, improve the accuracy of the angle estimate, and provide resolution in doppler when necessary. By making an angle measurement based on the signals that appear simultaneously in more than one antenna beam, the accuracy is improved compared to time-shared single-beam tracking systems (such as conical scan or sequential lobing) which suffer degradation when the echo signal amplitude changes with time. Thus the accuracy of monopulse is not affected by amplitude fluctuations of the target echo. It is the preferred tracking technique when accurate angle measurements are required.

The monopulse angle method may be used in a tracking radar to develop an angle error signal in two orthogonal angle coordinates that mechanically drive the boresight of the tracking antenna using a closed-loop servo system to keep the boresight positioned in the direction of the moving target. In radars such as the phased array, angle measurements can be obtained in an open-loop fashion by calibrating the error-signal voltage in terms of angle.

There are several methods by which a monopulse angle measurement can be made. The most popular by far has been the *amplitude-comparison monopulse* which compares the amplitudes of the signals simultaneously received in multiple squinted beams to determine the angle. When the term *monopulse* is used by itself with no other descriptors, it generally refers to the amplitude-comparison version.

Amplitude-Comparison Monopulse For simplicity, this form of monopulse is first described for the measurement of only one angle coordinate. Two overlapping antenna patterns with their main beams pointed in slightly different directions are used, as in Fig. 4.3a. The two beams in this figure are said to be *squinted,* or *offset.* They might be generated by using two feeds slightly displaced in opposite directions from the focus of a parabolic reflector. The essence of the amplitude-comparison monopulse method is in

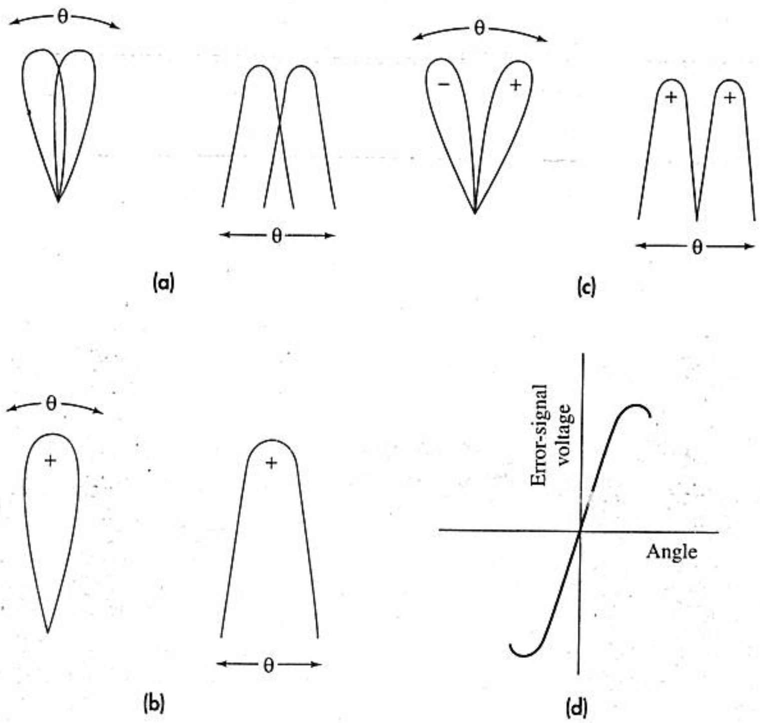

Figure 4.3 Monopulse antenna patterns and error signal. The left-hand sketches in (a) to (c) are in polar coordinates; right-hand sketches are in rectangular coordinates. (a) Two squinted antenna beams; (b) sum pattern of two squinted beams shown in (a); (c) difference pattern; (d) error signal as a function of the angle from boresight.

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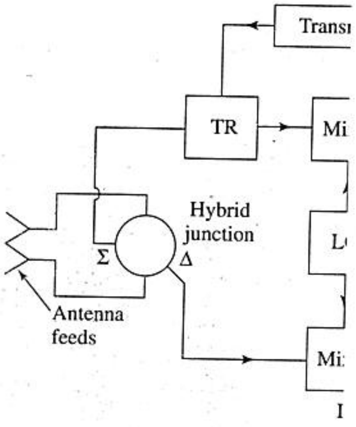
Figure 4.4 Simple block diagram of the amplitude-comparison monopulse in one angle coordinate. Σ denotes the sum channel. Δ denotes the difference channel.



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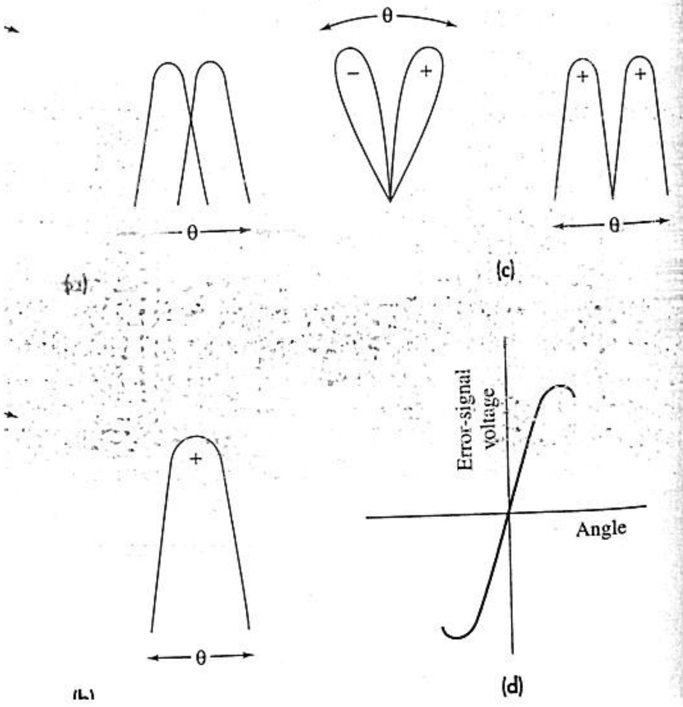

taking both the sum and the difference* of the two squinted antenna patterns, which are shown in Figs. 4.3b and 4.3c. The sum pattern is employed on transmission, while both the sum and the difference patterns are used on reception. The signal received with the difference pattern provides the magnitude of the angle error. The direction of the angle error is found by comparing the phase of the difference signal with the phase of the sum signal, as explained below. Signals received from the sum and difference patterns are amplified separately and combined in a phase-sensitive detector to produce the angle-error signal, Fig. 4.3d. The sum signal also provides target detection and range measurement, as well as act as a reference for determining the sign of the angle measurement.

Block Diagram A simple block diagram of the amplitude-comparison monopulse tracking radar for a single angular coordinate is shown in Fig. 4.4. The two adjacent antenna feeds are connected to the two input arms of a *hybrid junction,* which is a four-port microwave device with two input and two output ports. When two signals (such as the signals from the two squinted beams) are inserted at the two input ports, the sum and difference of the two are found at the two output ports. (There are several methods for obtaining a hybrid junction, as indicated later.) On reception, the output of the sum and difference ports are each heterodyned to an intermediate frequency and amplified in the superheterodyne receiver. It is important that the sum and difference channels have the same phase and amplitude characteristics. For this reason, a single local oscillator (LO) is shared by the two channels. The transmitter is connected to the sum port of the hybrid junction. A duplexer (TR) is included in the sum channel for the protection of the sum-channel receiver. Although it might not be needed for protection of the difference-channel receiver, a duplexer is often inserted in the difference channel so as to maintain the phase and amplitude balance of the two channels. Automatic gain control, not shown, is also used to help maintain balance.

The outputs of the sum and difference channels are the inputs to the *phase-sensitive detector,* which is a nonlinear device that compares two signals of the same frequency.

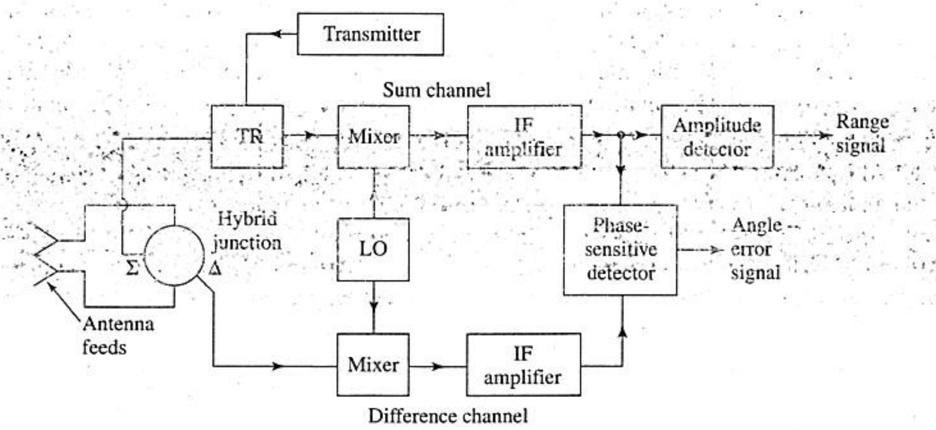

Figure 4.4 Simple block diagram of the amplitude-comparison monopulse in one angle coordinate. Σ denotes the sum channel; Δ denotes the difference channel.

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*It is sometimes said that a simultaneous-lobing tracking radar should not be called monopulse unless it employs the sum and difference patterns.

In this case, the two signals are those of the sum and difference channels. The output of a phase-sensitive detector is the angle-error signal. Its magnitude is proportional to $|\theta_T - \theta_0|$, where θ_T = target angle and θ_0 = boresight, or crossover, angle. The sign of the output of the phase-sensitive detector indicates the direction of the angle error relative to the boresight. If the sum signal in the IF portion of the receiver is $A_s \cos \omega_{\mathrm{IF}} t$, the difference signal will be either $+A_d \cos \omega_{\mathrm{IF}} t$ or $-A_d \cos \omega_{\mathrm{IF}} t$, depending on which side of boresight is the target. (In the above, $A_s > 0$ and $A_d > 0$.) Since $-A_d \cos \omega_{\mathrm{IF}} t = A_d \cos (\omega_{\mathrm{IF}} t + \pi)$, the sign of the difference signal may be found with the phase-sensitive detector by determining whether the difference signal is in phase with the sum signal or 180° out of phase; that is, whether the output phase is 0 or π radians.

Although a phase comparison is part of the amplitude-comparison monopulse radar, the magnitude of the angle-error signal is determined by comparing the echo-signal amplitudes received with simultaneous squinted beams. The separation of the two antenna feeds is small so that the phases of the signals in the two beams are almost equal when the target angle is not far from boresight.

Hybrid Junctions[4] As mentioned, the hybrid junction is a four-port device that provides at its two output ports the sum and difference of the signals that are at its two input ports. For monopulse radar, they are usually constructed from waveguide; but they can also be in coax or stripline. The hybrid junction known as the *magic-T,* sketched in Fig. 4.5a, consists of an E-plane T-junction (shown vertical) and an H-plane T-junction (shown horizontal) arranged as indicated. A signal, whose E-field (electric field) is indicated by the solid arrow, is shown as the input at port 1. It is divided equally in power and appears with the same phase at both ports 3 and 4. Nothing will appear at port 2. A signal whose E-field is indicated by the dashed arrow is the input at port 2. It is divided equally between ports 3 and 4, and no energy appears at port 1. The nature of the E-plane junction is such as to make the two signals at ports 2 and 3 out of phase by 180°, as is indicated by the dashed arrows being reversed in direction. Thus the output of port 4 is the *difference* of the signals at ports 1 and 2; and the output of port 3 is the *sum* of ports 1 and 2. The magic-T is inherently a broadband device. As shown, it is bulky, but its arms can be folded to make it more compact without changing its electrical characteristics. Folding means making arms 3 and 4 to be parallel to arm 2 (by folding either up or down) or they may be folded forward to be parallel to arm 1.

The *rat-race,* or *hybrid-ring junction,* is shown sketched in Fig. 4.5b. Ports 1 and 2 are the two inputs. A signal at port 1 can reach port 4 by two separate paths, one clockwise and the other counterclockwise. The two paths are of the same length (3/4 wavelength), so they reinforce and a signal will appear at this output port. The signal input at port 1 also reaches port 3 by two paths—one which travels 5/4 wavelength and the other 1/4 wavelength. They are also in phase, so a signal will appear at port 3 from port 1. At port 2, however, the two signals from port 1 are 180° out of phase (the clockwise signal travels one wavelength and the counterclockwise signal travels one-half wavelength). Thus a signal that is input at port 1 will be divided equally and appear at ports 3 and 4, but not appear at 2. Similarly, a signal input at port 2 will appear at ports 3 and 4 and not at port 1. At port 4, however, the signal from port 2 can be seen to be 180° out of phase with the signal that arrives there from port 1. Thus the output of port 4 is the *difference* of the

Figure 4.5 Examples of hybrid junctions as might be used in monopulse radar. (a) Magic-T; (b) rat-race, or hybrid-ring junction; (c) 3-dB directional coupler obtained by use of two rectangular waveguides with narrow walls touching and with quarter-wavelength spacing between the two coupling holes.

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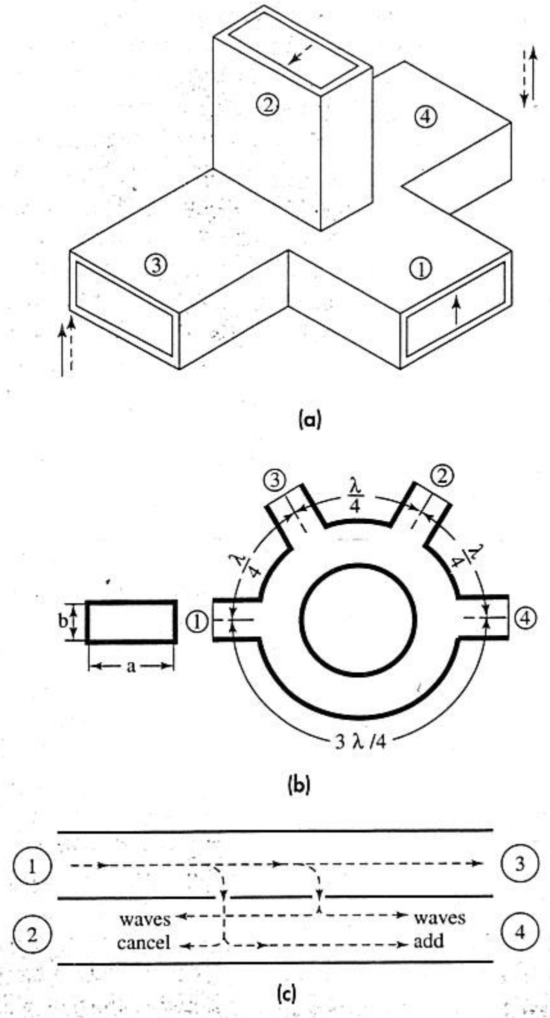
Figure 4.5 Examples of hybrid junctions as might be used in monopulse radar. (a) Magic-T; (b) rat-race, or hybrid-ring junction; (c) 3-dB directional coupler obtained by use of two rectangular waveguides with narrow walls touching and with quarter-wavelength spacing between the two coupling holes.



(a)

(b)

(c)

input signals at ports 1 and 2; and port 3 is the *sum* of the signals at ports 1 and 2. Since the operation of this device depends on the lengths between ports being some fraction of a wavelength, it will be frequency sensitive and not as broadband as the magic-T.

The *3-dB directional coupler* is a relatively compact form of hybrid junction that can also be used to obtain the sum and difference signals for monopulse. One method of obtaining a 3-dB directional coupler is to align two rectangular waveguides with their narrow walls touching, as in Fig, 4.5c. Microwave energy from one of the waveguides is coupled to the other by means of appropriate holes or slots between the two waveguides. Because of the quarter-wave spacing between the two coupling holes shown in the figure, this configuration is a frequency-sensitive device, but by employing more than two coupling holes or by using slots instead of holes, it can be made to operate over a useful frequency band.[5] (In the configuration of Fig. 4.5c, a 90° phase shift has to be inserted in either port 1 or 2 in order to provide the sum and difference at the other two.)

Monopulse in Two Angle Coordinates A block diagram of a monopulse radar for extracting angle-error signals in both azimuth and elevation is shown in Fig. 4.6. The cluster of four feed horns generate four partially overlapping (squinted) beams. The four feeds might be used to illuminate a parabolic reflector, Cassegrain reflector, or a space-fed phased array antenna. The arrangement of the four feeds is shown in the upper left-hand portion of the figure. All four feeds are used to generate the sum pattern on transmission and reception. The difference pattern in one plane is formed by taking the sum of two adjacent feeds and subtracting them from the sum of the other two adjacent feeds. The difference pattern in the orthogonal plane is obtained similarly. For example, based on the arrangement of the feeds shown in Fig. 4.6, the sum pattern is found from $A + B + C + D$; the azimuth difference pattern is obtained from $(A + B) - (C + D)$; and the elevation difference pattern is $(B + D) - (A + C)$. Note that the upper feeds form the lower beams when radiated by a reflector antenna. A total of four hybrid junctions are needed to obtain the sum pattern and the two difference patterns. The three mixers for the sum, elevation difference, and azimuth difference channels use a common local oscillator to better maintain the phase relationships among the three channels. Two phase-sensitive detectors extract the angle-error information; one for azimuth and the other for elevation. Range information is extracted from the output of the sum channel after envelope detection.

Since a phase comparison is made between the output of the sum channel and each of the difference channels, it is important that large relative phase differences not occur among the three channels. The phase difference between channels should be maintained to within 25° or better for reasonably proper performance.[6]

Automatic Gain Control (AGC) AGC is required in the receiving system in order to maintain a stable closed-loop servo system for angle tracking and to insure that the

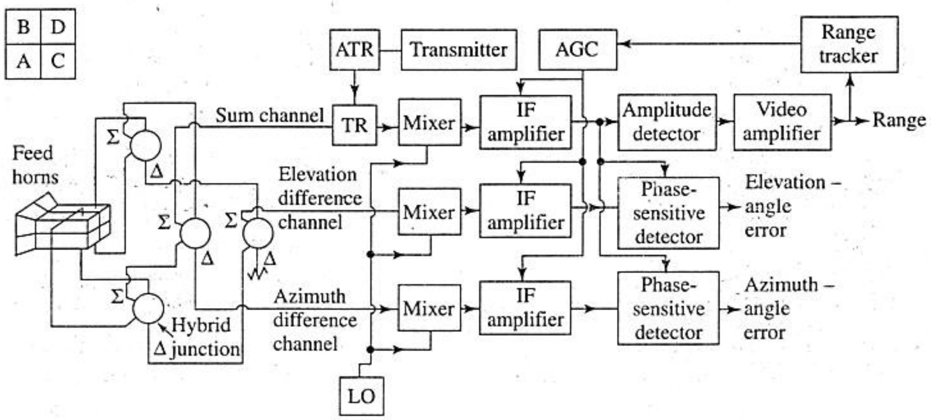


Figure 4.6 Block diagram of two-coordinate (azimuth and elevation) amplitude-comparison monopulse tracking radar. Diagram in the upper left corner represents the four-horn feed. (After Fig. 18.9, Ref. 1.)

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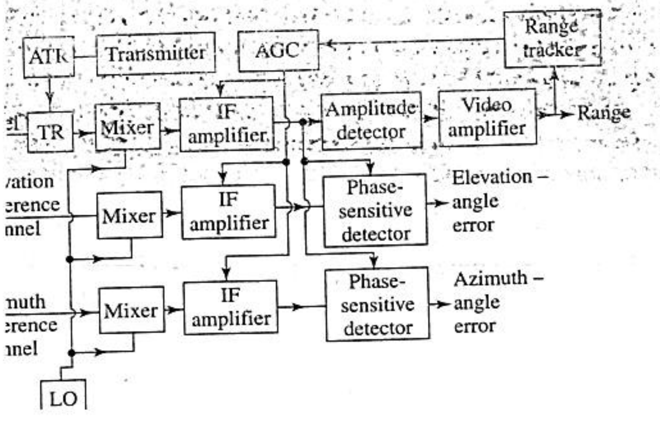
terns. The error signal is the output
angle is found to be $\theta_q = 0.31\theta_B$, wh
beams. This corresponds to a crossov
squint angle, based on a different cri
$0.46\theta_B$, which corresponds to a crosso
out that the analysis of Rhodes (as we

guration of Fig. 4.5c, a 90° phase shift has to be inserted
provide the sum and difference at the other two.)

dinates A block diagram of a monopulse radar for ex-
both azimuth and elevation is shown in Fig. 4.6. The
rate four partially overlapping (squinted) beams. The four
ate a parabolic reflector, Cassegrain reflector, or a space-
e arrangement of the four feeds is shown in the upper
. All four feeds are used to generate the sum pattern on
e difference pattern in one plane is formed by taking the
l subtracting them from the sum of the other two adjacent
n the orthogonal plane is obtained similarly. For example,
he feeds shown in Fig. 4.6, the sum pattern is found from
difference pattern is obtained from $(A + B) - (C + D)$; and
ı is $(B + D) - (A + C)$. Note that the upper feeds form the
y a reflector antenna. A total of four hybrid junctions are
tern and the two difference patterns. The three mixers for
and azimuth difference channels use a common local os-
phase relationships among the three channels. Two phase-
angle-error information; one for azimuth and the other for
is extracted from the output of the sum channel after enve-

n is made between the output of the sum channel and each
is important that large relative phase differences not occur
e phase difference between channels should be maintained
sonably proper performance.[6]

C) AGC is required in the receiving system in order to
p servo system for angle tracking and to insure that the

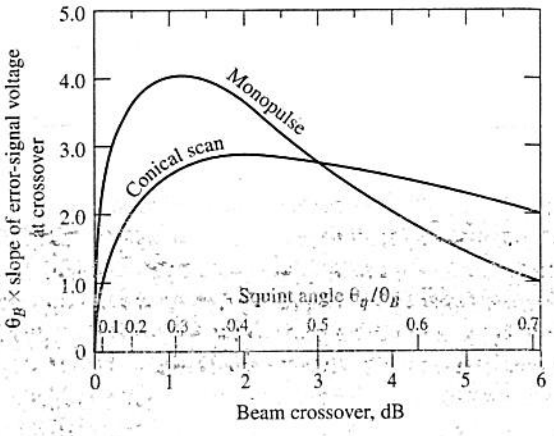


angle-error signal is not affected by changes in the received signal amplitude. As indicated in the block diagram of Fig. 4.6, the AGC signal is obtained from the peak voltage of the sum channel and generates a negative dc voltage proportional to the peak signal voltage. The AGC signal from the sum channel is fed back to control the gain of all three channels so as to provide a constant angle sensitivity independent of changes in target cross-section fluctuations or changes in range.

Antennas for Monopulse The assemblage of hybrid junctions, waveguides, and other microwave components needed to extract the sum and difference signals in a monopulse radar is called a *comparator.* The comparator circuitry of the early monopulse radars was quite large and bulky. If it were placed at the feed of a parabolic reflector antenna, it would cause considerable blockage of the antenna radiation and result in high sidelobes and reduced angle accuracy. For this reason, the original amplitude-comparison monopulse radar that was developed by the Naval Research Laboratory employed a metal-plate lens antenna. A lens does not cause aperture blocking, but it experiences greater loss than does a reflector antenna because there will be unwanted reflections from both the input surface and the output surface of the lens. With advances in microwave hardware technology, the size of the comparator circuitry was reduced and the AN/FPS-16 precision tracking radar (introduced in the late 1950s) was able to use a reflector antenna with the microwave circuitry at the focus of the parabolic reflector. The four waveguide transmission lines to the four feeds at the focus were made of Invar to reduce the adverse effects of temperature differences that might be experienced by the waveguides. The introduction of the Cassegrain reflector antenna (also in the late 1950s) allowed the microwave circuitry to be placed behind the parabolic reflector at its apex without aggravating the antenna blockage problem. Also, the feed system at the apex is easier to support mechanically than if it had to be placed in front of the reflector at the focus. Almost all continuous tracking precision monopulse radars employ the Cassegrain antenna. The monopulse principle can also be used with phased array antennas.

Optimum Squint Angle The greater the squint angle, the greater will be the slope of the angle-error signal at boresight and the better will be the accuracy of the angle measurement. As the squint angle increases, however, the on-axis gain of the sum pattern decreases. Thus there will be an optimum value of the squint angle. Figure 4.7 plots the slope of the error signal as a function of the squint angle θ_q, assuming the shape of the squinted beams can be modeled by a gaussian function and that mutual coupling between the feeds can be ignored. (The basis for this curve was described in the first edition of this text.[7]) The signal received in the sum channel is proportional to the square of the sum pattern (the sum pattern on transmit times the sum pattern on receive), and the signal in the difference channel is proportional to the product of the sum and the difference patterns. The error signal is the output of the phase-sensitive detector. The optimum squint angle is found to be $\theta_q = 0.31\,\theta_B$, where θ_B is the half-power beamwidth of the squinted beams. This corresponds to a crossover 1.2 dB down from the peak. A different optimum squint angle, based on a different criterion, is given by both Rhodes[8] and Sherman[9] as $0.46\,\theta_B$, which corresponds to a crossover 2.6 dB down from the peak. Berger[10] has pointed out that the analysis of Rhodes (as well as Sherman) which gives a greater optimum squint

Figure 4.7 Slope of the angle-error signal at crossover for monopulse and conical-scan tracking radars. θ_B = half-power beamwidth, θ_q = squint angle.

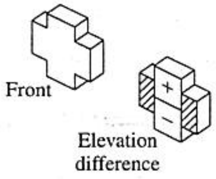


angle applies for one-way beacon tracking (instead of two-way radar tracking) since it assumes a one-way signal is being tracked, but the curve in Fig. 4.7 is based on two-way radar tracking.

Monopulse Antenna Feed Systems[11] The question of optimum sum and difference patterns also can be examined on the basis of optimum antenna aperture illuminations rather than the concept of optimum squint angle. The desired illumination of the antenna has to be convenient to implement and produce low antenna sidelobes. The sum and difference patterns for a reflector or lens antenna are determined by the system of feeds that are used. The original four-horn feed system is the simplest to consider, but it cannot provide a difference pattern and a sum pattern that are independently optimized. The sum pattern should have maximum gain on axis, which requires a uniform aperture illumination. The difference pattern should have an aperture illumination that results in a large slope of the error signal at the beam crossover. Also, the antenna patterns should have low sidelobes and be able to maintain their favorable characteristics over a wide bandwidth. If circular polarization is needed, the demands on the feed system are further increased and often some compromise in performance must be accepted.

An improvement over the original four-horn monopulse system is shown in Fig. 4.8. This has been approximated in some precision tracking radars with a five-horn feed consisting of one horn generating the sum pattern surrounded by four horns generating the difference patterns. What makes the arrangement of Fig. 4.8 more suitable for monopulse tracking than the original four-horn feed is that analysis indicates that the size of the feed system generating the difference pattern should be about twice that of the feed generating the sum pattern.[12] This is approximately true of the feed of Fig. 4.8. Another approximation to the ideal is a 12-horn feed, but it is relatively large and complex.[13] Simpler and more compact feed systems can be obtained by using higher-order waveguide modes to obtain independent control of the sum and difference patterns. These are called *multimode feeds.*

Figure 4.8 Approximately "ideal" feed illumination for monopulse sum and difference channels.[1]



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can be switched to operate with eithe
feed does not provide optimum sum a
mise between complexity and efficien
trackers. In a radar with dual-polar
between the polarizations can degrad
polarized target scattering.

Phased Array Monopulse Difference
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the difference patterns by means of se
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pattern for good angle accuracy and lc
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nation[14] is widely used to design a p
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patterns, which are known as Bayliss

Two-Channel and One-Channel Monc
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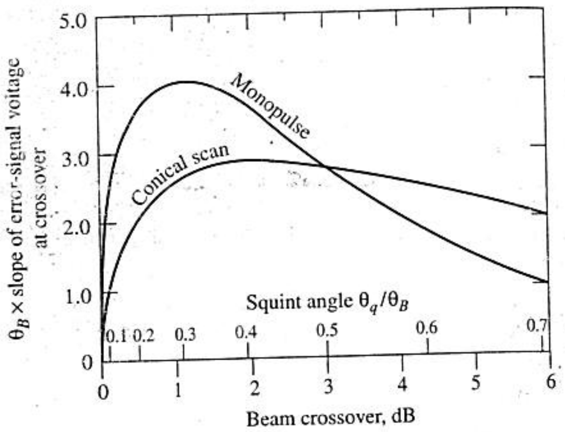

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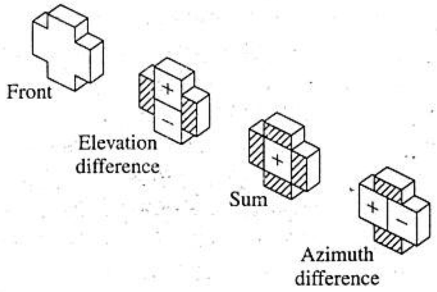

Figure 4.8 Approximately "ideal" feed illumination for monopulse sum and difference channels.[1]

For circular polarization, a five-horn feed system can be obtained so that the antenna can be switched to operate with either horizontal, vertical, or circular polarization. This feed does not provide optimum sum and difference patterns; but it is a practical compromise between complexity and efficiency in obtaining circular polarization for monopulse trackers. In a radar with dual-polarization monopulse tracking, insufficient isolation between the polarizations can degrade the angle accuracy due to crosstalk from cross-polarized target scattering.

Phased Array Monopulse Difference Patterns If monopulse angle measurement is required with a phased array antenna, it is possible to independently control the sum and the difference patterns by means of separate beam-forming systems for the phased array. The sum pattern may be chosen for maximum gain and low sidelobes, and the difference pattern for good angle accuracy and low sidelobes. In Sec. 9.11, the synthesis of good antenna patterns based on the Taylor aperture illumination is discussed. The Taylor illumination[14] is widely used to design a pattern with predetermined peak sidelobes for radar antennas, such as the sum beam of a monopulse tracking antenna. An extension of the Taylor method, due to Bayliss,[15] is also widely used to obtain good monopulse difference patterns, which are known as Bayliss patterns.

Two-Channel and One-Channel Monopulse[16–20] Three channels, or three receivers, are required to obtain monopulse angle tracking in two orthogonal angle coordinates. Good phase and amplitude balance must be maintained among the three receivers. To simplify this problem, monopulse radars that need only two or even one receiver were considered in the past. Systems with less than three receivers that process two or even three of the monopulse channels on a shared basis were conceived when receiver hardware was large and its technology was based on vacuum tubes. Over the years, improved technology has allowed better and smaller receivers so that the need for compromising the performance of a monopulse radar by employing fewer than three receiving channels has become less important.

Conopulse[21] This is another attempt to obtain the benefits of monopulse, but with only two channels rather than three. Conopulse, also called *scan with compensation* by the Russians,[22] employs two simultaneous beams that are squinted in opposite directions from the antenna axis. The pair are mechanically rotated around the boresight axis. The monopulse; but their rotation allows the angle measurement in the two orthogonal coordinates to be obtained by time sharing a single channel. The sum and difference of the two squinted beams are processed similar to a conventional monopulse radar.

Since it provides a measurement of angle with simultaneous beams, the accuracy of conopulse is not degraded by amplitude fluctuations of the target as happens with conventional conical scan radars. A single-pulse measurement is not obtained as in a true monopulse, so it has a lower angular data rate than can be obtained with a three-receiver system. Although two receivers are used in conopulse rather than three, it has the disadvantage of requiring the two beams to be rotated mechanically. This can be difficult especially when the polarization has to be maintained constant on rotation. As with other one- and two-receiver monopulse systems, time and the advancement of technology have made conopulse almost obsolete.

Phase-Comparison Monopulse In a *phase-comparison monopulse*, two antenna beams are used to obtain an angle measurement in one coordinate, just as in amplitude-comparison monopulse. The two beams, however, look in the same direction and cover the same region of space rather than be squinted to look in two slightly different directions. In order for the two beams to look in the same direction, two antennas have to be used in the phase-comparison monopulse, Fig. 4.9a, rather than using two feeds at the focus of a

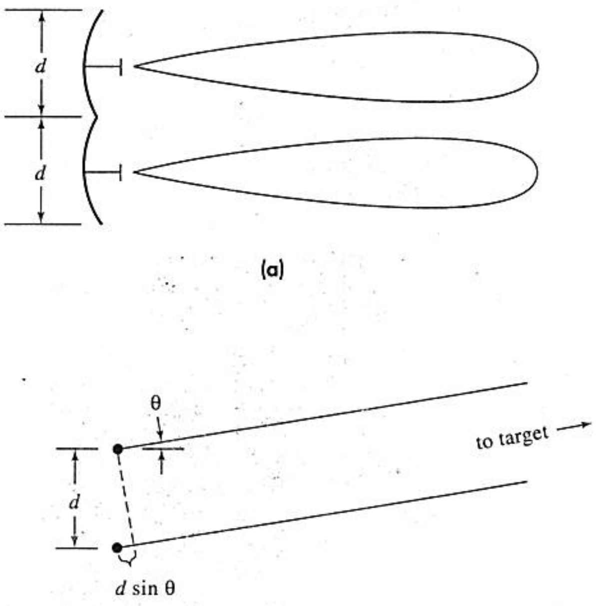

Figure 4.9 Phase-comparison monopulse in one angle coordinate. (a) Two antennas radiating identical beams in the same direction; (b) geometry of the signals at the two antennas of (a) when received from a target at an angle θ, measured with respect to the perpendicular to the baseline of the two radiators.

single antenna as is the case for an ampl
the signals are the same, but their phases
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$$\Delta\phi =$$

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Angle information can also be extr
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One of the limitations of phase-con
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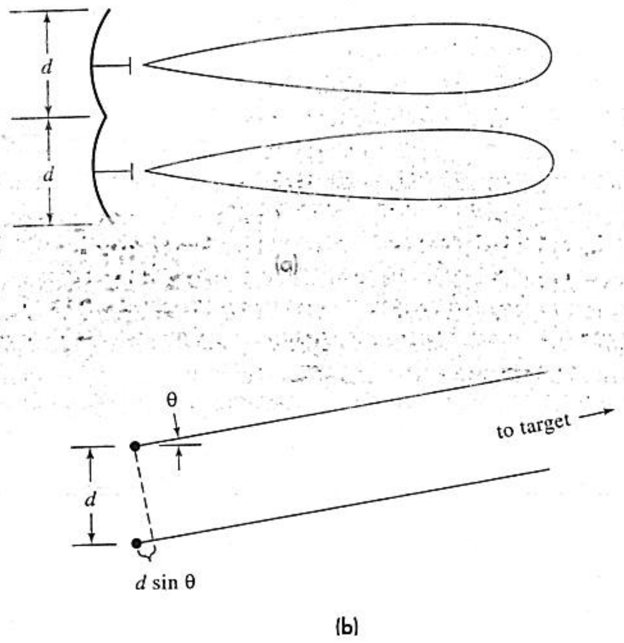


(a)

(b)

single antenna as is the case for an amplitude-comparison monopulse. The amplitudes of the signals are the same, but their phases are different. This is just the opposite of the amplitude-comparison monopulse. Consider two antennas spaced a distance d apart, as in Fig. 4.9b. If the signal arrives from a direction θ with respect to the normal to the baseline, the phase difference in the signals received in the two antennas is

$$\Delta\phi = 2\pi\frac{d}{\lambda}\sin\theta \tag{4.1}$$

where λ = wavelength. A measurement of the phase difference of the signals received in the two antennas can provide the angle θ to the target. The phase-comparison monopulse is sometimes known as an *interferometer radar.*

The phase-comparison monopulse was invented during World War II about the same time as amplitude-comparison monopulse. Its early implementation was less efficient than that of amplitude-comparison monopulse. Four reflector antennas were used arranged in two rows of two columns. One of the antennas might be used as the transmitter (for purposes of this discussion, assume it is the aperture at the upper left of the two-by-two set of apertures). It also provides range information on reception. The other three antennas are used as receivers to obtain the azimuth and elevation angles. The upper right and the lower right antennas might obtain the phase difference in elevation which gives the elevation angle. The lower left and the lower right might obtain the azimuth angle. (The lower right antenna in this case is used for both the elevation and azimuth measurements.) A disadvantage of this method of obtaining the two angle coordinates is that only one-fourth of the available antenna area is used for transmitting and only one-half the area is used on receive to obtain each angle coordinate. Thus, the gain and effective area of a phase-comparison monopulse operating in this manner is less efficient than if the same total antenna area had been used for amplitude-comparison monopulse that generates sum and difference beams.

Angle information can also be extracted in a phase-comparison monopulse by employing sum and difference patterns and processing the signals similar to that described for the amplitude-comparison method. The full antenna aperture area can then be utilized, which is an advantage over the phase-measurement method described above. An analysis of the sum and difference patterns for phase-comparison monopulse shows that a 90° phase shift has to be introduced in the difference signal so that the output of the phase-sensitive detector is an error signal whose amplitude is a function of the sine of the angle of arrival from the target measured with respect to the perpendicular to the two antennas. (The phase-sensitive detector in this case performs a multiplication of the sum and difference signals.)

One of the limitations of phase-comparison monopulse is the effect of grating lobes due to the separation d of the two antennas each of dimension d. Grating lobes in phased array antennas are discussed in Sec. 9.5, but they apply to this situation as well. If the spacing d between the phase centers of the antenna is greater than that of the antenna diameter, high sidelobes are produced in the sum pattern and ambiguities can occur in the angle measurement. Even when the spacing is the same as the antenna diameter, a poor antenna pattern can result. In practice, the separation between the two antennas should be less than the antenna diameter d if good radiation patterns are to be obtained on transmit and angle ambiguities are to be avoided on receive. In the past when parabolic reflectors were used, a portion of the right-hand side of one antenna was sliced off (truncated), and a portion of the left-hand side of the other antenna was also sliced off so that when the two sliced-off edges were butted together, the separation between the two truncated reflector antennas could be made less than the original diameter *d*.

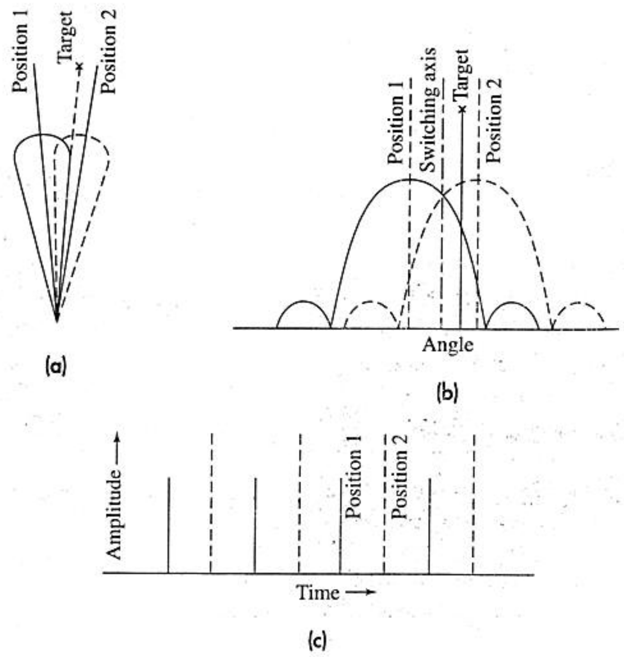
There has been little application of the phase-comparison monopulse as compared to the more popular amplitude-comparison method.

4.3 CONICAL SCAN AND SEQUENTIAL LOBING

The monopulse tracker described in the previous section utilized multiple fixed beams to obtain the angle measurement. It is also possible to time share a single antenna beam to obtain the angle measurement in a sequential manner, as was done in early tracking radars. Time sharing a single antenna beam is simpler and uses less equipment than simultaneous beams, but it is not as accurate.

Sequential Lobing The first U.S. Army angle-tracking air-defense radar in the 1930s (SCR-268) switched a single beam between two squinted angular positions to obtain an angle measurement. This is called *lobe switching, sequential switching,* or *sequential lobing.* Figure 4.10a is a polar representation of the antenna beam in the two switched positions. The same in rectangular coordinates is in Fig. 4.10b. The error signal obtained

Figure 4.10 Lobe-switching antenna patterns and the error signal (for one angle coordinate). (a) Polar representation of the switched antenna pattern; (b) rectangular representation; (c) error signal.



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difference in amplitude between the vol
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Two additional switching positions
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the right–left, up–down sectors are cove
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In a sequential lobing system, a pu
beam is squinted to the right, again w
squinted to the left, and when the beam is
right, up, left, down, right, and so forth.
it must have become obvious that the fo
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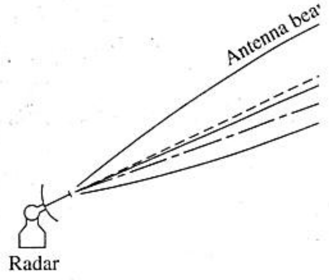
continuously rotated to obtain angle me
scan radar.

Conical Scan The basic concept of con
angle between the axis of rotation and
Consider a target located at position *A*.
the target's offset from the rotation axis
lated at a frequency equal to the beam
frequency). The amplitude of the modu
the target direction and the rotation axi
nates determines the phase of the coni
beam rotation. The conical-scan modula

Figure 4.11 Conical-scan tracking.



avoided on receive. In the past when parabolic reflectors
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ENTIAL LOBING

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U.S. Army angle-tracking air-defense radar in the 1930s
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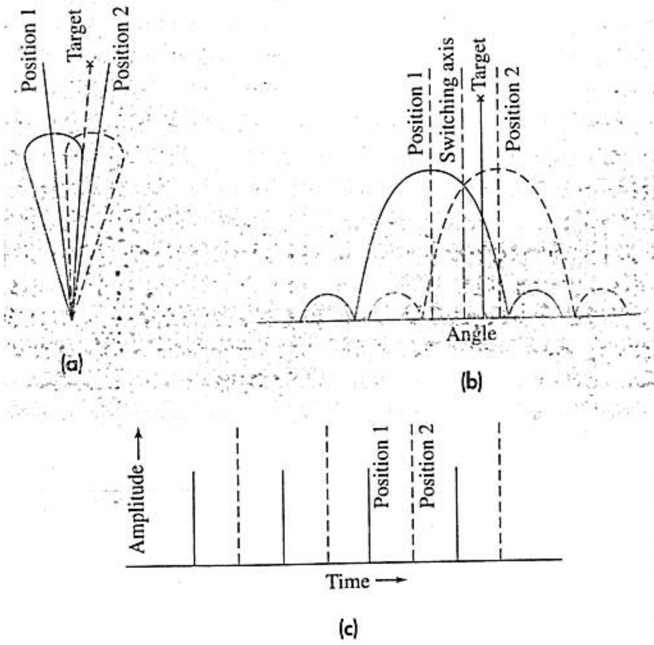
lar coordinates is in Fig. 4.10b. The error signal obtained



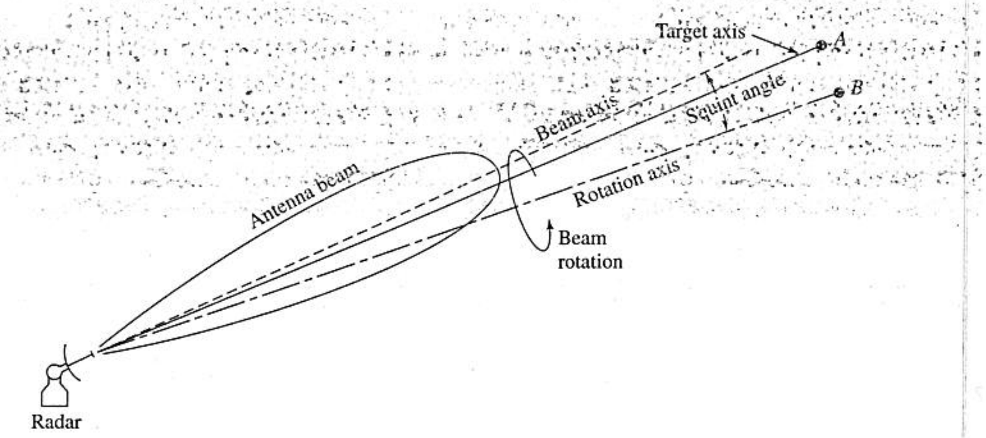
from a target not located on the switching axis (boresight) is shown in Fig. 4.10c. The difference in amplitude between the voltages obtained in the two switched positions is a measure of the angular displacement of the target from the switching axis. The direction in which to move the beam to bring the target on boresight is found by observing which beam position has the larger signal. When the echo signals in the two beam positions are equal, the target is on axis and its direction is that of the switching axis.

Two additional switching positions are needed to obtain the angle measurement in the orthogonal coordinate. Thus a two-dimensional sequentially lobing radar might consist of a cluster of four feed horns illuminating a single reflector antenna, arranged so that the right–left, up–down sectors are covered by successive antenna positions. A cluster of five feed horns might also be used, with a central feed used for transmission and four outer feeds used for reception on a sequential basis.

In a sequential lobing system, a pulse might be transmitted and received when the beam is squinted to the right, again when the beam is squinted up, when the beam is squinted to the left, and when the beam is squinted down. Thus the beam might be switched right, up, left, down, right, and so forth. After living with this type of scanning for a while, it must have become obvious that the four horns and RF switches could be replaced by a single feed that radiated a single beam squinted off axis. The squinted feed could then be continuously rotated to obtain angle measurements in two coordinates. This is a *conical-scan* radar.

Conical Scan The basic concept of conical scan, or *con-scan,* is shown in Fig. 4.11. The angle between the axis of rotation and the axis of the antenna beam is the squint angle. Consider a target located at position *A*. Because of the rotation of the squinted beam and the target's offset from the rotation axis, the amplitude of the echo signal will be modulated at a frequency equal to the beam rotation frequency (also called the conical-scan frequency). The amplitude of the modulation depends on the angular distance between the target direction and the rotation axis. The location of the target in two angle coordinates determines the phase of the conical-scan modulation relative to the conical-scan beam rotation. The conical-scan modulation is extracted from the echo signal and applied

Figure 4.11 Conical-scan tracking.



to a servo control system that continually positions the antenna rotation axis in the direction of the target. It does this by moving the antenna so that the target line of sight lies along the beam rotation axis, as at position B in Fig. 4.11. Two servos are required, one for azimuth and the other for elevation. When the antenna is "on target," the conical-scan modulation is of zero amplitude.

Block Diagram A block diagram of the angle-tracking portion of a conical-scan tracking radar is shown in Fig. 4.12. The antenna is mounted so that it can be mechanically positioned in both azimuth and elevation by separate motors. The antenna beam is squinted by displacing the feed slightly off the focus of the parabola.

The parabolic-antenna feed can be a rear-feed design for mechanical convenience. When the feed is designed to maintain the plane of polarization as it rotates about the axis, it is called a *nutating* feed. A *rotating* feed is one which causes the plane of polarization to rotate. The nutating feed is preferred over the rotating feed since a rotating polarization can cause the amplitude of the target echo signal to change with time even for a stationary target on-axis. A change in amplitude caused by a modulated echo signal can result in degraded angle-tracking accuracy. The nutating feed is usually more complicated, however, than the rotating feed. If the antenna is small enough (as in a missile guidance system), it might be easier to mechanically rotate the tilted reflector rather than the feed, thus avoiding the problems of either a rotary joint or a flexible RF joint for the nutating feed.

A typical conical-scan rotation speed might be in the vicinity of 30 rev/s. The same motor that provides the conical-scan rotation of the antenna beam also drives a two-phase reference generator with electrical outputs at the conical-scan frequency that are 90° apart in phase. These two outputs serve as reference signals to extract the elevation and azimuth errors as indicated in Fig. 4.12. The received echo signal is fed to the receiver from the antenna via two rotary joints (not shown in the block diagram). One rotary joint permits motion in azimuth; the other, in elevation.

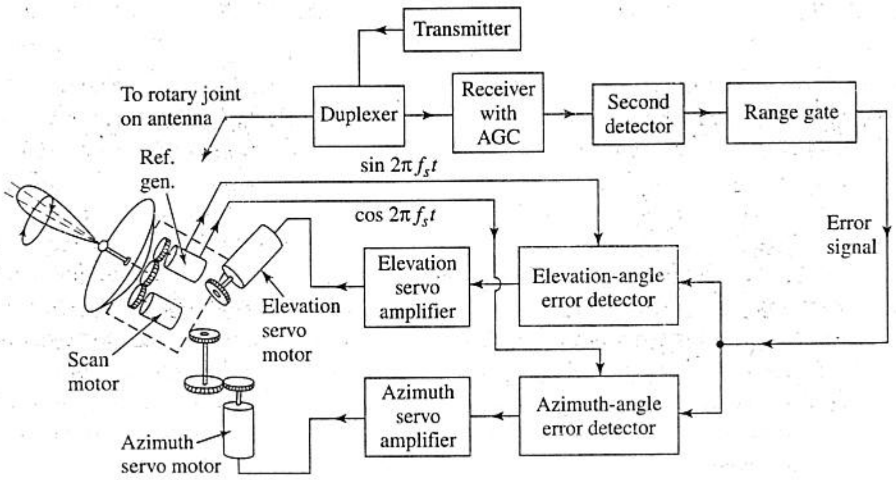


Figure 4.12 Block diagram of conical-scan tracking radar.

The receiver is a superheterodyne ex
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put into track by having the receiver sc
on to it and then continually track it in
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with a reference signal. The magnitude
proportional to the angle error, and its s
The angle error outputs are amplified an
servo motors. The angular position of
and azimuth of the antenna axis.

The video signal is a pulse-train m
4.13a. It is usually convenient to stretc
crease the energy at the conical-scan fr
sion. Pulse stretching, Fig. 4.13b, is ac
has also been known in the past as a *b*

The pulse repetition frequency mus
scan frequency for proper filtering and av
must be at least four pulses during each
obtain up–down and right–left comparis
that of the conical-scan frequency; but it

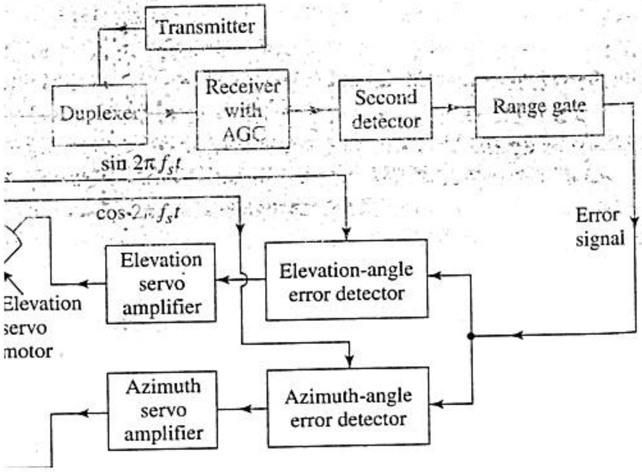
Automatic Gain Control As with m
scan radar. It has the purpose of maint

Figure 4.13 (a) Pulse-train with conical-scan modulation; (b) same pulse-train after stretching by a sample-and-hold circuit.

continually positions the antenna rotation axis in the di-
by moving the antenna so that the target line of sight lies
s at position *B* in Fig. 4.11. Two servos are required, one
evation. When the antenna is "on target," the conical-scan
e.

ram of the angle-tracking portion of a conical-scan track-
. The antenna is mounted so that it can be mechanically
elevation by separate motors. The antenna beam is squinted
off the focus of the parabola.
d can be a rear-feed design for mechanical convenience.
maintain the plane of polarization as it rotates about the
d. A *rotating* feed is one which causes the plane of polar-
feed is preferred over the rotating feed since a rotating po-
ude of the target echo signal to change with time even for
hange in amplitude caused by a modulated echo signal can
ig accuracy. The nutating feed is usually more complicated,
l. If the antenna is small enough (as in a missile guidance
nechanically rotate the tilted reflector rather than the feed,
either a rotary joint or a flexible RF joint for the nutating

ation speed might be in the vicinity of 30 rev/s. The same
l-scan rotation of the antenna beam also drives a two-phase
ical outputs at the conical-scan frequency that are 90° apart
rve as reference signals to extract the elevation and azimuth
2. The received echo signal is fed to the receiver from the
not shown in the block diagram). One rotary joint permits
in elevation.



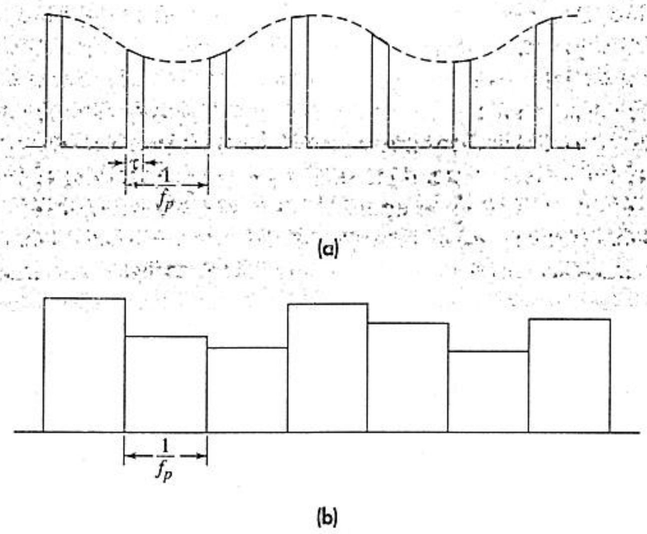
The receiver is a superheterodyne except for features related to the conical-scan tracking. The error signal is extracted in the video after the second detector. A single target is put into track by having the receiver scan a range gate to search for the target and lock on to it and then continually track it in range (as described later in the chapter). Range gating eliminates noise and excludes all targets other than the desired target. The error signal from the range gate is compared with both the elevation and azimuth reference signals in the angle-error detectors, which are phase-sensitive detectors. As described previously, the phase-sensitive detector is a nonlinear device in which the input signal is mixed with a reference signal. The magnitude of the d-c output from the angle-error detector is proportional to the angle error, and its sign (polarity) indicates the direction of the error. The angle error outputs are amplified and used to drive the antenna elevation and azimuth servo motors. The angular position of the target may be determined from the elevation and azimuth of the antenna axis.

The video signal is a pulse-train modulated by the conical-scan frequency, as in Fig. 4.13a. It is usually convenient to stretch the pulses before low-pass filtering so as to increase the energy at the conical-scan frequency and to perform analog-to-digital conversion. Pulse stretching, Fig. 4.13b, is accomplished by a *sample-and-hold* circuit; which has also been known in the past as a *boxcar* generator.

The pulse repetition frequency must be sufficiently large compared with the conical-scan frequency for proper filtering and avoiding inaccuracy of the angle measurement. There must be at least four pulses during each revolution of the conical scanning beam (so as to obtain up–down and right–left comparisons). The prf, therefore, must be at least four times that of the conical-scan frequency; but it is preferable that it be more than 10 times greater.

Automatic Gain Control As with monopulse radar, AGC is employed in the conical-scan radar. It has the purpose of maintaining constant angle-error sensitivity in spite of

Figure 4.13 (a) Pulse-train with conical-scan modulation; (b) same pulse-train after stretching by a sample-and-hold circuit.



amplitude fluctuations or changes of the echo signal due to changes in range. Constant angle-error sensitivity is required to provide stable tracking. AGC is also important for avoiding saturation by large signals which could cause the loss of the scanning modulation and the accompanying error signal. It also attempts to smooth or eliminate as much of the noiselike amplitude of the target echo signal as is practical without disturbing the extraction of the desired echo signal at the conical-scan frequency. The gain of the AGC loop at the conical-scan frequency should be low so that the error signal will not be suppressed by the AGC action.

The required dynamic range* for the AGC will depend on the variation in range over which targets are tracked and the variation expected in the target cross section. If, for example, the range variation were 10 to 1, its contribution to the required dynamic range would be 40 dB. The target cross section might contribute another 40-dB variation. Another 10 dB might be allowed to account for other variations in the parameters of the radar equation. Hence, the dynamic range in this example that is required for operation of the receiver AGC might be of the order of 90 dB. In practice, a large dynamic range cannot be obtained with only one stage of AGC.[23]

Optimum Squint Angle The greater the squint angle in the conical-scan tracker the greater will be the slope of the error signal around boresight and the more accurate will be the angle measurement. In Fig. 4.7 is shown the theoretical slope of the error signal for a conical-scan radar when the target is on boresight, or crossover, computed for an antenna pattern with a gaussian shape. The maximum slope occurs at a squint angle equal to 0.41 of the half-power beamwidth. The maximum is seen to be not too sensitive to squint angle in this case. A squint angle of $0.41\theta_B$ corresponds to a point on the antenna pattern of about 2 dB down from the peak. This means that when a conical-scan radar has a target in track, the echo signal is 4 dB less than if the target were viewed at the peak of the antenna beam. (This is sometimes called the *crossover loss.*) A monopulse radar, it will be recalled, tracks the target with the peak of the sum beam so that it does not incur such a loss. Thus the monopulse tracker will have a larger signal-to-noise ratio which provides more accurate tracking in both angle and range than that of the conical-scan tracker.

In a conical-scan tracker a compromise is often made between the range and angle accuracy by selecting a smaller squint angle than that which produces maximum angle-error-signal slope. A compromise value might be $\theta_q/\theta_B = 0.28$, which corresponds to a point on the antenna pattern about 1.0 dB below the peak. The two-way loss in antenna gain is 2.0 dB instead of 4.0 dB, which makes more accurate range tracking but lower accuracy angle tracking. If the radar is used to track a beacon on a one-way path rather than the two-way path of the radar "skin echo," the optimum squint angles are larger.[24]

Scan on Receive Only[25] Military conical-scan and lobe-switching tracking radars are especially vulnerable to electronic countermeasures (ECM) since it is easy for a hostile intercept receiver to detect and determine the conical-scanning frequency. With such

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*Dynamic range is the ratio, usually expressed in decibels, of the maximum to the minimum signal power over which a device (in this case, the AGC) can operate within some specified level of performance.

knowledge, a hostile ECM jammer ca
get (called *break-lock*) by retransmittin
ulation that is the inverse of the conica
is out of phase with the signal which
target, and break-lock might occur. T
and can degrade conical-scan or lobe-

To prevent the hostile ECM jamm
ing radar can operate with a nonscann
apply conical scanning or lobe switch
stands for *conical scan on receive onl*
is called LORO, or *lobe on receive on*

4.4 LIMITATIONS TO TRACKING AC

In this section several of the major eff
will be discussed, including:

- Glint, or angle noise, which affec
- Receiver noise, which also affect
racy at long range.
- Amplitude fluctuations of the ta
lobing trackers, but not monopuls

Other factors that influence the overal
ical properties of the antenna and pe
pointing of the antenna boresight is d
fects, and multipath.[26]

Glint This has also been called *angl*
scintillation; but *glint* is the term com
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scatterer, such as a sphere, does not s
multiple scattering centers, such as a
echo from a single scatterer generally
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and uniform. If, however, the target c
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sketched in Fig. 14.14b (exaggerated
vectorially across the aperture to give
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as a distortion of the echo wavefront.

The result of having a nonunifor
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knowledge, a hostile ECM jammer can cause a conical-scan radar to cease tracking a target (called *break-lock*) by retransmitting the received radar signal with an amplitude modulation that is the inverse of the conical-scan frequency. This produces a return signal that is out of phase with the signal which would have been received from the skin-echo of the target, and break-lock might occur. This type of countermeasure is called *inverse gain*, and can degrade conical-scan or lobe-switching tracking systems.

To prevent the hostile ECM jammer from detecting a conical-scan frequency, a tracking radar can operate with a nonscanning transmitting beam to illuminate the target and apply conical scanning or lobe switching only on receive. This is called COSRO, which stands for *conical scan on receive only*. The analogous operation with sequential lobing is called LORO, or *lobe on receive only*.

4.4 LIMITATIONS TO TRACKING ACCURACY

In this section several of the major effects that determine the accuracy of a tracking radar will be discussed, including:

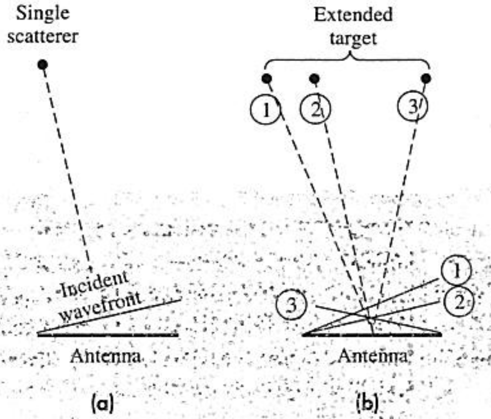
- Glint, or angle noise, which affects all tracking radars, especially at short range.
- Receiver noise, which also affects all radars, and mainly determines tracking accuracy at long range.
- Amplitude fluctuations of the target echo that bother conical-scan and sequential-lobing trackers, but not monopulse.

Other factors that influence the overall accuracy of a tracking radar include the mechanical properties of the antenna and pedestal, the servo system, the method by which the pointing of the antenna boresight is determined, the antenna beamwidth, atmospheric effects, and multipath.[26]

Glint This has also been called *angle noise, target noise, angle fluctuations,* and *angle scintillation;* but *glint* is the term commonly used. It occurs with complex targets that have more than one scattering center within the resolution cell of the radar. A single "point" scatterer, such as a sphere, does not show the phenomenon of glint. Complex targets with multiple scattering centers, such as aircraft, can cause glint and degrade tracking. The echo from a single scatterer generally arrives at the radar antenna with a uniform planar waveform that has a tilt which depends on the angle of arrival, Fig. 4.14a. The usual method for measuring angle almost always assumes that the arriving wavefront is planar and uniform. If, however, the target consists of multiple scatterers, each at a different angle, their individual echo signals arrive at the antenna with slightly different wave tilts, as sketched in Fig. 14.14b (exaggerated to show the principle). These tilted wavefronts add vectorially across the aperture to give a composite wavefront whose amplitude and phase are not uniform across the aperture. Glint from a complex target is sometimes thought of as a distortion of the echo wavefront.

The result of having a nonuniform wavefront from a complex target, when the radar is designed to process the echo wavefront that is planar, is an error in the measurement

Figure 4.14 (a) Plane wave from one scatterer incident on the antenna. (b) Plane waves from three scatterers incident on the antenna. Resultant aperture illumination is the vector sum of the three plane waves.



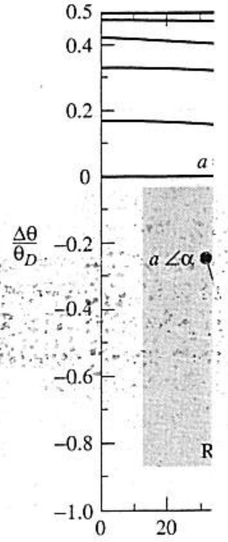
of the angle of arrival. The measured angle does not bear a simple relationship to some distinctive property of the target, such as its center, leading edge, or its largest scatterer. Furthermore, the measured angle of arrival can sometimes cause the boresight of the tracking antenna to point *outside* the angular extent of the target, which can cause the radar to break track. The greater the extent of the target in angle as seen by the radar, the worse will be the angle measurement, as we shall see. Glint, therefore, can be a major source of error when making angle measurements, especially at short range where the angular extent of the target can be relatively large. It bothers all continuous tracking radars that employ closed-loop angle tracking, whether conical-scan, sequential lobing, amplitude-comparison monopulse, or phase-comparison monopulse.

Example of Glint from a Simple Target Model Consider a target model consisting of two independent, isotropic scatterers separated by an angular distance θ_D as measured from the radar, Fig. 4.15a. (Sometimes this is called a *dumbbell target.*) The two scatterers are assumed to be located symmetrically to each side of the perpendicular from the antenna at $\pm\theta_D/2$. Although it may be a fictitious target model chosen for reasons of simplicity, it illustrates the effects that a complex (multiple-scatterer) target has on the accuracy of a tracking radar. The relative amplitude of the echo signals from the two isotropic scatterers is taken to be a (a number less than unity) and the relative phase difference is α. Differences in the phase might be due to differences in range between the two scatterers or to differences in the reflecting characteristics of the two scatterers. The angular error $\Delta\theta$ as measured from the larger of the two isotropic scatterers is given by J. E. Meade as[27]

$$\frac{\Delta\theta}{\theta_D} = \frac{a^2 + a\cos\alpha}{1 + a^2 + 2a\cos\alpha} \qquad [4.2]$$

This is shown plotted in Fig. 4.15b. The larger of the two scatterers is at $\Delta\theta/\theta_D = 0$, and the smaller is at $\Delta\theta/\theta_D = +1$. Positive values of $\Delta\theta$ correspond to the angular region to the left of the larger of the two scatterers; negative values lie outside the target, at angles to the right of the larger target. When the echo signals from both scatterers are in phase

Figure 4.15 Plot of Eq. (4.2) of the error $\Delta\theta/\theta_D$ as a function of a and α. Insert shows two isotropic scatterers of relative amplitude a and relative phase shift α, separated by an angular extent θ_D as viewed from the radar. The angle $\Delta\theta$ is measured with respect to the larger of the two scatterers.



($\alpha = 0$); $\Delta\theta/\theta_D$ reduces to $a/(a + 1)$, sor
scatterers. When the signals are of equ
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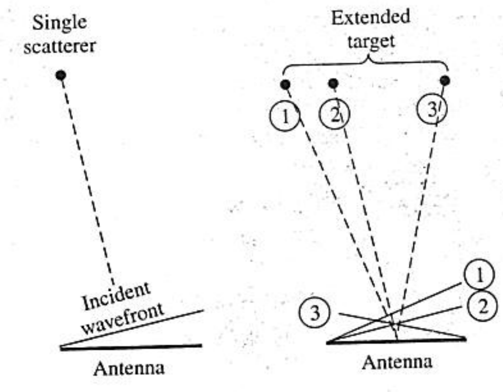

(a) (b)

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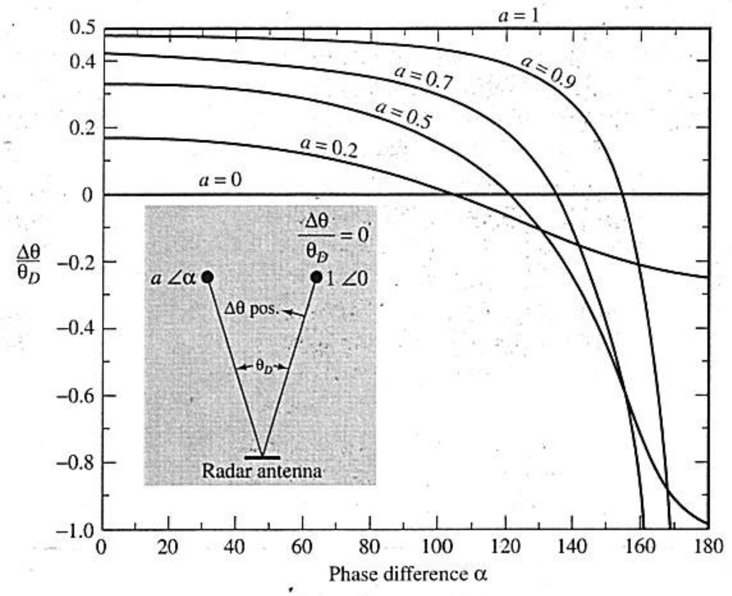

Figure 4.15 Plot of Eq. (4.2) of the error $\Delta\theta/\theta_D$ as a function of a and α. Insert shows two isotropic scatterers of relative amplitude a and relative phase shift α, separated by an angular extent θ_D as viewed from the radar. The angle $\Delta\theta$ is measured with respect to the larger of the two scatterers.

($\alpha = 0$), $\Delta\theta/\theta_D$ reduces to $a/(a+1)$, sometimes called the "center of gravity" of the two scatterers. When the signals are of equal amplitude ($a = 1$) and the phase difference $\alpha = \pi$ radians, Eq. (4.2) indicates the antenna points to $\Delta\theta/\theta_D = -\infty$; that is, the antenna is driven well outside the bounds of the target. It should be cautioned that an assumption made in deriving Eq. (4.2) is that the voltage of the angle-error signal is directly proportional to the angle error; that is, the angle-error signal is linear. This implies that angle errors are small; but when $\Delta\theta/\theta_D \to -\infty$, the angle error is not small. As was indicated in Fig. 4.3d, as the angle error increases, the angle-error signal voltage will no longer be linear and its slope can even change sign. Equation (4.2) no longer applies when $\Delta\theta/\theta_D$ becomes large. Nevertheless, the simple model of Eq. (4.2) describes the general nature of the behavior to be expected by a radar tracker subjected to glint from a complex target.

The relative phase, α, changes if the relative ranges to the two scatterers change. This can occur, for example if the aspect angle of an aircraft changes due to its flight path or atmospheric turbulence. Thus the value of α can vary with time. The radar tracker theoretically can point outside the target region a significant fraction of the time.

Equation (4.2) indicates that the tracking error $\Delta\theta$ for the two-scatterer target is proportional to the angular extent of the target θ_D, which is why the tracking error due to glint varies inversely with range. The error becomes larger as the range becomes shorter. Although this statement is based on the simple two-scatterer target, it is a reasonable approximation to a real target provided the angular extent is not greater than the antenna beamwidth. When the angular extent of the target is greater than the antenna beamwidth, the two scatterers can be resolved and there is no glint.

A slightly more complex model than the two-scatterer target considered above is one consisting of many individual scatterers, each of the same cross section, arranged uniformly along a line of length L perpendicular to the line of sight from the radar. The resultant cross section from such a target is assumed to behave according to the Rayleigh probability density function. It was found that the probability is 13.4 percent that the apparent direction of the target measured by the radar will be outside of the target region.[28] Similar results for a two-dimensional model consisting of equal cross-section scatterers uniformly spaced over a circular area indicate that the probability the apparent direction lies outside the target is 20 percent. Howard[29] states that measurements made on actual aircraft of the rms value of angle noise, expressed in the same length units as the target extent L in cross-range, are between $0.15L$ and $0.2L$. A small single-engine aircraft viewed nose-on might have a value near $0.1L$, and larger aircraft and aircraft viewed from the side approach $0.2L$.

Although glint is a deterministic phenomenon if the target configuration and its scattering properties are known, it has sometimes been analyzed in statistical terms.[30,31] The deterministic approach, however, helps in understanding what is taking place with the target and the radar, something that statistical models cannot do as well. Glint is usually thought of as a target effect; but to some extent, the radar enters also. Glint occurs when the radar cannot resolve the individual scatterers of a complex target; so that some radars might not be affected by glint that would seriously bother others.

Methods for reducing the effects of glint on radar tracking performance are discussed later in this section. The phenomenon of glint also occurs in the range dimension, as will be discussed in Sec. 4.6. A brief survey of radar glint, along with an extensive bibliography of the early work in this field, has been given by Wright.[31]

In addition to tracking radars, it has been said in the literature that glint also occurs with scanning surveillance radars.[32] This might not be completely accurate. Surveillance radars estimate the target direction as the antenna pointing angle where the echo signal is a maximum. The estimate of angle in scanning surveillance radars is often made by *beam splitting,* or something equivalent. Closed-loop angle tracking is not employed. A complex target might cause an error in the beam-splitting angle estimate because of the nonuniform response of the target with angle, but the error does not seem to produce an angle measurement that extends beyond the angular confines of the target as does the glint that occurs in a radar with closed-loop tracking. Thus, glint does not occur with a scanning radar, only one with closed-loop tracking.

Receiver Noise The noise at the input of a radar receiver affects the accuracy of radar tracking just as it does the detection capability of a radar. In Sec. 6.3, the accuracy of radar measurements is discussed, based on a noise model described by the gaussian probability density function. All theoretical expressions for the rms value of the error of a radar measurement (such as angle) are inversely proportional to the square root of the signal-to-noise ratio. From our previous discussion of the radar range equation in Chap. 2, we know that the range of a radar is inversely proportional to the fourth root of the signal-to-noise ratio. The rms value of a radar measurement error is, therefore, directly proportional to the square of the range. Receiver noise is a major factor limiting the accuracy of a radar at long range where signal-to-noise ratios are small. Section 6.2 also indicates that the rms error in the radar measurement of angle is directly proportional to the antenna beamwidth.

The theoretical accuracy of a trac
surement, has been given by Barton[3

$$\delta_{\text{ang}} =$$

where the constant $k = 1$ for a monc
half-power beamwidth, k_s = slope of
ent for monopulse and conical-scan
signal-to-noise ratio per pulse (assum
than 6 dB), f_p = pulse repetition freq
1, and $f_p/2\beta_n$ = number of pulses in
slope k_s for a good four-horn monop
is 1.5 when the offset angle is chose
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The theoretical accuracy of a tracking radar, given as the rms error in the angle measurement, has been given by Barton[33] and can be found in Howard,[34] It is

$$\delta_{\text{ang}} = \frac{k\theta_B}{k_s\sqrt{B\tau(\text{S/N})(f_p/\beta_n)}} \qquad \textbf{(4.3)}$$

where the constant $k = 1$ for a monopulse radar and 1.4 for a conical-scan radar, $\theta_B =$ half-power beamwidth, $k_s =$ slope of the angle-error signal at boresight (which is different for monopulse and conical-scan radars), $B =$ bandwidth, $\tau =$ pulse width, (S/N) = signal-to-noise ratio per pulse (assumed in the derivation of this expression to be greater than 6 dB); $f_p =$ pulse repetition frequency, and $\beta_n =$ servo bandwidth. Generally, $B\tau \approx 1$, and $f_p/2\beta_n =$ number of pulses integrated. According to Howard,[34] the value of the slope k_s for a good four-horn monopulse feed is 1.57. Its value for a conical-scan radar is 1.5 when the offset angle is chosen to optimize overall radar performance. Since the conical-scan radar does not track a target with its maximum antenna gain, the signal-to-noise ratio is lower than that of a monopulse radar. Earlier in this chapter, we have said that the conical-scan tracker might suffer a two-way loss of 2.0 dB. More elaborate expressions for the angle error for the conical-scan tracker[35] and the monopulse tracker[36] can be found in the literature, but the above expression is often suitable for many purposes.

Amplitude Fluctuations The amplitude of the radar echo from a complex target with multiple scattering centers will fluctuate as the aspect of the target changes with respect to the radar. (Changes in aspect may be due to the motion of the target in yaw, roll, or pitch. Aspect changes also occur even if the target moves in a straight line.) Conical-scan and sequential-lobing radars interpret any change in amplitude of the target echo signal as being due to the target not being on boresight. They then direct the antenna to move in a direction to make the "error signal" zero. Thus a change in amplitude due to fluctuations in the target echo during the time interval of the sequential measurement can degrade the accuracy of the measurement. Amplitude fluctuations in the target echo signal, which are also known as *target fading,* do not affect the angle-error measurement accuracy of simultaneous lobing or monopulse systems that extract an angle-error voltage with each pulse.

Since the percentage modulation of the echo signal due to fluctuations in the target cross section is independent of range if AGC is used, the angle error as a result of amplitude fluctuations will be independent of range.

Amplitude fluctuations from aircraft targets are classified as either low frequency or high frequency. According to Howard,[29] the low-frequency pulse-to-pulse amplitude fluctuations might be concentrated mainly below 10 Hz at X band. These are due to variations in the target cross section caused by changes in the relative distances of the individual scattering centers. The amplitude spectrum does not seem to depend strongly on the size of the target. An aircraft with a large wingspan has its scattering centers (the engines, for example) spaced wider than would an aircraft with a small wingspan so that a higher fluctuation frequency would be expected if the rate of change of yaw were the same in the two cases. The large aircraft, however, has slower rates of yaw than a small aircraft so that the frequency extent of the spectra might be expected to be similar. The spectral width of the amplitude fluctuations is closely proportional to the radar frequency, since a change in the relative distances of the scatterers will result in a larger change in wavelengths if the frequency is high than if it is low.

High-frequency amplitude fluctuations can be caused by reflections from propellers and jet engines. The frequency of propeller modulation depends on the number of blades and the rotation rate. The modulation is not sinusoidal and has harmonics of the fundamental frequency. The fundamental frequency of the propeller modulation and its harmonics do not depend on the radar frequency.

The effect of amplitude fluctuations on the accuracy of conical-scan tracking can be reduced by choosing a conical-scan frequency that corresponds to a low value of the target's amplitude fluctuation spectrum. If the amplitude fluctuation noise power were large at the conical-scan or lobing frequency, it could not be readily eliminated by AGC or filtering. A typical conical-scan frequency, for example, might be 30 Hz. Generally the higher the scan frequency, the less the noise due to amplitude fluctuations. At the higher scan frequencies, however, propeller modulation might be present and needs to be avoided. A sufficiently high scanning frequency, however, will have little degradation in tracking because of amplitude fluctuations. It has been reported that experimental measurements with radars operating with pulse repetition frequencies from 1000 to 4000 Hz and a lobing or scan rate one-quarter of the prf are not limited by amplitude fluctuations of the target.[37]

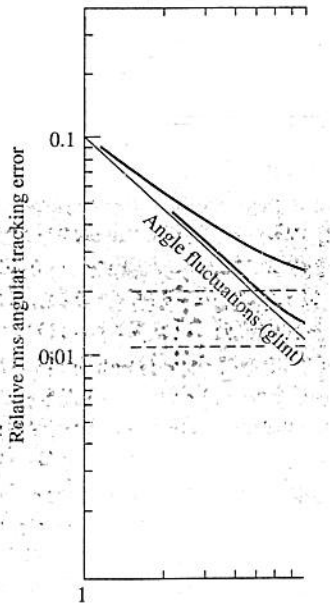
Servo Noise This is the hunting action of the tracking servomechanism which results from backlash and compliance in the gears, shafts, and structures of the antenna mount. The magnitude of the noise is independent of the target echo and will therefore be independent of range.

Summary of Errors The contributions of glint, receiver noise, and amplitude fluctuations to the accuracy of a tracking radar as a function of range is illustrated in Fig. 4.16. The error due to glint varies inversely with range; receiver noise causes the error to vary as the square of the range; and both amplitude fluctuations and servo noise are independent of range. This is a very qualitative plot showing the general nature of each of these factors. Two resultant curves are shown. Curve A might be representative of conical-scan and sequential-lobing trackers. It assumes that the error due to servo noise is less than that due to amplitude fluctuations. Curve B might represent monopulse trackers since it does not include the effect of amplitude fluctuations. Tracking accuracy deteriorates at both long and short range with the best angular accuracy occurring at the intermediate ranges.

The best tracking radars have been able to achieve an angle accuracy of about 0.1 milliradian. Such accuracy does not come easy. It can only be achieved by full attention to the many internal and external factors affecting tracking accuracy and by timely, accurate calibration.[38]

Methods for Reducing Angle Errors Due to Target Glint Glint can be debilitating to a military tracking radar or a radar guided missile. It is important, therefore, to reduce its adverse effects when highly accurate tracking is required. There have been a number of methods proposed to reduce glint. Some can provide significant improvement but may require operating the radar in a manner that is not always best for achieving the radar mission. Other methods might not degrade the major task of the radar, but they do not always

Figure 4.16 Relative contributions to the angle tracking error due to glint, amplitude fluctuations, receiver noise, and servo noise. Curve A represents the composite error for a conical-scan or sequential-lobing radar; curve B represents the composite error for monopulse.



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Frequency Agility The angle error due
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$$\Delta f \text{ (Hz)} = \frac{c \text{ (m/s)}}{2D \text{ (m)}}$$

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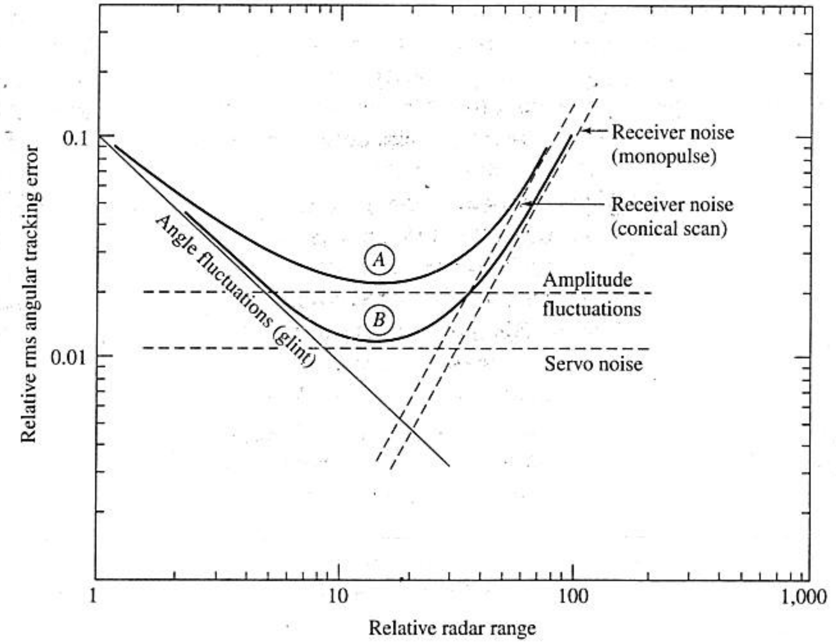

Figure 4.16 Relative contributions to the angle tracking error due to glint, amplitude fluctuations, receiver noise, and servo noise. Curve A represents the composite error for a conical-scan or sequential-lobing radar; curve B represents the composite error for monopulse.

have sufficient effect on reducing glint effects. As with many things, compromises usually have to be made.

Frequency Agility The angle error due to glint depends on the radar frequency since the relative phase α in the simple two-scatterer model depends on frequency. A change in the relative phase α can change the glint error (Fig. 4.15); it can be smaller or it can be larger. If the relative phase α is due primarily to the difference in range ΔR between the two scatterers, then the phase difference $\alpha = 4\pi(\Delta R)f/c$, where f = radar frequency, c = velocity of propagation, and $f/c = \lambda$ = radar wavelength. A change in radar frequency results in a change in the relative phase α and a change in the angle error $\Delta\theta$. There must be a sufficient change in frequency to decorrelate the phase measurement and make the measurements independent. Decorrelation occurs when the phase α changes by more than 2π radians. With this criterion, the frequency should be changed by an amount[39]

$$\Delta f\ (\text{Hz}) = \frac{c\ (\text{m/s})}{2D\ (\text{m})} \quad \text{or} \quad \Delta f\ (\text{MHz}) = \frac{150}{D\ (\text{m})} \qquad [4.4]$$

where D = the depth of the target. (In the two-scatterer case, D is the same as ΔR.) The depth D of an aircraft target as seen by radar usually is not the same as the projected physical size of the target since the extremities of the target might be too small to be detected by the radar or they might be masked by other scatterers.

There are several methods that have been proposed to use the frequency dependence of glint to reduce its effect on tracking accuracy. One method is based on the observation that a large glint error is accompanied by a low echo-signal power. This inverse relationship between glint error and receiver signal power was apparently recognized as early as the mid-1950s.[40] This can be seen qualitatively with the two-scatterer model. When the amplitudes of the two signals are almost equal and their relative phase is almost 180°, Fig. 4.15 indicates that glint errors will be large. But when the two signals are almost equal in amplitude and almost 180° out of phase, they will destructively interfere at the antenna and result in a low echo-signal amplitude. Thus when the signal received by the radar is found to be low, when it is not normally expected to be low, it is likely that the angle measurement is in error. To take advantage of this effect, several different frequencies are radiated with frequency separation greater than that given by Eq. (4.4). The angle estimates of the received echo signals are weighted according to some criterion (such as proportional to their signal-to-noise ratios), and the average is taken. Several other weightings were analyzed by Loomis and Graf.[41] It was found that simply using the angle measurement associated with the largest signal amplitude provides the most accurate estimate of angle. The reduction in rms tracking error by processing only that signal whose frequency results in the largest echo amplitude is approximately

$$\delta_{\text{rms}} \approx \frac{\delta_g}{N} \qquad 1 \leq N \leq 4 \tag{4.5}$$

where δ_g is the single-frequency (no agility) glint error and N is the number of independent frequencies. More than four frequencies were found to offer no significant improvement in accuracy.

Although pulse-to-pulse frequency agility can reduce the effects of glint, it has some drawbacks. Detection of moving targets in clutter using MTI or pulse doppler methods is not compatible with pulse-to-pulse frequency agility. To employ doppler processing, the frequency must remain constant for a significant number of pulses. Frequency diversity is possible by transmitting either simultaneously or in sequence a number of constant-frequency pulses at each of several frequencies that are separated by more than the Δf of Eq. (4.4).

Pulse-to-pulse frequency agility reduces the glint found in conical-scan and sequential-lobing radars, but it can increase the amplitude fluctuations in such radars because of the dependence of radar cross section on frequency. It might result in a net increase in the angle error, and is not always appropriate to use with such radars.

In some crowded radar bands, it might not be easy to achieve the required range of frequencies needed to obtain a reduction in the glint error. If, for example, the effective depth D of a target were 10 m, Eq. (4.4) indicates that the change in frequency must be at least 15 MHz to decorrelate the glint error. If four different frequencies were required, there must be at least 45 MHz of bandwidth available.

Range Resolution It was mentioned that glint occurs when there are multiple scatterers within the radar resolution cell. Range resolution can be quite good in a microwave radar, far better than the angle resolution. Therefore, if the radar has sufficiently high range-resolution to be able to resolve the multiple scatterers that constitute a target, angle glint (as well as range glint) will not occur and the tracking accuracy in angle as well as range will be improved compared to that of a low-resolution system. If, for example, the radar has to have a range resolution of one meter to resolve the various target

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scatterers, the required spectral width must be 150 MHz. The higher microwave frequencies are therefore more suitable for this method of glint reduction than are lower frequencies.

In some respects the use of high range-resolution for reduction of angle glint is related to the use of frequency agility for the same purpose. Both take advantage of wide bandwidth. The frequency agility method uses a finite number of discrete narrowband frequencies within a wide frequency band rather than a continuous spectrum as is required for high range-resolution. If both methods use the same extent of spectral bandwidth, it is suspected that the high-resolution method should produce more accurate tracking than the use of frequency agility. High range-resolution can be used in conjunction with MTI or pulse doppler radar if digital signal-processing technology is not limited by the wide bandwidth required for high resolution.

Servo Bandwidth and AGC Bandwidth[31] Angular error due to glint may be reduced by keeping the servo bandwidth small. This might not be a good idea in practice since the servo bandwidth usually is determined by the requirement that the tracker be able to follow a maneuvering target. Too narrow a servo bandwidth might cause the track of the maneuvering target to be broken and the target lost.

The effects of glint also may be reduced by reducing the bandwidth (increasing the time constant) of the AGC system.[42] A narrowband AGC does not respond to rapid fluctuations in signal amplitude with the result that the echo-signal amplitude might not maintain constant signal level. This can cause a reduction in the angle-error sensitivity during large angle-noise peaks, and smaller rms tracking noise can result. This reduction in angle noise, however, is accompanied by a new component of noise due to amplitude fluctuations associated with the echo signal. Narrowing of the AGC bandwidth generates additional noise in the vicinity of zero frequency that can result in poor tracking. In spite of the potential benefits of a narrowband AGC, a wideband (fast) AGC is usually preferred especially at short and medium ranges where target maneuvers result in high angular rates and the lag in the tracking can be large if a narrowband AGC were used.

Thus narrow servo and/or AGC bandwidth as a means for reducing glint produce other undesirable effects. Bandwidths should be selected so as to be consistent with the various factors that can affect the tactical requirements that determine the acceptable tracking error and probability of breaking lock on a target.

Filtering of Angle Noise One of the first methods for dealing with the angle error due to glint was to consider it as a noise that could be filtered if its characteristics were known.[43] This is one reason glint is sometimes called angle noise. The noise model has not been too successful, however, since the statistical description of glint is considered to be nongaussian and nonstationary.[44] Glint can often be better modeled as deterministic or nonstatistical[45] rather than statistical. Another problem in modeling glint as noise to be filtered is that glint errors are "spiky." They tend to be of large value only when the phase difference α in the two-scatterer model is near π radians. Filtering to smooth the relatively large spikes in the glint can result in a bandwidth too narrow to maintain the track of a maneuvering target, as mentioned above when discussing the servo and AGC bandwidth. It has continued to be fashionable to consider glint as a noise problem, but there has not been the success that one might desire.

Excising of Measurements Associated with Fades It has been mentioned previously that when the glint error is large, the received signal amplitude is small. If the signal level is properly monitored so as to recognize a low signal amplitude, the corresponding angle measurement can be removed (censored) and the tracking error improved. It has been suggested[46] that when a Kalman tracking filter is used in conjunction with a rank detector preprocessor to detect fades and remove the accompanying angle measurement an improvement of 15 percent in the angle tracking accuracy can be obtained.

Polarization[47] It has been suggested that polarization agility can reduce the glint error based on the expectation that the scattering centers will be different with different polarizations. The assumption is that the target echo will be produced by scatterers with widely different polarization response characteristics so that glint will be decorrelated when there is a change in polarization. In practice, however, it might not be expected that polarization agility can decorrelate the glint errors as well as can frequency agility. It has been said[44] that with polarization agility "the improvements are often modest (at best)."

Spatial and Aspect Diversity It also has been suggested that glint can be reduced with either spatial or aspect diversity.[48] By spatial diversity is meant viewing of a target from a different location. The required separation of the antennas for spatial diversity need not be large. Aspect diversity requires that the target rotate with respect to the radar so as to change its aspect with respect to the radar. Not all targets cooperate by changing their aspects sufficiently to obtain the necessaray diversity. Furthermore, a change in aspect takes time, which is usually not available with weapon control radars subject to glint. Both spatial and aspect diversity, therefore, have operational limitations that tend to restrict their practical application for glint reduction.

Avoiding Closed-Loop Tracking As mentioned previously in this section, a radar that extracts the angle of a target without performing closed-loop tracking is not susceptible to the large errors caused by glint. There have been many solutions proposed for reducing the adverse effects of glint. No one method solves all problems, each has its advantages and disadvantages, and no one solution is universally applicable. As with so many other things, compromises might have to be made in order to deal with the potential effects of glint.

4.5 LOW-ANGLE TRACKING

A radar that tracks at low elevation angles illuminates the target via two paths, as shown in Fig. 4.17. One is the direct path from radar to target. The other is the path that includes a reflection from the earth's surface. It is as though the radar were illuminating two targets, one above the surface and the other its image below the surface. This is an example of the classic two-scatterer model mentioned in the previous section on glint. An error in the measured elevation angle of the target occurs because of the effect of glint. The error can be large enough to seriously degrade the quality of the tracking. At low grazing

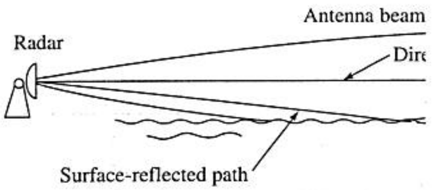

Figure 4.17 Low-angle tracking illustratin
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The effects of multipath depend o
face. Three regions can be identified,[49]

1. *Sidelobe region.* Elevation angles
main beam, illuminate the surface.
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beamwidths above the horizon.[50]
2. *Main-beam region.* The effects of
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3. *Horizon region.* At grazing angles
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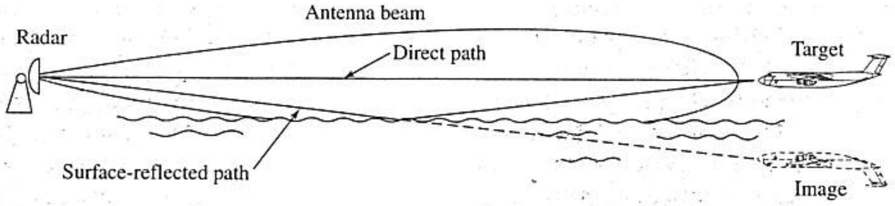

Figure 4.17 Low-angle tracking illustrating the surface-reflected path and the target's image below the surface.

angles over a perfectly smooth reflecting surface, the reflection coefficient from the surface is approximately −1 (Sec. 8.2). That is, its phase is in the vicinity of 180° and its magnitude is approximately unity so that the signal amplitude reflected from the surface is almost equal to the signal amplitude incident on the surface. This is, unfortunately, close to the worse condition for the angle error due to glint, as can be seen from the plot for the two-scatterer target model of Fig. 4.15. For this reason, the tracking of targets at low elevation angles can produce significant errors in the elevation angle and can cause loss of target track. The surface-reflected signal is sometimes called the *multipath signal* and the glint error due to the geometry of Fig. 4.17, a *multipath error.* Multipath errors can be a serious limitation to the radar guidance of missiles to targets low on the water as well as to surface or shipborne radars used for defense against low-altitude cruise missiles or sea-skimmer missile attack.

The effects of multipath depend on what part of the antenna pattern strikes the surface. Three regions can be identified,[49] according to elevation angle:

1. *Sidelobe region.* Elevation angles are such that the near-in sidelobes, rather than the main beam, illuminate the surface. The accuracy of a precision tracking radar (such as the AN/FPQ-6) begins to be degraded when the elevation angle is less than six beamwidths above the horizon.[50]
2. *Main-beam region.* The effects of multipath can begin to be severe when the elevation angle is less than about 0.8 beamwidth.
3. *Horizon region.* At grazing angles approaching zero degrees when there is specular reflection from the surface, the echo signal from the target and its image are approximately equal and out of phase so that combined direct and surface-reflected signal is very low. This reduction in signal-to-noise ratio further aggravates the accuracy problem.

Figure 4.18 shows an experimental measurement of the elevation-angle error obtained with an *S*-band radar as a function of range for an aircraft flying at low altitude.[51,52] The antenna beamwidth in this case was 2.7°. The aircraft flew out in range at a nearly constant altitude of 3300 ft. The start of the track is at about 4° elevation. At this angle the antenna sidelobes, rather than the main beam, illuminate the surface and the effect of multipath on angle accuracy is relatively small. At the center of Fig. 4.18 where the elevation angle is less than 2°, the main beam illuminates the surface and the effect of the surface-reflected wave becomes significant. Large elevation errors occur, which cause the antenna

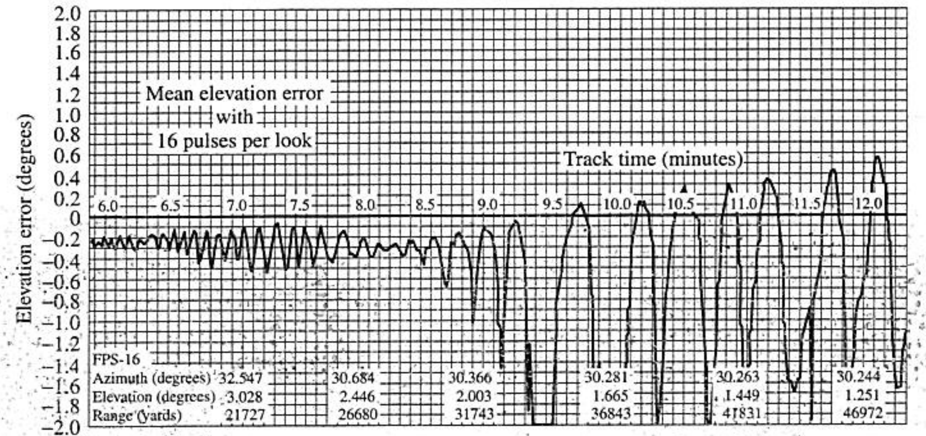

Figure 4.18 Example of the measured elevation tracking error using a phased array radar with 2.7° beamwidth. The aircraft target flew out in range at a nearly constant altitude. The numbers along the zero-error line indicate the track time in minutes.
(From Linde.[51])

to look at the image below the ground rather than at the target. The errors are cyclic because a phase greater than 2π radians appears to the radar as if it where within 0 and 2π radians. It is seen in the example of Fig. 4.18 that there are times the antenna can point at an angle greater than 2° below the target. The tracking has been described as "wild" and great enough to cause the radar to lose track. The effect is most pronounced over a smooth water surface where the surface-reflected signal is strong. It can be so great that it becomes impossible to maintain a track at low altitudes with conventional tracking radars. According to Barton,[49] in the horizon region when the magnitude of the reflection coefficient exceeds 0.7 and the target is below 0.7 beamwidth, "there will be a strong tendency for the radar to track a centroid of reflection at or near the horizon." (This did not appear to occur for the data shown in Fig. 4.18.)

The multipath problem is similar to the glint error that results from tracking a classical two-scatterer target. Careful examination, however, of the theoretical glint error given in Fig. 4.15 and the experimental data of Fig. 4.18 show a significant difference. The two-scatterer model indicates there will be large errors when the surface reflection coefficient approaches −1. The large tracking errors appear to the side of the larger scatterer of the pair rather than the smaller scatterer. Generally, it is expected that in the multipath situation, the larger scatterer will be the target and the image will be the smaller (because the reflection coefficient is not greater than 1). The data of Fig. 4.18 show, however, that the large elevation angle errors are in the direction of the image rather than the true target. Thus the antenna is more likely to look into the ground than in the direction of the sky. Howard et al.[50] state that this difference can be explained by the failure to account for the amplitude distortion across the aperture, in addition to the phase distortion.

Although it has been easy to accept the two-scatterer target model as applied to low-angle tracking multipath case, there is a difference between the two. In the two-scatterer

model there are two propagation paths: t
terer and back. In the multipath case, t
are: (1) the path from radar to target an
to target via reflection from the surfac
path); (3) the path from radar directly to
and (4) the inverse of path no. 3 which i
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is the effect of surface roughness which
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the roughness of a surface depends on it
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Methods for Reducing Multipath Effects a
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Narrow Beamwidth The surest meth
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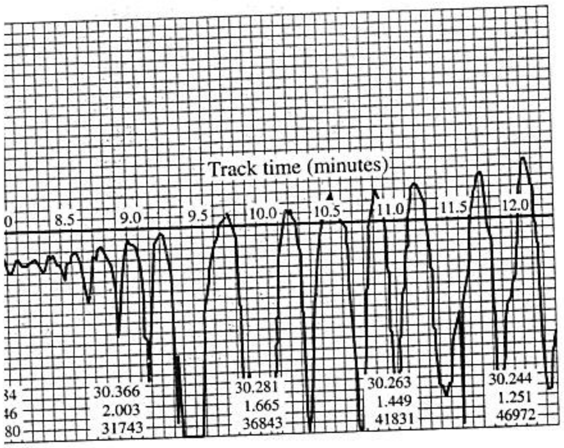

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between the two. In the two-scatterer

model there are two propagation paths: the two two-way paths from the radar to each scatterer and back. In the multipath case, there are actually four propagation paths.[53] These are: (1) the path from radar to target and return by the same path; (2) the path from radar to target via reflection from the surface and return by the same path (this is the image path); (3) the path from radar directly to target and return via reflection from the surface; and (4) the inverse of path no. 3 which is the path from radar to target via the surface reflection, or image, and return directly to the radar. Thus paths no. 3 and 4 are the same except for direction of travel. (These four paths are made use of in multipath time-delay height finding to obtain the height of a target using high-range resolution with a fan-beam antenna pattern rather than a pencil-beam pattern.) The echoes from the four paths in the multipath geometry will provide a different composite echo signal at the radar than that obtained from the two-scatterer model. It should be expected, therefore, that the nature of the glint error in the multipath situation will be different from that predicted by the two-scatterer model, as has been demonstrated by experiment.

Another complication with surface multipath not modeled by the two-scatterer target is the effect of surface roughness which results in two components of the surface reflected signal; one is specular scatter and the other is diffuse scatter.[49]

With a rough surface, the angle error due to multipath is reduced because the surface-reflected wave is of lower magnitude (the reflection coefficient is less). Note that the roughness of a surface depends on its physical variations in height relative to the radar wavelength. The higher the radar frequency, the greater will be the "electrical" roughness of the surface (in wavelengths) for a given physical roughness, so that the effect of multipath on the elevation-angle accuracy might be less at the higher frequencies. At millimeter-wave frequencies, the surface reflection is more likely to be diffuse scatter rather than specular scatter.[54]

In addition to causing errors in elevation-angle tracking, it is also possible for multipath to introduce errors in the azimuth-angle tracking channel. This can be caused by *cross talk* where a portion of the elevation-angle channel signal enters in some manner the azimuth-angle channel. It might also be caused by the target-image plane departing from the vertical as when over sloping land or when the radar is on a rolling or pitching ship.

Methods for Reducing Multipath Effects at Low Angles There have been a number of methods demonstrated or proposed for reducing the large elevation angle errors that can occur due to the multipath experienced at low elevation angles.[49,55,56] There is not, however, a single method suitable for all applications where low-angle tracking is required. Each has its limitations. They are mainly for eliminating the large errors that occur when the main beam, rather than the sidelobes, illuminate the surface. Many of the methods mentioned below assume the use of a monopulse tracker. Only the first three seem to have had application. The others are mentioned because of some particular technical interest, and can be skipped if desired.

Narrow Beamwidth The surest method for reducing or eliminating tracking errors due to multipath is to have a narrow antenna beam that does not illuminate the surface. The beamwidth of an antenna is approximately $\theta_B \approx \lambda/D$ radians, where λ = radar wavelength and D = antenna dimension, both in the same units. Thus a narrow beamwidth requires a large antenna, a high radar frequency, or both. Although a narrow beamwidth can eliminate the multipath problem, it is not always possible to do so in practice since there may be compelling reasons for not using a large antenna or for operating the radar at high frequency.

A method that has been successfully used operationally to obtain low-angle tracking capability is to employ two radars, one at X band (9 GHz) and the other at K_a band (35 GHz), using a single antenna system to provide operation at the two frequencies.[57,58] The lower frequency radar generally has a longer range. Target acquisition can be initiated with the lower-frequency tracker and then precision low-altitude tracking can be obtained by switching to the higher-frequency tracker. It has been said that with the dual-frequency tracker "targets at 100-ft altitude were successfully tracked over water with less than 0.4 mils multipath error to ranges in excess of 30,000 yds." Another advantage of a dual-frequency radar for military applications is that it makes hostile electronic countermeasures more difficult since both frequencies have to be jammed.

Illogical Target Trajectory Prior knowledge of potential target behavior can be used to reduce the effects of low-angle multipath without overly complicating the radar. Since aircraft or missile targets will not likely go below the surface of the earth and are limited in their ability to accelerate upward and downward, radar tracking data indicative of unreasonable target behavior can be recognized and rejected. In some situations, the target might be flying fast enough and the inertia of the antenna might be great enough to dampen the angle-error excursions caused by multipath.

Off-Axis, or Off-Boresight, Monopulse Tracking Advantage can be taken of the fact that large angle errors are usually limited to a region of low elevation angle predictable from the antenna pattern and the terrain. It should be possible, therefore, to determine when the target is in the low-angle region by sensing large elevation-angle errors. The antenna is then locked at a small positive elevation angle (usually about 0.7 to 0.8 beamwidth) while continuing closed-loop azimuth-angle tracking. With the beam fixed at a positive elevation angle, the target's elevation angle may be determined open-loop from the error-signal voltage. Alternatively, the elevation angle may simply be assumed to be halfway between the horizon and the antenna boresight. In the extreme, the peak-to-peak tracking error would not exceed 0.7 to 0.8 beamwidth, and the rms error would be typically about 0.3 beamwidth. The tracking accuracy is only slightly improved, but wide swings of the antenna and loss of track are avoided.

Double-Null Elevation-Difference Pattern[59,60] A monopulse radar when tracking a single target attempts to have the null of its difference pattern pointing in the direction of the target. When this occurs at low elevation angles the echo signal that arrives in the lower beam of the difference pattern via the surface reflection can result in a glint error. By using a more complicated antenna pattern than that of the usual four-horn monopulse antenna, a second null can be independently steered to the direction of the surface-reflected echo signal (the image echo) so as to cancel it before it reaches the radar receiver. The second null can be obtained by employing a third pair of feeds in the vertical

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where h_a = antenna height, h_t = target
of 20 m, target height of 30 m, and a
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obtained by employing a third pair of feeds in the vertical

plane. The signals in elevation from the three pairs of vertical feeds are combined to produce two nulls, one in the direction of the target and the other in the direction of its image, as has been described by White in the cited references. The second null is maintained in the direction of the image, as computed by Snell's law for the measured target range.

A conventional four-element feed in a monopulse tracker has only one degree of freedom in the vertical plane (as well in the horizontal plane). It is designed to track only a single target. When multipath occurs, there are two target signals present (the actual target and its image). A conventional monopulse radar cannot cope since it is designed on the assumption that there is only a single target present. When a third pair of feed-elements is employed in the vertical, two degrees of freedom result so that there are now two nulls that can be positioned in the direction of the target and its image. This can be extended to even more feeds in the elevation plane (providing additional degrees of freedom and nulls) which enables better control of the nulling of the unwanted image.

Experiments over water have demonstrated good tracking (0.05 to 0.1 beamwidth rms) with the double-null technique to elevations as low as 0.25 beamwidth.[60]

There have been several other variants of this approach. The signal incident on the antenna aperture can be sampled at multiple points across the aperture (especially if an array antenna is used) and the maximum likelihood decision criterion employed to determine the location of the target and its image. Barton[55] states that these methods degrade in the presence of diffuse surface reflection. They also require more complicated feed structures and processing than a conventional monopulse.

High Range-Resolution The surface-reflected signal travels a longer path than the direct signal so it may be possible in some cases to separate them by use of high range-resolution waveforms. By tracking only the direct signal, the angle errors introduced by multipath are avoided. The range resolution ΔR required to separate the direct from the ground-reflected signal is approximately

$$\Delta R = \frac{2h_a h_t}{R} \tag{4.6}$$

where h_a = antenna height, h_t = target height, and R = range. For a radar antenna height of 20 m, target height of 30 m, and a range of 4 km, the range resolution ΔR must be 0.3 m. This requires a pulse width of 2 ns and a bandwidth of 500 MHz, which is a shorter pulse and a greater bandwidth than usually found in operational radars. If the target were a sea-skimmer antiship missile at an altitude as low as 2 m above the sea, the bandwidth required to eliminate the multipath effect is too great to be practical for most applications. Thus range resolution has not usually been a satisfactory solution to the multipath problem.

Frequency Agility It was stated in Sec. 4.4 in the discussion of the two-scatterer model that use of more than one frequency each sufficiently separated from one other could smooth the angle error due to glint and produce an average result that was less likely to have large errors. The frequencies had to be separated by the amount given by Eq. (4.4) in order to obtain independent values of the glint error. The same can occur with the elevation-angle measurement when multipath is present if D in Eq. (4.4) is taken as the difference in the path lengths; but there are two reservations. First, the average measurement of angle is more likely to be somewhere near the horizon rather than indicate the elevation angle of the target. Second, the bandwidth within which the various frequencies must occur is likely to be large. It is likely to be comparable to the bandwidth, discussed in the above, that is required of a short pulse for resolving the direct target echo from the image target echo. If a sufficiently large bandwidth were available to the radar designer, it might be better to employ that bandwidth for high range-resolution rather than for frequency agility. We have indicated previously, however, that this bandwidth is often larger than can be conveniently obtained in practice, especially when the target is at a very low altitude.

Doppler Resolution Since the target and its image are at different elevation angles, their doppler frequency shifts are slightly different. With sufficient doppler resolution, the target can be separated from its image. In practice, however, the difference in the doppler frequencies generally is too small to be used for isolating the target from its image, unless exceptionally long observation times are employed.

Clutter Fence A fence surrounding the radar can mask the echo from the image, especially when the near-in sidelobes are a factor in creating a multipath error. Fences can be expensive and are only of value when the radar is at a fixed site. Since the main beam illuminates the top edge of the fence, diffracted energy might illuminate the image.

Polarization Vertical polarization, which is often used in tracking radars, reduces the surface-reflected signal from the image when the image elevation angle is in the vicinity of the Brewster angle (Sec. 8.2). It has no special advantage, however, at low grazing angles when the angle to the image is much less than the Brewster angle.

Complex Angle (CA)[49,61] The normal monopulse receiver uses only the in-phase (or the out-of-phase) component of the difference signal. When a multipath signal is present along with the direct signal, the difference signal has a quadrature component. The in-phase and quadrature components of the error signal define a *complex angle* error signal. In the complex plane, with the in-phase and quadrature components as the two axes, the locus of the complex angle as a function of elevation angle is a spiral path. By measuring the complex angle, the target elevation can, in principle, be inferred. In using the complex-angle technique, the radar antenna is fixed at some angle above the horizon and an open-loop measurement of the complex angle is compared with a predicted set of values for the particular radar installation, antenna elevation-pointing angle, and terrain properties. A given in-phase and quadrature measurement does not give a unique value of the elevation angle since the plot of the complex angle shows multiple, overlapping turns of a spiral with increasing elevation angle of the target. The ambiguity can be resolved with frequency diversity or by continuous tracking over a long enough interval to recognize the ambiguous spirals.

This technique is limited by the need to resolve ambiguities, by the echoes from the real surface being different from theoretical when the surface is rough and the reflection is diffuse, and by random variations in the measurements which are difficult to remove by calibration because they vary rapidly with time and depend on target position.

Superresolution In general, two equal-a
are separated by at least 0.8 beamwidth.
lution depends on the phase between the
Many attempts have been made in the
beamwidth, but without the desired succe
on *spectral estimation* or *spectral analys*
interest for low-altitude tracking because
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Such methods do provide enhanced reso
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and that it has little, if any, value in solv

Superresolution methods produce i
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Spurious responses can be obtained whe
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and whose promises have not materializ

Maximum Likelihood Estimation The
that describe the application of maxim
target's elevation angle in a multipath sit
also has been applied in conjunction wit
antennas.[68,69] There have been some
limitations.

Electro-Optical and Infrared Optical
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Other Comments In addition to the a
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inuous tracking over a long enough interval to recognize

y the need to resolve ambiguities, by the echoes from the
m theoretical when the surface is rough and the reflection
ations in the measurements which are difficult to remove
idly with time and depend on target position.

Superresolution In general, two equal-amplitude signals can be resolved in angle if they are separated by at least 0.8 beamwidth. Sometimes it can be better than this since resolution depends on the phase between the two signals as well as the signal-to-noise ratio. Many attempts have been made in the past to improve angular resolution beyond 0.8 beamwidth, but without the desired success. *Superresolution*[62] is an example that is based on *spectral estimation* or *spectral analysis* to provide resolution in angle. It has been of interest for low-altitude tracking because of the claim that it can produce improved resolution compared to conventional linear methods, but it does not work for radar signals. Such methods do provide enhanced resolution of uncorrelated signals (such as independent noise), as occur with multiple jamming signals or the radio astronomy observation of cosmic sources. They are not applicable, however, for the resolution of correlated signals—and radar echo signals are correlated since they originate from the same transmitter. W. D. White[63] has shown the limitation of superresolution for coherent echo signals and that it has little, if any, value in solving the radar low-angle tracking problem.

Superresolution methods produce impressive-looking plots with sharp responses indicating the target locations. Depending on the algorithm used, however, the amplitude and position of the responses might not always be related to the features of the target. Spurious responses can be obtained when the algorithm used is nonlinear. Of importance, but of lesser concern compared to its other limitations, is that the signal-to-noise ratio must be high to use these methods and many of the algorithms are computationally complex. Superresolution is a technique whose name implies more than has been delivered and whose promises have not materialized as advertised.

Maximum Likelihood Estimation There have been many papers in the literature that describe the application of maximum likelihood estimation (MLE) to obtain the target's elevation angle in a multipath situation. Only a few are referenced here.[64–66] MLE also has been applied in conjunction with multiple frequencies[67] and with three-aperture antennas.[68,69] There have been some interesting results, but the technique has had limitations.

Electro-Optical and Infrared Optical and IR sensors offer the advantage of far better angular resolution than can be obtained with radar. They have the important advantage of not suffering from the multipath problem. Both optical and IR have been used to supplement radar coverage at low angles. At low angles, they are of short range since they are seriously limited by high attenuation in the clear atmosphere as well as in rain. Furthermore, they do not provide range or doppler velocity measurements. If reliable all-weather capability is necessary, radar is the sensor that has to be seriously considered.

Other Comments In addition to the above there have been several other methods proposed or investigated for mitigating the effects of glint when tracking a target at low angle. These include height diversity,[70] the use of neural nets,[71] the use of maximum likelihood estimation based on deterministic modeling that requires finding only four unknowns and which doesn't need to know the range,[72] the use of a threshold in the sum channel that must be exceeded in order to accept an elevation-angle measurement (this eliminates the large errors that can occur when the direct and the image signals are almost out of phase—the condition for a large glint error and for a small signal in the sum channel),[73] and the use of bias compensation to reduce the glint error along with a threshold on the sum signal that eliminates measurements made with small signal-to-noise ratio.[74] The large number of publications on this subject is an indication of the importance of low-angle tracking and that there has been a lack of a good all-purpose solution.

When conditions permit, the use of a narrow beamwidth is the best method to ensure accurate tracking at low angle. Off-axis tracking with the antenna at a fixed elevation, and with the elevation angle measurement made open-loop, is simple and can provide relief from the wild swings of the antenna caused by multipath glint.

The low-angle tracking problem as discussed here concentrated on the effect of multipath. Radars concerned with low-angle tracking also have to be able to detect targets in the presence of clutter echoes that can be many orders of magnitude larger than the target, so that doppler methods, as discussed in Chap. 3, need to be considered.

In this section, the radar was usually considered to be located on or near the surface and tracking a target at low altitude. The problem of low-angle multipath is also important for missile guidance at low altitudes.[75]

4.6 TRACKING IN RANGE[76,77]

In the early days of radar, tracking of a target in range was usually done manually by an operator who watched an A-scope or similar presentation and positioned a handwheel to maintain a marker on the display over the desired target pip. The setting of the handwheel was a measure of the target range and was converted to an electrical signal and supplied to a data processor. Manual tracking has many limitations and it cannot be used in systems such as missiles where there is no operator present. It was soon replaced by closed-loop automatic tracking, such as the *split-gate tracker.*

Split-Gate Tracker The technique for automatically tracking in range is based on the split range gate. Two range gates, as indicated in Fig. 4.19, are generated. One is the *early gate* and the other is the *late gate.* The video echo pulse is shown in Fig. 4.19a, the relative position of the two gates at a particular instant is in Fig. 4.19b, and the difference signal is in Fig. 4.19c. In this example the portion of the signal in the early gate is less than that of the late gate. The signals in the two gates are integrated and subtracted to produce the difference error signal. The sign of the difference indicates the direction the two range gates have to be moved in order to have the pair straddle the echo pulse. The amplitude of the difference determines how far the pair of gates are from the "center" of the pulse, sometimes called the centroid. When the error signal is zero, the range gates are centered on the pulse and the position of the two gates gives the target's range. Deviation of the pair of gates from the center of the echo pulse increases the signal energy in one of the gates and decreases it in the other. This produces an error signal that causes the two pulses to be moved so as to reestablish equilibrium.

Range gating allows a single target to be isolated. The gate rejects unwanted signals and improves the signal-to-noise ratio by eliminating noise from other ranges. The AGC

Figure 4.19 Split-gate range tracking: (a) Echo pulse; (b) early–late range gates; (c) difference signal between early and late range gates.

circuits respond only to the short time int
target is expected. The range-gate width
extraneous noise, but not so narrow that
excluded. Generally, the gate width is ap
of the leading edge of the echo pulse is
serted to move the gates forward. With l
erably narrower than with normal radar t

Range Glint A target with multiple scat
rors because of glint similar to the glint
cussed in Sec. 4.4.[79]

Assume a two-scatterer model, simil
scatterers separated in range rather than
the other is at $R_2 = cT_2/2$, where $c =$ ve
spective two-way time delays to the two
unresolved. The error ΔT_R due to range
tive to the center of the two scatterers, is

$$\Delta T_R = \frac{\Delta T}{2} \cdot \frac{}{1 -}$$

where $\Delta T = 2(R_2 - R_1)/c =$ time extent
signals from the two scatterers $(a \leq 1)$;
pression is equivalent to the angle-glint
referred to the center of the two scatter
scatterer. The range measurement error

Some reservations need to be menti
glint error. It is based on the time delay

on for a large glint error and for a small signal in the
ias compensation to reduce the glint error along with a
liminates measurements made with small signal-to-noise
lications on this subject is an indication of the impor-
hat there has been a lack of a good all-purpose solution.
use of a narrow beamwidth is the best method to ensure
f-axis tracking with the antenna at a fixed elevation, and
ment made open-loop, is simple and can provide relief
nna caused by multipath glint.
lem as discussed here concentrated on the effect of mul-
w-angle tracking also have to be able to detect targets in
at can be many orders of magnitude larger than the tar-
discussed in Chap. 3, need to be considered.
s usually considered to be located on or near the surface
ude. The problem of low-angle multipath is also impor-
altitudes.[75]

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ng of a target in range was usually done manually by an
pe or similar presentation and positioned a handwheel to
over the desired target pip. The setting of the handwheel
ge and was converted to an electrical signal and supplied
cking has many limitations and it cannot be used in sys-
re is no operator present. It was soon replaced by closed-
s the *split-gate tracker.*

ue for automatically tracking in range is based on the split
indicated in Fig. 4.19, are generated. One is the *early gate*
The video echo pulse is shown in Fig. 4.19a, the relative
articular instant is in Fig. 4.19b, and the difference signal
the portion of the signal in the early gate is less than that
the two gates are integrated and subtracted to produce the
n of the difference indicates the direction the two range
er to have the pair straddle the echo pulse. The amplitude
w far the pair of gates are from the "center" of the pulse,
When the error signal is zero, the range gates are centered
of the two gates gives the target's range. Deviation of the
f the echo pulse increases the signal energy in one of the
er. This produces an error signal that causes the two pulses
h equilibrium.
gle target to be isolated. The gate rejects unwanted signals
se ratio by eliminating noise from other ranges. The AGC

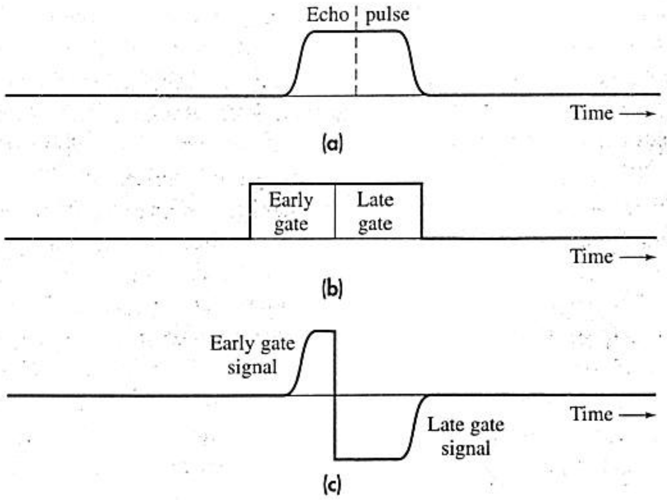

Figure 4.19 Split-gate range tracking: (a) Echo pulse; (b) early–late range gates; (c) difference signal between early and late range gates.

circuits respond only to the short time interval of the range gate where the echo from the target is expected. The range-gate width should be sufficiently narrow so as to minimize extraneous noise, but not so narrow that an appreciable fraction of the signal energy is excluded. Generally, the gate width is approximately equal to the pulse width. If tracking of the leading edge of the echo pulse is desired rather than its center, a bias can be inserted to move the gates forward. With leading-edge track, the gates should be "considerably narrower than with normal radar tracking."[78]

Range Glint A target with multiple scatterers distributed in range can cause tracking errors because of glint similar to the glint error experienced in angle tracking that was discussed in Sec. 4.4.[79]

Assume a two-scatterer model, similar to that considered for angle glint, but with the scatterers separated in range rather than angle. One scatterer is at a range $R_1 = cT_1/2$ and the other is at $R_2 = cT_2/2$, where c = velocity of propagation and T_1 and T_2 are the respective two-way time delays to the two scatterers. The two scatterers are assumed to be unresolved. The error ΔT_R due to range glint in the measurement of the time delay, relative to the center of the two scatterers, is found to be[79]

$$\Delta T_R = \frac{\Delta T}{2} \cdot \frac{1 - a^2}{1 + a^2 + 2a\cos(2\pi f_0 \, \Delta T)} \qquad [4.7]$$

where $\Delta T = 2(R_2 - R_1)/c$ = time extent of the target; a = ratio of the amplitudes of the signals from the two scatterers ($a \leq 1$); and f_0 is the radar carrier frequency. This expression is equivalent to the angle-glint expression of Eq. (4.2) if the error in Eq. (4.2) is referred to the center of the two scatterers as it is here rather than referred to the larger scatterer. The range measurement error can be larger than the extent of the target.

Some reservations need to be mentioned about the use of this expression for range-glint error. It is based on the time delay (or range) of a target being given as the rate of change of the echo signal phase with respect to frequency, or $\delta\phi/\delta f$. This can be seen by differentiating Eq. (3.1) as a function of frequency. Cross and Evans state[79] that the split-gate range tracker makes a measurement equivalent to finding range from the derivative of phase with respect to frequency. When the target consists of multiple scatterers, a glint error is introduced when using this criterion for extracting time delay.[80]

If, however, range is determined without a closed-loop tracker, a glint error does not occur. There can be range errors in this case due to the effect of noise, but they do not generate the type of effects that can happen when glint is possible. A glint error does not appear, for example, when the measurement is made manually by viewing the output signal on an A-scope display (amplitude versus range). A complex target with multiple scatterers within the radar resolution cell can cause inaccuracy in the measurement of the exact center of the target, but an operator would not be misled as would an automatic closed-loop tracker to position the range gate well outside of the target extent or the resolution of the pulse. Thus Eq. (4.7) does not apply to manual tracking or its electronic equivalent that doesn't used closed-loop tracking.

If range glint is a problem, some of the methods previously described for reducing angle glint might offer relief. The best approach, when sufficient bandwidth is available, is to employ high range-resolution. If the individual scatterers of a target can be resolved in range, both angle glint and range glint are not a problem. Tracking in range is generally much more accurate than tracking in angle (as measured by cross-range distance) so that any effects of range glint, if it occurs at all, is less of a concern than errors in angle, or cross-range.

4.7 OTHER TRACKING RADAR TOPICS

Target Acquisition A tracking radar must first find and acquire (lock on to) its target before it can operate as a tracker. Most tracking radars employ a narrow pencil beam for accurate tracking in angle; but it can be difficult to search a large volume for targets when using a narrow antenna beamwidth. Some other radar, therefore, must first find the target to be tracked and then designate the target's coordinates to the tracker. These radars have been called *acquisition radars* or *designation radars* and are surveillance radars that search a large volume.

The tracker is slewed to the direction of the target based on the target coordinates supplied by the acquisition radar. These coordinates are not always accurate enough to bring the tracker directly onto the target. Some searching in both azimuth and elevation angle might have to be done by the tracker in order to find the target. There have been several different types of patterns employed to search a limited angular region, as was described in Sec. 5.7 of the 2d edition of this book; but the raster scan has been one of the most popular. The *raster,* or *TV, scan* paints a rectangular search area in a uniform manner. An airborne intercept radar, for example, might acquire its target by scanning a 3° pencil beam over a target space 60° in azimuth by 15.5° in elevation by scanning six elevation steps, or bars.[81] The search space is relatively large in this example; but it can be much smaller if the target location information provided to the tracker is more accurate.

Raster scan is a simple and convenient
known as *N*-bar scan, where *N* is the nu

If a 2D air-surveillance radar (rang
a surface-based mechanical tracking ra
nodding-beam scan in elevation, which
izontal. Surface-based mechanical track
second and perhaps take another second
can take place in under two seconds fro

The target must be found in range a
the tracking radar receiver range gate
wards in space. As has been mentioned
the noise the receiver must handle and
gate is scanned from minimum to maxi
target echo signal it detects. In some
gates to shorten the acquisition time.[76]

A multifunction phased array radar
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gets and perform surveillance with
information obtained by a phased array
beam can be placed directly on the tar
For this reason the target designation
function phased array radar must be mu
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Servo System The automatic tracking
utilizes the angle-error signals to maint
the target. The servo system introduces
lag error will depend on the nature of t
gradual turn, or a rapid maneuver). The
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servo system, which has often been us
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R TOPICS

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information provided to the tracker is more accurate.

Raster scan is a simple and convenient means for searching a limited sector. It is also known as *N*-bar scan, where *N* is the number of azimuth scans, or bars.

If a 2D air-surveillance radar (range and azimuth) is used for designating a target to a surface-based mechanical tracking radar, the tracker might acquire its target with a nodding-beam scan in elevation, which is a raster scan in the vertical rather than the horizontal. Surface-based mechanical tracking radars can be designed to slew 180° in one second and perhaps take another second to bring the target into track, so that acquisition can take place in under two seconds from the time of designation.

The target must be found in range as well as in angle. During the acquisition process, the tracking radar receiver range gate is scanned in range as the pulse propagates outwards in space. As has been mentioned, narrow range gates are important for restricting the noise the receiver must handle and to have only one target within the gate. The range gate is scanned from minimum to maximum range and is usually set to acquire the first target echo signal it detects. In some trackers there might be several contiguous range gates to shorten the acquisition time.[76]

A multifunction phased array radar for air defense usually performs as both the acquisition radar and the tracking radar. There is usually not much time that can be allocated for target acquisition in a multifunction radar that must maintain track on many targets and perform surveillance with adequate revisit times. The target-designation information obtained by a phased array needs to be accurate enough so that the tracking beam can be placed directly on the target without having to perform a search in angle. For this reason the target designation data from the surveillance portion of the multifunction phased array radar must be much more accurate than in air-defense systems that employ separate tracking and surveillance radars.

Servo System The automatic tracking of a target in angle employs a servo system that utilizes the angle-error signals to maintain the pointing of the antenna in the direction of the target. The servo system introduces a lag in the tracking that results in an error. The lag error will depend on the nature of the target trajectory (whether it is a straight line, a gradual turn, or a rapid maneuver). The error also depends on the ability of the servo system to accommodate to changes in speed, velocity, or acceleration. A so-called *Type II servo system*, which has often been used in tracking radar, theoretically has no steady-state error when the target velocity is constant. For this reason, it is also known as a *zero-velocity-error system*. A steady-state error will exist, however, for a step-acceleration input. The operation of the Type II servo is similar to the alpha-beta tracker discussed in Sec. 4.9 for automatic tracking in a scanning surveillance radar. There are other types of servo systems depending on the required tracking accuracy and the expected target characteristics.[82] The effect of velocity and acceleration on a servo system can be described by the frequency response of the tracking loop.[83]

Servo Bandwidth The tracking bandwidth of a servo system is that of a low-pass filter. There are conflicting requirements on the choice of tracking bandwidth. On the one hand, the bandwidth should be narrow to minimize the effects of noise or jitter, reject unwanted signal components (such as the conical-scan frequency or aircraft-engine modulation), and to provide a smoothed output of the desired measurement parameters. A wide tracking bandwidth, on the other hand, is desired for following rapid changes in the target trajectory or the changes in the vehicle carrying the radar. Thus a wide bandwidth is needed so as not to lose track of a maneuvering target, but a narrow bandwidth is needed for sensitivity. The choice of servo bandwidth, therefore, usually must be a compromise.

A target at long range will have low angular rates of change and a low signal-to-noise ratio. The bandwidth can then be narrow to increase sensitivity and yet follow the target with minimum tracking lag. At short range, on the other hand, angular rates are likely to be large so that a wide bandwidth tracking filter is needed in order to follow the target without loss of track. Thus the loss in sensitivity because of the wider bandwidth is offset by the greater target signal at the shorter ranges. At shorter ranges, errors due to target glint can become a problem; hence, the bandwidth should be no wider than necessary in order to keep glint errors from becoming excessive. The tracking bandwidth can be made variable or even adaptive to conform automatically to the target conditions.

Lowest Servo Resonant Frequency Another restriction on the tracking bandwidth of a mechanical tracker is that it should be small compared to the lowest natural resonant frequency of the antenna and its structural foundation in order to prevent the antenna system from oscillating at its resonant frequency. Figure 4.20 illustrates the bounds of measured data on the lowest resonant frequency as a function of antenna size. This figure is based on a compilation by the Aerospace Corporation of the lowest servo resonant frequencies for 190 individual radar, radio-telescope, and communications parabolic-reflector antenna systems. Also shown a
radars. Howard[83] states that it is desired
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always practical. He mentions that the
29-ft diameter Cassegrain reflector anten
times its servo bandwidth of 3.5 Hz. He
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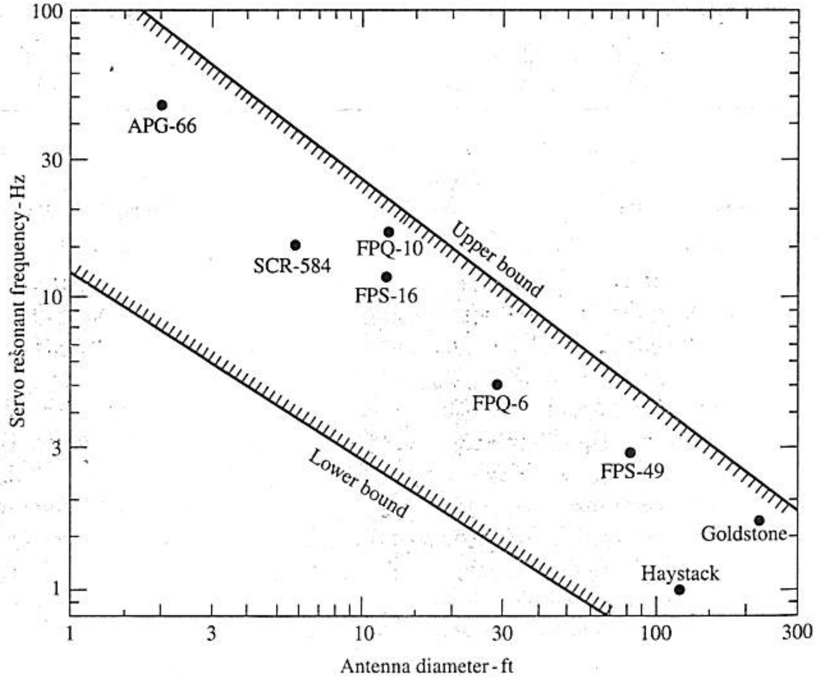

Figure 4.20 Bounds of the servo resonant frequency as a function of antenna diameter for actual tracking radars using parabolic-reflector antennas. (Based on extensive data compiled January 1994 by D. D. Pidhayny and Alan R. Lewis of the Aerospace Corporation.)

Precision "On-Axis" Tracking[84,85] Some
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precise tracking radar that achieves bett
tracking.

The output of a conventional servo
error. The on-axis tracker accounts for t
center of the beam or on the null axis o
accuracy by reducing coupling between
by minimizing the generation of cross
system nonlinearities.

On-axis tracking includes (1) the u
stored prediction of the target trajector
(2) removal of the static and dynamic s
(3) use of appropriate coordinates for fil

The radar's angle-error signals are s
ment based on a target-trajectory model
This is especially useful for situations
approximately known, as when tracking
is the same as the prediction, no adjustm
cording to the stored prediction. If they
changed until they do. Thus the pointing
the stored target-trajectory prediction w
servo loop that points the antenna is ma
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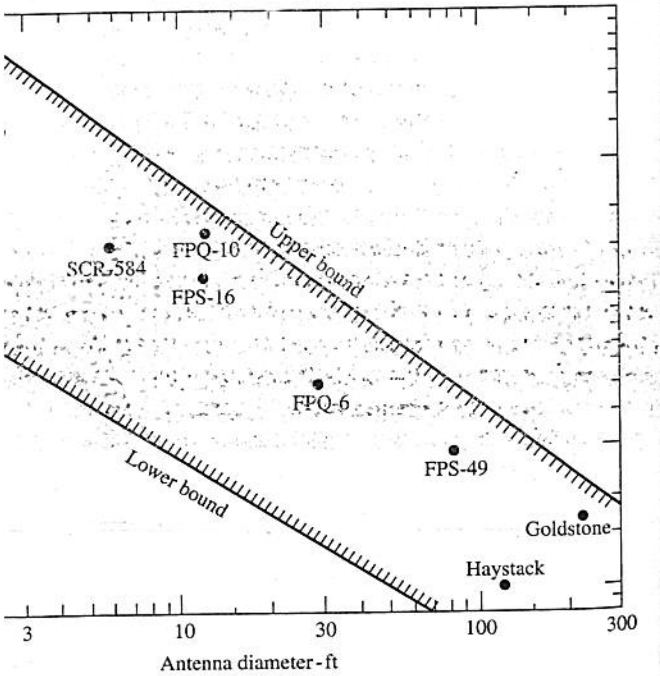

reflector antenna systems. Also shown are the resonant frequencies for several tracking radars. Howard[83] states that it is desired that the lowest resonant frequency be at least 10 times the servo bandwidth. This might be difficult to do with large antennas, and is not always practical. He mentions that the highly accurate AN/FPQ-6 radar tracker with a 29-ft diameter Cassegrain reflector antenna (Fig. 4.1a) has a resonant frequency only three times its servo bandwidth of 3.5 Hz. He also states that the smaller 12-ft antenna (such as for the AN/FPS-16) can provide a servo bandwidth up to 7 or 8 Hz.

Precision "On-Axis" Tracking[84,85] Some of the most precise tracking radars are those associated with the instrumentation used at missile test-ranges.[86] One such class of highly precise tracking radar that achieves better than usual performance is known as *on-axis tracking.*

The output of a conventional servo system lags its input, which results in a tracking error. The on-axis tracker accounts for this lag and keeps the target being tracked in the center of the beam or on the null axis of the difference pattern. This improves tracking accuracy by reducing coupling between the azimuth and elevation angle-track channels, by minimizing the generation of cross polarization, and by reducing the effects of any system nonlinearities.

On-axis tracking includes (1) the use of adaptive tracking whose output updates a stored prediction of the target trajectory rather than control the antenna servo directly, (2) removal of the static and dynamic system biases and errors by prior calibration, and (3) use of appropriate coordinates for filtering (smoothing) the target data.

The radar's angle-error signals are smoothed and compared to a predicted measurement based on a target-trajectory model updated by the results of previous measurements. This is especially useful for situations where prior knowledge of the target trajectory is approximately known, as when tracking ballistic missiles or satellites. If the measurement is the same as the prediction, no adjustment is made and the antenna beam is pointed according to the stored prediction. If they do not agree, the target trajectory prediction is changed until they do. Thus the pointing of the antenna is performed open-loop based on the stored target-trajectory prediction which is updated by the radar measurements. The servo loop that points the antenna is made relatively wideband (a high data rate) to permit fast response when tracking targets have high acceleration. The adjustment of the predicted position based on the measured position, however, is performed with a narrow bandwidth. This error-signal bandwidth is adaptive and can be made very narrow, yet the system will continue to point open-loop based on the stored target-trajectory prediction and the wide bandwidth of the antenna-pointing servos. The radar makes its measurements of the target in the polar coordinates of range, azimuth, and elevation (r, θ, ϕ). A target on a straight-line trajectory has a curvilinear track in polar radar coordinates which can generate apparent accelerations and can complicate the processing. These can be avoided by converting the polar coordinates to rectilinear coordinates (x, y, z) for data smoothing and comparison with prediction. After updating the target prediction, the rectilinear coordinates are converted back to radar polar coordinates to drive the antenna.

Systematic tracking errors include (1) error in the zero reference of the encoders used to indicate the orientation of the antenna axis, (2) misalignment of the elevation axis with respect to the azimuth axis (nonothogonality), (3) droop or flexing of the antenna and mount caused by gravity, (4) misalignment of the antenna with respect to the elevation axis (skew), (5) noncoincidence of the azimuth plane of the mount to the local reference plane (mislevel), (6) insufficient dynamic range in the servo system, (7) finite transit time that results in the target being in a different position by the time the echo is received by the radar (which could be important for tracking of space objects), and (8) bending and additional time delay of the propagation path due to atmospheric refraction. Systematic errors are determined by prior measurement. They are then used to adjust the encoded position of the antenna to provide the correct target position.

A boresight telescope mounted on the radar antenna permits calibration of the mechanical axis of the antenna with respect to a star field. This calibration accounts for bias in azimuth and elevation, mislevel, skew, droop, and nonorthogonality. Tracking a visible satellite with the radar permits the position of the RF axis to be determined relative to the mechanical (optical) axis. The difference between the position measured by the optics and that measured by the radar is obtained after correction is made for the difference in atmospheric refraction for optical and RF propagation. This type of dynamic calibration requires that the radar be large enough to track satellites.

The calibration and compensation procedures to insure the tracking radar is of the highest accuracy might take several hours before the radar is ready for use. Such calibration might have to be repeated regularly. This is something that can be tolerated in precision instrumentation radars where time might not be important, but such times are less likely to be available for operational military radars. Also the performance of on-axis tracking can be degraded when the target performs unanticipated maneuvers.

There is nothing unique about any of the individual processes that enter into on-axis tracking. They can each be applied individually, if desired, to any tracking radar to improve the accuracy of track.[87]

Tracking in Doppler Coherent radars can also track the doppler frequency shift of the moving target echo. This is especially important for airborne pulse doppler radars and missile-guidance radars. The tracking doppler filter not only provides a measure of relative velocity, but also improves the ability of the radar to isolate the moving target echo from much larger clutter echoes. The doppler tracking filter is sometimes called a *speed gate.* Modulations of the target echo due to moving parts such as the propellers of piston engines or the compressor stages of jet engines extend the doppler spectrum and can degrade tracking accuracy.

Track While Scan (Limited Sector Scan) It was said at the beginning of this chapter that in the past the term *track while scan* has been applied to two different types of tracking radars. The name has been used to denote the tracking performed by a rotating-antenna air-surveillance radar which obtains target location updates each time the antenna beam rotates past the target, which might be from about 1 to 12 seconds. The name track while scan for this type of radar is now seldom used since almost all modern air-surveillance radars provide the equivalent with what is called *automatic detection and track (ADT),* which is discussed in Sec. 4.9. Here we will briefly discuss the type of track-while-scan (TWS) radar used to rapidly scan a relatively narrow angular sector, usually in both

azimuth and elevation. It combines the s
may be performed with a single narrow-
of beams) that might cover a rectangular
performed with two orthogonal fan beam
evation. TWS radars have been used in a
air-defense systems.

A difference between a continuous t
signal in a continuous tracker is used in
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of the antenna. Its angle output is sent
difference is that the TWS radar can pro
within its sector of coverage, while the
which is why it is sometimes called a *sin*
mitters and antennas, the energy availabl
a STT since the TWS shares its radiate
centrate it in the direction of a single targ
radar might be preferred when multiple
tracking accuracy only has to be good en
guidance systems to home on the target.
needed, a single-target tracker might be

Limited sector-scan TWS radars hav
or *Ground-Controlled Approach* (GCA)
radars allow a ground controller to dire
tracking it as it lands. The ground control
his or her heading up, down, right, or l
have been used which are electromecha
twice per second. The azimuth sector th
tor 6 or 7°. Landing radars using limited-
19, operate differently than scanning fa
beam over a region 20° in azimuth and 1
AN/TPN-19 used multiple receive beam
ing a phased array, the AN/TPN-19 co
20-Hz data rate. In the past, radars for
used by the military. Civilian pilots pref
landing is in the aircraft's cockpit rathe

Track-while-scan radars have also b
in surface-to-air missile systems for bo
the former Soviet Union.

Generally, TWS systems using fan b
that operate with one or more pencil be
surface clutter, it is more vulnerable to
problems with associating multiple targ

The advantage of TWS compared t
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scan a relatively narrow angular sector, usually in both

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azimuth and elevation. It combines the search function and the track function. Scanning may be performed with a single narrow-beamwidth pencil beam (or a monopulse cluster of beams) that might cover a rectangular sector in a raster fashion. Scanning can also be performed with two orthogonal fan beams, one that scans in azimuth and the other in elevation. TWS radars have been used in airport landing radars, airborne interceptors, and air-defense systems.

A difference between a continuous tracker and the TWS radar is that the angle-error signal in a continuous tracker is used in a closed-loop servo system to control the pointing of the antenna beam. In the TWS radar, however, there is no closed-loop positioning of the antenna. Its angle output is sent directly to a data processor. Another significant difference is that the TWS radar can provide simultaneous tracks on a number of targets within its sector of coverage, while the continuous tracker observes only a single target, which is why it is sometimes called a *single-target tracker* (STT). With comparable transmitters and antennas, the energy available to perform tracking is less in a TWS radar than a STT since the TWS shares its radiated energy over an angular sector rather than concentrate it in the direction of a single target. In airborne-interceptor applications, the TWS radar might be preferred when multiple targets have to be maintained in track and the tracking accuracy only has to be good enough to launch missiles which contain their own guidance systems to home on the target. On the other hand, if highly accurate tracking is needed, a single-target tracker might be preferred.[81]

Limited sector-scan TWS radars have been used in *Precision Approach Radars* (PAR) or *Ground-Controlled Approach* (GCA) systems that guide aircraft to a landing.[88] These radars allow a ground controller to direct an aircraft to a safe landing in bad weather by tracking it as it lands. The ground controller communicates to the pilot directions to change his or her heading up, down, right, or left. In the control of aircraft landing, fan beams have been used which are electromechanically scanned over a narrow sector at a rate of twice per second. The azimuth sector that is scanned might be 20° and the elevation sector 6 or 7°. Landing radars using limited-scan phased array antennas, such as the AN/TPS-19, operate differently than scanning fan beams since they electronically scan a pencil beam over a region 20° in azimuth and 15° in elevation at a rate of twice per second. The AN/TPN-19 used multiple receive beams to obtain a monopulse angle measurement. Being a phased array, the AN/TPN-19 could simultaneously track up to six aircraft at a 20-Hz data rate. In the past, radars for the control of landing aircraft have been mainly used by the military. Civilian pilots prefer to use landing systems in which the control of landing is in the aircraft's cockpit rather than from a voice originating from the ground.

Track-while-scan radars have also been used successfully for the control of weapons in surface-to-air missile systems for both land and ship-based air defense, especially by the former Soviet Union.

Generally, TWS systems using fan beams have some limitations compared to systems that operate with one or more pencil beams. The fan-beam system can see more rain and surface clutter, it is more vulnerable to electronic countermeasures, and there might be problems with associating multiple targets that appear in the two beams.

The advantage of TWS compared to a continuous tracker is that multiple targets can be tracked. Because it shares its energy over a region of space, the TWS radar needs to have a larger transmitter to obtain the same detection and tracking capabilities of a STT that dwells continuously on a single target. If the target's angle is found from the centroid of the angle measurements obtained as the TWS antenna beam scans past the target, inaccuracies can occur if the target signal fluctuates in amplitude. TWS radars are also more vulnerable to angle jamming than are continuous trackers.[89] TWS radars can use monopulse angle measurements in an open-loop manner, similar to a phased array. Since the monopulse measurement is not made with closed-loop tracking, a TWS radar should not experience the wild fluctuations in angle caused by glint when there are multiple scatterers within the resolution cell or when there is multipath at low elevation angles.

Tracking with Phased Array Radar Tracking with a phased-array radar is more like that of a track-while-scan radar or automatic tracking with a surveillance radar than the continuous single-target tracker that has been the subject of most of this chapter thus far. The advantage of a phased array is that it can have a much higher data rate than radars with mechanically scanned antennas and it can simultaneously track multiple targets by time sharing a single antenna beam. This is possible because of the rapid inertialess beam positioning that, in some systems, can switch the antenna beam from one direction to another within microseconds. There is no closed-loop feedback to control the positioning of the beam as in a STT. When it is time to update a track, the computer controlling the radar directs the beam in an open-loop fashion to the expected present position of the target to either transmit or to receive the expected echo signal. Many targets can be tracked simultaneously in this manner.

An example of a phased-array instrumentation radar used for multiple target tracking on missile ranges is the AN/MPS-39 that was shown in Fig. 4.1b. It is also known as MOTR (Multiple Object Tracking Radar). This is a transportable *C*-band radar capable of tracking up to 10 targets simultaneously with an angle accuracy of 0.2 mrad. Its space-fed lens array is mounted on an elevation-over-azimuth tracking pedestal so that its 60° cone-angle coverage can be positioned anywhere in the hemisphere. A 1° (at broadside) beamwidth is obtained with a 12-ft diameter aperture. The monopulse tracking capability is achieved with a four-horn triple-mode feed. The manufacturer's literature states it is able to can acquire a target in less than 1 s. The advantage of a phased array for range instrumentation is that a single system simultaneously can track a drone target or targets, the aircraft that launches a weapon, multiple parts of a destroyed target, and other aircraft that might be observing the test or be in the vicinity. Without the phased array, a separate single-target tracker, such as the AN/FPS-16 or equivalent, would have to be used for each target that is to be tracked.

An excellent review of tracking with phased arrays and multifunction phased array radar has been given by Barton.[90]

Signal-to-Noise Ratio In Chapter 2, we found that reliable detection of a target required an integrated or single-pulse signal-to-noise ratio of the order of 12 to 15 dB. The tracking accuracy of the best radars is about 0.1 mrad. Such highly accurate tracking in angle requires much higher signal-to-noise ratios than required for detection. As indicated by Eq. (4.3) or the discussion of angle accuracy in Sec. 6.3, integrated or single-pulse signal-to-noise ratios need to be more th
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Distinguishing Feature of Monopulse Th
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4.8 COMPARISON OF TRACKERS

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signal-to-noise ratios need to be more than 40 dB to achieve the inherent accuracy available in the best of the precision trackers.

Distinguishing Feature of Monopulse There are other types of simultaneous tracking methods, in addition to amplitude-comparison monopulse, that can obtain an angle measurement based on a single pulse. One might, for example determine the angle-error signal in one angular coordinate by taking the difference of the signals produced by two squinted beams at the video outputs of two separate receivers. Obtaining an accurate difference signal in this manner requires that the total gains of the two receiver channels be equal and remain that way. The high stability required to maintain balance of the two channels is not practical considering the total amount of gain there is in a receiver from the input antenna to the output difference circuit. The ineffectiveness of such a method was the reason why amplitude-comparison monopulse was invented during World War II by Robert Page of the U.S. Naval Research Laboratory.[91] By taking the sum and the difference of the two squinted beams right at the antenna, there is no need for ultrastable receivers as would be required to make an accurate measurement of angle in the video. It is the sum and difference networks at the antenna that distinguish monopulse from other simultaneous angle-measurement methods.

4.8 COMPARISON OF TRACKERS

In this chapter we have concentrated on two major tracking systems: the amplitude-comparison monopulse and the conical scan. There are several other types of trackers that were mentioned and others that could have been mentioned, but these two are the only ones that will be considered in the comparison in this section since they are quite representative of simultaneous tracking and sequential scanning.

Signal-to-Noise Ratio When the target is being tracked, the signal-to-noise ratio from a monopulse radar is greater than that from a conical-scan radar since the monopulse antenna views the target at the peak of its sum pattern. The conical-scan radar views the target at some angle off the peak of the antenna beam. Thus the signal-to-noise ratio of monopulse might be from 2 to 4 dB greater than with conical scan.

Accuracy The monopulse radar will have greater angle accuracy since its signal-to-noise ratio is higher (important when accuracy is limited by thermal noise). Also its angle accuracy is not affected by fluctuations in the amplitude of the echo signal as are sequential scanning systems. Both monopulse and conical-scan systems are degraded by the wandering of the apparent position of the target caused by glint. Monopulse, because of its better signal-to-noise ratio, has a better range accuracy than conical scan.

Complexity The monopulse radar is the more complex of the two since it requires RF combining circuitry at the antenna and three receiving channels. Conical scan has only one receiving channel and uses a single feed, but it has to rotate or nutate the antenna beam at a high speed. In the early days of tracking radar, the relative complexity of monopulse was more pronounced. Receivers were big since they were based on vacuum-tube technology, and the combining circuitry was also large. Many a tracking radar development started out with monopulse, but had to switch to conical scan when its size or cost became too large. This is no longer a major consideration. Receivers are now solid state and small, and the combining circuitry has been made small by specially designed devices and the use of multimode feed systems. Thus complexity seldom need be a reason for not choosing monopulse. The Cassegrain is a popular antenna for monopulse since the combining circuitry and low-noise receiver front-ends can be placed behind the reflector where they can be better supported mechanically and not encounter the loss that can occur with long transmission lines.

A space-fed phased array radar can implement monopulse by using a multiple feed system similar to that used in a Cassegrain reflector antenna or a paraboloid reflector. With a corporate or constrained feed system in a phased array, the generation of multiple squinted beams requires a more complicated beam-forming network.

Minimum Number of Pulses As the name implies, a monopulse radar can perform an angle measurement in two coordinates on the basis of a single pulse. A phased array radar might make such a single-pulse angle measurement if the signal-to-noise ratio received on a single pulse is large enough. Usually, a number of pulses are integrated in a monopulse single-target tracker to increase the signal-to-noise ratio and the measurement accuracy. The conical-scan tracker requires a minimum of four pulses per revolution of the beam to extract an angle measurement in two coordinates. Ten pulses per revolution is more likely than four. Generally the pulse repetition frequency (prf) is at least 10 times the conical-scan frequency. (There have been exceptions to this, however.)

The monopulse radar first makes its angle measurement and then integrates a number of measurements to obtain the required signal-to-noise ratio and to smooth (reduce) the error. The conical-scan radar, on the other hand, integrates a number of pulses first (in its narrowband filter) and then extracts the angle measurement. The two tracking radars would have to integrate the same approximate number of pulses to achieve the same signal-to-noise ratio (assuming comparable radar systems), except that the conical-scan tracker has to process more pulses than the monopulse because of its 2 to 4 dB lower signal-to-noise ratio compared to the monopulse tracker, as mentioned above.

Susceptibility to Electronic Countermeasures The military conical-scan tracker is more vulnerable to spoofing countermeasures that take advantage of its conical-scan frequency. It can also suffer from deliberate amplitude fluctuations. A well-designed monopulse tracker is much harder to deceive.

Application Monopulse trackers should be used when good angle accuracy is wanted and/or when susceptibility to electronic countermeasures is to be minimized. When high-performance tracking is not necessary, the conical-scan tracker might be used because of its lower cost and reduced complexity.

4.9 AUTOMATIC TRACKING WITH SU

This section is concerned with tracking
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4.9 AUTOMATIC TRACKING WITH SURVEILLANCE RADARS

This section is concerned with tracking performed by an air-surveillance radar rather than a single target tracker, or STT. Tracking with air-surveillance radars is done at a much longer revisit time (lower data rate) between observations than STTs. STTs have revisit times of the order of a tenth of a second; air-surveillance radars have revisit times of a few to many seconds. The STT tracks only a single target; the air-surveillance radar may have many hundreds, or even thousands, of targets in track.

A long-range or a medium-range air-surveillance radar can have within its coverage a large number of aircraft targets as well as many individual clutter echoes. In the busy parts of the continental United States, a long-range radar might have more than 600 aircraft within view during the heavy air-traffic part of the day. Military radars might have to deal with many more than that number. In the early days of air-surveillance radars, when there were fewer aircraft in the sky and they didn't fly as fast as modern jets, target tracking was done manually by operators using grease pencils to mark the position of a target on each antenna scan, calculate its speed, and determine its direction. An alert, trained operator can update a target track manually at a rate of about once per two seconds.[92,93] With a civil air-traffic control radar antenna rotating at the relatively slow rate of 5 rpm, a good operator might be able to hold in track 5 or 6 aircraft. Such a rate cannot be sustained, however, for more than about 20 to 30 minutes before the operator's performance is reduced. With the higher antenna rotation rates of military radars, manual tracking of aircraft is even more limited. When there are more aircraft than can be tracked manually, automatic methods must be used for target detection, coordinate extraction, and tracking. This is called *automatic detection and track* (ADT).

ADT requires a good radar that eliminates clutter echoes and other undesired signals. This might sound like an obvious statement that can be said for many things; but when ADT was first introduced it was mistakenly applied to the then existing radars which had poor or no MTI, or any other means for reducing clutter. Its performance was a disaster when used with poor radars. A tracking system can be designed to recognize and eventually eliminate clutter echoes that do not form logical tracks; but it takes time and computer capacity which might not be available when a large number of targets must be maintained in track. Thus good tracking starts with a good radar that eliminates unwanted clutter echoes and other extraneous signals.

When clutter targets cannot be completely eliminated by doppler processing, the ADT radar has to employ CFAR to maintain a *constant false-alarm rate.* (CFAR techniques are discussed in Sec. 5.7.) A CFAR senses the local clutter and noise environment in the vicinity of the radar echo signal, and automatically adjusts the receiver decision-threshold to maintain a constant false-alarm rate. When the environment consists of range-extensive clutter such as from land, sea, or rain, the clutter signal is used to change the threshold whenever the target echo competes with clutter. The required change in threshold due to a change in the clutter environment occurs almost instantaneously as the clutter seen by the radar changes. CFAR works fine to keep the ADT from being overloaded by echoes that are not from aircraft; but it comes at a price. An increase in the detection threshold to maintain a constant false-alarm rate reduces the detection probability, thus some targets might not be detected. As discussed in Sec. 5.7, CFAR can introduce a loss of one or more dB, it can suppress desired echoes from targets in the vicinity of the target which is benefiting from the CFAR action, and it degrades the ability of the radar to resolve two closely spaced targets. CFAR may be needed in many radar systems; but one would like to have a radar that can accurately track a large number of targets without the accompanying limitations of CFAR.

Functions of an ADT[94–96] The functions performed by an ADT system include target detection, track initiation, track association, track update, track smoothing (filtering), and track termination. Each will be briefly discussed, assuming a ground-based 2D (range and azimuth) air-surveillance radar with mechanically rotating antenna.

Automatic Detection (This is reviewed in Sec. 5.5.) One approach is to first quantize the range and sometimes the azimuth angle (similar to what was done in the MTD discussed in Sec. 3.6). The quantization increment in range might be the pulse width and that in angle might be the azimuth beamwidth. At each range-azimuth quantization cell, the pulses received during the time the antenna scans past the target are integrated and a detection decision is made. CFAR generally is incorporated before the decision process in order to prevent excessive false alarms due to clutter echoes. Pulse integration is performed in some form of automatic detector, or integrator, such as discussed in Sec. 5.6. Another approach to automatic detection is the *moving window detector* which examines continuously the last n pulses and announces the presence of a target if at least m out of n of the pulses exceed a preset threshold.

A by-product of the automatic detection decision with a moving window detector or something similar, is an angle measurement made by *beam splitting*.[97] If n pulses are expected to be received from a target, beam splitting involves recognizing the beginning and end of the n pulses and locating their center. Angle accuracy depends on how well the beginning and end of the train of n pulses can be determined, as well as the number of pulses available and their signal-to-noise ratio. The beam splitting decision logic usually has no prior knowledge of a target's beginning. The logic must be sufficiently sensitive to quickly recognize the increased density region that signifies the start of an echo-signal pulse train, yet it must not be so sensitive that it generates false starts due to noise alone. Once a target's beginning is recognized, the device must sense the end of the increased density region. If the decision logic is too sensitive to change, it could cause a single target to split into two. A rough rule of thumb often quoted is that the accuracy of beam splitting is about one-tenth of a beamwidth when the signal-to-noise ratio is high enough to provide a good probability of detection.

Track Initiation In principle, a track can be initiated from the target-location information obtained on two successive scans of the radar antenna. In practice, however, target information from three or more scans is usually needed to initiate a track. Two scans would be adequate when there is only one or a few aircraft within view; but when the radar has in view a large number of echoes, one or more additional scans may be needed to
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prevent false tracks from being initiated. Thus it is more usual to require three or more scans before establishing a track.

A *clutter map* is used to store the locations of fixed clutter echoes and prevent tracks from being initiated based on a clutter echo combined with a real target detection. Such tracks can eventually be recognized as false and can be dropped, but it takes time and computer capacity to do so when there are a large number of them. Clutter echoes for inclusion in the clutter map are those echoes that do not change their location with time or that change location too slowly to be targets of interest.

The process of initiating a track in a dense environment of targets and clutter not eliminated by the radar can be quite demanding in both computer software and hardware. Initiation of a new track may take more computer time and capability than any other aspect of ADT.

Requiring three scans for a civil air-traffic control radar to establish a track is usually not a burden. Waiting three scans for track establishment, however, may be an excessively long time for a military air-defense radar that has to direct weapon-control radars to defend against high-speed attackers that "pop up" at short range over the horizon. It is possible to quickly acquire the target on the basis of a single scan past the target if the radar can obtain a quick second look. This might be done with a *look-back beam* directed to the angle of the original detection. The quick look-back can provide confirmation of detection and an estimate of target's radial velocity. A phased array radar is well suited for this purpose, but mechanical rotating radars can also be outfitted with a fixed look-back beam. (One approach is shown in the antenna of Fig. 9.54.) Look-back might also be accomplished with a 3D radar whose electronically scanning beam in elevation is returned to the elevation angle of initial detection, before the radar beam entirely scans past the target.

Track Association When a new detection is received that is not at the location of a clutter echo stored in the clutter map, an attempt is made to associate it with an existing track. Association with an existing track is aided by establishing for each track a small search window, or gate, within which the detection of the target on the next scan of the radar antenna is predicted to appear. The gate should be as small as possible in order to avoid having more than one echo fall within it when the traffic density is high or when two tracks are close to one another. On the other hand, a large gate region is needed if the tracker is to follow target turns or maneuvers. More than one gate size is used to overcome this dilemma. Figure 4.21 shows a small nonmaneuvering gate situated around the predicted position of the target in track. The size of the gate is determined by the estimated errors in the predicted position and the estimated errors in speed and direction of the track. The detection threshold might be lowered in the gate region to increase the probability of detection. When an echo is not found within the nonmaneuvering gate, the larger region encompassing the maneuvering gate is then searched. The size of the maneuvering gate is determined by the estimate of the maneuvering capability of the target under track.

One reason the target might not appear in the nonmaneuvering gate is that its radar cross section might decrease, or fade, so that it is not detected. When this is the case, it

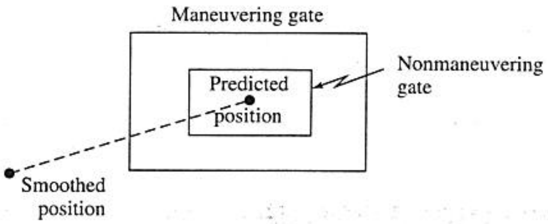

Figure 4.21 Maneuvering and nonmaneuvering gates centered at the target's predicted position. (From G. V. Trunk[110])

is possible for a false track to occur when a noise spike or an echo from another target is found in the maneuvering gate. To avoid the problem caused by a target fade and a false indication appearing in the larger maneuvering gate, the track can be divided into two tracks. (This is know as *bifurcation* of the track.) One is the original track with no new detection in the nonmaneuvering gate. The other is a new track based on the signal found in the maneuvering gate. After receiving the target position on the next scan of the radar (or sometimes after two scans), a decision is made as to which of the two tracks should be dropped.

Tracking is usually done in Cartesian coordinates, but the correlation gates are defined in polar (r, θ) coordinates.

Track Smoothing (α-β Tracker) On the basis of a series of past target detections, the automatic tracker makes a smoothed (filtered) estimate of the target's present position and velocity, as well as its predicted position and velocity. One method for accomplishing this is with the α-β (alpha-beta) tracker that computes the present smoothed target-position $\bar{x}_n$ and smoothed velocity $\bar{\dot{x}}_n$ with the following equations

$$\text{smoothed position} = \bar{x}_n = x_{pn} + \alpha(x_n - x_{pn}) \qquad \textbf{[4.8a]}$$

$$\text{smoothed velocity} = \bar{\dot{x}}_n = \bar{\dot{x}}_{n-1} + \frac{\beta}{T_s}(x_n - x_{pn}) \qquad \textbf{[4.8b]}$$

The predicted position on the next scan (the $n + 1$st) is then

$$x_{p(n+1)} = \bar{x}_n + \bar{\dot{x}}_n T_s \qquad \textbf{[4.8c]}$$

where x_{pn} = predicted position of the target on the nth scan, x_n = measured position on the nth scan, α = position smoothing parameter, β = velocity smoothing parameter, and T_s = time between observations. If $\alpha = \beta = 0$, the tracker uses no current target information, only the smoothed data from prior observations. When $\alpha = \beta = 1$, no smoothing of the data is included at all. Thus the closer α and β are to zero, the more important is the smoothed track in determining the predicted track. The closer they are to 1, the more important is the currently measured data. If target acceleration is significant, a third equation can be added to describe an α-β-γ tracker, where γ = acceleration smoothing parameter.

Benedict and Bordner[98] show that if the transient response to a maneuvering target can be modeled by a ramp function, the output noise variance at steady state is minimized

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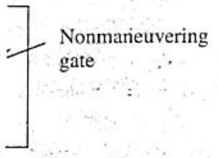

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in an α-β tracker when $\beta = \alpha^2/(2 - \alpha)$. It was stated that the analysis does not, and cannot, specify the optimum value of α. The value of α is determined by the bandwidth and will depend on the system application. In selecting α, a compromise usually must be made between good smoothing of the random measurement errors (requiring a narrow bandwidth) and a rapid response to maneuvering targets (wide bandwidth). Trunk[99] states that an α and a β satisfying the above relation can be chosen so that the tracking filter will follow a specified g turn.

Another criterion for selecting the α-β values is based on the best linear track fitted to the radar data in a least squares sense:[100]

$$\alpha = \frac{2(2n - 1)}{n(n + 1)} \qquad \beta = \frac{6}{n(n + 1)} \qquad [4.9]$$

where n is the number of the scan or target observation ($n > 2$). The above equations for α and β are also called the Kalman gain components.[101]

The classical α-β tracker is designed to minimize the mean-square error in the smoothed position and velocity. This type of tracker is said to be relatively easy to implement, but it does not handle the maneuvering target. Some means has to be included to detect maneuvers and change the values of α and β accordingly.

The two tracking gates described in connection with Fig. 4.21 is one example of how to deal with a large maneuver. Another example is an adaptive α-β tracker which varies the smoothing parameters to achieve a variable bandwidth that allows the radar to follow target maneuvers.[102] When the target is not maneuvering the adaptive tracking algorithm provides heavy smoothing. If the target maneuvers or makes a turn, the filter bandwidth is widened so as to allow the track filter to follow. As the selection of the values of α and β become more sophisticated and requires knowledge of the statistics of the measurement errors and the prediction errors, the α-β tracker approaches the Kalman filter.

Track Smoothing (Kalman Filter) The Kalman filter is similar to the α-β tracker except it can inherently provide for the maneuvering target.[103] A model for the measurement error has to be assumed, as well as a model for the target trajectory and the disturbance or uncertainty of the trajectory.[104] Such disturbances might be due to neglect of higher order derivatives in the model for the dynamics; random motions due to atmospheric turbulence, and deliberate target maneuvers. The Kalman filter can utilize a wide variety of models for measurement of noise and disturbance; but it is often assumed that these are described by white noise with zero mean.[105] A maneuvering target does not always fit such a model since its measurements are likely to be correlated. The proper inclusion of realistic models increases the complexity of the calculations. Furthermore, it may be difficult to describe ahead of time the precise nature of the trajectory disturbances.

When the Kalman filter is modeled with the target trajectory as a straight line, and the measurement noise and the trajectory disturbance are modeled as white, gaussian noise with zero mean, the Kalman filter equations reduce to the α-β tracker equations with α and β computed sequentially by the Kalman filter procedure.

Blackman[106] states that "Experience with airborne radars has shown the versatility of Kalman filters to be almost indispensable when dealing with problems presented by missing data, variable measurement noise statistics, and maneuvering targets with dynamic capabilities." The Kalman filter has better performance than the α-β tracker since it utilizes more information. The α-β tracker, however, might be considered when the target's maneuver statistics are not known or in a dense target environment where computational simplicity is important.

The Kalman filter[107] and the α-β tracker also can be applied to control digitally the feedback loop in the single-target tracker.

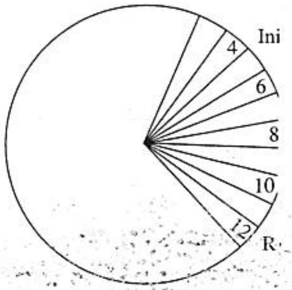
Track Termination If the radar does not receive target information on a particular scan, the smoothing and prediction operation can be continued by properly accounting for the missing data.[108] (This is sometimes called *coasting.*) When data from a target is missing for a number of consecutive scans, the track is terminated. Although the criterion to be used for determining when to terminate a track depends on the application, it has been suggested that when three target reports are used to establish a track, five consecutive misses is a suitable criterion for termination.[109]

Tracking Performed on a Sector Basis To avoid having to correlate all new detections with all existing tracks, the correlation and track updating process can be done on a sector basis. The 360° of azimuth coverage might be divided, for example, into 64 sectors. Figure 4.22 shows sectors 4 through 12. As given by Trunk,[110] the following actions occur:

- Radar has reported all its detections found in Sector 11 and is now obtaining detections from Sector 12.
- Detections from Sectors 9, 10, and 11 are examined to see if they correlate with clutter cells from Sector 10 in the stored clutter map. Any detections associated with clutter cells are deleted from the detection file.
- Detections from Sectors 7, 8, and 9 are examined for possible association with the firm tracks in Sector 8. At this point, all detections from clutter cells have been removed from Sector 9 and below. Detections that are found to be associated with firm tracks are deleted from the detection file and are used to update the appropriate track, as with an α-β tracker.
- Preference is given to firm tracks. Thus tentative tracks are examined two sectors behind the firm tracks.
- Remaining detections not associated with either clutter cells or tracks are used to initiate new tentative tracks. Both a tentative track and a clutter cell are established until enough information is obtained to determine which of the two can be deleted.

Maneuvering Targets Target maneuvers and crossing trajectories can cause problems in tracking systems unprepared to cope with them. Some of the methods for handling maneuvering targets have been mentioned. Bar-Shalom[111] points out that a commercial aircraft that can turn at rates up to 3°/s completes a 90° turn in 30 s, so that a radar with a scan time of 10 s (rotation rate of 6 rpm) will obtain only three observations during the turn. He states that "very few of the existing schemes among the many in the literature (even adaptive ones with maneuver detection) can track such a target with good accuracy."

Figure 4.22 Various operations of a track-while-scan system performed on a sector basis.
(From G. V. Trunk[110])



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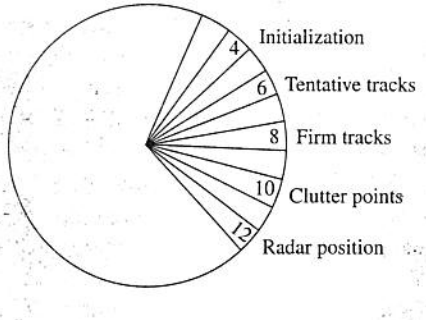

Figure 4.22 Various operations of a track-while-scan system performed on a sector basis.
(From G. V. Trunk[110])

He mentions algorithms and tracking methods to employ, but the radar must also be included. A 10-s scan time, or 6 rpm antenna rotation rate, is used for long-range civil air-traffic control radars where 90° turns are unlikely. Thus such radars are seldom exposed to a 90° turn in 30 s. Medium-range air-traffic control radars that observe traffic in the vicinity of airports, where aircraft are more likely to make a 90° turn, have shorter scan times than 10 s. The ASR-9, for example, has a scan time of 4.8 s. Military radars that have to deal with targets that maneuver more than do civil airliners, also have shorter scan times. In addition to the antenna scan time, the performance of an ADT system depends on the accuracy of the radar measurements, as well as the ability of the radar to resolve targets, reject clutter, eliminate discrete clutter echoes, and reject interference. Obtaining a good ADT is a total system problem, and should not be done in isolation by the control-system theorist without coordination with the radar systems designer.

Narrowband Data Communications Allowed by ADT One of the corollary advantages of ADT it that it allows a reduction in the bandwidth of the radar output since the information content of processed video detections or processed target tracks occupy significantly less bandwidth than the raw radar data. Narrowband telephone lines can be used for transmission rather than wideband microwave data links. Thus, if circumstances permit, when the radar has to communicate its output to a remote location, it is often better to extract the information right at the radar and transmit processed information rather than raw data.

Meaning of Target Detection When Tracking is Performed When the operators of early radars viewed the radar display, a single blip seen on the scope was taken to mean a target was detected. It was soon found that this was not sufficient, especially when clutter or noise appeared on the display. For greater reliability of detection, the operator required that echoes (blips) be seen on two consecutive scans, or two out of three (or some other combination) before the presence of a target was indicated. This is especially important when the noise or clutter has higher tails in its probability density function than the gaussian. With many modern ADT methods, the presence of a target is generally not finally confirmed until a track is formed. This criterion can employ a higher false-alarm rate per observation since multiple target observations are employed and the resulting track must be realistic. Thus the single-scan detection-threshold can be lowered and still achieve a very low probability of a false track.

Track-Before-Detect The probability of detection can be improved for weak targets, or the detection range extended for conventional-size targets, by noncoherently integrating the radar echoes received over multiple scans of the antenna. With such long-duration integration, the target can move beyond the resolution cell of the radar and may traverse many resolution cells during the integration time. In order to perform integration, knowledge is required of the speed and direction of each target in order to properly associate the echoes from scan to scan. Target trajectory information, of course, is usually not known beforehand, so scan-to-scan integration must be performed assuming all possible trajectories. A correct trajectory is one that provides a realistic speed and direction for the type of target being observed. In other words, the target must be *tracked* before it is *detected,* which is why this method was originally called *track-before-detect.* It has also been called *retrospective detection* and *long-term integration,* as well as *scan-to-scan integration.*

Track-before-detect can provide greater sensitivity because of the large number of pulses that it integrates. Also, the single-scan probability of false alarm can be much higher because of the requirement that the pulses being integrated form a logical target track from scan to scan. It can, however, be much more demanding of computer capability than conventional ADT. Track-before-detect was first examined experimentally in the 1960s, when data processing technology was still based on vacuum tubes. What it could do was quite limited at that time. As solid-state digital computer technology became available with much better capabilities, so could the performance of track-before-detect be significantly improved.

An analytical investigation[112] of a hypothetical radar with track-before-detect for detection of sea-skimming missiles by a shipborne radar when sea clutter is a problem concluded that "long-term integration [track-before-detect] provides around 10 dB increase in detection sensitivity over conventional cumulative detection . . . in 'Beaufort' sea state 4." Track-before-detect, or retrospective detection, was experimentally investigated[113] using an AN/FPS-114 shore-based sea-surveillance radar. The conclusions were that the single-scan probability of false alarm can be of the order of 10^{-3} rather than the 10^{-5} to 10^{-8} that might be typically required for conventional automatic tracking systems.

In addition to requiring increased data processing capability, track-before-detect also requires a longer observation time, which may be something that is not be available in all tracking applications. Unusual target maneuver during the scan-to-scan integration time might also limit performance.

Weak echoes on each scan are used to form the track. They will have lower signal-to-noise ratio than a radar designed to make the detection decision based on what is received with only a single scan. Thus the conventional detection philosophy as discussed in Chap. 2 has to be modified for use with track-before-detect.

The outputs of each resolution cell, whether from weak targets or from noise, are examined over *N* scans to determine if they form logical tracks. Tracks may be found by an exhaustive search of all possible trajectories based on the data from all *N* scans. The number of possible trajectories to be examined with exhaustive search can easily become impracticably large. The processing load can be narrowed by limiting the range of target speeds and placing restrictions on the type of target trajectories. Even this is usually not sufficient. Barniv,[114] however, suggests that by applying a dynamic programming algorithm the amount of computation can be significantly reduced so as to become feasible.

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It can be applied with curved as well as straight-line target trajectories. When conditions permit, dynamic programming can perform the equivalent of an exhaustive search, but in a more convenient manner and with significantly less computer capability. In his example of tracking using a set of (passive) infrared mosaic-sensor images (a nonradar example), Barniv found that the use of dynamic programming typically required five or more orders of magnitude less computations than what was needed if employing an exhaustive search.

Multiple-Radar Tracking When multiple radars view a common volume, there can be improved tracking, the data rate can be greater than any of the radars acting alone, there is less vulnerability to electronic countermeasures, and less likelihood of having missed detections due to reduced echo-signal strength caused by nulls in one of the antenna patterns or changes in the target aspect. There are two related cases: one is when the radars are collocated, as on the same ship or at the same land site; the other, is when they are at separated locations and netted together.

Integrated Tracking from Collocated Radars at a Single Site When more than one radar, covering approximately the same volume in space, are located in the same vicinity, their individual outputs can be combined to form a single track. The radars might operate in different frequency bands, have different antenna characteristics, and different data rates. There is more than one way to combine the outputs of multiple radars.[115] A good approach is to combine all the detections from each radar to form a single track and to update the track rather than develop separate tracks at each radar and either select the best track or combine them in some other manner.[116] The data from the various radars do not arrive at the tracker at a uniform rate. The development of a single track file by the use of the total data available from all radars produces a better track than combining the tracks developed individually at each radar. It reduces the likelihood of a loss of data as might be caused by antenna lobing, target fading, interference, and clutter since integrated processing permits the favorable weighting of the better data and lesser weighting of the poorer data. This method of combining data from multiple radars has been known as either *Automatic Detection and Integrated Tracking* (ADIT) or *Integrated Automatic Detection and Tracking* (IADT).

Integrated Tracking from Multiple Sites When radars at multiple sites cover the same area, tracking can be combined as described above for the collocated radars; that is, the individual target data points (location and time), rather than the tracks, are transmitted to a single tracking center for processing into a single track. Farina and Studer[117] call this *centralized architecture.* They call a *distributed architecture* one in which the tracks are first formed at each radar site based only on the measurements from a single radar. These are transmitted to a tracking center which combines the tracks to establish a single track for each target. The distributed architecture allows the track information to be transmitted over telephone lines rather than wider bandwidth links, and it can employ less capable computer resources. The composite tracking accuracy it produces, however, is not as accurate as that with the centralized architecture.

To track targets over a large area as for air-traffic control or military air defense, multiple radars are located so that as a target leaves the coverage of one radar it enters the coverage of the other and a continuous track is maintained. There needs to be some overlap in the coverages so that tracks can be properly handed over from one radar to the other. One of the problems that plagued early multisite radars was being able to associate radar detections or tracks made by one radar with data or tracks made by another radar. The absolute location of a radar site, even when fixed, was not always known accurately so that the central tracking facility might generate multiple tracks from a single target. This situation is even more serious when trying to net the radars from multiple ships or aircraft. Methods were developed for merging the data from multiple sites to provide a single track when the location or orientations of the radars was inaccurate.[118] The availability of GPS (Global Positioning System), however, readily provides the accurate location of a radar and eliminates the problem of associating data from radars located far apart.

Multiradar tracking (MRT) developed for the air-traffic control system of the Rome Flight Information Region integrates five radars sited on the west side of the center and south of Italy.[119,120] Alenia ATC radars were used with ranges up to 170 nmi. They were separated approximately 135 nmi apart. The filtering algorithm used an α-β tracker. The measured tracking accuracy of this system when the target flew a straight line course, was said to be better than 0.3 nmi. The observed accuracy with an accelerating path (acceleration was not further described) was 0.8 nmi.

Combined Tracking with Radar and Passive Direction Finding Radar provides the range and angle to a target. Passive direction finding (DF) provides angle and not range. The angle accuracy obtained by a radar is usually more accurate than the angle accuracy obtained by DF, so there is no gain in using the DF measurement in the tracking filter to produce a more accurate track. Passive DF, also called Electronic Support Measures (ESM), however, can assist in target recognition since it receives the emitted signal and can recognize the type of system that emitted it. Signals from hostile aircraft are likely to be distinctive and different from signals emitted by other aircraft, and can be used to recognize the nature of the target. This is of importance for military air-defense radars since some form of target recognition is needed to separate friendly and neutral aircraft from hostile aircraft.

Although DF systems provide target recognition and an angle measurement, they do not provide range so a track cannot be formed. If the passive angle track can be associated with a radar track, then the target being tracked by the radar can be recognized based on the information received by the passive DF system. Statistical methods for achieving this have been described.[121,122]

REFERENCES

1. Howard, D. D. "Tracking Radar." In *Radar Handbook,* M. Skolnik, Ed. New York: McGraw-Hill, 1990, Chap. 18.
2. Sherman, S. M. *Monopulse Principles and Techniques.* Norwood, MA: Artech House, 1984.
3. "IEEE Standard Radar Definitions," *IEEE Std 686–1997*, New York, 1997.
4. Sherman, S. M. Ref. 2, Sec. 4.4.
5. Sherman, S. M. Ref. 2, Sec. 4.4.
6. Page, R. M. "Monopulse Rada
132–134.
7. Skolnik, M. I. *Introduction to Ra*
Sec. 5.4.
8. Rhodes, D. R. *Introduction to M*
9. Sherman, S. M. Ref. 2, Sec. 6.4,
10. Berger, H. "On the Optimum S
Beacon Tracking Systems." *IEE*
11. Howard, D. D. Ref. 1, pp. 18.11-
12. Hannan. P. W. "Optimum Feeds
IEEE Trans. AP-9 (September 1
13. Barton, D. K. *Radars, Vol. 1, Mon*
papers nos. 11 and 12.
14. Elliott, R. S. *Antenna Theory and*
Sec. 5.11.
15. Bayliss, E. T. "Design of Mono
Lobes." *Bell System Tech. J.* 47 (
16. Chubb, C. F., B. L. Hulland, an
ceiver, U. S. Patent 3,239,836, M
17. Sherman, S. M. Ref. 2, Sec. 7.14
18. Thomson, D. "Monopulse Desig
(May 1985), pp. 307–310.
19. Howard, D. D. Ref. 1, pp. 18.19-
20. Rubin, W. L., and S. K. Kamen.
with Application to Monopulse."
21. Peebles, P. Z., Jr., and H. Sakam
Trans. AES-16 (November 1980)
22. Bakut, P. A., and I. S. Bol'shakov.
II. Moscow: Sovetskoye Radio, 1
NTIS, AD 645775, June 28, 196
23. Field, J. C. G. "The Design of
Radar Receivers." *IEE Proc.*, Pt.
24. Howard, D. D. Ref. 1, pp. 18.6–
25. Van Brunt, L. B. *Applied ECM,*
1982, pp. 570–575.
26. Barton, D. K. *Modern Radar Syst*
Chap. 11, Radar Error Analysis.