An Introduction to Antenna Test Ranges, Measurements and Instrumentation

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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. Each of these characteristics are evaluated using a suitable antenna test range.

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 \( 4\pi \times 1 \) 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 in Figure 2.

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.

A few of the more commonly used antenna test ranges are shown in Figure 1. 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.

Figure 1: Common Antenna Test Range Configurations

![Rectangular Anechoic Chamber](image)

![Compact Antenna Test Range](image)

![Outdoor Elevated Range](image)

![Ground Reflection Range](image)

![Planar Near-Field](image)

![Cylindrical Near-Field](image)

![Spherical Near-Field](image)

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°). 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 $\Delta$ 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 emerging 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 $D$ between the wavefront and the edges of the antenna aperture.

A criterion that is commonly employed in determining the minimum permissible value of range length is to hold $\Delta$ to a maximum of $1/16$ wavelength (equivalent to 22.5° 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:

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

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

The major effect of a small deviation $D$ 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 present.

Variations of the Amplitude of the Incident Field

A second and important sitting 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 ±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 is 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. From the viewpoint of suppressing range surface reflections, it is also desirable to maintain the test height, 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.

**Rectangular Anechoic Chamber**

The most common antenna test range configuration is the rectangular anechoic chamber. This chamber type is configured for far-field measurements and is typically designed to operate at frequencies above 1-2 GHz. The range length is designed to meet the 2*D^2/λ phase taper requirement for the antenna under test, and the walls, floor and ceiling are coated with microwave absorber to minimize reflection into the test zone. This absorber is designed to reduce reflected signal over the chamber’s 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 driving the trend toward more advanced test ranges such as the compact range and near-field ranges.

**Elevated Antenna Test Ranges**

In addition to minimizing phase taper across the aperture of the antenna under test, 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:

\[
\frac{d_t}{4d} \leq \frac{\lambda R}{4d} \quad (2)
\]

(1) Where:
- \(d_t\) = maximum source antenna dimension
- \(\lambda\) = wavelength
- \(R\) = range length
- \(d\) = maximum test aperture dimension

From the point of suppressing range surface reflections, it is also desirable to maintain the test height \(H\), greater than or equal to 6\(D\). If one must, for practical reasons, employ test heights less than approximately 4\(D\), 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 applicable to ground-reflection range geometries are shown in Box 1.

**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. The three most common techniques are the planar, cylindrical and spherical near-field methods.

**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.

Recording and processing of the data are handled using automated antenna measurement systems. These systems offer 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

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![Diagram](image)
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.

A block diagram of a typical outdoor range is shown in Figure 4.

**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.

Anechoic chambers can be configured for either manual or automatic control. A block diagram of a typical indoor far-field range configured for automated control is shown in Figure 5.

**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. See Figure 6.

**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. Figure 7 above is one example of a planar near-field application where the test antenna is to be tested in both transmit and receive modes.

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 Products, Microwave Instrumentation Technologies, LLC.

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.
Performance Counts.

When it comes to testing your antenna products and systems,

Microwave Instrumentation Technologies is the performance leader. More than forty-five years ago we helped define the concept of antenna measurement with the introduction of the first microwave antenna pattern recorder.

Over the years, as a division of Scientific-Atlanta, Inc., we became the leading global supplier of microwave measurement products and systems. We introduced the first commercial planar scanner, the first compact range, the first automatic measurement system and the first spherical near-field measurement system.

Today, we're an independent company – Microwave Instrumentation Technologies, LLC – and our performance as a global supplier of microwave measurement products and systems is still unsurpassed. We're continuing our leadership tradition with world-class products that offer unmatched accuracy, flexibility and speed for component, near field, far field, and compact range measurement applications.

And our customer service – whether for small repairs, turnkey installations, calibrations or range relocations – is second to none.

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