The extrapolation technique, when combined with the generalized three-antenna measurement technique (Newell 1988 [B135]; Newell, Baird, and Wacker [B136]; Repjar, Newell, and Tamura [B157]), is capable of yielding not only the gains but also the polarizations of the three antennas as discussed in Clause 9. There is the restriction that none of the three antennas be nominally circularly polarized. If one of the antennas is circularly polarized, then only that antenna's characteristics can be completely determined. If two or more of the antennas are nominally circularly polarized, the method fails. However, if all three antennas are dual-port circularly-polarized antennas, then the polarization and gain properties of each port of each antenna can be determined if the port-to-port ratio of one antenna has been determined using a linearly-polarized antenna (Newell, Kremer, and Guerrieri [B138]).

The extrapolation range should have a precision movable tower or robotic arm that allows boresight between the transmitting and the receiving antennas to be maintained as it is moved over the length of the range. Measurements may be conducted at distances less than $2D^2/\lambda$, where D is the maximum dimension of the antennas under test. The distance from the antenna aperture to the ground (antenna height) should be at least 15% of the maximum separation between antennas. This places a practical limitation on the gains of antennas that may be tested since the required maximum separation distance between antennas increases as the gains of the antennas increases. Since the antenna heights should also be proportionally increased, it becomes increasingly difficult and expensive to construct a movable tower that maintains boresight over the required length of the range. However, with the use of new robotic arms this is becoming easier to achieve (Gordon et al. [B73]). Antennas with gains of about 40 dB represent a practical upper limit (Kanda [B105]).

Gain uncertainties as low as a few hundredths of a dB are achievable when the three-antenna method is combined with the extrapolation method.

8.4 Gain-transfer measurements

8.4.1 Measurement of linearly-polarized antennas

The gain-transfer method measures the unknown realized gain of an AUT by comparison with a gain standard. The AUT is either radiating, or illuminated by, a polarization-matched plane wave. The received power into a matched load is measured. The AUT is replaced by a gain standard, leaving all other conditions the same. The received power into a matched load is again measured. Starting with the Friis transmission formula, Equation (55), and substituting the standard for the AUT and then taking the ratio, the AUT realized gain, G_{AUT}, is given in Equation (59).

$$G_{AUT}\left(dB\right) = G_S\left(dB\right) + 10\log_{10}\left(P_{AUT} / P_S\right) \tag{59}$$

where

G_S	is the realized gain of the gain standard
P_{AUT}	is the received power with the AUT mounted
P_S	is the received power with the gain standard mounted

In order to reduce measurement errors, the gain standard should be aligned such that the peak of its radiation pattern is aligned to the range antenna. The peaking operation should take into consideration azimuth, elevation, and polarization.

To reduce reflections, absorber is usually required behind the gain standard. When exchanging the AUT and a pyramidal standard gain horn antenna on an antenna positioner, care should be taken to mount the standard gain horn in a manner such that the standard gain horn's phase center is placed at the measurement system origin (Pivnenko, Nielsen, and Breinbjerg [B150]).

Equation (59) assumes matched connections for the AUT and gain standard. In practice, the realized gain will be measured due to mismatch (see Figure 49). Reflection coefficients at the interface plane should be measured as a function of frequency and used to correct impedance mismatch errors in measured gains. Refer to 8.5 and 11.2 for a more detailed description of this error, and Clause 11 for a detailed discussion on measuring antenna impedance.

8.4.2 Measurement of circularly- and elliptically-polarized antennas

For circularly-polarized AUTs it is possible to calibrate circularly-polarized gain standards, but the gains of circularly-polarized AUTs are most commonly measured with the use of linearly-polarized gain standards. This is valid because the total power of the wave radiated by an antenna can be separated into two orthogonal linearly-polarized components. Partial gain measurements can be performed using two orthogonal linearly-polarized gain standards from which the total gain of the AUT can be determined. A single linearly-polarized gain standard may be employed and rotated 90° to achieve the two orthogonal polarizations (see IEEE Std 145-2013). See also Clause 9 for more details.

There are a few important aspects to note when determining the circularly-polarized gain of an AUT using the gain-transfer method with a linearly-polarized range antenna and a linearly-polarized gain standard. The first measurement is with the gain standard aligned for maximum, co-polarized response to one polarization configuration of the range antenna. The measurement is then repeated with the gain standard and range antennas oriented for the orthogonal polarization. These two gain standard measurements are used to normalize the two corresponding orthogonal measurements of the AUT to complete the gain-transfer process. Typically, this two-step gain-transfer measurement process sets the polarization reference directions and the relative phase relationship between the two orthogonal configurations of the range antenna. Therefore, it is recommended to rotate the gain standard to coincide with the desired polarization coordinate system. It is also recommended to minimize any potential phase errors that may occur between the two measurements. Two common sources of phase error during orthogonal gain-transfer measurements are caused by flexing cables and changes in the physical distance between the gain standard and the range antenna. More discussion on the topic of determining polarization properties from measured linear field components using the gain-transfer method is contained in Dobbins, Jerauld, and Hess [B50].

8.5 Errors in gain measurements

The overall error in gain measurements consists of random and systematic errors, which together are the measurement uncertainty. In the ideal case:

a) The antenna range produces a uniform plane wave at the receiving antenna.

b) The AUT, gain standard, and range antennas are reciprocal, impedance matched, aligned, and polarization matched.

c) Components in the test equipment are impedance matched, with a stable generator and receiver, and with adequate sensitivity and dynamic range.

A list of typical contributions to the uncertainties is given in Table 4. Deviations from the conditions in category a) are normally the most difficult to correct. For a far-field gain measurement, the separation between the transmitting and receiving antennas should be large, and multipath and other extraneous scattering effects absent. An error comes about from focusing effects as the distance from an antenna transitions from the radiating near-field to the far-field regions (see Figure 3 in Paquay [B144]). A second effect is that of nonuniform illumination of the AUT due to the relative sizes of the transmitting and receiving antennas and their separation. For typical antennas, the amplitude taper is about 0.25 dB at the separation $2D^2/\lambda$, an error of about 0.1 dB can be expected (Hollis, Lyon, and Clayton [B84]). The recommendation for placing the AUT at a distance that satisfies the far-field conditions applies to the gain standard as well. Non-uniform plane waves can reduce the power received by the gain standard substantially (proximity effect), particularly for pyramidal horns (Chu and Semplak [B41]; Slayton [B175]).

In the absence of a more accurate gain calibration (see 8.3), computed directivity values for pyramidal standard gain horns (Chu and Semplak [B41]; Slayton [B175]), may be used as a gain reference assuming the ohmic losses of the horn are negligible. These computed gain values are typically based on the physical dimensions of the horn and are often provided by the horn manufacturer. There are two common errors associated with these computed values. The first error is due to diffraction from the edges of the horn that cause a frequency-dependent ripple in the on-axis gain (and directivity). To account for this ripple, the computed gain values may be used with typical uncertainty bounds, e.g., ± 0.5 dB (3σ) for gain values less than approximately 17 dBi and ± 0.3 dB (3σ) for gain values greater than approximately 17 dBi. The reference port for the computed gain curves is with respect to the waveguide port of the horn. A second common gain error is caused by ohmic and dielectric losses in any coaxial-to-waveguide or other attached adapters. These losses should be determined and subtracted from the computed gain values and the resulting uncertainty adjusted as appropriate.

Errors due to impedance mismatch can be corrected using standard techniques for calibrating microwave test equipment. If reflection coefficients at the transmitting or receiving antennas are known, then factors of the form $1-|\Gamma|^2$ can be inserted into the Friis transmission formula to correct for mismatch (see Clause 11). In cases where these reflection coefficients are not known, the insertion of matching attenuators or isolators can significantly reduce impedance mismatch errors at the expense of system dynamic range (Swanstrom [B183]).

Polarization mismatch can be quantified as well. The most general form of the polarization efficiency equation accounts for arbitrary elliptical polarizations with arbitrary alignment of the polarization axes (see Equation 3.91 in Section 3.6 of Hollis, Lyon, and Clayton [B84]; Pike [B148]). The effect of polarization mismatch can be illustrated with the following examples. First consider the case where the gain of a circularly-polarized AUT is measured using the gain-transfer method (see 8.4). Suppose that the AUT is purely circularly-polarized, and that the gain standard is purely linearly polarized, but that the range antenna has a finite axial ratio. The expected error due to the finite axial ratio of the range antenna is shown in Table 2, which affects both the gain standard measurement and the AUT measurement.

Table 2—Errors in the measured gain of a purely circularly-polarized antenna[a] due to finite axial ratio of the range antenna

Range antenna axial ratio (dB)	Measurement error (dB)	
	Same sense	Opposite sense
20	+0.828	−0.915
25	+0.475	−0.503
30	+0.270	−0.279
35	+0.153	−0.156
40	+0.086	−0.087
45	+0.049	−0.049
50	+0.027	−0.028

[a] The AUT is purely circularly polarized. The gain standard is purely linearly polarized. The major axes of the polarization ellipses of the gain standard and range antenna are aligned for a single normalization measurement, then the range antenna is first rotated to 0° then rotated to 90° during the AUT measurement.

Next consider the case of the measurement of a linearly-polarized AUT with an axial ratio of 25 dB using an ideal gain standard (linearly polarized) and a range antenna having a finite axial ratio. The errors expected for several different axial ratios are given in Table 3.

Table 3—Errors in the measured gain of a linearly-polarized[a] antenna due to finite axial ratio of the range antenna

Range antenna axial ratio (dB)	Measurement error (dB)	
	Same sense	Opposite sense
20	+0.035	−0.063
25	+0.014	−0.041
30	+0.002	−0.029
35	−0.005	−0.022
40	−0.009	−0.019
45	−0.011	−0.016
50	−0.012	−0.015

[a] The AUT has an axial ratio of 25 dB. The gain standard is purely linearly polarized. The major axes of the polarization ellipses of the AUT, gain standard, and range antenna are all aligned.

For the preceding examples, the errors due to polarization mismatch can be significant, especially when a linearly-polarized gain standard is used to measure circularly-polarized AUTs by means of the gain-transfer method. The effect is less severe when a nominally linearly-polarized AUT is being measured.

When multiple sources of gain error are known or can be estimated, the root-sum-square (RSS) value may be taken as the total uncertainty, or both the arithmetic sum and the RSS values may be reported. For a normal distribution (see caution in 13.1), the 99.5% confidence interval for the measurement corresponds to $\pm 3\sigma$, where σ is the RSS value of the standard deviations of individual measurements that make up the gain measurement. Numerical values for the uncertainties are not included in Table 4, as these should be characterized individually for each test facility. Uncertainty evaluation is considered further in Clause 13.

Table 4—Sources of uncertainty in gain measurements

(A) Uniform plane wave
Far-field condition/planarity of the wave produced in the range
Multiple reflections
Multipath
Gain characterization of the gain standard
(B) Alignment and impedance matching
Alignment/positioning of AUT and gain standard
Impedance mismatch of antennas
Polarization mismatch
(C) Test equipment
Impedance mismatch in cables and test equipment
Test equipment dynamic range, sensitivity, and calibration drift

8.6 Directivity measurements

To determine the directivity, the complete radiation pattern should be measured. The peak directivity is the maximum value of the radiation intensity divided by the total radiated power as shown in Equation (47). To obtain the total radiated power, the radiation intensity must be measured in two orthogonal polarizations. The power in both polarizations is summed using Equation (48) or Equation (49). The power flux density in one polarization divided by the total radiated power in both polarizations is the partial directivity.

When the AUT has been designed to be linearly polarized, then the radiated power flux density is normally measured in two orthogonal linear polarizations. The AUT is normally oriented so that its designed polarization aligns with one of the two measured polarizations. The orthogonal polarization is referred to as the *cross-polarization*.

For AUTs that have been designed to be circularly polarized, right and left circular polarizations may be used. If the maximum coupling is obtained with the use of, say, right circular polarization, then left circular is the cross-polarization.

For either of the preceding cases, the manner in which the AUT is used operationally usually dictates which orthogonal polarizations should be measured. For example, if a circular polarized antenna is to be used operationally to receive a known linearly-polarized signal, then measurement of appropriate orthogonal linear polarizations may be desirable. Practical considerations may dictate which approach is taken. It is usually more difficult to produce a circularly-polarized field than a linearly-polarized one with sufficient purity to make accurate measurements.

The radiation intensity may be measured by sampling the field over a sphere centered on the AUT. This can be accomplished by making conical cuts, successive ϕ cuts through the pattern at increments of θ, or by great-circle cuts, successive θ cuts at increments of ϕ. The number of increments required is determined by the complexity of the antenna pattern. The number of increments increases as the pattern becomes less uniform. The sampling theorem requires that the field is adequately sampled as shown in Equation (60), (Hansen [B76]).

$$\Delta\phi, \Delta\theta \leq \frac{360}{2ka+10} \text{ (degrees)} \tag{60}$$

where

- k is the wavenumber
- a is the radius of a sphere, centered on the measurement coordinate system origin, that circumscribes all the radiating parts of the antenna

An antenna with a narrow main lobe is likely to have a large number of narrow sidelobes that should be included in the measurement and subsequent integration. During the measurement process, a normalized value of the field is usually recorded instead of the absolute value, as the scale factor does not influence the directivity calculation.

8.7 Gain measurements for large antennas

Measuring the gain of antennas large enough that an antenna test range is impractical requires specialized techniques. For some applications, such as radio telescopes, gain should be accurately characterized over elevation, including effects such as gravity-induced structural deviations. This can be accomplished with airborne transmitters, extraterrestrial radio sources, or satellite-borne beacons. More discussion on the use of airborne transmitters for gain and pattern measurements is contained in 12.7.

The locations and radiation flux densities of extraterrestrial radio sources are known accurately enough for use in gain measurements (Perley and Butler [B146]). These sources cover a broad frequency spectrum from tens of megahertz to millimeter wave and terahertz bands. Narrowband satellite beacons can usually provide a sufficient signal-to-noise ratio (SNR) to test moderate gain antennas. The beacon is usually limited to a single frequency, and for accurate measurements a geostationary satellite is desirable. If the incident flux densities from satellites are not accurately known, the gain-transfer method should be employed for these sources.

9. Measurement of polarization

9.1 General

Polarization is a fundamental characteristic of an antenna radiation pattern. For any direction of propagation, the polarization is the description of the path traced by the electric field as a function of time and propagation distance. There are three types of polarizations: linear, circular, and elliptical. Linear and circular polarizations are special cases of elliptical polarization.

In order to characterize the polarization of an antenna radiation pattern, it is convenient to decompose the pattern into orthogonal field components that are best suited for the particular application and also to define figures of merit like the axial ratio, sense, and tilt angle that quantify the polarization performance of an antenna. These terms are described in IEEE Std 145-2013 and mathematically defined in this subclause.

Far-field radiation patterns are most often defined with the spherical $r\theta\phi$-coordinate system as shown in Figure 41. The $r\theta\phi$-coordinate system is related to the xyz-coordinate system by the following usual relation shown in Equation (61):

$$(x, y, z) = \left(r\sin(\theta)\cos(\phi), r\sin(\theta)\sin(\phi), r\cos(\theta)\right) \tag{61}$$

The far-field radiation pattern can be decomposed in different pairs of orthogonal components tangential to the spherical surface (it is well-known that the component perpendicular to the spherical surface, i.e., radial component, has a negligible strength). Such orthogonal components can conveniently be chosen depending on the polarization properties of the AUT.

As shown in Figure 39, the E_θ and E_ϕ components are the ones aligned with the θ axis and ϕ axis and, in many cases, they are directly measured. The E_θ and E_ϕ components are related to the E_x, E_y, and E_z components (those aligned with the x, y, and z axis, respectively) with the expressions provided in Equation (62) and Equation (63) (see Appendix VII.1.3 in Balanis *Antenna Theory* [B15]).

$$E_\theta = E_x\cos(\theta)\cos(\phi) + E_y\cos(\theta)\sin(\phi) - E_Z\sin(\theta) \tag{62}$$

$$E_\phi = E_x\sin(\phi) + E_y\cos(\phi) \tag{63}$$

When both the amplitude and phase information of the two orthogonal far-field measurements are available, other field components can be derived. For linearly-polarized antennas, a particularly useful definition is the one introduced by Ludwig [B124] known as *Ludwig's third definition (Ludwig-3)*, which, for polar-pointing antennas, describes the co-polarized (E_{co}) and cross-polarized (E_{cx}) field components on any point of the sphere with Equation (64) and Equation (65), respectively:

$$E_{co} = E_\theta\cos(\phi - \phi_0) - E_\varphi\sin(\phi - \phi_0) \tag{64}$$

$$E_{cx} = E_\theta\sin(\phi - \phi_0) + E_\varphi\cos(\phi - \phi_0) \tag{65}$$

Where the *polarization reference angle* ϕ_0 is chosen to make the co-polarization unit vector parallel to the linearly-polarized field in some chosen direction, which is typically the main beam direction.

For circularly-polarized (CP) antennas, the far-field radiation pattern can be decomposed into right-hand $(E_{RHCP})(E_{RHCP})$ d left-hand (E_{LHCP}) field components that can be defined in terms of the Ludwig-3 components as shown in Equation (66) and Equation (67), respectively:

$$E_{RHCP} = \frac{E_{co} + jE_{cx}}{\sqrt{2}} \tag{66}$$

$$E_{LHCP} = \frac{E_{co} - jE_{cx}}{\sqrt{2}} \tag{67}$$

where the right side of the equation is obtained by setting the polarization reference angle ϕ_0 equal to 0 (any other value simply corresponds to a constant phase offset) (Milligan [B132]; Hansen [B76].[8] The polarization sense of the field is indicated by the CP field component with larger magnitude. Note that these CP equations and definitions of polarization sense are based on an $e^{+j\omega t}$ time convention and relative to the direction of propagation as specified by IEEE Std 145-2013. Refer to 1.4 for more discussion on time and polarization conventions.

As described in Chapter 3 of Hollis, Lyon, and Clayton [B84], the axial ratio (*AR*), tilt angle (τ), and polarization sense are important quantities that allow the description of the polarization properties of the radiated field in any point of the sphere.

The *AR* is defined as shown in Equation (68),

$$AR = \frac{\text{major axis}}{\text{minor axis}} = \frac{|E_{RHCP}| + |E_{LHCP}|}{|E_{RHCP}| - |E_{LHCP}|} \quad 1 \le |AR| \le \infty \tag{68}$$

where the major and the minor axis are those of a generic tilted elliptical polarization. In accordance with IEEE Std 145-2013, Equation (68) yields a signed value that is positive for right-hand sense and negative for left-hand sense.[9]

[8] Hansen [B49] incorporates an $e^{-i\omega t}$ time convention so the polarization unit vectors derived in that work must be conjugated to conform with the $e^{+j\omega t}$ convention used here. When determining field components, the complex unit vector is conjugated again during the dot product operation, yielding Equation (66) and Equation (67). This complex dot product is shown in Milligan [B136] (using the $e^{+j\omega t}$ convention) to relate circular field components to linear $\theta\phi$ components, and also in Dobbins, Jerauld, and Hess [B165] where the physical basis for the conjugation is discussed. The $e^{\pm j\phi}$ terms incorporated into equations (2.192) through (2.195) of Hansen [B49] are typically omitted to allow the polarization unit vector discontinuity to exist at $\theta = 0$, consistent with the standard spherical coordinate system, as shown in Figure 40.

[9] Readers should be aware that this convention for *AR* is not consistent across the literature, with some authors using the same convention as the IEEE (e.g., Stutzman [B126]; Stutzman and Thiele 2012 [B166]), some defining *AR* so it is always positive (e.g., Balanis *Antenna Theory* [B8]; Kraus [B115]; Milligan [B136]), and others choosing the opposite signs for sense (e.g., Balanis *Advanced Engineering* [B169]; Stutzman and Thiele 1981 [B168]). Some other publications (e.g., International Telephone and Telegraph Corporation [B170]) define *AR* as the inverse ratio of minor axis/major axis.

Alternatively, AR can be calculated using the polarization ellipse magnitudes of the semimajor axis (OA) and semiminor axis (OB) defined in terms of the E_θ and E_ϕ components in Equation (70) and Equation (71), respectively:

$$AR = OA / OB \tag{69}$$

where

$$OA = \sqrt{0.5\left[\left|E_\theta\right|^2 + \left|E_\phi\right|^2 + \sqrt{\left|E_\theta\right|^4 + \left|E_\phi\right|^4 + 2\left|E_\theta\right|^2\left|E_\phi\right|^2\cos\left(2\Delta\psi\right)}\right]} \tag{70}$$

$$OB = \sqrt{0.5\left[\left|E_\theta\right|^2 + \left|E_\phi\right|^2 - \sqrt{\left|E_\theta\right|^4 + \left|E_\phi\right|^4 + 2\left|E_\theta\right|^2\left|E_\phi\right|^2\cos\left(2\Delta\psi\right)}\right]} \tag{71}$$

where

$\Delta\psi$ is the difference between the phase of the two field components

When computing AR using the ratio of Equation (70) to Equation (71) the result is a positive value. A linearly-polarized antenna will have a very high $|AR|$ (ideally $|AR| = \infty$) while a circularly-polarized antenna will have an AR close to the unity (ideally $|AR| = 1$).

The tilt angle (τ) is a measurement of the inclination of the polarization ellipse relative to the *x* axis and is defined in Equation (72) in terms of the E_θ and E_ϕ components:

$$\tau = \frac{\pi}{2} - \frac{1}{2}\tan^{-1}\left(\frac{2\left|E_\theta\right|\left|E_\phi\right|}{\left|E_\theta\right|^2 - \left|E_\phi\right|^2}\cos\Delta\psi\right) \tag{72}$$

The knowledge of the tilt angle is useful in cases of linearly or elliptically-polarized fields, but not in the case of a circularly-polarized field (Balanis *Antenna Theory* [B15]).

Another widely used quantity for the description of the polarization properties of a field is the cross-polar discrimination (*XPD*) which is simply the ratio between the amplitude of two measured (or derived) orthogonal field components as shown in Equation (73).

$$XPD = \frac{|\text{First component}|}{|\text{Second component}|} \tag{73}$$

where

$|\text{First component}| \geq |\text{Second component}|$

It should be noted that the AR is always greater (or at least equal) to the XPD (see Section 12.7.3 of Barclay [B18]). Both AR and XPD are often expressed in decibels, computed using the $20\log_{10}|\bullet|$ function because they represent ratios of field values. When expressing AR in decibels, the polarization sense should be stated explicitly as either right-hand or left-hand rather than through the use of a sign.

9.2 Polarization measurements

The polarization characteristics of an antenna can be measured in a measurement setup capable of measuring two orthogonal field components. For full pattern polarization measurements, the range length should be sufficiently long enough that both the range antenna and the AUT are in far-field conditions. However, along the main beam direction, polarization measurements may be performed at distances as short as $D^2/4\lambda$. In this type of measurement, the antenna polarization characteristic is determined with respect to the reference coordinate system established by the range antenna and measurement setup. The accurate alignment and quality of the range antenna will therefore influence the measurement uncertainty. The range antenna should have either known or sufficient polarization purity as to not influence the measurement result. Different types of polarization measurements can be performed depending on the capability of the system to acquire amplitude and phase field data (Joy and Paris [B104]; Newell, 1975 [B134].

If the measurement system is capable of measuring amplitude and phase, only two orthogonal components of the radiated field are needed. Any other component can be determined with the expressions similar to those reported in 9.1. In a similar manner, polarization characteristics such as AR, polarization sense, and tilt angle can be derived with the expressions reported in 9.1. It is critical for accurate characterization of polarization to maintain phase coherence between orthogonal phase measurements as discussed in 5.3. Reduction of radiated leakage is also important to help minimize polarization measurement errors. Polarization mismatch errors are discussed in 8.5. Further discussions on quantifying polarization measurement errors are provided in Betjes [B21] and Rousseau [B163]. A discussion on the topic of determining polarization properties from measured linear field components is contained in Dobbins, Jerauld, and Hess [B50].

If the measurement system captures only amplitude measurements, the range antenna should directly measure the desired component. For example, to measure the $\theta\phi$- or the Ludwig-3 components, a linearly-polarized range antenna properly oriented should be used. To measure the CP components, a circularly-polarized range antenna should be used. Moreover, in order to measure the AR and the tilt angle, several points should be acquired while rotating a linearly-polarized range antenna over 360°. By doing this, the AR can be computed as the ratio between the peak and the minimum of the acquired signal and the tilt angle by looking at the angular coordinate corresponding to the peak of the acquired signal. Of course, the accuracy of this procedure depends on the considered sampling density. Moreover, in case of elliptical or circular polarized field, this procedure does not allow determining the polarization sense of rotation.

When performing polarization measurements, the alignment of the measurement system and of the AUT is of primarily importance. A detailed description of the different alignment procedures is reported in Clause 5.

It is highlighted that the availability of amplitude and phase data may permit improvement of the polarization measurements by using post-processing techniques. Examples are:

- Time domain filtering: If a sufficient number of frequency points are available, the signal can be transformed to the time-domain (with a Fourier or chirp Z-transformation) and filtering may be applied to remove unwanted echo/noise contributions with longer time dependency with respect to the direct signal (Boyles [B26]).
- Averaging of different datasets separated by distances of multiples of $\lambda/4$: This technique is described in detail in Foged "Deliverable A1.2D2" [B58] and is well suited in order to mitigate the effect of multiple reflections. The technique is based on the acquisition of two (or more) measurements performed at distances differing by a quarter of a wavelength (or multiples of a quarter of a wavelength) that are then averaged considering a proper phase correction term. The goal of this technique is to have the reflections add out of phase and thus cancel out.
- Correction of the measured AUT polarization to remove errors due to the cross-polar field of the range antenna: Ideally, the range antenna should not radiate any cross-polarized field. The non-

ideal cross-polar behavior of the range antenna can be corrected using an auxiliary antenna with high polarization purity (Kolesnikoff [B111]; Walkenhorst and Nichols [B190]). The auxiliary antenna properties may be used to more accurately characterize the polarization properties of the range antenna without any a priori knowledge, using a specialized case of the more generic three-antenna method (see Chapter 5, section 5.2.4 of Hansen [B76]; Newell 1975 [B134]; Newell 1988 [B135]; Newell et al. [B137]). A pyramidal standard gain horn (SGH) is recommended as a linear polarization reference antenna due to its high polarization purity (axial ratio typically greater than 40 dB) and mechanical surfaces that permit easy alignment of the polarization axis to the range coordinate system.

— If the data are sampled over 360° instead of just two orthogonal sampling points, more accurate polarization information can be extracted from a Fourier analysis of the acquired data (Hansen [B76]; Jones and Hess [B102]).

If the AUT is circularly polarized or not perfectly linearly polarized, the spinning linear (or rotating range antenna) method provides a rapid measurement technique for determining the axial ratio magnitude as a function of pattern angle. This method is based only on amplitude data. The AUT is rotated slowly as in a conventional pattern measurement while the linearly-polarized range antenna is rotated rapidly. The rotational speed of the AUT and range antenna should be adjusted such that the pattern of the AUT does not change appreciably during one-half revolution of the range antenna. The pattern of the antenna is recorded in a full cut showing rapid variations. The difference between adjacent minima and maxima on the antenna pattern gives the axial ratio in that direction. Polarization sense cannot be obtained with this amplitude-only measurement method (Hollis, Lyon, and Clayton [B84]; Stutzman [B180]). An example of the spinning linear measurement is shown in Figure 50.

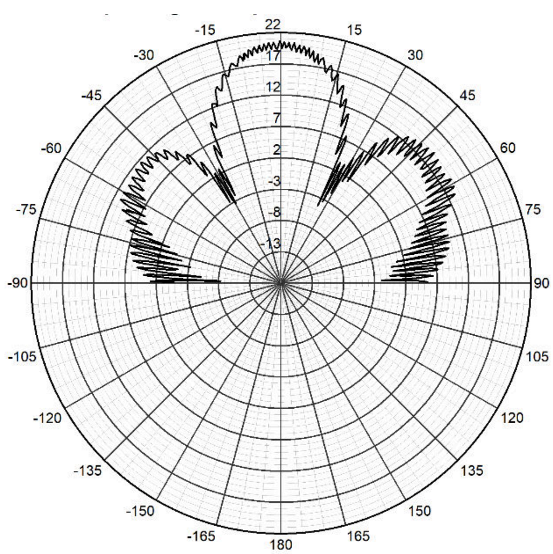

Figure 50—Example of spinning linear antenna measurement

10. Measurement of radiation efficiency

10.1 General

The radiation efficiency of an antenna is the ratio of the total power radiated by the antenna to the net power accepted by the antenna at its terminals during the radiation process. The difference between these two powers is the power that is dissipated within the antenna. Radiation efficiency is an inherent property of an antenna and does not depend on system factors, such as those due to impedance or polarization mismatch.

A fundamental method for determining radiation efficiency relies on the measurements described in Clause 8. As noted in 8.1, radiation efficiency is equal to the ratio of the gain in any specified direction to the directivity in that same direction as shown in Equation (74).

$$\eta = \frac{G}{D} \tag{74}$$

where

η is the radiation efficiency

G is the gain

D is the directivity

It is usually convenient to take the direction of maximum radiation for this determination of radiation efficiency. In measuring peak gain and directivity, all the precautions mentioned in 8.1 and 8.5 should be carefully observed. Even when the appropriate steps are taken, the uncertainty associated with the measurement of the gain and directivity should be considered in the evaluation of the result.

If the antenna is electrically small and simple, an equivalent series circuit can frequently be found in which the real part of the input impedance, that is, the antenna resistance, is equal to the sum of the radiation resistance and a loss resistance (Newman, Bohley, and Walter [B139]). The radiation resistance accounts for all radiated power, and the loss resistance accounts for all dissipation within the antenna. For antennas such as dipoles and loops, where the theoretical pattern can be integrated, the radiation resistance is best found by calculation from the dimensions (Kraus [B114]; Terman [B184]). The antenna resistance is obtained from measurements of input impedance as discussed in Clause 11. The radiation efficiency is then determined by Equation (75):

$$\eta = \frac{Z_{\text{radiation}}}{Z_{\text{antenna}}} \tag{75}$$

where

$Z_{\text{radiation}}$ is the radiation resistance

Z_{antenna} is the total resistance

This method is valid only if the antenna can be accurately represented as a series circuit. When the dissipation cannot be represented by a resistance in series with the radiation resistance, as in the case of an antenna coated with lossy dielectric or an antenna over a lossy ground, the method should not be used and the methods shown in 10.2, 10.3, and 10.4 should be considered. Furthermore, the calculated radiation resistance and the measured antenna resistance should be referred to the same set of antenna terminals. It should also be noted that the input impedance of this type of antenna can present a large mismatch to the connecting transmission line, and a matching network having appreciable dissipation might be used. Such a loss is not usually included within the meaning of radiation efficiency, although it is clear that the loss would be important to the system as a whole.