Module 4: ANTENNA MEASUREMENTS

Introduction, Concepts- Reciprocity, Near and far fields, Coordinate system, Sources of errors, Pattern measurement arrangement, Measurement of Directivity, Gain(by comparison, Absolute and 3-Antenna Methods), Radiation pattern.

Introduction

- The analytical models used to analyze, synthesize and numerically compute the radiation characteristics of antennas are
  - GTD (Geometrical Theory of Diffraction) Method
  - Moment Method
  - Finite Difference Time Domain Method
  - Finite Element method

- use test antenna in its receiving mode for antenna measurements. If the test antenna is reciprocal, the receiving mode characteristics (gain, radiation pattern. etc.) are identical to those transmitted by the antenna.

- Since as per reciprocity theorem,
  - the transmitting and receiving antenna patterns are the same.
  - Power flow is the same in either way.

Introduction

- In practical antenna measurements, the important conditions for the validity of reciprocity theorem are
  - The EMFs in the terminals of the interchanged antennas are of the same frequency.
  - The media are linear, passive and isotropic.
  - The power flow is equal for matched impedances only.

Introduction

- The ideal condition for measuring far-field radiation characteristics is the illumination of the test antenna by plane waves:

  - uniform amplitude and phase, which is not practical.

- it can be approximated by separating the test antenna from the illumination source by a large distance on an outdoor range.

- At large radii, the curvature of the spherical phase front produced by the source antenna is small over the test antenna aperture.

Introduction

- If the separation distance is equal to the inner boundary of the far-field region. $2D^2/\lambda$, then the maximum phase error of the incident field from an ideal plane wave is about 22.5°.

- In addition to phase front curvature due to finite separation distances, reflections from the ground and nearby objects are possible sources of degradation of the test antenna illumination.

Introduction

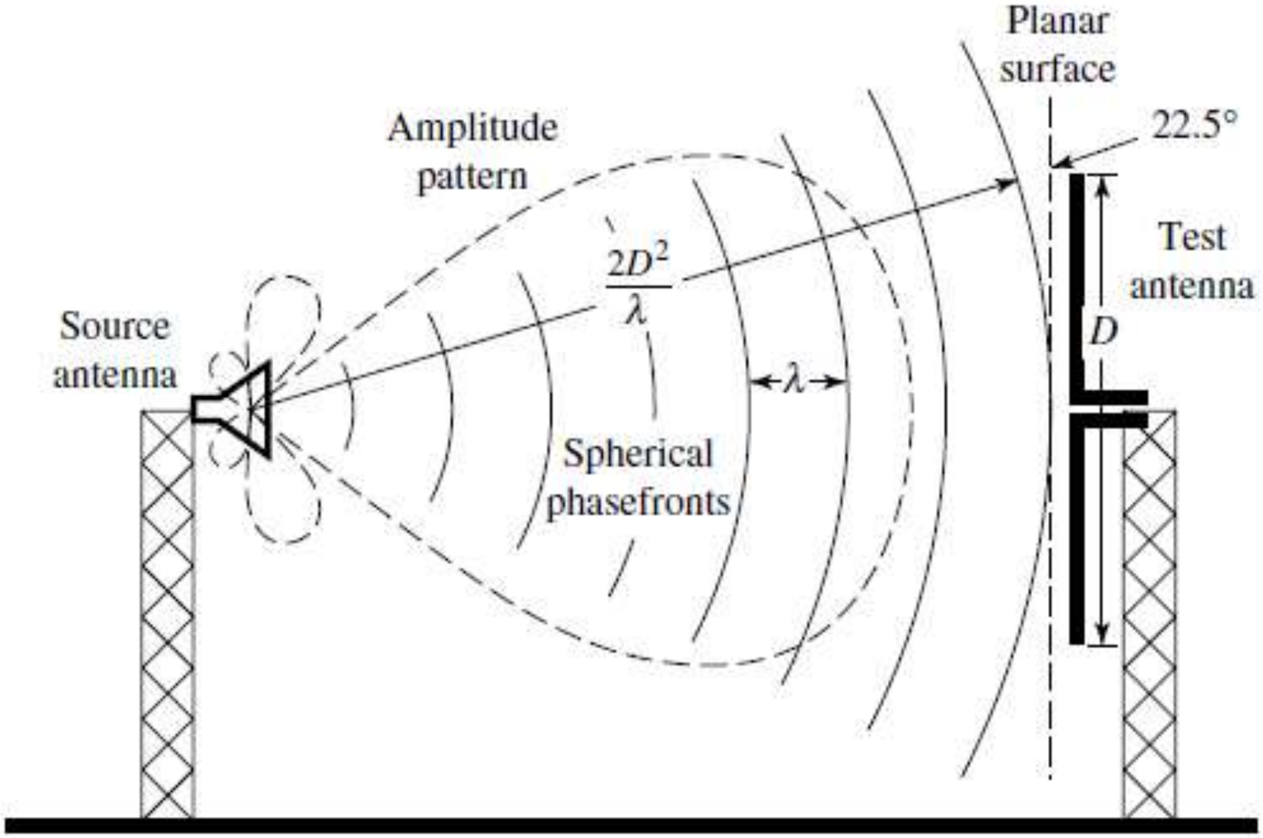


Figure 17.1 Phase error at the edges of a test antenna in the far-field when illuminated by a spherical wave.

Introduction

- Experimental investigations suffer from a number of drawbacks such as:

1. For pattern measurements, the distance to the far-field region ($r > 2D^2/\lambda$) is too long even for outside ranges. It also becomes difficult to keep unwanted reflections from the ground and the surrounding objects below acceptable levels.

2. In many cases, it may be impractical to move the antenna from the operating environment to the measuring site.

Introduction

3. For some antennas, such as phased arrays. the time required to measure the necessary characteristics may be enormous.

4. Outside measuring systems provide an uncontrolled environment, and they do not possess an all-weather capability.

5. Enclosed measuring systems usually cannot accommodate large antenna systems (such as ships. aircraft, large spacecraft. etc.).

6. Measurement techniques. in general, are expensive.

Introduction

- Some of the above shortcomings can be overcome by using special techniques. such as
  - Indoor measurements,
  - Far-field pattern prediction from near-field measurements.
  - Scale model measurements, and
  - Automated commercial equipment specifically designed for antenna measurements and utilizing computer assisted techniques.

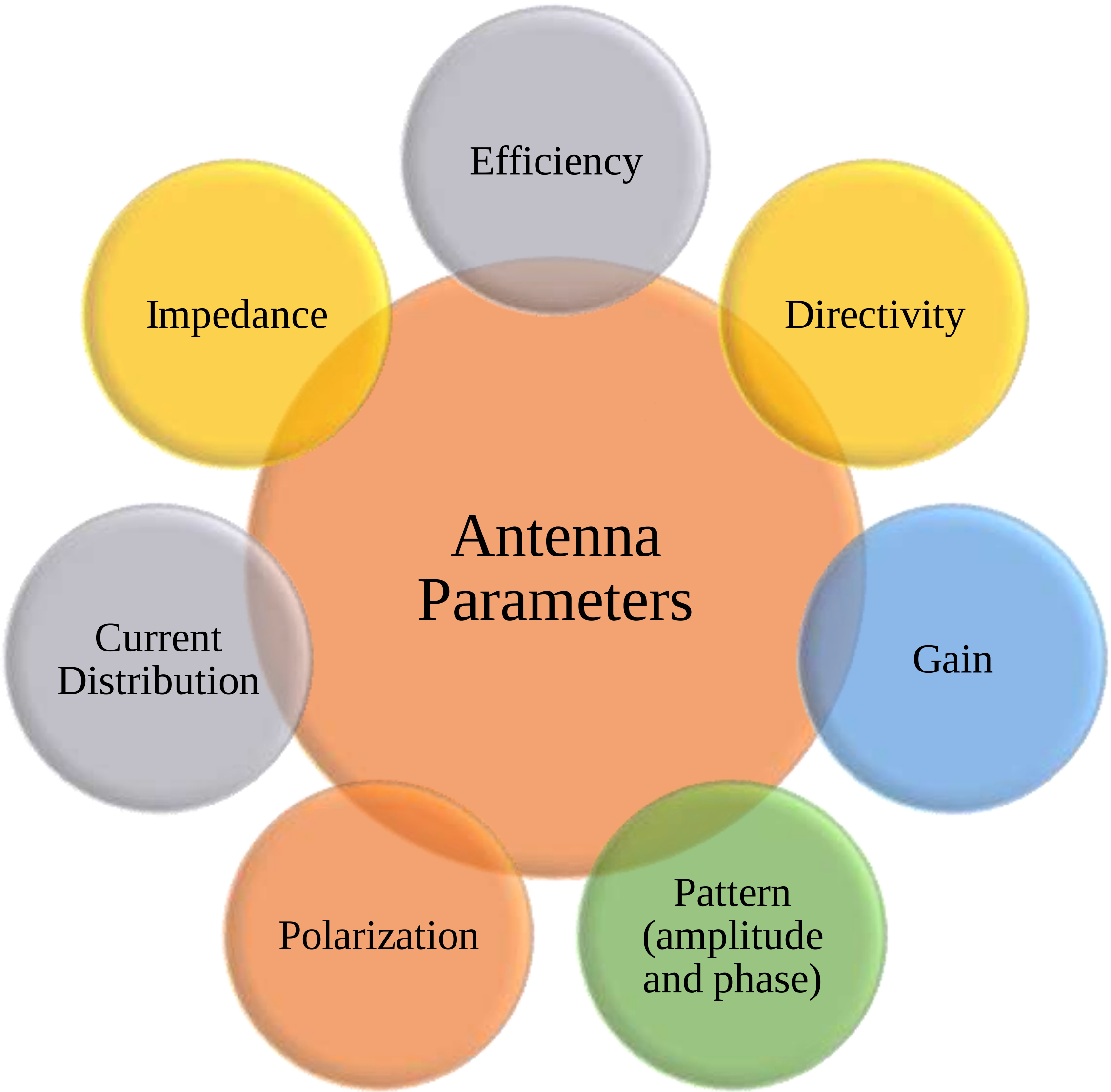
Introduction

- Because of the accelerated progress made in aerospace/defense related systems (with increasingly small design margins), more accurate measurement methods were necessary.

- To accommodate these requirements, improved instrumentation and measuring techniques were developed which include

  - tapered anechoic chambers,
  - compact and extrapolation ranges,
  - near-field probing techniques,
  - improved polarization techniques,
  - swept-frequency measurements,
  - indirect measurements of antenna characteristics, and
  - automated test systems.

Antenna System's Performance



ANTENNA RANGES

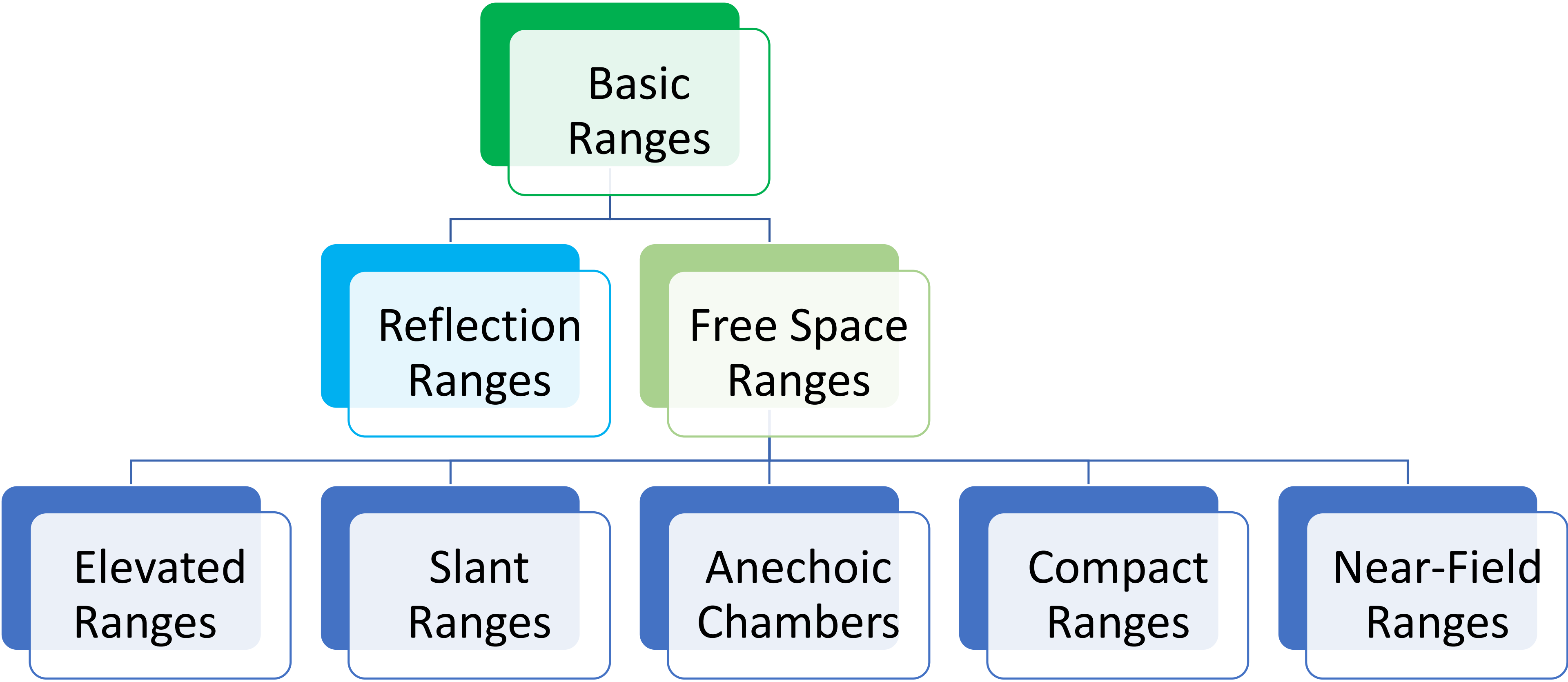
- The testing and evaluation of antennas are performed in antenna ranges.

- Antenna facilities are categorized as *outdoor and indoor ranges, and limitations are associated* with both of them.

- Outdoor ranges are not protected from environmental conditions whereas indoor facilities are limited by space restrictions.

- Because some of the antenna characteristics are measured in the receiving mode and require far-field criteria, the ideal field incident upon the test antenna should be a uniform plane wave. To meet this specification, a large space is usually required and it limits the value of indoor facilities.

ANTENNA RANGES



Reflection Ranges

- In general, there are two basic types of antenna ranges: the *reflection and the free-space* ranges.

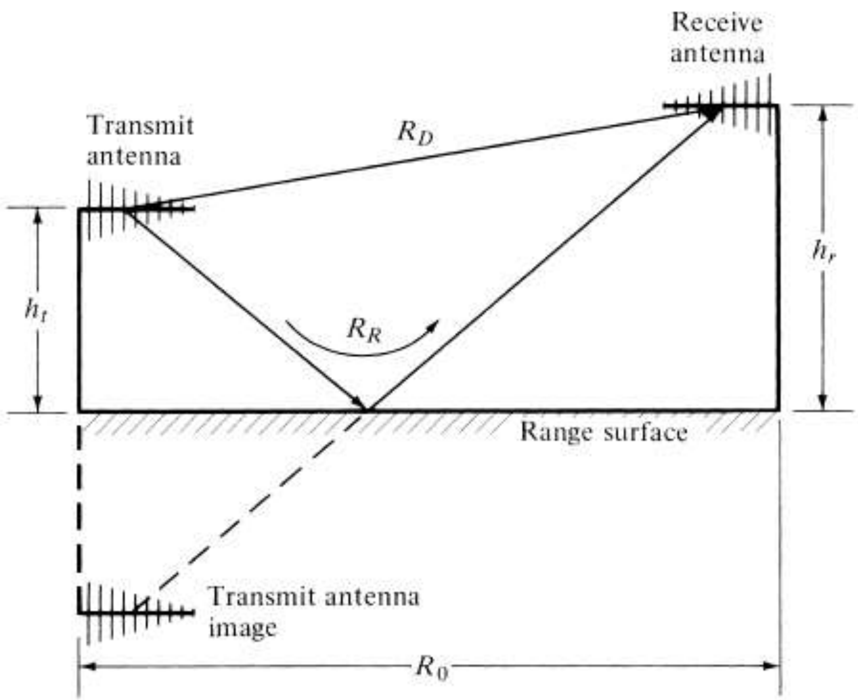


Figure 17.2 Geometrical arrangement for reflection range. (SOURCE: L. H. Hemming and R. A. Heaton, "Antenna Gain Calibration on a Ground Reflection Range," *IEEE Trans. Antennas Propagat.*, Vol. AP-21, No. 4, pp. 532–537, July 1973. © (1973) IEEE)

Reflection Ranges

- The reflection ranges, if judiciously designed , can create a constructive interference in the region of the test antenna which is referred to as the “quiet zone.” This is accomplished by designing the ranges so that specular reflections from the ground, as shown in Figure 17.2, combine constructively with direct rays.

- Usually it is desirable for the illuminating field to have a small and symmetric amplitude taper. This can be achieved by adjusting the transmitting antenna height while maintaining constant that of the receiving antenna.

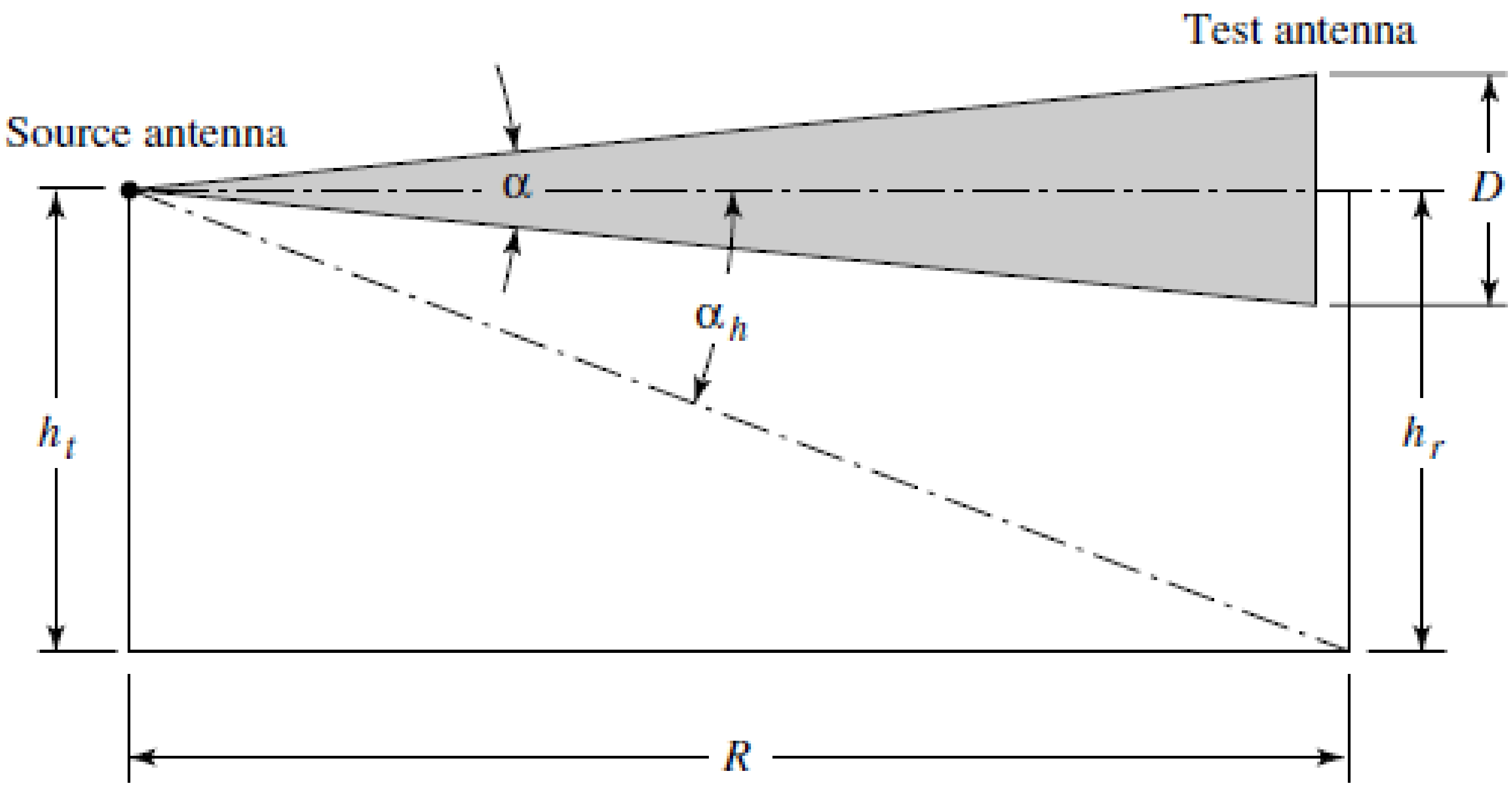
- These ranges are of the outdoor type, where the ground is the reflecting surface, and they are usually employed in the UHF region for measurements of patterns of moderately broad antennas.

- They are also used for systems operating in the UHF to the 16-GHz frequency region.

Free-Space Ranges

- Free-space ranges are designed to suppress the contributions from the surrounding environment and include
  - *elevated ranges,*
  - *slant ranges,*
  - *anechoic chambers,*
  - *Compact ranges, and*
  - *near-field ranges.*

Elevated Ranges



(a) Elevated (after [7])

Elevated Ranges

- Elevated ranges are usually designed to operate mostly over smooth terrains. The antennas are mounted on towers or roofs of adjacent buildings. These ranges are used to test physically large antennas. A geometrical configuration is shown in Figure 17.3(a).

- The contributions from the surrounding environment are usually reduced or eliminated by
  1. carefully selecting the directivity and side lobe level of the source antenna
  2. clearing the line-of-sight between the antennas
  3. redirecting or absorbing any energy that is reflected from the range surface and/or from any obstacles that cannot be removed
  4. utilizing special signal-processing techniques such as modulation tagging of the desired signal or by using short pulses

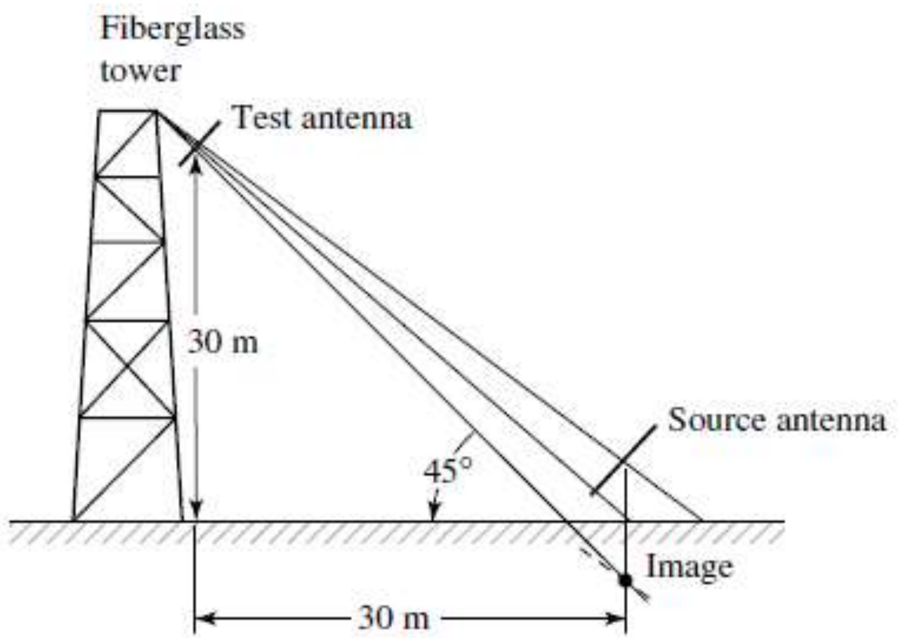
Elevated Ranges

- In some applications, such as between adjacent mountains or hilltops, the ground terrain may be irregular. For these cases, it is more difficult to locate the specular reflection points (points that reflect energy toward the test antenna).

- To take into account the irregular surface, scaled drawings of the vertical profile of the range are usually constructed from data obtained from the U.S. Geological Survey.

- The maps show ground contours, and they give sufficient details which can be used to locate the specular reflection points, determine the level of energy reflected toward the test antenna, and make corrections if it is excessive.

Slant Ranges



(b) Slant (after P. W. Arnold [10])

Figure 17.3 Geometries of elevated and slant ranges. (SOURCES: *IEEE Standard Test Procedures for Antennas*, IEEE Std 149–1979, published by IEEE, Inc., 1979, distributed by Wiley; and P. W. Arnold, "The 'Slant' Antenna Range," *IEEE Trans. Antennas Propagat.*, Vol. AP-14, No. 5, pp. 658–659, September 1966. © (1966) IEEE).

Slant Ranges

- Slant ranges are designed so that the test antenna, along with its positioner, are mounted at a fixed height on a nonconducting tower while the source (transmitting) antenna is placed near the ground, as shown in Figure 17.3(b).

- The source antenna is positioned so that the pattern maximum, of its free-space radiation, is oriented toward the center of the test antenna.

- The first null is usually directed toward the ground specular reflection point to suppress reflected signals.

- Slant ranges, in general, are more compact than elevated ranges in that they require less land.

Anechoic Chambers

- To provide a controlled environment, an all-weather capability, and security, and to minimize electromagnetic interference, indoor anechoic chambers have been developed as an alternative to outdoor testing.

- By this method, the testing is performed inside a chamber having walls that are covered with RF absorbers.

- The availability of commercial high-quality RF absorbing material, with improved electrical characteristics, has provided the impetus for the development and proliferation of anechoic chambers.

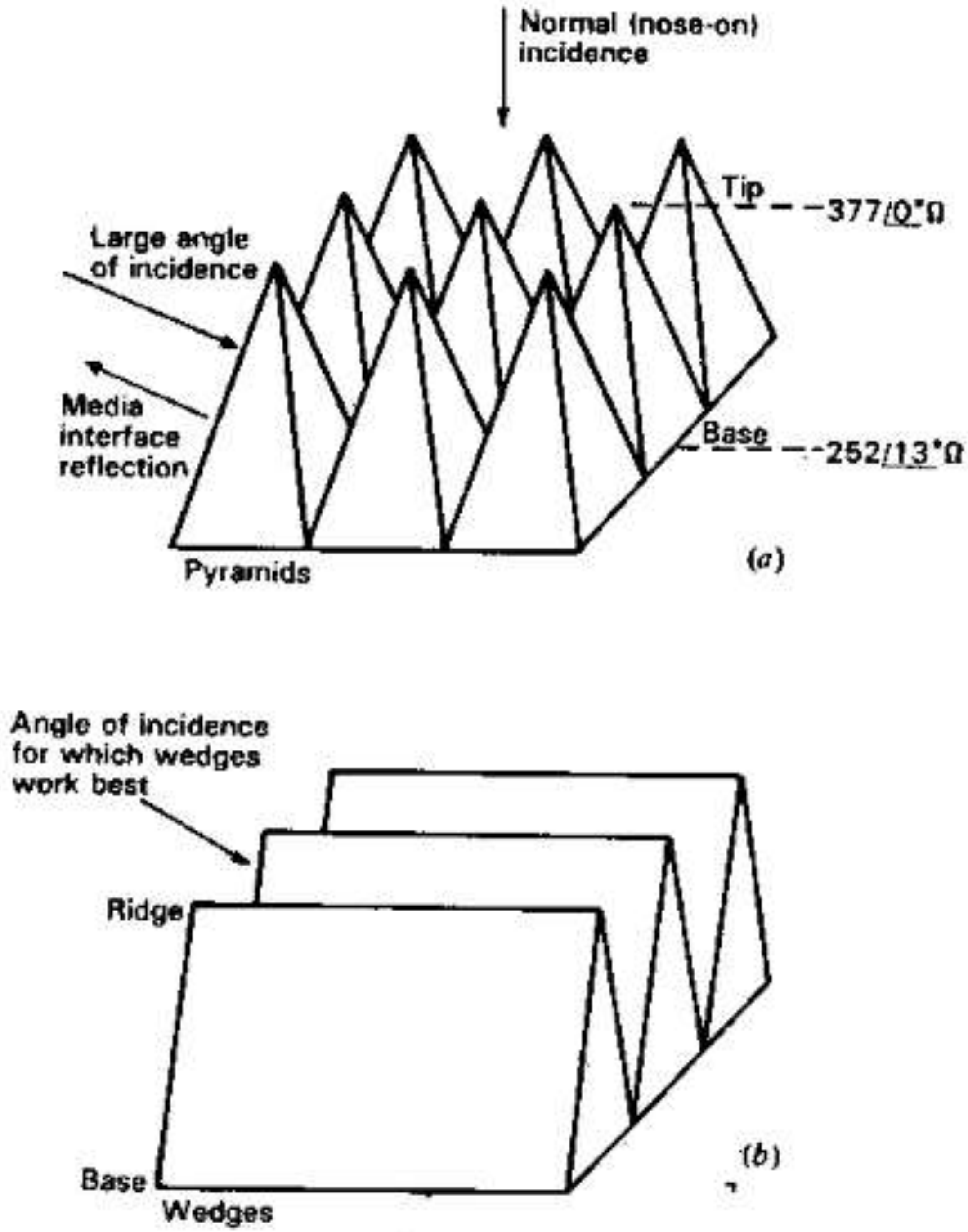
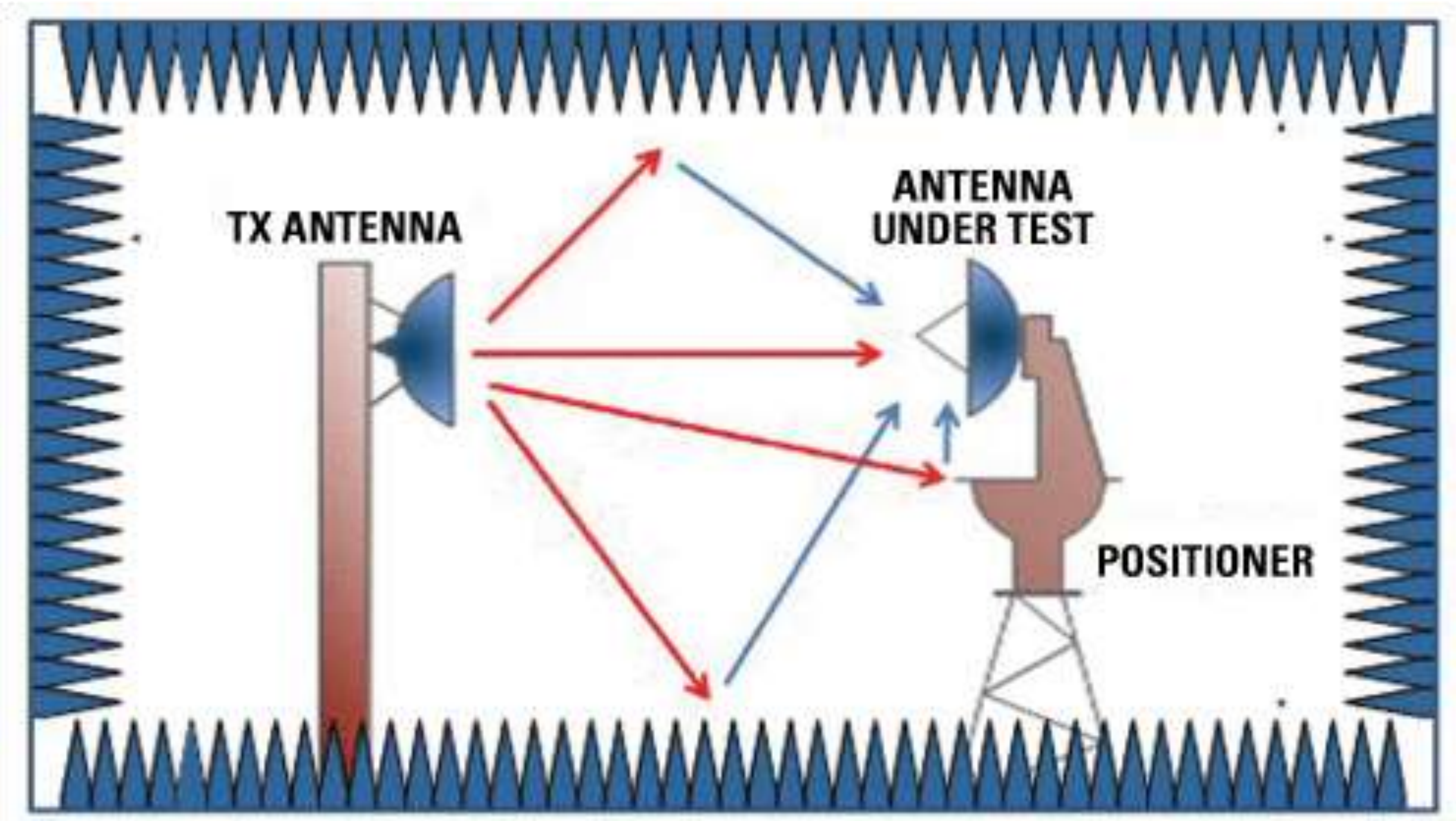
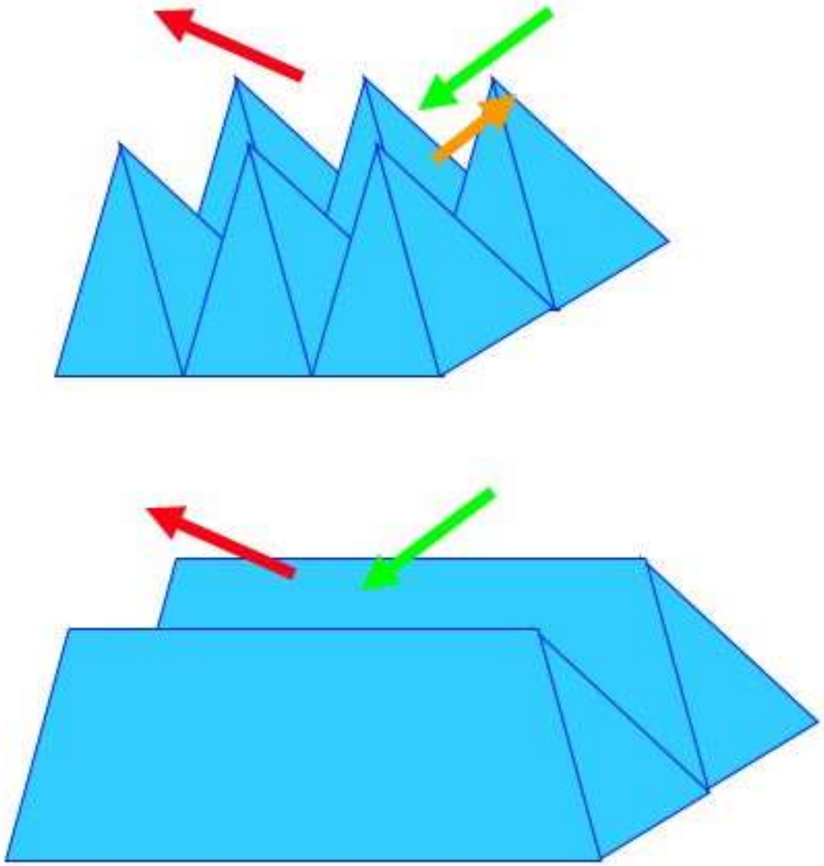


Figure 18-14 (*a*) Pyramid and (*b*) wedge forms of wave absorbers.

Anechoic Chamber



Absorbers



Wedge and pyramid

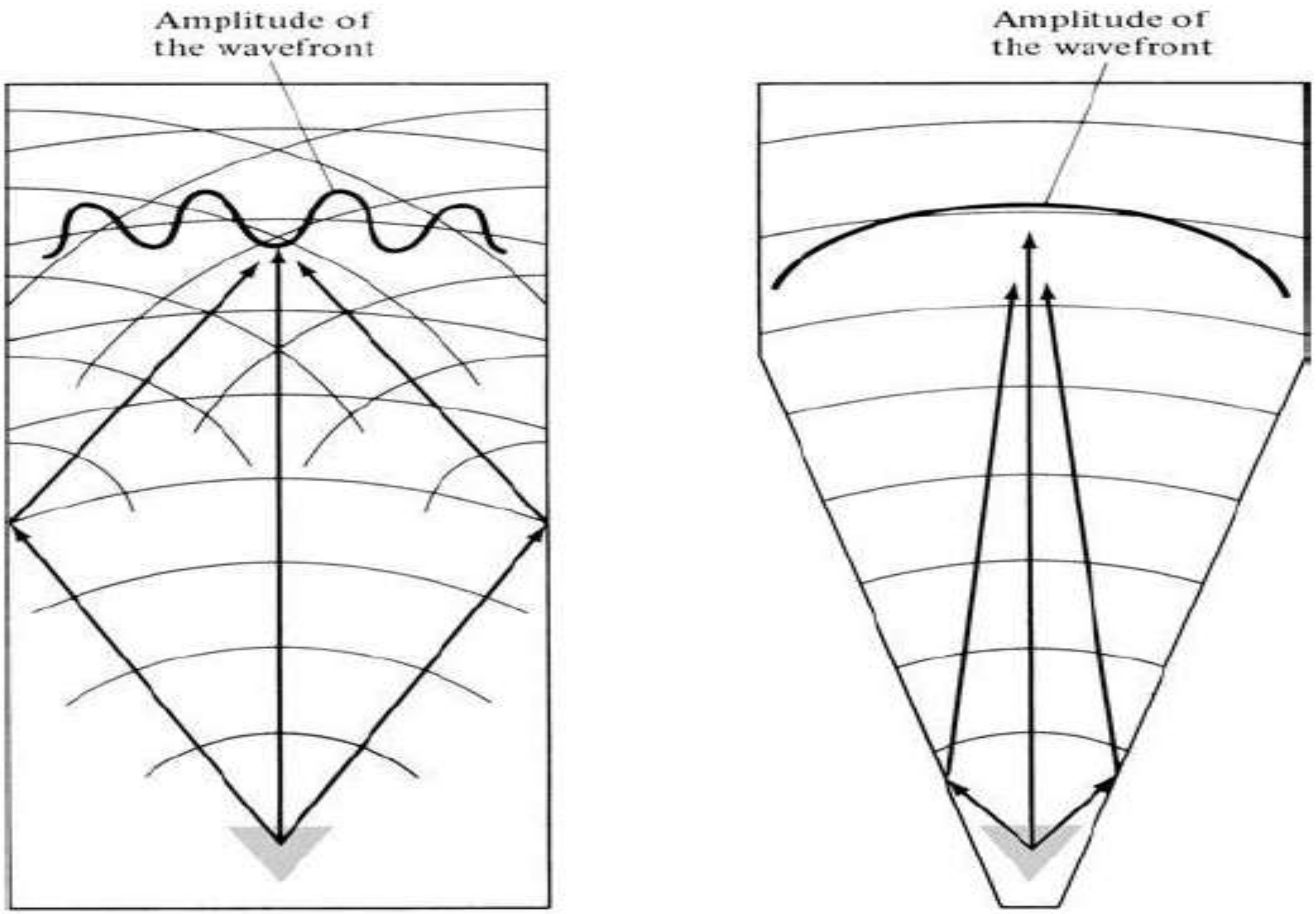
Electric Losses

A variant of pyramidal absorber wedge does not show backscattering. Preferred technology for QZ treatment and for RCS chambers.

Anechoic Chambers

- Anechoic chambers are mostly utilized in the microwave region, but materials have been developed which provide a reflection coefficient of −40 dB at normal incidence at frequencies as low as 100MHz.
- In general, as the operating frequency is lowered, the thickness of RF absorbing material must be increased to maintain a given level of reflectivity performance.
- An RF absorber that meets the minimum electrical requirements at the lower frequencies usually possesses improved performance at higher frequencies.

Anechoic Chambers



(a) Rectangular chamber (b) Tapered chamber

Figure 17.4 Rectangular and tapered anechoic chambers and the corresponding side-wall specular reflections. (SOURCE: W. H. Kummer and E. S. Gillespie, "Antenna Measurements—1978," *Proc. IEEE*, Vol. 66, No. 4, pp. 483–507, April 1978. © (1978) IEEE)

Anechoic Chambers

- Presently there are two basic types of anechoic chamber designs: the *rectangular* and the *tapered chamber.*

- *The design of each is based on geometrical optics* techniques, and each attempts to reduce or to minimize specular reflections.

- The geometrical configuration of each, with specular reflection points depicted, is shown in Figures 17.4(a) and 17.4(b).

Anechoic Chambers

- The rectangular chamber is usually designed to simulate free-space conditions and maximize the volume of the quiet zone.

- The design takes into account the pattern and location of the source, the frequency of operation, and it assumes that the receiving antenna at the test point is isotropic.

- Reflected energy is minimized by the use of high quality RF absorbers. Despite the use of RF absorbing material, significant specular reflections can occur, especially at large angles of incidence.

Anechoic Chambers

- Tapered anechoic chambers take the form of a pyramidal horn. They begin with a tapered chamber which leads to a rectangular configuration at the test region, as shown in Figure 17.4(b).

- At the lower end of the frequency band at which the chamber is designed, the source is usually placed near the apex so that the reflections from the side walls, which contribute to the illuminating fields in the region of the test antenna, occur near the source antenna.

- For such paths, the phase difference between the direct radiation and that reflected from the walls near the source can be made very small by properly locating the source antenna near the apex.

Anechoic Chambers

- Thus the direct and reflected rays near the test antenna region add vectorially and provide a relatively smooth amplitude illumination taper. This can be illustrated by ray-tracing techniques.

- As the frequency of operation increases, it becomes increasingly difficult to place the source sufficiently close to the apex that the phase difference between the direct and specularly reflected rays can be maintained below an acceptable level.

- For such applications, reflections from the walls of the chamber are suppressed by using high gain source antennas whose radiation toward the walls is minimal. In addition, the source is moved away from the apex, and it is placed closer to the end of the tapering section so as to simulate a rectangular chamber.

Compact Ranges

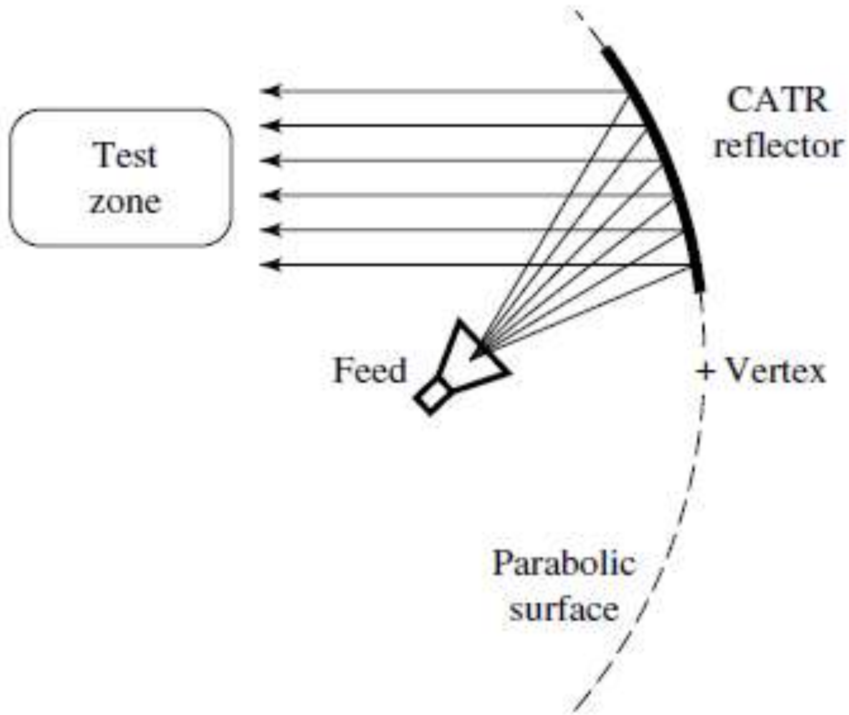


Figure 17.5 A Compact Antenna Test Range (CATR) synthesizes planar phase fronts by collimating spherical waves with a section of paraboloidal reflector.

Compact Ranges

- Microwave antenna measurements require that the radiator under test be illuminated by a uniform plane wave. This is usually achieved only in the far-field region, which in many cases dictates very large distances. The requirement of an ideal plane wave illumination can be nearly achieved by utilizing a compact range.

- A *Compact Antenna Test Range (CATR) is a collimating device which generates* nearly planar wavefronts in a very short distance (typically 10–20 meters) compared to the $2D^2/\lambda$ *(minimum) distance required to produce the same size test region using* the standard system configuration of testing shown in Figure 17.1.

Compact Ranges

- Some attempts have been made to use dielectric lenses as collimators , but generally the name compact antenna test range refers to one or more curved metal reflectors which perform the collimating function.

- Compact antenna test ranges are essentially very large reflector antennas designed to optimize the planar characteristics of the fields in the near field of the aperture.

- Compact range configurations are often designated according to their analogous reflector antenna configurations: parabolic, Cassegrain, Gregorian, etc.

Compact Ranges

- One compact range configuration is that shown in Figure 17.5 where a source antenna is used as an offset feed that illuminates a paraboloidal reflector, which converts the impinging spherical waves to plane waves. Geometrical Optics (GO) is used in Figure 17.5 to illustrate general CATR operation.

- The rays from a feed antenna can, over the main beam, be viewed as emanating from a point at its phase center.

- When the phase center of the feed is located at the prime focus of a parabolic reflector, all rays that are reflected by the reflector and arrive at a plane transverse to the axis of the parabola have traveled an equal distance.

- Therefore, the field at the aperture of the reflector has a uniform phase; i.e., that of a plane wave. In addition to Geometrical Optics, analysis and design of CATRs have been performed with a number of other analytical methods.

Compact Ranges

- Compact range test zone fields have been predicted by the Method of Moments (MoM), but at high frequencies, the large electrical size of the CATR system makes the use of MoM, Finite-Difference Time-Domain (FD-TD), and Finite Element Method (FEM) impractical.

- High-frequency techniques, however, are well suited for compact range analysis because the fields of interest are near the specular reflection direction, and the reflector is electrically large.

- The Geometrical Theory of Diffraction(GTD) is, in principle, an appropriate technique, but it is difficult to implement for serrated-edge reflectors due to the large number of diffracting edges. To date, Physical Optics (PO) is probably the most practical and efficient method of predicting the performance of CATRs.

Compact Ranges

- The major drawbacks of compact ranges are
  - aperture blockage,
  - direct radiation from the source to the test antenna,
  - diffractions from the edges of the reflector and feed support,
  - depolarization coupling between the two antennas, and wall reflections.

- The use of an **offset feed** eliminates aperture blockage and reduces diffractions. Direct radiation and diffractions can be reduced further if a **reflector with a long focal length** is chosen.

- With such a reflector, **the feed can then be mounted below the test antenna** and the depolarization effects associated with curved surfaces are reduced.

- Undesirable radiation toward the test antenna can also be minimized by the use of **high-quality absorbing material**.

Near-Field/Far-Field Methods

- The dimensions of a conventional test range can be reduced by making measurements in the near-field, and then using analytical methods to transform the measured near-field data to compute the far-field radiation characteristics. These are referred to as *near-field to far-field (NF/FF) methods.*

- *These techniques are usually used to* measure patterns, and they are often performed indoors. Therefore, they provide a controlled environment and an all-weather capability, the measuring system is **time and cost effective**, and the computed patterns are as accurate as those measured in a far-field range.

- However, such methods require more complex and expensive systems, more extensive calibration procedures, more sophisticated computer software, and the patterns are not obtained in real time.

Near-Field/Far-Field Methods

- The near-field measured data (usually amplitude and phase distributions) are measured by a scanning field probe over a preselected surface which may be a *plane, a cylinder, or a sphere. The measured data are then transformed to the far-field using* analytical Fourier transform methods.

- The complexity of the analytical transformation increases from the planar to the cylindrical, and from the cylindrical to the spherical surfaces. The choice is primarily determined by the antenna to be measured.

- In general, the planar system is better suited for high-gain antennas, especially planar phased arrays, and it requires the least amount of computations and no movement of the antenna.

- Although the cylindrical system requires more computations than the planar, for many antennas its measuring, positioning, and probe equipment are the least expensive.

Near-Field/Far-Field Methods

- The spherical system requires the most expensive computation, and antenna and probe positioning equipment, which can become quite significant for large antenna systems. This system is best suited for measurements of low-gain and omnidirectional antennas.

- Generally, implementation of NF/FF transformation techniques begins with measuring the magnitude and phase of the tangential electric field components radiated by the test antenna at regular intervals over a well-defined surface in the near field. By the principle of *modal expansion, the sampled E-field data is used to determine the* amplitude and phase of an angular spectrum of plane, cylindrical, or spherical waves.

- Expressing the total field of the test antenna in terms of a modal expansion, allows the calculation of the field at any distance from the antenna. Solving for the fields at an infinite distance results in the far-field pattern.

Near-Field/Far-Field Methods

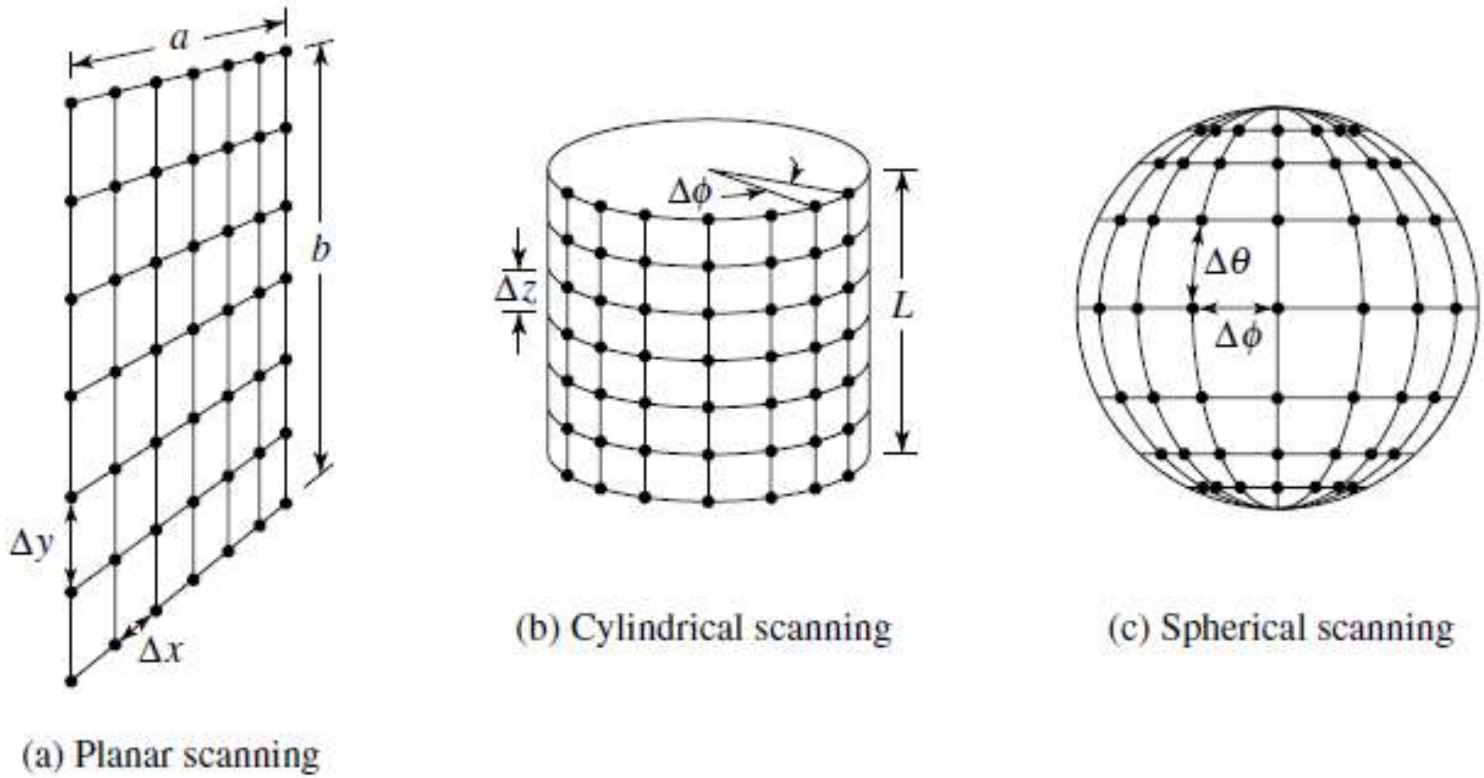


Figure 17.12 Three near-field scanning surfaces that permit convenient data acquisition (planar, cylindrical, and spherical).

Near-Field/Far-Field Methods

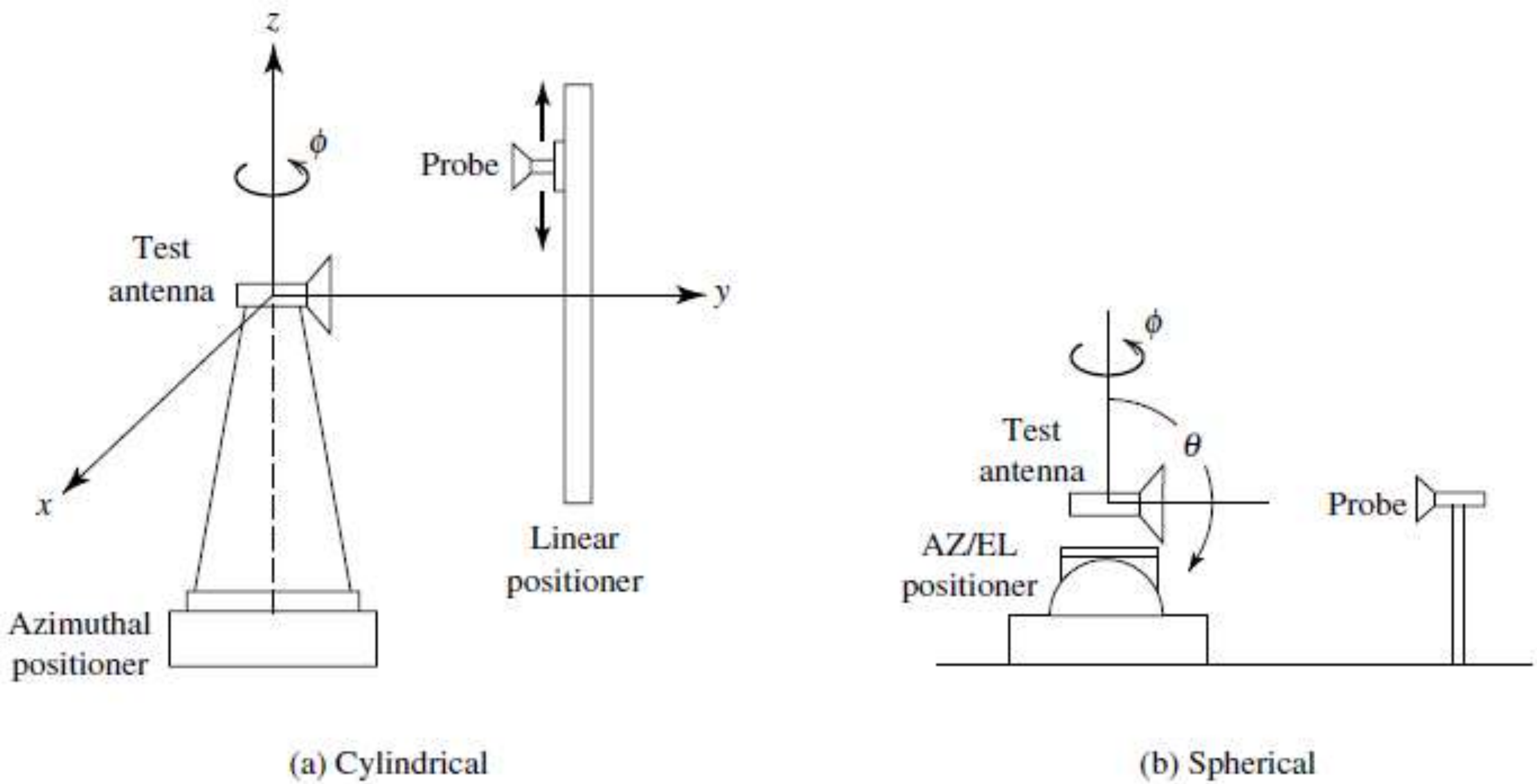


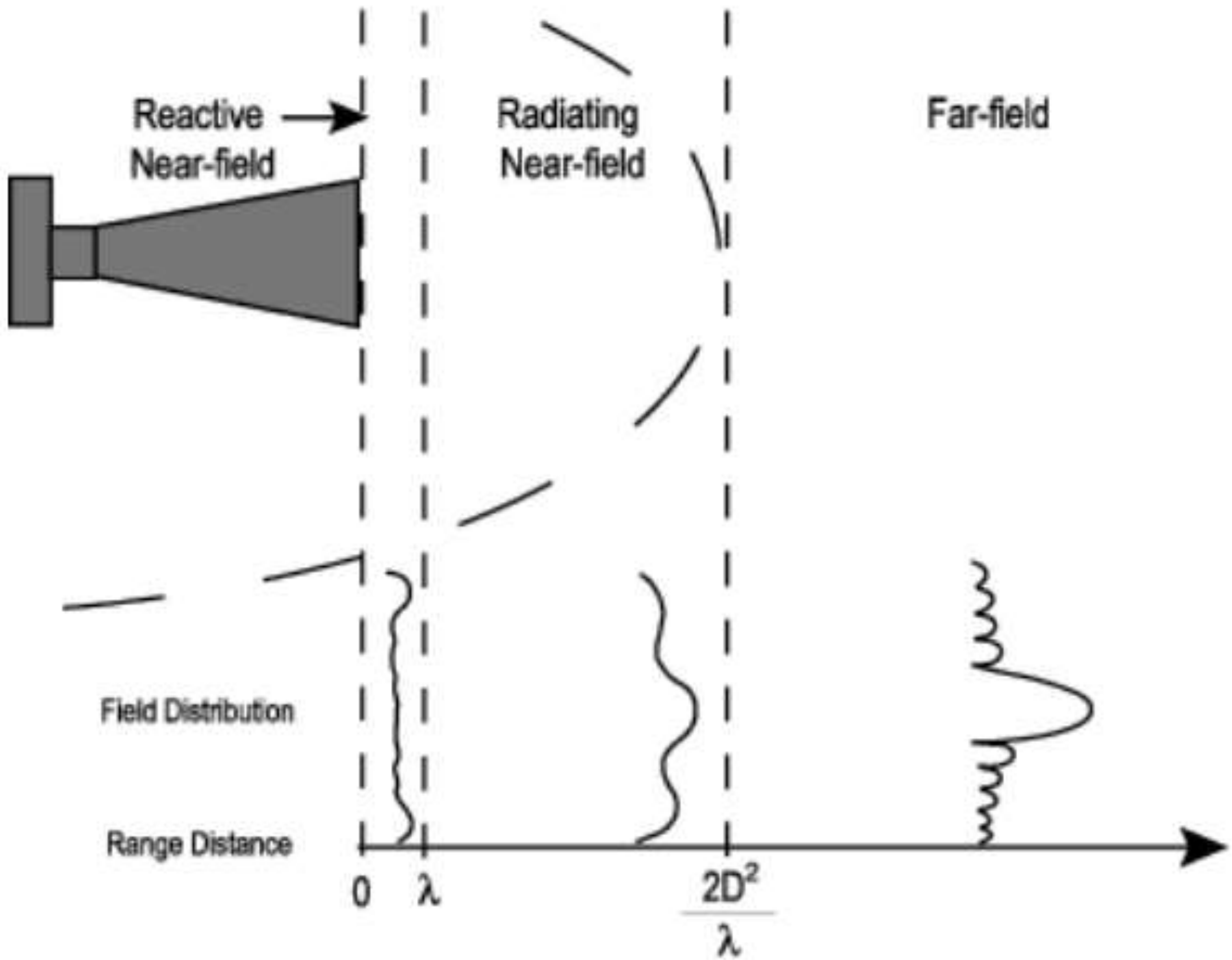
Figure 17.14 Schematic representation of typical cylindrical and spherical surface near-field positioning systems.

Near-Field vs Far-Field Measurements

- Near-field measurements
- testing can be accomplished indoors, eliminating problems due to weather, electromagnetic interference, security concerns, etc by using anechoic chambers and compact ranges.
- Cost of facility implementation is a critical determining factor in range selection.

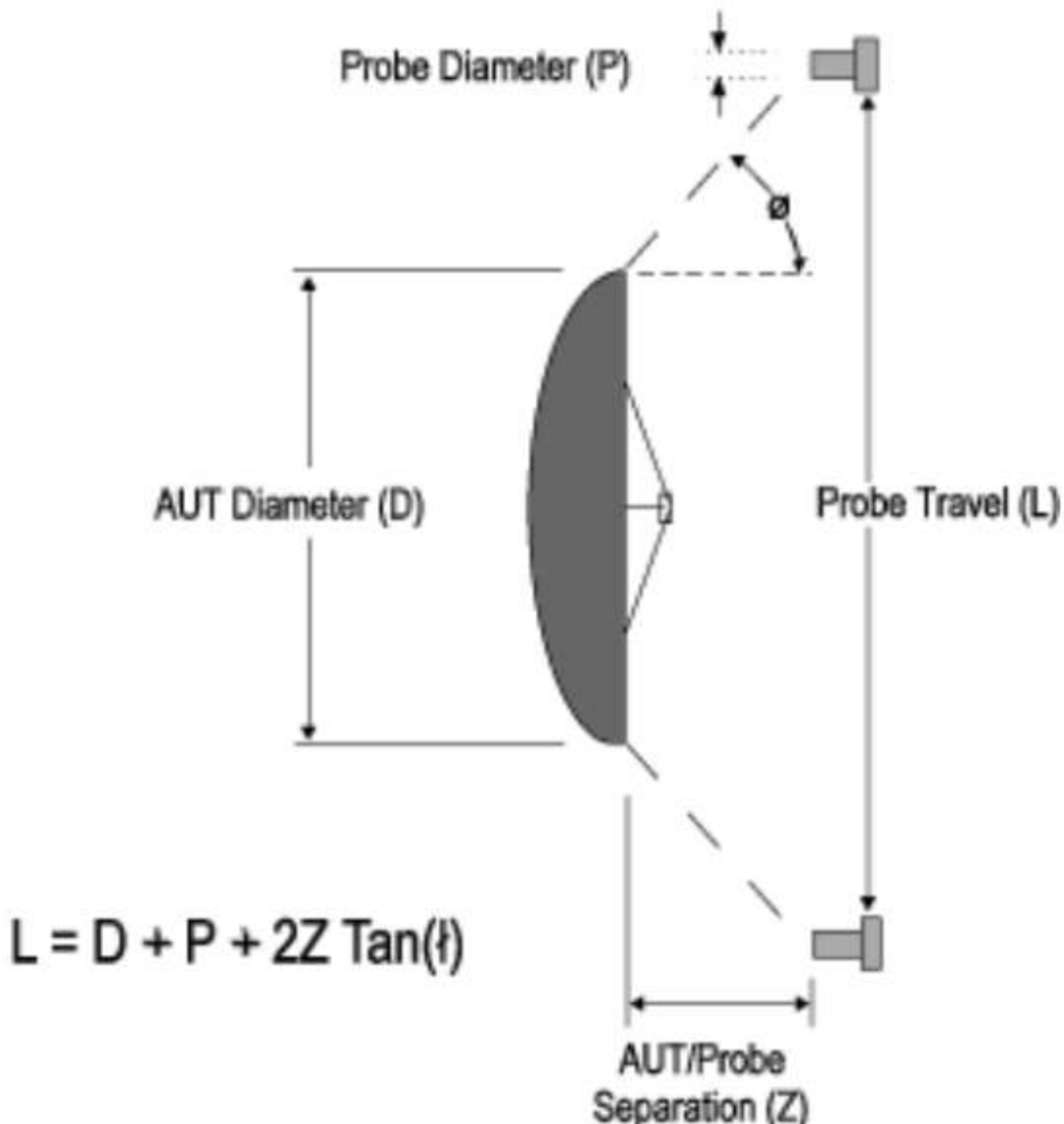
- Far-Field Measurements
- Far-field ranges are often considered to be less expensive than near-field ranges.
- When considering the value of the real-estate required for an outdoor far-field range, the situation may reverse.
- An indoor far-field compact range would typically cost 3-4 times more than a planar near-field range capable of testing the same size aperture, due to the larger chamber size required and cost of the compact range reflectors.

Near Field Measurement



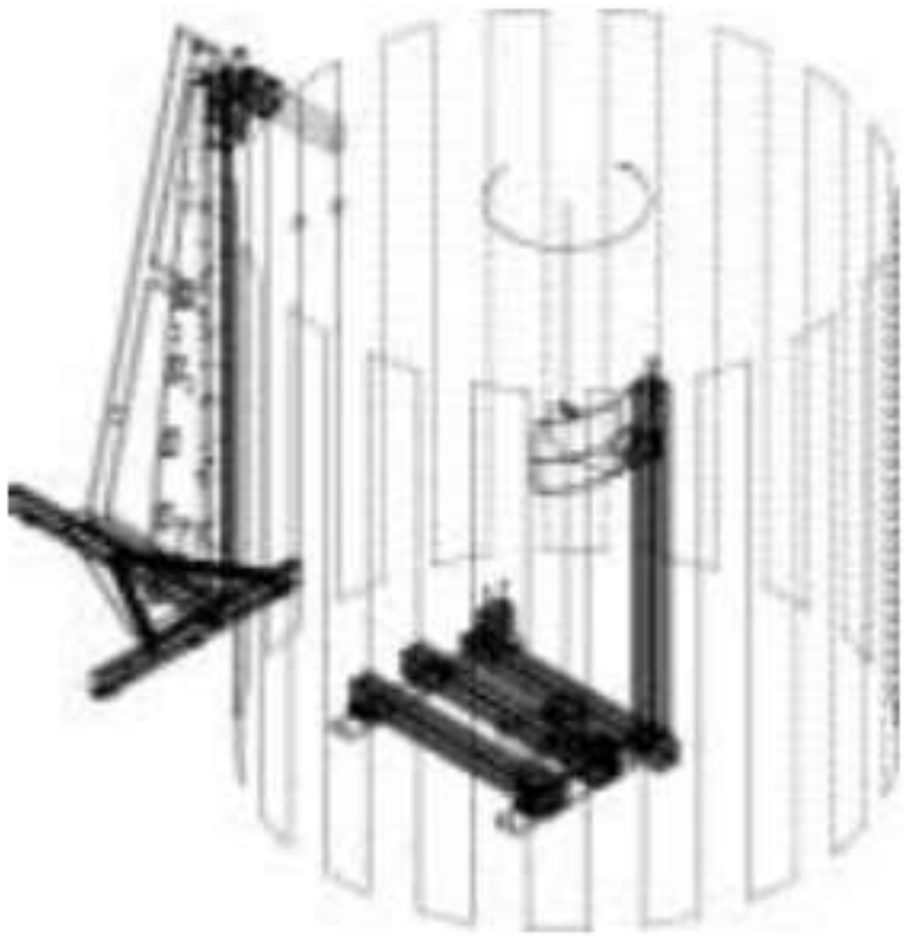
Near Field Measurement

SCAN SIZE DETERMINATION



Near Field Measurement-Planar

Near Field measurement-cylindrical

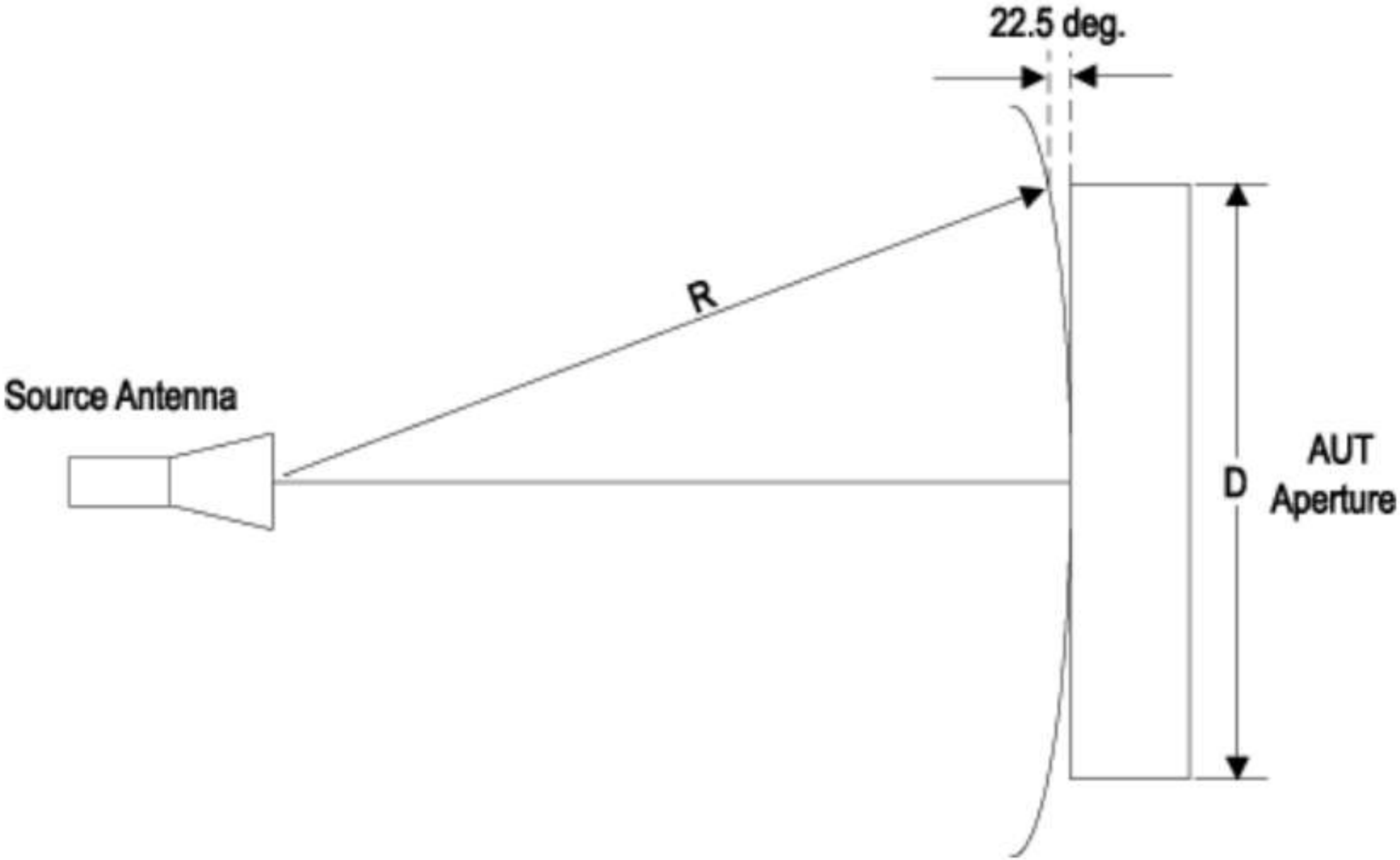


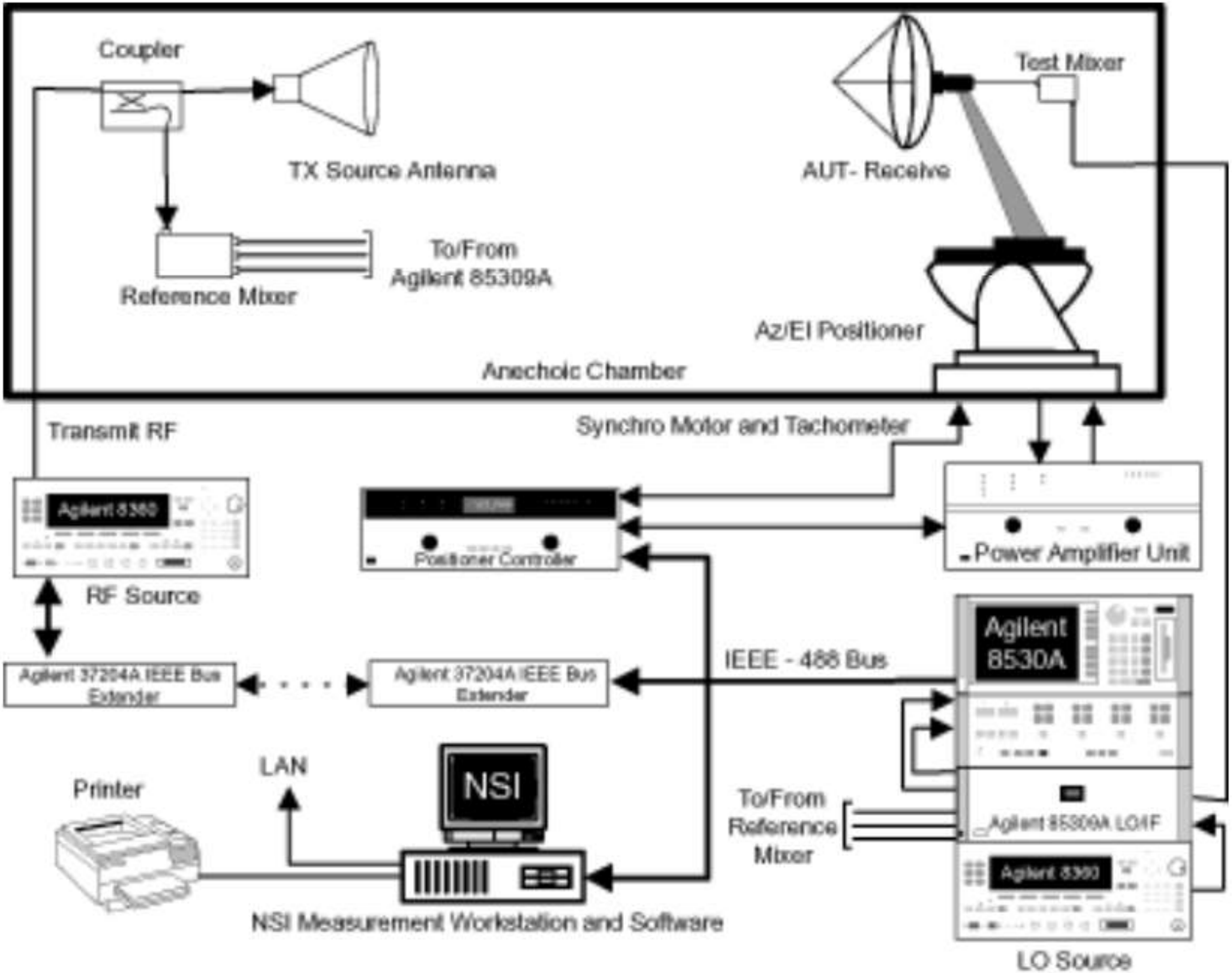
Near Field Measurement-spherical

Near Field Measurement- the choice of co-ordinates

ANTENNA TYPE/PARAMETER	PLANAR	CYLINDRICAL	SPHERICAL
High-gain Antennas	excellent	good	good
Low-gain Antennas	poor	good	excellent
Stationary AUT	yes	possible	possible
Zero-gravity Simulation	excellent	poor	variable
Alignment Ease	simple	difficult	difficult
Speed	fast	medium	slow

Far-Field Measurements





Coupler
TX Source Antenna
AUT- Receive
Test Mixer
Reference Mixer
To/From
Agilent 85309A
Az/El Positioner
Anechoic Chamber
Transmit RF
Synchro Motor and Tachometer
Agilent 8360
RF Source
Positioner Controller
Power Amplifier Unit
Agilent
8530A
IEEE - 488 Bus
Agilent 37204A IEEE Bus Extender
Agilent 37204A IEEE Bus Extender
LAN
Printer
NSI
To/From
Reference
Mixer
Agilent 85309A LO/IF
Agilent 8360
NSI Measurement Workstation and Software
LO Source

Table 2. Comparison of measurements in the near field and in the far field

Parameter	Near Field	Far Field
measured EMF component	E, H & S	E or H, and S on mwaves
other magnitudes measurement	I, T, (SA, SAR) "HESTIA"	unnecessary
spatial components	3	1 or 2
polarization	quasi-ellipsoidal	linear or elliptical
environment	complex, multipath propagation & interference	usually simple
frequency spectrum	wide, often unknown, many fringes	usually single frequency
antennas	small, omnidirectional	resonant, directional
temporal & spatial EMF alternations	significant	usually negligible
uncertainty	3, 6 or more dB	around 1 dB
temperature sensitivity	significant	unessential
susceptibility	significant	ommitable
influence of surroundings	significant	usually ommitable
procedures	complex	simple
agreement with theory	reasonable	good
measured levels	V/m, kV/m	mV/m, mV/m

Advantages and Disadvantages of Near-Field Measurements

- Advantages
  - Very compact antennas having large far-field distances can be measured indoors in a small space.
  - As the measured field is a complete description of the radiation, many kinds of antenna parameters can be computed from the data.
  - A useful diagnostic tool since defective elements of an array are found easily.
  - If measurements are performed carefully, far-filed patterns of very low side lobe (-55dB) antennas can be determined accurately.
  - Very demanding – as the phase has to be measured accurately, most near-field ranges are limited at frequencies below <60GHz.

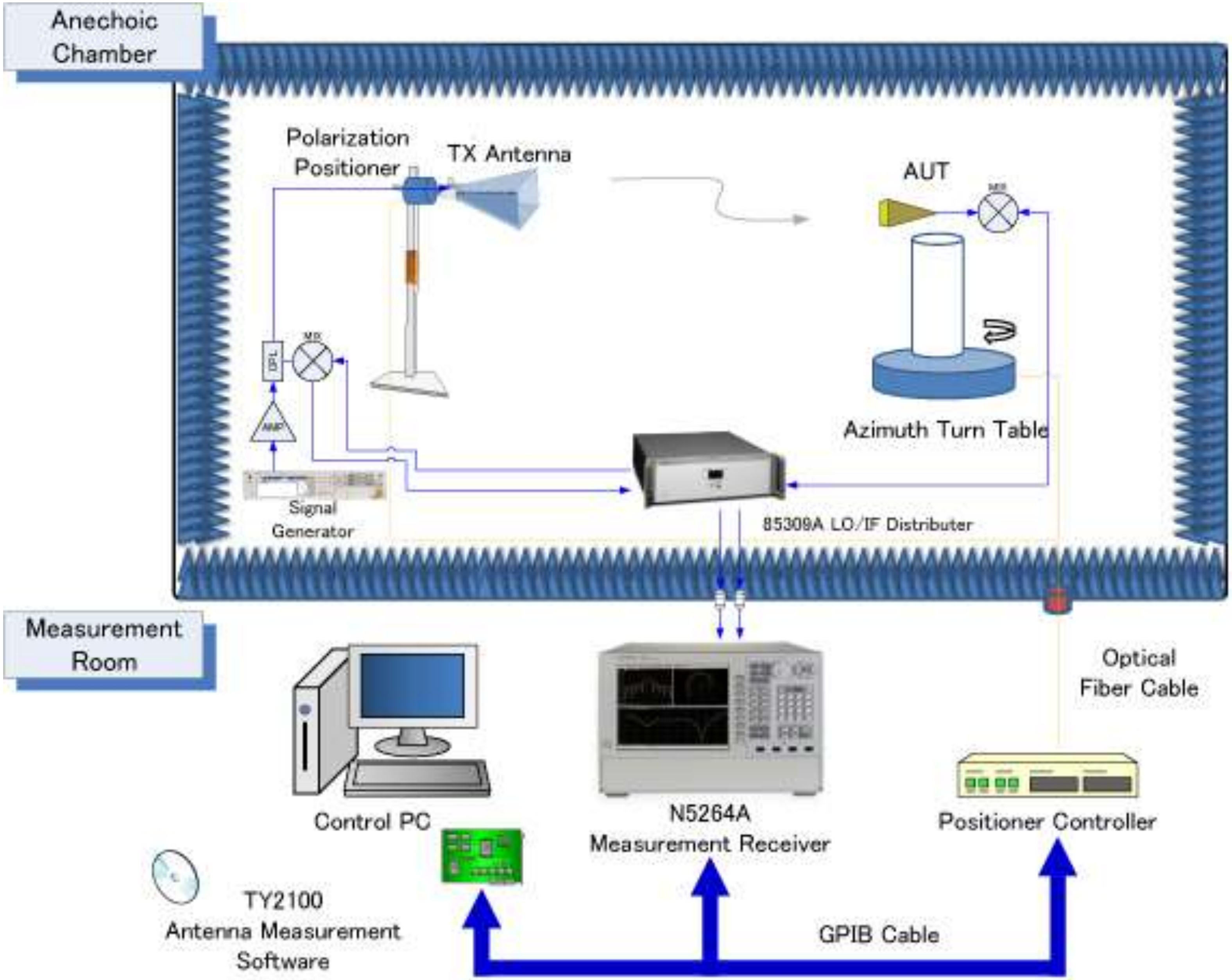
Advantages and Disadvantages of Near-Field Measurements

- Sources of Error
    - Inaccurate probe positioning
    - Reflections
    - Moving cables
    - Receiver nonlinearity
    - Inaccurate probe correction
    - Limited scan area

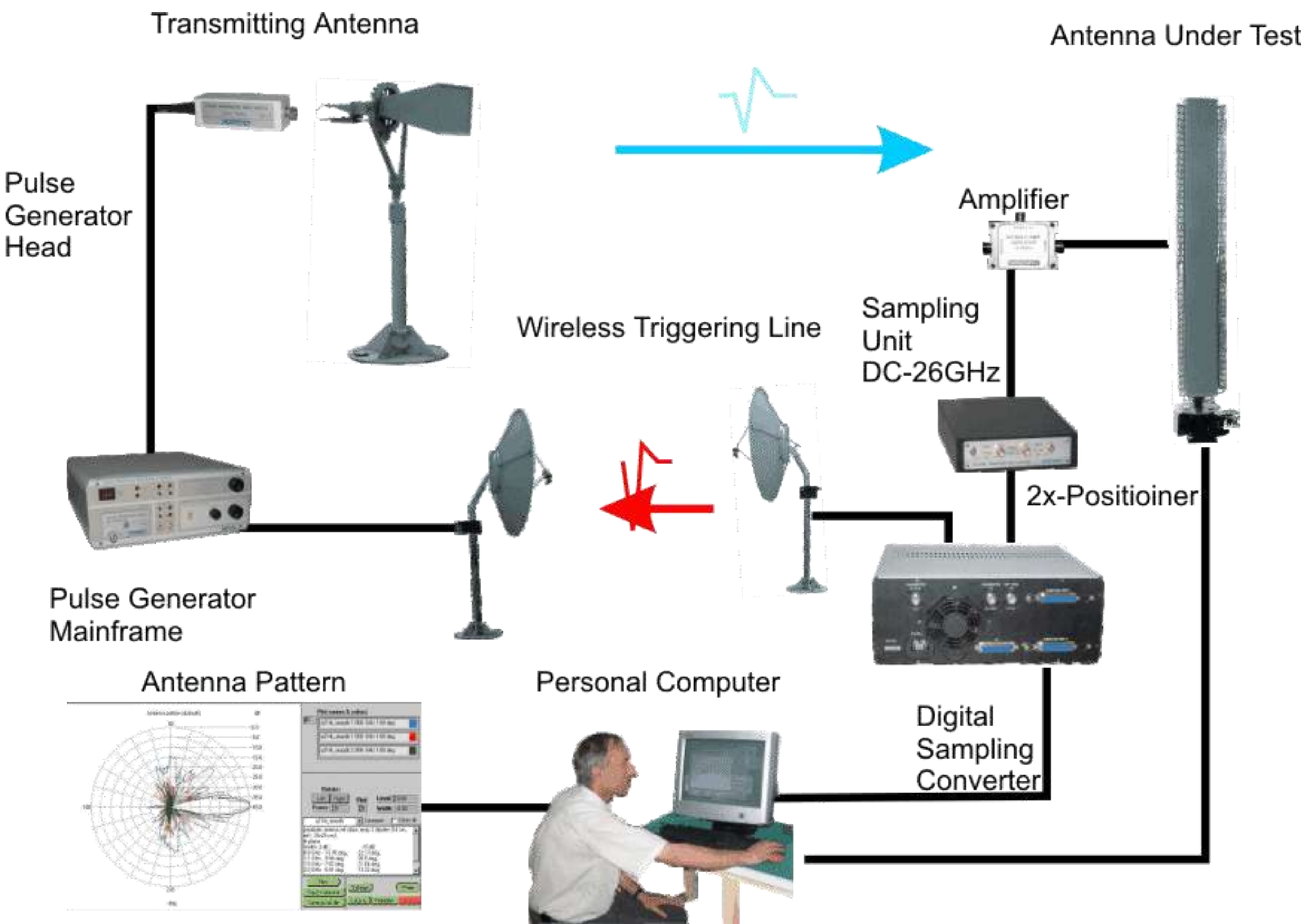
Advantages and Disadvantages of Far-Field Measurements

- Advantages
  - The measured field pattern is valid for any distance in the far-field region, only simple transformation of the field strength according to 1/r is required.
  - If a power pattern is required, only power (amplitude) measurement is needed.
  - The result is not very sensitive to the changes in the location of the phase center of the antennas and thus the rotation of the AUT doesn’t cause significant measurement error.
  - Coupling and multiple reflections between the antennas are not significant.
- Disadvantages
  - It requires large distance between the antennas leading to large antenna ranges.

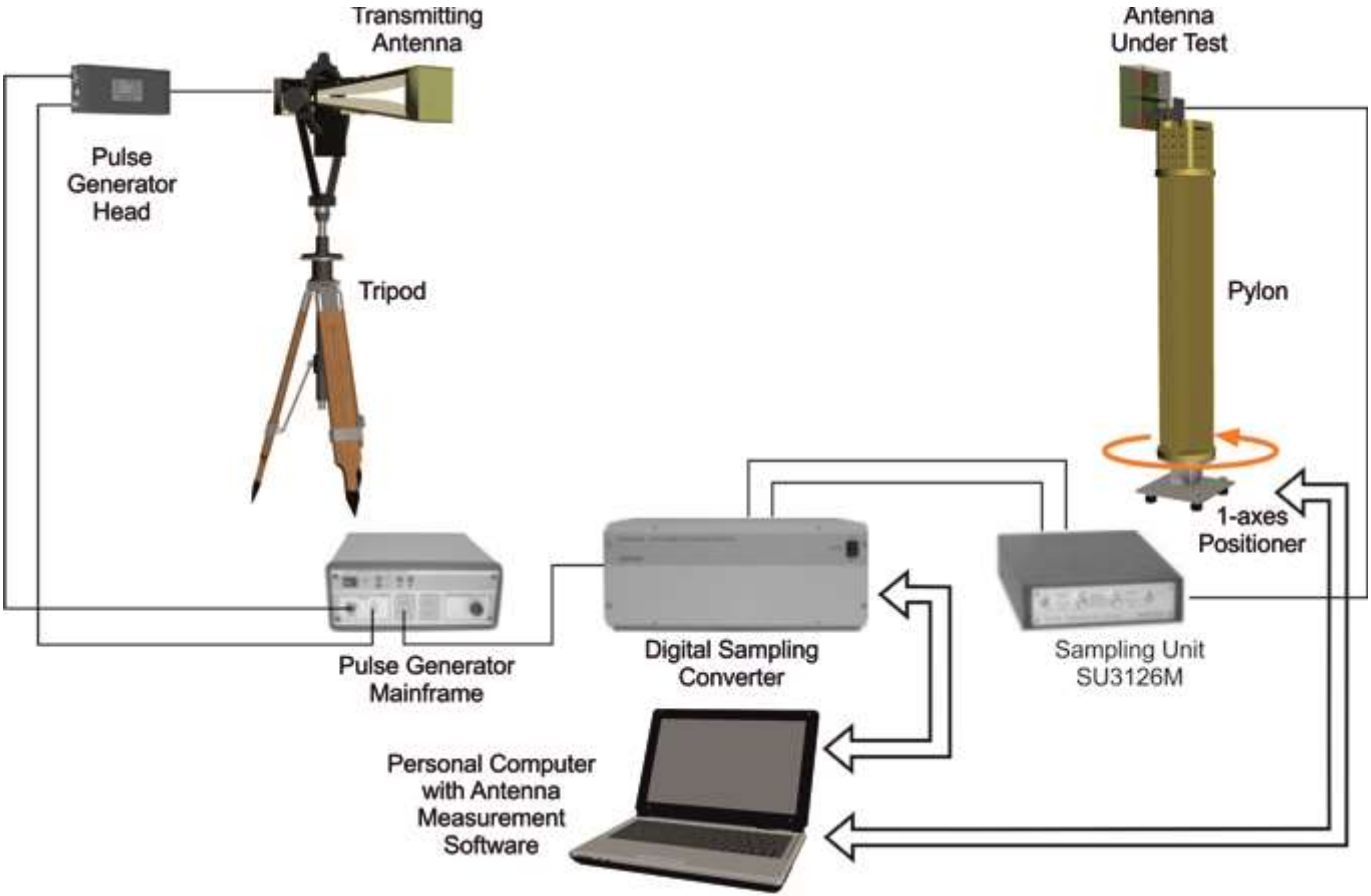
Measurement System



Measurement in Time Domain



Far Field Measurement



Radiation Pattern

- The radiation patterns (amplitude and phase), polarization, and gain of an antenna, which are used to characterize its radiation capabilities, are measured on the surface of a constant radius sphere.

- Any position on the sphere is identified using the standard spherical coordinate system of Figure 17.16. Since the radial distance is maintained fixed, only the two angular coordinates *(ϑ, φ) are needed for positional identification.*

- A representation of the radiation characteristics of the radiator as a function of ϑ *and* φ for a constant radial distance and frequency, is defined as the *pattern of the antenna.*

Radiation Patterns

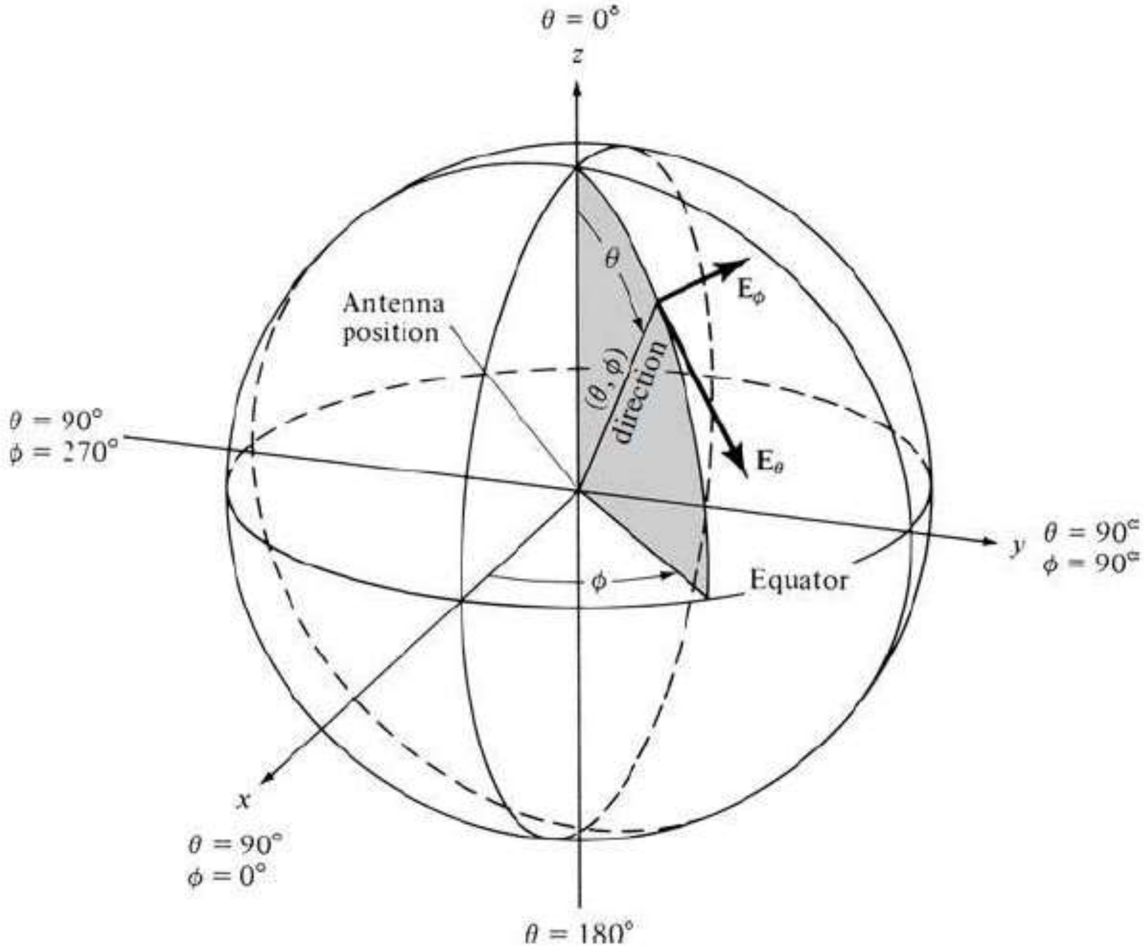


Figure 17.16 Spherical coordinate system geometry. (SOURCE: *IEEE Standard Test Procedures for Antennas*, IEEE Std 149–1979, published by IEEE, Inc., 1979, distributed by Wiley).

Radiation Patterns

- In general, the pattern of an antenna is three-dimensional. Because it is impractical to measure a three-dimensional pattern, a number of two-dimensional patterns are measured. They are used to construct a three-dimensional pattern.

- The number of two-dimensional patterns needed to construct faithfully a three dimensional graph is determined by the functional requirements of the description, and the available time and funds.

- The minimum number of two-dimensional patterns is two, and they are usually chosen to represent the orthogonal principal *E- and H-plane* patterns.

Radiation Pattern

- A two-dimensional pattern is also referred to as a *pattern cut, and it is obtained by* fixing one of the angles (*ϑ or φ) while varying the other.*

- *Eg.,from* Figure 17.16, pattern cuts can be obtained by fixing *φj ($0 \le \varphi j \le 2\pi$) and varying ϑ($0 \le \vartheta \le \pi$). These are referred to as elevation patterns*.

- Similarly *ϑ can be maintained fixed ($0 \le \vartheta i \le \pi$) while φ is varied ($0 \le \varphi \le 2\pi$). These are designated as azimuthal patterns. Part ($0 \le \varphi \le \pi/2$) of the $\vartheta i = \pi/2$ azimuthal patternis.*

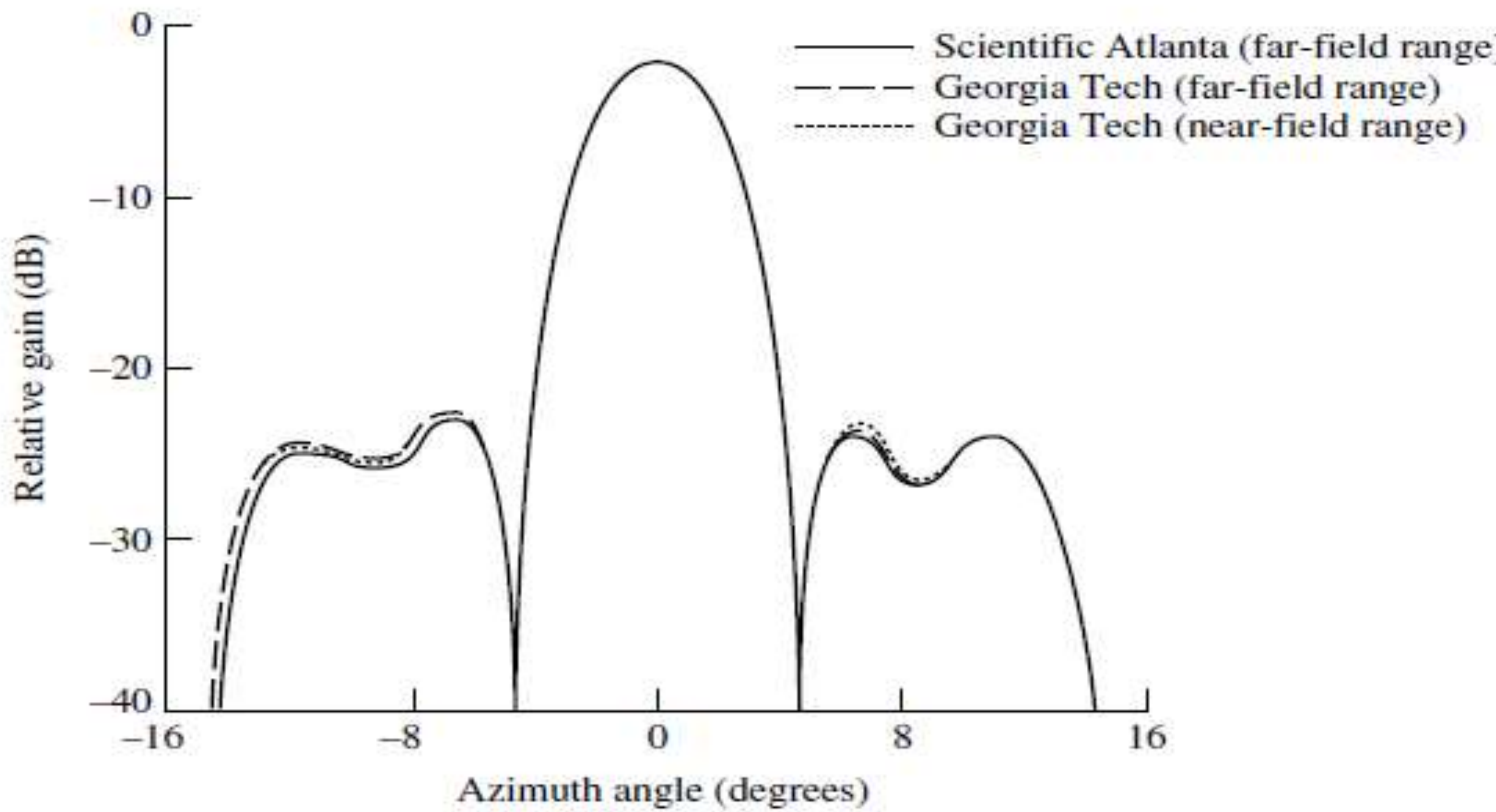
Radiation Pattern

- The patterns of an antenna can be measured in the transmitting or receiving mode. The mode is dictated by the application. However, if the radiator is reciprocal, as is the case for most practical antennas, then either the transmitting or receiving mode can be utilized. For such cases, the receiving mode is selected.

- The analytical formulations upon which an amplitude pattern is based, along with the advantages and disadvantages for making measurements in the transmitting or receiving mode.

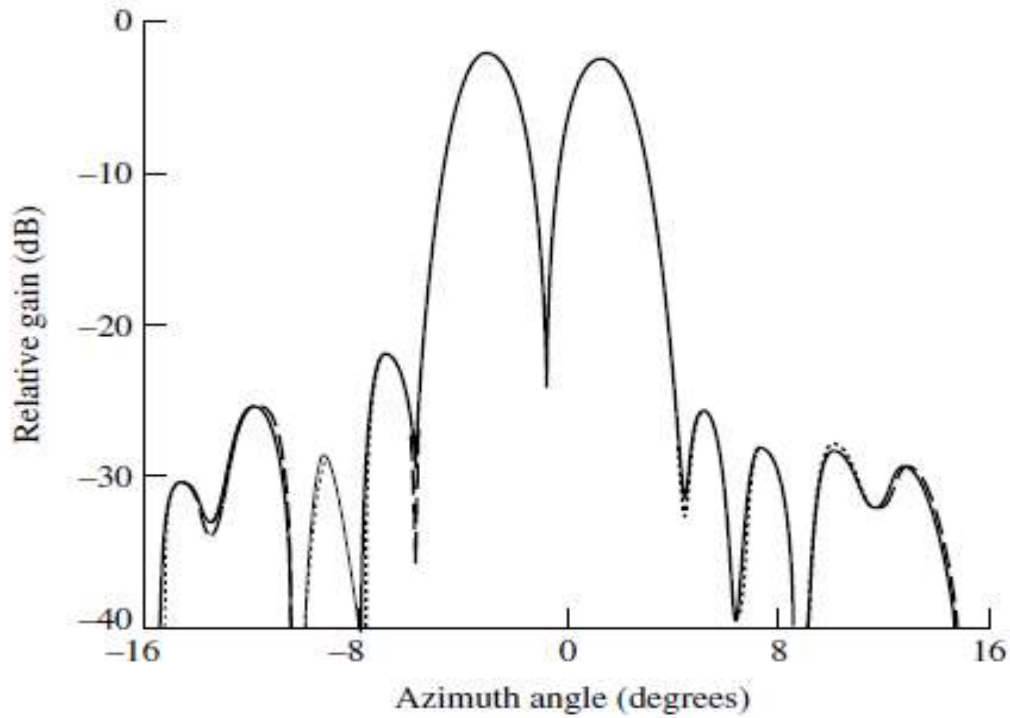
- The analytical basis of a phase pattern. Unless otherwise specified, it will be assumed here that the measurements are performed in the receiving mode.

Radiation Patterns



(a) Sum mode

Radiation Patterns



(b) Difference mode

Figure 17.15 Measured and computed sum and difference mode principal-plane far-field patterns for a four-foot parabolic reflector. (SOURCE: E. D. Joy, W. M. Leach, Jr., G. P. Rodrique, and D. T. Paris, "Applications of Probe Compensated Near-Field Measurements," *IEEE Trans. Antennas Propagat.*, Vol. AP-26, No. 3, pp. 379–389, May 1978. © (1978) IEEE)

Instrumentation

- The instrumentation required to accomplish a measuring task depends largely on the functional requirements of the design.

- An antenna-range instrumentation must be designed to operate over a wide range of frequencies, and it usually can be classified into five categories:
    1. source antenna and transmitting system
    2. receiving system
    3. positioning system
    4. recording system
    5. data-processing system

Instrumentation

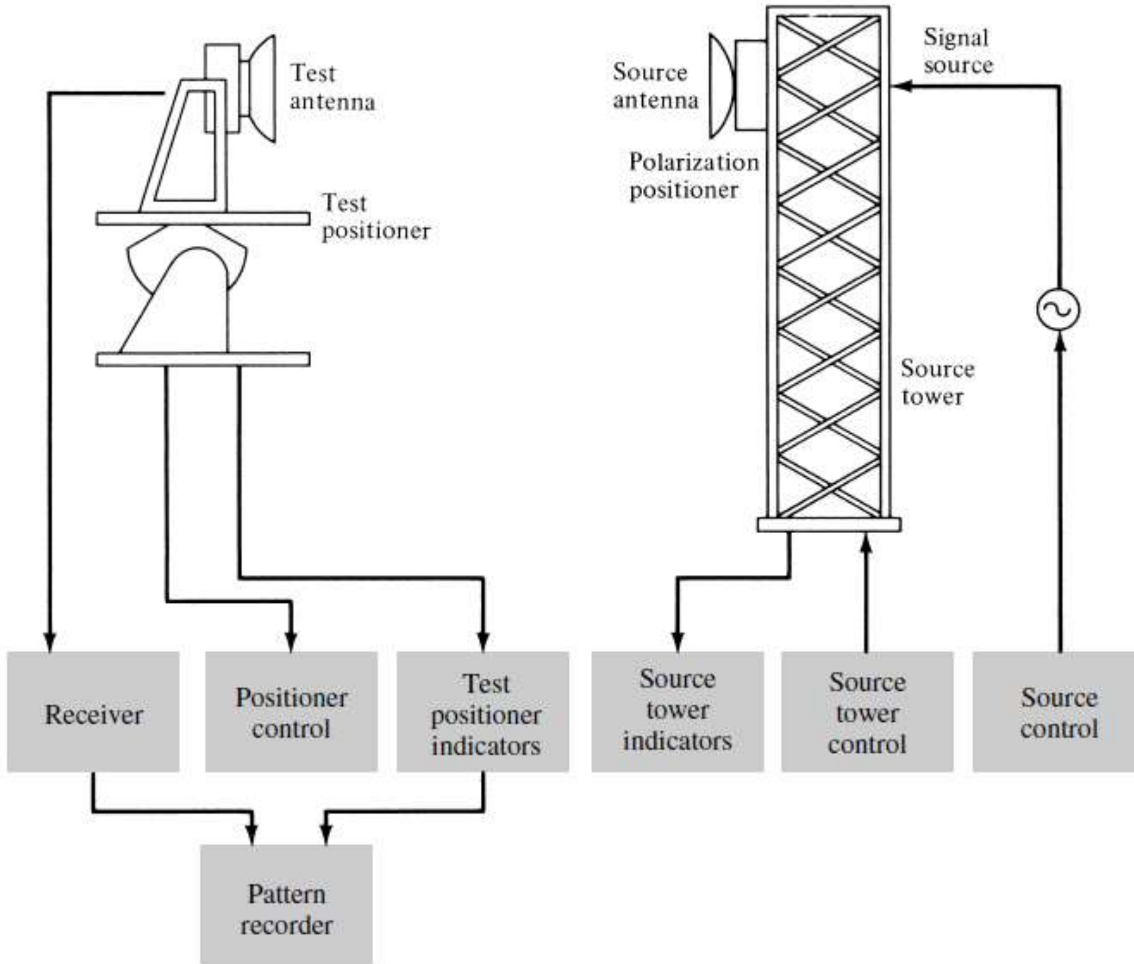


Figure 17.17 Instrumentation for typical antenna-range measuring system. (SOURCE: *IEEE Standard Test Procedures for Antennas*, IEEE Std 149–1979, published by IEEE, Inc., 1979, distributed by Wiley)

Instrumentation

- The source antennas are usually log-periodic antennas for frequencies below 1 GHz, families of parabolas with broadband feeds for frequencies above 400 MHz, and even large horn antennas.

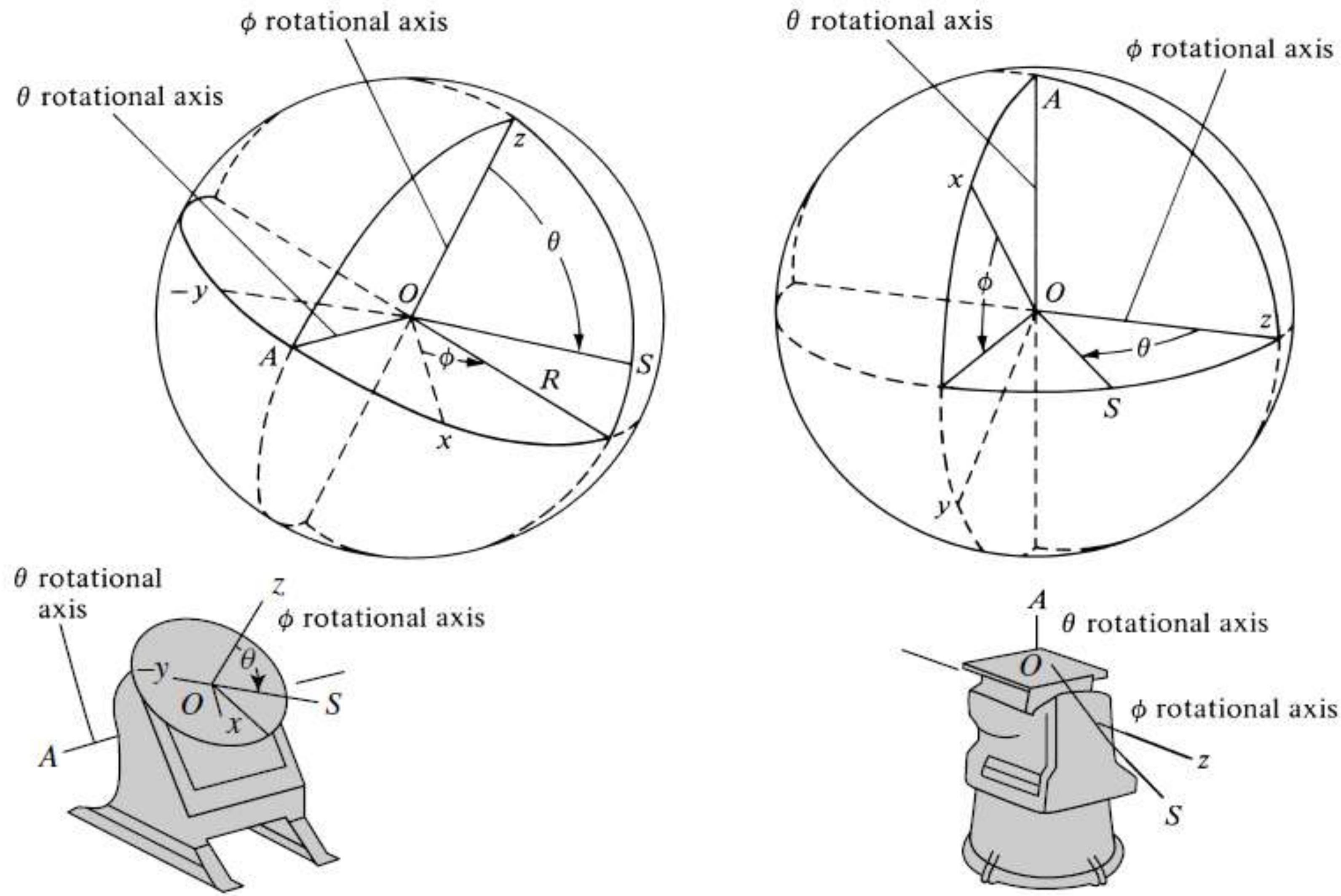
- The system must be capable of controlling the polarization. Continuous rotation of the polarization can be accomplished by mounting a linearly polarized source antenna on a polarization positioner.

- Antennas with circular polarization can also be designed, such as crossed log-periodic arrays, which are often used in measurements.

- The transmitting RF source must be selected so that it has frequency control, frequency stability, spectral purity, power level, and modulation.

Instrumentation

- The receiving system could be as simple as a bolometer detector, followed possibly by an amplifier, and a recorder.
- More elaborate and expensive receiving systems that provide greater sensitivity, precision, and dynamic range can be designed.
- One such system is a heterodyne receiving system, which uses double conversion and phase locking, which can be used for amplitude measurements.
- A dual-channel heterodyne system design is also available, and it can be used for phase measurements.



(a) Azimuth–over–elevation positioner

(b) Elevation–over–azimuth positioner

Figure 17.18 Azimuth-over-elevation and elevation-over-azimuth rotational mounts. (SOURCE: *IEEE Standard Test Procedures for Antennas*, IEEE Std 149–1979, published by IEEE, Inc., 1979, distributed by Wiley)

Instrumentation

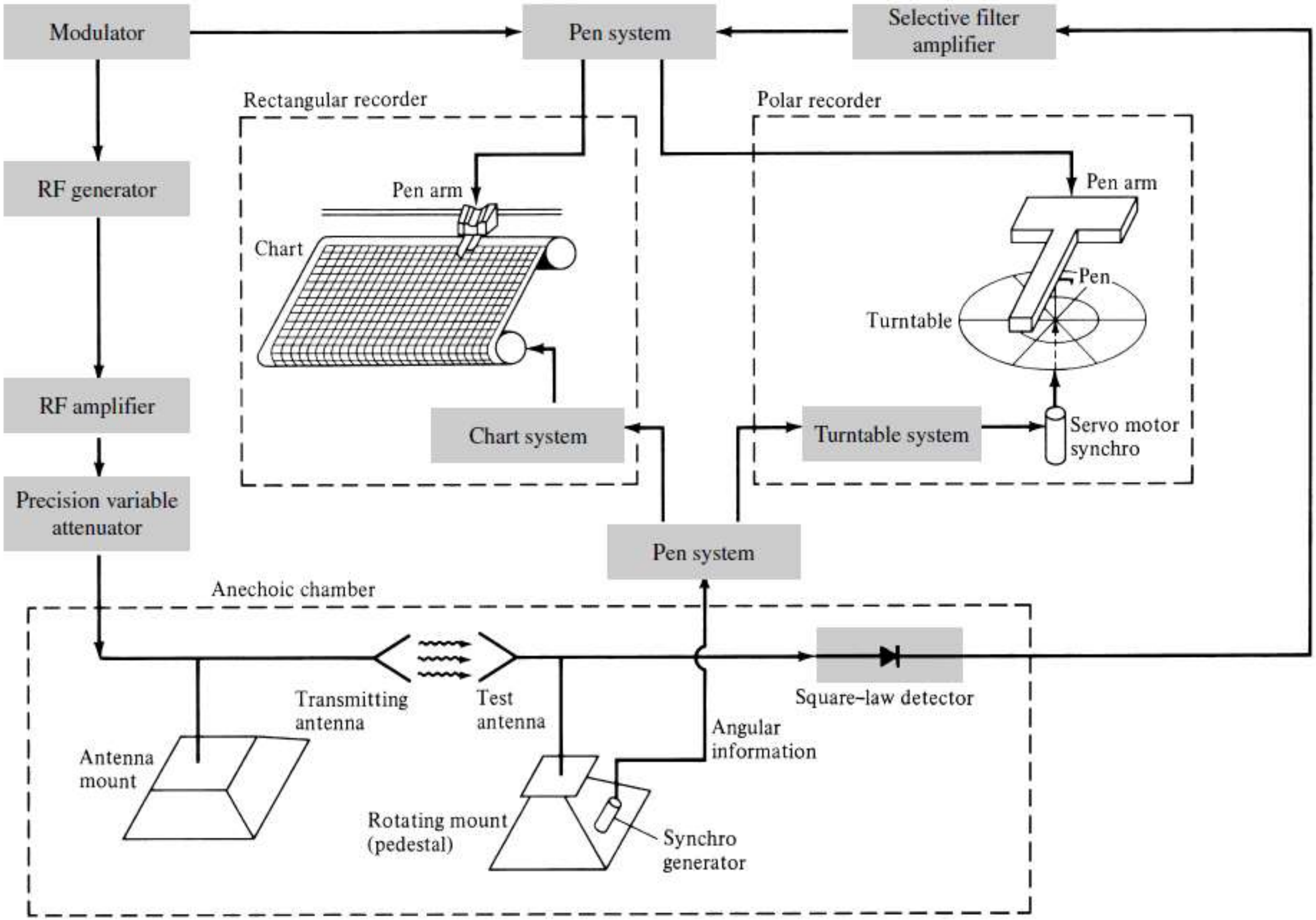
- To achieve the desired plane cuts, the mounting structures of the system must have the capability to rotate in various planes. This can be accomplished by utilizing rotational mounts (pedestals), two of which are shown in Figure 17.18.
- Tower-model elevation-over-azimuth pedestals are also available.
- There are primarily two types of recorders; one that provides a linear (rectangular) plot and the other a polar plot.
- The polar plots are most popular because they provide a better visualization of the radiation distribution in space.

Instrumentation

- Usually the recording equipment is designed to graph the relative pattern.
- Absolute patterns are obtained by making, in addition, gain measurements.
- The recording instrumentation is usually calibrated to record relative field or power patterns.
- Power pattern calibrations are in decibels with dynamic ranges of 0–60 dB.
- For most applications, a 40-dB dynamic range is usually adequate and it provides sufficient resolution to examine the pattern structure of the main lobe and the minor lobes.

Instrumentation

- In an indoor antenna range, the recording equipment is usually placed in a room that adjoins the anechoic chamber.
- To provide an interference free environment, the chamber is closed during measurements.
- To monitor the procedures, windows or closed circuit TVs are utilized.
- In addition, the recording equipment is connected, through synchronous servo-amplifier systems, to the rotational mounts (pedestals) using the traditional system shown in Figure 17.19(a).



(a) Traditional system

Instrumentation

- The system can record rectangular or polar plots.
- Position references are recorded simultaneously with measurements, and they are used for angular positional identification.
- As the rotational mount moves, the pattern is graphed simultaneously by the recorder on a moving chart.
- One of the axes of the chart is used to record the amplitude of the pattern while the other identifies the relative position of the radiator.
- A modern configuration to measure antenna and RCS patterns, using a network analyzer and being computer automated, is shown in Figure 17.19(b).

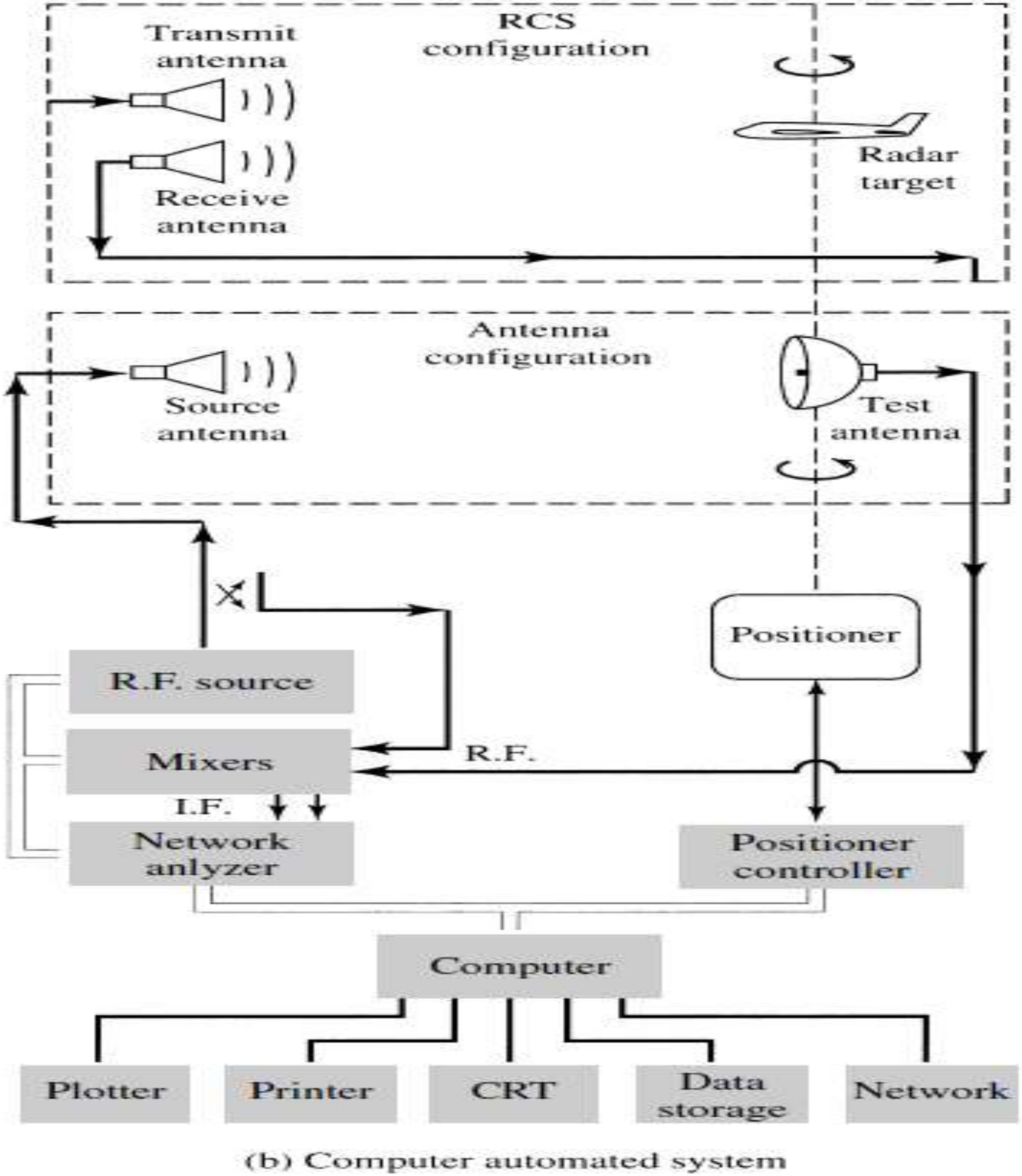


Figure 17.19 Block diagrams of typical instrumentations for measuring rectangular and polar antenna and RCS patterns.

Amplitude Pattern

- The total amplitude pattern of an antenna is described by the vector sum of the two orthogonally polarized radiated field components.

- The pattern on a conventional antenna range can be measured using the system of Figure 17.17 or Figure 17.19 with an appropriate detector.

- The receiver may be a simple bolometer (followed possibly by an amplifier), a double-conversion phase-locking heterodyne system , or any other design.

Amplitude Pattern

- In many applications, the movement of the antenna to the antenna range can significantly alter the operational environment.
- Therefore, in some cases, antenna pattern measurements must be made *in situ to preserve the environmental performance characteristics.*
- A typical system arrangement that can be used to accomplish this is shown in Figure 17.20.

Amplitude Pattern

- The source is mounted on an airborne vehicle, which is maneuvered through space around the test antenna and in its far-field, to produce a plane wave and to provide the desired pattern cuts.

- The tracking device provides to the recording equipment the angular position data of the source relative to a reference direction.

- The measurements can be conducted either by a point-by-point or by a continuous method. Usually the continuous technique is preferred.

Amplitude Pattern

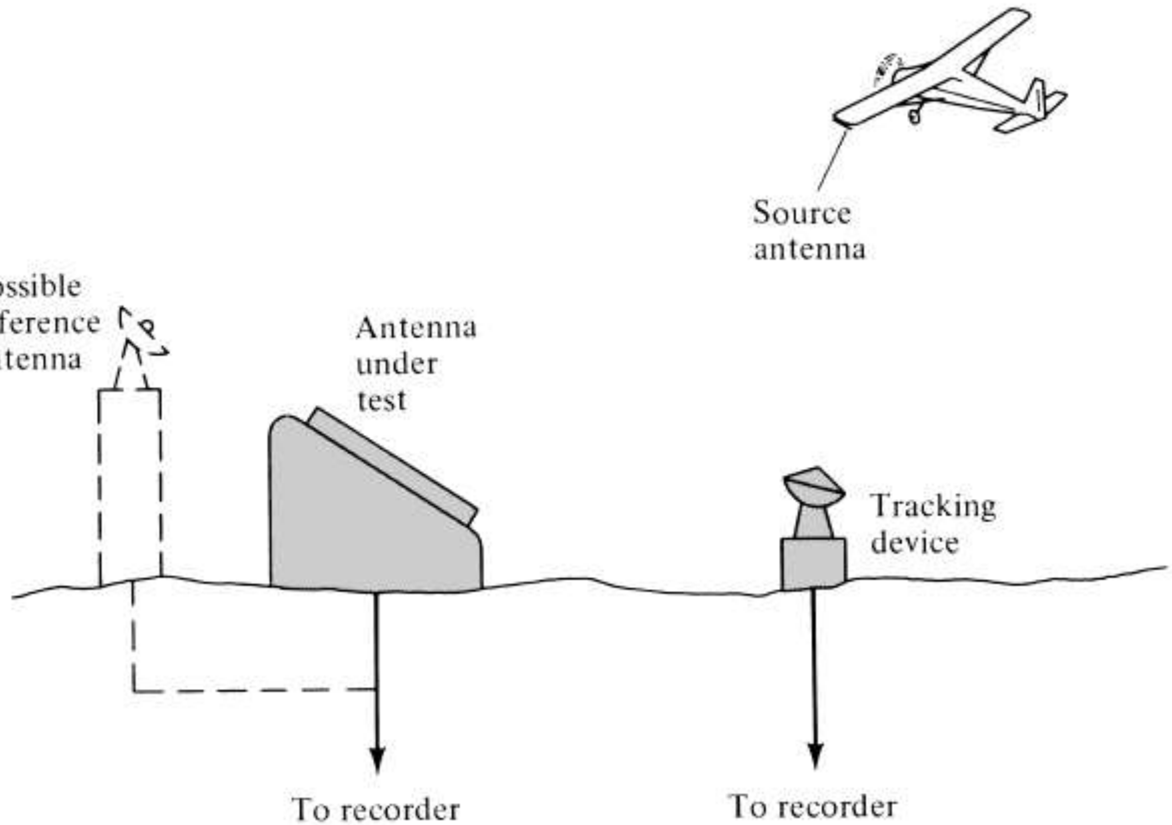


Figure 17.20 System arrangement for *in situ* antenna pattern measurements. (SOURCE: *IEEE Standard Test Procedures for Antennas*, IEEE Std 149–1979, published by IEEE, Inc., 1979, distributed by Wiley)

Phase Measurements

- Phase measurements are based on the analytical formulations.

$$\mathbf{E}_u = \hat{\mathbf{u}} E(\theta, \phi) e^{j\psi(\theta,\phi)} \frac{e^{-jkr}}{r}$$

- The phase pattern of the field, in the direction of the unit vector $\hat{\mathbf{u}}$, is given by the ψ(θ,ϕ) phase function .

- For linear polarization, $\hat{\mathbf{u}}$ is real, and it may represent $\hat{\mathbf{a}}_\theta$ or $\hat{\mathbf{a}}_\phi$ in the direction of θ or ϕ.

- 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.

Phase Measurements

- 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 17.21(a) and 17.21(b).

- For the design of Figure 17.21(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.

Phase Measurements

- 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 17.21(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.

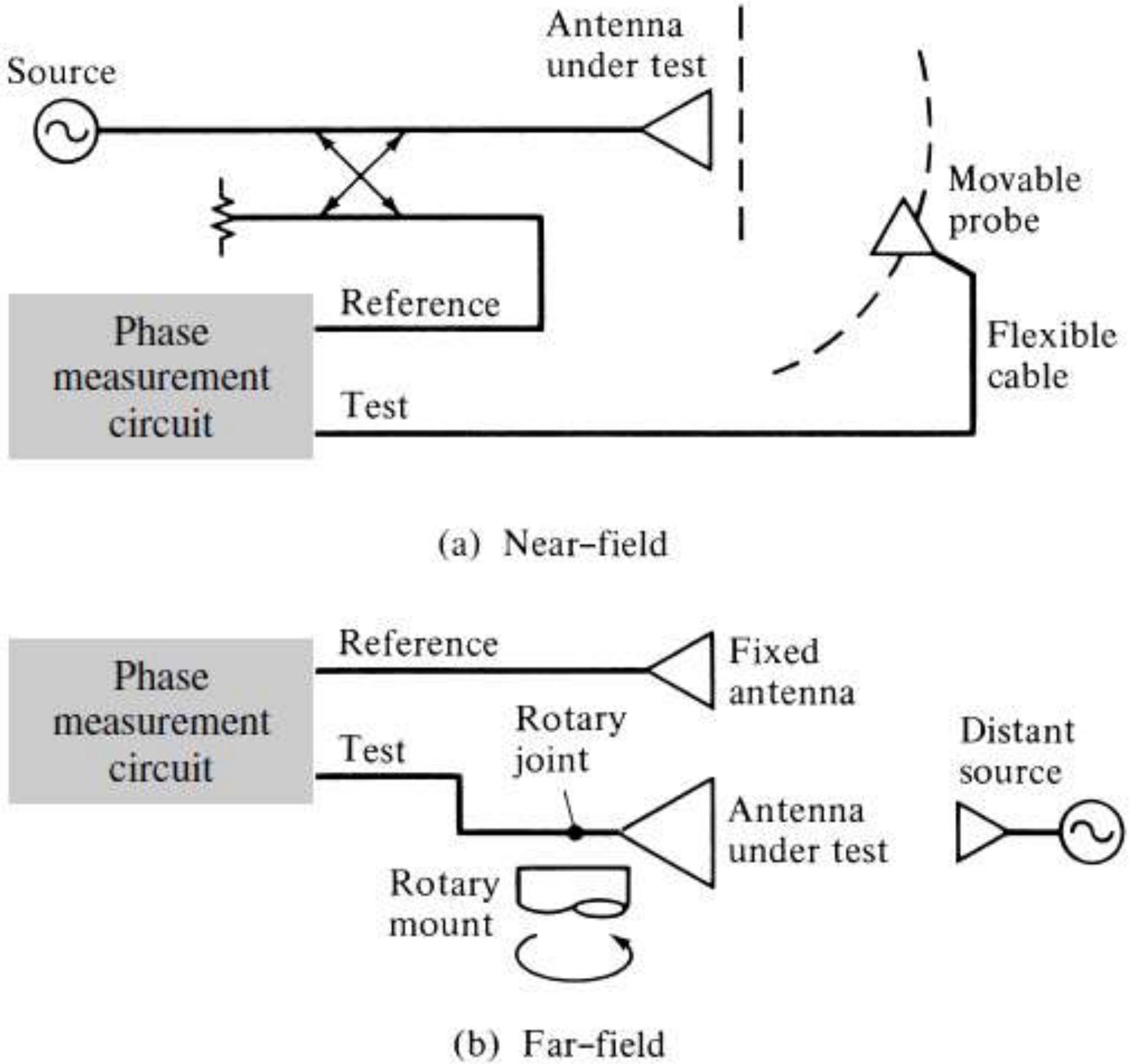


Figure 17.21 Near-field and far-field phase pattern measuring systems. (SOURCE: *IEEE Standard Test Procedures for Antennas*, IEEE Std 149–1979, published by IEEE, Inc., 1979, distributed by Wiley)

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.

Gain Measurements

- 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 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.

Gain Measurements

- 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.*

Gain 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).

Gain Measurements

- 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.

Absolute-Gain Measurements

- There are a number of techniques that can be employed to make absolute-gain measurements.

- All of these methods are based on the Friis transmission formula which assumes that the measuring system employs, each time, two Antennas.

- 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.

Absolute-Gain Measurements

- Equation can be written in a logarithmic decibel form as

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

- where

  $(G_{0t})_{dB}$ = gain of the transmitting antenna (dB)
  $(G_{0r})_{dB}$ = gain of the receiving antenna (dB)
  P_r = received power (W)
  P_t = transmitted power (W)
  R = antenna separation (m)
  λ = operating wavelength (m)

Absolute-Gain Measurements

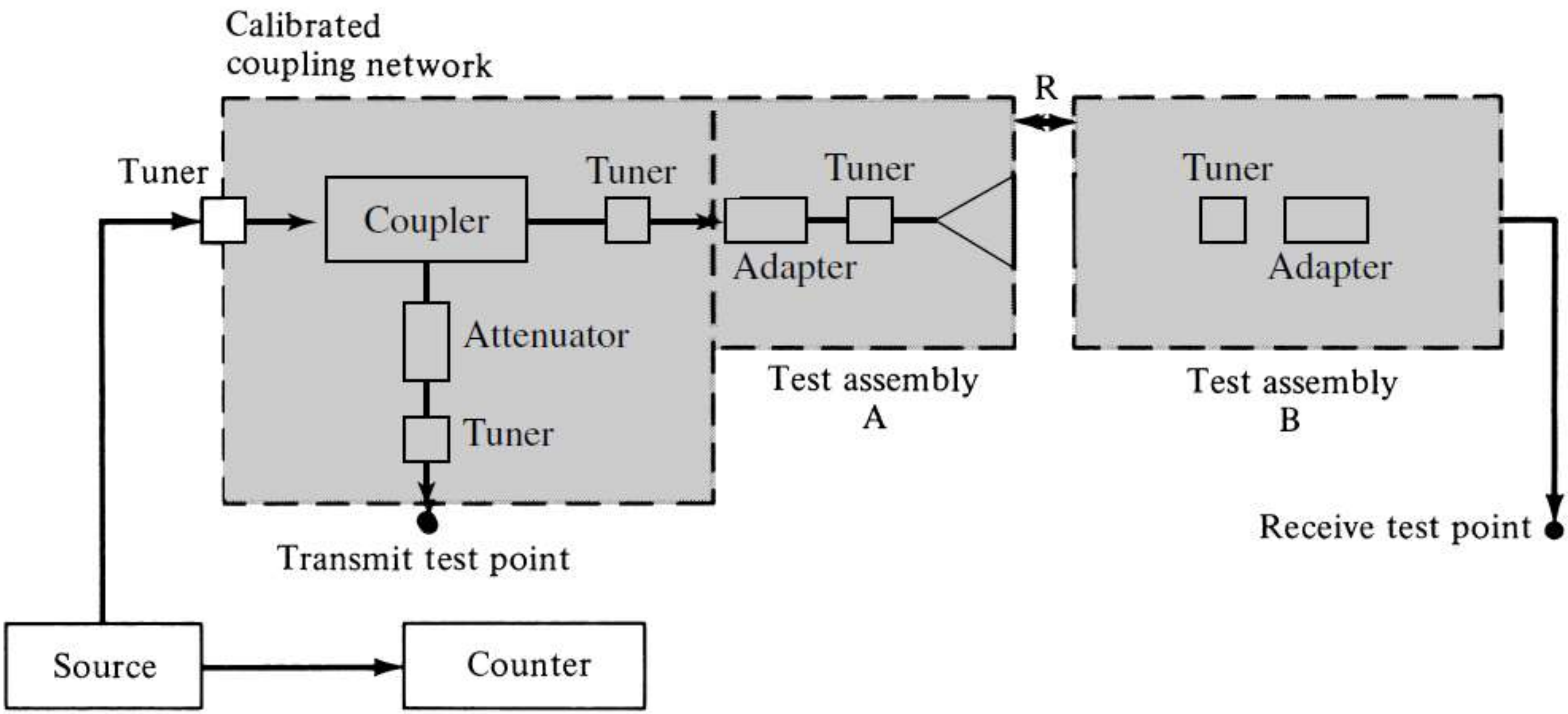
- If the transmitting and receiving antennas are identical *($G_{0t} = G_{0r}$), the above equation reduces to*

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

- By measuring *R, λ, and the ratio of P_r/P_t, the gain of the antenna can be found.*

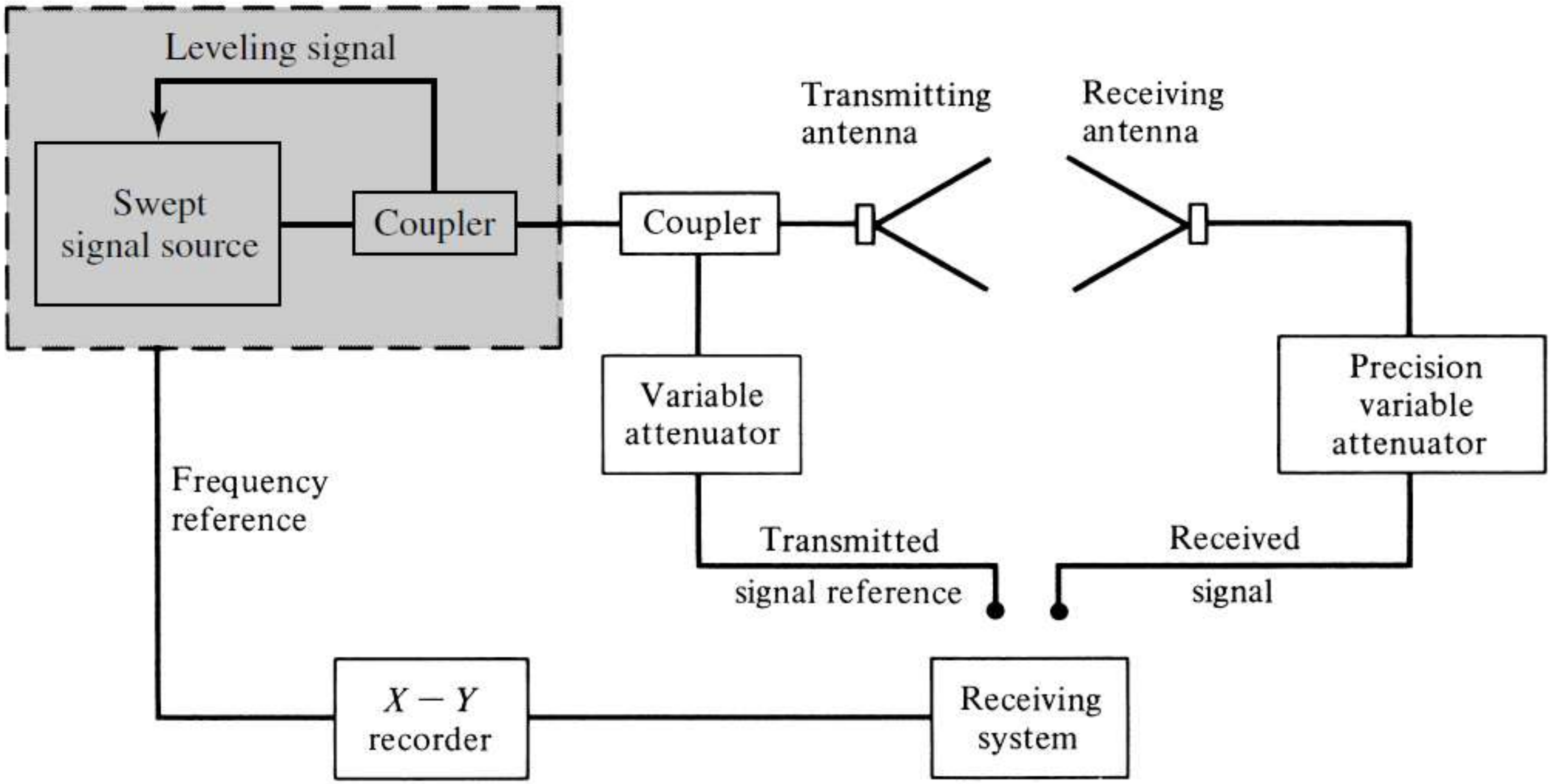
- *At* a given frequency, this can be accomplished using the system of Figure 17.22(a). The system is simple and the procedure straightforward. For continuous multi-frequency measurements, such as for broadband antennas, the swept-frequency instrumentation of Figure 17.22(b) can be utilized.

Absolute-Gain Measurements



(a) Single frequency

Absolute-Gain Measurements



(b) Swept frequency

Figure 17.22 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)

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 mentioned above gain equation. Thus

Three-Antenna Method

(a-b Combination)

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

(a-c Combination)

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

(b-c Combination)

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

Three-Antenna Method

- From these three equations, the gains *$(G_a)_{dB}$, $(G_b)_{dB}$, and $(G_c)_{dB}$ 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

Three-Antenna Method

- 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.

- There are no rigorous methods to account for proximity effects and multipath interference.

- These 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.

Extrapolation Method

- The extrapolation method is an absolute-gain method, which can be used with the three-antenna method, and it was developed to rigorously account for possible errors due to proximity, multipath, and non-identical 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.

Extrapolation Method

- 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 are to be determined.
- For the determination of gains, amplitude measurements are sufficient.

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.

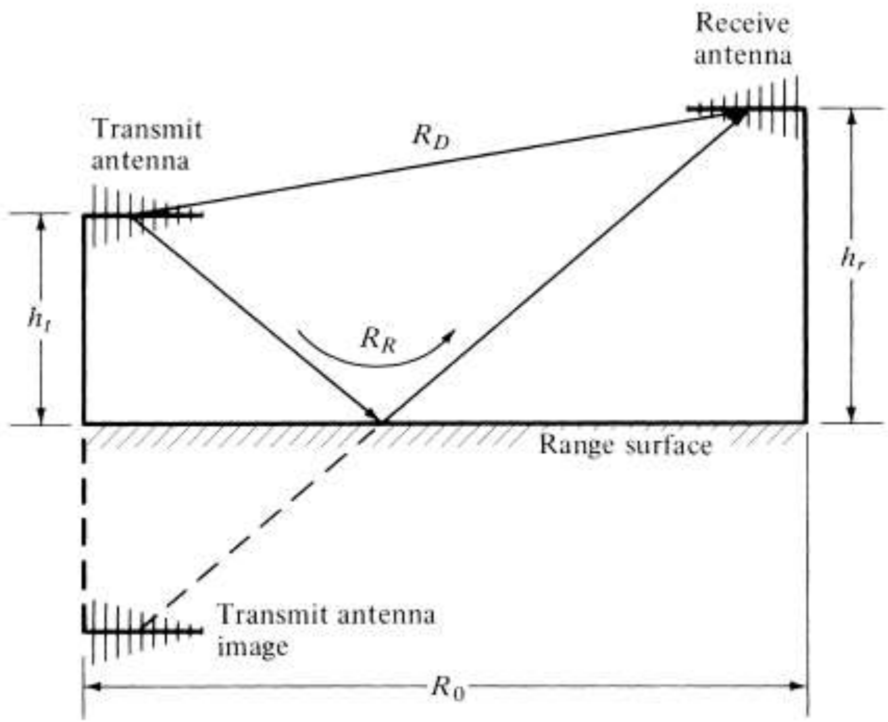


Figure 17.2 Geometrical arrangement for reflection range. (SOURCE: L. H. Hemming and R. A. Heaton, "Antenna Gain Calibration on a Ground Reflection Range," *IEEE Trans. Antennas Propagat.*, Vol. AP-21, No. 4, pp. 532–537, July 1973. © (1973) IEEE)

Ground-Reflection Range Method

- The method takes into account the specular reflections from the ground (using the system geometry of Figure 17.2), and it can be used with some restrictions and modifications with the two or three-antenna methods.

- 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.

Ground-Reflection Range Method

- 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 17.2 is utilized.

- Usually it is desirable that the height of the receiving antenna *hr be much* smaller than the range *R0 (hr R0).*

Ground-Reflection Range Method

- *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

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

Ground-Reflection Range Method

- where *DA and DB are the directivities (relative to their respective maximum values)* along *RD, and they can be determined from amplitude patterns measured prior to the* gain measurements.

- *RD,RR, λ, an dPr/Pt are also measured.*

- *The only quantity that* needs to be determined is the factor *r which is a function of the radiation pattern s of* the antennas, the frequency of operation, and the electrical and geometrical properties of the antenna range.

Ground-Reflection Range Method

- 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 minimized.

- 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

Ground-Reflection Range Method

- it can be shown that *r can be determined from*

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

- Now all parameters included can either be measured or computed from measurements. The free-space range system of Figure 17.22(a) can be used to perform these measurements.

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.*

Gain-Transfer (Gain-Comparison) Measurements

- The procedure requires two sets of measurements. In one set, using the test antenna as the receiving antenna, the received power *(PT) into a matched load is recorded.*

- *In* the other set, the test antenna is replaced by the standard gain antenna and the received power *(PS) 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.

Gain-Transfer (Gain-Comparison) Measurements

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

$$(G_T)_{\mathrm{dB}} = (G_S)_{\mathrm{dB}} + 10\log_{10}\left(\frac{P_T}{P_S}\right)$$

- where *(GT)dB and (GS)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.

Gain-Transfer (Gain-Comparison) Measurements

- One antenna can replace the other by a simple, but very precise, 180◦ rotationof 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.

Gain-Transfer (Gain-Comparison) Measurements

- 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.

Gain-Transfer (Gain-Comparison) Measurements

- 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

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

- *GTV and GTH are, respectively, the partial power gains with respect to vertical-linear* and horizontal-linear polarizations.

Gain-Transfer (Gain-Comparison) Measurements

- *GTV is obtained 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 *GTH.*
- *Usually a single linearly polarized standard gain* antenna (a linear *λ/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.

Gain-Transfer (Gain-Comparison) Measurements

- 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.

Gain-Transfer (Gain-Comparison) Measurements

- 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.

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 D by Kraus or D by Tai and Pereira, whereas the other relies on the numerical techniques.
- The computations can be performed very efficiently and economically with modern computational facilities and numerical techniques.

DIRECTIVITY MEASUREMENTS

- 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.

- 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.

DIRECTIVITY MEASUREMENTS

- The other method requires that the directivity be computed using (2-35) where *Prad* is evaluated numerically using (2-43).
- The *F(ϑi, φj) function represents the radiation* intensity or radiation pattern, as defined by (2-42), and it will be obtained by measurements.
- *Umax in (2-35) represents the maximum radiation intensity of F(ϑ,φ) in all* space, as obtained by the measurements.
- The radiation pattern is measured by sampling the field over a sphere of radius *r.*

DIRECTIVITY MEASUREMENTS

- The pattern is measured in two-dimensional plane cuts with φ_j *constant* ($0 \le \varphi_j \le 2\pi$) and ϑ *variable* ($0 \le \vartheta \le \pi$), *as shown in Figure 2.19, or with* ϑ_i *fixed* ($0 \le \vartheta_i \le \pi$) and φ *variable* ($0 \le \varphi \le 2\pi$).

- *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 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.

DIRECTIVITY MEASUREMENTS

- 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 into a computer at a later time.

- If on-line computer facilities are available, the measurements can be automated to provide essentially real-time computations.

DIRECTIVITY MEASUREMENTS

- 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 polarized such that the field is represented by both *ϑ and φ components, the partial directivities $D\vartheta$ (ϑ, φ) and $D\varphi$(ϑ, φ) must each be found.*

- *This is* accomplished from pattern measurements with the probe positioned, respectively, to sample the *ϑ and φ components.*

DIRECTIVITY MEASUREMENTS

- *The total directivity is then given by*

$$D_0 = D_\theta + D_\phi$$

where

$$D_\theta = \frac{4\pi U_\theta}{(P_{\text{rad}})_\theta + (P_{\text{rad}})_\phi}$$

$$D_\phi = \frac{4\pi U_\phi}{(P_{\text{rad}})_\theta + (P_{\text{rad}})_\phi}$$

- *U_ϑ, $(P_{rad})_\vartheta$ and U_φ, $(P_{rad})_\varphi$ represent the radiation intensity and radiated power as* contained in the two orthogonal *ϑ and φ field components, respectively.*

DIRECTIVITY MEASUREMENTS

- The same technique can be used to measure the field intensity and to compute the directivity of any antenna that possesses two orthogonal polarizations.

- Many antennas have only one polarization (ϑ *or* φ*). This is usually accomplished by design and/or* proper selection of the coordinate system.

- In this case, the desired polarization is defined as the *primary polarization.*

- *Ideally, the other polarization should be zero. However,* in practice, it is non-vanishing, but it is very small.

DIRECTIVITY MEASUREMENTS

- Usually it is referred to as the *cross polarization, and for good designs it is usually below −40 dB.*

- The directivity of circularly or elliptically polarized antennas can also be measured.

- Precautions must be taken so as to which component represents the primary polarization and which the cross-polarization contribution.

Sources of Error

- Phase error and amplitude taper due to finite measurement distance.

- Reflections from surroundings, direct and reflected waves interference, harmful in measurement of low side lobes, the ripple path length difference of the wave changes rapidly as a function of position.

- Coupling to the reactive near field at LFs.

- Three dimensional vector field measurements – alignment errors.

Sources of Error

- Man made interfering signals at outdoor ranges.
- Effects of atmosphere at large distances.
- Incorrect use of cables without shielding may leak and act as antennas.
- Impedance mismatch between the instruments and antennas.
- Imperfections of the transmitter, receiver and positioner cause measurement errors.