Fall 2019

EECE 588
Lecture 24

Prof. Wonbin Hong

Antenna Measurements

- Antenna measurements involve experimental characterization of the radiation parameters of the antenna.
- These include:
  - Far Field Radiation Patterns
  - Antenna Gain
  - Directivity
  - Input Impedance
  - Radiation Efficiency
  - Polarization
  - Current Distribution
- In what follows, we will study the most popular available measurement techniques for each category.

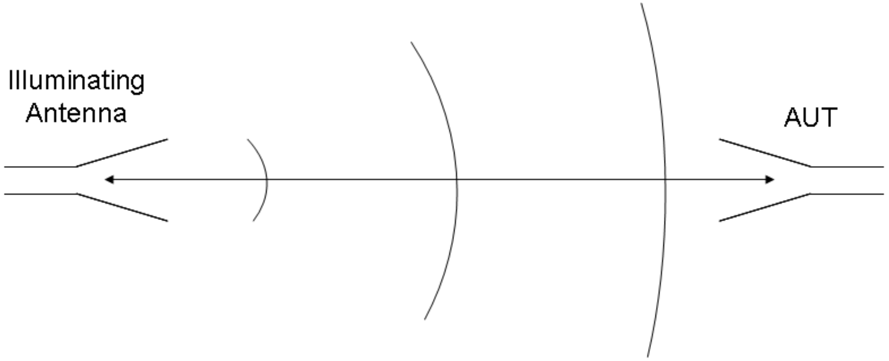
Far Field Radiation Patterns

Reciprocity

- If an antenna is reciprocal, its receiving and transmitting properties are the same.
  - Most antennas are reciprocal.
  - Example of a non-reciprocal antenna: An active antenna integrated with an amplifier.
- Therefore, antenna measurements for a reciprocal antenna can be performed when the Antenna Under Test (AUT) is operating in either transmitting or receiving mode.
  - The measured gain, radiation pattern, etc. are the same in the receive and transmit modes.
- To measure the far field characteristics of AUT, it has to be illuminated with a uniform plane wave if AUT is in a receiving mode.
- This means that AUT must be located in the far field of the illuminating source. The illuminating source is most likely another antenna.

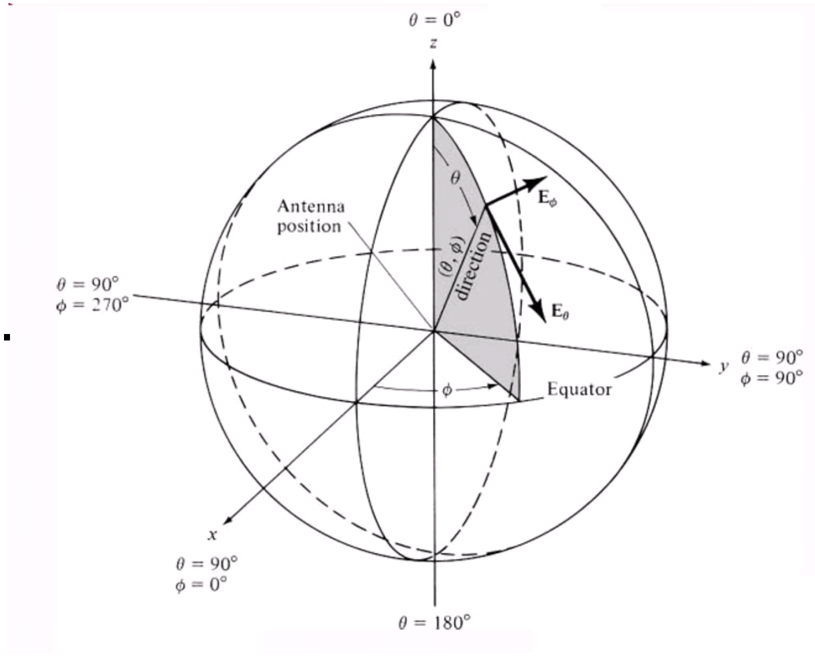
Far Field Characteristics

- If AUT is operating in transmit mode, a receiver antenna should be located in the far field of AUT.
- If the two antennas are located in free space, the radiation patterns of AUT can be measured by placing it in the far field of an illuminating source and measure the power received by AUT.
- AUT can be rotated to measure the power received in different directions (radiation patterns).



Far Field Radiation Pattern Measurements

- Far field pattern measurements: Anechoic chamber, CATR, slanted range, etc.
- The patterns are measured at the surface of a constant radius sphere.
- Any position on the surface of the sphere is identified using the standard spherical coordinate system.



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Free Space?

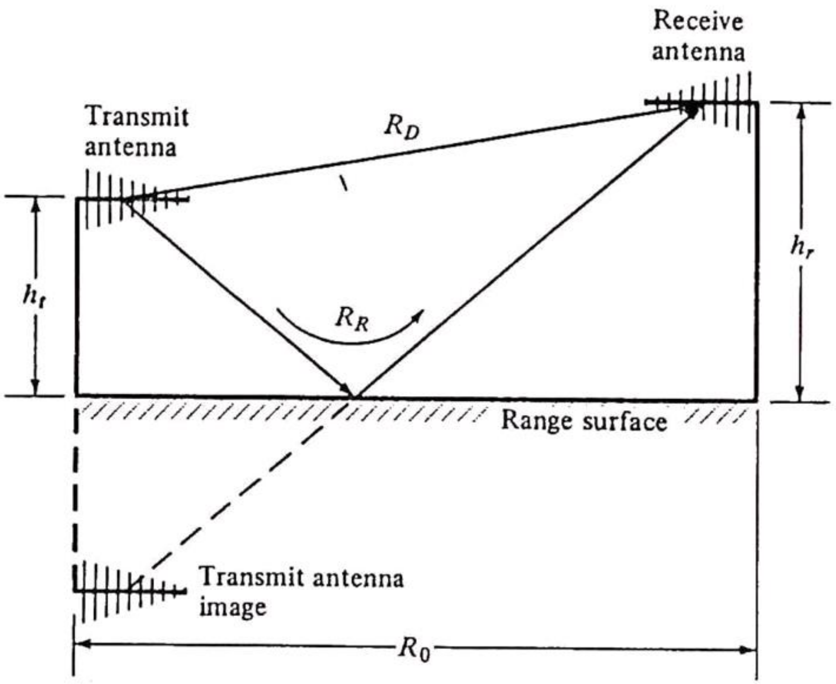
- The main problem with this is that the two antennas cannot be located in free space without the presence of ground, supporting structures, or other scatterers.
- So, what do we do?
- There are a number of conceivable solutions that can be used.
- These include:
  - Antenna Ranges
  - Anechoic Chambers
  - Near-Field, Far-Field Techniques

Antenna Ranges

- Antenna ranges are used to test and evaluate the performance of antennas.
  - Outdoor ranges: Exposed to environment
  - Indoor ranges: limited space
- The following types of antenna ranges are used extensively:
  - Reflection range
  - Free space range

Reflection Ranges

- Signal is received from two paths:
  - Direct and Specular Reflection
- The range can be designed such that these two signals add constructively (arrive with the same phase)
- These ranges are usually outdoor and ground is used as the reflector



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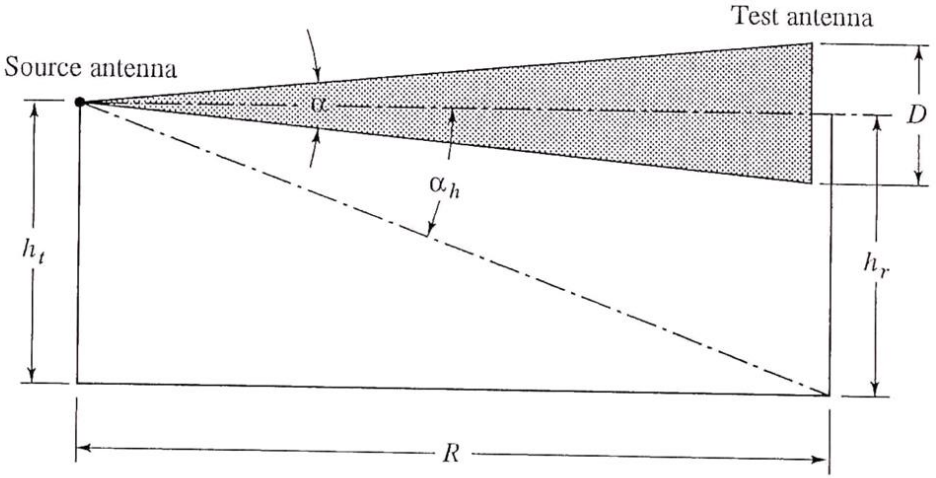
Free Space Ranges

- Free space ranges are designed to suppress the contributions from the surrounding environment.
- Free space ranges include:
  - Elevated Ranges
  - Slant Ranges
  - Anechoic Chambers
  - Compact Ranges
  - Near Field Ranges

Elevated Ranges

- In elevated ranges, the antennas are usually mounted on towers or roofs of nearby buildings.
- Elevated ranges are usually used to test physically large antennas.
- The contributions from surrounding environment (reflection from ground, etc) are minimized by:
  - Controlling the directivity and side-lobe levels of the illuminating antenna.
  - Ensuring that the line of sight between the two antennas is clear.
  - Absorbing energy from unwanted reflections.
  - Using short pulses.



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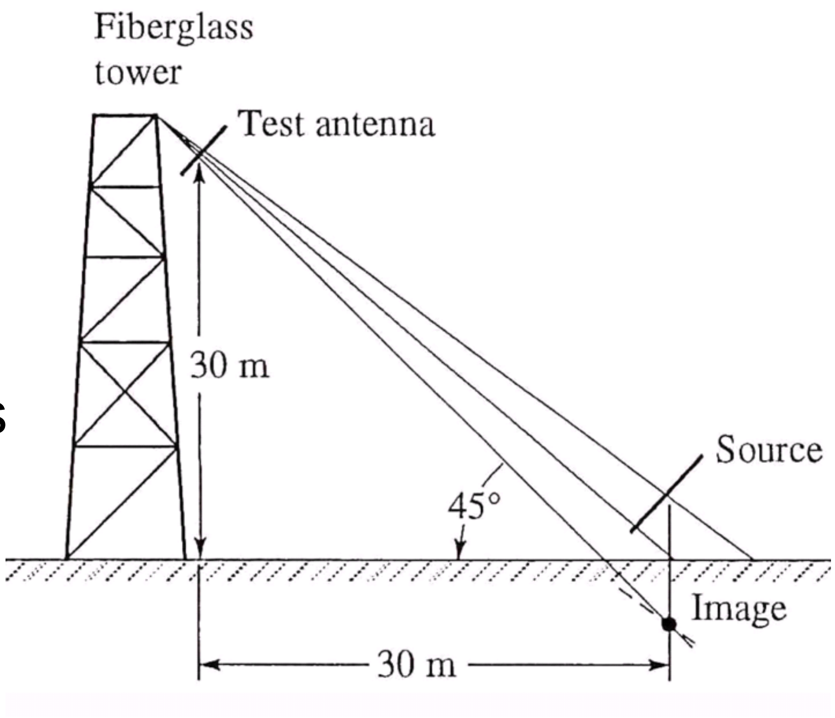
Slant Ranges

- In slant ranges, AUT is mounted on a non-conducting tower.
- The source antenna is located near ground.
- The direction of maximum radiation of the source antenna is oriented towards AUT.
- The first null of the source is usually directed towards the specular reflection point to suppress reflected signals.

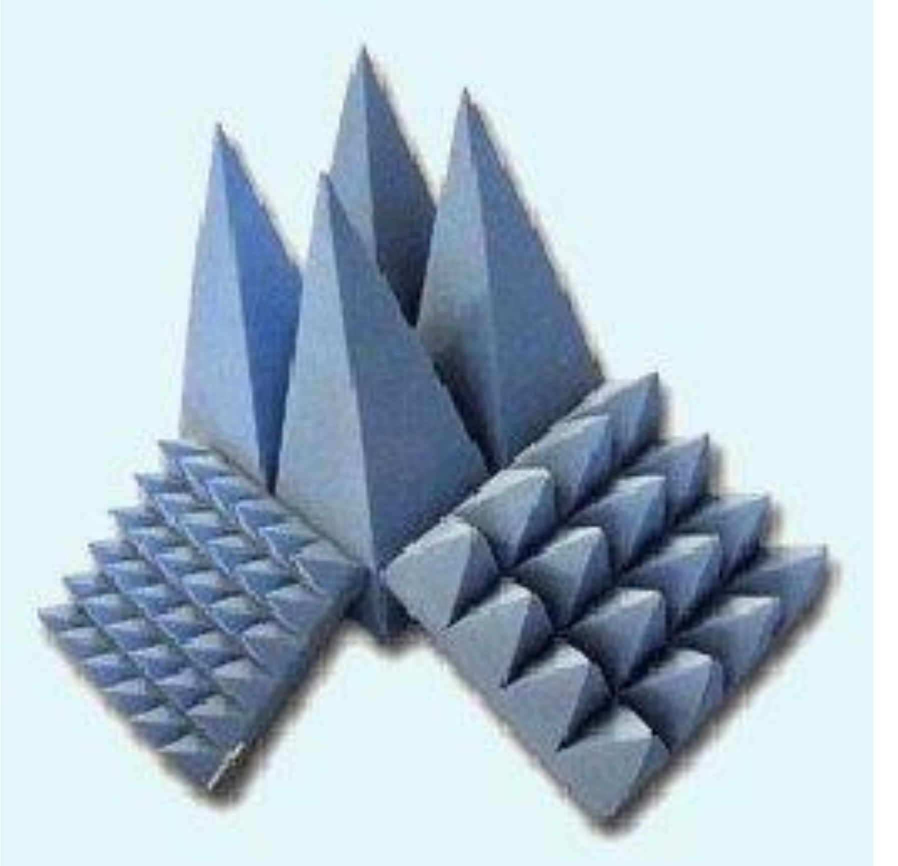


Anechoic Chambers

- Anechoic Chambers are indoor environments that provide a controlled environment and minimize electromagnetic interference.
- An anechoic chamber consist of a large metallic enclosure, whose walls are covered with microwave abrosbing materials.
- The metallic enclosure effectively shields the volume inside the chamber from outside EM interference.
- The important part of anechoic chambers is the RF absorbing materials.
- RF absorbing materials used in anechoic chambers usually provide reflection coefficients better than -40 dB.
    - It means that is an EM wave in incident normally to the surface of RAM, the reflected wave would be 40 dB smaller.

RF and Microwave Absorbing Materials

- Absorbers usually have a pyramidal or wedge shape.
- The absorber shape is optimized for minimizing reflections.
  - Since the material is gradually introduced to the incident wave, reflections are minimized.
- The absorber material is very lossy and dissipates the energy of the incident EM wave.



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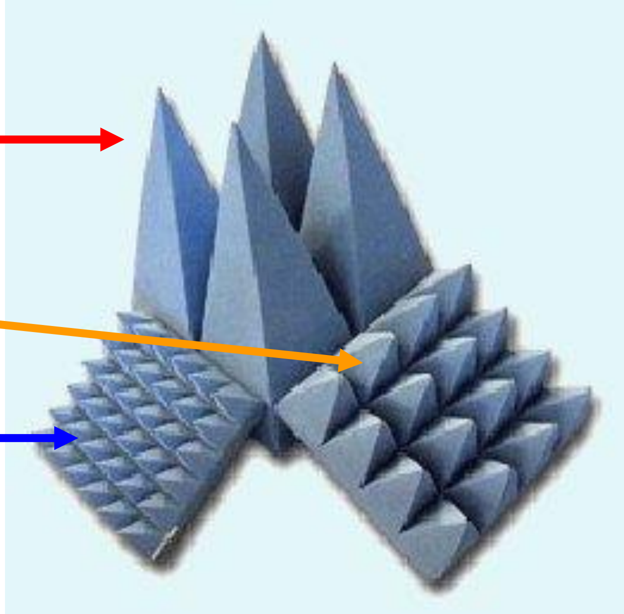
RF and Microwave Absorbing Materials

- The size of the absorber determines its lowest frequency of operation.
  - At lower frequencies, the wavelength is larger.
  - Therefore, a larger absorber must be used.
  - Usually absorbers that perform well at low frequencies, perform well at high frequencies as well.
  - The reverse is not true!

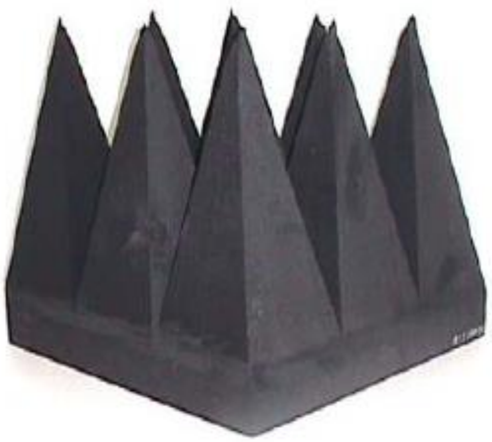
Low, Lowest Frequency of Operation

Intermediate, Lowest Frequency of Operation

Higher, Lowest Frequency of Operation



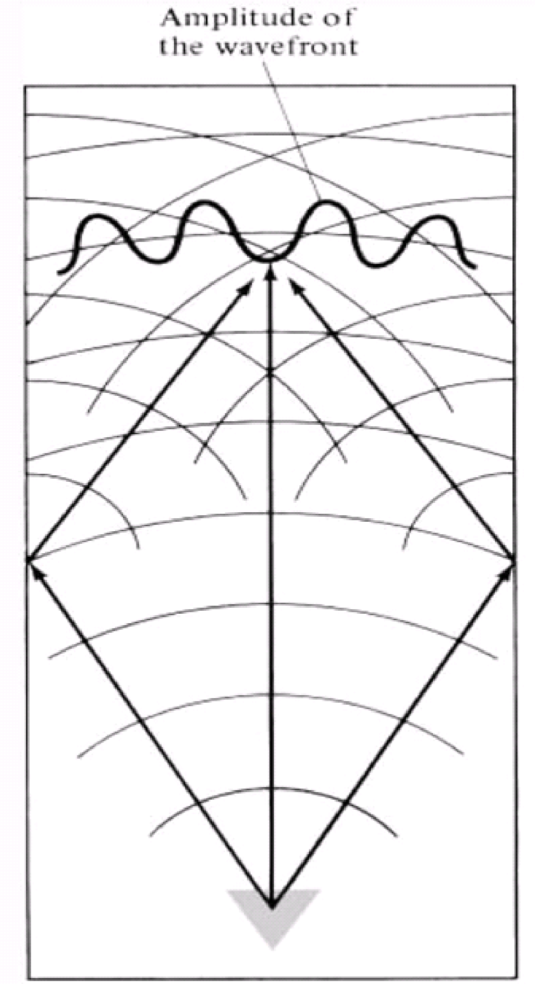
Anechoic Chamber



- There are two basic types of anechoic chamber designs:
  - The Rectangular Chamber
  - The Tapered Chamber
- The design of each chamber is based on the geometrical optics techniques.
- Each chamber attempts to reduce or minimize specular reflection:
  - The rectangular chamber is usually designed to simulate free space conditions and maximize the volume of the quite zone.
  - The pattern and location of the source and the frequency of operation must be taken into account.
  - It is also assumed that the receiving antenna at the test point is isotropic

Anechoic Chambers

- Reflected energy can be minimized by the use of high quality RF absorbers.
- Even though RAM is used, still significant reflections can occur, especially at large angles of incidence.
- Remember that as the angle of incidence of the EM wave in increased (from normal), the performance of the RAM is degraded.
  - i.e., its reflection coefficient is increased.



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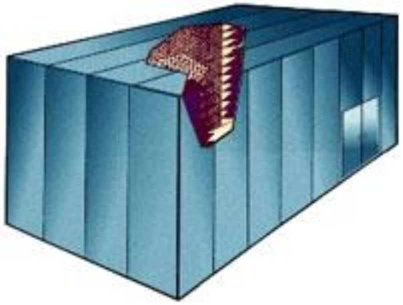
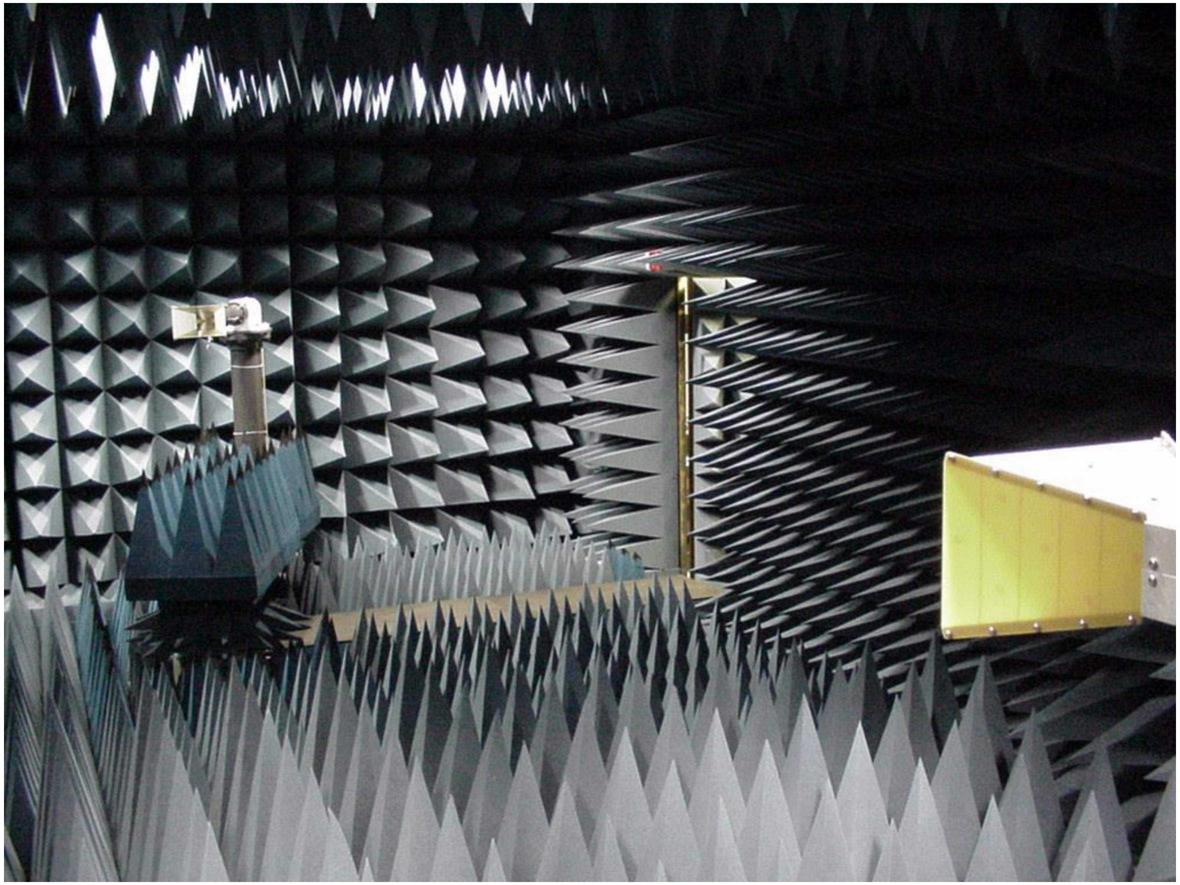
Rectangular Anechoic Chamber



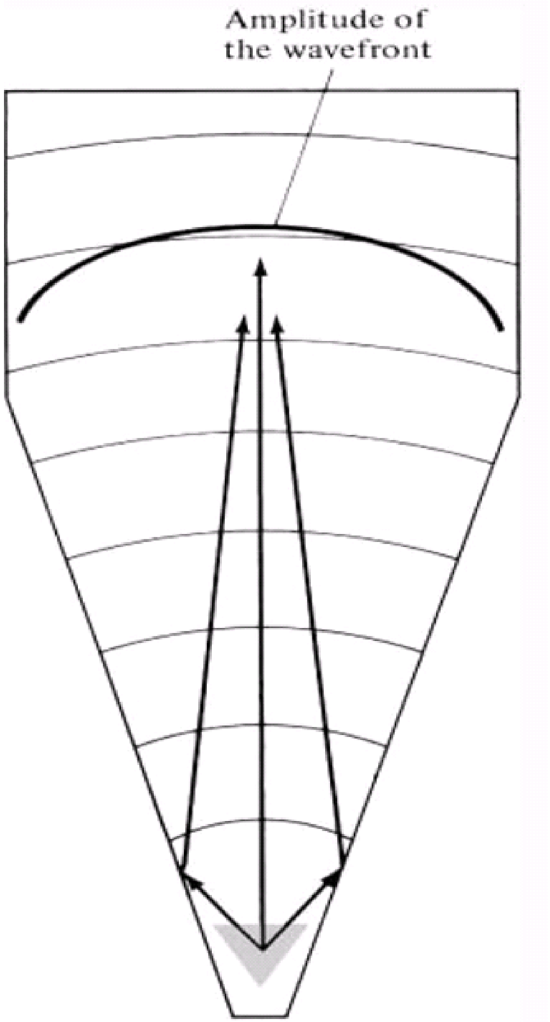
Outside

Inside



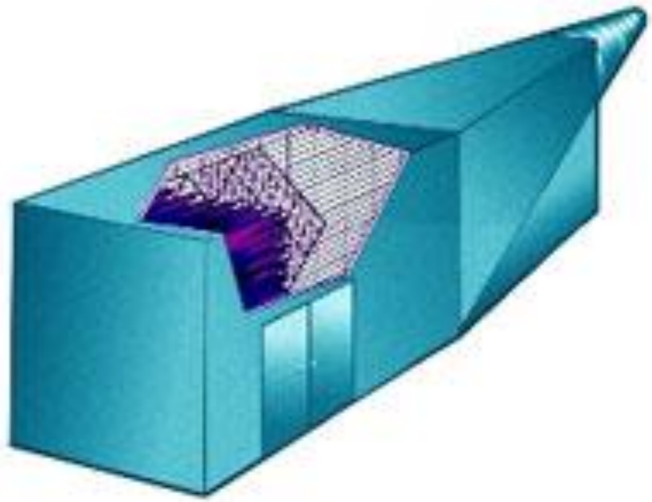
Tapered Anechoic Chamber

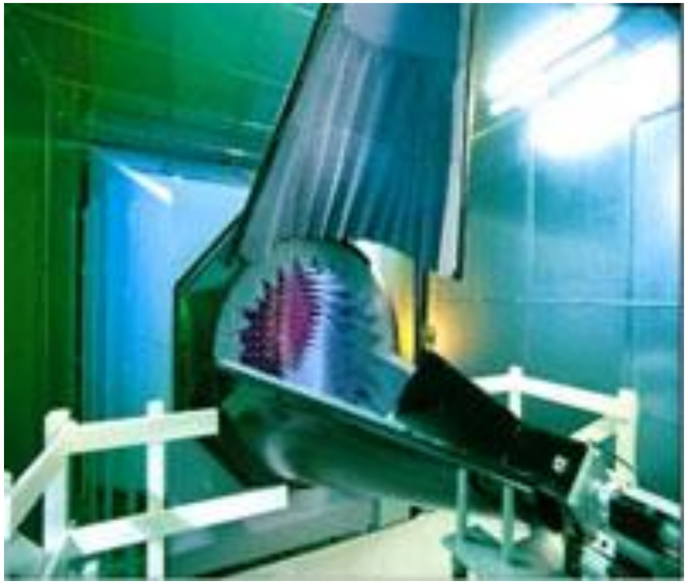
- Tapered anechoic chambers take the form of a pyramidal horn.
- The chamber begins with a tapered chamber that leads to rectangular configuration at the end.
- At low frequencies, the source is placed near the apex.
- This way, the reflections from the side walls occur close to the source.
- Therefore, the phase difference between the direct path and the reflections is minimized.



Tapered Anechoic Chambers

- This way, a smooth illumination taper is obtained.
- At higher frequencies, it becomes difficult to place the source sufficiently close to the apex.
- At such frequencies, a high gain antenna is usually used and the source is placed inside the chamber closer to the rectangular region





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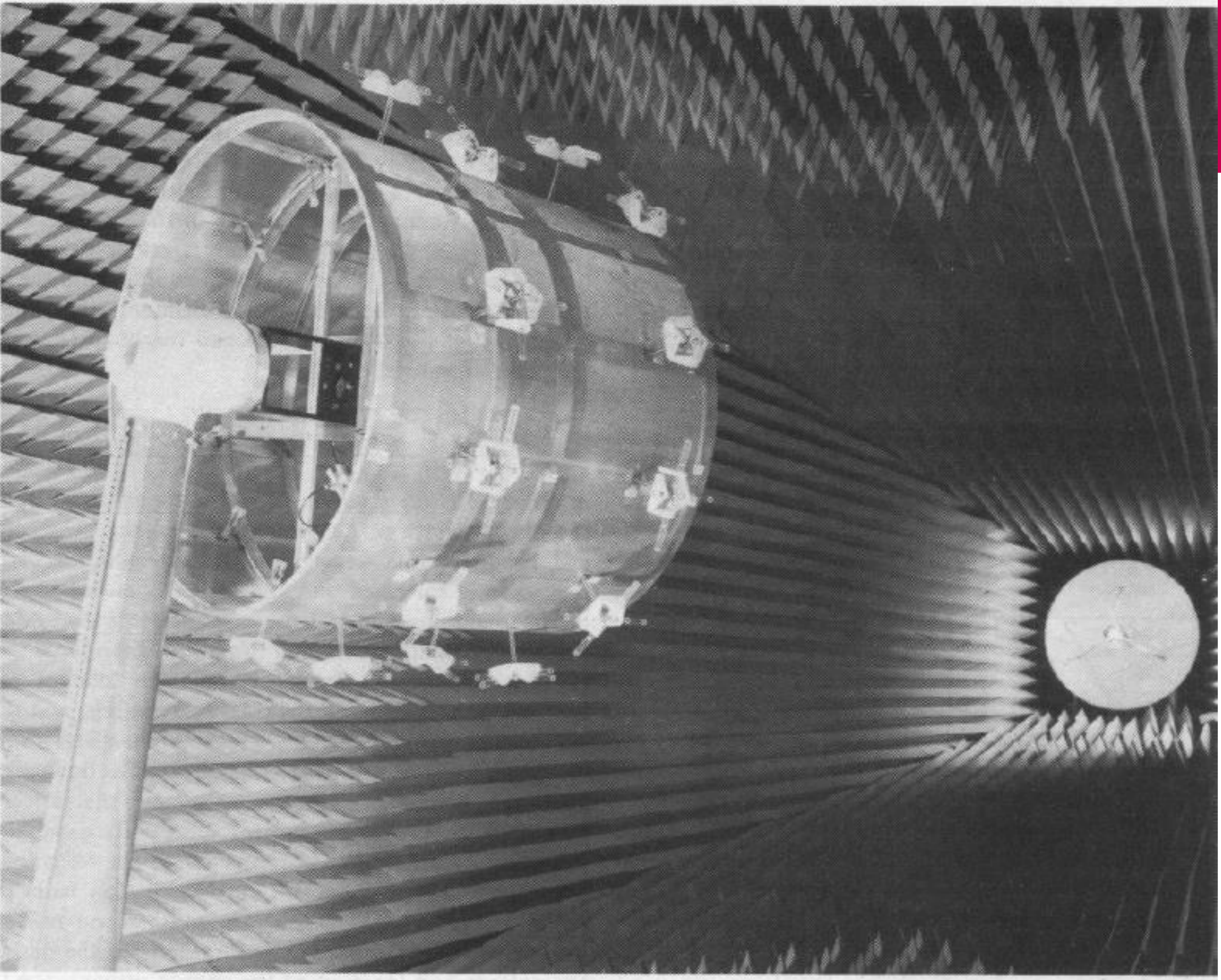

Fig. 5. Large tapered anechoic chamber (courtesy the Aerospace Corporation).

Anechoic Chambers

- Bandwidth of the chamber is a function of:
  - Far field requirements
  - Maximum dimension of AUT
  - The size of the quite zone that is desired
  - Types of absorbers
- The antenna under test must be in the far field of the illuminating antenna.
- Generally chambers operating at low frequencies tend to be quite large.

The Ultimate Anechoic Chamber

Benefield Anechoic Facility, Edwards Air Force

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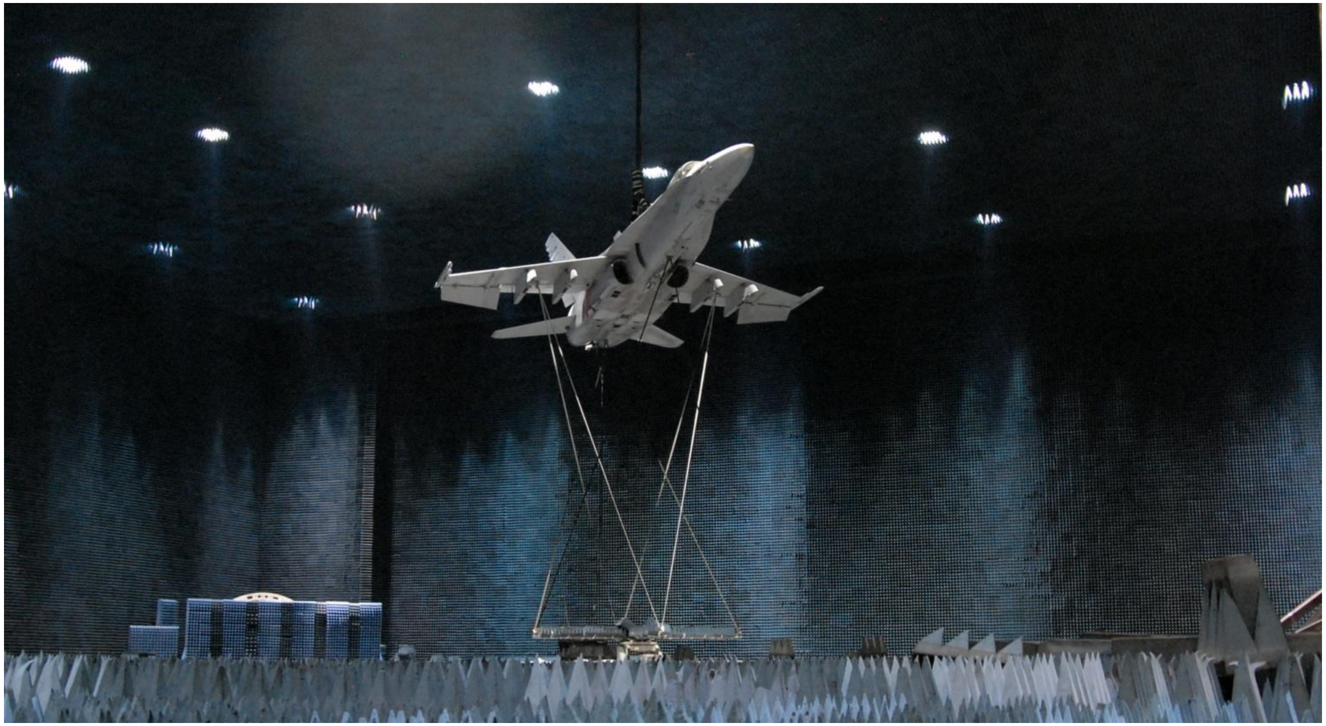
The Ultimate Chamber

- The largest in the world:
  - 250 x 264 x 70-foot steel plate box enclosed in a metal hangar building.
  - The walls, ceiling, and floor are covered in 816,000 pyramidal foam cones.
  - Equipped with a turntable (160 feet in diameter) capable of carrying objects weighing up to 1 million pounds.
  - The turntable can rotate 360 degrees and has two hoists each with a 40-ton capacity.

The Ultimate Anechoic Chamber

- The 772nd Test Squadron, together with Naval Air Weapons Station China Lake, conducts full antenna pattern testing on a Navy F/A-18 Hornet at the Benefield Anechoic Facility here Jan. 22. The purpose of the antenna test is to evaluate how the entire F-18 system affects antenna pattern and what parts of the aircraft can significantly change the pattern.The team completed testing Jan. 22. (Air Force photo by Senior Airman Julius Delos Reyes)



The Ultimate Anechoic Chamber

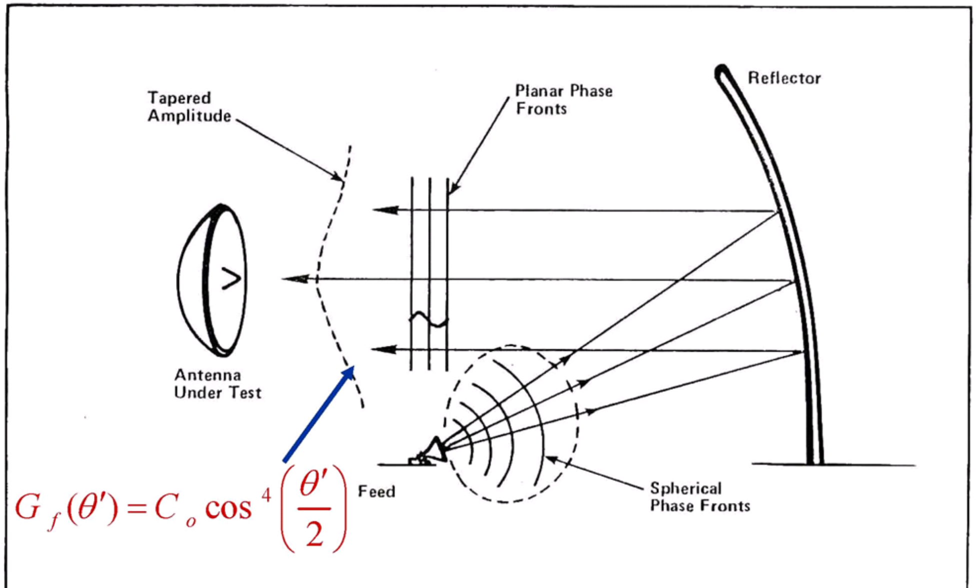
The Ultimate Anechoic Chamber

Compact Ranges

- Antenna measurements require that the AUT is illuminated by a uniform plane wave.
- This is achieved in the far field region of an antenna, which usually requires a large distance.
- A Compact Antenna Test Range (CATR) is a collimating device, which generates nearly planar wave fronts in a very short distance compared to the $2D^2/\lambda$.
- In a CATR, one or more curved metal reflectors are used to perform the collimating function.
- CATRs are basically very large reflector antennas designed to optimize the planar characteristics of the fields in near field of the aperture.

Compact Ranges

- A source antenna is used as an offset feed, which illuminates a paraboloidal reflector.
- The paraboloidal reflector converts the spherical waves to plane waves.
- The EM wave reflected from the reflector is a plane wave.



COMPACT RANGE SCHEMATIC

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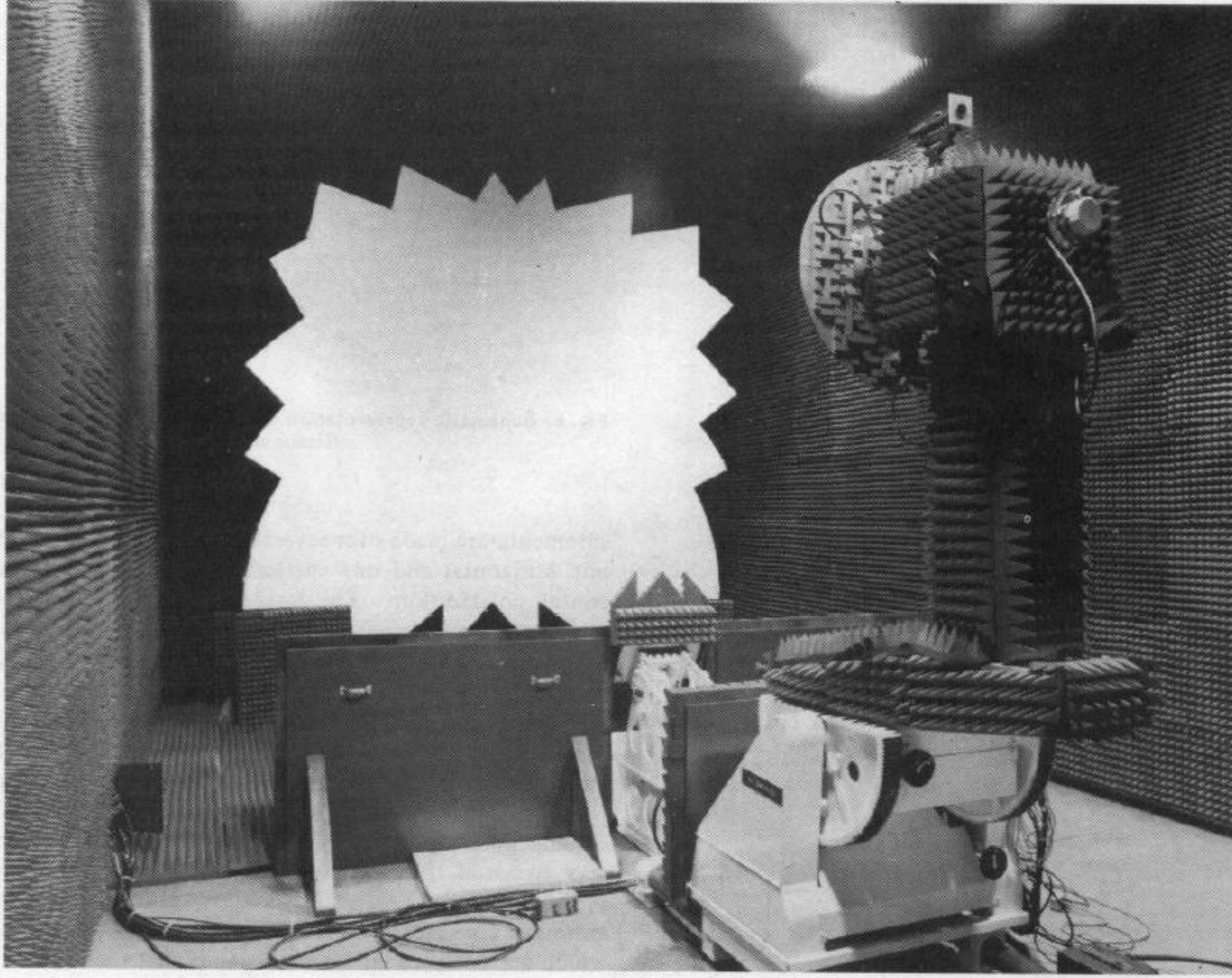


Fig. 9. Example of a compact range (courtesy Hughes Aircraft Co.).

Compact Ranges

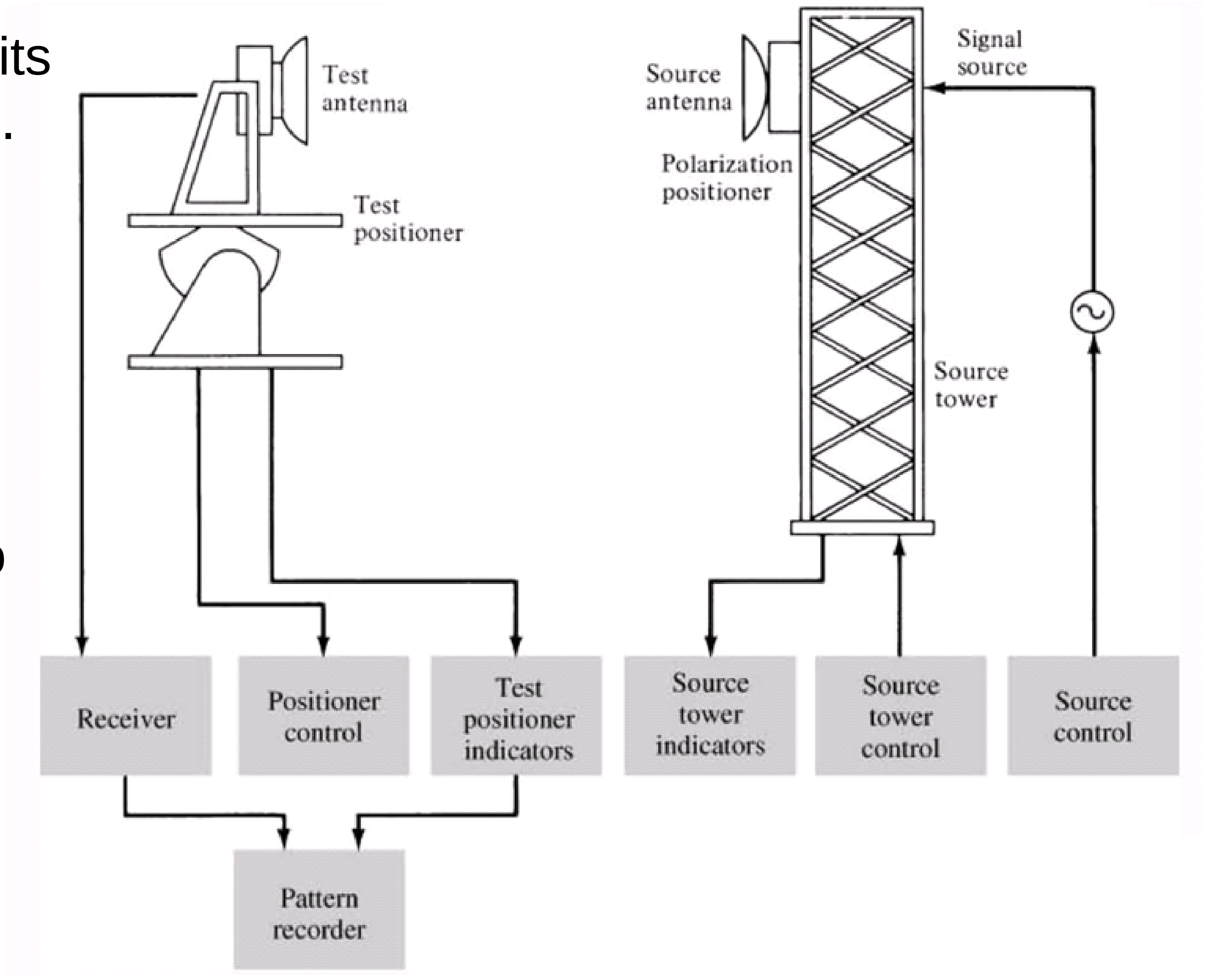
- Drawbacks of CATRs:
  - Aperture Blockage
  - Diffractions from the edges of reflector
  - Depolarization coupling between the two antennas
  - Direct radiation from the source antenna to AUT
- Solutions:
  - Offset feeds eliminates aperture blockage and reduces edge diffractions.
  - Direct radiation and diffractions can be reduced further if a reflector with long focal length is chosen.
    - This way, the feed can be mounted below the AUT
    - Also, this reduces the depolarization effects usually caused by the curved surfaces

Far Field Pattern Measurement Instrumentation

- Pattern measurement as a function of θ and φ for a constant radial distance
- Measurement can be done either in receiving or transmitting modes (if the antenna is reciprocal).
- Necessary instruments:
  - Source antenna and TX system
  - Receiving system
  - Positioning system
  - Recording system
  - Data-processing system

Far Field Pattern Measurement Instrumentation

- Source antenna transmits a CW microwave signal.
  - Signal generator
  - Network Analyzer, etc.
- The receiver antenna receives this signal.
- A detector connected to the AUT detects the power of this signal.
  - Power meter
  - Spectrum analyzer
  - Network Analyzer



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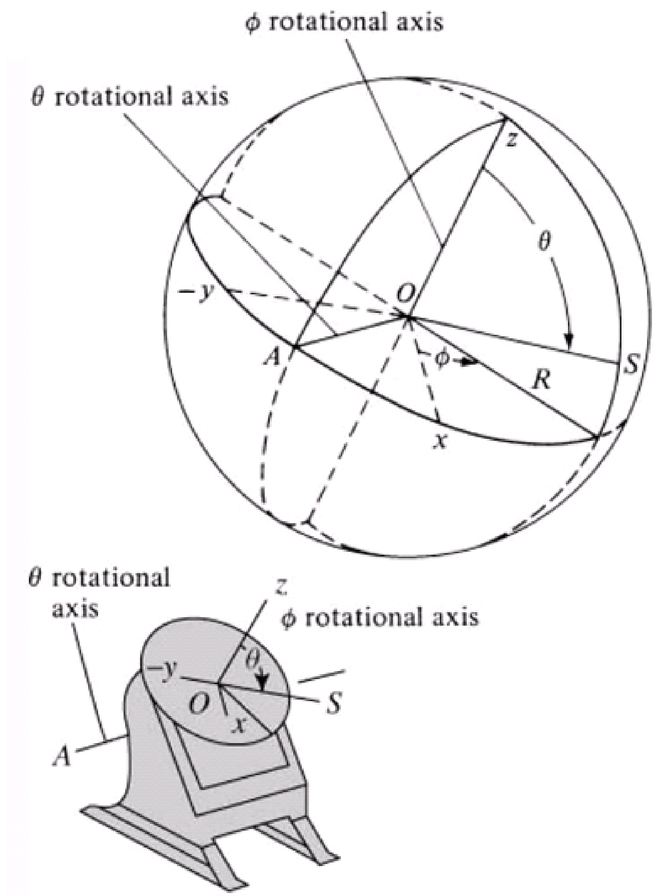
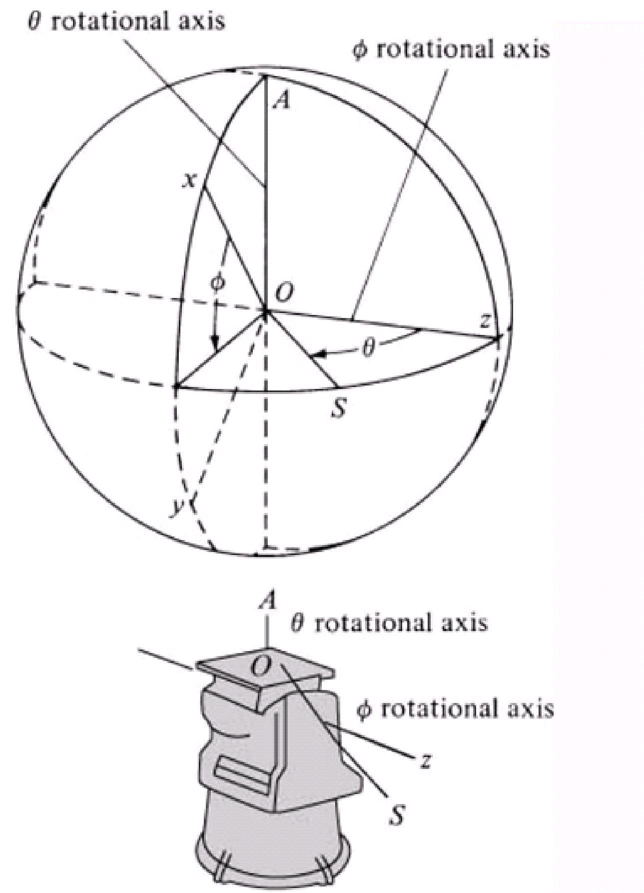
Far Field Pattern Measurement Instrumentation

- AUT is then rotated and this process is repeated in a 360° range for a finite number of angles.
  - In the azimuth plane φ=0-360°
  - In the elevation plane, from θ=0° to 180°
- AUT is mounted on a positioner.
  - one, two, or three axes of rotation.
- The measured data are recorded in a computer
  - This computer controls the system and the movement of the positioner, etc.
- Many anechoic chambers are fully automatic.
- In small anechoic chambers, a vector network analyzer can be used both as a transmitter and a receiver
  - one port connected to the TX antenna and the other one to the RX

Far Field Pattern Measurement Instrumentation

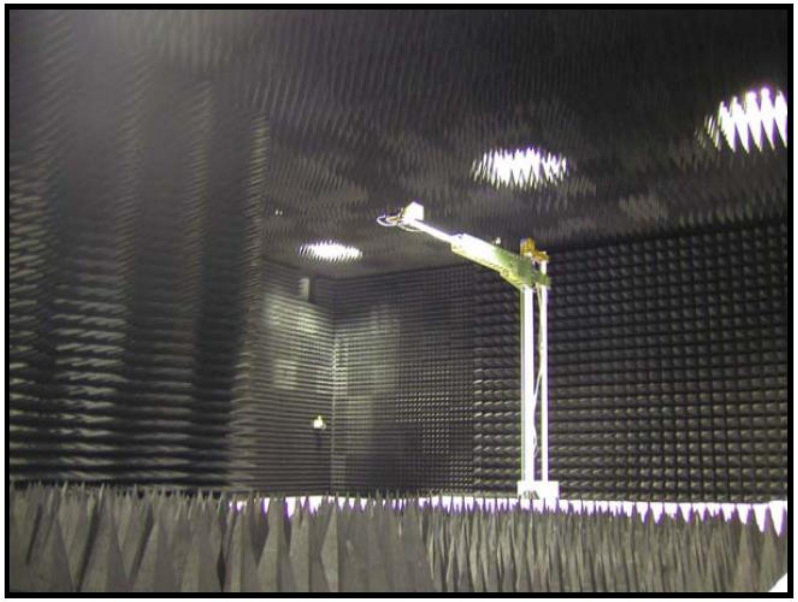


Azimuth-over-Elevation Positioner

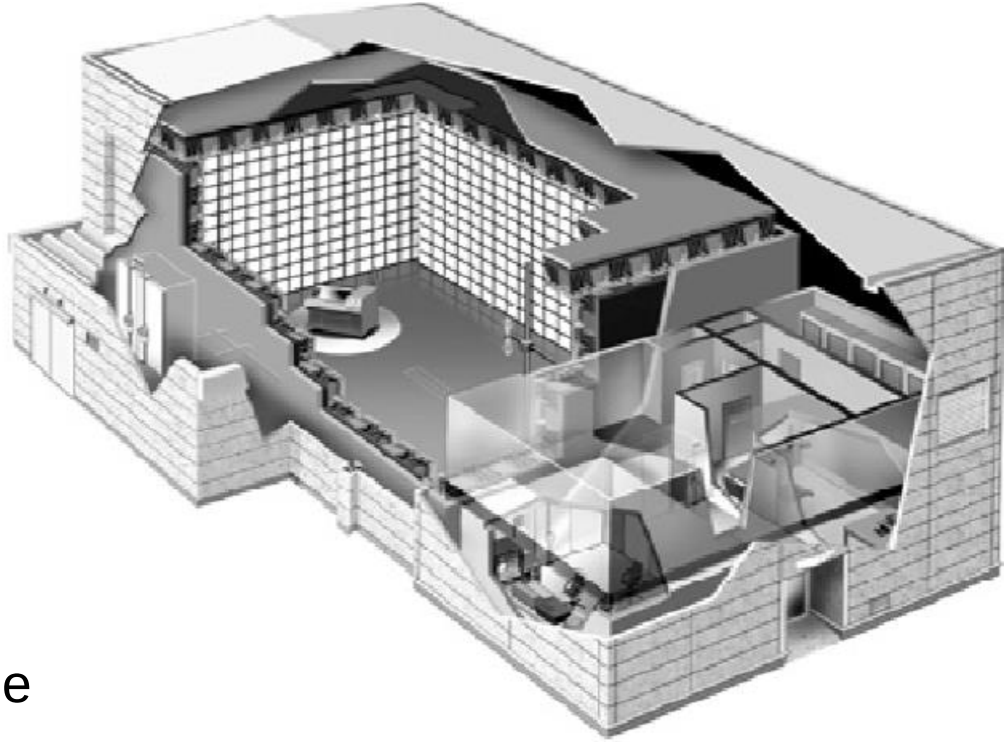


Elevation-over-Azimuth Positioner

Far Field Pattern Measurement Instrumentation



A large anechoic chamber with the antenna positioner.



A typical modern antenna measurement facility that includes an anechoic chamber and the measurement room.

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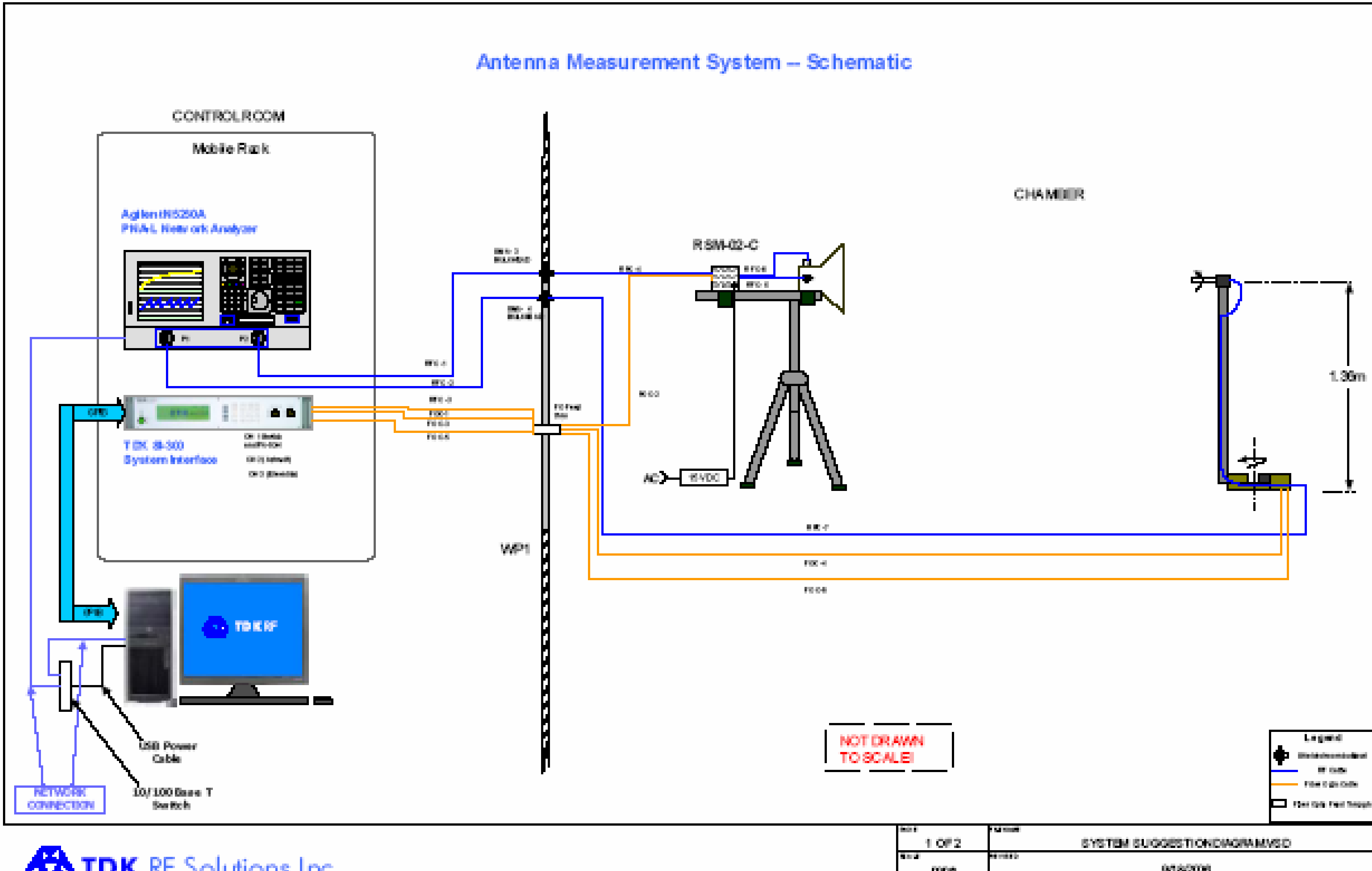
Far Field Pattern Measurement Instrumentation



TDK RF Solutions Inc.

Far Field Pattern Measurement Instrumentation

Antenna Measurement System -- system components

2 OF 2	SYSTEM SUGGESTION DIAGRAM VSD
none	9/10/2005

Near Field/Far Field Measurements

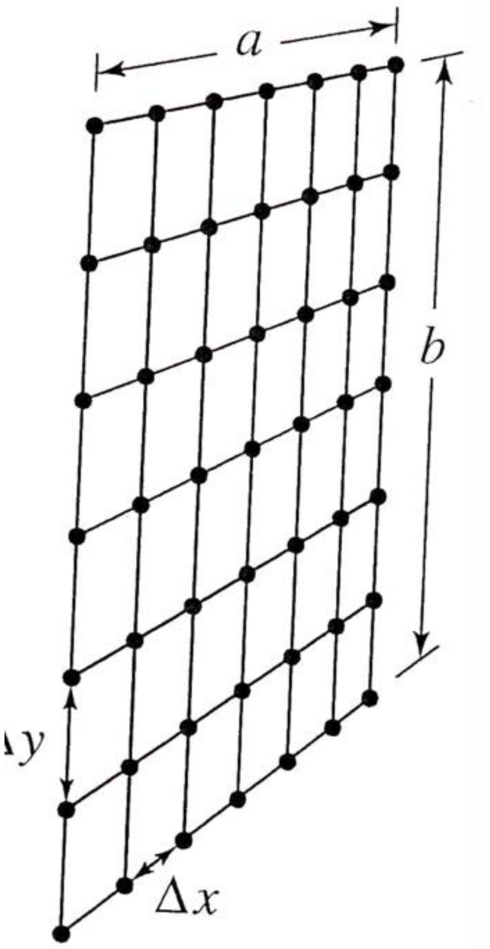
- **Near-field radiation pattern measurements:**
  - Is a popular measurement technique.
  - Could be an alternative to the far field measurement techniques.
- **Very useful for relatively large antennas**
  - Far-field distance ($2D^2/\lambda$) becomes prohibitively large
  - Far-field measurements cannot easily be done
- **Circumvents Other Problems:**
  - reflections from scatterers
  - mechanical movements of very large and heavy antennas

Near Field/Far Field Measurements

- **The method is based on measuring:**
  - the amplitude AND phase of the electric field in the vicinity of AUT.
- **Remember uniqueness theorem:**
  - Fields everywhere outside a closed surface can be obtained if the tangential component of the electric field is known over the surface of that closed surface.
- **Near field techniques:**
  - Mostly used to measure the radiation patterns
  - Require more complex and expensive systems
  - More extensive calibration procedures
  - More sophisticated computer software

Near Field/Far Field Measurements

- **Three main configurations**:
  - Planar
  - Cylindrical
  - Spherical
- **Each configuration specifies a surface of the coordinate system over which the probe of the near field system is scanned**
- **Planar configuration:**
  - the probe is moved on a rectangular grid at a fixed distance from the center of the radiating element to map the near field



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Near Field/Far Field Measurements: Rectangular

- **The scanned area should extend to infinity**
  - Necessary to measure the pattern precisely
  - In practice only a portion of the infinite plane can be scanned
  - Therefore, only an approximate pattern can be reconstructed.
- **The planar near-field configuration**:
  - most appropriate for antennas with high gain and narrow beam
  - Therefore, the scanned area can be confined to a relatively small area around the antenna boresight.
- **In the cylindrical scanning configuration data are collected on the surface of a cylinder with the test antenna at the center.**

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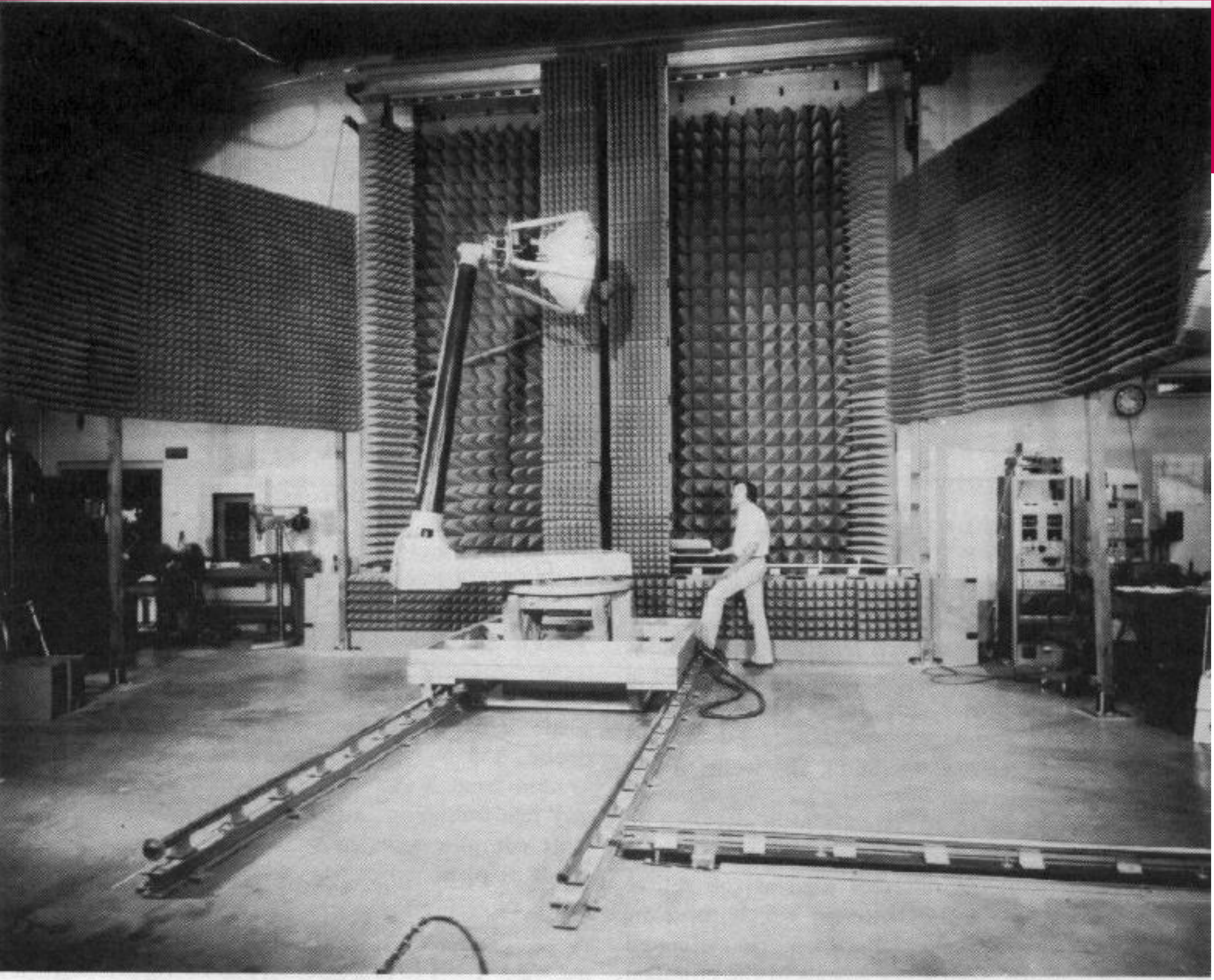
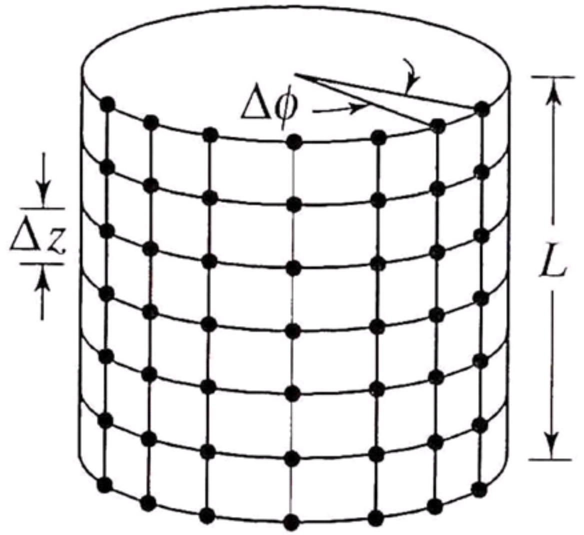


Fig. 12. Planar near-field measuring system (courtesy National Bureau of Standards, Boulder, CO).

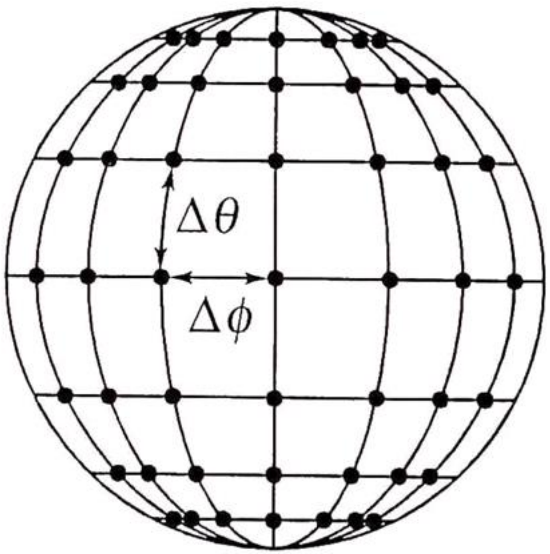
Near Field/Far Field Measurements: Cylindrical

- Probe is moved parallel to the cylinder axis
- After a complete vertical scan the antenna under test is rotated about the cylinder axis by a small angle Δφ
- Repeating this process many times (N =2π/ Δφ), the tangential electric field over a cylindrical grid with resolution (Δz, ρ Δφ) can be measured.
  - This acquisition scheme is useful for antennas with wide azimuthal and narrow vertical beams.
  - Similar to the planar configuration, in cylindrical scanning the probed area in the vertical direction should be confined to a finite range over which the field strength is significant



Near Field/Far Field Measurements: Spherical

- Field samples are collected at a fixed distance (r_0) from the antenna radiation center (phase center).
- In practice the sampling is accomplished by moving the probe on a constant φ-arc and by rotating the antenna under test.
- This configuration is the most sophisticated one among the three mentioned schemes.
    - However, it has the advantage of mapping the entire closed surface which allows accurate reconstruction of far-field over the entire 4π solid angle around the antenna



Near Field/Far Field Measurements

- The accuracy in characterization of radiation pattern of an antenna is influenced by the following parameters of the measurement setup:
  - Spatial resolution of the scanned grid
  - Probe distance from the aperture of the antenna under test
  - Extent of the probed area
  - Precision in positioning the probe
  - Accuracy in amplitude and phase measurements
  - Temporal stability of the measurement system

Near Field/Far Field Measurements

- The measurement accuracy can be improved by
  - Increasing the sampling rate and number of sampled points
  - Increasing the probe distance from the antenna aperture.
- These, all require longer measurement time.
- This leads to a trade-off between cost and accuracy.
- Depending on the antenna configuration, size, frequency, and the desired information regarding the radiation characteristics of an antenna, there are also trade-offs between near-field and far-field measurements.

Near Field/Far Field Measurements

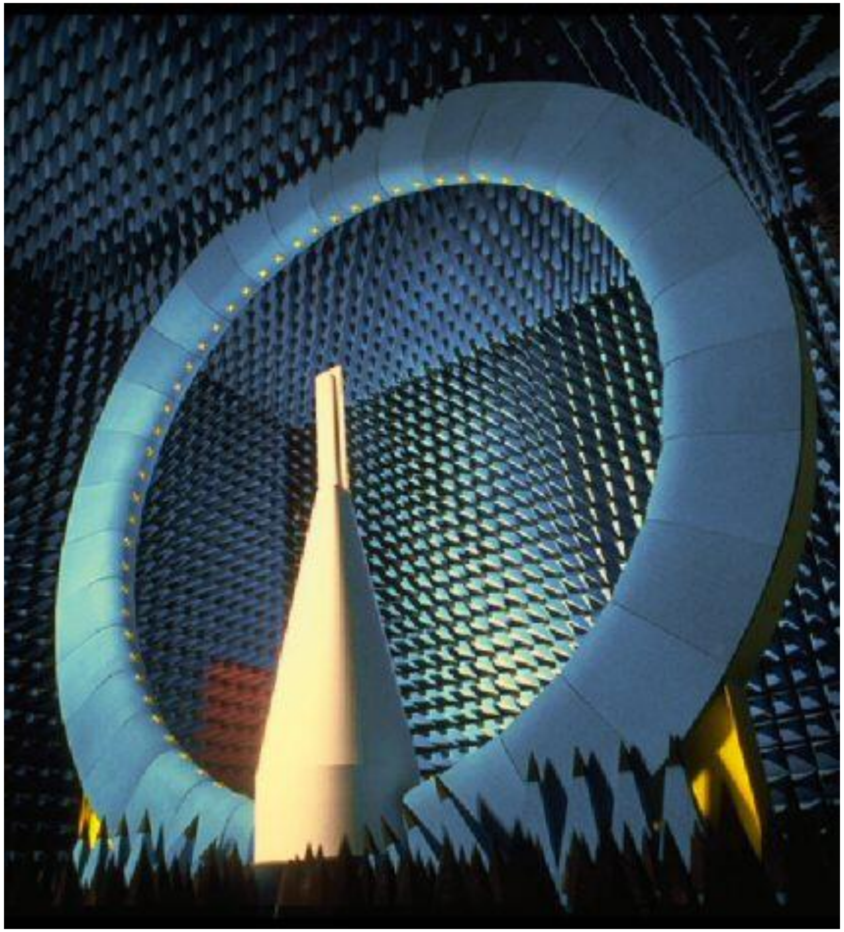
- Advantages of near-field techniques are:
  - The radiation pattern in any desired plane can be computed.
  - Field computation is possible at any distance from the antenna.
  - The experiment can be performed in a relatively small area under a controlled environment unaffected by inclement weather condition.
  - Antennas with large electrical and physical dimensions can be measured
- Disadvantages include:
  - The measurement is time consuming
  - requires significant amount of post processing.
  - The probe detector must be capable of measuring both the magnitude and phase of the field
  - The probe must be stable over the entire measurement time.
  - The measurement system and the associated algorithms for data processing are complicated.

Near Field/Far Field Measurements

- Near-field probes are small antennas, which are not generally isotropic radiators.
- As the probe scans the near-field region of AUT, the direction of signal arrival with respect to the probe coordinate may vary as a function of the probe position.
- For accurate far-field computation, the effect of radiation characteristics of the probe must be taken into account.
- Remember that the presence of the probe in the near field of the antenna distorts AUT's near field
- This can be taken into account theoretically.
- Algorithms that account for the probe radiation characteristics are referred to as probe-compensated near-field methods

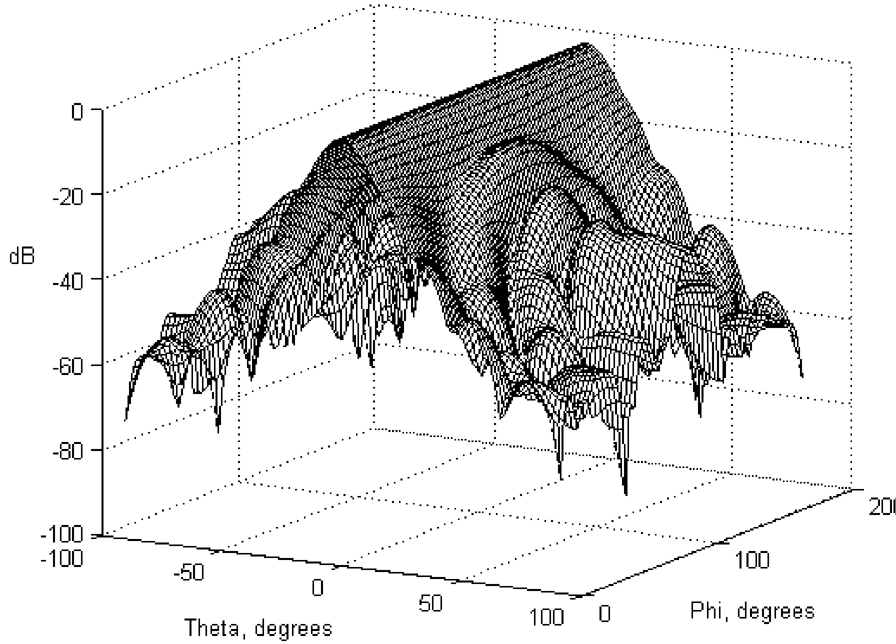
Near Field/Far Field Measurements

- Photograph of a near-field spherical measurement system is shown.

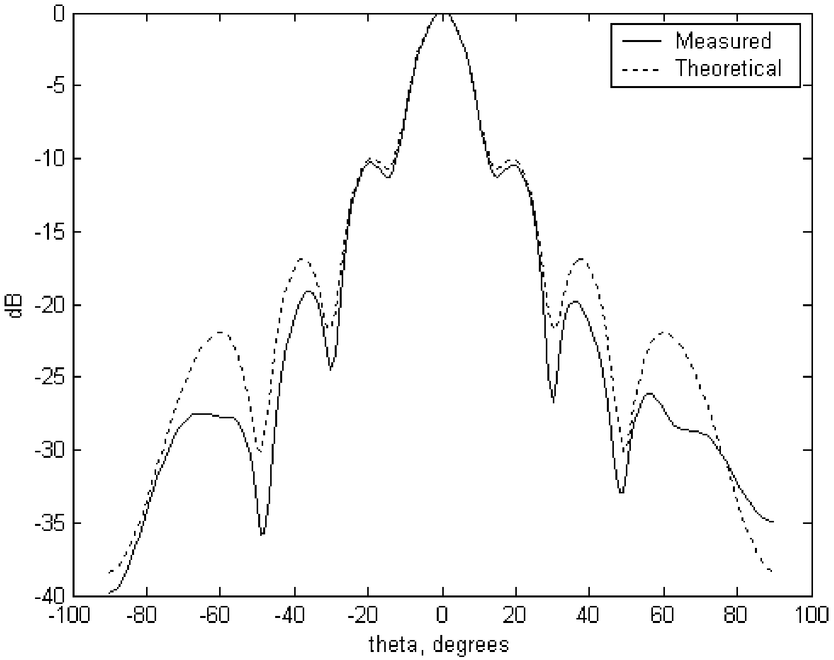


Near Field/Far Field Measurements

- Radiation patterns of a horn antenna obtained using a simple planar near field measurement are shown.

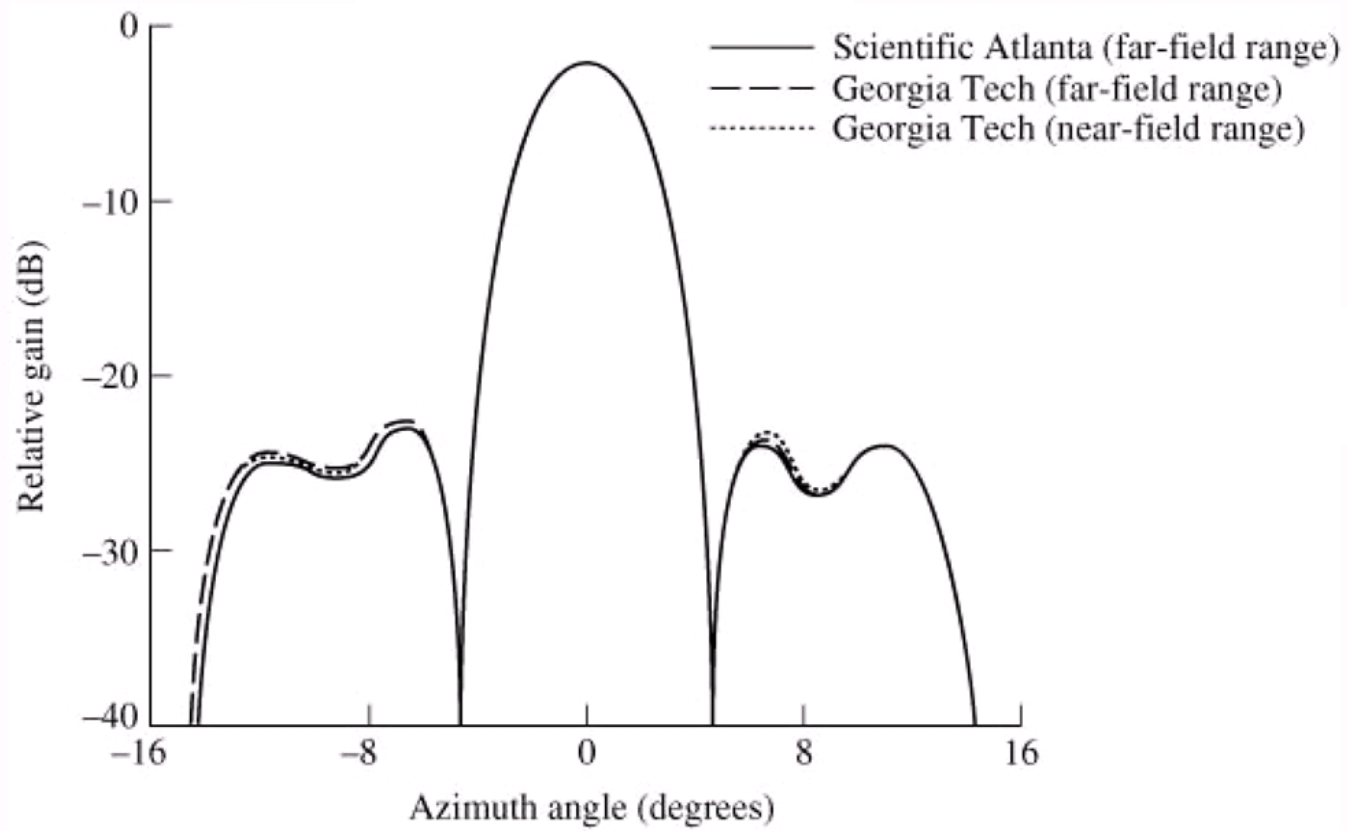


3D



E-Plane Cut

Near Field/Far Field Measurements



- Near and far-field measured patterns of a 4 foot reflector antenna with a gain of 30 dB.

Antenna Gain Measurement Techniques

Gain Measurement Techniques

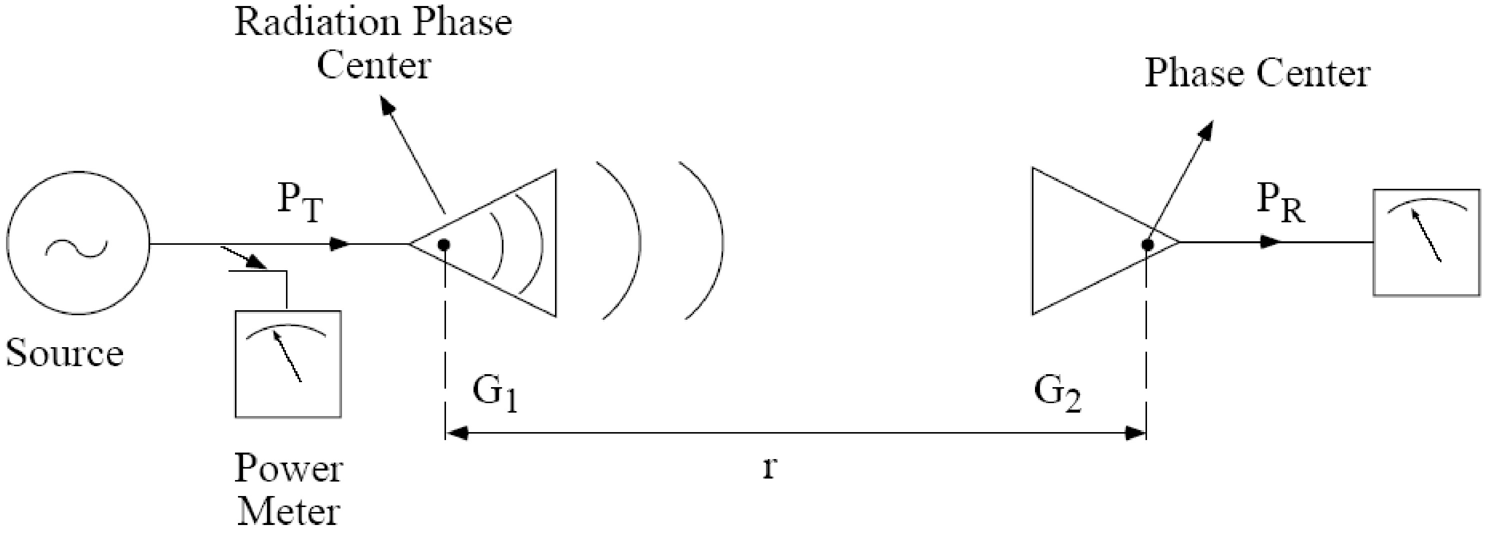
- The gain of an antenna used in a communication system must be known with a high degree of accuracy for link budget calculations.
- A number of different gain measurement techniques exist that fall into two different categories:
  1. Absolute gain measurements techniques
  2. Relative gain measurement techniques
- Four simple gain measurement methods are introduced.
- All these methods require similar test equipment
  - They are different only in terms of the measurement algorithm and the measurement setup

Absolute Gain Measurement Techniques

- In absolute gain measurement techniques, Friis transmission formula is the fundamental equation that is used for the calculation of unknown antenna gains.
- Three methods are considered here which are slightly different in terms of the number of available polarization matched antennas.
- These methods are:
  1. Three-antenna method.
  2. Twin-antenna method.
  3. Reflector method

Absolute Gain Measurement Techniques

- The measurement setup for the twin- or three-antenna measurement methods is shown.
- In this setup two impedance-matched antennas with matched polarizations are positioned apart by distance *r*.
- The separation distance, *r*, is chosen so that the antennas are in the far-field region of each other.



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Absolute Gain Measurement Techniques

- The antennas are separated by $2D^2/\lambda$, where D is the maximum dimension of the largest antenna used in the setup.
- In this configuration it is assumed that the antennas are placed in free-space, or equivalently, no scatterer is in the vicinity of the antennas.
- It should be noted here that the separation distance is measured from the phase center of the antennas.
- The phase center of an antenna is defined as the point from which the spherical wave propagation is originated.
  - The phase center of a dipole antenna is at its feed point.
  - The phase center of a pyramidal horn is near its apex.
- The knowledge of exact location of phase center is not critical when the separation distance is much larger than the antenna dimensions.

Absolute Gain Measurement Techniques

- In the three-antenna measurement method, three dissimilar antennas with gains G_1, G_2, and G_3 are permuted as the transmitter and receiver pairs and the received power for each configuration is recorded
- Using the Friis transmission formula and expressing the gains in dB, three linear equations are obtained that can be solved simultaneously to find G_1, G_2, and G_3.
  - r_{ij} is the separation distance between the i^{th} and j^{th} antenna.
  - P_R^{ij} represents the received power for permutation ij.

$$G_1 + G_2 = 20\log\left(\frac{4\pi r_{12}}{\lambda}\right) - 10\log\left(\frac{P_T}{P_R^{12}}\right)$$

$$G_2 + G_3 = 20\log\left(\frac{4\pi r_{23}}{\lambda}\right) - 10\log\left(\frac{P_T}{P_R^{23}}\right)$$

$$G_3 + G_1 = 20\log\left(\frac{4\pi r_{31}}{\lambda}\right) - 10\log\left(\frac{P_T}{P_R^{31}}\right)$$

Absolute Gain Measurement Techniques

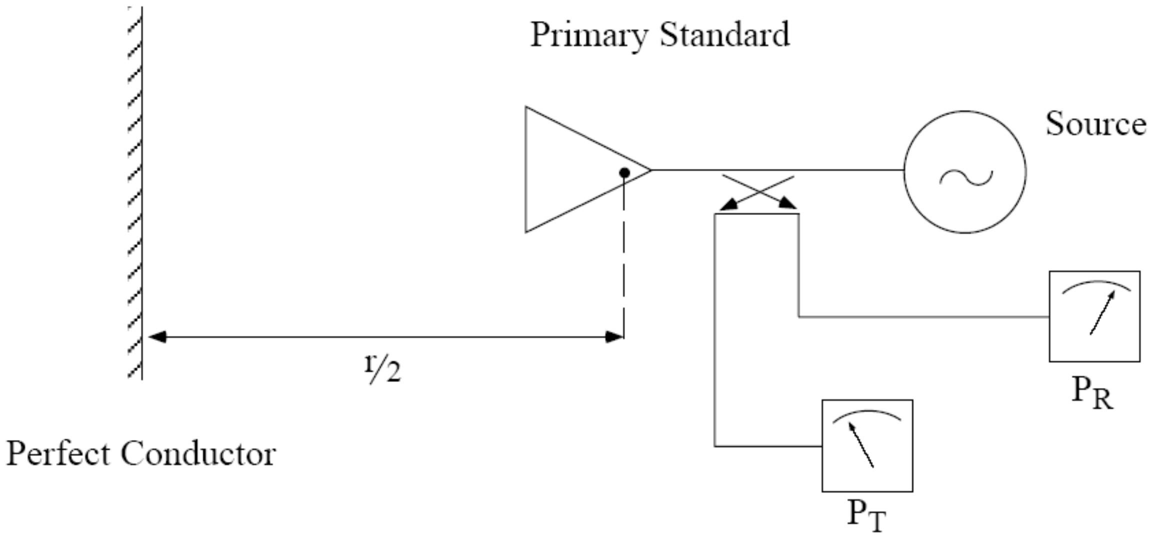
- The complexity of this procedure can be reduced if two identical antennas are available.
- In this case, which is referred to as twin-antenna method, only one transmission measurement is needed.
- If the gain of the unknown antenna (primary standard) is denoted by G and the separation distance between the twin antennas is represented by r, the unknown gain can be obtained from:

$$G = 10\log\left(\frac{4\pi r}{\lambda}\right) + 5\log\left(\frac{P_R}{P_T}\right)$$

Absolute Gain Measurement Techniques

- If two identical primary antennas cannot be found, an alternative approach is the reflector method.
- A perfectly conducting surface is used to generate a mirror image of the primary antenna as shown.
- The gain is therefore:

$$G = 10\log\left(\frac{4\pi r}{\lambda}\right) + 5\log\left(\frac{P_R}{P_T}\right)$$



Absolute Gain Measurement Techniques

- R must be chosen so that the far-field criterion is satisfied.
- The size of the reflector plays an important role in the accuracy of the gain measurement.
- The rule of thumb is to choose the size of the ground plane to be much larger than the wavelength and the 3-dB footprint of the antenna on the ground plane.
- The latter requirement is imposed in order to reduce the effect of edge diffraction.
- In cases where the typical size of the antenna aperture is small the separation distance (r) and the size of the reflector can be relatively small which are of practical importance.
- However, it should be noted that when the separation distance is small, the multiple reflection between the transmitter and receiver (or the antenna and the reflector) can cause a significant error in the gain measurement.

Absolute Gain Measurement Techniques

- Note that in these approaches, we assume that
  1. The antennas are polarization matched
  2. The antennas are impedance matched (i.e. reflection coefficient is zero)
- If the antennas are not polarization matched or if the input reflection coefficient is not zero, modifications to the Friis transmission formula can be made to take these effects into account.

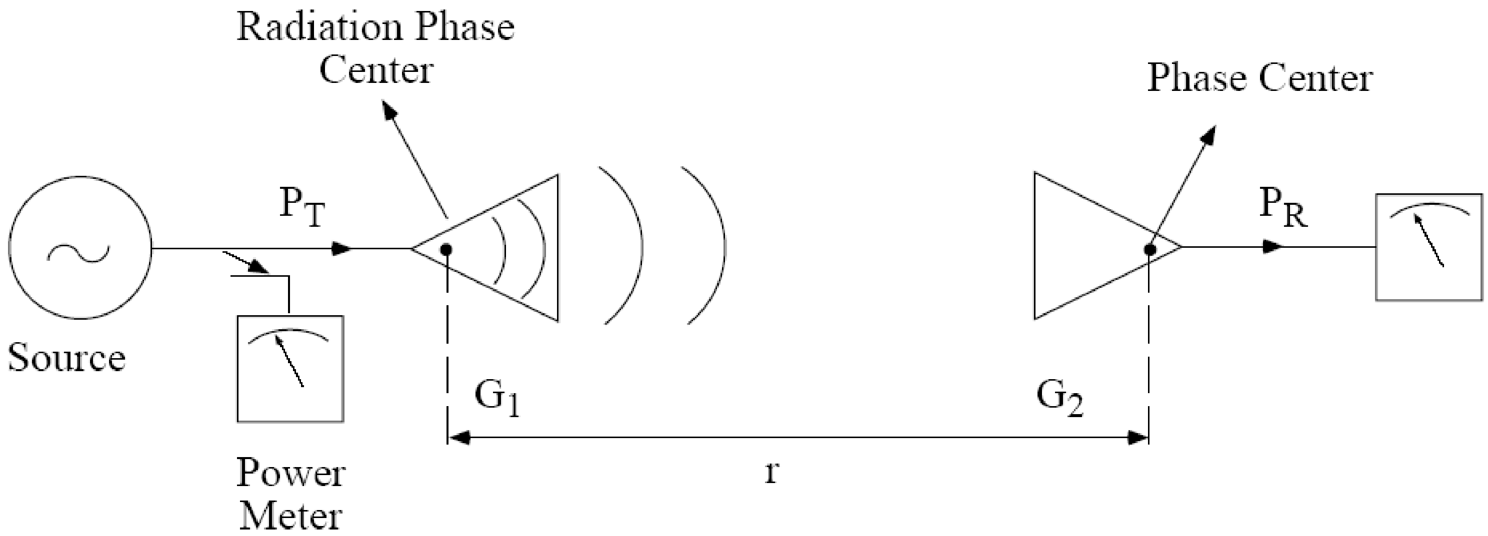
Relative Gain Measurement Technique

- The most common method of gain measurement is the relative gain measurement technique or the method of substitution.
- Three antennas are involved:
  - AUT, an antenna with known gain, and a receiver antenna
  - The receiver antenna’s gain need not be known
- Since all parameters in the Friis transmission formula are fixed except the gain of the receiver antenna, it can easily be shown that

$$G_u = \frac{P_R^u}{R_R^s} G_s$$

Relative Gain Measurement Technique

- P_{Ru} and P_{Rs} are the received powers when the antenna under test and the primary standard gain antennas are connected to the receiver.
- Advantage over the absolute gain measurement techniques:
  - The accuracy in the measurement of range and wavelength does not affect the antenna gain measurements.



Impedance Measurements

Impedance Measurements

- Input impedance of an antenna can be measured using a variety of techniques.
  - Slotted waveguides, Network Analyzers, VSWR measurements, etc
- These days, the input impedances of antennas are usually measured using Vector Network Analyzers.

Impedance Measurement

- Vector network analyzer is an advanced microwave equipment capable of measuring the magnitude and phase of the reflection and/or transmission coefficient of a device under test.
- VNAs come in two, four, eight, … port configurations suitable for measuring the S parameters of 2, 4, 8, … port microwave network.
- A VNA can also be used to measure the mutual impedance between two antennas.

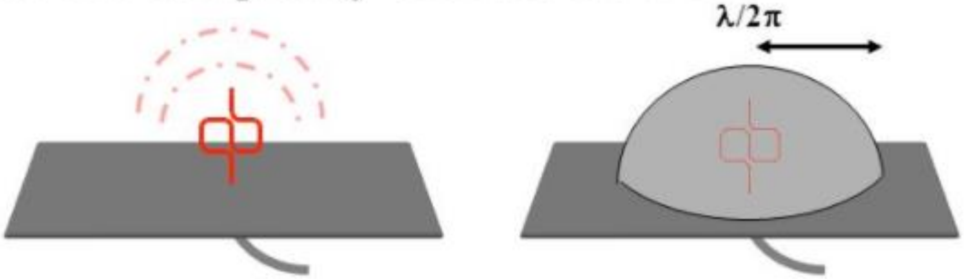
Directivity Measurements

Directivity Measurements:

- Once the radiation patterns of the antenna are measured, directivity can be calculated
- To do this accurately, the 3D pattern of the antenna must be measured
- This can be best done by using a near field measurement system
- Alternatively, far field radiation patterns of the antenna can be measured in a number of different cuts
- The 3D pattern can be reconstructed from these different cuts

Radiation Efficiency Measurements

- η and Q measured using the Wheeler cap method.
- The input impedance of the AUT is measured at the resonant frequency of the antenna with and without a *cap*. The cap is a metallic surface that completely encloses the AUT.



@ at resonance f_0: $Z_{in}=R_r+R_\Omega+jX_{in}$ $Z_{cap}=R_\Omega+jX_{cap}$

@ RLC model: $\eta=\dfrac{R_r}{R_r+R_\Omega}=\dfrac{\mathrm{Re}\{Z_{in}\}-\mathrm{Re}\{Z_{cap}\}}{\mathrm{Re}\{Z_{in}\}}$ $Q=\dfrac{\omega}{2R_r}\left[\dfrac{dX_{in}}{d\omega}+\left|\dfrac{X_{in}}{\omega}\right|\right]$

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