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Foreword

(This Foreword is not a part of ANSI/IEEE Std 149-1979, IEEE Standard Test Procedures for Antennas.)

This document is a major revision of IEEE Std 149-1965 which it supersedes. It represents the second revision of the standard since the original issuance in 1948 of 48IRE2S2, Standards on Antennas—Methods of Testing. Practically every topic contained in the previous standard has been expanded to reflect the great changes that have taken place, since 1965, in metrology and instrumentation technology as applied to antenna measurements.

This document contains sections on the design, evaluation, and operation of antenna ranges, electromagnetic radiation hazards, and environmental factors which did not appear in the preceding standard. The section on the determination of scattering cross-section, which appeared previously, has been omitted since it will appear as a separate standard at a later date.

Suggestions for the improvement of this standard will be welcome. They should be sent to:

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IEEE Standard Test Procedures for Antennas

1. Scope

This document comprises test procedures for the measurement of antenna properties. It is a comprehensive revision and extension of the previous test procedure ANSI/IEEE Std 149-1965 (Reaff 1971).

Throughout this standard it is assumed that the antenna to be measured can be treated as a passive, linear, and reciprocal device. Therefore its radiation properties can be measured in either the transmitting or the receiving mode. Many of the test procedures described can, however, be adapted for use in the measurement of antenna systems containing circuit elements that may be active, nonlinear, or nonreciprocal. For these cases there is no simple relationship between the antenna system's transmitting and receiving properties. Therefore measurements shall be performed for the mode or modes in which the antenna system has been designed to be used.

A fundamental property of any antenna is its radiation pattern. The measurement of radiation patterns on an antenna range is discussed in Section 3., with the emphasis placed on amplitude patterns. The design of antenna ranges, or antenna test facilities, is described in Section 4.

The instrumentation required for the antenna range, directions for the evaluation of an (existing) range, and the operation of ranges are discussed in Sections 5., 6., and 8., respectively. A variety of special measurement techniques are included in Section 7.

The working environment in which an antenna is installed may substantially modify the intrinsic pattern of an antenna. Consequently measurements *in situ* are frequently required. These are discussed in Section 9.

For each direction of space, the radiation pattern is characterized by amplitude, phase, and polarization. The latter characteristics are taken up in Sections 10. and 11., respectively.

The relative amplitude-pattern information may be converted into absolute intensities through information derived from the measurement of antenna gain. The determination of gain and closely related directivity is described in Section 12.. Errors in conventional gain calibration measurements are discussed particularly in 12.5. Losses in the antenna itself can be of importance in some types of antennas. These losses can be accounted for by the radiation efficiency. Procedures for their determination are treated in Section 13.

Section 14. deals with boresight measurements, which are concerned with the precise determination of the direction of the beam or tracking axis of an antenna system. The sensitive components of the antenna frequently require protection from harsh influences of the environment. The electrically transmissive shield or radome which provides this protection shall frequently be evaluated so that its effect on the radiation pattern is understood. This topic is treated in Section 15.

Power transfer from generator to antenna is controlled by the input impedance to the antenna. This important parameter frequently limits the useful bandwidth of the antenna. Measurement procedures and network descriptions appropriate from low to microwave frequencies are presented in Section 16.

An important class of antennas relies on ground to enhance the received signal. In this case the ground shall be considered as an integral part of the antenna. The modification of antenna concepts and additional data on the ground-wave propagation are presented in Section 17.

The antenna and its associated circuits rather than the capacity of the transmitter generator may limit the amount of power, either average power or peak power, that can be effectively radiated. It is desirable therefore to determine these limitations as well as the environmental factors that may modify them independently of the system context. Procedures for testing power-handling capacity are outlined in Section 18.

Another concern to the antenna engineer is that of radiation hazards. It is well known that radio-frequency (rf) fields of sufficient intensity can cause damage to biological tissue. Therefore it is usually necessary to determine the level of the radiation intensity in the vicinity of antennas radiating high radio-frequency power so that appropriate safety precautions can be taken before personnel enter the area. This important aspect of antenna measurements is discussed in Section 19.

Mechanical or structural properties along with environmental factors are described in Section 20. Because these properties are so varied and specialized in nature, no attempt has been made to include descriptions of actual measurements in this test procedure. The environmental impact of an antenna is also an important consideration for the antenna engineer. One aspect of environmental impact is that of aesthetics. Large antenna structures are necessarily conspicuous, and their appearance is of concern to those who live in their vicinity. This is particularly true in an urban setting. Since the aesthetic quality of the antenna structure is highly subjective, it is beyond the scope of this document to suggest any evaluation procedure.

Throughout this test procedure an attempt has been made to discuss measurement techniques as thoroughly as is practicable. However, in general step-by-step procedural descriptions have been avoided. References are provided which are illustrative of measurement techniques and in which details may be found. Because measurement techniques undergo continuing refinement, the reader should be alert to references on the subject of antenna measurement that will have appeared after this test procedure was prepared.

Many commonly used terms used in this test procedure are defined in ANSI/IEEE Std 145-1973, Definitions of Terms for Antennas. Commonly used terms that do not appear in that standard are italicized in this test procedure.

2. Standards References

When the following standard documents referenced in the text are superseded by an approved revision, the revision shall apply.

ANSI C95.1-1974, Safety Level of Electromagnetic Radiation with Respect to Personnel.

ANSI C95.3-1973, Techniques and Instrumentation for the Measurement of Potentially Hazardous Electromagnetic Radiation at Microwave Frequencies.

ANSI/IEEE Std 100-1977, Dictionary of Electrical and Electronics Terms.

ANSI/IEEE Std 145-1973, Definitions of Terms for Antennas.

ANSI/IEEE Std 148-1959 (Reaff 1971), Measurement of Waveguides and Components.

IEEE Std 211-1977, Standard Definitions of Terms for Radio Wave Propagation.

IEEE Std 291-1969, Standards Report on Measuring Field Strength in Radio Wave Propagation.

3. Antenna-Range Measurements of Radiation Patterns

3.1 General

Associated with the antenna under test is an operational coordinate system [1, pp 5.4–5.7],¹ usually a spherical one. Generally this coordinate system is defined by the system in which the antenna is used, although at times, for testing a specific antenna, it may be necessary to define a different coordinate system. The Inter-Range Instrumentation Group of the Range Commanders Council [2, p 120], for example, has defined a coordinate system specifically for use with rockets, missiles, and space vehicles (Fig 1).

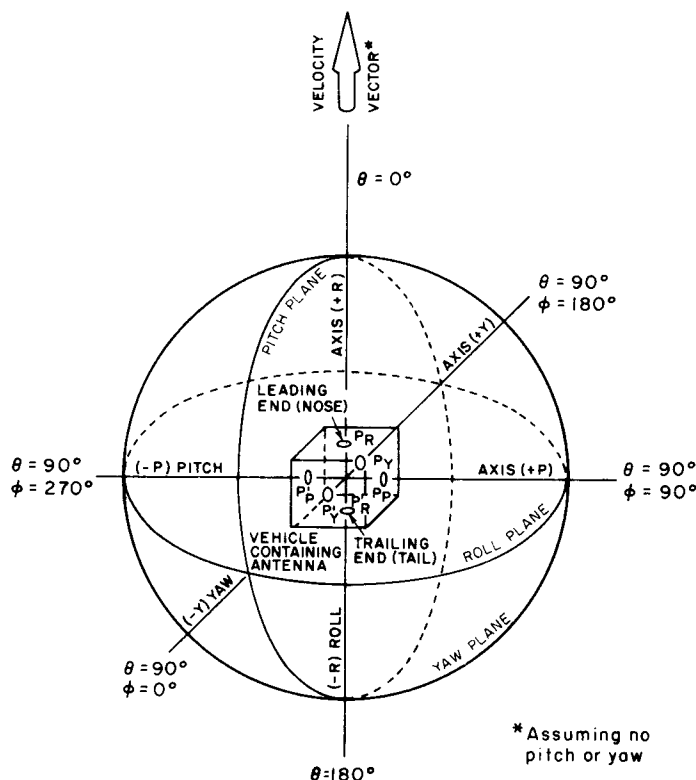


Figure 1—Coordinate System of Inter-Range Instrumentation Group

The antenna's coordinate system is typically defined with respect to a mechanical reference on the antenna. A means of establishing the mechanical reference should be provided. The standard spherical coordinate system used in antenna measurements is shown in Fig 2.

To completely characterize the radiation field of an antenna, one shall measure its relative amplitude, relative phase, polarization, and the power gain on the surface of a sphere the center of which is located at the antenna under test. A representation of any of these radiation properties as a function of space coordinates is defined as a radiation pattern, or antenna pattern, of the test antenna. Since the distance R from the antenna under test to the measuring point is fixed, only the two angular coordinates are variables in a given radiation pattern. Usually the radio frequency of operation is treated as a parameter, with the radiation pattern being measured at specified frequencies. For some antenna applications it is necessary to make frequency a variable. If frequency is varied continuously, such a procedure is called a swept-frequency technique; it is discussed in 7.4. It is impractical to measure the radiation pattern of an antenna completely, and therefore it is necessary to resort to sampling techniques. For example, with the frequency of

¹Numbers in brackets correspond to those of the Bibliography, Section 21, of this standard.

operation and polarization fixed, the θ coordinate can be varied incrementally, and for each increment the desired antenna property can be measured continuously over the range of ϕ . If the increments are small enough, then for all practical purposes the complete antenna pattern is obtained. The resulting patterns taken for all increments of θ are usually referred to as a set of radiation patterns.

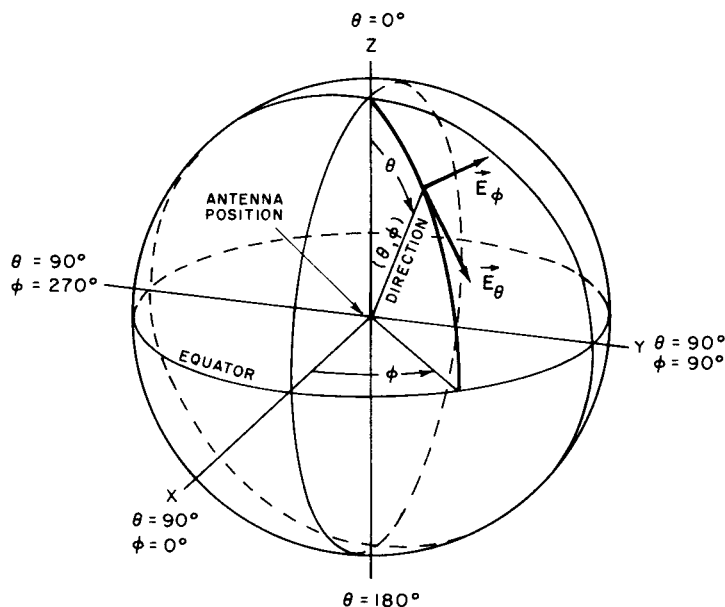


Figure 2—Standard Spherical Coordinate System Used in Antenna Measurements

There are situations in which the operational antenna illuminates structures in its immediate vicinity which alter the radiation field of the isolated antenna. In these cases it may be necessary for measurements of the radiation field to include with the antenna those relevant parts of the nearby structures. The use of scale models is quite common for such cases (see 7.1). Throughout this standard the expression “test antenna” or, alternately, “antenna under test” shall mean the antenna itself plus any structure included with it. This means that the test antenna can be physically larger than the antenna alone.

3.2 Pattern Cuts

A direct method of measuring the radiation pattern of a test antenna is to employ a suitable source antenna, which can be positioned in such a manner that it moves relative to the test antenna along lines of constant θ and constant ϕ (see Fig 2). The loci of constant θ directions describe cones; hence measurements made with ϕ as the variable and θ as a parameter are called *conical cuts* or ϕ cuts. Those made with θ as the variable and ϕ as a parameter are called *great-circle cuts* or θ cuts. Note, however, that the conical cut for $\theta = 90^\circ$ is also a great-circle cut.

Though rarely done, it is possible to position the antenna in such a manner that the loci of directions describe a spiral. For this case both θ and ϕ are variables, and the resultant motion is called a *spiral cut*. When spiral cuts are being made, it is usual for the motion in θ to be slowly varying with respect to that in ϕ ; hence for each 360° rotation in ϕ the resulting pattern is approximately a conical cut.

Principal-plane cuts refer to orthogonal great-circle cuts which are through the axis of the test antenna’s major lobe. For this definition to hold, the beam axis shall lie either in the equator of the spherical coordinate system ($\theta = 90^\circ$) or at one of the poles ($\theta = 0^\circ$ or $\theta = 180^\circ$).

If the positioner system is designed to provide θ and ϕ cuts, then the alignment of the axis of a pencil-beam antenna along the poles is usually avoided. This is because the ϕ cut for the $\theta = 0^\circ$ orientation yields only a polarization pattern

(see 11.2.2). When near the poles θ cuts involve radical changes in the direction of polarization of the incident field relative to the test antenna's polarization, except when the incident field is identically circularly polarized. For these reasons if the test antenna is of a pencil-beam type, it is usually oriented with its beam axis in any desired direction in the equator (most often in the $\phi = 0^\circ$ or $\phi = 180^\circ$ direction).

3.3 Basic Antenna-Range Configurations

There are two basic range configurations that accomplish the position requirement for θ and ϕ cuts [1, pp 5.12-5.24]. One is the *fixed-line-of-sight* configuration. Here the test antenna and its associated coordinate system are rotated about a suitable axis (usually one passing through the phase center (see 10.3) of the test antenna). If the test antenna is operating in the receive mode, then the signal that it receives from an appropriately located fixed source antenna is recorded. The other one is called the *movable-line-of-sight* configuration. For this case the source antenna is moved incrementally or continuously along the circumference of a circle centered approximately at the phase center of the antenna under test. If it is moved incrementally, then for each position of the source antenna the test antenna is rotated and the received signal is recorded. Alternately the test antenna can be rotated incrementally, and for each of its positions the source antenna is moved continuously along its circumferential path.

If the test antenna and the source antenna are both reciprocal devices, the functions of receive and transmit may be interchanged. The measured patterns should be identical. This means that the test antenna may be used in either the receive or the transmit mode; most often it is used in the receive mode. In the following, unless otherwise stated, the test antenna shall be considered as the receiving antenna, and it will be illuminated by the field of the transmitting source antenna.

4. Antenna-Range Design

4.1 General

Antenna ranges have been developed for the purpose of measuring the radiation patterns of antennas independent of their operational environment. The antenna range consists of the appropriate instrumentation and the physical space required for the measurements. In this section the design is discussed. Evaluation and use of antenna ranges are described in Sections 6. and 8.. Emphasis is placed on the measurement of the relative amplitude patterns. The measurement of relative phase, polarization, and power gain is discussed in Sections 10., 11., and 12., respectively. It should be pointed out that the various criteria for antenna-range design presented here, as well as the methods of evaluation, apply equally well to other types of ranges usually found at antenna testing facilities, such as *radome ranges* and *scattering ranges*. Radome measurements are discussed in Section 15., and scattering ranges are beyond the scope of this standard.

The ideal incident field for measuring the radiation characteristics of the test antenna is that of a uniform plane wave. In practice it is only possible to approximate such a field. Attempts to do this have led to the development of two basic types of ranges:

- 1) *Free-space ranges*. This type of range is designed in such a manner that all the effects of the surroundings are suppressed to acceptable levels.
- 2) *Reflection ranges*. This type of range is designed to judiciously use reflections in order to produce an approximated plane wave.

Typical ranges that come under the free-space-range classification are: the elevated range, the slant range, the compact range, and most anechoic chambers.

The *elevated range* [3] includes those ranges in which the test and source antennas are located on towers, on adjacent mountain peaks, on the roofs of adjacent buildings or on diagonally opposing sides of abandoned quarries. Generally, however, it is designed over an approximately flat area, and the effects of the surroundings are suppressed:

- 1) by careful choice of the source antenna with regard to directivity and side-lobe level
- 2) by clearance of the line of sight along the range surface
- 3) by redirection or absorption of energy reaching the range surface or obstacles that cannot be removed
- 4) by special signal-processing techniques such as modulation tagging of the desired signal
- 5) by use of short pulses

The *ground-reflection range* [4] is designed to make use of the energy that is specularly reflected from the range surface to create a constructive interference with the direct-path energy in the region of the test antenna. With proper design the illuminating field will have a small, essentially symmetric amplitude taper. This is usually achieved by adjusting the height of the source antenna above the range surface with the test antenna at a fixed height.

Since the elevated range over a flat surface and the ground-reflection range are so basic to antenna-pattern measurements, their design will be discussed in detail in 4.3 and 4.4, respectively. Other range types will be discussed in 4.5.

4.2 Antenna-Range Design Criteria

4.2.1 General

To establish the design criteria for either basic range type, one must consider the following:

- 1) the coupling between source and test antennas
- 2) the transverse and longitudinal amplitude taper of the illuminating wave front
- 3) the phase curvature of the illuminating wave front
- 4) spatial variations in the illuminating wave front caused by reflections
- 5) interference from spurious radiating sources

Items (1)–(3) are discussed in this section. The problems associated with reflections from the range surface and other obstacles are discussed in 4.3 and Section 6.

Outdoor ranges are usually subjected to interference from signal sources outside the range area. These sources can be mobile communications, radar, or telemetry systems. The use of filters can often suppress the effect of these interfering signals.

4.2.2 Effect of Mutual Coupling Between Source and Test Antennas

The total field of any antenna consists of a radiation part and a reactive part. The radiation field decays as the reciprocal of the distance from the antenna, whereas the reactive field decays at least as rapidly as the reciprocal of the square of the distance from the antenna. Usually the spacing between source and test antennas is large enough so that the level of the reactive field of the source antenna is negligible. However, practical situations do arise for which this may not be the case. In these cases the test antenna will couple to the reactive field, and for some types of measurements this produces an error. Such effects are considered negligible when the spacing is greater than about 10 wavelengths. Based upon calculations made for a very short dipole antenna at 10 wavelengths from the antenna, the level of the inductive field (which is the part of the reactive field that would couple) will be 36 dB below that of the radiation field.

In addition to the reactive field coupling, the reradiative coupling or mutual coupling between source and test antennas is also of concern [5]. For this case, part of the energy received by the test antenna is reradiated toward the source antenna. In turn, part of the energy received by the source antenna is again reradiated toward the test antenna. While this level is quite low, it can cause a measurable error in the level of the signal observed near the peak of the test

antenna's major lobe. The effect on the side-lobe levels is usually negligible. A careful analysis [1, pp 14.3–14.5] was performed; it was based upon identical source and test antennas, each with a $(\sin x)/x$ antenna pattern, a 50 percent aperture efficiency, and an equivalent power reflection coefficient of 0.25. The level of the reradiated signal reaching the test antenna was at least 45 dB below that of the original received signal when the ratio of the plane angle subtended at the source antenna by the diameter of the test antenna, to the 3 dB beamwidth of the source antenna was made equal to or less than 0.3. This ratio corresponds to a subtended angle that is approximately equal to the source antenna's beam width at the 0.25 dB level. It is generally considered good practice to adhere to a 0.25 dB criterion for the amplitude taper of the direct illuminating field [1, pp 14.13–14.15], [4].

4.2.3 Effect of a Transverse Amplitude Taper over the Test Aperture

An amplitude taper of the illuminating field can produce an error in the measured antenna pattern of the test antenna. This effect is dependent upon the aperture excitation function of the test antenna. For typical excitation functions the effect of the amplitude taper of the incident field is a reduction in measured gain with a slight modification to the close-in side lobes. This effect can be evaluated by recognizing that the variation of the amplitude of the incident field over the aperture of the test antenna on receive is analogous to a modification of the aperture illumination from its feed on transmit. Suppose that the test antenna has an aperture illumination from its feed on transmit given by $f(x, y)$. If it is used on receive and is illuminated by an incident field with an amplitude variation given by $g(x, y)$, then the measured radiation pattern is essentially the same as that for the transmitting case, with the feed modified to produce a distribution over the test antenna aperture given by $f(x, y) \cdot g(x, y)$. For example, consider a test antenna having a circular aperture with a 10 dB *cosine-on-pedestal* distribution the far-field radiation pattern of which is to be measured with the use of a source antenna that produces a circularly symmetric amplitude taper over the aperture of the test antenna. The taper is assumed to have a $(\sin x)/x$ form. One can now compute the directivity of the equivalent distribution, which is the product of the cosine-on-pedestal and $(\sin x)/x$ functions for various tapers. If the amplitude taper varies to -0.5 dB at the periphery of the aperture, an apparent directivity reduction of approximately 0.15 dB will result as compared to the case without taper. If the amplitude taper varies to -0.25 dB at the periphery of the aperture, one obtains a reduction in directivity of about 0.10 dB.

Generally it is better to choose a source antenna that yields a 0.25 dB taper, rather than one with a broader beamwidth which would produce a smaller amplitude taper. This is because the use of broader beamwidth source antennas usually results in an increased error due to the reflections (see Section 6.). Conversely, there are situations in which it may be necessary to use a source antenna with a narrower beam in order to reduce the effect of reflections. If a more directive source antenna is used, the alignment of the source antenna becomes more critical. Care shall be exercised in orienting the source antenna so that the peak of its beam is centered on the test antenna to prevent an excessive and asymmetrical illumination taper with a resultant increase in measurement error.

4.2.4 Effect of a Longitudinal Amplitude Taper at the Test Antenna

To achieve a given accuracy in the measurement of the radiation pattern of a test antenna, the illuminating field shall be sufficiently constant in amplitude along the range axis, as well as in planes normal to the range axis. Consider an end-fire antenna under test with an active region having a maximum dimension L along the range axis. If the separation between the source antenna and the center of the active region is R_0 , then the ratio ρ_p of the power density at the forward extreme of the active region to that at the rear is given by [7]

$$10 \log (\rho_p) = 20 \log \frac{R_0 + L/2}{R_0 - L/2} \text{ [dB]}$$

Severe axial variations of the illuminating field can cause a measurement error, particularly in the minor lobe structure of radiation patterns. For most antenna types that have a significant depth to their active regions, such an error is usually considered to be negligible when the power density over the region is constant to within 1 dB. This condition corresponds to an approximate restraint on R_0 of

$$R_0 \geq 10L$$

The criterion for such structures as high-gain end-fire antennas often is more restrictive than the greater of the previously discussed range-length criteria that were based on the suppression of reactive-field coupling and phase curvature.

4.2.5 Effect of Phase Variation over the Test Aperture

A criterion has to be established for the phase variation of the illuminating field over the test antenna. For most practical situations the phase variation is a function solely of the separation between the source antenna and the antenna under test. If, in the absence of reflections, the 0.25 dB criterion for amplitude variation is adhered to, then the corresponding phase variation will be very close to that of a spherical wave emanating from the phase center of the source antenna. This is true for spacings considerably less than $2d^2/\lambda$, where d is the diameter of the source antenna. For example, calculations [1, pp 14.5–14.11] made for a source antenna with a 30 dB Taylor distribution revealed that its phase pattern differed from that of a spherical wave by at most 2° between the 1 dB points of its amplitude pattern at a spacing of d^2/λ . Thus the expected phase variation can be determined by assuming that the phase front at the test antenna is a sphere. It can readily be shown [4] that for a test-antenna diameter D and a separation R , a phase deviation $\Delta\phi$ will be given by

$$\Delta\phi \approx \frac{\pi D^2}{4\lambda R}$$

A commonly employed criterion for determining the minimum allowable separation between source and test antennas is to restrict $\Delta\phi$ to $\pi/8$ rad. This results in the restriction that $R \geq 2D^2/\lambda$.

The effect of phase variation is that the nulls of the pattern are partially filled, and the amplitudes of the side lobes are changed. An example is shown in Fig 3 which depicts calculated patterns of a circular aperture with a 30 dB Taylor distribution at separations of $2D^2/\lambda$, $4D^2/\lambda$, and approaching infinity. It is possible to correct for phase deviations by changing the focus of the test antenna, a technique that is discussed in 7.2.

4.3 Design of Elevated Ranges

4.3.1 Elevated Ranges over Flat Surfaces

In view of the interdependence between the diameter of the test antenna and the range or separation between source and test antennas, it is convenient to specify the separation as $R = KD^2/\lambda$, where K is a number to be chosen for a particular measurement (see Fig 3). It can be shown [1, pp 14.15–14.28] that for elevated ranges the 0.25 dB criterion for amplitude taper leads to a criterion for the diameter of the source antenna, namely, that

$$d \leq 0.37KD$$

This assumes that the main lobe of the source antenna has a $(\sin x)/x$ amplitude characteristic.

If the elevated range is designed over a flat surface as shown in Fig 4, then steps shall be taken to suppress the reflections from the range surface in the region near the range axis.

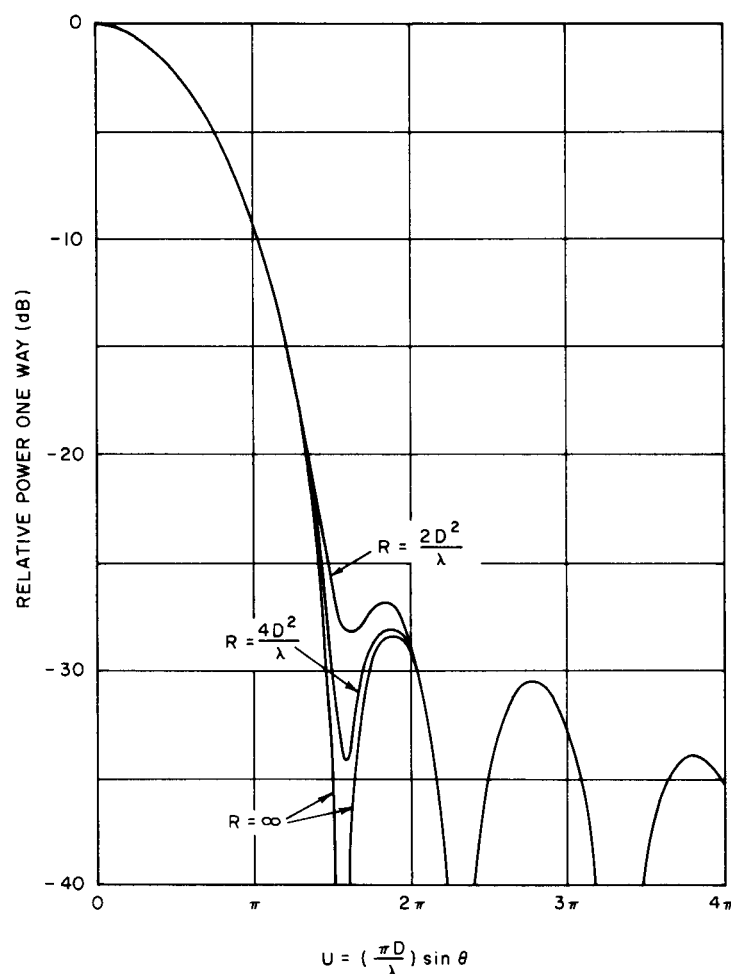


Figure 3—Calculated Radiation Patterns Illustrating the Effect of Quadratic Phase Errors Encountered in Measuring Patterns at the Ranges Indicated. A 30 dB Taylor Distribution Is Assumed

As a basic design goal, the range surface in front of the test antenna should not intercept any energy contained in the main lobe of the source antenna. It is suggested that the first null in the radiation pattern of the source antenna be directed toward the base of the test antenna tower. This leads to the imposition of a minimum-size restriction on the source antenna, namely,

$$d \geq 1.5KD^2/h_T$$

where h_T is the height of the receiving antenna. This result is based upon the fact that typical source antennas have a main-lobe width of approximately $3\lambda/d$ rad. A comparison of the two criteria for the diameter of the source antenna shows that the height of the test antenna should satisfy the inequality

$$h_T \geq 4D$$

where D is the diameter of the antenna under test. The source antenna should be elevated to the same height as the test antenna. For physically small antennas this requirement is easily met. However, as the antenna's size is increased, it becomes more difficult, and in some cases impractical, to satisfy.

4.3.2 Elevated Ranges over Irregular Surfaces

Elevated ranges are often designed over irregular terrain, for example, between two adjacent mountain peaks or perhaps between two hilltops. Such ranges are useful for the testing of physically large antennas. For these ranges the location of the points of specular reflection, which reflect energy toward the test antenna, may not be immediately obvious. When designing these ranges it is usually necessary to construct a scaled drawing of the vertical profile of the range, showing the exact ground contour [8] from data obtained from the U.S. Geological Survey map of the area. These maps give detailed information on the topography of the ground by means of contour lines plotted every 20 ft in elevation above sea level, which should be adequate for ranges operating as high in frequency as UHF. For microwave frequencies it may be necessary to locate the points experimentally using directive antennas (see Section 6.). Once the points of specular reflection are determined, the level of the reflected energy at the test antenna can be estimated [8], and corrective measures can be taken if the level of reflected energy is excessive. For these ranges the restriction on the height of the test antenna is removed, since the mountain itself is part of the test-antenna tower.

4.3.3 Estimation of Errors Due to Reflections

To illustrate the effect of reflections on the measured radiation patterns of a test antenna, consider the following examples. Suppose that the nominal side lobe levels of both source and test antennas are 25 dB below their respective maximum levels and the range surface produces a 10 dB attenuation of the reflected wave. Then the extraneous signal level will be approximately 60 dB below the direct-path signal level for the case where the main lobe of the test antenna is pointing toward the source antenna. The graph of Fig 5 can be used to determine the possible error in the relative amplitude pattern of the test antenna due to this reflected signal. Fig 5 shows that the measured value of the peak of the beam will be in error by less than 0.01 dB. However, if the peak of the main lobe of the test antenna is pointed toward the range surface and a -25 dB side lobe is directed toward the source antenna, the relative level of the extraneous signal will be only 10 dB below the level of the direct-path signal, and the measurement error is -3.3 to $+2.4$ dB.

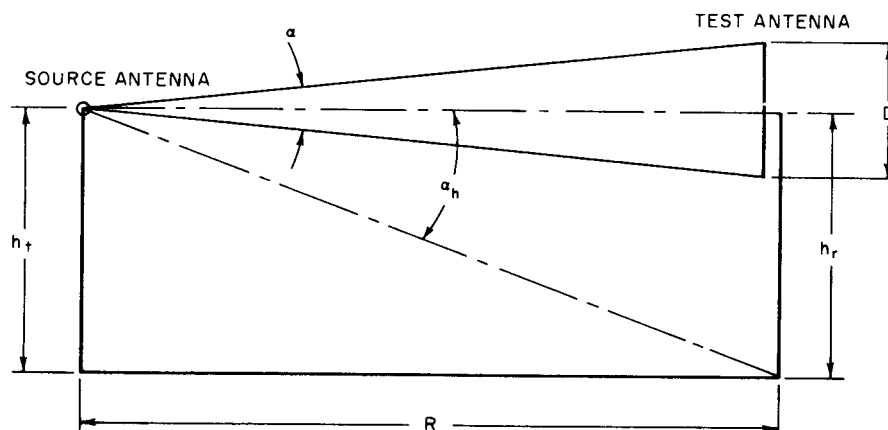


Figure 4—Elevated-Range Geometry

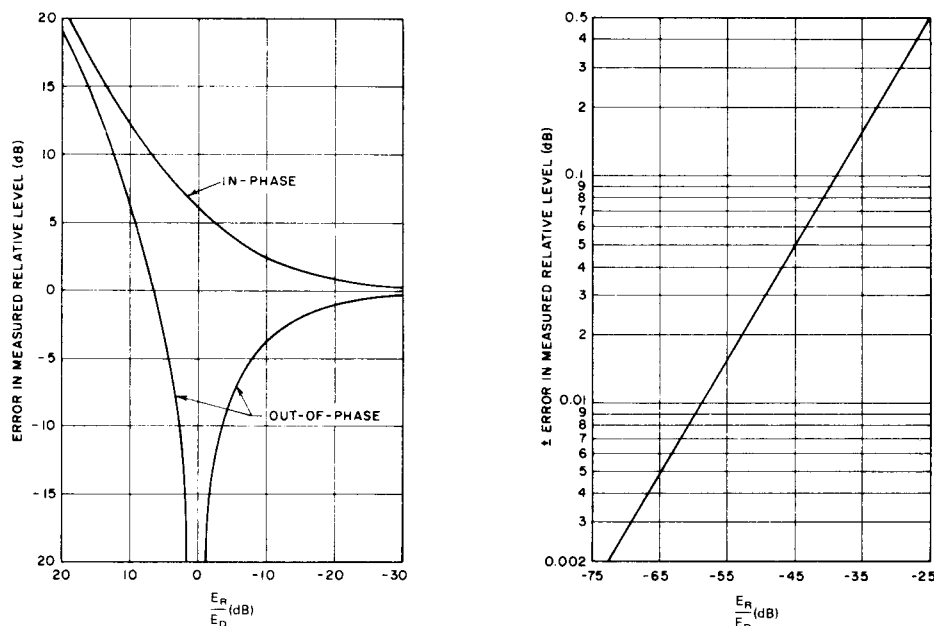


Figure 5—Possible Error in Measured Relative Pattern Level Due to Coherent Extraneous Signals
Linear Scales Are Employed for Signal Ratios of +20 to -30 dB; the Plus-or-Minus Errors Are
Essentially Equal for Ratios of -25 dB or Less, as Indicated in the Logarithmic Plot for Ratios down
to -75 dB

This example illustrates the fact that it is never advisable to direct the main beam of the test antenna toward the ground when measuring side lobes. The operational procedure for the range should be planned in such a way as to ensure that this does not happen. A means of rotating the test antenna through 180° about the axis of the main lobe should be provided for this purpose.

4.3.4 Use of Diffraction Fences and Longitudinal Ramps to Redirect Reflected Energy

When the antenna under test is essentially omnidirectional or when the required measurement calls for extremely small errors, then other means of suppressing the reflected signal will be required. Two methods which have found wide usage are diffraction fences and longitudinal ramps [1, pp 14.28–14.37].

Diffraction fences are metallic screens which are strategically located on the range in such a manner as to redirect, from the antenna under test, a portion of the energy that would, in the absence of the fence, be reflected from the range surface toward the test antenna. Diffraction fences can be of simple wooden frame construction covered with an ordinary conducting screen that has a mesh size of approximately 0.1 wavelength or less. When designing diffraction fences care shall be exercised to reduce the diffraction by their top edges. The effect of this diffracted field can be estimated by means of the theory of Fresnel diffraction by a half-plane. This leads to a result given in terms of Fresnel integrals, which are usually presented in graphical form as Cornu's spiral. The fences should be designed and located in such a way that they will not be illuminated by the main lobe of the source antenna. Thus it might be desirable to use several fences, each with a lower height than if a single fence were used. Additional suppression of the diffracted field can be achieved by installing either tuned slots or serrations on the top edge of the fence. Tuned slots are more effective; however, they are frequency sensitive. The fences should also be tilted, especially if multiple fences are used, to suppress multiple reflections.

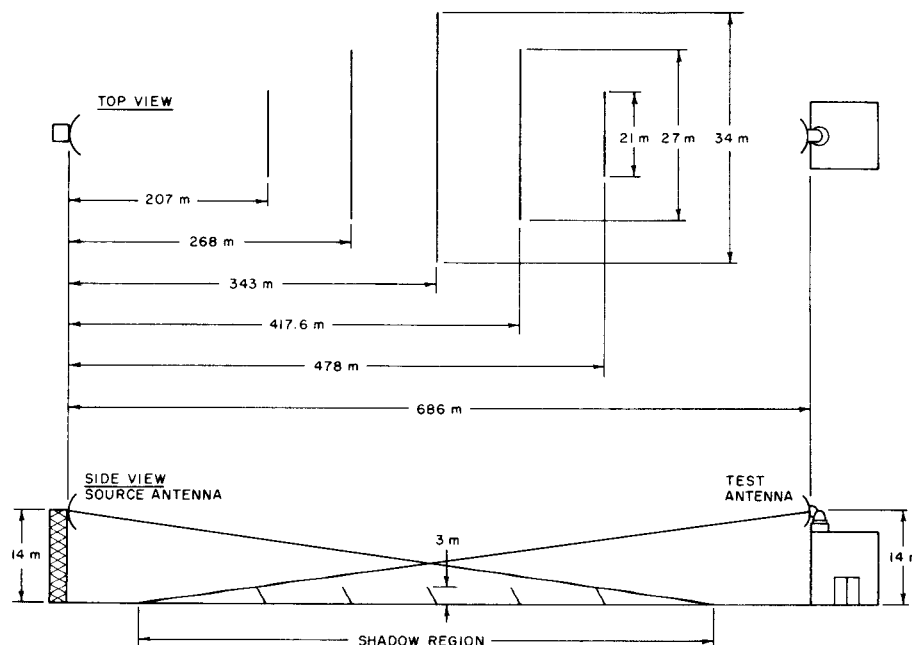


Figure 6—Example Configurations of a 686 Meter Elevated Range with Diffraction Fences

The necessary width of the fences has been empirically determined to span approximately 20 Fresnel zones constructed on the range surface. A possible diffraction-fence configuration for the 686 meter elevated antenna range is shown in Fig 6, and a sketch of a typical diffraction fence with serrations is shown in Fig 7. To save in cost, all fences are usually made identical in shape. The actual number of fences required and their positions and orientation should be determined experimentally (see 6.2).

A *longitudinal ramp* is a wedge-shaped reflecting surface symmetrically placed on the ground with its apex parallel to the range axis. Its purpose is to scatter the incident energy away from the test antenna. It can provide a moderate suppression of reflected energy at the test antenna; but generally it is less effective than a diffraction fence. Ideally the width of the base of the ramp should be such that it spans about 20 Fresnel zones as laid out on the ground surface between source and test antennas. The apex angle is usually chosen to be about 120° . For many situations these dimensions yield a prohibitively large structure, and a compromise is required, thus reducing the effectiveness of the ramp. For those ranges where the grazing angles of the incident energy are very small, more Fresnel zones are spanned by a ramp of a given size. Hence for these ranges one would expect the ramp to be more effective. Another design factor is the construction of the apex itself. Generally it is necessary to round it off rather than having it as a sharp edge. This results in a degradation at the higher frequencies. An obvious disadvantage of the ramp is that it fixes the range axis. If either the source antenna or the test antenna is moved in the transverse direction, the symmetry of the range is destroyed, and the unwanted reflected energy level at the test antenna increases. If the range has permanent tracks installed for the longitudinal motion of the antenna towers, then this is of little concern.

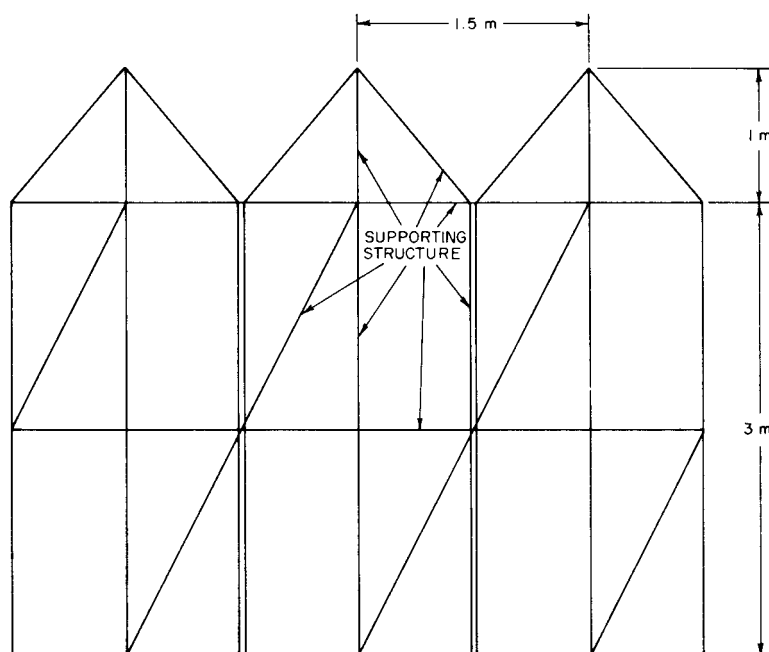


Figure 7—Example Configuration of a Diffraction Fence with Serrations
All Lines Indicate Supporting Structure; Not Shown Is the Wire-Mesh Covering

4.4 Design of Ground-Reflection Ranges

For the *ground-reflection range* the amplitude taper of the illuminating field at the test antenna in the horizontal direction will be the same as for the elevated range, and the criterion for the source-antenna size applies. In the vertical direction the reflected signal from the surface between the antennas combines with the direct signal to form an interference pattern (see Fig 8). By an adjustment of the height of the source antenna, the first interference lobe can be peaked at the center of the test antenna [4]. For a given frequency the height of the source antenna h_t is given approximately by

$$h_t \approx \frac{\lambda R}{4h_r}$$

where h_r is the height of the test antenna. The expected field at the test antenna will be dependent upon the complex reflection coefficient of the reflecting surface. Attempts are made, in the design of these ranges, to make the magnitude of the reflection coefficient approximately equal to 1.

The vertical amplitude taper of the illuminating field is determined by the height of the test antenna. In particular if the 0.25 dB criterion is applied, the height of the test antenna should be

$$h_r \geq 3.3D$$

where D is the diameter of the test antenna [4], [9]. Usually it is recommended that the criterion be

$$h_r \geq 4D$$

It is not always practical to position physically large test antennas at this height. For example, if it is necessary that the height of the test antenna be only $2D$, then the amplitude taper will be about 1 dB. This yields less accurate results but might be satisfactory for some applications. As previously discussed, the effect of amplitude taper is usually a reduction in measured gain and a slight modification in the side lobes. Also if the excitation of the test antenna is known, the error in gain produced by a known amplitude taper can be estimated.

Thus far it has been assumed that the magnitude of the reflection coefficient of the ground is equal to 1. Since this is not exactly true, the virtual center of radiation will not be midway between the source antenna and its image, but rather it will be some distance h'_t above that point, as shown in Fig 8. It has been found that for any range length greater than $2D^2/\lambda$ the apparent phase center is located directly beneath the source antenna at an approximate height above the range surface given by

$$h'_t \approx \frac{1 - |\Gamma|}{1 + |\Gamma|} h_t$$

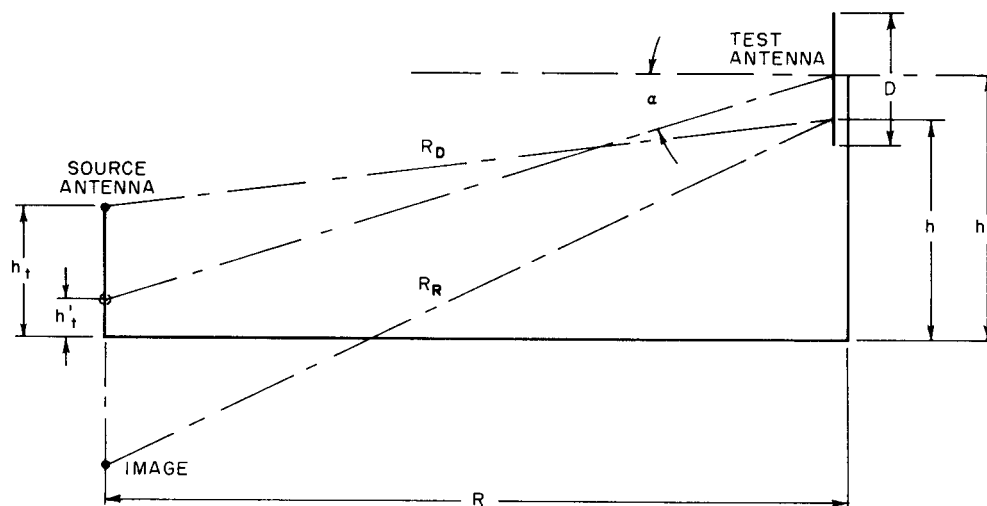


Figure 8—Ground-Reflection-Range Geometry

where $|\Gamma|$ is the magnitude of the reflection coefficient of the range surface for the polarization used at the angle of incidence determined from the range geometry. It is therefore necessary to calculate the direction from the test antenna to the virtual center of radiation and to orient the test antenna accordingly by providing the test antenna positioner with a tilt axis so that the entire positioner can be appropriately tilted.

It is crucial to the operation of a ground-reflection range that the surface of the range be prepared in such a manner that the energy incident upon it is specularly reflected [10]. This necessitates the specification of the “smoothness” of the surface. The Rayleigh criterion for smoothness is usually employed [1, pp 14.37–14.39], [3]. A useful form of it is given by

$$\Delta h \leq \frac{\lambda}{M \sin \psi}$$

where Δh is the root-mean-square deviation of the irregularities relative to the median surface, λ is the wavelength, ψ is the angle an incident ray makes with the horizontal (the grazing angle), and M is the smoothness factor. Smoothness factors ranging from 8 to 32 or greater are commonly used. This range of values corresponds to surfaces that are tolerable to very smooth. Of course Δh shall be computed for the highest operating frequency to be used.

The grazing angle ψ shall be kept small in order to avoid operating at the Brewster angle, which occurs at approximately 14° (measured from the horizontal) over land [11]. As the Brewster angle is approached, the magnitude of the reflection coefficient of the flat range surface decreases to a low value for waves that are vertically polarized, whereas the reflection coefficient for horizontal polarization is unaffected. This is undesirable if the range is to be used for both polarizations (see 6.4). It should be noted that the Brewster angle is dependent upon the electric properties of the material used in the construction of the range surface (and subsurface). For example, if the range surface were water, then the Brewster angle would decrease to approximately 4° [12]. In order for the polarization characteristics to be about the same as those for a range over land, the grazing angle shall be correspondingly smaller. This usually means that the length of the range would have to be increased.

Obviously the region directly between test and source antennas is the most critical, and as one moves from the centerline of the range, the requirement for surface smoothness becomes less demanding. A possible ground-reflection-range layout is depicted in Fig 9 [1, pp 14.39–14.41]. Notice that the range is divided into three areas: the primary area which is a nominally rectangular region located directly between source and test antennas, a secondary surface extending beyond the primary area, and a cleared area beyond that. The width of the primary surface is determined by constructing Fresnel zones over the range surface centered upon the specular reflection point that had been determined by the use of geometrical optics (ray tracing). The width of the primary surface should be such that about 20 Fresnel zones are contained within its boundaries. The surface tolerance of the secondary region can be reduced by a factor of 2 or 3. Its overall width should be about twice that of the primary region, but it should extend past the position of the test antenna by an amount of at least one quarter of the range length. In the actual design there would be no abrupt change in surface tolerance, but rather a gradual change from the primary to the secondary regions. The cleared area should be maintained by range personnel and kept free of all major reflecting obstacles. If practicable, it should extend from the edge of the secondary region at the source end of the range to points defined by the width of the first nulls in the horizontal plane of the source antenna's radiation pattern at the test-site end of the range. The cleared region should then continue as a rectangular area beyond the test site to a distance approximately equal to one half the range length.

In an alternate form of the ground-reflection range, the test antenna is mounted with its positioner on a nonconducting tower of sufficient height so that the source antenna is placed within a few wavelengths of the ground and the test antenna is centered upon the first interference lobe. This type of range is a variation of the slant range discussed in 4.5 [9], [13]. It is common practice to cover the reflection region of the ground in front of the source antenna with a smooth conducting surface. Since the source antenna is close to the ground, the extent of the conducting surface is relatively small so that it becomes economically feasible.

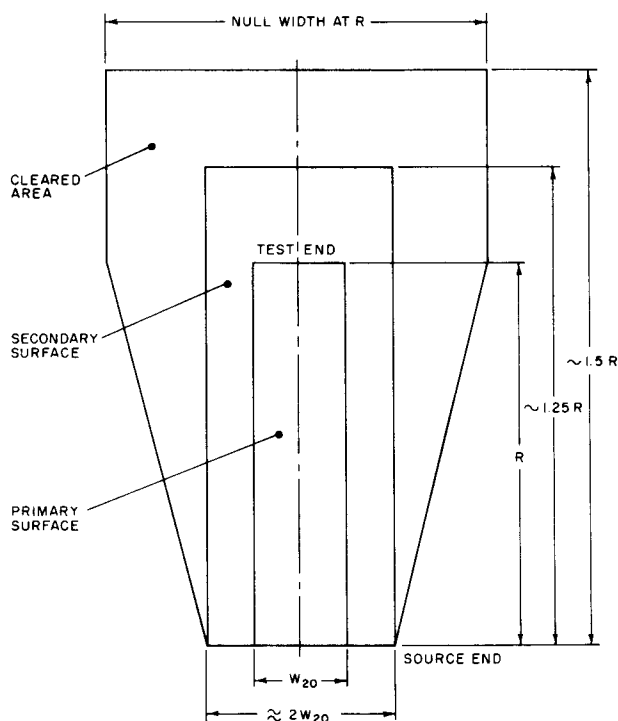


Figure 9—Possible Layout for a Ground-Reflection Range

Ground-reflection ranges find their greatest use at lower frequencies, especially in the VHF region of the spectrum, because of the difficulty of suppressing reflections in equivalent free-space ranges. However, ground-reflection ranges have been designed to operate at frequencies as high as about 35 GHz.

4.5 Other Ranges

4.5.1 Slant Range

The *slant range* [9], as the name implies, is designed with the source antenna near the ground and the test antenna along with its positioner mounted on a nonconducting tower at a fixed height, as depicted in Fig 10. The source antenna is located and oriented so that its free-space radiation-pattern maximum points toward the center of the test region and its first null is pointing toward the specular reflection point on the ground. In this way the reflected signal is suppressed. Alternate forms of the slant range are classed as reflection ranges in as much as reflections from the ground are used in order to approximate a plane wave at the test region [13], [14]. This type of slant range is a variation of the ground-reflection range and is discussed in 4.4. Slant ranges have been designed with towers where the height can be changed so that the spacing between source and test antennas can be varied. In general a slant range requires less land for a given spacing than an elevated range.

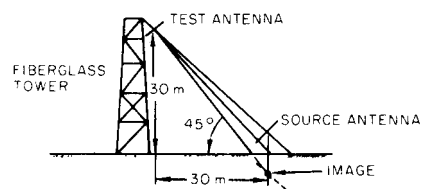


Figure 10—Slant-Range Geometry

4.5.2 Compact Range

The *compact range* [15], is one in which the test antenna is illuminated by the collimated energy in the aperture of a larger point or line focus antenna. For example, a precision paraboloidal antenna can be used to collimate the energy as shown schematically in Fig 11. The linear dimensions of the reflector is usually chosen to be at least three times that of the test antenna so that the illumination at the test antenna sufficiently approximates a plane wave. An offset feed for the reflector is recommended to prevent aperture blockage and to reduce the diffracted energy from the feed structure which may contaminate the field in the test region. To further reduce the effects of the diffraction from the feed structure and also to suppress any direct radiation from the feed antenna in the direction of the test region, the reflector can be designed with a focal length long enough that the feed antenna can be mounted directly below the test antenna. If this is done, then high-quality absorbing material can be placed between test and feed antennas to absorb the unwanted radiation. The use of a relatively long-focal-length reflector has the additional advantage that for a given size reflector the depolarization effect associated with curved reflectors is lessened. Diffraction from the edges of the reflector can be reduced by designing the reflector with serrations about the edges.

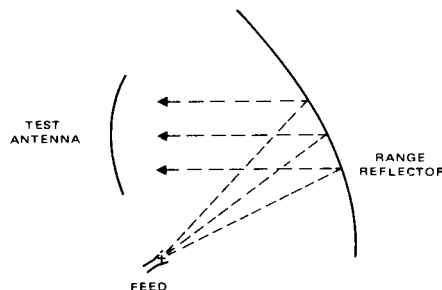


Figure 11—Schematic Representation of a Compact Range Using a Reflector and Feed

In order to obtain good results with a compact range, the reflector shall be constructed with sufficient accuracy. Small deviations in the fabricated reflector surface can result in significant variations in the amplitude and phase distribution of the incident field at the test antenna. To assess the effect of surface deviations not only their shapes and maximum deviations shall be specified but, also very importantly, their areas. For example, if the reflector has small deviations

that do not exceed $\lambda/100$ and their individual sizes are also small (less than one square wavelength), then the integrated effect of all the deviations over the entire reflector will be quite small, and hence a fairly uniform amplitude distribution of the incident field over the test antenna will be obtained. On the other hand, suppose the reflector had a single surface deviation near the center of the reflector, extending over an area comparable to 1 Fresnel zone. Then a very significant change in the incident field would be expected [16]. As indicated by this example, the range reflector shall be fabricated with great care.

The compact range can be evaluated in the same manner as conventional ranges by the use of field-probing techniques (see 6.2). Since the illuminating field is obtained by the reflection from a curved surface, some depolarization is to be expected. The field probing should, therefore, include measurements of polarization as well as amplitude and phase, especially if the measurements to be made depend upon the polarization characteristics in the illuminating field.

4.5.3 Image-Plane Range

The *image-plane range* consists of a precision ground plane surrounded by absorbing material or with serrations along its edges which reduce the edge effects due to its finite size. The antenna under test is cut into two parts along its image plane, and the part above the image plane is mounted onto the ground plane.

NOTE — The image plane of an antenna refers to an imaginary plane through the antenna over which the tangential electric field is zero.

The radiation pattern of the resulting configuration in the half-space above the ground plane is equivalent to that of the entire antenna radiating into free space. (This is not true for the input impedance.) That this is so can be shown by evoking image theory, hence the name image-plane range. The radiation pattern above the ground plane is measured by moving a source antenna in such a manner as to appropriately sample the field. This type of range has the obvious disadvantage that its use is restricted to those antennas that have an image plane, that is, antennas that exhibit linear polarization over a plane with excitations having even symmetry for polarizations normal to the plane (sum mode) or odd symmetry for polarizations parallel to the plane (difference mode). Perhaps even more restrictive is the fact that if the antenna is not designed to operate as an image-plane antenna, it shall be cut along its image plane. This means that this range is generally relegated to developmental and research work.

4.5.4 Anechoic Chambers

There are two basic types of anechoic chambers, the rectangular and the tapered types [17].

- 1) The *rectangular anechoic chamber* is usually designed to simulate free-space conditions. High-quality absorbing material is used on surfaces that reflect energy directly toward the test region in order to reduce the reflected energy level. Even though the sidewalls, floor, and ceiling are covered with absorbing material, significant specular reflections can occur from these surfaces, especially for the case of large angles of incidence. One precaution that can be taken is to limit the angles of incidence to those for which the reflected energy is below the level consistent with the accuracy required for the measurements to be made in the chamber. Often, for high-quality absorbers, this limit is taken to be a range of incidence angles of 0° to 70° (as measured from the normal to the wall). For the rectangular chamber this leads to a restriction of the overall width or height of the chamber such that

$$W \geq \frac{R}{2.75}$$

where R is the separation between source and test antennas and W is the overall width or height of the chamber. The actual width and height chosen shall depend upon the magnitude of the errors that can be tolerated and upon the measured characteristics of the absorbing material used to line the walls. Additionally the room width and the size of the source antenna should be chosen such that no part of the main lobe of the source antenna is incident upon the sidewalls, ceiling, and floor.

- 2) The *tapered anechoic chamber* is designed in the shape of a pyramidal horn that tapers from the small source end to a large rectangular test region, as shown in Fig 12. This type of anechoic chamber has two modes of operation. At the lower end of the frequency band for which the chamber is designed it is possible to place the source antenna close enough to the apex of the tapered section so that the reflections from the sidewalls, which contribute directly to the field at the test antenna, occur fairly close to the source antenna. Using ray-tracing techniques, one can show that for a properly located source antenna there is little change in the phase difference between the direct-path and the reflected-path rays at any point in the test region of the tapered chamber. The net effect is that these rays add vectorially in such a manner as to produce a slowly varying spatial interference pattern and hence a relatively smooth illumination amplitude in the test region of the chamber. It should be emphasized that the source antenna shall be positioned close enough to the apex for this condition to exist. The position is best determined experimentally, although a useful way of estimating its required position can be obtained by drawing an analogy between the tapered anechoic chamber and the ground-reflection range (see 4.4). By use of this analogy the perpendicular distance h_t from the source antenna to the chamber wall should satisfy the inequality

$$h_t < \frac{\lambda R}{4h_r}$$

where λ is the wavelength, R is the separation between source and test antennas, and h_r is the perpendicular distance from the fixed test antenna to the chamber wall. If the source antenna is moved forward in the chamber, then the interference pattern becomes more pronounced, with deep nulls appearing in the region of the test antenna.

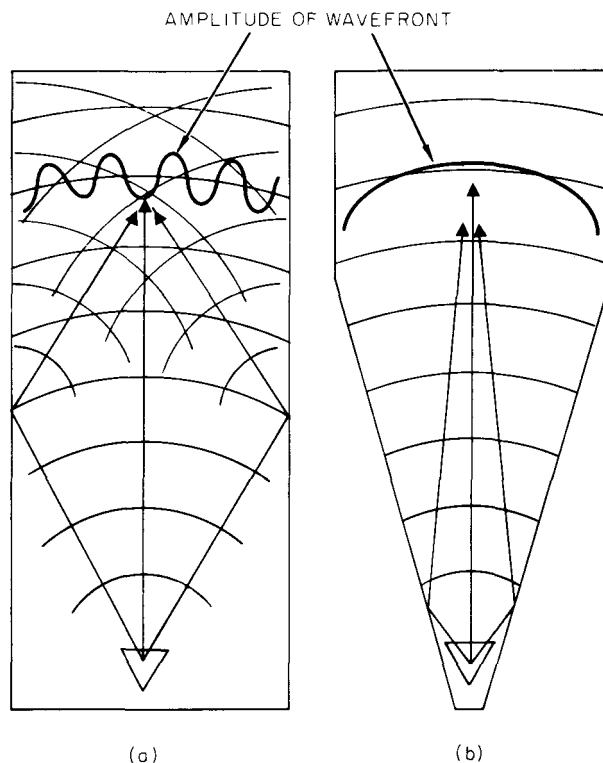


Figure 12—Specular Reflections from Sidewalls in Anechoic Chamber
(a) Rectangular Chamber. (b) Tapered Chamber

As the frequency of operation is increased, it becomes increasingly difficult to place the source antenna near enough to the apex. When this occurs, a higher gain source antenna is used in order to suppress reflections. It is moved away from the apex, and the chamber is then used in the free-space mode similar to the rectangular chamber.

The field does not spread in the manner of a spherical wave, hence the tapered chamber cannot be used for any gain measurement based directly upon the Friis transmission formula, such as the two-antenna or three-antenna gain-transfer methods [6].

5. Antenna-Range Instrumentation

5.1 General

The instrumentation required for an antenna test range can be classified into five subsystems:

- 1) source antenna and transmitting system
- 2) receiving system
- 3) positioning system
- 4) recording system
- 5) data-processing system

The extent of the instrumentation required depends upon the functional requirements imposed by the measurements to be made. The instrumentation may range from very simple systems designed for making only principal-plane patterns of simple antennas to highly automated systems in which computers are programmed to control all aspects of the measurement, including the data processing for the complete characterization of highly complex antennas.

A block diagram of the basic instrumentation elements of an antenna test range is shown in Fig 13. The control units, indicators, receiver, recorders, and tuning units for the transmitters are usually located in a master-control console. The signal source itself is usually located at a remote antenna tower.

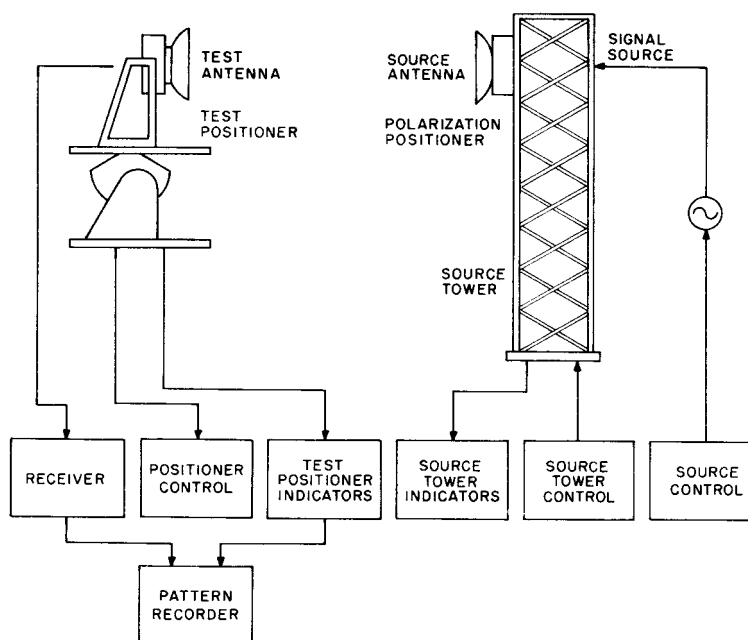


Figure 13—Block Diagram of Typical Antenna-Measurement System

5.2 Source Antennas for Antenna Ranges

With the exception of a few highly specialized installations, antenna test ranges are designed to operate over a wide band of frequencies. This means that they shall be equipped with a family of source antennas and transmitters covering the entire band. The antennas shall, of course, have the beamwidths and polarization properties consistent with the measurements to be performed on the range.

For frequencies below 1.0 GHz, log-periodic arrays are often used, and for frequencies above 400 MHz families of parabolas with broad-band feeds are most often used. In some cases large horn antennas have been utilized. A means for controlling the polarization is usually required. As will be discussed in 5.5, this can be accomplished by mounting a linearly polarized source antenna on a polarization positioner. Then the direction of polarization can be continuously rotated. This feature is required for some types of measurements. Some other types of measurements require circular polarization so that a well-equipped antenna test range usually has families of both linear and circularly polarized source antennas. The circularly polarized antennas can be designed so that they can produce right-hand or left-hand circular polarization, as well as orthogonal linear polarizations. Crossed log-periodic arrays are examples of such antennas. In addition, a set of gain-standard antennas is necessary if power-gain measurements are to be made using the gain-transfer method (see 12.3).

5.3 Transmitting Systems

The selection of the transmitter depends upon several system considerations [1, pp 15.11–15.37]. There are a number of types of signal sources available such as triode cavity oscillators, klystrons, magnetrons, backward wave oscillators, and various solid-state oscillators.

Whatever type of signal source is chosen, the following performance requirements apply:

- 1) *Frequency control.* A means shall be available to tune the signal source to the desired frequency. Depending upon the type of signal source used, mechanical, electromechanical, or electrical means may be employed. If the transmitter is remote, a means of remote control is highly desirable. A calibrated position servo loop or a rate servo loop can be used to control a motor that mechanically tunes the oscillator. For the case of oscillators that can be electrically tuned, an adjustable, regulated power supply is required.
- 2) *Frequency stability.* Since the antennas and their associated radio-frequency circuitry are highly frequency sensitive, it is necessary that the signal-source frequency remain constant over the measurement period, which may be in excess of 30 minutes. Frequency variations of the order of 0.01 to 0.1 percent are usually acceptable. But for more precise measurements, a frequency stability of one part in 10^6 or better may be required.

The following are several methods of frequency stabilization in common use:

- a) control of the operating environment, such as by immersion of the oscillator in a temperature-controlled oil-bath
 - b) coupling of the oscillator to a high- Q cavity
 - c) electronically referencing the oscillator to a microwave cavity (the Pound system) [18]
 - d) electronically referencing the frequency to a stable source (automatic frequency control)
 - e) phase locking the frequency to a stable source (automatic phase control)
- The particular scheme used depends upon the type of oscillator used.
- 3) *Spectral purity.* Some types of oscillators are rich in harmonics which, if transmitted, would contaminate the desired signal. In some cases spurious or nonharmonically related signals are generated. To eliminate these unwanted signals one can either use filters or employ a receiver that will discriminate between desired and undesired signals.

- 4) *Power level.* The required power output of the signal source for a particular measurement is dependent upon the source and test antenna gains, the receiver sensitivity, the transmission loss between the two antennas, and the dynamic range required for the measurement. Typical detectors used in antenna instrumentation systems have sensitivities on the order of -50 to -65 dBm. If a receiver is used, this figure may be improved as much as 30 to 60 dB. Power levels provided by typical antenna-range signal sources range from 0 to 33 dBm. Since most antenna tests are amplitude measurements, it is important that the output of the signal source be relatively constant. For most measurements a variation of ± 0.05 dB, which is easy to obtain, is not significant; but for some cases, such as insertion-loss or gain-transfer measurements, variations of ± 0.01 to ± 0.02 dB for short periods of time may be required. For these cases an automatic power-level control shall be provided.
- 5) *Modulation.* For some systems amplitude modulation is required; hence the signal sources should have that capability. There are cases where special pulse shaping is required to reduce the distortion of the pulse spectrum.

5.4 Receiving Systems

The receiving subsystem used in the *antenna-amplitude-pattern measurement system* may be simply a bolometer detector (usually mounted directly on the test antenna or, in the case of a scale model, inside the model) and its associated amplifier, the output of which supplies the signal to the recorder. With this system the transmitter is usually modulated. Also the dynamic range of the system is limited to the range over which the bolometer has a square-law characteristic, usually about 40 dB. The simple *detector-amplifier receiving system* finds wide application for antenna ranges where extensive scale-model work is done or where quasi-isotropic antennas are tested. With this system the detected signal can be fed to an amplifier by means of a high-impedance cable, thus reducing the reflections from the cable connecting the test antenna to the console (see 7.1).

The simple bolometer-amplifier system lacks the dynamic range, sensitivity, and frequency discrimination for most antenna measurements. This has led to the development of superheterodyne receivers specifically for use in antenna measurements. These receivers are typically designed to operate over an extremely wide range of frequencies, from a few megahertz to above 100 GHz. The harmonics of the local oscillator are used for operation in the millimeter and submillimeter range and, for the case of low-frequency reception, the received signal is upconverted to a frequency within the range of the receiver [1, pp 15.38–15.49].

It is desirable that the receiver be physically located in the master console, whereas the antenna under test may be remotely located. To avoid the degradation of excessive cable attenuation at lower frequencies and the inconvenience of long runs of waveguide at higher frequencies, the first mixer is usually mounted directly on the terminals of the antenna under test. A single coaxial cable carries the local oscillator power to the mixer and provides the return of the intermediate-frequency signal from the mixer to the receiver. This places a limitation on the allowable cable attenuation for proper mixing, usually about 15 dB.

The receivers are often equipped for both manual and motor-driven tuning. The motor control can be used for a mechanical automatic frequency control and can be designed in such a manner that the receiver can be used for swept-frequency measurements.

Antenna-pattern recorders are typically designed to operate at a fixed 1 kHz audio carrier frequency; for these cases the output of the receiver shall be 1 kHz. Antenna-pattern-range receivers are usually designed for continuous-wave reception, and the 1 kHz amplitude modulation is introduced in the receiver. The need for remote adjustment of the modulation frequency of the signal source is thus eliminated.

A bolometer is most often used for detecting the 1 kHz modulation of the intermediate-frequency carrier. The dynamic range of the receiving system is limited by the square-law range of the bolometer (about 40 dB), unless some means of compensation is provided. Compensation can be accomplished by the introduction of a bias voltage in the intermediate-frequency amplifier to vary its gain by the use of an auxiliary potentiometer connected to the pen drive.

The bias voltage can be controlled so that the receiver gain increases as the recorder pen moves downscale. The system does require a set of adjustments for proper operation, with which the dynamic range can be increased to about 60 dB.

If the signal source is not sufficiently frequency stabilized to eliminate all significant frequency drift, then an automatic frequency control must be employed. The automatic frequency control may also be needed to compensate for local oscillator drift. It shall be capable of operation over the dynamic range of the input signal, that is, more than 40 dB.

A useful circuit which is sometimes incorporated into measurement receivers is one that compensates for small transmitter power-level variations. This circuit requires that the signal from the transmitter be monitored continuously during the measurement.

If greater sensitivity, precision, and dynamic range are required, the *double-conversion phase-locked receiver* may be employed. This type of receiver produces the required 1 kHz output signal by conversion rather than by square-law detection. Heterodyning to such a low second intermediate frequency is made possible by the use of phase-lock techniques. A block diagram of a single-channel double-conversion heterodyne circuit is shown in Fig 14 [1, pp 9.9–9.13]. The phase-lock circuit causes the first intermediate frequency to be synchronous (locked) to the frequency of a highly stable crystal oscillator. Because of the purity of the crystal-oscillator spectrum, the intermediate-frequency contains almost no frequency-modulation components within the passband of the phase-lock loop. This permits the intermediate-frequency signal to be converted to 1 kHz by means of a second crystal oscillator, which is in turn phase-locked so that its frequency differs from the intermediate frequency by precisely 1 kHz. The bandwidth of the first intermediate-frequency amplifier is typically of the order of 10 MHz, while that of the second intermediate-frequency amplifier is of the order of 100 Hz.

The noise bandwidth of the double-conversion system is approximately equal to twice that of the output bandwidth of the receiver, that is, usually 200 Hz. This is in contrast to that of the conventional receiver employing square-law detection. The noise bandwidth of the latter is approximately $\sqrt{2B_1 \cdot B_2}$, where B_1 is the bandwidth of the intermediate-frequency amplifier and B_2 , the bandwidth of the postdetection amplifier. Typically B_1 and B_2 are chosen to be 1 MHz and 100 Hz, respectively. A considerable improvement in sensitivity is obtained by using the double-conversion phase-locked receiver rather than the conventional receiver.

An additional advantage of the double-conversion phase-locked receiver is the fact that the change in output voltage is linearly proportional to the change in input voltage rather than input power. In receivers with square-law detectors a 10 000:1 change in output voltage is required to represent a 100:1 change in input voltage. The double-conversion phase-locked receiver requires only a 100:1 output ratio to represent a 100:1 input ratio. It is quite easy to achieve a 1000:1 output ratio, giving a 60 dB dynamic range. Although dynamic ranges of 80 dB can be achieved with extreme care in design, a 60 dB dynamic range appears to satisfy most measurement problems.

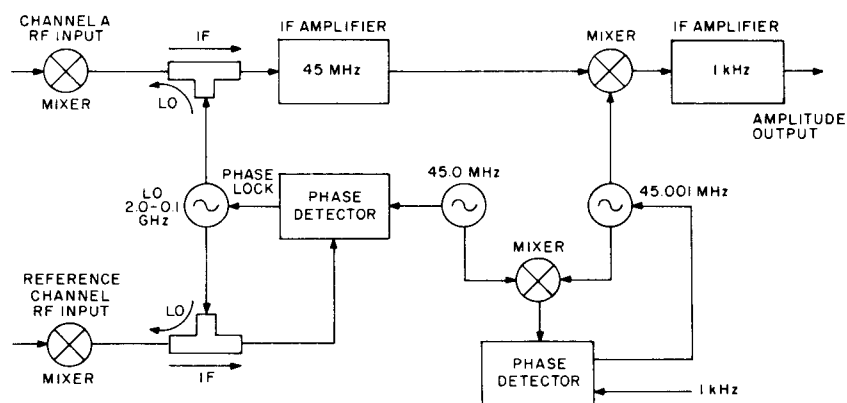


Figure 14—Basic Heterodyne Receiving System Using Double Conversion and Phase Locking

For some antenna-measurement applications the rate at which data can be taken is of importance. While often the data rate is limited by the rate at which the antenna under test (or the source antenna in the case of a movable line-of-sight range) can be physically moved, there are situations where the data rate is limited by the bandwidth of the output circuit of the receiver. For these cases, in order to increase the data rate, the output bandwidth has to be increased. This will also reduce the sensitivity, and hence the dynamic range, of the system so that there is a trade-off between increased data rate and system sensitivity. Usually in order to increase the output bandwidth the output frequency shall also be increased. Since the sensitivity of bolometer detectors decreases rapidly with increased modulation frequency, it is impractical to increase the output frequency of a conventional receiver. With the double-conversion phase-locked receiver a detector is not used, so one has a choice of output frequencies. For example, if the output frequency is such that the output bandwidth can be increased by a factor of 10, then for this receiver the data rate will increase by a factor of 10 with a corresponding decrease in system sensitivity of 10 dB.

The phase-locked receiver requires a reference signal that can be obtained either from a reference antenna or, where distances are short, by a direct sample from the signal source.

If phase measurements are also required, then a dual-channel double-conversion phased-locked receiver may be used [1, pp 9.9–9.13], [19]. A block diagram is shown in Fig 15. The circuit is similar to that shown in Fig 14 except that it has two signal channels, designated A and B, which are fed by the same first and second local oscillators. The output voltage of each channel is directly proportional to the input microwave voltage of that channel, and the signal level in each channel can vary independently over the dynamic range of the system.

One of the primary areas of concern in a system of this nature is that of eliminating interchannel interference. By the use of isolators, proper shielding, and careful design, the interchannel isolation can be maintained greater than 90 dB. An interchannel isolation of this magnitude results in linearity errors over a 60 dB dynamic range of less than ± 0.25 dB.

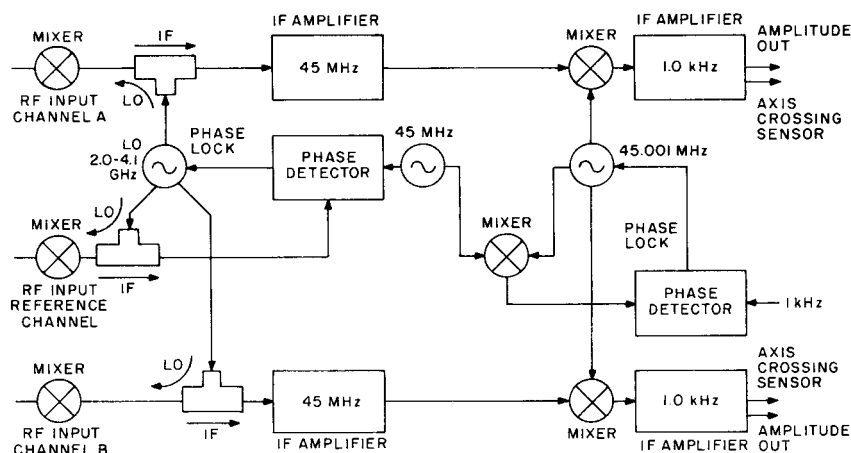


Figure 15—Dual-Channel Heterodyne Receiving System for Phase Measurements

After the heterodyning of the two input signals to a final frequency of 1 kHz, phase measurement becomes essentially a time measurement. Fig 15 shows a second output from each of the 1 kHz intermediate-frequency amplifiers feeding an axis-crossing sensor. As the name implies, each axis-crossing sensor senses the time of the axis crossover of the 1 kHz signal. Specifically it senses each positive axis crossing. At that instant each axis-crossing sensor provides a narrow pulse output. Measurement of the time between axis crossings of the signal in channel A and that in channel B can be directly translated to degrees at 1 kHz, and consequently to the input radio-frequency signal. With a system of this type, amplitude variations of the signals in the two signal channels and the phase difference between them can be measured simultaneously. Amplitude and phase readouts can be provided in either analog or digital form as required.

If the receiver is to be used in an automated system, it is highly desirable that it be computer compatible, that is, its output should be such that the receiver can be interfaced directly with a computer. Also, an agile local oscillator is required if the operating frequency has to be changed during the course of the measurement.

5.5 Positioning Systems

5.5.1 Antenna Positioners

For either the fixed- or the movable-line-of-sight methods (see 3.3) two orthogonal axes are required if true θ and ϕ cuts are to be made. These axes are designated as the θ rotational axis and the ϕ rotational axis and are depicted in Fig 16. The ϕ axis, which permits cuts in ϕ with θ as the parameter, is the OZ axis of the coordinate system. The θ axis, which provides for θ cuts with ϕ as the parameter, is coincident with the line OA drawn through the origin normal to the line OS , where OS defines the direction to the source antenna. These axes are employed in all spherical-coordinate positioner configurations [1, pp 5.12–5.24].

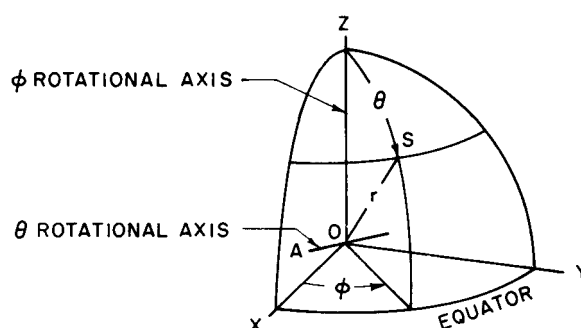


Figure 16—The Two Orthogonal Axes of Rotation Required by an Antenna Positioner Using Spherical Coordinates

A possible positioner configuration for the movable-line-of-sight system is shown in Fig 17. It consists of a gantry which provides the θ rotation and an azimuth positioner which provides the ϕ rotation. This scheme is of restricted utility, since the distance between the two antennas is limited. It is useful for testing small antennas such as primary feeds for reflector antennas. An alternate approach to the use of a gantry is to mount the source antenna on a carriage that moves along a fixed semicircular arch centered upon a turntable on which the test antenna is mounted. By control of the movements of the carriage and the turn-table both θ and ϕ cuts can be obtained. Arches with radii as large as 19.8 meters have been constructed [20]. This type of range is primarily used for testing vehicle-mounted VHF and UHF antennas, as well as scaled models of high-frequency antennas (see 7.1) [20].

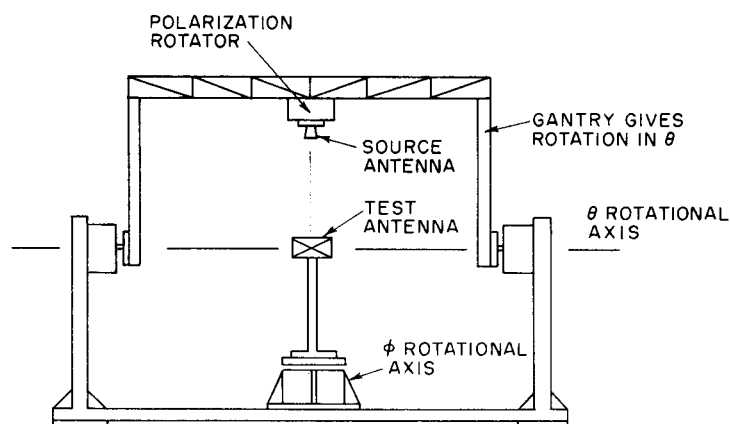
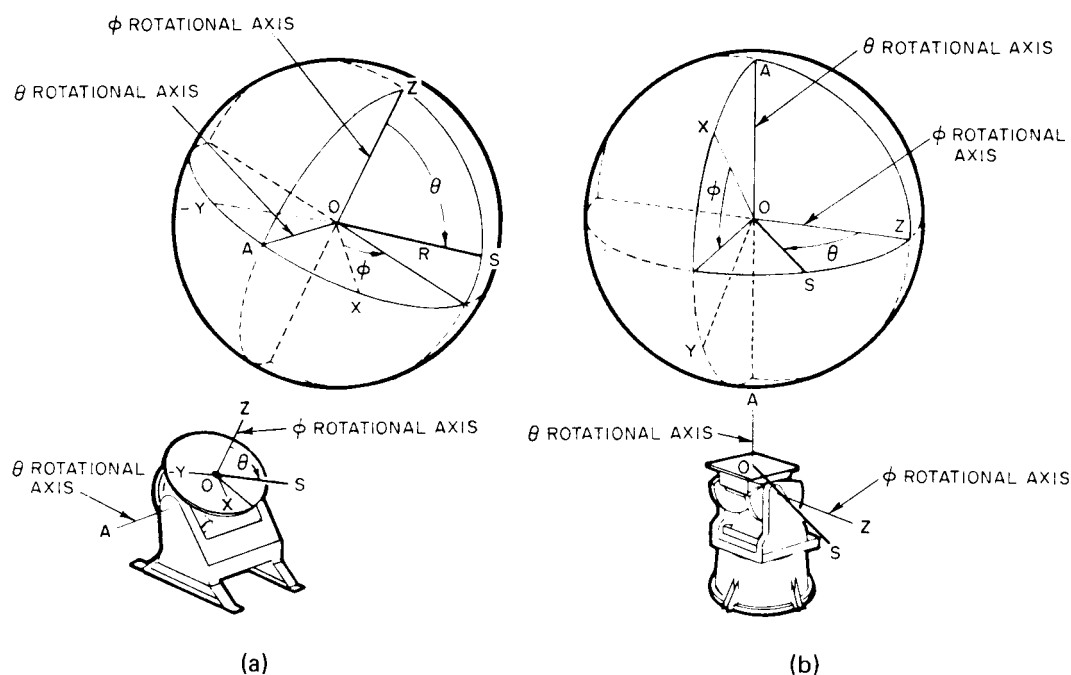


Figure 17—Positioner Configuration in which the Source Antenna Is Supported by a Gantry that Provides the θ Rotation

In the case of the fixed-line-of-sight system the θ and ϕ rotations are provided completely by the positioner for the test antenna. Two positioners which meet the requirements for this system are the azimuth-over-elevation and the elevation-over-azimuth types. These positioners and their associated coordinate systems are shown in Fig 18. An alternate example of an elevation-over-azimuth positioner is the model tower (see Fig 19). Greater flexibility can be obtained by the use of additional axes; for example, azimuth-over-elevation-over-azimuth positioners are frequently employed.

It is desirable that the operational coordinate system of the test antenna be coincident with that of the positioner. Otherwise the interpretation of the measured data and the evaluation of errors become difficult. Moreover, the physical characteristics of the test antenna and the general shape of its radiation pattern are important considerations in the selection of a positioner. Indeed it is often necessary that a positioner be designed explicitly to satisfy a specific measurement requirement where nonstandard motions are required [3].



(a) Azimuth-over-Elevation Positioner.

(b) Elevation-over-Azimuth Positioner

Figure 18—Two Standard Positioner Configurations and their Associated Spherical Coordinate Systems

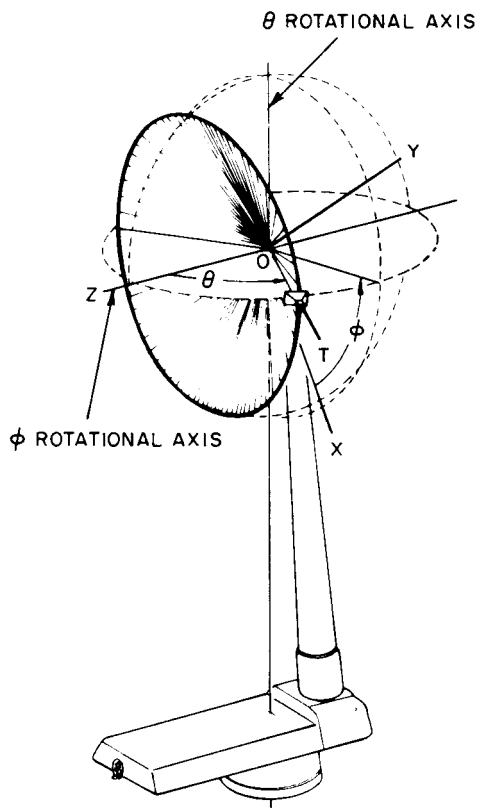


Figure 19—Model Tower and Its Associated Spherical Coordinate System

Specially designed positioners may be required when the radiation pattern of the test antenna is essentially isotropic. For this case the positioner has to be designed so that it does not significantly alter the radiation pattern of the antenna under test. One method is to suspend the antenna on the end of a long nonmetallic boom. Another method is to mount the antenna on a plastic foam tower. For either of these methods, obtaining the motions required for a complete set of radiation patterns is difficult.

If the measurement requires the use of orthogonal polarizations, then the source antenna should be provided with a means to change its polarization. Source antennas can be designed in such a manner that their polarization can be electrically switched between two orthogonal linear or circular polarizations. For the case of orthogonal linear polarizations, a more common method is to use a source antenna positioner that is capable of rotating a linearly polarized source antenna through at least 180° , although for some methods of polarization measurement the direction of polarization shall be rotated continuously through 360° during the measurement (see 11.2).

5.5.2 Antenna-Positioner Errors

The errors introduced in the measurement of radiation patterns by positioners are angle errors or pointing errors. The following is an outline of errors associated with positioners [1, pp. 5.32–5.41]:

- 1) Geometric error
 - a) *Coordinate-axis-alignment error.* Improper alignment of the coordinate system of the test antenna with that of the antenna positioner.
 - b) *Orthogonality error.* Nonorthogonality of the two rotation axes of the antenna positioner.
 - c) *Collimation error.* Nonorthogonality of the θ axis with the line from the origin of the positioner coordinate system to the source antenna (line OS in Fig 16)
 - d) *Axis runout and axis wobble*

- 2) *Shaft-position error.* Errors in the determination of the shaft-position angle
- 3) *Deflection errors.* Structural changes in the positioner because of thermal expansion and contraction and changes in the forces applied to the positioner

Some of the geometric errors are inherent in the design and construction of the positioner. However, for well-designed positioners these errors are generally very small, and their magnitudes can usually be determined from the manufacturer's information. For errors due to the installation of the positioner and the mounting of the test antenna, range personnel do have some control. This is especially true in the case of mounting the test antenna onto the positioner. Care should be exercised in the design of the mount so that the test antenna's coordinate system coincides with that of the positioner.

Shaft-position-angle information can be obtained by the use of synchro systems, potentiometers, or digital encoders. Typically commercial positioners use dual synchro systems with the transmitters geared at ratios of 1:1 and 36:1 with respect to each axis. The readout system may be of either an analog type or a digital type. The analog type consists of a synchro receiver indicator, whereas the digital type requires an analog-to-digital converter. Readout errors of approximately 0.05° to less than 0.01° are typical, depending upon the unit considered. Direct-drive digital encoders are more accurate than the geared synchro system and are used where high precision is required. High-accuracy digital encoders may either be of the multipole-resolver type or of the optical type.

Deflection errors due to solar heating can be reduced by solar reflectors, insulating shields, reflecting paint, and barriers. Those due to changes in bending moments applied at the antenna mounting surfaces can frequently be reduced by incorporating counter balance weights in the design of the antenna mount in such a way that the change in bending moment is reduced.

5.6 Antenna-Pattern Recorder

The *antenna-pattern recorder* provides a means of obtaining a visual display of the antenna pattern. It is used to plot the relative signal strength received by the test antenna as a function of the angular position of the antenna. The signal to be plotted is obtained from the output of a receiver or directly from a microwave detector, depending upon the type of receiving system used. The position information is normally obtained from synchro transmitters or digital encoders geared to the positioner axes. In addition to the measurement of signal strength, the relative phase angle between two signals can be recorded if the receiving system provides a dc output with an amplitude in proportion to the radio-frequency phase angle.

Typical antenna-pattern recorders are electro-mechanical devices employing servo systems to drive the recorder axes. A chart servo system usually positions the recording paper as a function of the angular position of the antenna. A pen servo system positions a recording pen in response to the amplitude of the input signal. Ink-writing systems are mostly used in preference to electric, thermal, pressure-sensitive, or photographic systems because of the high quality, high writing speed, reproducibility, economy, and simplicity of an ink system.

The antenna pattern may be recorded in either polar or rectangular form. The polar form is often preferred for plotting patterns of antennas that are not highly directional. The polar format is particularly useful for visualizing the power distribution in space. Such a plot is illustrated in Fig 20(a).

In the rectangular format [Fig 20(b)] the signal amplitude is the y axis (ordinate) and the position angle is the x axis (abscissa). The rectangular format permits narrow beam patterns to be recorded in finer detail because the pattern does not become crowded in regions of relatively low gain as it does in a polar graph. To provide adequate resolution in a rectangular display of patterns of different beamwidths, selectable chart scales are required.

An expanded rectangular-coordinate chart scale is obtained by deriving the angle information from a synchro transmitter geared to the positioner axis, so that the synchro shaft rotates a number of times for one revolution of the positioner turntable. A 36:1 synchro ratio is commonly employed, resulting in one turn of the synchro shaft corresponding to 10° of positioner rotation. This ratio is especially convenient for a readout of the positioner angles with devices such as dual-pointer synchro indicators, since the 36:1 ratio is compatible with the decimal numbering system.

NOTE — A ratio such as 16:1 or 32:1 is used in dual-speed synchro systems in which position angles are read as binary numbers.

With dual-speed 1:1 and 36:1 synchro transmitters the recorder chart scale (or one chart cycle) is 10° of 360° . An intermediate 60° chart cycle can also be provided by gearing a synchro to the chart axis of the recorder at a 6:1 ratio. Thus six rotations of the 36:1 synchro transmitter are required for one chart cycle.

A rectangular-coordinate recorder in which the chart paper is driven by the chart servo is referred to as a strip-chart recorder. If the pen is driven in both the x and the y coordinates, the recorder is referred to as an x - y recorder. Usually polar recordings are obtained by driving a turntable with the chart servo. However, an x - y recorder can be used to generate polar plots by electronically performing the coordinate conversion. For practical reasons the transformation is made using 1:1 synchro information only.

Antenna pattern recorders usually provide for a selection of amplitude functions. The pen deflection may be directly proportional to the amplitude of the input signal to the recorder, or the response may be proportional to the square, square root, or logarithm of the input. If the proper pen function is selected for the particular type of detector used, either a linear or a square-law detector, the recording may be presented as a function of the power, radio-frequency voltage, or relative signal level in decibels. This leads to the following pattern formats.

Relative power patterns illustrate the variation of power density at a fixed distance from the antenna as a function of angular coordinates [Fig 21(a)]. Power patterns are most useful in assessing small power variations between 100 and 10 percent of the peak value. Power variations in the range below 10 percent of full scale are difficult to resolve without changing gain levels. Power patterns are used in calculating directivity, and sometimes in making measurements to determine half-power beamwidths of antennas because of the increased resolution afforded at the higher signal levels. They would not be useful in measurement problems where low side lobe levels and high front-to-back ratios are of interest.

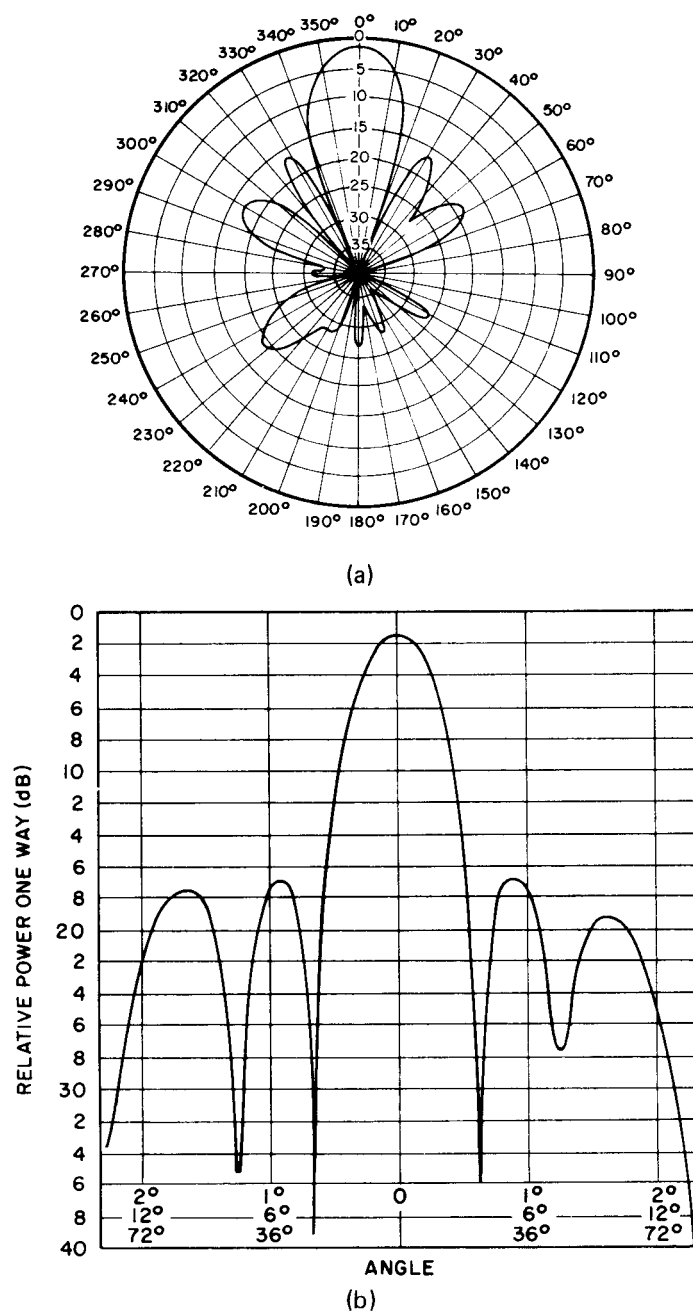


Figure 20—Polar and Rectangular Logarithmic Plots of a Normalized Radiation Pattern
(a) Polar Plot. (b) Rectangular Plot

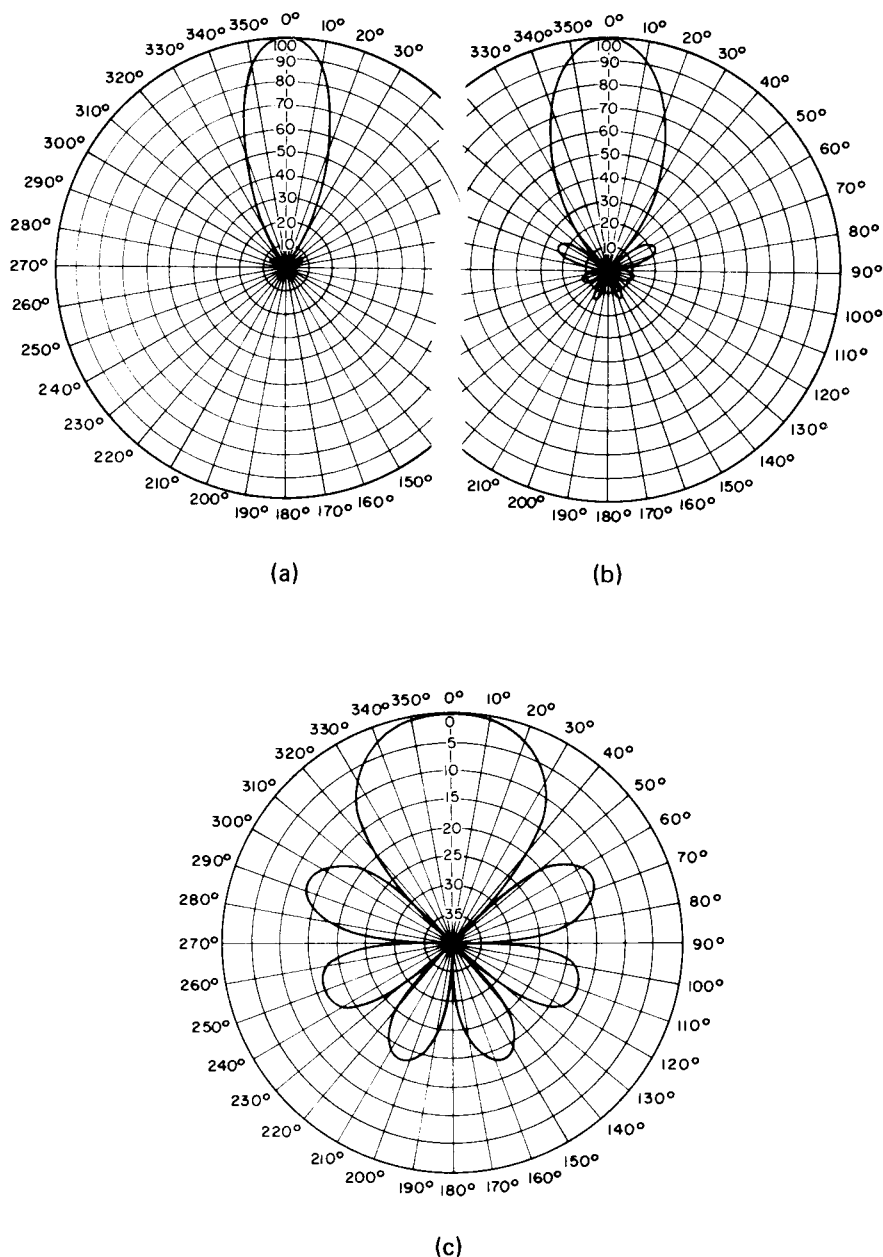


Figure 21 — Power, Field, and Decibel Plots of the Same Antenna Pattern
(a) Relative Power Pattern. (b) Relative Field Pattern. (c) Decibel Pattern.

Relative field patterns show the variation of the electric field intensity at a fixed distance from the antenna as a function of angular coordinates [Fig 21(b)]. Field patterns provide greater side lobe resolution while still displaying small variations in field level near the maximum. The half-power level on this format is 0.707 times the full-scale value.

If the recorder scales are linearly calibrated in decibels, a *logarithmic relative gain pattern* results. This format is particularly useful since antenna gain is usually specified in decibels. The decibel scale provides constant resolution over the entire display range, and a wider dynamic range can be displayed than with other formats. Comparison of patterns is also easier with a decibel scale, since a difference in system gain is equivalent to a constant offset of the recorded data. A recording range of 40 dB is most often used, because this range is usually sufficient to show the side lobe levels of interest, and it generally provides sufficient resolution for an examination of the main lobe structure.

[Fig 21(c)]. However, to achieve a 40 dB dynamic range when operating from a square-law detector, the recorder shall have an 80 dB usable dynamic range. In order for the recorder noise to be small relative to the minimum input signal level, the noise level should be approximately 110 to 120 dB below the full-scale input.

There are other formats for the presentation of antenna patterns which have found wide use. A complete radiation pattern can be presented on a single page as a *contour plot* by connecting points of equal signal levels with lines to form isolevel contours in the manner employed for topographic contour maps. Key levels are numerically identified to permit interpretation of the graph. One such system employs different colors to highlight the contours. These approaches usually require the use of computer graphics.

An alternate approach, which has found wide acceptance, is the *radiation distribution table* which provides the same basic information as the contour plot, but accomplishes it in a simpler manner. A portion of a radiation distribution table is shown in Fig 22. Signal levels are printed numerically in decibels at preselected intervals of θ and ϕ . The graph shown was made by scanning in ϕ and stepping in θ after each ϕ cut. In the figure the angular increments are 0.5° in θ and ϕ , and the dynamic range is 40 dB. Signal levels are sensed by an encoder coupled to the servo-driven logarithmic potentiometer in an antenna-pattern recorder and printed on the data form.

The contour effect is obtained by printing the even values of signal level and omitting the odd values or by underlining either the odd or the even numbers.

5.7 Data-Processing and Control Computers

Although not shown in the block diagram of Fig 13, an on-line instrumentation minicomputer provides a natural solution to the data-gathering, control, and data-processing requirements of an automatic antenna-measurement system. Instrumentation computers can be equipped with a variety of input-output devices, depending on the requirements of the particular measurement program. Magnetic tape, teletype, and paper-tape input-output units are commonly employed for programming the computer and recording and storing data. The computer also becomes a source of stored routines that can be called up to meet the basic demands of the system.

In addition to solving the on-line data-processing and control requirements, the computer can be programmed for analysis and reduction of the measured data. For example, the polarization properties of the antenna can be calculated as well as its directivity. Computer plotters can be employed to provide a variety of visual displays of antenna patterns. Not only can contour plots be produced, but also three-dimensional presentations. For lengthy programs or for programming convenience, the recorded data can be processed by a larger central computer at the user's facility.

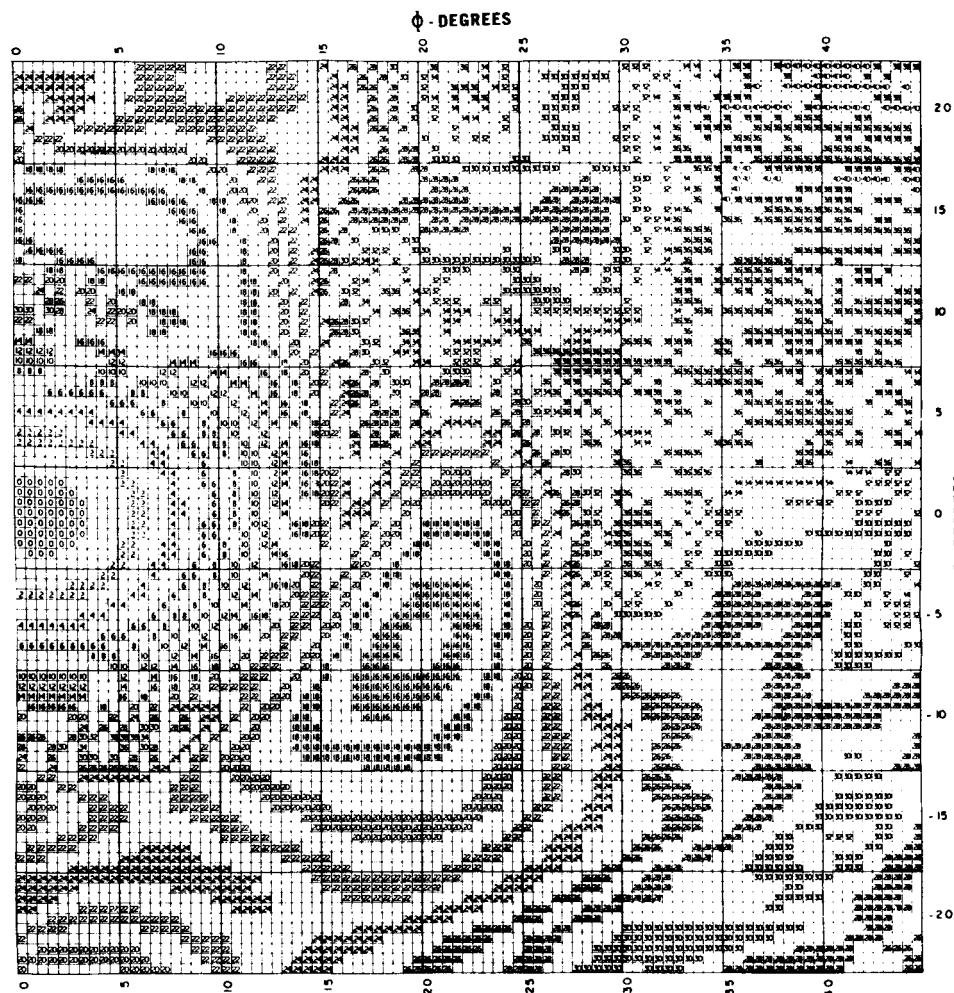


Figure 22—Radiation Distribution Table Recorded by Scanning in ϕ and Stepping in θ Data Are Presented at 0.5° Increments over a 40 dB Dynamic Range

6. Antenna-Range Evaluation

6.1 General

Once an antenna-pattern range has been designed, constructed, and instrumented, it is necessary to experimentally determine the state of the illuminating electro-magnetic field over the *test region*, that is, the region where the test antenna is to be mounted. Indeed, a continuing program of experimental evaluation is usually required to determine whether or not the errors experienced will be less than those required for the measurements to be performed using the range. The extent of the experimental evaluation depends upon the desired accuracies of the measurements to be made on the range and the possible need for official documentation of these accuracies.

The illuminating field over the test region will deviate from that predicted from calculations based upon a highly ideal range geometry because of reflections from various mounting structures, cables, obstacles on or near the range surface, and from irregularities in the range surface itself. In addition radio-frequency interference is often a cause of difficulty.

It is convenient to investigate separately that part of the field which is incident from the general direction of the source antenna and that which arrives from wide angles with respect to a line drawn from the center of the test region toward the phase center of the source antenna. The former is often referred to as the *near-axis incident field*, and the latter as the *wide-angle incident field*. The near-axis incident field may be determined from a field-probe measurement over a plane perpendicular to the range axis and coincident with the expected location of the test antenna. This plane is called the *test aperture*.

6.2 Field-Probe Measurements over Test Aperture

Prior to making field-probe measurements, it is necessary to align the axes of the positioner. For example, the vertical axis (ϕ axis in the case of an azimuth-over-elevation positioner, or the θ axis for an elevation-over-azimuth positioner, including the model tower, can be aligned by use of a clinometer or a precision level. In the case of the model tower a plumb bob can also be used. The horizontal axis can be aligned optically. For the model tower a scope can be mounted in the tower head. In this way the scope's optical line of sight corresponds to the horizontal axis (ϕ axis) of the model tower, and thus alignment can be checked. Once the axes have been aligned, the field probe can be mounted. The field probe consists of an antenna, usually a pyramidal horn or a log periodic dipole antenna, mounted upon a carriage or track such that it can be moved along an I-beam support. The entire unit is mounted on an appropriate positioner in such a manner that the incident field may be sampled as a function of position over the test aperture. A sketch of a typical field probe is shown in Fig 23 [1, pp 14.42–14.63]. The motion of the probe antenna is remotely controlled, and by the use of a synchro system or potentiometers, which indicate the instantaneous position of the probe antenna, a continuous automatic plot of the received field amplitude as a function of position can be made. These data are usually presented as decibel plots.

The probe antenna should be moderately directive in order to discriminate against wide-angle reflections and also reflections from the probe-mounting structure. As an added precaution an absorbing baffle should be placed behind the probe antenna. The E - and H -plane beamwidths of the probe antenna should be such that a major portion of the range surface is contained within its half-power beamwidth. A useful criterion which ensures that this condition is met is given by

$$\theta_3 \geq 2 \tan^{-1} \left(\frac{4h_r}{R} \right)$$

where h_r is the height of the test antenna, R is the range length, and θ_3 is the 3 dB beamwidth of the probe antenna.

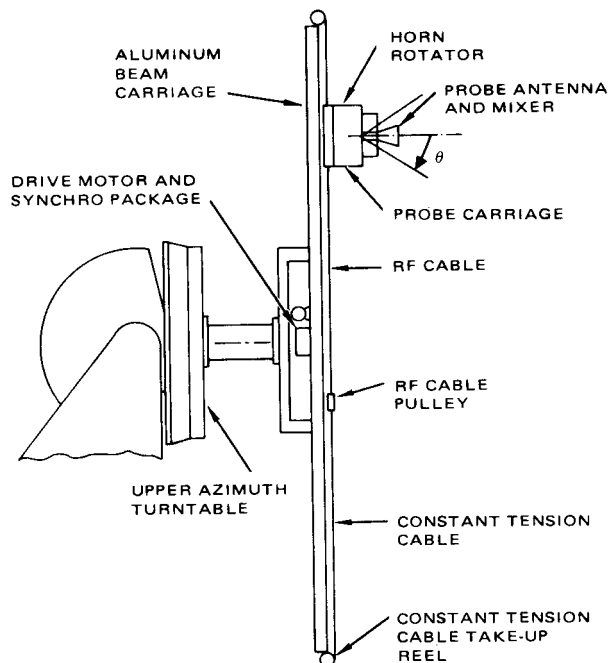


Figure 23—Typical Field-Probe Mechanism

A means of rotating the probe antenna about its axis shall also be provided so that two orthogonal polarizations, vertical and horizontal, may be measured. This is necessary because the range might be used with either polarization, and hence the incident field should be probed for both cases. It is good practice to measure also the cross-polarized components for both orientations of polarization of the source antenna, because not only may the source antenna itself generate a cross-polarized component, but some depolarization usually accompanies the reflection of waves from irregular or curved objects.

One of the principal objectives of the probe measurement is to determine the source of the reflections so that remedial action can be taken. If there is only one principal source of reflection contributing to the incident field, it is a rather simple matter to locate it from the measured data. Suppose that the direct wave is incident upon the aperture from a direction perpendicular to the plane of the aperture and the reflected wave arrives at an angle θ with respect to that direction. From Fig 24 it is seen that an interference pattern over the test aperture results. The spatial period P of the resultant waveform is given by

$$P = \frac{\lambda}{\sin \theta}$$

If the probe antenna were moved along a line in the test aperture which is formed by the intersection of a plane containing the directions of propagation of both the direct and the reflected waves and the plane containing the test aperture, then the measured field should be that depicted in Fig 24. However, if the

probe were rotated to any other orientation in the test aperture, then the spatial period would increase and have a value given by

$$P' = \frac{\lambda}{\sin \theta \cos \alpha}$$

where α is the angle between the probe path which yielded the result shown in Fig 24 and the new orientation. From these results it is seen that by probing the field over radial lines centered on the test aperture the direction from which

the reflected signal arrives can be determined. Furthermore the peak-to-peak amplitude of the interference pattern yields a measure of the relative amplitude of the reflected wave E_R to the direct wave E_D . This ratio, expressed in decibels, is given by

$$\frac{E_R}{E_D} \text{ (dB)} = 20 \log \left[\frac{-1 + \text{antilog}(\sigma/20)}{1 + \text{antilog}(\sigma/20)} \right]$$

where σ is the difference in decibels between the maxima and minima of the measured pattern. The ratio E_R/E_D (dB) is plotted as a function of σ in Fig 25. Generally there are several reflected waves, with the reflected wave from the ground being the predominant one. For this case the measured field is a composite spatial distribution. Usually, however, the principal sources of reflection can be located from the data.

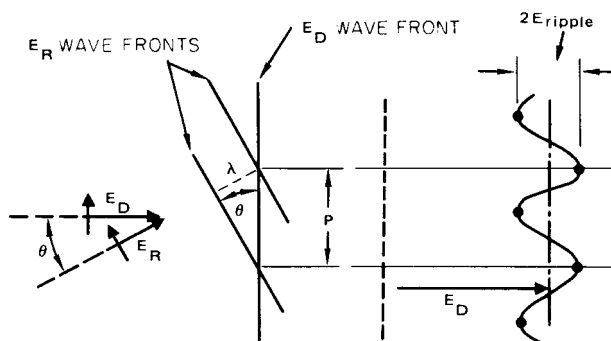


Figure 24—Spatial Interference Pattern Due to a Reflected Wave

6.3 Incident-Field Measurements Near the Range Axis on an Elevated Range

For elevated ranges, if the amplitude distribution has excessive variations, then some means of either absorbing the reflected energy or redirecting it from the test aperture shall be employed. In the case of reflection from the range, surface diffraction fences usually are very effective. The field probe can be used in the adjustment of the position, size, and orientation of the fences.

Another important use of the field probe is in the alignment of the source antenna. Since the source antenna is directive, any misalignment might yield an excessive asymmetrical amplitude taper in the illumination field over the test aperture. The alignment procedure shall be performed in both the azimuthal and the elevation planes, which corresponds to horizontal and vertical motions of the field-probe antennas, respectively. A convenient method of alignment is as follows. First, from a horizontal traverse of the probe antenna two equal power points are located for reference. The source antenna is then adjusted until the geometrical mean of these two equal-power points coincides with the center of the test aperture. Next the source antenna is rotated 180° about its axis and again checked for alignment. If the source antenna is still aligned, it indicates that the beam axis of the source antenna is coincident with the roll axis of the source antenna's positioner. If it is not, then corrective measures shall be taken, that is, the source antenna shall be reoriented with respect to the positioner mounting surface or, perhaps, in the case of a reflector antenna its primary antenna may need repositioning. Then the alignment procedure is repeated until the beam of the source antenna is symmetric about the roll axis of its positioner and at the same time is properly aligned with respect to the test aperture. This entire procedure is repeated for the vertical plane.