A MICROWAVE TELEMETRY AUTOMATIC TRACKING ANTENNA

EDUARDO BEJARANO
Electronic Engineer
White Sands Missile Range
New Mexico

Introduction An S-band (2200-2300 Mc) automatic tracking telemetry conical scanner antenna was developed using the tracking mount and servo system of a T-9 radar tracker. The T-9 radar tracker is part of Fire Control System T-38, "Skysweeper," 75mm anti-aircraft gun.

The development objectives were:

1. To develop a light and highly mobile system.
2. To develop a conical scanner and feed assembly which would adapt easily to the existing tracking mount.
3. To obtain high angular tracking rates.
4. To develop a system for the purpose of conducting microwave telemetry propagation studies during the interim period 1964 through 1970. The VHF telemetry band (215-265 Mc) is to be vacated by 1970.

The modification of the T-9 servo and the mechanical adaptation of the conical scanner antenna to the tracking mount were performed in-house. Temec, Inc of San Diego, California, a subsidiary of the Cubic Corporation, designed and constructed the conical scanner.

Theory of Operation In the broad classification of electronic tracking systems, the T-9 tracker may be classified as a passive system employing conical scanning for target acquisition. It is a passive system in that it uses the received RF telemetry signal to derive angular position error signals which the servo system uses to drive the tracker mount so as to keep the antenna pointed toward the source of the telemetry signal. The operating frequency band is from 2200-2300 Mc.

The conical scan antenna pattern provides the basis for the derivation of angular position errors. Figure 1 shows a typical conical scan antenna pattern.

The angle between the reflector axis and the beam axis is called the squint angle. Consider a source of telemetry signals located on the target axis (Figure 1). The received signal will be amplitude modulated at a frequency equal to the rotation frequency of the antenna beam. The amplitude of the received signal modulation depends on:

1. The shape of the beam pattern.
2. The squint angle.
3. The angle between the target line of sight and the reflector axis.

The phase of the modulation depends on the direction of the angle between the target and the reflector axis. The conical scan modulation is extracted from the received telemetry signal and applied to the T-9 servo control system which continually positions the antenna on the target. Two separate servo channels are required because the tracking problem is two dimensional. When the antenna is on target (Figure 1, when the target axis coincides with the reflector axis), the conical scan modulation is zero, thus no tracking error is produced.

The T-9 antenna is a parabolic reflector with an offset feed which is rotated about the axis of the reflector. The feed is mechanically rotated by a synchronous motor at 1800 RPM. The same motor that provides the conical scan rotation of the antenna beam also drives a two-phase generator with two outputs 90° apart in phase. These two outputs serve as a reference to extract the elevation and azimuth errors.

The 2200-2300 Mc UHF spectrum is amplified by a low noise preamplifier and is down-converted to the VHF telemetry band 215-260 Mc. The specific UHF signal is converted to a desired VHF frequency by tuning a variable local oscillator in the down-converter, and by tuning the standard VHF telemetry receiver which follows the down-converter to the chosen VHF frequency. The telemetry data is obtained from either the VHF receiver output video or predetected output. The conical scan modulation on the telemetry signal remains unchanged throughout the down conversion process. The 30 Mc first IF output of the VHF telemetry receiver is fed to an external high gain 30 Mc IF amplifier, or tracking receiver, where the conical modulation is extracted. The conical scan modulation is passed through a low pass filter to remove the telemetry data and harmonics of the conical scan frequency.

The conical scan modulation is then fed to the T-9 servo system input, where it is compared with the elevation and azimuth reference signals in the angle-error detectors which are phase-sensitive detectors. The output of the phase-sensitive detectors is a DC voltage which reverses polarity as the phase of the input signal changes through 180°. The magnitude of the DC output from the angle-error detector is proportional to the error magnitude, and the sign (polarity) is an indication of the direction of the error. The angle-error detector outputs are amplified and drive the antenna elevation and azimuth servo motors. When the antenna is directly on target, the error signal is zero.

Basic Considerations There are several basic considerations upon which the design of a telemetry automatic tracker are based. These considerations are associated with the functions that the tracker per forms:

- It maintains the highly-directive beam aligned with the vehicle carrying the telemetry transmitter.
- It provides a high antenna gain for telemetry communication with the vehicle.

An additional function is that it may provide vehicle direction readout. Basic considerations in the design of a conical scanner telemetry antenna may include the following:

1. Crossover loss: Because one of the functions of the telemetry tracker is communication with a vehicle, it must provide the highest antenna gain possible at boresight. The crossover level of a conical scanner is a direct relation to the degree of feed offset. The telemetry conical scanner antenna is necessarily a compromise between the required tracking performance and the telemetry system sensitivity. Basically, the greater the offset, the higher the servo loop tracking gain will be, since the amplitude modulation introduced as a function of the angle off boresight is higher for greater feed offsets. The relation between the modulation factor m and the point error ϵ (for small values of ϵ) may be expressed mathematically as:

$$m = \frac{g'(\phi_o)}{g(\phi_o)} \cdot \epsilon \tag{1}$$

where: $g(\phi)$ is the antenna voltage gain function.

ϕ is the angle measured from the direction of maximum gain.

ϕ_o is the crossover angle or half the apex angle of the cone described by the line of maximum gain as a result of conical scan.

$g(\phi_o)$ is thus the antenna voltage gain evaluated at zero angle or boresight.

$G'(\phi_o)$ is the derivative of the gain pattern on boresight.

Pelchat[1] has approximated the main lobe pattern of a conical scan antenna to a second-order Lambda function of argument $4\phi/BW$[*]

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[*] An antenna voltage pattern that approximates this function is obtained by assuming a circular aperture with parabolic aperture distribution. Variations of the antenna pattern are obtained by different aperture distributions. For a general discussion on antenna aperture distributions, see Reference Note 4.

where: ϕ remains as defined above, and
BW is the 3 db antenna beamwidth

The pattern function (g ϕ_o) and its derivative (g'ϕ_o) is plotted in Figure 2. This figure illustrates the necessity for a telemetry conical scanner to be a compromise between sensitivity and tracking performance. For convenience, the crossover angle is plotted as a fraction of the antenna beamwidth. The figure illustrates that with increasing ϕ_o /BW ratio, the antenna voltage pattern drops off smoothly. In other words, as the crossover null-depth increases, the antenna boresight gain decreases. Inversely, as the crossover depth increases, the derivative of the antenna voltage pattern evaluated at zero, g' (ϕ_o), increases rapidly until it levels off at a value of ϕ_o /BW = 0.675. A good compromise for a telemetry conical scqnner antenna might be chosen at the intersection of the two curves at (ϕ_o / BW = 0.375.

2. Error Modulation: Although the maximum modulation is set once the ratio ϕ_o /BW is defined, it is necessary to ascertain that a conical scanner antenna does not modulate the incoming signal so much that it degrades the telemetry data. Figure 3 is a plot of equation (1). The pointing error, ϵ , is used as a fraction of the beamwidth. Also plotted on the curve is a plot of the crossover loss in db versus the ϕ_o /BW ratio. This curve is obtained from the g(ϕ_o) curve in Figure 2, and provides easy entry into the chart when the crossover loss is known. A telemetry antenna with ϕ_o /BW = 0.375 and crossover loss of 1.5 db yields 50 per cent modulation when the pointing error is as large as ha of the beamwidth.

3. Physical Size: A second compromise in the development of a telemetry tracker is that of antenna size. The dish size is governed mainly by the following functions: required system gain; the necessary focus-to-diameter ratio required for proper feed offset design and reflector illumination characteristics; and the desired pedestal velocity and acceleration capabilities.

The required antenna gain for the T-9 tracker was calculated from the following assumptions:

a.	Radiated signal power level:	2 watts (+33 dbm)
b.	Free space range:	100 miles (-144 db)
c.	Transmitting source:	isotropic
d.	Carrier to noise ratio:	13 db
e.	Receiver bandwidth:	750 Kc
f.	Fade Margin:	10 db
g.	Frequency:	2250 Mc

The signal power level arriving at the antenna under line of sight range condition is:

= (transmitted power level) - (free space loss) - (fade margin)
= +33 - 144 - 10 = -121 dbm

The noise level at the antenna (KTB) where

$K = 1.38 \times 10^{-23}$ watts/cycle/degree K
$T = 290°$ Kelvin
B = Receiver bandwidth in cps is:

$$\text{Noise power } (N_{Pdb}) = \frac{KTB}{10^{-3}} = -115 \text{ dbm}$$

The level to which the antenna must raise the signal and still satisfy the required signal to noise ratio:

NP + S/N = 115 + 13 = -102 dbm

The required antenna gain is therefore:

A = -102 dbm - (-121 dbm) = 19 db

This figure represents the absolute gain of the antenna and will be degraded by such system losses as rotary joint loss, cable loss, preamplifier noise figure, preselector insertion loss, and antenna pattern crossover. Realistic values for these system losses are:

Rotary joint loss:	0.5 db
Cable loss:	0.3 db
Preselector insertion loss:	0.5 db
Antenna crossover loss:	1.5 db
Preamplifier noise figure:	4.5 db
Total Loss:	7.3 db

The required antenna gain should be increased to overcome these losses. The required gain, then, should be in the order of 26.5 db. A six foot parabolic reflector theoretically yields this gain. The T-9 antenna uses a six foot dish with a focus-to-diameter ratio (F/D) of 0.375. This F/D ratio allows considerable feed tilt with respect to bearnwidth without gain degradation. [2, 3]

Particular attention should be given to the side lobe level of a conical scanner since poor side lobe characteristics can result in unstable tracking at low elevation angles and also in ambiguous lock. Dickstein[2] has further references on the design criteria for the T-9 conical scan antenna.

T-9 Tracker Characteristics

1. Conical Scanner Antenna The T-9 conical scanner antenna has the following characteristics:

Antenna gain	28 db
Beamwidth	4.5°
Crossover loss	1 db
Polarization	Right hand circular
Side lobe level	-26 db down
Operating frequency band	2.2 - 2.3 Gc
VSWR	1.4: 1 maximum
Scan rate	1800 RPM
Reference generator	2 phase @ 90°

2. RF System:

Telemetry System Threshold: The system threshold is defined as

$$S_{TM} = P_N \times NF_S \times \frac{S_o}{N_o}$$

where:

P_N = system input noise power (KTB)
NF_S = system noise figure
S_o / N_o = output (predetected S/N ratio)

Since the expression for system threshold includes the system noise figure, NFS, this will be calculated first. $_{NFS}$ includes the overall receiver noise figure (NF_{REC}, Figure 4), the effect of antenna-to-preamplifier cable loss, and the antenna noise temperature.

The tunnel diode preamplifier exhibits a noise figure of 4. 5 db and a gain of 17 db. The mixer has a noise figure of approximately 12 db with a conversion loss of 12 db. The telemetry receiver has a noise figure of 8 db, approximately.

$$NF_{REC} = 2.82 + \frac{15.8-1}{50} + \frac{(6.3-1)(15.8)}{50} = 4.79$$

$$NF_{REC} = 6.82 \text{ db}$$

The effect of the antenna to prearnplifier cable and rotary joint losses (assumed to be 1.3 db) on the receiver noise figure is:

$$NF = 1.35 + \frac{4.79-1}{.742} = 6.47 = 8.1 \text{ db}$$

The cable and rotary joint are considered to be passive, dissipative, elements whose internal temperature is assumed to be at 290° K such that the loss noise factor is equal to the loss itself.

The equivalent noise temperature is:

$$T_{REC} + \text{loss} = (NF -1) (290) = 5.47 (290) = 1587°K$$

The antenna noise Temperature, T_A, is assumed to be about 250°K. The resulting system equivalent noise temperature, T_E, is:

$$T_E = T_A + T_{REC} = 250 + 1587 = 1837°K$$

The system noise figure is:

$$NF_S = \frac{1837}{290} + 1 = 7.33 = 8.66 \text{ db}$$

The system threshold may be calculated knowing that the receiver bandwidth is 500 Kc. A 10 db predetected signal-to-noise ratio is also assumed.

$$S^{TM} = -117 \text{ dbm} + 8.66 + 10$$
$$S_{TM} = -98.3$$

This figure indicates that the system will provide predetected telemetry data which is 10 db above the noise when the input level is -98.3 dbm.

Table I shows the system threshold for various receiver bandwidths. Figure 5 shows the telemetry threshold characteristic tracker in terms of range versus receiver bandwidth. The output predetected signal to noise ratio is assumed to be 10 db and the transmitting source is assumed to be isotropic.

3. T-9 Tracking Sensitivity: The tracking sensitivity of the T-9 tracker is much lower than for telemetry data because the tracking bandwidth is narrower. The post-detected tracking bandwidth is computed to be 10 Kc. If a conservative post-detected tracking signal-to-noise ratio of 10 db (although it is possible to track with a lower S/N ratio) is assumed as the threshold for reliable tracking, then the tracking sensitivity becomes:

ST = (KTB) (S/N) (NF) = -134 + 10 + 8.66 = -115.4 dbm

4. Tracking Rates: The measured angular tracking rates are shown in Table II.

Description of Components

1. RF Components:

a. Antenna: The antenna is a Temec Model 215 2200-2300 Mc conical scanner antenna. It consists of a six foot expanded aluminum parabolic reflector and an offset circular wave guide feed, terminated by a splash plate at the reflector focus. The output signal is coupled through a right hand circular polarizer section, a high speed noncontacting rotary joint, and a wave guide-to-coaxial transition piece to a 50 ohm N type connector. The antenna exhibits a gain of 28 db with side lobes which are 26 db down from the main lobe, and a gain crossover of approximately one db. The scan rate of 1800 RPM is accomplished by driving the feed assembly with a one-half horsepower synchronous motor through a Gilmer drive belt. A two-phase reference generator is mounted on the same motor shaft.

b. Preamplifier: The preamplifier is an International Microwave Corporation Tunnel Diode Amplifier, Model ACR 2250-15. It exhibits a gain of 17 db with a noise figure of 4.5 db. Its center frequency is 2250 Mc with a bandwidth of 100 Mc.

c. Converter: The converter consists of an Empire BCM-321 BI (AS) balanced crystal mixer, with an approximate noise figure of 12 db. Its conversion loss is about 12 db. The local oscillator is an FXR L772 tunable klystron oscillator which operates from 950 Mc to about 2100 Mc. To eliminate local oscillator long term drift, a Dymec 2650A Klystron synchronizer is used with the FXR oscillator.

d. Telemetry Receiver: The telemetry receiver is a Defense Electronics receiver, Model TMR 2A. It is a double conversion receiver with a tuning head operating from 215 to 265 Mc. It has plug-in second (2nd) IF amplifiers with the following bandwidths:

(1) 100 Kc
(2) 300 Kc
(3) 500 Kc
(4) 1.0 Mc

The receiver exhibits a noise figure of eight db.

2. Tracking Components:

a. Tracking Receiver: The tracking receiver consists of a RSE Electronics 30 Mc amplifiers. It has a gain of 110 db, a bandwidth of two Mc and a noise figure of 1.5 db. The AGC circuitry on the amplifier was extended to all of the IF stages for extended AGC response. The AGC amplifier and AGC passband filter were constructed in-house.

b. Error Filter: The error filter, which includes the error output amplifier was built in house. The passband of the error filter is centered on 30 cycles and has a bandwidth of approximately 30 cycles. The output stage provides individual errors for azimuth and elevation with controls for adjusting the tracking sensitivity for each channel.

c. Servo Control System: The output of the error filter feeds the servo system. Since the servo system has two identical channels, azimuth and elevation, only one channel will be described.

Figure 5 shows a block diagram of the T-9 servo control system. The antenna system has three modes of operation: automatic track, manual, and slave.

In the automatic track mode, the angle-error detector compares the conical scan modulation and the reference generator signals. In the manual mode and slave mode, the error signal is derived from manually controlled selsyn generators and the reference is the power line frequency. , Thus, the error for automatic track is 30 cycles per second, and in manual (or slave), the error is 60 cycles per second.

The output of the angle-error detector is fed to a servo amplifier which in turn supplies the field current to a DC generator which is driven at constant speed. The armature of this generator feeds the armature of the servo drive motor, the field of which is excited separately. The torque produced by the servo drive motor then positions the antenna mount in coincidence with the input error.

Two stabilization loops are provided in the servo system. The innermost loop (see Figure 6) provides torque feedback to the servo amplifier to limit the torque produced by the drive motor. This feature is particularly important during the manual mode where the input error can become excessive, The second-inner loop comprises a tachometer feedback stabilization loop, which reduces servo hunt. The third inner loop is a potentiometer feedback network that varies the gain of the azimuth servo amplifier as a function of the cosecant of the scanner elevation angle. This loop desensitizes the azimuth channel when the scanner is pointing at low elevation angles.

Conclusions The T-9 tracker met all the design objectives stated in the introduction to this report.

1. The system is light and easily transportable. The tracker can be towed at speeds up to 30 MPH over paved roads.

2. The conical scanner antenna exhibits a good gain, fair efficiency, and excellent side lobe characteristics. The mechanical dynamic balance of the antenna and tracker mount is satisfactory.

3. The resultant angular tracking rates are better than were expected. The angular velocities obtained are 150° per second in azimuth and 50° per second in elevation. With proper site selection, these tracking rates should meet the majority of tracking requirements at WSMR.

4. The system threshold allows tracking beyond the design objectives.

Bibliography

1. G. M. Pelchat, "The Effect of Receiver and Antenna Noise on the Performance of a Conical Scan Tracking System," The Microwave Journal, Vol VIII, Nr 2, Feb 65.

2. Harold Dickstein, "Conical Scanner Antenna System for T-9 Tracker," Temec Document # TM 11, Cubic Corporation.

3. Silver, S. , "Microwave Antenna Theory and Design," MIT Radiation Laboratory Series, Vol 12, McGraw-Hill Book Co, Inc, New York, 1949.

4. Skolnik, Merrill I., "Introduction to Radar Systems," McGraw-Hill Book Company, Inc, New York, 1962.

TABLE I

TELEMETRY SYSTEM THRESHOLD*

RECEIVER BANDWIDTH	THRESHOLD (DBM)
100KC	-105.4
300KC	-100.6
500KC	-98.4
1.0 MC	-95.4

TABLE II

TRACKING RATES

PARAMETER	ELEV. CHANNEL	AZIMUTH CHANNEL
ANGULAR VELOCITY	40 °/SEC.	150 °/SEC.
ANGULAR ACCELERATION	20 °/SEC.^{2}	60°/SEC.^{2}

* CALCULATED WITH A 10 DB PREDETECTED S/N RATIO

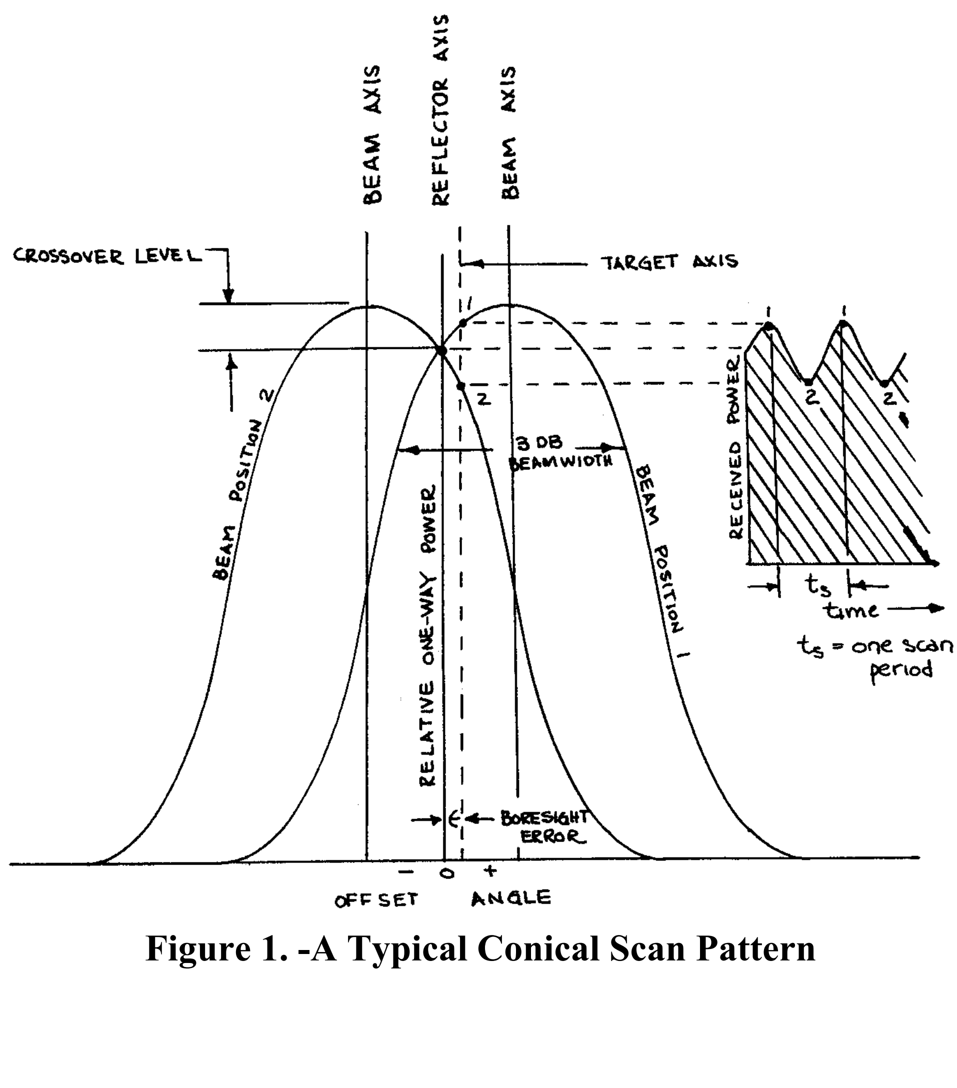

Figure 1. -A Typical Conical Scan Pattern

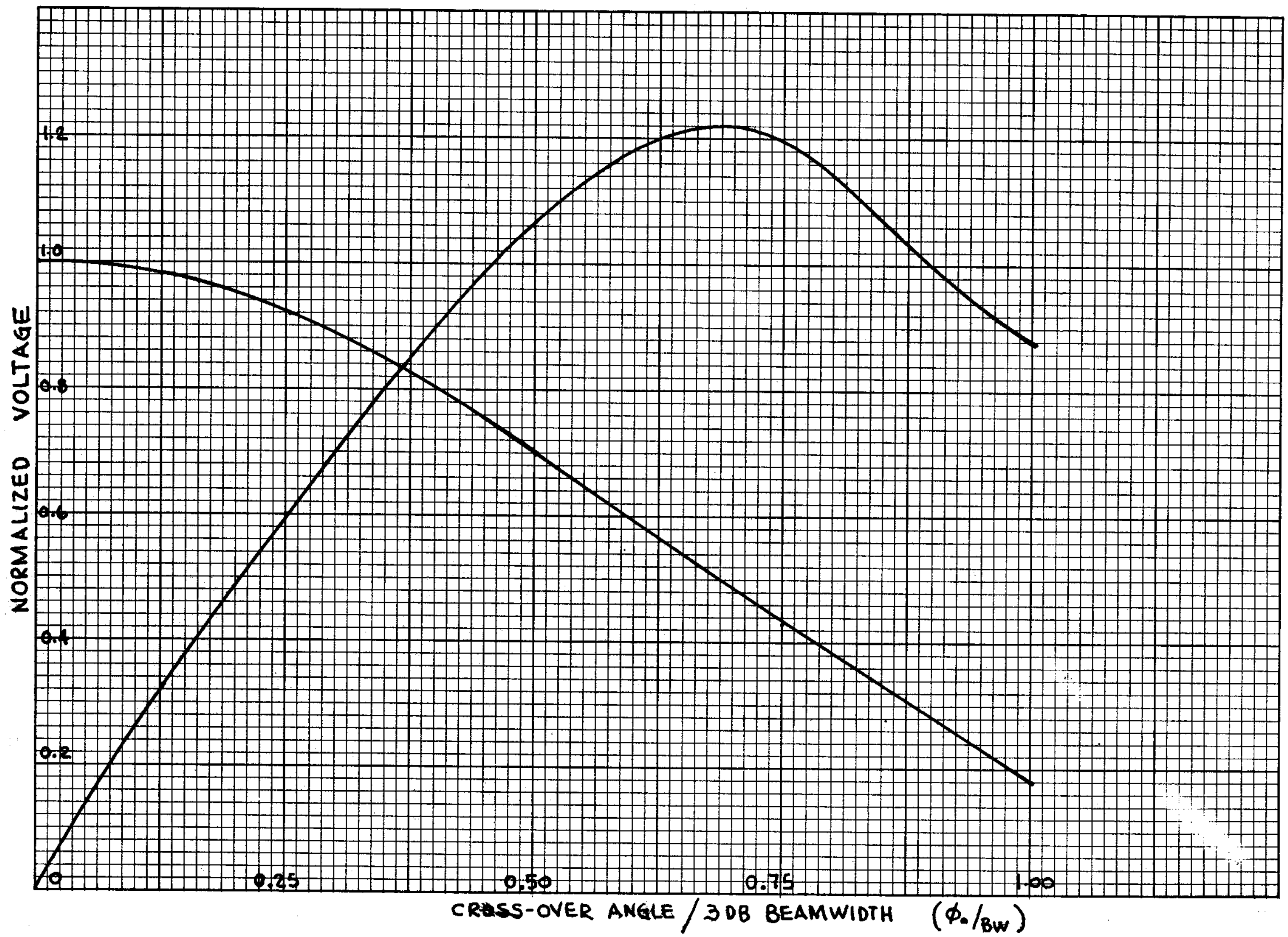

Figure 2. -Assumed Antenna Voltage Pattern

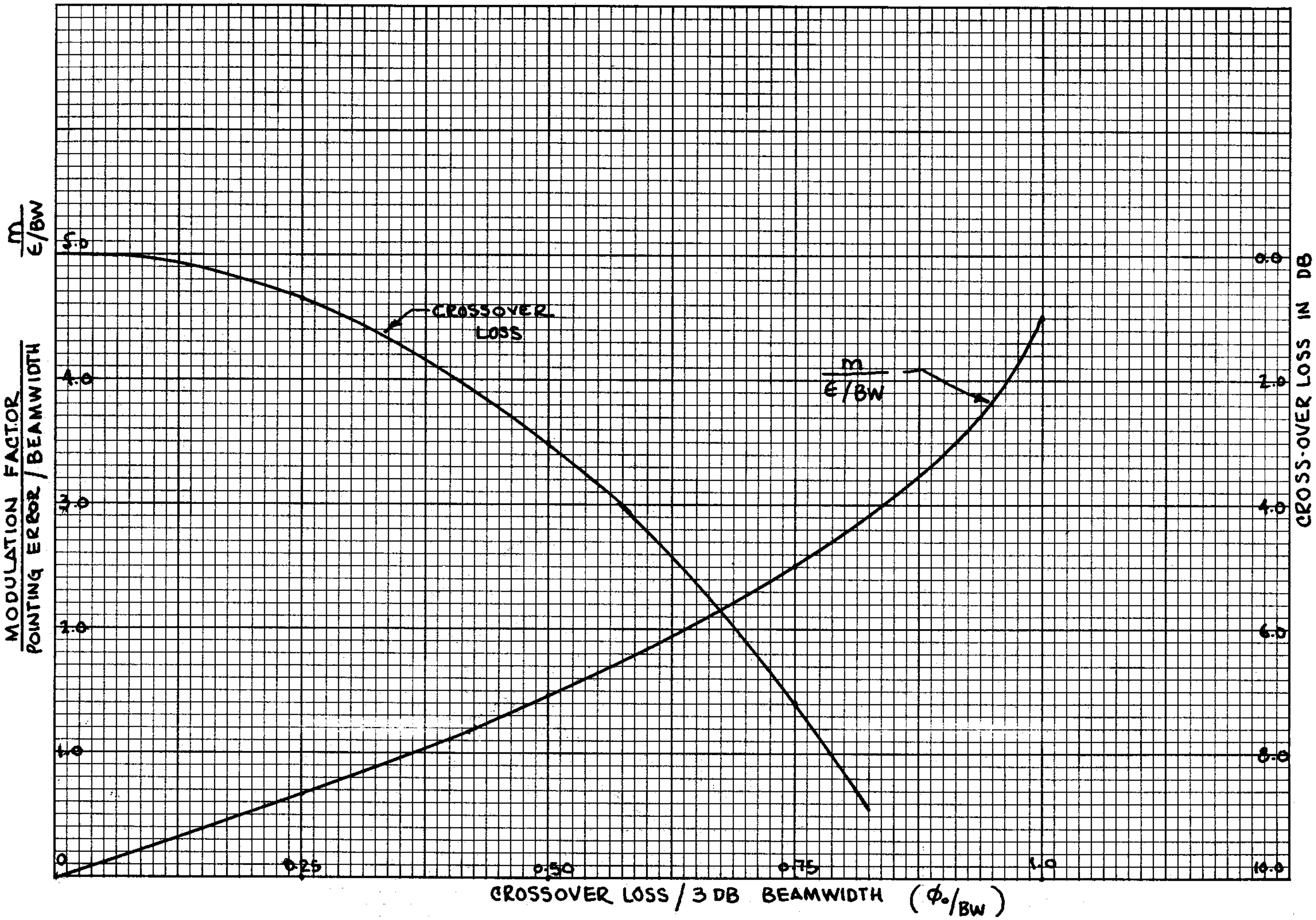

Figure 3. -Modulation Factor and Crossover Loss Versus Crossover Angle

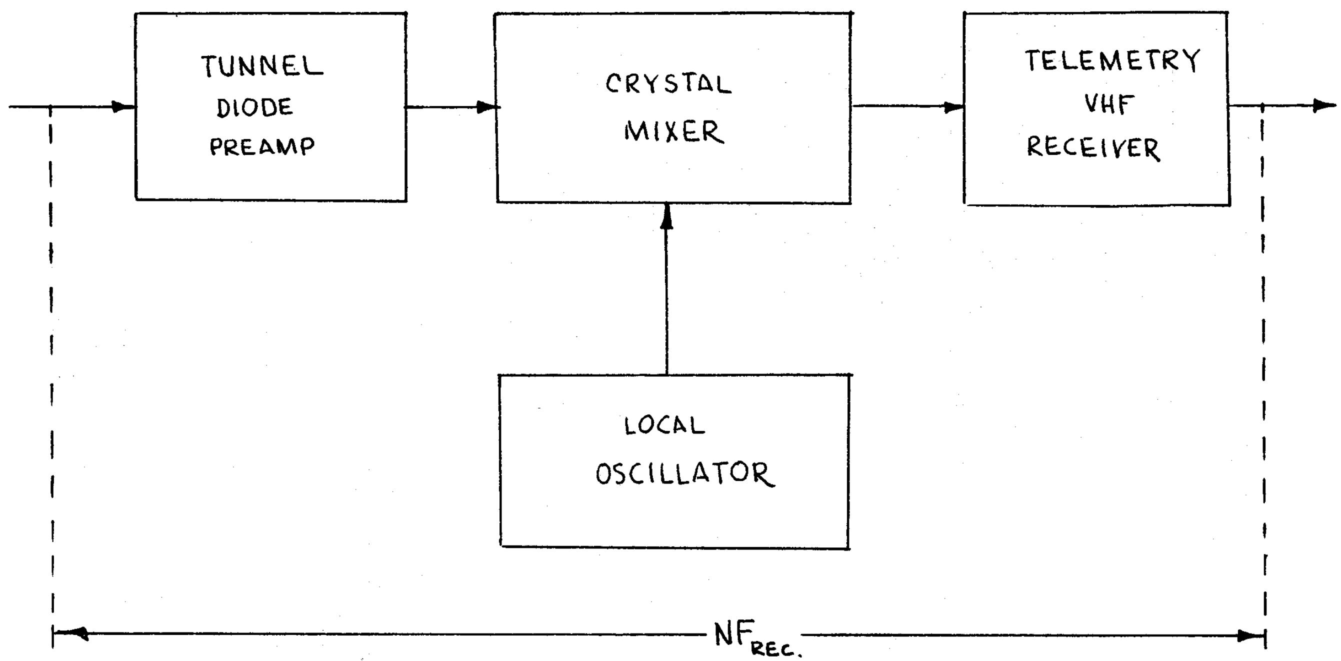

Figure 4. -RF System Block Diagram

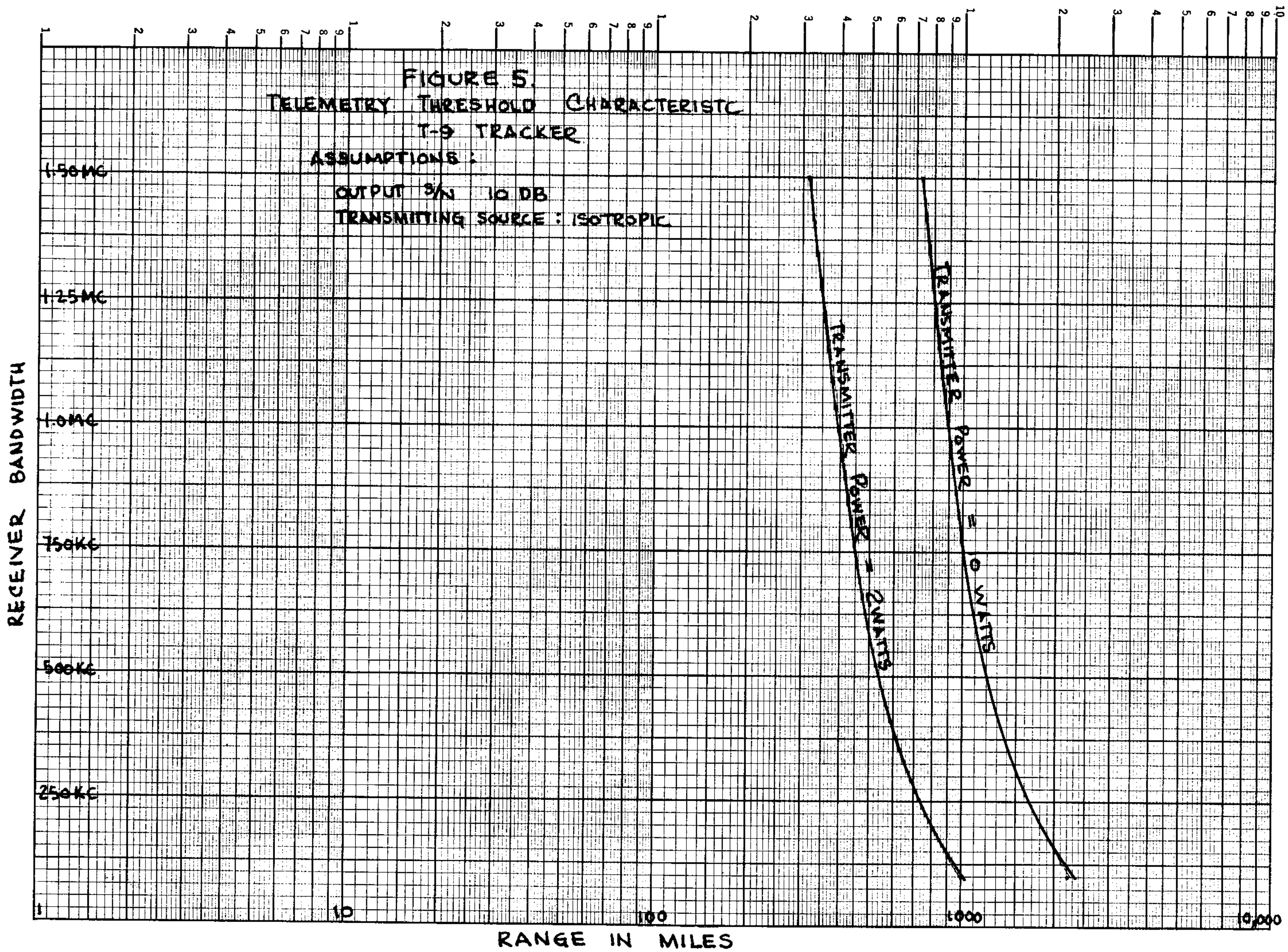

Figure 5. -Telemetry Threshold Characteristic T-9 Tracker

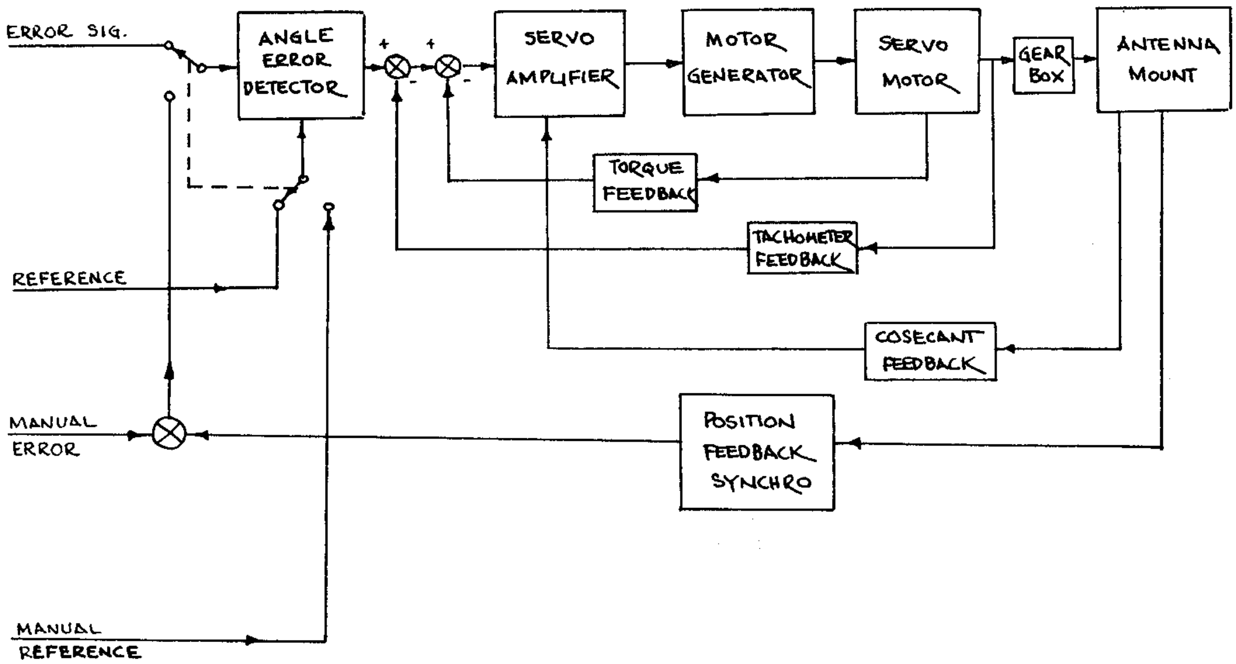

Figure 6. -T-9 Servo System

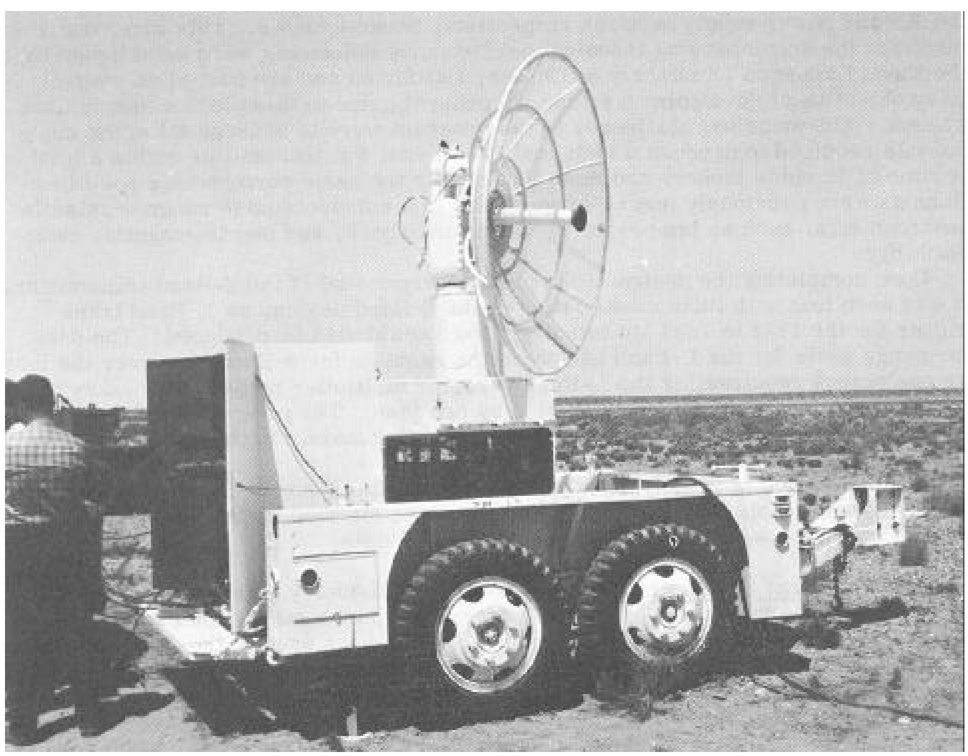

Figure 7. -T-9 Tracking Antenna