CHAPTER 18
TRACKING RADAR

Dean D. Howard
Locus, Inc., a subsidiary of Kaman Corp.

18.1 INTRODUCTION

A typical tracking radar has a pencil beam to receive echoes from a single target and track the target in angle, range, and/or doppler. Its resolution cell—defined by its antenna beamwidth, transmitter pulse length, and/or doppler bandwidth—is usually small compared with that of a search radar and is used to exclude undesired echoes or signals from other targets, clutter, and countermeasures. Electronic beam-scanning phased array tracking radars may track multiple targets by sequentially dwelling upon and measuring each target while excluding other echo or signal sources.

Because of its narrow beamwidth, typically from a fraction of 1° to 1 or 2°, a tracking radar usually depends upon information from a search radar or other source of target location to acquire the target, i.e., to place its beam on or in the vicinity of the target before initiating a track. Scanning of the beam within a limited angle sector may be needed to fully acquire the target within its beam and center the range-tracking gates on the echo pulse prior to locking on the target or closing the tracking loops.

The primary output of a tracking radar is the target location determined from the pointing angles of the beam and position of its range-tracking gates. The angle location is the data obtained from synchros or encoders on the antenna tracking axes shafts (or data from a beam-positioning computer of an electronic-scan phased array radar). In some cases, tracking lag is measured by converting tracking-lag-error voltages from the tracking loops to units of angle. This data is used to add to or subtract from the angle shaft position data for real-time correction of tracking lag.

There are a large variety of tracking-radar systems, including some that achieve simultaneously both surveillance and tracking functions. A widely used type of tracking radar and the one to be discussed in detail in this chapter is a ground-based system consisting of a pencil-beam antenna mounted on a rotatable platform which is caused by motor drive of its azimuth and elevation position to follow a target (Fig. 18.1). Errors in pointing direction are determined by sensing the angle of arrival of the echo wavefront and corrected by positioning the antenna to keep the target centered in the beam.

The principal applications of tracking radar are weapon control and missile-

FIG. 18.1 AN/FPQ-6 C-band monopulse precision tracking radar installation at the NASA Wallops Island Station, Va. It has a 29-ft-diameter antenna and a specified angle precision of 0.05 mrad rms.

range instrumentation. In both applications a high degree of precision and an accurate prediction of the future position of the target are generally required. The earliest use of tracking radar was in gunfire control. The azimuth angle, the elevation angle, and the range to the target were measured, and from the rate of change of these parameters the velocity vector of the target was computed and its future position predicted. This information was used to point the gun in the proper direction and to set the fuzing time. The tracking radar performs a similar role in providing guidance information and steering commands for missiles.

In missile-range instrumentation, the tracking-radar output is used to measure the trajectory of the missile and to predict future position. Tracking radar which computes the impact point of a missile continuously during flight is also important for range safety. Missile-range instrumentation radars are normally used with a beacon to provide a point-source target with high signal-to-noise ratio. Some of these systems achieve a precision of the order of 0.1 mil in angle and a range accuracy of 5 yd.

This chapter describes the conical-scan, sequential-lobing, and monopulse (both phase comparison and amplitude comparison) tracking-radar techniques, with the main emphasis on the amplitude-comparison monopulse radar.

18.2 SCANNING AND LOBING

The first technique used for angle tracking of targets by radar was to sense the target location with respect to the antenna axis by rapidly switching the antenna beam from one side of the antenna axis to the other, as in Fig. 18.2. The original tracking radars of this type, such as the SCR-268, used an array of radiating elements which could be switched in phase to provide two beam positions for the lobing operation. The radar operator observed an oscilloscope that displayed side by side the video returns from the two beam positions. When the target was on axis, the two pulses were of equal amplitude (Fig. 18.2a); when the target moved off axis, the two pulses became unequal (Fig. 18.2b). The radar operator, observing the existence of an error and its direction, could position the antenna to regain a balance between the two beam positions. This provided a manual tracking loop.

This lobing technique was extended to continuous rotation of the beam around the target (conical scan) as in Fig. 18.3.[1] Angle-error-detection circuitry is provided to generate error voltage outputs proportional to the tracking error and with a phase or polarity to indicate the direction of errors. The error signal actuates a servosystem to drive the antenna in the proper direction to reduce the error to zero.

Continuous beam scanning is accomplished by mechanically moving the feed of an antenna since the antenna beam will move off axis as the feed is moved off the focal point. The feed is typically moved in a circular path around the focal point, causing a corresponding movement of the antenna beam in a circular path around the target. A typical block diagram is shown in Fig. 18.4.[2] A range-tracking system is included which automatically follows the target in range, with range gates that turn on the radar receiver only during the time when the echo is expected from the target under track. Range gating excludes undesired targets and noise. The system also includes an automatic gain control (AGC) necessary to maintain constant angle sensitivity (volts of error-detector output per degree of
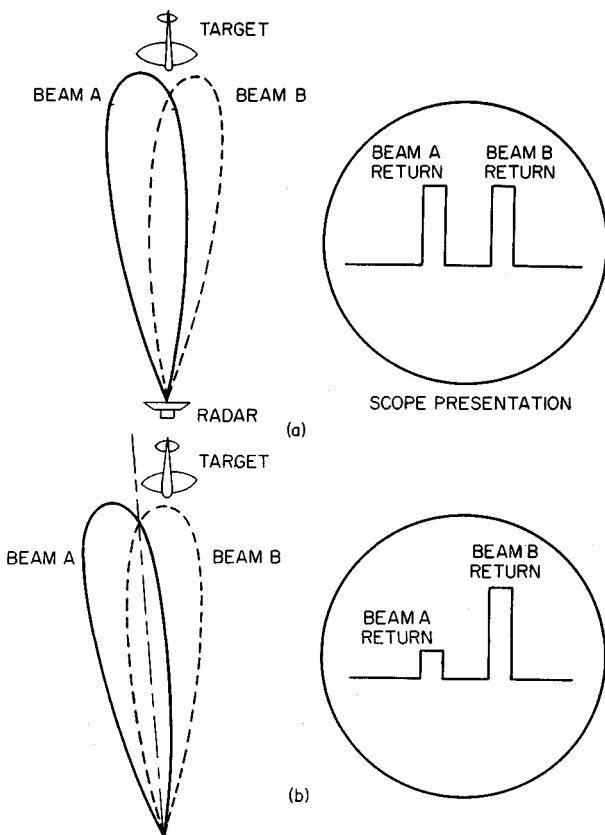
FIG. 18.2 Angle error sensing in one coordinate by switching the antenna beam position from one side of the target to the other. (*a*) Target located on the antenna axis. (*b*) Target at one side of the antenna axis.

error) independent of the amplitude of the echo signal. This provides the constant gain in the angle-tracking loops necessary for stable angle tracking.

The feed scan motion may be either a rotation or a nutation. A rotating feed turns as it moves with circular motion, causing the polarization to rotate. A nutating feed does not rotate the plane of polarization during the scan; it has a motion like moving one's hand in a circular path.

The radar video output contains the angle-tracking-error information in the envelope of the pulses, as shown in Fig. 18.5. The percentage modulation is proportional to the angle-tracking error, and the phase of the envelope function relative to the beam-scanning position contains direction information. Angle-tracking-error detection (error demodulation) is accomplished by a pair of phase detectors using a reference input from the scan motor. The phase detectors perform essentially as dot-product devices with sine-wave reference signals at the frequency of scan and of proper phases to obtain elevation error from one and
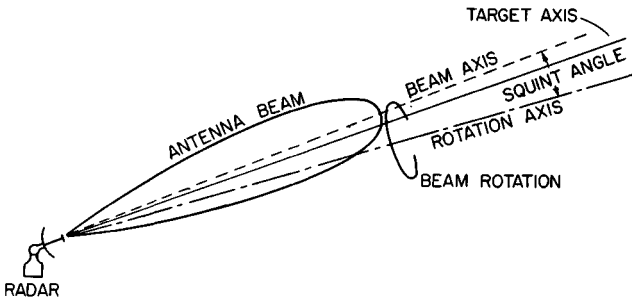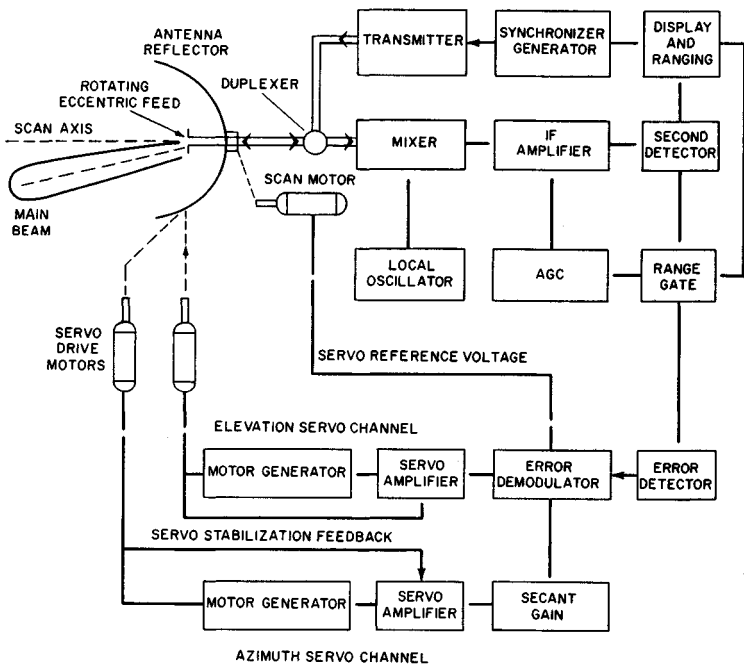
FIG. 18.3 Conical-scan tracking.

FIG. 18.4 Block diagram of a conical-scan radar.

azimuth error from the other. For example, the top scan position may be chosen as zero phase for a cosine function of the scan frequency. This provides a positive voltage output proportional to the angle error when the target is above the antenna axis. The reference signal to the second phase detector is generated with a 90° phase relation to the original reference. This provides a similar error voltage proportional to the azimuth-angle error and with polarity corresponding to the direction of error.

A secant correction (Fig. 18.4) is necessary in any conventional elevation-over-azimuth tracking radar where the elevation drive system rotates when the
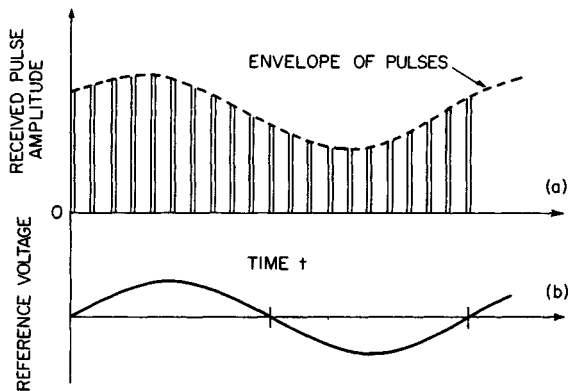
FIG. 18.5 (a) Angle error information contained in the envelope of the received pulses in a conical-scan radar. (b) Reference signal derived from the drive of the conical-scan feed.

antenna changes azimuth. A target flying a passing course by the radar will, at its closest point to the radar, cause the azimuth servo to drive faster at high elevation angles than at low elevation angles. In the extreme, when the target passes directly overhead, the azimuth drive would have to flip the antenna 180° at the instant when the target crosses overhead. This effect requires the azimuth-tracking loop gain to change approximately as the secant of elevation angle in order to maintain essentially constant overall azimuth loop gain. In practical tracking radars with the conventional elevation-over-azimuth mount the elevation angle is typically limited by this effect to a maximum of 85° since the servo bandwidth required for higher elevation angles exceeds practical limits.

A major parameter in a conical-scan radar is the size of the circle to be scanned relative to the beamwidth. Figure 18.6 shows a circle representing the 3 dB contour of the beam at one position of its scan. The half-power beamwidth is θ_B. The dashed circle represents the path described by the center of the beam as it is scanned. The radius of the dashed circle is β, the offset angle. The compromise that must be made in choosing β is between the loss of signal or antenna gain L_k (crossover loss) and the increase in angle sensitivity k_s of the angle-sensing circuits.

High angle-error sensitivity is desired to obtain higher voltage from the angle error detectors for a given true angle error relative to undesired voltages in the receiver output. The undesired receiver output includes angle errors caused by receiver thermal noise. For a given signal-to-noise ratio (SNR) the thermal-noise effects are inversely proportional to angle error sensitivity. Unfortunately, increasing β to increase k_s also increases the loss L_k, which reduces the SNR.

The relative values of k_s and L_k depend upon whether the target provides a beacon response that removes the transmitting modulation from the received signal or whether two-way skin tracking is performed. Two-way tracking gives a greater depth of modulation, or angle sensitivity, for a given β but doubles the loss in decibels. Figure 18.7 shows the loss of antenna gain and angle sensitivity as a function of β for the two cases.[2] The rms error caused by receiver thermal noise is inversely proportional to k_s and proportional to $\sqrt{L_k}$ (L_k expressed as power loss). The peaks of the dotted curves labeled $k_s/\sqrt{L_k}$ indicate the optimum offset angle β for minimizing receiver thermal-noise effects on angle tracking. However, the range-tracking system of the radar is affected by L_k only, and a β
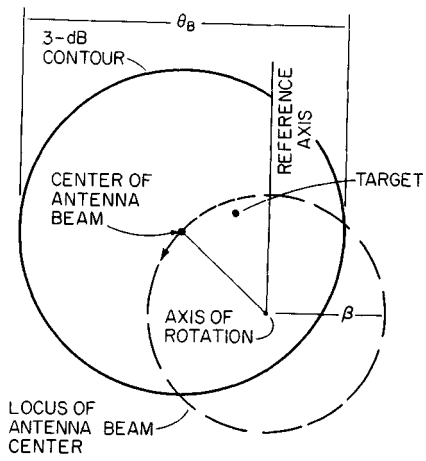
FIG. 18.6 Conical-scan-radar antenna beam 3 dB contour (solid circle) and path of rotation (dashed circle) of the beam center.
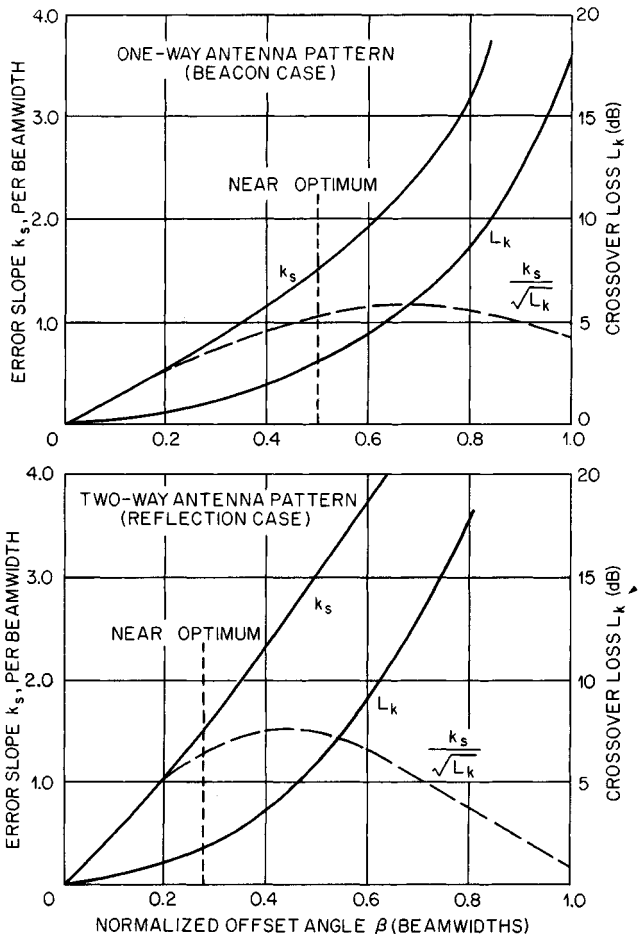

FIG. 18.7 Error slope k_s and crossover loss L_k.

18.7

of zero maximizes range-tracking performance. Therefore, values of β indicated by the vertical dashed lines are chosen smaller than optimum for angle tracking as a compromise between angle- and range-tracking performance.

The tracking-error information in beam-scanning tracking radars is a time fluctuation of the echo signal amplitude. Other sources of echo-signal-amplitude fluctuation such as target scintillation (Sec. 18.8) can cause false indications of tracking error. The undesired fluctuations that cause difficulty occur at about the same rate as the scan rate. Since target scintillation energy of aircraft is concentrated in the lower frequency range below approximately 100 Hz (particularly the troublesome propeller modulation), it is desirable to increase the scan rate as high as possible. The maximum practical rate is one-fourth of the pulse repetition frequency (PRF) so that four pulses provide a complete scan with one each up, down, right, and left. The maximum PRF and, consequently, maximum scan rate are limited by the maximum range of targets to be tracked by the radar. At a PRF of 1000 Hz the unambiguous range extends to about 80 nmi (at this range the echo is returning at the time when the radar is ready for its next transmission). The radar can track beyond this range by using nth-time-around tracking as described in Sec. 18.5.

High scan rates are difficult to achieve with mechanical scanning devices in a large antenna, and a variety of techniques to scan electronically have been used. In a small antenna such as that used in missile-homing heads, the dish rather than the feed may be tilted and rotated at high revolutions per minute (r/min) to achieve high scan rates. Scan rates of hundreds of r/min are frequently used—in some instances, as high as 2400 r/min, as in the AN/APN-58 target seeker. In the target seeker application the PRF can be high since the target is at short range. The coming of the jet aircraft caused additional problems for lobing systems because jet turbines cause significant modulations at high frequencies in regions near the maximum practical mechanical or electronic lobing rates. A further problem in scanning and lobing systems is a limitation on long-range tracking. At long ranges the time required for the radar signal to travel to the target and back becomes a significant portion of a scan cycle. For example, at a 100-Hz scan rate and the target at 460 mi, a signal transmitted on an up lobe will return as an echo when the antenna is looking on a down lobe, canceling the effect of the scan and the angle-error-sensing capability. In applications where this effect is significant, compensation can be provided if the range to the target is measured.

18.3 MONOPULSE (SIMULTANEOUS LOBING)

The susceptibility of scanning and lobing techniques to echo amplitude fluctuations was the major reason for developing a tracking radar that provides simultaneously all the necessary lobes for angle-error sensing. The output from the lobes may be compared simultaneously on a single pulse, eliminating any effect of time change of the echo amplitude. The technique was initially called *simultaneous lobing*, which was descriptive of the original designs. Later the term *monopulse* was used, referring to the ability to obtain complete angle error information on a single pulse. It has become the commonly used name for this tracking technique.

The original monopulse trackers suffered in antenna efficiency and complexity of microwave components since waveguide signal-combining circuitry was a relatively

new art. These problems were overcome, and monopulse radar with off-the-shelf components can readily outperform scanning and lobing systems. The monopulse technique also has an inherent capability for high-precision angle measurement because its feed structure is rigidly mounted with no moving parts. This has made possible the development of pencil-beam tracking radars that meet missile-range instrumentation-radar requirements of 0.003° angle-tracking precision.

This chapter is devoted to tracking radar, but monopulse is used in other systems including homing devices, direction finders, and some search radars. However, most of the basic principles and limitations of monopulse apply for all applications. A more general coverage is found in Refs. 3 and 4.

Amplitude-Comparison Monopulse. A method for visualizing the operation of an amplitude-comparison monopulse receiver is to consider the echo signal at the focal plane of an antenna.[5] The echo is focused to a "spot" having a cross-section shape approximately of the form $J_1(X)/X$ for circular apertures, where $J_1(X)$ is the first-order Bessel function. The spot is centered in the focal plane when the target is on the antenna axis and moves off center when the target moves off axis. The antenna feed is located at the focal point to receive maximum energy from a target on axis.

An amplitude-comparison monopulse feed is designed to sense any lateral displacement of the spot from the center of the focal plane. A monopulse feed using the four-horn square, for example, would be centered at the focal point. It provides a symmetry so that when the spot is centered equal energy falls on each of the four horns. However, if the target moves off axis, causing the spot to shift, there is an unbalance of energy in the horns. The radar senses the target displacement by comparing the amplitude of the echo signal excited in each of the horns. This is accomplished by use of microwave hybrids to subtract outputs of pairs of horns, providing a sensitive device that gives signal output when there is an unbalance caused by the target being off axis. The RF circuitry for a conventional four-horn square (Fig. 18.8) subtracts the output of the left pair from the output of the right pair to sense any unbalance in the azimuth direction. It also subtracts the output of the top pair from the output of the bottom pair to sense any unbalance in the elevation direction.

The Fig. 18.8 comparator is the circuitry which performs the addition and subtraction of the feedhorn outputs to obtain the monopulse sum and difference signals. It is illustrated with hybrid-T or magic-T waveguide devices. These are four-port devices which, in basic form, have the inputs and outputs located at right angles to each other. However, the magic T's have been developed in convenient "folded" configurations for very compact comparator packages. The performance of these and other similar four-port devices is described in Ref. 3, Chap. 4.

The subtractor outputs are called difference signals, which are zero when the target is on axis, increasing in amplitude with increasing displacement of the target from the antenna axis. The difference signals also change 180° in phase from one side of center to the other. The sum of all four horn outputs provides a reference signal to allow angle-tracking sensitivity (volts per degree error) even though the target echo signal varies over a large dynamic range. AGC is necessary to keep the gain of the angle-tracking loops constant for stable automatic angle tracking.

Figure 18.9 is a block diagram of a typical monopulse radar. The sum signal, elevation difference signal, and azimuth difference signal are each converted to intermediate frequency (IF), using a common local oscillator to maintain relative phase at IF. The IF sum-signal output is detected and provides the video input to
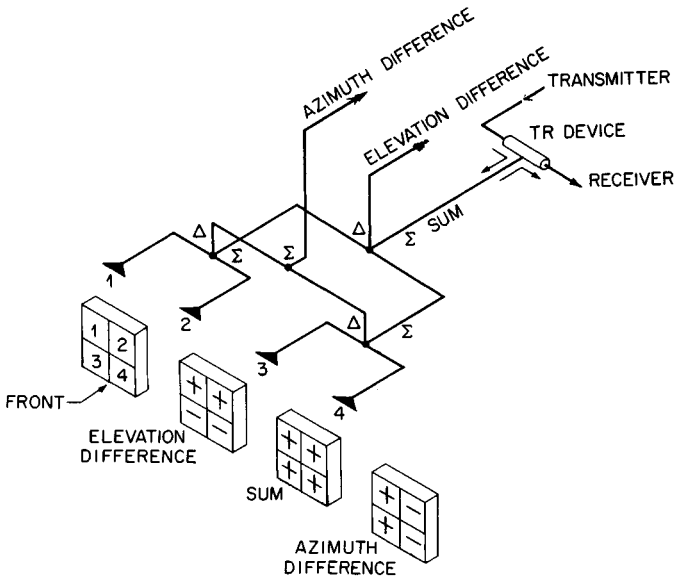
FIG. 18.8 Microwave-comparator circuitry used with a four-horn monopulse feed.
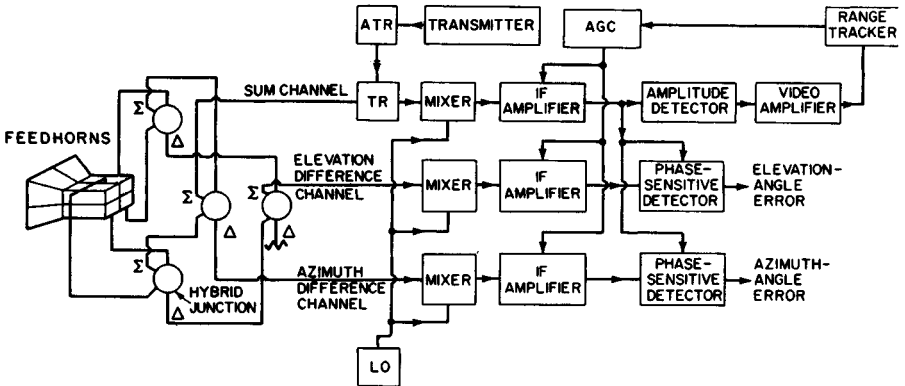

FIG. 18.9 Block diagram of a conventional monopulse tracking radar.

the range tracker. The range tracker determines the time of arrival of the desired target echo and provides gate pulses which turn on portions of the radar receiver only during the brief period when the desired target echo is expected. The gated video is used to generate the dc voltage proportional to the magnitude of the Σ signal or $|\Sigma|$ for the AGC of all three IF amplifier channels. The AGC maintains constant angle-tracking sensitivity (volts per degree error) even though the target echo signal varies over a large dynamic range by controlling gain or dividing by $|\Sigma|$. AGC is necessary to keep the gain of the angle-tracking loops constant for stable automatic angle tracking. Some monopulse systems, such as the two-

channel monopulse, can provide instantaneous AGC or normalizing as described later in this section.

The sum signal at the IF output also provides a reference signal to phase detectors which derive angle-tracking-error voltages from the difference signal. The phase detectors are essentially a dot-product device producing the output voltage

$$e = \frac{|\Sigma|\ |\Delta|}{|\Sigma|\ |\Sigma|} \cos \theta \qquad \text{or} \qquad e = \frac{\Delta}{|\Sigma|} \cos \theta$$

where e = angle-error-detector output voltage
$|\Sigma|$ = magnitude of sum signal
$|\Delta|$ = magnitude of difference signal
θ = phase angle between sum and difference signals

The dot-product error detector is only one of a wide variety of monopulse angle error detectors described in Ref. 3, Chap. 7.

Normally, θ is either 0° or 180° when the radar is properly adjusted, and the only purpose of the phase-sensitive characteristic of the detector is to provide a plus or minus polarity corresponding to $\theta = 0°$ and $\theta = 180°$, respectively, giving direction sense to the angle-error-detector output.

In a pulsed tracking radar the angle-error-detector output is bipolar video; that is, it is a video pulse with an amplitude proportional to the angle error and whose polarity (positive or negative) corresponds to the direction of the error. This video is typically processed by a boxcar circuit which charges a capacitor to the peak video-pulse voltage and holds the charge until the next pulse, at which time the capacitor is discharged and recharged to the new pulse level. With moderate low-pass filtering, this gives a dc error voltage output employed by the servo amplifiers to correct the antenna position.

The three-channel amplitude-comparison monopulse tracking radar is the most commonly used monopulse system. The three signals may sometimes be combined in other ways to allow use of a two-channel or even a single-channel IF system as described later in this section.

Monopulse-Antenna Feed Techniques. Monopulse-radar feeds may have any of a large variety of configurations. For two-angle tracking such as azimuth and elevation, the feeds may include three or more apertures.[6] Single apertures are also employed by using higher-order waveguide modes to extract angle-error-sensing difference signals. There are many tradeoffs in feed design because optimum sum and difference signals, low sidelobe levels, omnipolarization capability, and simplicity cannot all be fully satisfied simultaneously. The term *simplicity* refers not only to cost saving but also to the use of noncomplex circuitry which is necessary to provide a broadband system with good boresight stability to meet precision-tracking requirements. (Boresight is the electrical axis of the antenna or the angular location of a signal source within the antenna beam at which the angle-error-detector outputs go through zero.)

Some of the typical monopulse feeds are described to show the basic relations involved in optimizing the various performance factors and how the more important factors can be optimized by a feed configuration but at the price of lower performance in other areas. Many new techniques have been added since the original four-horn square feed in order to provide good or excellent performance in all desired feed characteristics in a well-designed monopulse radar.

The original four-horn square monopulse feed is inefficient since the optimum feed size in the plane of angle measurement for the difference signals is approx-
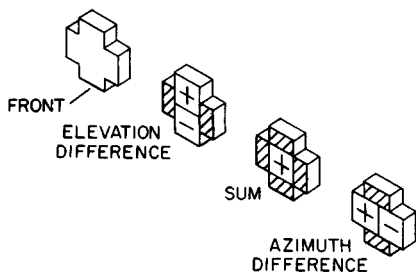
FIG. 18.10 Approximately ideal feed-aperture *E*-field distribution for sum and difference signals.

imately twice the optimum size for the sum signal.[7] Consequently, an intermediate size is typically used with a significant compromise for both sum and difference signals. The optimum four-horn square feed, which is subject to this compromise, is described in Ref. 3 as based on minimizing the angle error caused by receiver thermal noise. However, if sidelobes are a prime consideration, a somewhat different feed size may be desired.

The limitation of the four-horn square feed is that the sum- and difference-signal *E* fields cannot be controlled independently. If independent control could be provided, the *ideal* would be approximately as described in Fig. 18.10 with twice the dimension for the difference signals in the plane of error sensing than that for the sum signal.[7]

A technique used by the MIT Lincoln Laboratory to approach the ideal was the 12-horn feed (Fig. 18.11). The overall feed, as illustrated, is divided into small parts and the microwave circuitry selects the portions necessary for the sum and difference signals to approach the ideal. One disadvantage is that this feed requires a very complex microwave circuit. Also, the divided four-horn portions of the feed are each four element arrays which generate large feed sidelobes in the *H* plane because of the double-peak *E* field. Another consideration is that the 12-horn feed is not practical for focal-point-fed parabolas or reflectarrays because of its size. A focal-point feed is usually small to produce a broad pattern and must be compact to avoid blockage of the antenna aperture. In some cases the small size required is below waveguide cutoff, and dielectric loading becomes necessary to avoid cutoff.

A more practical approach to monopulse-antenna feed design uses higher-order waveguide modes rather than multiple horns for independent control of sum- and difference-signal *E* fields. This allows much greater simplicity and flexibility. A triple-mode two-horn feed used by RCA[7,8] retracts the *E*-plane septa to allow both the TE_{10} and TE_{30} modes to be excited and propagate in the double-width septumless region as illustrated in Fig. 18.12. At the septum the double-humped *E* field is represented by the combined TE_{10} and TE_{30} modes subtracting at the center and adding at the TE_{30}-mode outer peaks. However, since the two modes propagate at different velocities, a point is reached farther down the double-width guide where the two modes add in the center and subtract at the outer humps of the TE_{30} mode. The result is a sum-signal *E* field concentrated toward the center of the feed aperture.

This shaping of the sum-signal *E* field is accomplished independently of the difference-signal *E* field. The difference signal is two TE_{10}-mode signals arriving at the septum of Fig. 18.12 out of phase. At the septum it becomes the TE_{20} mode, which propagates to the horn aperture and uses the full width of the horn as desired. The TE_{20} mode has zero *E* field in the center of the waveguide where the septum is located and is unaffected by the septum.

The AN/FPS-16 radar feed used two retracted septum horns illustrated in Fig. 18.13. The TE_{20}-mode signals are added for the *H*-plane difference signal, the combined TE_{10} and TE_{30} modes are added for the sum signal, and they are subtracted for the E-plane difference signal. Since this is a focal-point feed, it is small in size (wavelengths) and RF currents tend to flow around the top and bottom
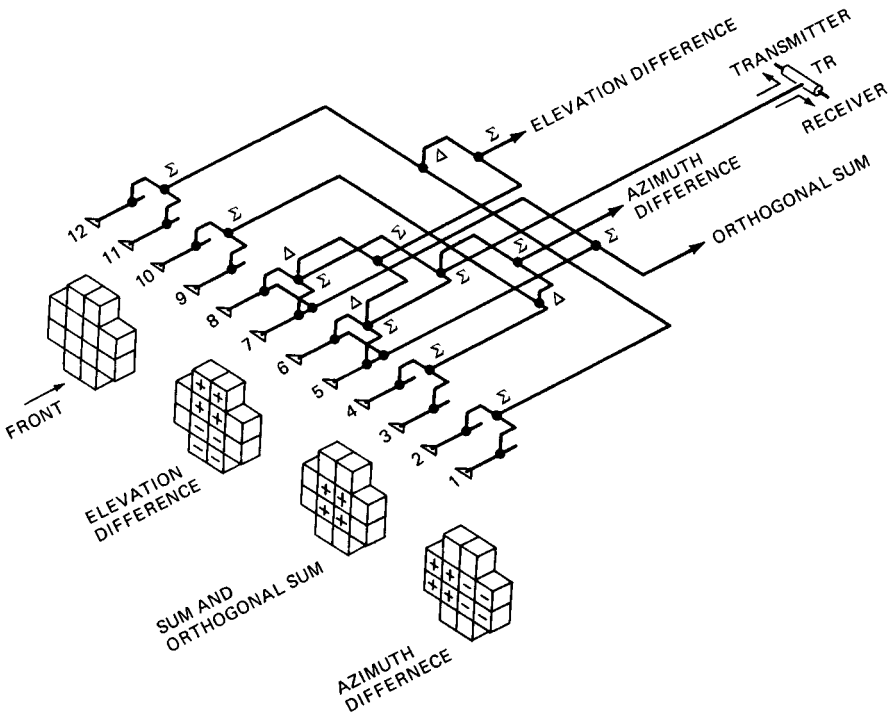
FIG. 18.11 Twelve-horn feed.

edges at the E-field peaks in the middle of the horns. This results in the need for the top and bottom matching stubs seen in Fig. 18.13.

A further step in feed development is the four-horn triple-mode feed illustrated in Fig. 18.14.[7] This feed uses the same approach as described above but with the addition of a top and bottom horn. This allows the E-plane difference signal to couple to all four horns and uses the full height of the feed. The sum signal uses only the center two horns to limit its E field in the E plane as desired for the ideal field shaping. The use of smaller top and bottom horns is a simpler method of concentrating the E field toward the center of the feed, where the full horn width is not needed.

The feeds described thus far are for linear-polarization operation. When circular polarization is needed in a paraboloid-type antenna, square or circular cross-section horn throats are used. The vertical and horizontal components from each horn are separated and comparators provided for each polarization. The sum and difference signals from the comparators are combined with 90° relative phase to obtain circular polarization. Use of the previously described feeds for circular polarization would require the waveguide circuitry to be prohibitively complex. Consequently, a five-horn feed is used as illustrated in Fig. 18.15.

The five-horn feed is selected because of the simplicity of the comparator which requires only two magic (or hybrid) T's for each polarization. The sum and difference signals are provided for the two linear-polarization components and, in an AN/FPQ-6 radar, are combined in a waveguide switch for selecting
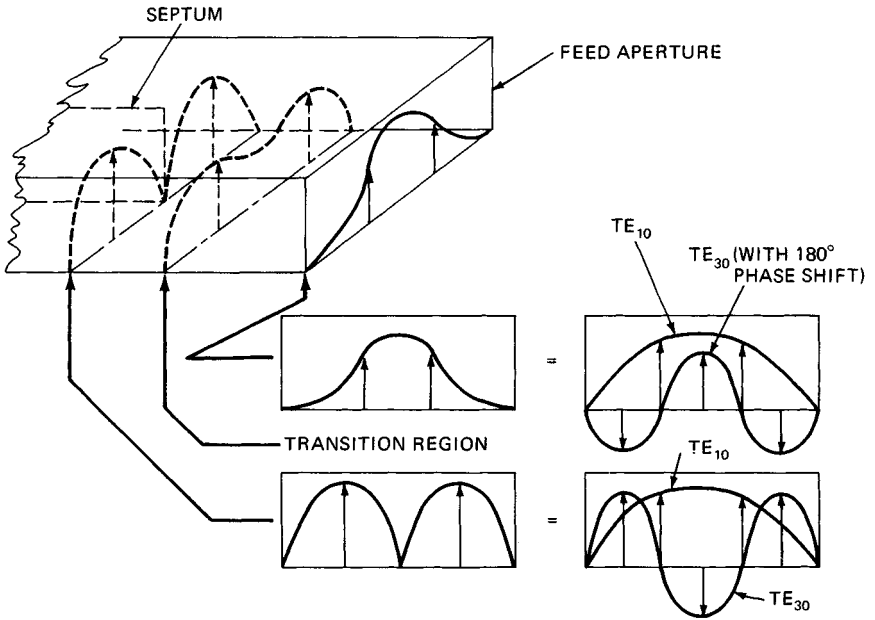
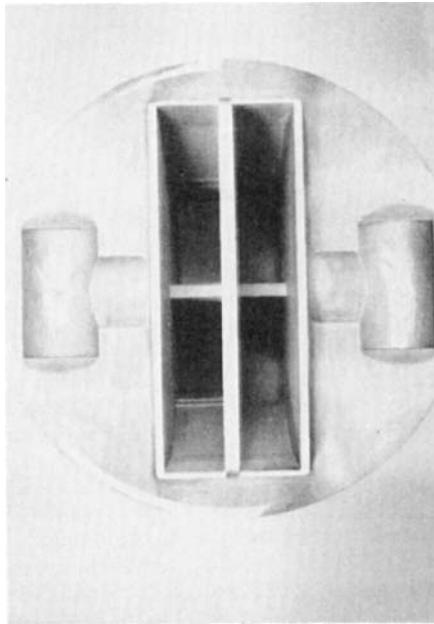**FIG. 18.12** Use of retracted septum to shape the sum-signal E field.

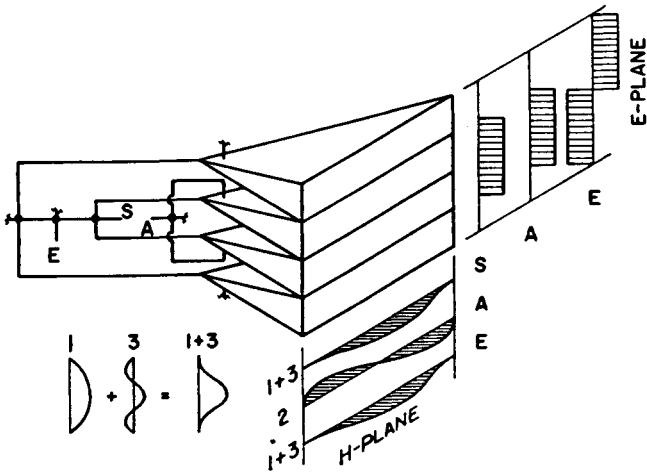**FIG. 18.13** AN/FPS-16 feed, front view. (*From S. M. Sherman, Ref. 3.*)

FIG. 18.14 Four-horn triple-mode feed. (*From P. W. Hannan, Ref. 7; copyright 1961, IEEE.*)
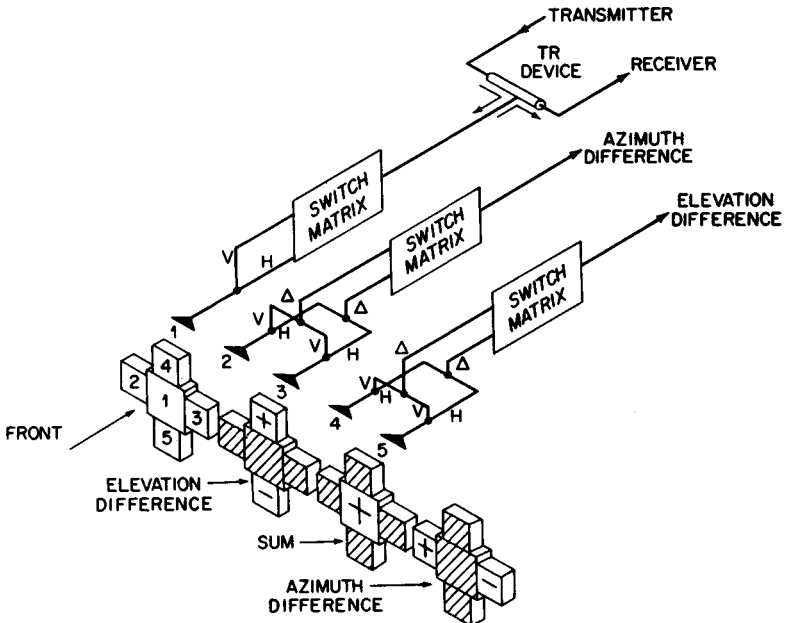

FIG. 18.15 Five-horn feed with coupling to both linear-polarization components, which are combined by the switch matrix to select horizontal, vertical, or circular polarization.

polarization. The switch selects either the vertical or the horizontal input component or combines them with a 90° relative phase for circular polarization. This feed does not provide optimum sum- and difference-signal E fields because the sum horn occupies space desired for the difference signals. Generally an undersized sum-signal horn is used as a compromise. However, the five-horn feed is a

practical choice between complexity and efficiency. It has been used in several instrumentation radars including the AN/FPQ-6, AN/FPQ-10, AN/TPQ-18, and AN/MPS-36[9,10] and in the AN/TPQ-27 tactical precision-tracking radar.[11]

The multimode feed techniques can be expanded to other higher-order modes for error sensing and E-field shaping.[12,13,14] The difference signals are contained in unsymmetrical modes such as the TE_{20} mode for H-plane error sensing and combined TE_{11} and TM_{11} modes for E-plane error sensing. These modes provide the difference signals, and no comparators, as shown in Fig. 18.8, are used.[12] Generally, mode-coupling devices can give good performance in separating the symmetrical and unsymmetrical modes without significant cross-coupling problems.

Multiband monopulse feed configurations are practical and in use in several systems. A simple example is a combined X-band and K_a-band monopulse paraboloid antenna radar. Separate conventional feeds are used for each band, with the K_a-band feed as a Cassegrain feed and the X-band feed at the focal point.[15] The Cassegrain subdish is a hyperbolic-shaped grid of wires reflective to parallel polarization and transparent to orthogonal polarization. It is oriented to be transparent to the X-band focal-point feed behind it and reflective to the orthogonally polarized K_a-band feed extending from the vertex of the paraboloid.

Monopulse feed horns at different microwave frequencies can also be combined with horns interlaced. The multiband feed clusters will sacrifice efficiency but can satisfy multiband requirements in a single antenna.

AGC (Automatic Gain Control). To maintain a stable closed-loop servosystem for angle tracking, the radar must maintain essentially constant loop gain independent of target size and range. The problem is that monopulse difference signals from the antenna are proportional to both the angle displacement of the target from the antenna axis and the echo signal amplitude. For a given tracking error, the error voltage would change with echo amplitude and cause a corresponding change in loop gain.

AGC is used to remove the angle-error-detector-output dependence on echo amplitude and retain constant tracking loop gain. A typical AGC technique is illustrated in Fig. 18.16 for a one-angle coordinate tracking system. The AGC system detects the peak voltage of the sum signal and provides a negative dc voltage proportional to the peak signal voltage. The negative voltage is fed to the IF amplifier stages, where it is used to decrease gain as the signal increases. A high gain in the AGC loop is equivalent to dividing the IF output by a factor proportional to its amplitude.
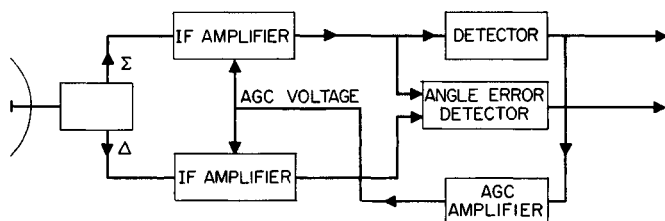

FIG. 18.16   AGC in monopulse tracking.

In a three-channel monopulse radar, all three channels are controlled by the AGC voltage, which effectively performs a division by the magnitude of the sum

signal or echo amplitude. Conventional AGC with a control voltage is band-limited by filters, and the gain is essentially constant during the pulse repetition interval. Also, the AGC of the sum channel normalizes the sum echo pulse amplitude to similarly maintain a stable range-tracking servo loop.

The angle-error detector, assumed to be a product detector, has an output

$$|e| = k \, \frac{\Delta \, \Sigma}{|\Sigma||\Sigma|} \cos \theta$$

where $|e|$ is the magnitude of the angle error voltage. Phases are adjusted to provide 0 or 180° on a point-source target. The resultant is

$$|e| = \pm \, k \, \frac{\Delta}{|\Sigma|}$$

Complex targets can cause other phase relations as a part of the angle scintillation phenomenon.[3] The above error voltage proportional to the ratio of the difference signal divided by the sum signal is the desired angle-error-detector output, giving a constant angle error sensitivity.[3]

With limited AGC bandwidth, some rapid signal fluctuations modulate $|e|$, but the long-time-average angle sensitivity is constant. These fluctuations are largely from rapid changes in target reflectivity, $\sigma(t)$, that is, from target amplitude scintillation. The random modulation of $|e|$ causes an additional angle noise component that affects the choice of AGC bandwidth.

At very low signal-to-noise ratios ($SNR < 4$ dB) the AGC voltage is limited to a minimum value by the noise level. Therefore, as the signal decreases into the noise, the IF gain remains constant and the resultant angle sensitivity decreases. Consequently, the effect of thermal noise on tracking performance differs from the linear relations, which are accurate to within about 1 dB for an SNR of 4 dB or greater. Reference 2 discusses means for calculating thermal-noise effects for very low SNR conditions.

The AGC performance in conical-scan radars provides a similar constant angle error sensitivity. One major limitation in conical-scan radars is that the AGC bandwidth must be sufficiently lower than the scan frequency to prevent the AGC from removing the modulation containing the angle error information. The very low SNR effects on conical scan differ from the effects on monopulse, as discussed in detail in Ref. 2.

Phase-Comparison Monopulse.   A second monopulse technique is the use of multiple antennas with overlapping (nonsquinted) beams pointed at the target. Interpolating target angles within the beam is accomplished, as shown in Fig. 18.17, by comparing the phase of the signals from the antennas (for simplicity a single-coordinate tracker is described). If the target were on the antenna boresight axis, the outputs of each individual aperture would be in phase. As the target moves off axis in either direction, there is a change in relative phase. The amplitudes of the signals in each aperture are the same so that the output of the angle error phase detector is determined by the relative phase only. The phase-detector circuit is adjusted with a 90° phase shift in one channel to give zero output when the target is on axis and an output increasing with increasing angular displacement of the target with a polarity corresponding to the direction of error.[3,4]

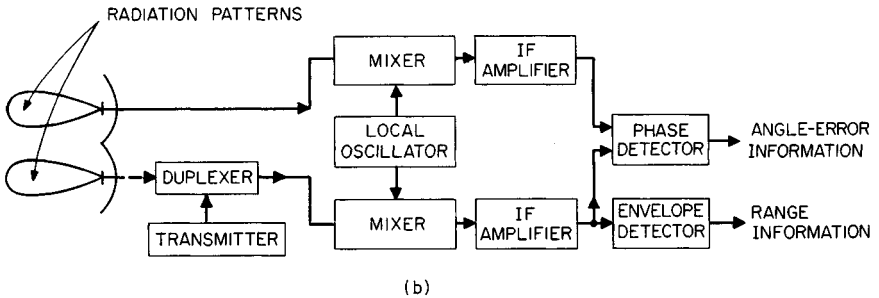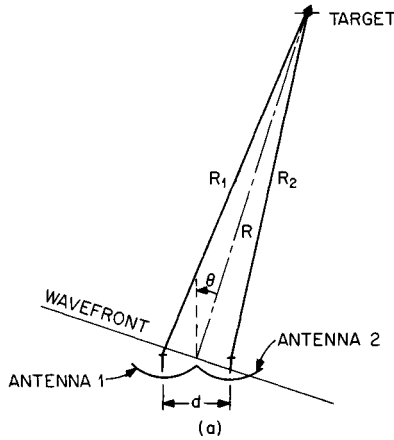Typical flat-face corporate-fed phased arrays compare the output of halves of

FIG. 18.17 (*a*) Wavefront phase relationships in a phase comparison monopulse radar. (*b*) Block diagram of a phase comparison monopulse radar (one angle coordinate).

the aperture and fall into the class of phase-comparison monopulse. However, the basic performance of amplitude- and phase-comparison monopulse is essentially the same.[3]

Figure 18.17 shows the antenna and receiver for one angular-coordinate tracking by phase-comparison monopulse. Any phase shifts occurring in the mixer and IF amplifier stages cause a shift in the boresight of the system. The disadvantages of phase-comparison monopulse compared with amplitude-comparison monopulse are the relative difficulty in maintaining a highly stable boresight and the difficulty in providing the desired antenna illumination taper for both sum and difference signals. The longer paths from the antenna outputs to the comparator circuitry make the phase-comparison system more susceptible to boresight change due to mechanical loading or sag, differential heating, etc.

A technique giving greater boresight stability combines the two antenna outputs at RF with passive circuitry to yield sum and difference signals, as shown in Fig. 18.18. These signals may then be processed as in a conventional amplitude-comparison monopulse receiver. The system shown in Fig. 18.18 would provide a relatively good difference-channel taper, having smoothly tapered *E* fields on each antenna. However, a sum-signal excitation with the two antennas provides a two-hump in-phase *E*-field distribution which causes high sidelobes since it looks like a two-element array. This problem may be reduced by allowing some

aperture overlap but at the price of loss of angle sensitivity and antenna gain.

Monopulse Tracking with Phased Arrays. In general, phased-array tracking radars fall in either the amplitude- or the phase-comparison class, depending on the feed technique. Feedthrough lens arrays acting as an RF lens and reflectarrays acting like a parabolic reflector may use any of the described multihorn or multimode feeds, and the same general factors in optimizing a feed apply. Monopulse angle-error sensing can be accomplished in a corporate-feed array by using the two halves of the array (the top and bottom halves can also be used for elevation) as a phase-comparison tracker. Array antennas which use the two halves of the aperture for phase-comparison angle error sensing generally provide a good taper for the sum pattern, but the difference-signal E field across the array reaches a peak toward the center with a sudden 180° phase change. This sharp discontinuity at a maximum amplitude point causes undesired high sidelobes. Techniques such as use of separate feeds can provide the desired shaping of the difference-signal E-field distribution.

FIG. 18.18 (*a*) RF phase-comparison monopulse system with sum and difference outputs. (*b*) Vector diagram of the sum and difference signals.

The monopulse electronic-scan phased array is used in instrumentation radar to meet requirements for simultaneously tracking multiple targets.[16-18] An example is the Multiobject Tracking Radar (MOTR), AN/TPQ-39, built for the White Sands Missile Range for high-precision tracking. The MOTR provides a 60° cone of electronic pulse-to-pulse beam coverage plus mechanical pedestal movement to cover the hemisphere. High accuracy and efficiency can be maintained over the ± 30° electronic-scan coverage, and this coverage moves mechanically as needed to optimally move the electronic-scan coverage along with the target configuration to be tracked.[14,19]

One- and Two-Channel Monopulse. Monopulse radars may be constructed with fewer than the conventional three IF channels. This is accomplished by combining the sum and difference signals by some means so that they may be individually retrieved at the output. These techniques provide some advantages in AGC or other processing techniques but at the cost of *SNR* loss or of cross coupling between azimuth and elevation information.

A single-channel monopulse system called SCAMP (single-channel monopulse processor)[20] provides the desired constant angle error sensitivity by normalizing the difference signals with the sum signal in a single IF channel, as shown in Fig. 18.19. The signals are each converted from RF to different IF frequencies by separate local oscillators (LOs) of different frequencies for each signal. They are amplified in a single IF amplifier of sufficient bandwidth for all three signals at different frequencies. At the IF output the signals are hard-limited and separated by three narrowband filters. The signals are then converted to the same frequency
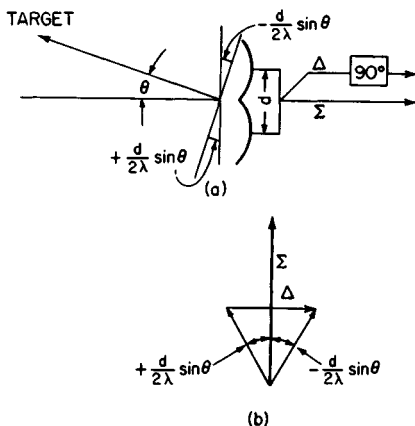
by beating two of the signals with the frequency difference between their LOs and the LO of the third signal. The angle-error voltage is then determined by either a conventional phase detector or simply an amplitude detector.[14] The effect of AGC action and normalizing is performed by hard limiting which causes a weak-signal suppression of the difference signal similar to the effects of hard limiting on a weak signal in noise.[20]
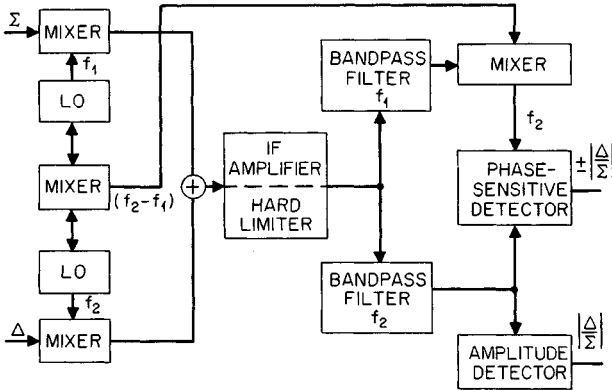

FIG. 18.19 Block diagram of SCAMP, a single-channel monopulse tracking system, demonstrating angle tracking in one angle coordinate. (The system is capable of tracking in both coordinates.) (*From W. L. Rubin and S. K. Kamen, Ref. 20.*)

The single-channel monopulse provides in effect an instantaneous AGC. Performance in the presence of thermal noise is about equal to that of the three-channel monopulse. However, the limiting process generates a significant cross-coupling problem,[21] causing a portion of the azimuth-error signal to appear in the elevation-angle-error-detector output and elevation error to appear in the azimuth-angle-error-detector output. Depending on the receiver configuration and the choice of IF frequencies, the cross modulation could cause serious errors and allow vulnerability to jamming. Reference 21 describes how the sum- and difference-channel bands in the wideband IF can be arranged to minimize cross coupling and suggests use of narrow banding to separate each signal before limiting in order to reduce jamming effects.

A two-channel monopulse receiver[22] may also be used by combining the sum and difference signals at RF, as shown in Fig. 18.20. The microwave resolver is a mechanically rotated RF coupling loop in circular waveguide. The azimuth and elevation difference signals are excited in this guide with E-field polarization oriented at 90°. The energy into the coupler contains both difference signals coupled as the cosine and sine of the angular position of the coupler, $\omega_s t$, where ω_s is the angular rate of rotation. The hybrid adds the combined difference signals Δ to the sum signal Σ. The $\Sigma + \Delta$ and $\Sigma - \Delta$ outputs each look like the output of a conical-scan tracker except that the modulation function differs by 180°. In case of failure of one channel, the radar can be operated as a scan-on-receive-only conical-scan radar with essentially the same performance as a conical-scan radar. The advantage of two channels with opposite-sense angle-error information on one with respect to the other is that signal fluctuations in the received signal are
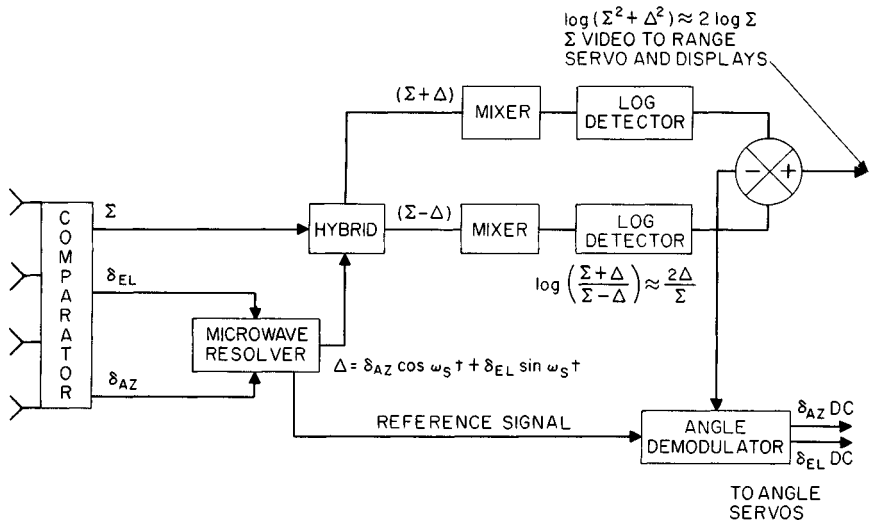
FIG. 18.20 Block diagram of a two-channel monopulse radar system. (*From R. S. Noblit, Ref. 22.*)

canceled in the postdetection subtractor at the IF output which retrieves the angle-error information. The log IF performs essentially as instantaneous AGC, giving the desired constant angle-error sensitivity of the difference signal normalized by the sum signal. The detected Δ information is a bipolar video where the error information is contained in the sinusoidal envelope. This signal is separated into its two components, azimuth- and elevation-error information, by an angle demodulation. The demodulator, using a reference from the drive on the rotating coupler, extracts the sine and cosine components from Δ to give the azimuth- and elevation-error signals. The two-channel monopulse technique is used in the AN/SPG-55 tracking radar and the AN/FPQ-10 missile-range instrumentation radar. The modulation caused by the microwave resolver is of concern in instrumentation radar applications because it adds spectral components in the signal which complicate the possible addition of pulse doppler tracking capability to the radar.

This system provides instantaneous AGC operation with only two IF channels and operation with reduced performance in case of failure of either channel. However, there is a loss of 3 dB *SNR* at the receiver inputs although this loss is partly regained by coherent addition of the Σ-signal information. The design of the microwave resolver must minimize loss through the device, and high precision is required to minimize cross coupling between azimuth and elevation channels. The resolver performance is improved by the use of ferrite switching devices to replace the mechanical rotating coupler.

Conopulse. Conopulse (also called scan with compensation) is a radar tracking technique that is a combination of monopulse and conical scan.[23,24] A pair of antenna beams is squinted in opposite directions from the antenna axis and rotated like a conical-scan-radar beam scan. Since they exist simultaneously, monopulse information can be obtained from the pair of beams. The plane in which monopulse information is measured rotates. Consequently,

elevation and azimuth information is sequential and must be separated for use in each tracking coordinate. Conopulse provides the monopulse advantage of avoiding errors caused by amplitude scintillation, and it requires only two receivers. However, it has the disadvantage over conventional monopulse radar of lower angle data rate and the mechanical complexity of providing and coupling to a pair of rotating antenna feedhorns.

18.4 SERVOSYSTEMS FOR TRACKING RADAR

The servosystem of a tracking radar is the portion of the radar that receives as its input the tracking-error voltage and performs the task of moving the antenna beam in a direction that will reduce to zero the alignment error between the antenna axis and the target. For two-angle tracking with a mechanical-type antenna there are typically separate axes of rotation for azimuth and elevation and separate servosystems to move the antenna about each axis. A conventional servosystem is composed of amplifiers, filters, and a motor that moves the antenna in a direction to maintain the antenna axis on the target. Range tracking is accomplished by a similar function to maintain range gates centered on the received-echo pulses. This may be accomplished by analog techniques or by digital-counter registers that retain numbers corresponding to target range to provide a closed tracking loop digitally rather than mechanically.

Servosystems may contain hydraulic-drive motors, conventional electric motors geared down to drive the antenna, or direct-drive electric motors where the antenna mechanical axis shaft is part of the armature and the motor field is built into the supporting case. The direct drive is heavier for a given horsepower but eliminates gear backlash. The conventional motors may be provided in a duplicate drive with a small residual opposing torque to reduce backlash. Amplifier gain and filter characteristics as well as motor torque and inertia determine the velocity and acceleration capability or the ability to follow higher-order motions of the target.

It is desired that the antenna beam follow the center of the target as closely as possible, which implies that the servosystem should be capable of moving the antenna quickly. The combined velocity and acceleration characteristics of a servosystem can be described by the frequency response of the tracking loop, which is essentially a low-pass filter characteristic. Increasing the bandwidth increases the quickness of the servosystem and its ability to follow closely a strong, steady signal. However, a typical target causes scintillation of the echo signal, giving erroneous error-detector outputs, and at long range the echo is weak, allowing receiver noise to cause additional random fluctuations in the error-detector output. Consequently, a wide servo bandwidth which reduces lag errors allows the noise to cause erroneous motions of the tracking system. Therefore, for best overall performance it is necessary to limit the servo bandwidth to the minimum necessary to maintain a reasonably small tracking-lag error. There is an optimum bandwidth that minimizes the rms of the total erroneous outputs including both tracking lag and random noise, depending upon the target, its trajectory, and other radar parameters.

The optimum bandwidth for angle tracking is range-dependent. A target with typical velocity at long range has low angle rates and a low SNR, and a narrower servo passband will follow the target with reasonably small tracking lag while minimizing the response to receiver thermal noise. At close range the signal is

strong, overriding receiver noise, but target angle scintillation errors proportional to the angular span of the target are large. A wider servo bandwidth is needed at close range to keep tracking lag within reasonable values, but it must not be wider than necessary or target scintillation errors become excessive.

The low-pass closed-loop characteristic of a servosystem is unity at zero frequency, typically remaining near this value up to a frequency near the low-pass cutoff, where it may peak up to higher gain, as shown in Fig. 18.21. The peaking is an indication of system instability but is allowed to be as high as tolerable, typically up to about 3 dB above unity gain to obtain maximum bandwidth for a given servomotor drive system. System A of Fig. 18.21 is a case of excessive peaking of about 8 dB. The effect of the peaking is observed by applying a step error input to the servosystem. The peaking of the low-pass characteristic results in an overshoot when the antenna axis moves to align with the target. High peaking causes a large overshoot and a return toward the target with an additional overshoot. In the extreme, as in system A of Fig. 18.21, the antenna zeros in on the target with a damped oscillation. An optimum system compromise between speed of response and overshoot, as in system B, allows the antenna to make a small overshoot with a reasonably rapid exponential movement back to the target. This corresponds to about 1.4-dB peaking of the closed-loop low-pass characteristic.
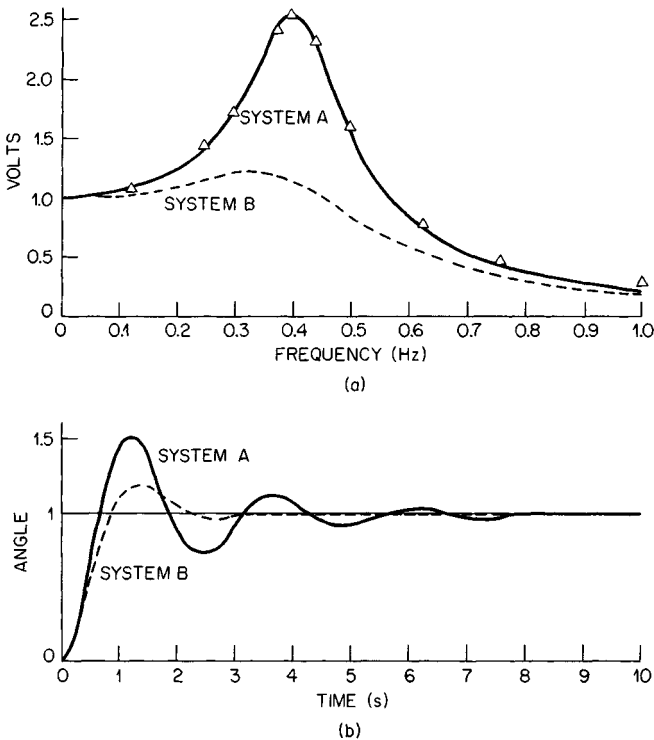

FIG. 18.21 (a) Closed-loop frequency-response characteristics of two servosystems. (b) Their corresponding time response to a step input.

To maximize the servo closed-loop bandwidth for a given motor drive system, tachometer feedback must be used. The tachometer provides a negative feedback voltage proportional to the servomotor speed. As the servomotor rotates the antenna toward a target, the error voltage decreases, dropping to zero when the antenna axis arrives at the target. However, the tachometer feedback provides a retarding motor torque opposing the system inertia that causes the overshoot, thus reducing the overshoot.

Resonances of the antenna and servosystem structure (the structure foundation is one of the most critical items) must be kept well above the bandwidth of the servosystem; otherwise the system can oscillate at the resonant frequency. A factor of at least 10 is desirable for the ratio of system resonant frequency to servo bandwidth. The high resonant frequency is difficult to obtain with a large antenna, such as the AN/FPQ-6 radar with a 29-ft dish, because of the large mass of the system. The ratio was pushed to a very minimum of about 3 to obtain a servo bandwidth of about 3.5 Hz. A smaller radar with a 12-ft dish, for example, can provide a servo bandwidth up to 7 or 8 Hz with conventional design.

A convenient method for calculating tracking error for a given target trajectory and servosystem is the use of the equation[25]

$$e(t) = \frac{\dot{\theta}(t)}{K_v} + \frac{\ddot{\theta}(t)}{K_a} - \frac{\dddot{\theta}(t)}{K_j} - \cdots$$

where $e(t)$ = tracking error as function of time
$\dot{\theta}(t)$ = angular velocity of target relative to radar versus time
$\ddot{\theta}(t)$ = angular acceleration
$\dddot{\theta}(t)$ = next higher order of angular motion (descriptively called *jerk*)
K_v = velocity constant of servosystem
K_a = acceleration constant
K_j = jerk constant of servosystem

A servosystem could be specified by selecting values for the three constants and, with a known target trajectory $\theta(t)$, the lag error calculated by using the
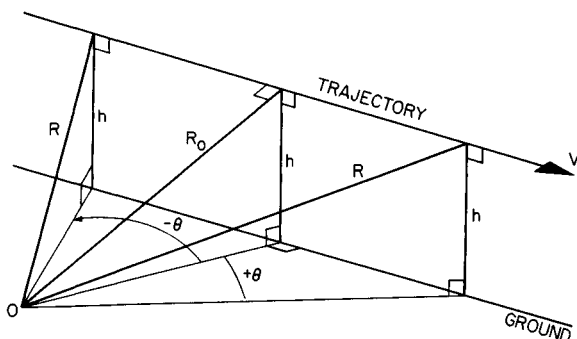

FIG. 18.22 Target trajectory on a passing course. (*From A. S. Locke, Ref. 25.*)

above equation. An example trajectory is shown in Fig. 18.22 for an aircraft flying a straight course past the radar with a minimum distance R_0 at altitude h. The figure shows that minimum range and maximum elevation angle occur when the radar is looking normal to the target path. The azimuth angle θ, with minimum range as the $0°$ azimuth reference point, starts at about $-90°$ and ends at about $+90°$, with its maximum rate of change $\theta(t)$ at minimum range. For target parameters of a velocity of 500 kn, crossover range of 1000 yd, and altitude of 1500 ft, the derivatives of azimuth angle are $\dot{\theta}_{max} = 18.6°/s$, $\ddot{\theta}_{max} = 4°/s^2$, and $\dddot{\theta}_{max} = 4.2°/s^3$. Choosing example servosystem constants $K_v = 100$, $K_a = 111$, and $K_j = 1111$ results in a tracking-lag function

$$e(t) = \frac{\dot{\theta}(t)}{100} + \frac{\ddot{\theta}(t)}{111} - \frac{\dddot{\theta}(t)}{1111} \cdots$$

By substituting values for the derivatives, a time plot of tracking lag may be determined as shown in Fig. 18.23.
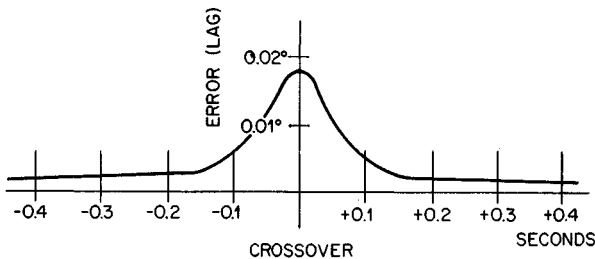

FIG. 18.23 Azimuth-tracking error for the passing-course target. *(From A. S. Locke, Ref. 25.)*

The range and elevation lag errors may be similarly determined by calculation of derivatives of $R(t)$ and $\phi(t)$, respectively, and use of the constants for these tracking systems. Elevation constants are similar to those for the azimuth system. The range tracker may be an inertialess electronic system with a double integration in the tracking loop. This is called a Type II system[25] with a $K_v = \infty$, causing velocity lag to be zero. The remaining significant lag components are the acceleration and jerk lags.

Electronically steerable arrays provide a means for inertialess angle tracking. However, because of this capability the system can track multiple targets by rapidly switching from one to another rather than continuously tracking a single target. The tracker simply places its beam at the location where the target is expected, corrects for the pointing error by converting error voltages (with a known angle error sensitivity) to units of angle, and moves to the next target. The system determines where the target was and, from calculations of target velocity and acceleration, predicts where it should be the next time the beam looks at the target. The lag error in this case is dependent on many factors, including the accuracy of the value of angle sensitivity used to convert error voltages to angular error, the size of the previous tracking error, and the time interval between looks.