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Corrected Edition

When IEEE Std 149-1965 was originally approved, it included Section 11 — Definitions. That section was superseded by IEEE Std 145-1969, IEEE Standard Definitions of Terms for Antennas. This edition has been published without the superseded definitions, as reaffirmed in 1971 by the IEEE Standards Committee and approved by the American National Standards Institute.

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Test Procedure for ANTENNAS

1. INTRODUCTION

1.1 Foreword

This Test Procedure, which supersedes the previous issue, "Standards on Antennas—Methods of Testing" 48 IRE 2S2, is concerned with measurements of the properties which characterize antennas.

In Section 1.2, symbols and units to be used in this Test Procedure are defined. The effect of the environment on the antenna and its characteristics is discussed in Section 1.3, and certain precautions to be taken during the measurements are suggested. In Section 1.4, the usefulness of the reciprocity theorem in antenna measurements is cited, along with examples of situations in which this theorem does not apply. The characteristics of electromagnetic wave polarization are outlined in Section 1.5, with emphasis on those aspects which are important in the measurement of antennas. Section 1.6 treats those electromagnetic field regions which are of particular interest in antenna measurements. In Section 1.7, the features and limitations of scale models for antenna measurements are discussed.

In Sections 2 through 10, those antenna characteristics which may require measurement are considered. The techniques associated with the measurement of each are discussed, but no attempt is made to furnish step-by-step procedural descriptions. References which are illustrative of measurement techniques are provided in which details may be found. Since measurement techniques undergo continuing refinement, the reader should be alert to references on the subject of antenna measurement which appear after this Test Procedure was prepared.

Throughout this document, certain terms are italicized where they first appear in each section. Definitions of these terms are given in IEEE Std 145-1969, IEEE Standard Definitions of Terms for Antennas, and supersede those which appeared as Section 11 of the 1965 edition of IEEE Std 149-1965.

1.2 Symbols and Units

The basic symbols used in this Test Procedure are given in the following list. Rationalized MKS units are employed, and are listed for each symbol.

BW	= half-power beamwidth, degrees
D	= diameter or maximum dimension of an antenna aperture, meters
E	= electric field strength, volts per meter
f	= frequency, cycles per second
$G_{\max}$	= maximum power gain of an antenna
$G_{d\max}$	= directivity of an antenna
I	= current, amperes
L	= loss factor (ratio of power input to output)

n	= ratio of full-scale dimensions to scale-model dimensions
P	= power, watts
R	= distance from antenna to observation point, meters
S	= standing wave ratio (voltage or current)
T	= noise temperature, degrees Kelvin
V	= voltage, volts
Z	= impedance, ohms
θ	= co-latitude angle (see Figure 3)
λ	= free-space wavelength, meters
ρ	= voltage reflection coefficient
ϕ	= azimuthal angle (see Figure 3)
ψ	= antenna rotation angle

1.3 Environmental Factors

An *antenna* can be considered adequately tested only when the tests have recognized the environmental conditions of operation affecting antenna performance. Many of these environmental factors are of a specialized nature, and it is impractical to include the appropriate tests in this Test Procedure. Instead, a few cases will be briefly mentioned as examples of interest to the reader.

One category of environmental factors may be defined as directly affecting the material properties or structure of an antenna, and thus indirectly affecting the electrical characteristics. Mechanical loading of the antenna structure by wind and ice is a common, but nevertheless important, effect to be considered in the testing of many antennas. Vibration and shock tests are often made to assure that an antenna subject to severe accelerations will maintain its structural integrity, as well as to determine whether dynamic deformations are within allowable electrical limits. Antennas in exposed locations are often provided with lightning protection and anti-icing devices; the effect of such devices on the electrical characteristic must be evaluated.

Various natural or man-made environments may impose special requirements: for example, shipborne antennas may have to withstand water-wave impact and salt-water corrosion. Antennas on hypersonic vehicles must withstand very high temperatures and pressures, and antennas designed for satellite or space-probe application must withstand intense ionizing radiation, hard vacuum, and extreme temperatures. Those ground-based antennas which are intended to operate in the vicinity of a nuclear blast should maintain their essential properties in the wake of seismic waves, atmospheric shock waves, thermal radiation, ionizing radiation, blast-product erosion, and radioactive debris.

Certain antenna applications necessitate unusual attention to tests involving quite ordinary aspects of the physical

environment. For instance, rapid-scan antennas employing ferrite components are especially sensitive to changes in ambient temperature. Antennas in which intermodulation distortion must be minimized may have difficulty with non-linear corrosion films. In the case of precision tracking antennas, a *boresight error* can be caused merely by deflections resulting from nonuniform heating of the antenna by the sun. Large antennas rotated in the elevation plane may also undergo significant deflections because of the change in the effect of the gravitational force on the antenna.

The other category of environmental factors may be considered as directly affecting the electrical properties of the antenna. In some cases this electrical environment is permanent, and is included in the design as an integral part of the antenna. Familiar examples of this situation are the role of the earth in ground-based antennas, the superstructure in shipborne antennas, and the vehicle in antennas for airborne or space applications. Techniques for testing in these circumstances have been developed and are widely used; they are described in Sections 2.2 and 6 of this Test Procedure. Another example is the noise environment of an antenna, including galactic radiation, thermal atmospheric radiation, atmospheric and man-made static, and thermal earth radiation; many of these factors are recognized in Section 9, which describes tests of antenna *noise temperature*. A less familiar but more extreme example of permanent electrical environment occurs with low-frequency antennas designed to operate underground or beneath the surface of the sea.

In many cases the electrical environment of an antenna is transient, and causes problems of a more elusive nature. Moisture, when combined with impurities, can create conducting paths which are troublesome, especially in regions of high electric field. Even pure water, if it exists in a continuous film, may affect the performance of a microwave antenna by virtue of its high dielectric constant. Ice or snow are also factors which can directly affect the characteristics of an antenna. In the case of antennas for missile application, ionized gases may exist in the exhaust or may be generated by high vehicle velocity through the atmosphere; these gases are also a part of the electrical environment. Finally, certain antennas may be susceptible to precipitation static, which is a series of noise pulses created when charged particles such as raindrops discharge on an antenna.

There is a particular type of antenna environment that deserves special mention; namely, the *radome*. This is a structure¹ which often encloses an antenna to protect it from the physical environment. However in so doing, it introduces an electrical environment whose effects should not be overlooked.

One typical class of radome has a pointed shape and covers an antenna on the nose of an aircraft or missile. Another common type² has the shape of a truncated sphere; it is fixed to the ground and covers an antenna which is sometimes quite large in size. Most radomes are constructed essentially of dielectric materials, although some contain a significant amount of metal for greater strength.

Tests of radome effects are often made by observing the change in antenna performance as the radome is revolved around the antenna, or as the radome is alternately removed and replaced. Characteristics measured generally include *power gain*, amplitude of *radiation pattern*, and *input impedance*; other quantities sometimes investigated are phase, polarization, *boresight*, power-handling capability, and *noise temperature*. In determining the effect of a radome, it has usually been found that significant results are obtained only when the radome is tested together with exactly the same type of antenna with which it is to be used.

When an antenna is covered by a radome, it is necessary, of course, to determine whether the radome will withstand the destructive factors of the physical environment which otherwise would have been applied to the antenna itself.

1.4 Reciprocity

The reciprocity principle³ is of fundamental importance in the determination of many of the properties of antennas, because it permits the determination of these properties from measurements on the antennas in either the transmitting or the receiving condition. For example, the *radiation pattern* and gain characteristics of an antenna may be determined from measurements of the antenna during reception, and this is often done for convenience.

In describing methods of making measurements, it is generally desirable to limit the description to one condition of operation. It should be noted that reciprocity does not imply that antenna current distributions are the same for transmitting as for receiving. The reciprocity principle may not apply to antennas containing components such as ferrite devices or semiconductor diodes, or to antennas in the presence of a medium such as an ionized gas in a magnetic field.

1.5 Polarization

Polarization is a property of electromagnetic radiation describing the spatial orientation of the field vectors; in common practice only the electric field (*E*) vector is specified. For the case of radiation by an antenna, the electric field is generally sampled in small regions far from the antenna, where the electromagnetic wave is nearly uniform and plane, and where the *E*-vector lies in a plane nearly perpendicular to the direction of wave propagation. Coherent excitation of the antenna is always assumed, yielding radiation which is said to be completely polarized.

The *E*-vector, when observed at a fixed point in space, can vary periodically in amplitude, direction, or both; the manner in which it varies determines the type of polarization. When the tip of the *E*-vector traces an ellipse in a fixed plane perpendicular to the propagation direction, the

1 W. M. Cady, M. B. Karelitz, L. A. Turner "Radar Scanners and Radomes", M.I.T. Radiation Laboratory Series, vol. 26, McGraw-Hill, pp. 241-460; 1948.

2 W. Lavrench, "Electrical Performance of Rigid Ground Radomes", IRE Transactions on Antennas and Propagation, vol. AP-8, No. 6, pp. 548-558; November 1960.

3 E. C. Jordan "Electromagnetic Waves and Radiating Systems", Prentice-Hall, Chapter 10; 1950.

wave is said to be "elliptically polarized". This is the most general type of polarization, and is indicated in Figure 1(a). When the ellipse degenerates to a line, as indicated in Figure 1(b), the polarization is called "linear polarization". When the ellipse becomes a circle, as indicated in Figure 1(c), the term "circular polarization" is applied.

The direction of rotation of the E -vector in a fixed plane, observed looking in the direction of wave propaga-

tion, is the "handedness" of the elliptical or circular polarization.^{4, 5} Clockwise rotation is called right-handed and counterclockwise is called left-handed. It is interesting that the opposite sense of rotation is obtained if the fixed plane is observed looking against the direction of propagation. The opposite sense is also obtained if a series of planes are observed at one instant of time, and the resulting spiral (see Figure 1(a) or (c)) locus is used to define

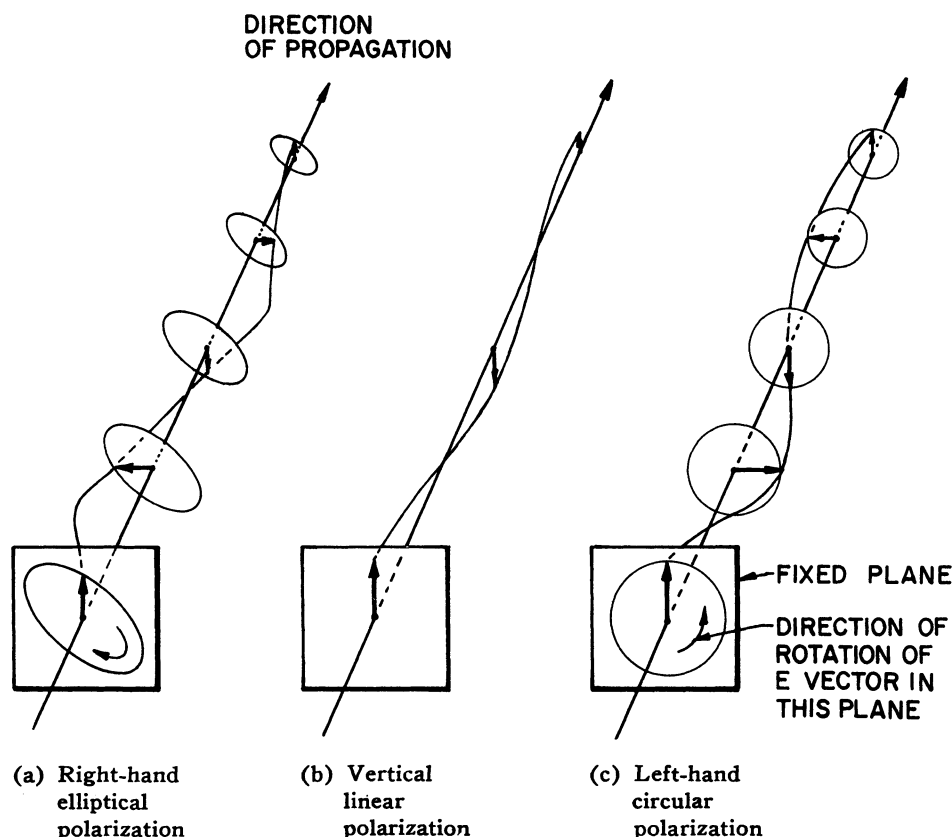


Figure 1
Electric field vectors of several types of polarization, shown at various points in space at one instant of time

the handedness. These two misinterpretations have been a source of some confusion.

Any given polarization can be resolved into two independent "orthogonal" components for convenience in representation or analysis. These are usually linear components in space quadrature, are sometimes oppositely-rotating circular components, and may also be elliptical components with a certain relationship. The relative magnitude and phase of the orthogonal components must be known in order to specify the polarization completely. It is interesting to note that two equal-magnitude linear components in both space and time quadrature constitute circular polarization. The general case of elliptical polarization may also be specified in terms of the "polarization ellipse" traced

out by the tip of the E -vector (see Figure 1(a)). The axial ratio of the ellipse, the orientation in space of the major axis, and the direction of rotation comprise the complete description. This representation of polarization is equivalent to and interchangeable with the resolution into components described above; the appropriate transformations are described in the literature.⁶

4 "IRE Standards on Wave Propagation: Definitions of Terms", IEEE No. 211 (formerly 50 IRE 24 S1); 1950.

5 J. D. Kraus, "Antennas", McGraw-Hill, pp. 470-471; 1950.

6 H. G. Booker, V. H. Rumsey, G. A. Deschamps, M. L. Kales, J. I. Bohnert, "Techniques for Handling Elliptically Polarized Waves with Special Reference to Antennas", Proc. IRE, vol. 39, pp. 535-552; May 1951.

The transfer of power between two antennas is dependent on the polarization characteristics of their radiated waves. When the two antennas have the same polarizations in the appropriate directions, maximum power is transferred. Any failure of correspondence in polarization causes a loss in the antenna system; for the extreme case of exact orthogonality between the two polarizations, no power is transferred. A useful example of an intermediate case involves a circularly-polarized and a linearly-polarized antenna; here the system loss is three decibels regardless of the relative orientations of the two antennas.

When the polarization characteristics of the two antennas are known, the polarization loss may be computed. A basic expression⁷ for the ratio of the power actually transferred to the power available for transfer with matched polarizations is:

$$\frac{P_{\text{transferred}}}{P_{\text{available}}} = \frac{|E_{n1}E_{n2} + E_{c1}E_{c2}|^2}{(|E_{n1}|^2 + |E_{c1}|^2)(|E_{n2}|^2 + |E_{c2}|^2)} \quad (1)$$

where E is a complex quantity defining the amplitude and phase of the electric field radiated by an antenna, the subscripts n and c refer to two orthogonal components of polarization, and the subscripts 1 and 2 refer to the two antennas involved in the power-transfer system. In defining these orthogonal components, one must be careful to consider their right or left hand nature from the respective viewpoints of the two waves propagating in opposite directions, while considering their space orientations from a single viewpoint. For convenience, the first polarization component may sometimes be regarded as the normal or desired component having a reference phase of zero, and the second as a *cross-polarization* or undesired component having a phase angle relative to the normal component. It may be seen from equation (1) that the polarization loss in a system of two antennas is not, in general, simply the sum of the individual losses into cross polarization; the system loss may be either greater or less depending on the phases of the two cross polarizations.

Various alternate methods for computing the polarization loss in the transfer of power between two antennas are available. Two methods employ equations involving parameters of the polarization ellipse^{8,9} or the circular-polarization components.^{10,11}

Another method employs a graphical technique in which the two polarizations are plotted on the surface of a Poincaré polarization sphere,^{12,13} and the loss is easily calcu-

lated from the angle between these two points at the center of the sphere. This latter method is particularly useful for the interpretation of complex situations.

1.6 Field Regions

The distribution of field strength around an antenna is a function of the distance from the antenna. In close proximity to the antenna, the field strength may include, in addition to the radiating field, a significant reactive (non-radiating) field. The strength of the reactive-field components decays rapidly with the distance from the antenna (inversely as distance raised to powers greater than unity). That region of space immediately surrounding the antenna in which the reactive components predominate, is known as the *reactive near-field region*. The size of this region varies for different antennas. For most antennas, however, the outer limit is of the order of a few wavelengths or less. For the particular case of an electrically-small dipole indicated in Figure 2(a), the reactive field predominates out to a distance of approximately $\lambda/2\pi$ where the radiating and reactive fields are equal.

Beyond the reactive near-field region, the radiating field predominates. The radiating region is divided into two subregions: the *radiating near-field region* and the *far-field region*. The former region exists for most electrically-large antennas, but not for electrically-small antennas. The latter region exists for all antennas.

In the radiating near-field region, the relative angular distribution of the field (the usual radiation pattern) is dependent on the distance from the antenna. The reason for this behavior is two-fold: (1) the relative phase relationship of field contributions from different elements of the antenna changes with distance, and (2) the relative amplitudes of these field contributions also change with distance. For an antenna focused at infinity, indicated in Figure 2(b), the radiating near-field region is sometimes referred to as the Fresnel region on the basis of analogy to optical terminology.

In the far-field region, the relative angular distribution of the field becomes essentially independent of distance. Correspondingly, the amplitude of the field is given, in the limit, by the reciprocal of the first power of distance. The reason for this behavior is that the relative phase and amplitude relationships between the field contributions from different elements of the antenna approach a fixed relationship. Although this situation is not attained precisely until the observation point is an infinite distance from the antenna, the relative angular distribution of the field at a comparatively short distance is often an adequate approximation of the field distribution at infinity. Thus the far-field region is considered to extend from this distance to infinity. For an antenna focused at infinity, the far-field region is sometimes referred to as the Fraunhofer region on the basis of analogy to optical terminology.

7 H. Jasik, "Antenna Engineering Handbook", McGraw-Hill, p. 17-7; 1961.

8 W. Sichak and S. Milazzo, "Antennas for Circular Polarization", Proc. IRE, vol. 36, pp. 997-1001; April 1948.

9 "Reference Data for Radio Engineers", International Telephone and Telegraph Corp., Fourth Edition, pp. 665-667; 1957.

10 L. Hatkin, "Elliptically Polarized Waves", Proc. IRE, vol. 38, p. 1455; December 1950.

11 V. H. Rumsey, "Transmission Between Elliptically Polarized Antennas", Proc. IRE, vol. 39, pp. 535-540; May 1951.

12 G. A. Deschamps, "Part II—Geometrical Representation of the Polarization of a Plane Electromagnetic Wave", Proc. IRE, vol. 39, pp. 540-544; May 1951.

13 "Reference Data for Radio Engineers", International Telephone and Telegraph Corp., Fourth Edition, pp. 667-670; 1957.

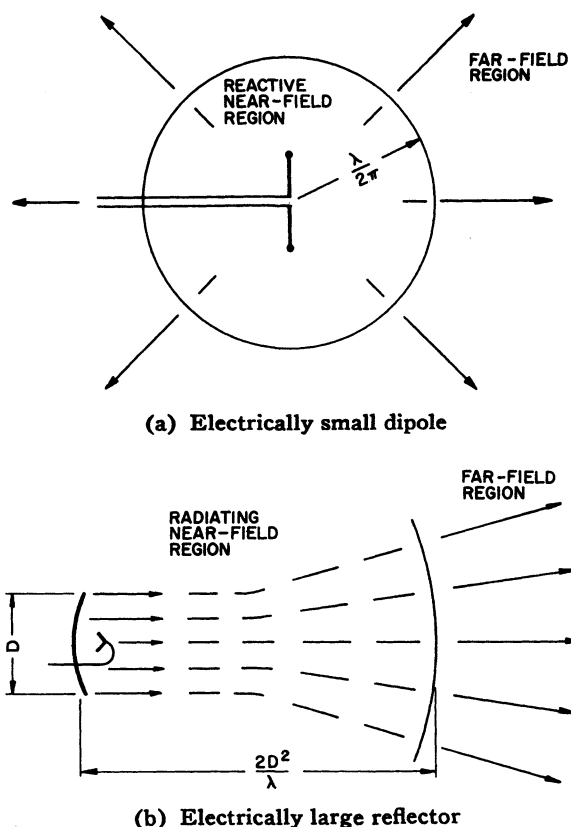


Figure 2
Field regions for two antenna types

For electrically-large antennas of the broadside-aperture type such as that shown in Figure 2(b), a commonly used criterion¹⁴ to define the distance in free space to the boundary between the radiating near-field and the far-field regions is

$$R = \frac{2D^2}{\lambda} \quad (2)$$

where D is the largest dimension of the aperture. The difference in path lengths between the center and edges of the aperture to the point at the region boundary is $\lambda/16$. At this boundary, the antenna gain over most of the *major lobe* of the radiation pattern differs from that at infinity by a very small factor, the exact value depending on the shape of the aperture and the illumination taper. However, for directions corresponding to *minor lobes* and pattern minima, the gain at the region boundary may differ from that at infinity by many decibels.

For most applications, it is the radiation pattern in the far-field region that is important. It is, therefore, customary to make measurements in the far-field region. If the distances involved are prohibitively great, measurements in what would normally be the near-field region can

¹⁴ S. Silver, "Microwave Antenna Theory and Design", M.I.T. Radiation Laboratory Series, vol. 12, McGraw-Hill, Section 6.9; 1949.

sometimes be used to infer the pattern in the far-field region (see Section 2.3).

For electrically-large antennas other than conventional broadside-aperture types, there is no recognized criterion defining the distance to the far-field inner boundary. However the $2D^2/\lambda$ criterion, when D is taken as the largest linear dimension, will usually give a distance which is well within the far-field region. Special precautions should be observed when the environment of the antenna plays a part in the formation of the radiation pattern. For such situations, the distance to the inner boundary of the far-field region is determined by the dimension of the entire radiating structure; this may involve a large metallic supporting surface (for example, an aircraft fuselage) in a mobile installation, or the ground terrain in a fixed installation (see Section 2.2).

Certain measurement situations do not permit separation of the useful space into simple near- and far-field regions. An important example of this class is that of a vertically polarized antenna operating over a ground of finite conductivity (see Section 6).

1.7 Scale Models

Scale-modeling techniques are often used when the measurement of the original antenna in its original environment is impractical. This situation frequently exists for antennas located on large support structures, such as ships, aircraft, and large man-made satellites, which influence the antenna properties. In such cases the original radiating system frequently cannot be subjected to full experimental control because of instability of the supporting vehicle or the surrounding medium, or because some of the radiation directions of interest are inaccessible to accurate measuring techniques of the usual types. In very large radiation systems the accessibility problems tend to become greater. In moving systems or changing environments, the stability problem may compel an unreasonable amount of statistical measurement. Another major situation for which scaling is often used is development work requiring successive modifications which are costly due to the large size or, occasionally, the very small size of the final antenna system. Thus the main motives for scale modeling are to obtain greater experimental control over the measurements, or to obtain an economic advantage in the measurement program.

Generally, the model is reduced in size from the full-scale antenna, but whether reduced or increased, the requirements^{15, 16, 17} for exact simulation by the model are as follows:

Linear dimensions of the model to be $1/n$ times those of the full-scale antenna.

¹⁵ G. Sinclair, E. C. Jordan, E. W. Vaughan, "Measurement of Aircraft Antenna Patterns Using Models", Proc. IRE, vol. 35, pp. 1451-1462; December 1947.

¹⁶ J. A. Stratton, "Electromagnetic Theory", McGraw-Hill, pp. 488-490; 1941.

¹⁷ R. W. King, "Electromagnetic Engineering", McGraw-Hill, vol. I, pp. 316-320; 1945.

Operating frequency and conductivity of the materials used in the model to be n times those of the full-scale antenna.

Electric permittivity and magnetic permeability of the materials used in the model to be the same as in the full-scale antenna.

In the above, n is an arbitrary number (generally, but not necessarily, greater than unity) which determines the scale of the model. Also in the above, the electric permittivity and magnetic permeability may be extended to their complex form¹⁸ to include electric and magnetic type losses, respectively; this is a substitute for the ordinarily-used electrical conductivity and the little-used, hypothetical, magnetic conductivity¹⁸, respectively. More general forms of scaling, which permit additional parameters to be changed, are occasionally desired; these are described in the literature.¹⁹

In a practical model it is usually not feasible to satisfy exactly the full set of requirements in the above list. However, in antennas which are not highly resonant, the error will usually be small if good conductors such as copper or aluminum are used to simulate good conductors, and if low-loss dielectric materials of identical electric permittivity and magnetic permeability are used to simulate low-loss dielectrics. The principal problem is presented by poor conductors or lossy dielectrics; in such cases it is not always possible to obtain materials which satisfy the scale-modeling requirements.

In constructing a scale model, not only the antenna needs to be simulated but also those portions of the surrounding structures and environment which have an appreciable effect on the properties of the antenna. Good judgment is required in determining how far to simulate the surroundings. In many cases it is difficult to construct simulated surroundings, due to their complexity and to their electromagnetically accidental nature. For example, when the antenna interacts with the earth, it has often proven to be impractical to accurately scale the highly variable and sometimes unknown properties of the soil.

While the *radiation pattern* is usually the antenna characteristic of most concern in model measurements, many other antenna properties of interest can also be reliably reproduced. If the exact scaling procedure described above is followed throughout the antenna system, all fields are reproduced exactly in shape, both externally and within the feed line. Thus *power gain*, *directivity*, *radiation efficiency*, *input impedance*, *mutual impedance*, *bore-sight error*, and in general all properties dependent only on field ratios, are preserved. If the modified scaling procedure is followed, efficiencies will not be reproduced but the remaining properties will be reproduced accurately enough for most purposes, providing that the antenna does not have extremes of current concentration or mismatch. Certain antenna characteristics, such as the power level for

high-voltage breakdown (see Section 8) and the *noise-temperature* (see Section 9), do not scale, because of the frequency-dependent nature of the mechanisms involved.

In the measurement of radiation patterns, it is likely that cables to the scale model will perturb the patterns appreciably. To overcome this the scale-model antenna may transmit from a battery-operated transmitter, or, alternatively, the scale-model antenna may contain a receiver from which the demodulated signal can be removed by means of high-resistance wire leads which minimize the disturbance of the radio frequency field. The support for the model should receive particular attention if the pattern null structure is to be accurately determined.

In the case of an input-impedance measurement using a scale model, it may sometimes be desired to determine the effect of a full-scale matching section for the antenna. To obtain this information, the matching section may be terminated in a network equivalent²⁰ to the impedance measured on the scale model. Special measurements on antennas which are electrically small, as is common at low frequencies, can often be made by quasi-static methods using electrostatic cages²¹. Here the charge induced by a known field strength is measured, allowing an equivalent area to be determined. For the case of scattering measurements of radar targets (see Section 10), model techniques are quite common because of the considerable difficulty in making measurements with the actual target.

In addition to the special problems of scale-model measurements referred to in this section, there are general procedures and precautions to be employed during any of the measurements. These procedures are essentially the same as those described in the following sections of this Test Procedure for full-scale antennas.

2. MEASUREMENTS FOR DETERMINATION OF AMPLITUDE PATTERNS

2.1 General

The *radiation pattern* of an antenna may represent any of the several properties of electromagnetic wave radiation as a function of space coordinates. In Section 2, only the pattern of radiation amplitude is considered; the other properties, such as phase and polarization, will be covered in Section 3. Furthermore, Section 2 is concerned with only the relative amplitudes of the antenna response; determination of the absolute values is treated in Section 4 which discusses gain measurements.

A system of space coordinates often employed for the two-dimensional pattern of an antenna is shown in Figure 3. In such a coordinate system, the radiation amplitude is determined on the surface of a sphere whose center is located at the antenna being tested. Since the distance (R) to the antenna is invariant, only the two angular coordinates are variables in a given set of patterns. As

18 N. Marcuvitz, "Waveguide Handbook", McGraw-Hill, M.I.T. Radiation Laboratory Series, vol. 10, pp. 18-23; 1951.

19 G. Sinclair, "Theory of Models of Electromagnetic Systems", *Proc. IRE*, vol. 36, pp. 1364-1370; November 1948.

20 R. M. Fano, "Theoretical Limitations on the Broadband Matching of Arbitrary Impedances", *Journal of the Franklin Institute*, 249, pp. 57-154; 1950.

21 J. T. Bolljahn and R. F. Reese, "Electrically Small Antennas and the Low-Frequency Aircraft Problem", *IRE Trans. on Antennas and Propagation*, vol. AP-1, pp. 46-54; October 1953.