

# An Introduction to Antenna Test Ranges, Measurements and Instrumentation

*The basic principles of antenna test and measurement are discussed along with an introduction to various range geometries, and instrumentation.*

By  
Jeffrey A. Fordham  
Microwave Instrumentation Technologies, LLC.

## Introduction

By definition, all of today's wireless communication systems contain one key element, an antenna of some form. This antenna serves as the transducer between the controlled energy residing within the system and the radiated energy existing in free space. In designing wireless systems, engineers must choose an antenna that meets the system's requirements to firmly close the link between the remote points of the communications system. While the forms that antennas can take on to meet these system requirements for communications systems are nearly limitless, most antennas can be specified by a common set of performance metrics.

## Antenna Performance Metrics

In order to satisfy the system requirements and choose a suitable antenna, system engineers must evaluate an antenna's performance. Typical metrics used in evaluating an antenna includes the input impedance, polarization, radiation efficiency, directivity, gain and radiation pattern.

### Input Impedance

Input impedance is the parameter which relates the antenna to its transmission line. It is of primary importance in determining the transfer of power from the transmission line to the antenna and vice versa. The impedance match between the antenna and the transmission line is usually expressed in terms of the standing wave ratio (SWR) or the reflection coefficient of the antenna when connected to a transmission line of a given impedance. The reflection coefficient expressed in decibels is called return loss.

### Polarization

The polarization of an antenna is defined as the polarization of the electromagnetic wave radiated by the antenna along a vector originating at the antenna and pointed along the primary direction of propagation. The polarization state of the wave is described by the shape and orientation of an ellipse formed by tracing the extremity of the electromagnetic field vector versus time. Although all antennas are elliptically polarized, most antennas are specified by the ideal polarization conditions of circular or linear polarization.

The ratio of the major axis to the minor axis of the polarization ellipse defines the magnitude of the axial ratio. The tilt angle describes the orientation of the ellipse in space. The sense of polarization is determined by observing the direction of rotation of the electric field vector from a point behind the source. Right-hand and left-hand polarizations correspond to clockwise and counterclockwise rotation respectively.

### Directivity

It is convenient to express the directive properties of an antenna in terms of the distribution in space of the power radiated by the antenna. The directivity is defined as  $4\pi$  times the ratio of the maximum radiation intensity (power radiated per unit solid angle) to the total power radiated by the antenna. The directivity of an antenna is independent of its radiation efficiency and its impedance match to the connected transmission line.

### Gain

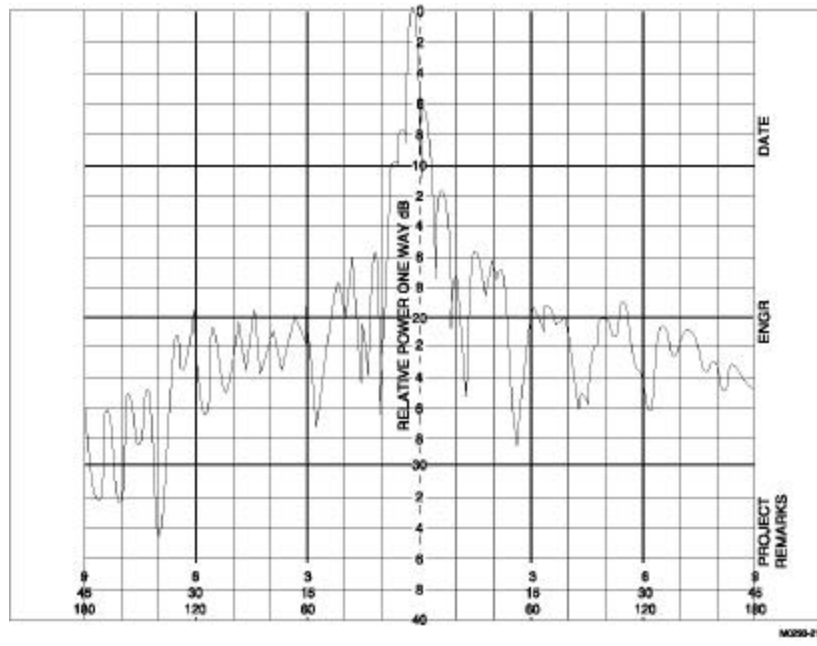
The gain, or power gain, is a measure of the ability to concentrate in a particular direction the net power accepted by the antenna from the connected transmitter. When the direction is not specified, the gain is usually taken to be its maximum value. Antenna gain is independent of reflection losses resulting from impedance mismatch.

### Radiation Efficiency

The radiation efficiency of an antenna is the ratio of the power radiated by the antenna to the net power accepted at its input terminals. It may also be expressed as the ratio of the maximum gain to the directivity.

### Radiation Pattern

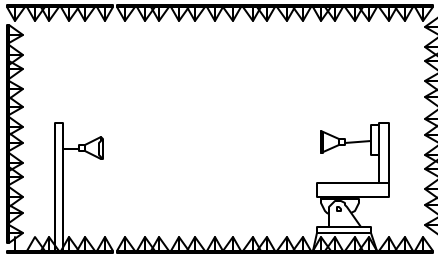
Antenna radiation patterns are graphical representations of the distribution of radiated energy as a function of direction about an antenna. Radiation patterns can be plotted in terms of field strength, power density, or decibels. They can be absolute or relative to some reference level, with the peak of the beam often chosen as the reference. Radiation patterns can be displayed in rectangular or polar format as functions of the spherical coordinates  $\theta$  and  $\phi$ . A typical antenna pattern in a rectangular format is shown below<sup>1</sup>.



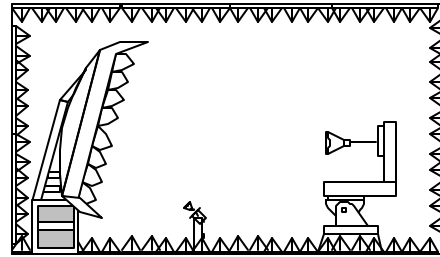
*Regular Pattern Plot*

## Antenna Range Siting Considerations

The choice of an antenna test range is dependent on many factors, such as the directivity of the antenna under test, frequency range and desired test parameters. Often the mechanical features of the antenna (size, weight and volume) can have as much influence on the selection of an antenna range as do the electrical performance factors. In selecting an antenna range to evaluate antenna performance, care must be taken to ensure the performance metrics are measured with sufficient accuracy.



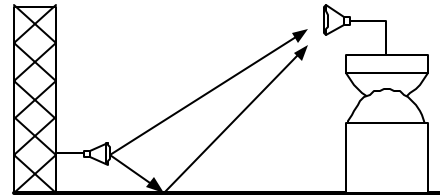
Rectangular Anechoic Chamber



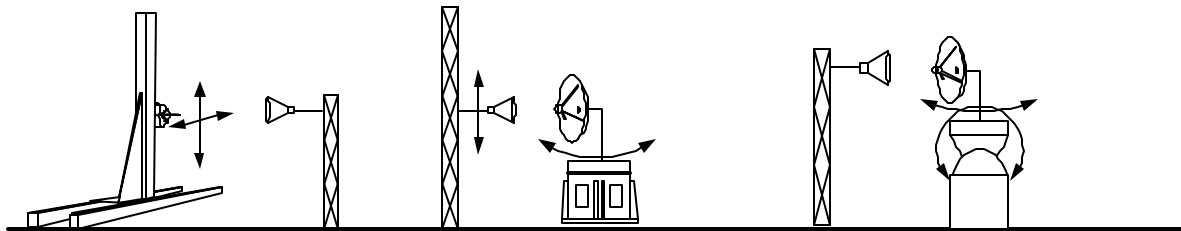
Compact Antenna Test Range



Outdoor Elevated Range



Ground Reflection Range



Planar Near-Field

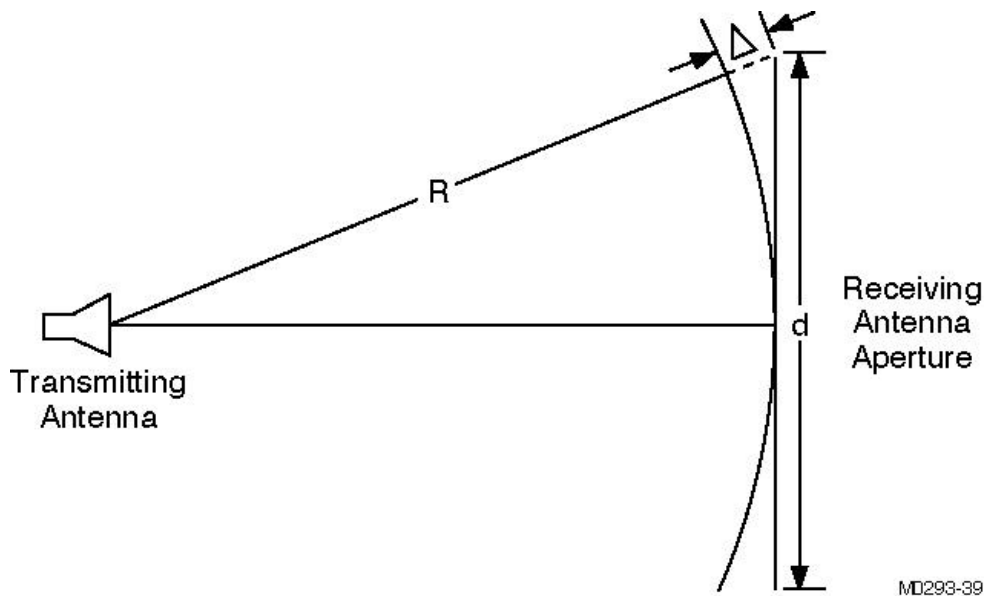
Cylindrical Near-Field

Spherical Near-Field

A few of the more commonly used antenna test ranges are shown in the accompanying diagram<sup>2</sup>. Regardless of the chosen test range, three key factors must be addressed and controlled to ensure a successful measurement. These factors are the phase variations of the incident field, the amplitude variations of the incident field and the stray signals created by reflections within the test range.

### Variations of the Phase of the Incident Field

In order to accurately measure an antenna's far zone performance, the deviation of the phase of the field across its aperture must be restricted. The criterion generally used is that the phase should be constant to within  $\pi/8$  radian ( $22.5^\circ$ ). Under normal operating conditions this criteria is easily achieved since there is usually a large separation between transmitting and receiving antennas. During antenna testing, it is desirable because of various practical considerations to make antenna measurements at as short a range as possible. Since the measurements must simulate the operating situation, it is necessary to determine the minimum separation between the transmitting antenna and the receiving antenna for a reasonable approximation of the far field gain and radiation patterns. At distances from a transmitting antenna, which are large compared with the antenna dimensions, the phase front of the emergent wave is nearly spherical in shape. For extreme separations, the radius of curvature is so large that for all practical purposes the phase front can be considered planar over the aperture of a practical antenna. As the antennas are brought closer together, a condition is reached in which, because of the short radius of curvature, there is an appreciable separation  $\Delta$  between the wavefront and the edges of the antenna aperture.



*Spherical Phase Front Tangent to a Plane Antenna Aperture*

A criterion that is commonly employed in determining the minimum permissible value of R is to hold  $\Delta$  to a maximum of  $1/16$  wavelength (equivalent to  $22.5^\circ$  of phase variation). If this condition is met, the receiving antenna is said to be in the far field of the transmitting antenna. The mathematical expression for this minimum range is:

(1)                      Where:

$$R \geq \frac{2D^2}{\lambda}$$

$R$  = range length  
 $D$  = aperture diameter of the antenna under test  
 $\lambda$  = Operating wavelength

The major effect of a small deviation  $\Delta$  is to produce minor distortions of the sidelobe structure. Larger values of  $\Delta$  will cause appreciable errors in the measured gain and lobe structure. Conversely, this condition can mask asymmetrical sidelobe structures which are actually present.

### **Variations of the Amplitude of the Incident Field**

A second and important siting consideration is the variation of the amplitude of the incident field over the aperture of the test antenna. Excessive variations in the field will cause significant errors in the measured maximum gain and sidelobe structure. This effect can be seen better from the viewpoint of reciprocity. Variations in the amplitude of the field over the aperture on receiving are analogous to the transmitting case of a modification of the aperture illumination by the primary feed. If the variation across the antenna under test is limited to about 0.5 dB, error in the measurements will be negligible for most applications. It is essential that the transmitting antenna be accurately directed so that the peak of its beam is centered on the aperture of the antenna under test. Improper alignment, which may not cause a noticeable loss of signal level, results in an asymmetrical aperture illumination and error in the measurement of the sidelobe structure.

### **Interference from Reflections**

The requirement of providing adequate separation between antennas to prevent excessive phase error makes it difficult to satisfy a further requirement, that the site be free of large reflections from the ground or other sources of reflection. Addition of reflected fields at the test antenna can produce erroneous gain and pattern measurements. For instance, an interfering field which is 30 dB below the direct path signal can cause a variation of  $\pm 0.25$  dB in the measured maximum gain and can seriously affect the measured sidelobe structure of the pattern. The usual method of minimizing the effects of fields caused by reflections are to (1) mount the transmitting antenna and test antenna sites on towers, (2) employ a directive transmitting

antenna, (3) avoid smooth surfaces which are oriented so that they produce direct reflection into the test antenna, and (4) erect screens or baffles to intercept the reflected wave near the reflection point.

An alternate procedure is to locate the transmitting and receiving antennas over a flat range and to take into account the specular reflection from the ground in making measurements. The heights of the antenna under test and the transmitting antenna are adjusted for a maximum of the interference pattern between the direct and ground reflected wave. Generally, it is more convenient to mount the test positioner and antenna on a fixed height tower or building and vary the height of the transmitting antenna. This can be accomplished with the transmitting antenna mounted to a motor driven elevator/carriage assembly that can travel up and down a tower.

In cases where the antenna range length is reasonably short, the entire range can be housed indoors in an anechoic chamber. An indoor far-field anechoic chamber has the same basic design criteria as an outdoor range except that the surfaces of the room are covered with RF absorbing material. This absorber is designed to reduce reflected signal over its design frequency range. Testing indoors offers many advantages to conventional outdoor ranges including improved security, avoiding unwanted surveillance and improved productivity due to less time lost because of weather and other environmentally related factors. The advantages of testing indoors are primarily responsible for the trend toward more advanced test ranges such as the compact range and near-field ranges.

## Amplitude Variation - Elevated Ranges

Variations in the amplitude of the field incident over a test aperture must also be restricted for accurate far-zone measurements. For range geometries employing comparatively large transmitting and test tower heights (i.e., elevated range geometries), it is advisable to restrict amplitude taper to the order of 1/4 dB or less by using the following criterion:

Where:

(2)	$d_t$	=	transmitting antenna diameter
	$\lambda$	=	wavelength
$d_t \leq$	$\frac{\lambda R}{4D}$	R	= range length
		D	= maximum test aperture dimension

From the viewpoint of suppressing range surface reflections, it is also desirable to maintain the test height H, greater than or equal to 6D. If one must, for practical reasons, employ test heights less than approximately 4D, the ground-reflection technique should be considered.

## Ground-Reflection Antenna Test Ranges

Ground-reflection antenna range geometries are often advantageous when the test situation involves low directivities and high accuracy requirements or when practical test heights are less than approximately four times the maximum vertical dimension of the test aperture. In this technique specular reflection from the range surface is caused to create constructive interference with the direct-path energy in the region of the test aperture, such that the peak of the first interference pattern lobe is centered on the test aperture. Four basic criteria are applicable to ground-reflection range geometries:

(3)	$R \geq \frac{2D^2}{\lambda}$		In these expressions:	R	=	range length
(4)	$h_r \geq 3.3D$	Vertical-plane amplitude taper 1/4 dB		D	=	test aperture diameter
(5)	$h_t = \frac{\lambda R}{4h_r}$	Peak of first interference lobe at $h_r$		$\lambda$	=	wavelength
(6)	$d_t \leq \frac{\lambda R}{4D}$	Horizontal-plane amplitude taper $\leq 1/4$ dB		$h_r$	=	height of the center of the test aperture
				$h_t$	=	height of the center of the transmitting antenna
				$d_t$	=	transmitting antenna diameter

## Compact Antenna Test Ranges

Compact ranges are an excellent alternative to traditional far-field ranges. Any testing that can be accomplished on a far-field range can be accomplished on a compact antenna test range. This method of testing allows an operator to employ an indoor anechoic test chamber at a reasonable cost and avoid the problems associated with weather and security often encountered when using an outdoor test range. In a research and development situation, the small size of a compact range allows it to be located convenient to the design engineers. In a manufacturing environment, the compact range can be located near to the final testing and integration facilities. By placing a compact range in a shielded chamber, one can eliminate interference from external sources. This last feature has become more important in the last several years as the proliferation of cell phone and wireless systems has created a background noise environment which has made antenna testing in a quiet electromagnetic environment more difficult.

The principle of operation of a compact range is based on the basic concepts of geometrical optics. Diverging spherical waves from a point source located at the focal point of a paraboloidal surface are collimated into a plane wave. This plane wave is incident on the test antenna. The resultant plane wave has a very flat phase front, but the reflector-feed combination introduces a small (but generally acceptable) amplitude taper across the test zone.

In principle, the operation of a compact range is straightforward; however, its ultimate design, construction, and installation should be carefully considered.

## Near-Field Antenna Test Ranges

Near-field ranges are used where large antennas are to be tested indoors in a relatively small space. This type of range uses a small RF probe antenna that is scanned over a surface surrounding the test antenna. Typically separation between the probe and the antenna structure is on the order of 4 to 10 wavelengths. During the measurement, near-field phase and amplitude information is collected over a discrete matrix of points. This data is then transformed to the far-field using Fourier techniques. The resulting far-field data can then be displayed in the same formats as conventional far-field antenna measurements.

In addition to obtaining far-field data, Fourier analysis techniques are used to back-transform the measured electromagnetic field to the antenna's aperture to produce aperture field distribution information. This offers the ability to perform element diagnostics on multi-element phased arrays.

In near-field testing, the test antenna is usually aligned to the scanner's coordinate system and then either the probe or the test antenna is moved. In practice it is easier and more cost effective to scan the RF probe over linear axes or the test antenna over angular axes. But this does not have to be the case. There are many scanning coordinate systems possible for collecting the near-field data. Three techniques are in common usage:

**Planar Near-Field Method** – With planar near-field scanning, the probe usually is scanned in X and Y linear coordinates over the aperture of the test antenna. A large planar scanner is used to move the probe over a very accurate plane located in front of the test antenna's aperture. Once aligned to the scan plane, the test antenna is not moved during the collection of the near-field data. Planar near-field provides limited angular coverage of the test antenna's field due to the truncation caused by the scanner's dimensions.

**Cylindrical Near-Field Method** – For this method the probe typically is scanned in one linear dimension using a single axis linear positioner. The test antenna is stepped in angle on a rotary axis oriented parallel to the linear axis. The resulting scan describes a cylindrical surface around the test antenna. Cylindrical near-field scanning can provide complete angular coverage of the test antenna's field in one plane. The orthogonal plane has limited angular coverage due to truncation caused by the finite length of the linear scanner.

**Spherical Near-Field Method** – Spherical near-field scanning normally involves installing the test antenna on a spherical scanning positioner. The probe antenna is normally fixed in space. The test antenna is normally scanned in one angular axis and stepped in an orthogonal angular axis. The resulting data is collected over a spherical envelope surrounding the test antenna. Full or nearly-full coverage of the test antenna's radiating field can be evaluated with this type of near-field system.

## Pulsed Antenna Measurements

Characterizing antennas under pulsed RF condition is becoming increasingly commonplace. Advanced radar and wireless systems and their enabling technologies such as monolithic microwave integrated circuits (MMICs) require testing methods to verify performance over a wide range of operating parameters. In addition to the pulse parameters, the major factors influencing pulsed RF testing include high transmit power levels, thermal management of the antenna under test (AUT) and its supporting equipment in the test environment, and interfacing to a highly integrated antenna assembly with its associated transmitting and control circuitry. Due to these issues, pulsed RF operation presents an additional set of test problems not often encountered in CW operation. As a result, instrumentation complexity increases and measurement system timing issues become critical.

The basic pulsed antenna test parameters are identical to those encountered in CW measurements. Gain, sidelobe levels, pointing accuracy, beamwidth, null locations and depths, and polarization parameters are essential to fully characterizing an antenna. In addition to the traditional time invariant antenna performance parameters, some new time dependent parameters emerge when testing under pulsed conditions. These include transient effects such as beam formation and distortions as a function of time within a pulse or over an ensemble of pulses, power output (i.e. gain) as a function of time within a pulse or pulse burst, etc.

Compounding these measurements is the additional burden of multi-channel, multi-frequency, and multi-state measurements as a function of pulse repetition frequency (PRF), duty factor (DF) and operating frequency. Due to the increasingly integrated nature of antennas with their transmitters, the measurement system must be responsive to external RF pulse generation and timing for both single and multiple pulse measurements.

## Antenna Range Instrumentation

Regardless of the type of antenna range to be implemented, the complement of instruments to operate the range is very similar. Differences occur due to the location of the various instruments with respect to the source and test antennas, types of measurements to be performed and the degree of automation desired. A description of the basic instrumentation subsystems and typical applications of different types of antenna ranges, will be presented here.

The instrumentation for measuring antenna patterns consists of four subsystems, which can be controlled from a central location. These subsystems are:

1. Positioning and Control
2. Receiving
3. Signal Source
4. Recording and Processing

The test antenna is installed on a positioner and is usually, tested in the receive mode. The motion of the positioner (rotation of the test antenna) is controlled by a positioner control unit located in the control room. The positioner is equipped with synchro transmitters or high accuracy encoders to provide angle data for the position indicator and the recording/processing subsystem.

To process the received signal for recording, the RF signal must be detected. In most cases microwave receivers are employed on the antenna range to accept the very low-level signals from the test antenna and to downconvert these signals to lower frequencies for processing. Microwave receivers offer many advantages including improved dynamic range, better accuracy, and rejection of unwanted signals that may be present in the area. Also phase/amplitude receivers provide the ability to measure phase characteristics of the received signal. Phase information is required for many types of antenna measurements.

A signal source provides the RF signal for the remote source antenna. The signal source can be permanently fixed on the ground or floor, or located on a tower near the source antenna, depending on the frequency of operation and mechanical considerations. The signal source is designed for remote operation. The source control unit is usually located in the control room with the measurement and control instrumentation.

Often, a computer subsystem is added to the instrumentation to automate the entire measurement sequence. This computer subsystem employs a standard bus interface, like the IEEE-488, to setup and monitor the individual instruments. High-speed data busses are utilized for the measurement data to maximize data throughput and productivity.

An automated antenna measurement system offers a high degree of repeatability, speed, accuracy, and efficiency with minimum operator interaction. Data storage is conveniently handled by a variety of media including a local hard drive, floppy disk, removable drives or bulk data storage on a local area network. After data acquisition is completed, an automated system supports analysis of the measured data such as gain and polarization plus a wide variety of data plotting formats such as rectangular, polar, three-dimensional, and contour plots.

## Typical Applications of Antenna Range Instrumentation

### Outdoor Far-Field Range

In an outdoor far-field range configuration, the test antenna is installed on the test positioner located on a tower, roof or platform outside the instrumentation control room. The receiver front end (Local Oscillator) is usually located at the base of the test positioner, with the mixer connected directly to the test antenna port. This configuration requires only a single RF path through the positioner, greatly simplifying system design. Use of the remote front end also minimizes local oscillator power loss to the mixer and maximum system sensitivity. An outdoor enclosure protects the local oscillator from the weather and temperature extremes. For multi-ported antennas, simultaneous measurements can be made on all ports through the use of multiplexers installed in front of the mixer. The receiver front end is remotely controlled from the control console through interfaces with the receiver.

The test positioner axes are controlled and read out by the positioner control and readout units. A typical control system consists of a control unit located in the operator's console. It is interfaced to a power amplifier unit located near the test positioner. This configuration keeps the high power drive signals near the positioner and away from sensitive measurement instruments while providing remote control of positioner functions from the equipment console. The position readout unit is located in the equipment console to provide real time readout of position axes to the operator or, in the case of an automated system, to the computer.

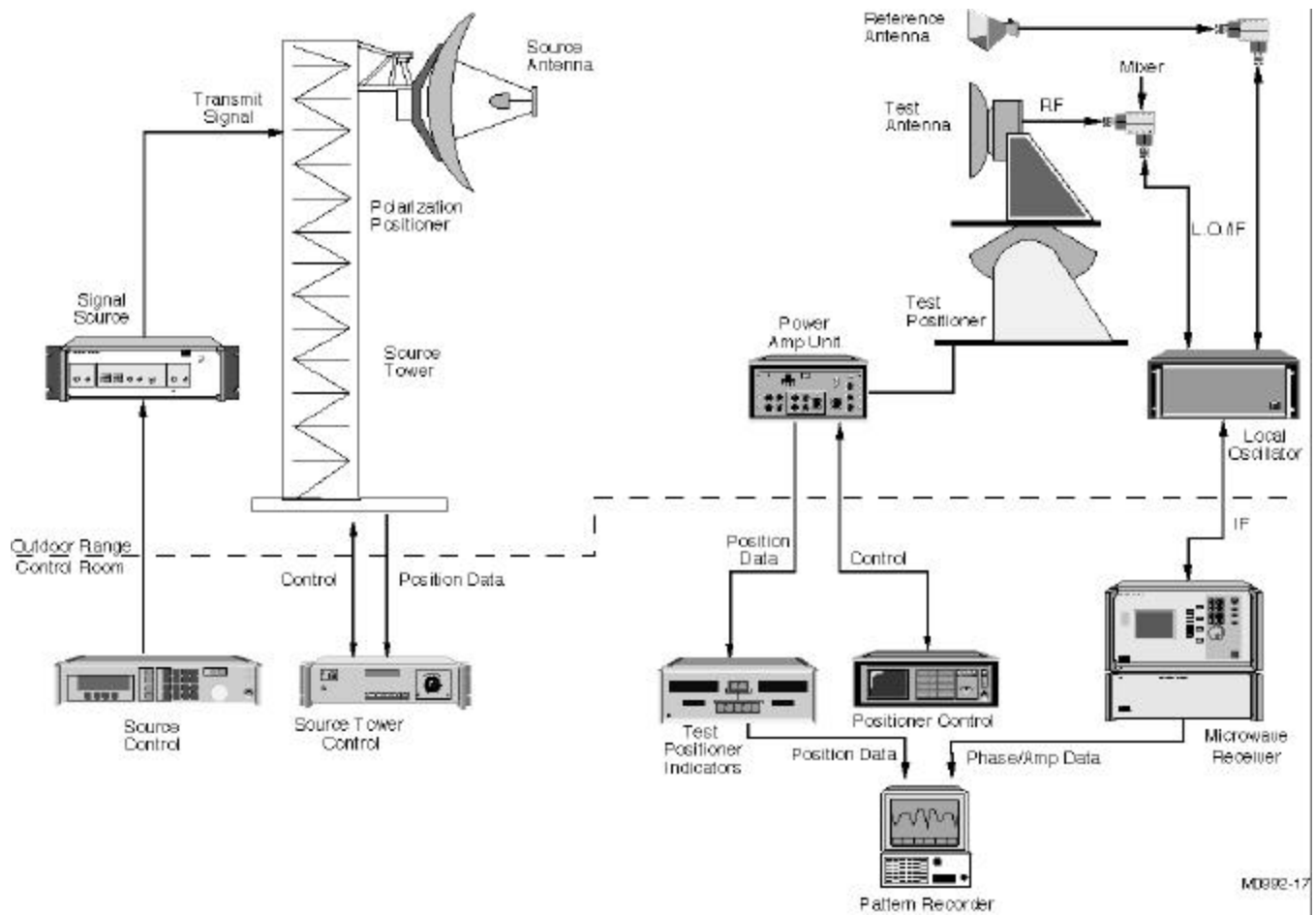
The source antenna is normally located at the opposite end of the range on a tower or other supporting structure. The signal source is installed near the source antenna to minimize signal loss. An outdoor enclosure protects the source from the elements. For some applications a multiplexer can be used between the signal source and a dual polarized source antenna. This configuration allows simultaneous co- and cross-polarization measurements to be performed. Motorized axes to position the source antenna's polarization, height and boresight are controlled by a positioner control and indicator system.

The signal source and positioner axes are remotely controlled from the operator's console via serial digital link(s). Twisted pair cable, fiber optics or telephone lines can be used to interface the digital link from the source site to the control console.

One or two positioner control systems may be used on an outdoor range depending upon the length of the range and the total number of axes to be controlled. On very long ranges, or in cases where the control room is not close to either positioner, it may be advantageous to use a separate control unit for each end of the range. Also, since outdoor ranges frequently have many axes due to the source tower axes, multiple controllers may be required to control all axes.

A block diagram of a typical outdoor range is shown below.





M0892-17

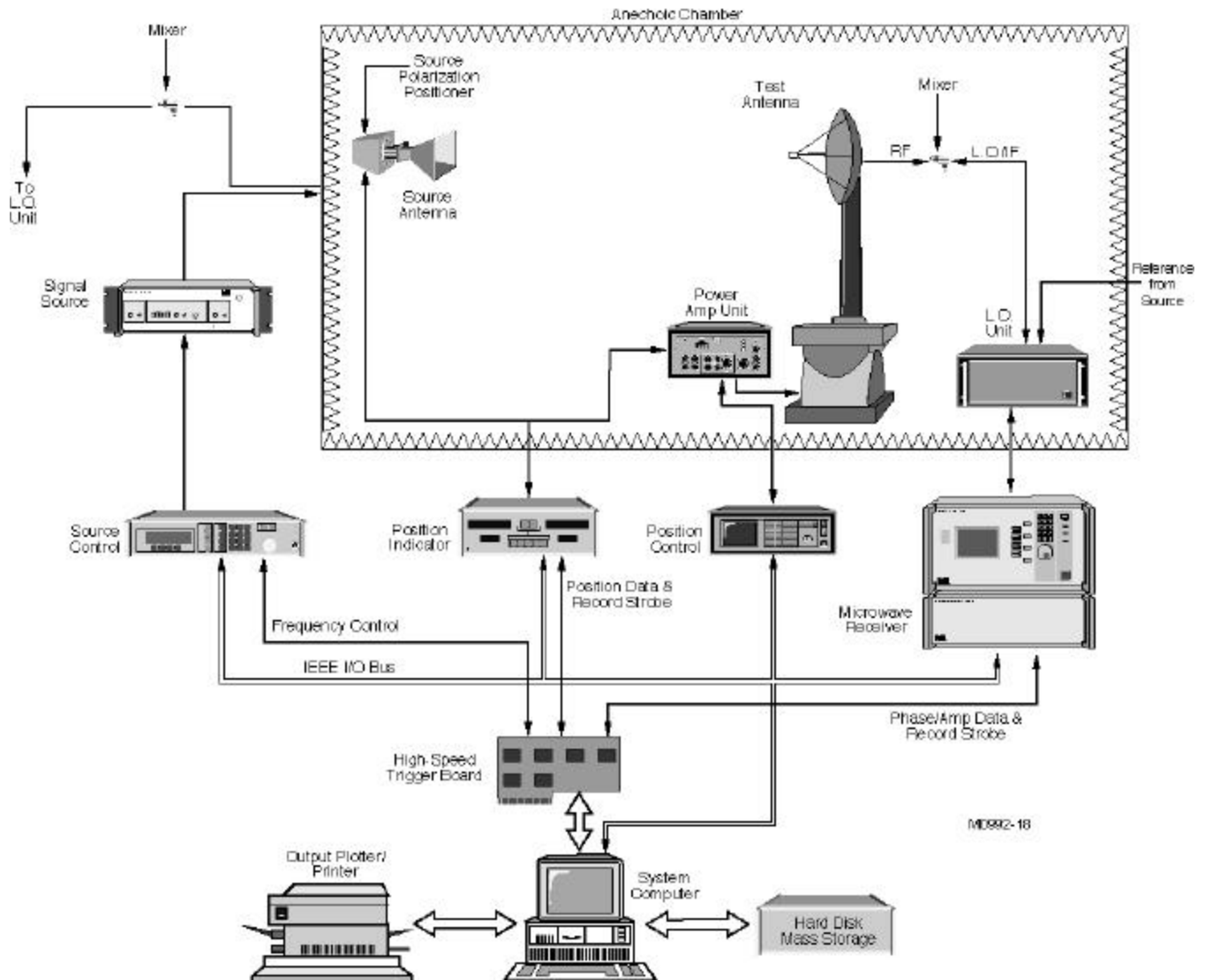
*Outdoor Range with Manual Control'*

## Indoor Far-Field Range

Anechoic Chambers are instrumented essentially the same way as outdoor ranges with range lengths the primary difference. The receiver front end is typically positioned near the test positioner with the mixer connected directly to the test antenna port. The source is located near the source antenna. The control room is generally centrally located and connected to both ends of the range via cables or digital links. Since these systems are located indoors, special enclosures for the receiver front end, positioner control, and signal source subsystems are not required.

Usually the source antenna requires only polarization control. This, as well as the short range length, usually allows a single positioner control unit to be used to control all the range axes.

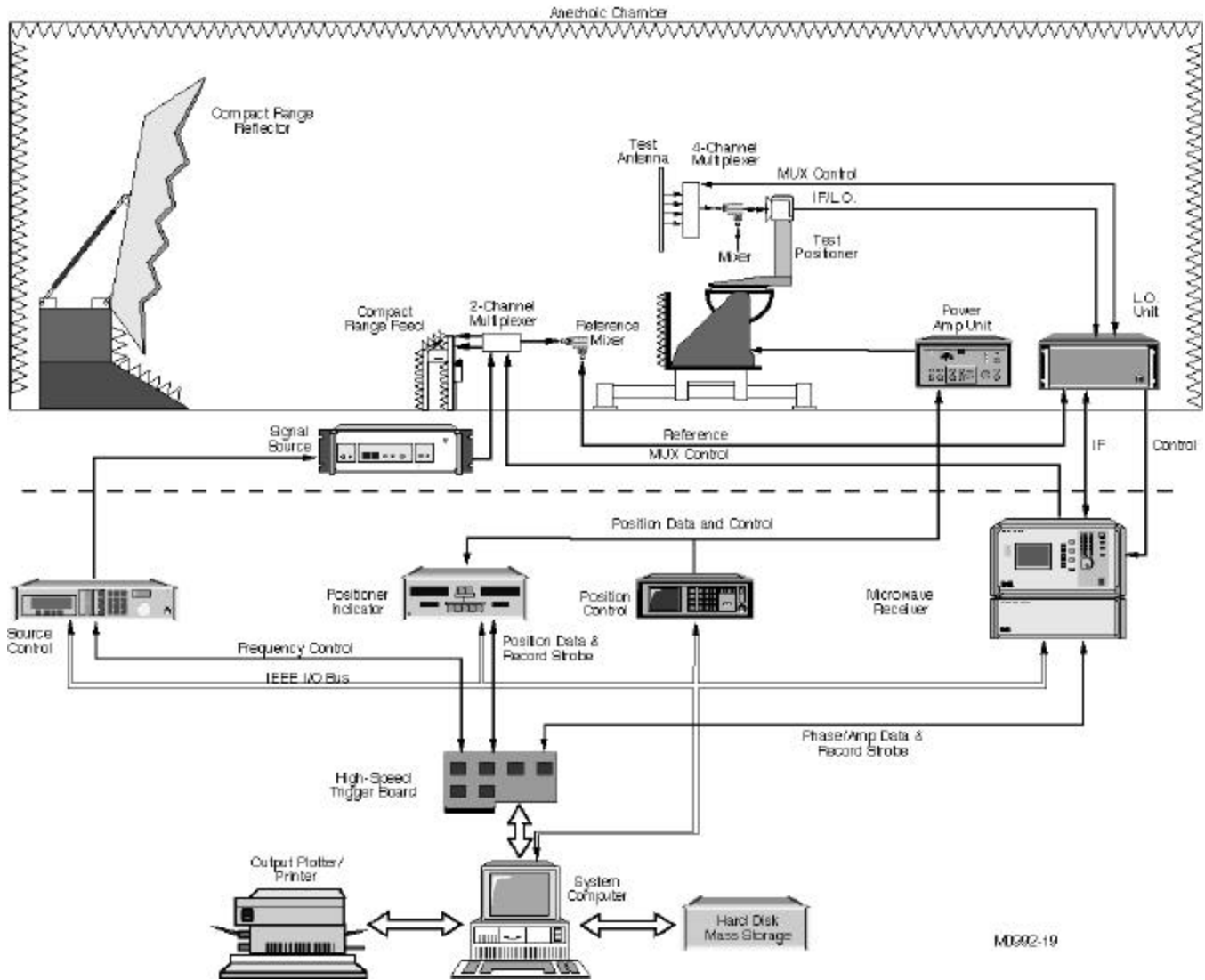
Anechoic chambers can be configured for either manual or automatic control.



*Indoor Range with Automatic Control!*

## Compact Range

In a point-source compact range, the feed is usually located just in front of and below the test antenna. In this configuration the receiver local oscillator and signal source can be located very close together. Special care must be taken to guard against direct leakage of the signal source into the test antenna. High quality RF cables and special shielding are sometimes used to insure against this stray leakage. Otherwise, instrumentation for the compact range is very similar to an anechoic chamber.

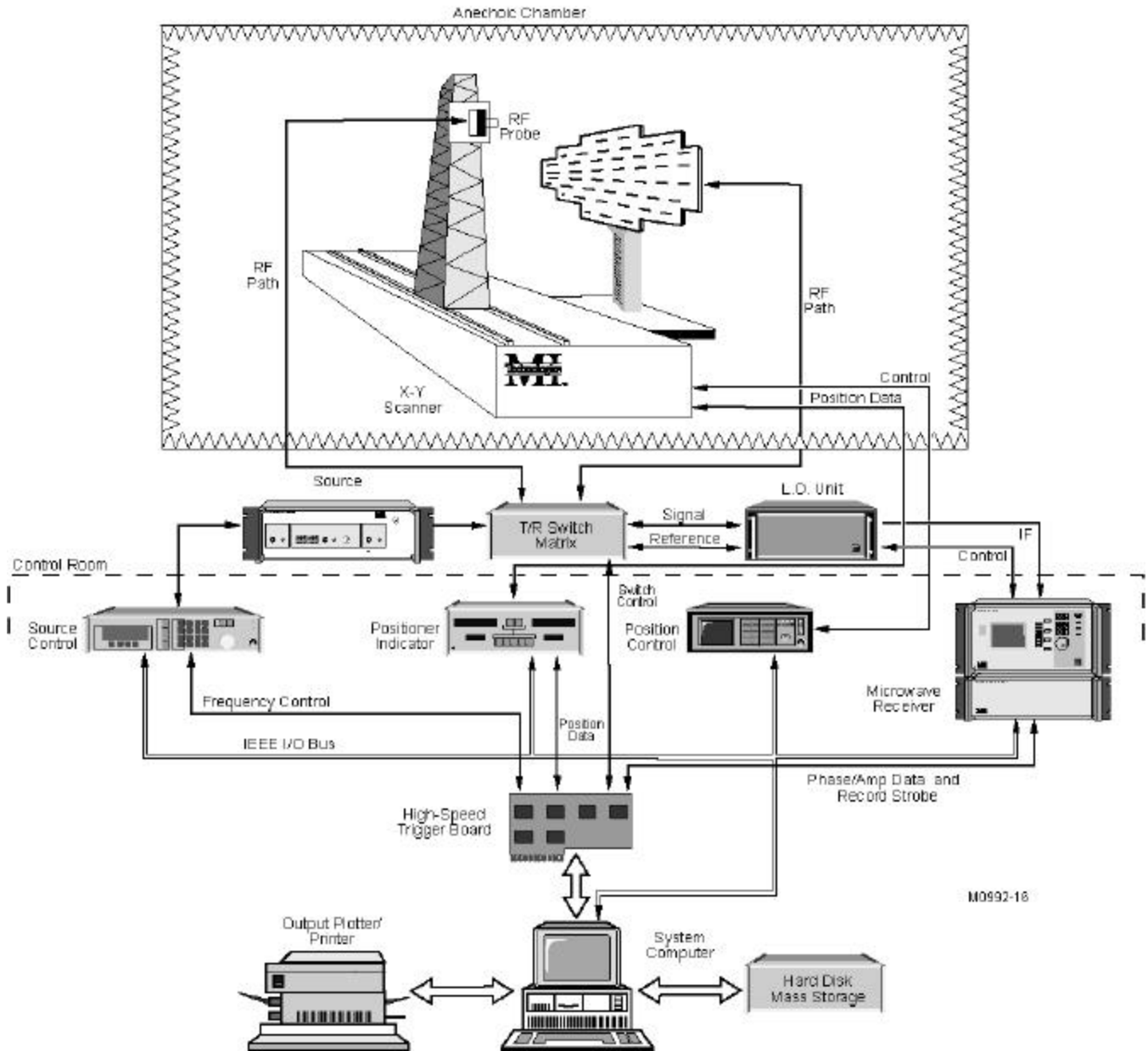


*Compact Range with Automatic Control Configured for Multiple Port Measurements<sup>1</sup>*

## Near-Field Range

Near-field ranges usually are configured for automatic control. The large numbers of measurements required, and the need to transform the near-field data to the far-field, requires the use of a computer system both for data acquisition and for data reduction and display.

The configuration of a near-field range is similar to a very short indoor range. The antenna may be tested in the transmit mode, receive mode, or both. Consequently, the design of the RF system and the location of the source and receiver front end must be considered for each application. The figure below is one example of a planar near-field application where the test antenna is to be tested in both transmit and receive modes.



*A Typical Planar Near-Field Application<sup>1</sup>*

## Conclusions

As technology progresses, the requirements placed upon wireless communication systems and their associated antennas will continue to become more stringent. For example, the desire to increase network capacity will result in the requirement to reduce adjacent channel interference within the system, which will result in more stringent antenna sidelobe and cross-polarization requirements.

The verification of the performance of antennas selected to meet these and other requirements will in turn require test ranges with higher accuracy measurement capability. Fortunately the technologies used to advance the art of antenna design is also being used to advance the design of antenna test and measurement ranges and instrumentation. Many of the simulation tools available to antenna designers is also used to design antenna ranges. The increased use of commercial off-the-shelf hardware and software, in conjunction with the increased use of automated test instrumentation networked into the local area network, will ensure that current state of the art antenna measurement systems will meet the needs of the advanced antennas and systems coming to the wireless market place.

## References:

- [1] Product Catalog, *Microwave Measurements Systems and Product*, Microwave Instrumentation Technologies, LLC.
- [2] R. Hartman and Jack Berlekamp, "Fundamentals of Antenna Test and Evaluation," *Microwave Systems New and Communications Tracking*, June 1988.
- [3] J.S. Hollis, T.J. Lyon, and L. Clayton, eds., *Microwave Antenna Measurements*, Scientific-Atlanta, Inc., 1985.
- [4] R.C. Johnson and Doren Hess, "Conceptual Analysis of Measurements on Compact Ranges," *Antenna Applications Symposium*, September 1979.
- [5] R.C. Johnson editor, *Antenna Engineering Handbook*, McGraw-Hill Inc., 3<sup>rd</sup> edition, 1993.

## Biography

Jeffrey A. Fordham received his BS and MS in electrical engineering from the Georgia Institute of Technology in 1989 and 1990, respectively. He has 10 years experience in the design and evaluation of antennas and systems. Primary antenna design experience has been in the design of space and millimeter wave aircraft antennas, and tracking and communication ground station systems. He joined Microwave Instrumentation Technologies when the company was formed from the test and measurement instrumentation group of Scientific-Atlanta. Current responsibilities include the analysis and design of compact, and near-field antenna test ranges.