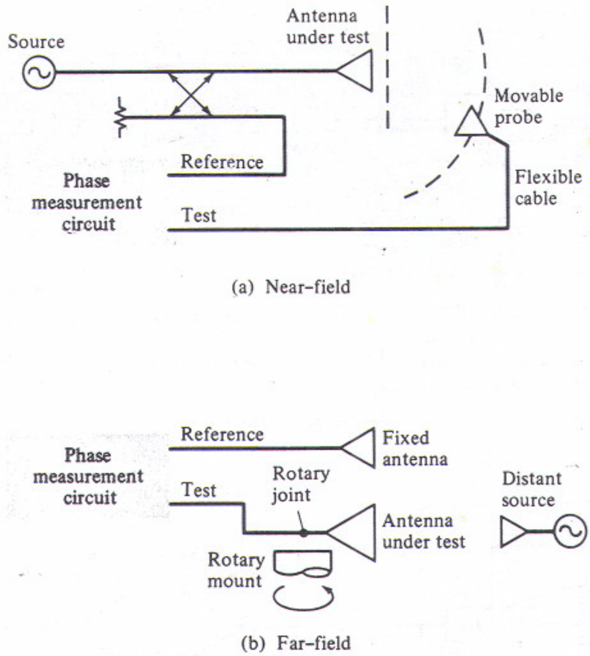

Figure 16.21 Near-field and far-field phase pattern measuring systems. (SOURCE: *IEEE Standard Test Procedures for Antennas*, IEEE Std 149-1979, published by IEEE, Inc., 1979, distributed by Wiley)

The phase of an antenna is periodic, and it is defined in multiples of 360°. In addition, the phase is a relative quantity, and a reference must be provided during measurements for comparison.

Two basic system techniques that can be used to measure phase patterns at short and long distances from the antenna are shown respectively, in Figures 16.21(a) and 16.21(b). For the design of Figure 16.21(a), a reference signal is coupled from the transmission line, and it is used to compare, in an appropriate network, the phase of the received signal. For large distances, this method does not permit a direct comparison between the reference and the received signal. In these cases, the arrangement of Figure 16.21(b) can be used in which the signal from the source antenna is received simultaneously by a fixed antenna and the antenna under test. The phase pattern is recorded as the antenna under test is rotated while the fixed antenna serves as a reference. The phase measuring circuit may be the dual-channel heterodyne system [7, Fig. 15].

16.4 GAIN MEASUREMENTS

The most important figure-of-merit that describes the performance of a radiator is the gain. There are various techniques and antenna ranges that are used to measure the gain. The choice of either depends largely on the frequency of operation.

Usually free-space ranges are used to measure the gain above 1 GHz. In addition, microwave techniques, which utilize waveguide components, can be used. At lower frequencies, it is more difficult to simulate free-space conditions because of the longer wavelengths. Therefore between 0.1–1 GHz, ground-reflection ranges are utilized. Scale models can also be used in this frequency range. However, since the conductivity

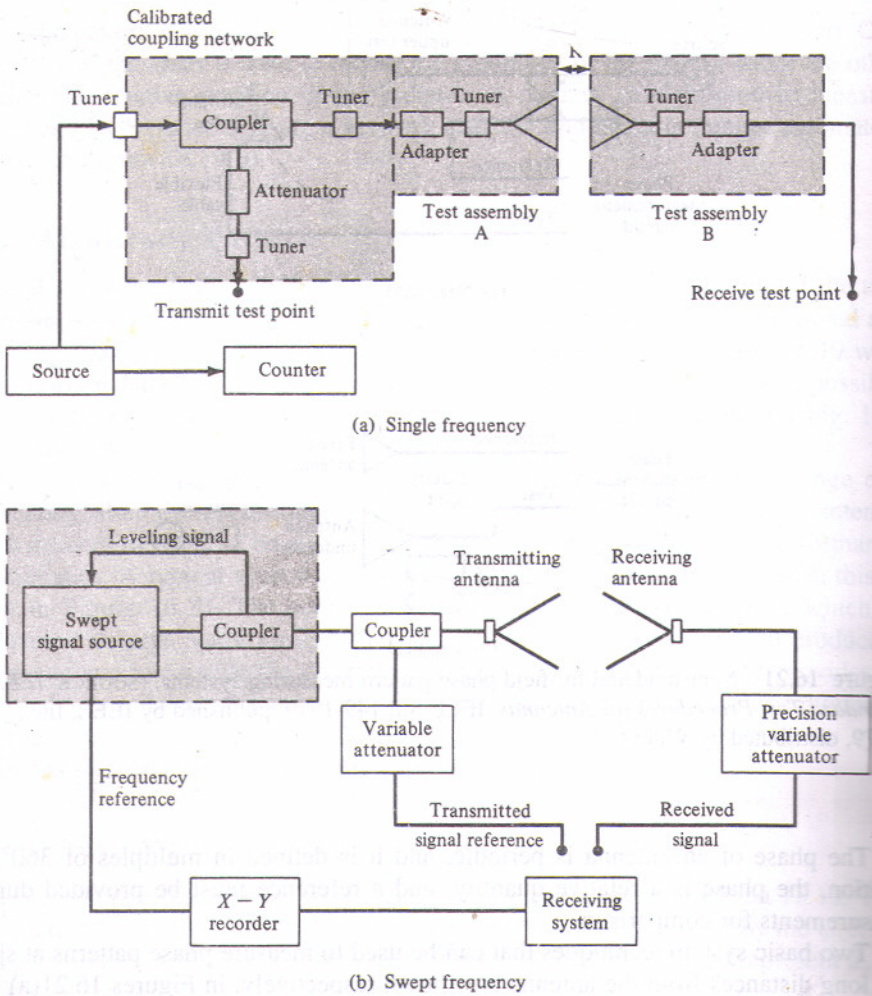

Figure 16.22 Typical two- and three-antenna measuring systems for single and swept frequency measurements. (SOURCE: J. S. Hollis, T. J. Lyon, and L. Clayton, Jr., *Microwave Antenna Measurements,* Scientific-Atlanta, Inc., Atlanta, Georgia, July 1970)

and loss factors of the structures cannot be scaled conveniently, the efficiency of the full scale model must be found by other methods to determine the gain of the antenna. This is accomplished by multiplying the directivity by the efficiency to result in the gain. Below 0.1 GHz, directive antennas are physically large and the ground effects become increasingly pronounced. Usually the gain at these frequencies is measured *in situ.* Antenna gains are not usually measured at frequencies below 1 MHz. Instead, measurements are conducted on the field strength of the ground wave radiated by the antenna.

Usually there are two basic methods that can be used to measure the gain of an electromagnetic radiator: *absolute-gain* and *gain-transfer* (or *gain-comparison*) measurements. The absolute-gain method is used to calibrate antennas that can then be used as standards for gain measurements, and it requires no *a priori* knowledge of the gains of the antennas. Gain-transfer methods must be used in conjunction with standard gain antennas to determine the absolute gain of the antenna under test.

The two antennas that are most widely used and universally accepted as gain standards are the resonant $\lambda/2$ dipole (with a gain of about 2.1 dB) and the pyramidal horn antenna (with a gain ranging from 12–25 dB). Both antennas possess linear polarizations. The dipole, in free-space, exhibits a high degree of polarization purity. However, because of its broad pattern, its polarization may be suspect in other than reflection-free environments. Pyramidal horns usually possess, in free-space, slightly elliptical polarization (axial ratio of about 40 to infinite dB). However, because of their very directive patterns, they are less affected by the surrounding environment.

16.4.1 Absolute-Gain Measurements

There are a number of techniques that can be employed to make absolute-gain measurements. A very brief review of each will be included here. More details can be found in [6]–[8]. All of these methods are based on Friis transmission formula [as given by (2-118)] which assumes that the measuring system employs, each time, two antennas (as shown in Figure 2.25). The antennas are separated by a distance R, and it must satisfy the far-field criterion of each antenna. For polarization matched antennas, aligned for maximum directional radiation, (2-118) reduces to (2-119).

A. Two-Antenna Method

Equation (2-119) can be written in a logarithmic decibel form as

$$(G_{0t})_{\text{dB}} + (G_{0r})_{\text{dB}} = 20\log_{10}\left(\frac{4\pi R}{\lambda}\right) + 10\log_{10}\left(\frac{P_r}{P_t}\right) \tag{16-14}$$

where

$(G_{0t})_{\text{dB}}$ = gain of the transmitting antenna (dB)

$(G_{0r})_{\text{dB}}$ = gain of the receiving antenna (dB)

P_r = received power (W)

P_t = transmitted power (W)

R = antenna separation (m)

λ = operating wavelength (m)

If the transmitting and receiving antennas are identical ($G_{0t} = G_{0r}$), (16-14) reduces to

$$(G_{0t})_{\text{dB}} = (G_{0r})_{\text{dB}} = \frac{1}{2}\left[20\log_{10}\left(\frac{4\pi R}{\lambda}\right) + 10\log_{10}\left(\frac{P_r}{P_t}\right)\right] \tag{16-15}$$

By measuring R, λ, and the ratio of P_r/P_t, the gain of the antenna can be found. At a given frequency, this can be accomplished using the system of Figure 16.22(a). The system is simple and the procedure straightforward. For continuous multifrequency measurements, such as for broadband antennas, the swept frequency instrumentation of Figure 16.22(b) can be utilized.

B. Three-Antenna Method

If the two antennas in the measuring system are not identical, three antennas (a, b, c) must be employed and three measurements must be made (using all combinations of the three) to determine the gain of each of the three. Three equations (one for each combination) can be written, and each takes the form of (16-14). Thus

(a-b Combination)

$$(G_a)_{\text{dB}} + (G_b)_{\text{dB}} = 20\log_{10}\left(\frac{4\pi R}{\lambda}\right) + 10\log_{10}\left(\frac{P_{rb}}{P_{ta}}\right) \tag{16-16a}$$

(a-c Combination)

$$(G_a)_{\text{dB}} + (G_c)_{\text{dB}} = 20\log_{10}\left(\frac{4\pi R}{\lambda}\right) + 10\log_{10}\left(\frac{P_{rc}}{P_{ta}}\right) \tag{16-16b}$$

(b-c Combination)

$$(G_b)_{\text{dB}} + (G_c)_{\text{dB}} = 20\log_{10}\left(\frac{4\pi R}{\lambda}\right) + 10\log_{10}\left(\frac{P_{rc}}{P_{tb}}\right) \tag{16-16c}$$

From these three equations, the gains $(G_a)_{\text{dB}}$, $(G_b)_{\text{dB}}$, and $(G_c)_{\text{dB}}$ can be determined provided R, λ, and the ratios of P_{rb}/P_{ta}, P_{rc}/P_{ta}, and P_{rc}/P_{tb} are measured.

The two- and three-antenna methods are both subject to errors. Care must be utilized so

1. the system is frequency stable
2. the antennas meet the far-field criteria
3. the antennas are aligned for boresight radiation
4. all the components are impedance and polarization matched
5. there is a minimum of proximity effects and multipath interference

Impedance and polarization errors can be accounted for by measuring the appropriate complex reflection coefficients and polarizations and then correcting accordingly the measured power ratios. The details for these corrections can be found in [7], [8]. There are no rigorous methods to account for proximity effects and multipath interference. These, however, can be minimized by maintaining the antenna separation by at least a distance of $2D^2/\lambda$, as is required by the far-field criteria, and by utilizing RF absorbers to reduce unwanted reflections. The interference pattern that is created by the multiple reflections from the antennas themselves, especially at small separations, is more difficult to remove. It usually manifests itself as a cyclic variation in the measured antenna gain as a function of separation.

C. Extrapolation Method

The extrapolation method is an absolute-gain method, which can be used with the three-antenna method, and it was developed [15] to rigorously account for possible errors due to proximity, multipath, and nonidentical antennas. If none of the antennas used in the measurements are circularly polarized, the method yields the gains and polarizations of all three antennas. If only one antenna is circularly polarized, this method yields only the gain and polarization of the circularly polarized antenna. The method fails if two or more antennas are circularly polarized.

The method requires both amplitude and phase measurements when the gain and the polarization of the antennas is to be determined. For the determination of gains, amplitude measurements are sufficient. The details of this method can be found in [8], [45].

D. Ground-Reflection Range Method

A method that can be used to measure the gain of moderately broad beam antennas, usually for frequencies below 1 GHz, has been reported [46]. The method takes into account the specular reflections from the ground (using the system geometry of Figure

16.2), and it can be used with some restrictions and modifications with the two- or three-antenna methods. As described here, the method is applicable to linear antennas that couple only the electric field. Modifications must be made for loop radiators. Using this method, it is recommended that the linear vertical radiators be placed in a horizontal position when measurements are made. This is desired because the reflection coefficient of the earth, as a function of incidence angle, varies very rapidly for vertically polarized waves. Smoother variations are exhibited for horizontally polarized fields. Circularly and elliptically polarized antennas are excluded, because the earth exhibits different reflective properties for vertical and horizontal fields.

To make measurements using this technique, the system geometry of Figure 16.2 is utilized. Usually it is desirable that the height of the receiving antenna h_r be much smaller than the range R_0 ($h_r \ll R_0$). Also the height of the transmitting antenna is adjusted so that the field of the receiving antenna occurs at the first maximum nearest to the ground. Doing this, each of the gain equations of the two- or three-antenna methods take the form of

$$(G_a)_{\text{dB}} + (G_b)_{\text{dB}} = 20 \log_{10}\left(\frac{4\pi R_D}{\lambda}\right) + 10 \log_{10}\left(\frac{P_r}{P_t}\right) - 20 \log_{10}\left(\sqrt{D_A D_B} + \frac{r R_D}{R_R}\right) \tag{16-17}$$

D_A and D_B are the directivities (relative to their respective maximum values) along R_D, and they can be determined from amplitude patterns measured prior to the gain measurements. R_D, R_R, λ, and P_r/P_t are also measured. The only quantity that needs to be determined is the factor r which is a function of the radiation patterns of the antennas, the frequency of operation, and the electrical and geometrical properties of the antenna range.

The factor r can be found by first repeating the above measurements but with the transmitting antenna height adjusted so that the field at the receiving antenna is minimum. The quantities measured with this geometry are designated by the same letters as before but with a prime (′) to distinguish them from those of the previous measurement.

By measuring or determining the parameters

1. R_R, R_D, P_r, D_A, and D_B at a height of the transmitting antenna such that the receiving antenna is at the first maximum of the pattern
2. R'_R, R'_D, P'_r, D'_A, and D'_B at a height of the transmitting antenna such that the receiving antenna is at a field minimum

it can be shown [46] that r can be determined from

$$r = \left(\frac{R_R R'_R}{R_D R'_D}\right)\left[\frac{\sqrt{(P_r/P'_r)(D'_A D'_B)}\, R_D - \sqrt{D_A D_B} R'_D}{\sqrt{(P_r/P'_r)}\, R_R + R'_R}\right] \tag{16-18}$$

Now all parameters included in (16-17) can either be measured or computed from measurements. The free-space range system of Figure 16.22(a) can be used to perform these measurements.

16.4.2 Gain-Transfer (Gain-Comparison) Measurements

The method most commonly used to measure the gain of an antenna is the gain-transfer method. This technique utilizes a gain standard (with a known gain) to determine absolute gains. Initially relative gain measurements are performed, which when compared with the known gain of the standard antenna, yield absolute values. The method can be used with free-space and reflection ranges, and for *in situ* measurements.

The procedure requires two sets of measurements. In one set, using the test antenna as the receiving antenna, the received power (P_T) into a matched load is recorded. In the other set, the test antenna is replaced by the standard gain antenna and the received power (P_S) into a matched load is recorded. In both sets, the geometrical arrangement is maintained intact (other than replacing the receiving antennas), and the input power is maintained the same.

Writing two equations of the form of (16-14) or (16-17), for free-space or reflection ranges, it can be shown that they reduce to [7]

$$(G_T)_{\text{dB}} = (G_S)_{\text{dB}} + 10\log_{10}\left(\frac{P_T}{P_S}\right) \tag{16-19}$$

where $(G_T)_{\text{dB}}$ and $(G_S)_{\text{dB}}$ are the gains (in dB) of the test and standard gain antennas.

System disturbance during replacement of the receiving antennas can be minimized by mounting the two receiving antennas back-to-back on either side of the axis of an azimuth positioner and connecting both of them to the load through a common switch. One antenna can replace the other by a simple, but very precise, 180° rotation of the positioner. Connection to the load can be interchanged by proper movement of the switch.

If the test antenna is not too dissimilar from the standard gain antenna, this method is less affected by proximity effects and multipath interference. Impedance and polarization mismatches can be corrected by making proper complex reflection coefficient and polarization measurements [8].

If the test antenna is circularly or elliptically polarized, gain measurements using the gain-transfer method can be accomplished by at least two different methods. One way would be to design a standard gain antenna that possesses circular or elliptical polarization. This approach would be attractive in mass productions of power-gain measurements of circularly or elliptically polarized antennas.

The other approach would be to measure the gain with two orthogonal linearly polarized standard gain antennas. Since circularly and elliptically polarized waves can be decomposed to linear (vertical and horizontal) components, the total power of the wave can be separated into two orthogonal linearly polarized components. Thus the total gain of the circularly or elliptically polarized test antenna can be written as

$$(G_T)_{\text{dB}} = 10\log_{10}(G_{TV} + G_{TH}) \tag{16-20}$$

G_{TV} and G_{TH} are, respectively, the partial power gains with respect to vertical-linear and horizontal-linear polarizations.

G_{TV} is obtained, using (16-19), by performing a gain-transfer measurement with the standard gain antenna possessing vertical polarization. The measurements are repeated with the standard gain antenna oriented for horizontal polarization. This allows the determination of G_{TH}. Usually a single linearly polarized standard gain antenna (a linear $\lambda/2$ resonant dipole or a pyramidal horn) can be used, by rotating it by 90°, to provide both vertical and horizontal polarizations. This approach is very convenient, especially if the antenna possesses good polarization purity in the two orthogonal planes.

The techniques outlined above yield good results provided the transmitting and standard gain antennas exhibit good linear polarization purity. Errors will be introduced if either one of them possesses a polarization with a finite axial ratio. In addition, these techniques are accurate if the tests can be performed in a free-space, a ground-reflection, or an extrapolation range. These requirements place a low-frequency limit of 50 MHz.

Below 50 MHz, the ground has a large effect on the radiation characteristics of the antenna, and it must be taken into account. It usually requires that the measurements are performed on full scale models and *in situ.* Techniques that can be used to measure the gain of large HF antennas have been devised [47]–[49].

16.5 DIRECTIVITY MEASUREMENTS

If the directivity of the antenna cannot be found using solely analytical techniques, it can be computed using measurements of its radiation pattern. One of the methods is based on the approximate expressions of (2-27) by Kraus or (2-30b) by Tai and Pereira, whereas the other relies on the numerical techniques that were developed in Section 2.6. The computations can be performed very efficiently and economically with modern computational facilities and numerical techniques.

The simplest, but least accurate method, requires that the following procedure is adopted:

1. Measure the two principal *E*- and *H*-plane patterns of the test antenna.
2. Determine the half-power beamwidths (in degrees) of the *E*- and *H*-plane patterns.
3. Compute the directivity using either (2-27) or (2-30b).

The method is usually employed to obtain rough estimates of directivity. It is more accurate when the pattern exhibits only one major lobe, and its minor lobes are negligible.

The other method requires that the directivity be computed using (2-35) where P_{rad} is evaluated numerically using (2-43). The $F(\theta_i, \phi_j)$ function represents the radiation intensity or radiation pattern, as defined by (2-42), and it will be obtained by measurements. $U_{\max}$ in (2-35) represents the maximum radiation intensity of $F(\theta, \phi)$ in all space, as obtained by the measurements.

The radiation pattern is measured by sampling the field over a sphere of radius r. The pattern is measured in two-dimensional plane cuts with ϕ_j constant $(0 \leq \phi_j \leq 2\pi)$ and θ variable $(0 \leq \theta \leq \pi)$, as shown in Figure 2.15, or with θ_i fixed $(0 \leq \theta_i \leq \pi)$ and ϕ variable $(0 \leq \phi \leq 2\pi)$. The first are referred to as elevation or great-circle cuts, whereas the second represent azimuthal or conical cuts. Either measuring method can be used. Equation (2-43) is written in a form that is most convenient for elevation or great-circle cuts. However, it can be rewritten to accommodate azimuthal or conical cuts.

The spacing between measuring points is largely controlled by the directive properties of the antenna and the desired accuracy. The method is most accurate for broad beam antennas. However, with the computer facilities and the numerical methods now available, this method is very attractive even for highly directional antennas. To maintain a given accuracy, the number of sampling points must increase as the pattern becomes more directional. The pattern data is recorded digitally on tape, and it can be entered to a computer at a later time. If on-line computer facilities are available, the measurements can be automated to provide essentially real-time computations.

The above discussion assumes that all the radiated power is contained in a single polarization, and the measuring probe possesses that polarization. If the antenna is