Antenna Measurements: Fundamentals and Advanced Techniques

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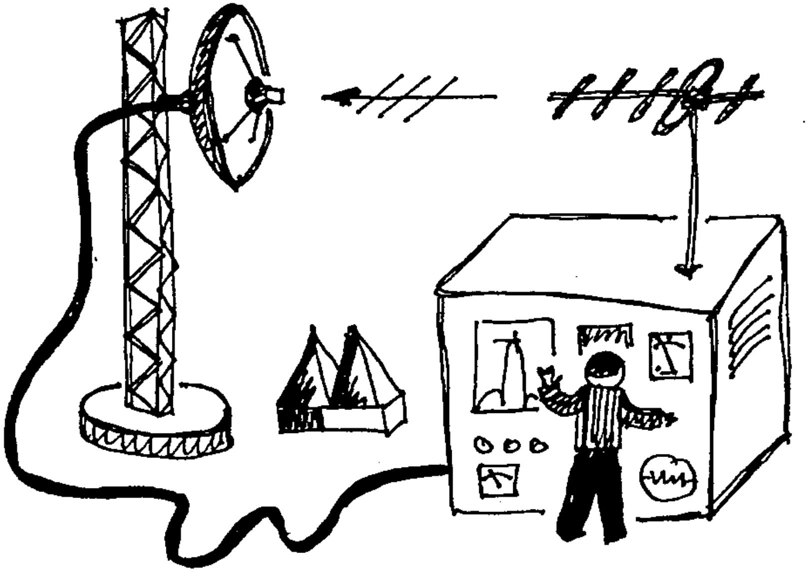
Antenna Measurements: Contents

- Overview of antenna parameters
- Field regions and classification of antenna ranges
- Far-field ranges
- Compact ranges
- Near-field techniques
- Gain and efficiency measurements
- Measurement uncertainty
- Antenna diagnostics
- ESoA course at DTU

Introduction

Why do they do antenna measurements?

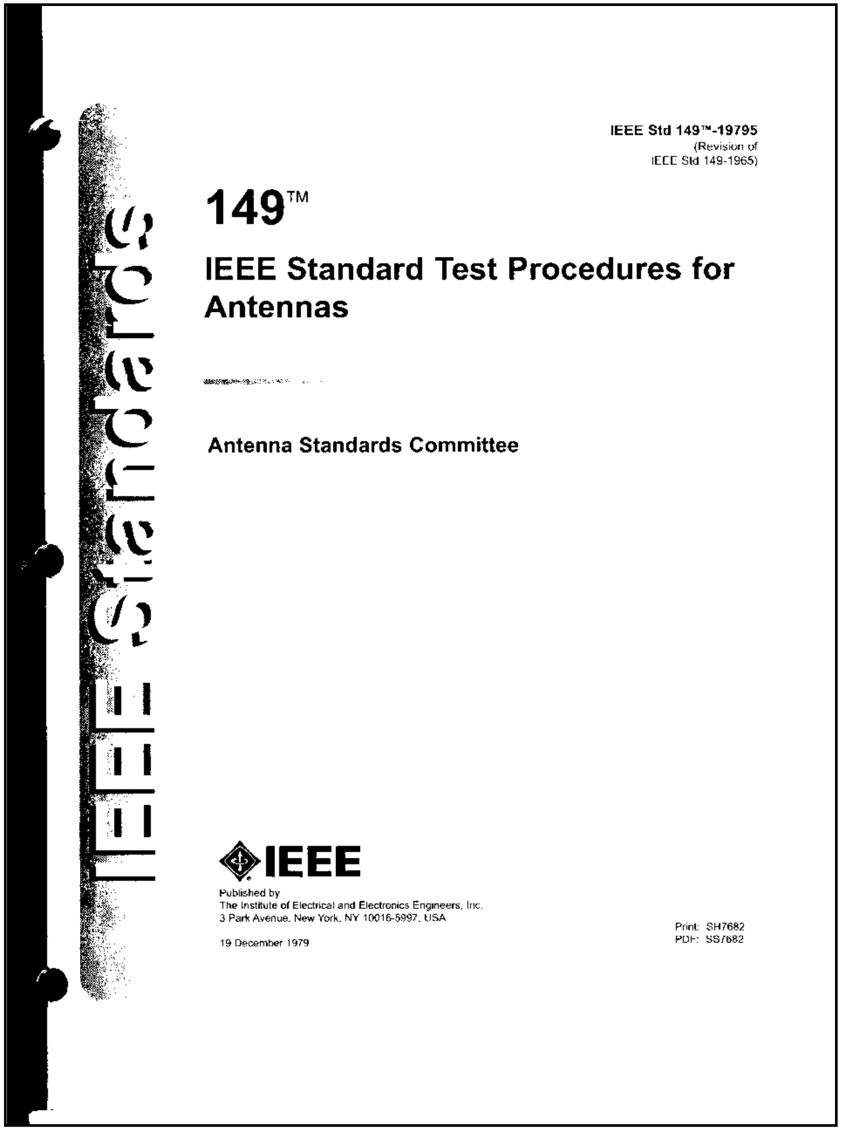
- Computation techniques deal with models – not real-life antennas
- Some parameters are too difficult to be computed or simply cannot be computed
- Validation of computation models
- In many applications, it is required that the antenna is certified by measurements:
  - satellite and airborn antennas
  - military applications
  - reference antennas



Antenna Parameters

- Antennas can be characterized by 10+ parameters:
  - Directivity, gain, beamwidth, sidelobe level, VSWR, polarization, coverage,...
- Most of these can be derived from just few:
  - Complex radiation pattern (amplitude and phase) in 2-, 4-planes or full-sphere
  - Gain (or efficiency)
  - Impedance (or scattering parameters)
- There are also some application-dependent parameters:
  - Effective isotropic radiated power, surface current distribution, antenna noise temperature, maximum available capacity, specific absorption rate, etc.

IEEE Standard Test Procedures for Antennas



IEEE Standards

IEEE Std 149™-19795
(Revision of
IEEE Std 149-1965)

149™

IEEE Standard Test Procedures for Antennas

Antenna Standards Committee

IEEE

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The Institute of Electrical and Electronics Engineers, Inc.
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19 December 1979

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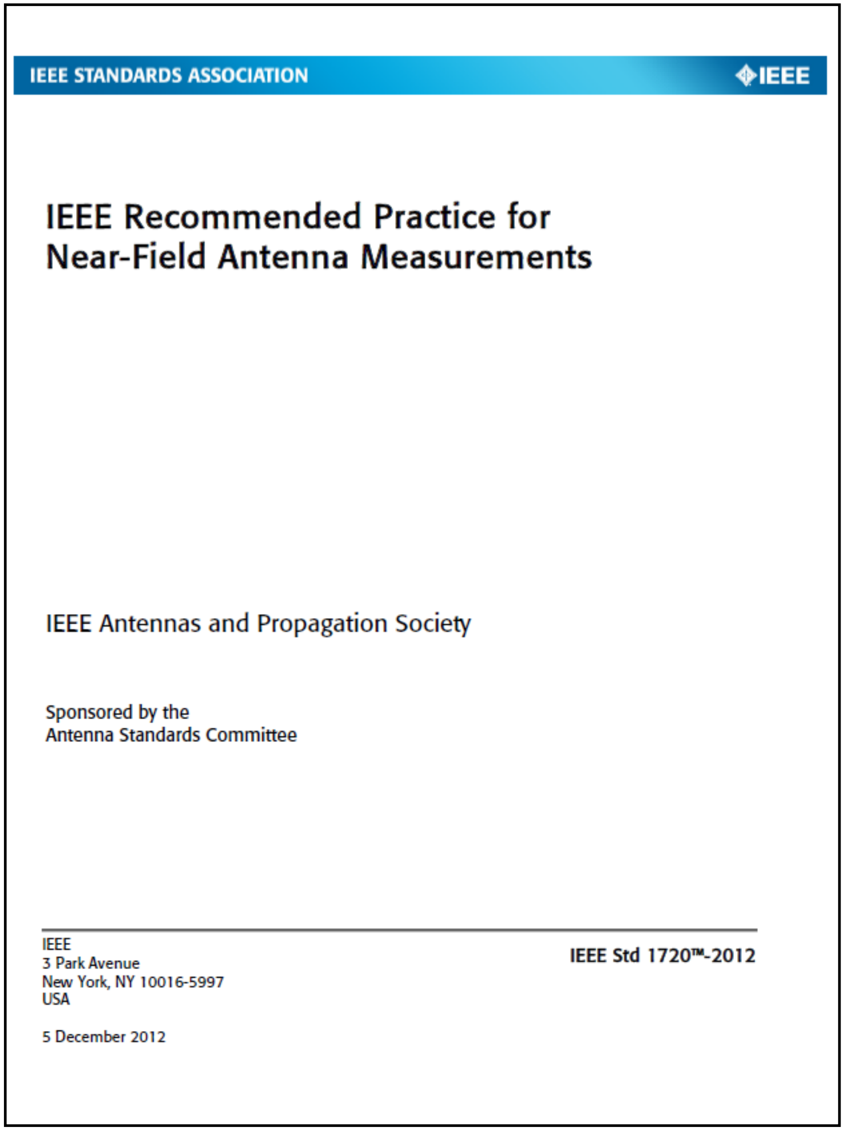
IEEE Std 149-1979

Definition of test procedures for (mainly) far-field measurements

Near-field and compact range measurements are just mentioned

An update of this standard is being planned

IEEE Standard Test Procedures for Antennas



IEEE STANDARDS ASSOCIATION

IEEE

IEEE Recommended Practice for Near-Field Antenna Measurements

IEEE Antennas and Propagation Society

Sponsored by the
Antenna Standards Committee

IEEE
3 Park Avenue
New York, NY 10016-5997
USA

5 December 2012

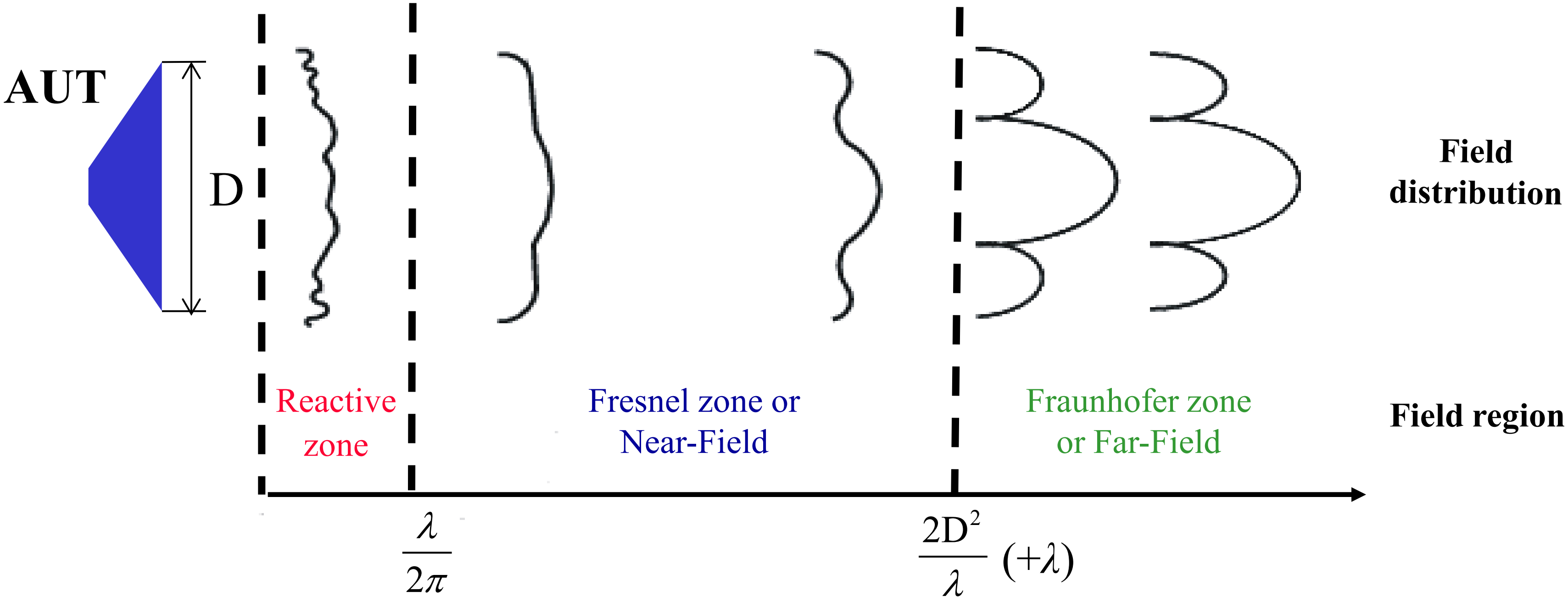
IEEE Std 1720™-2012

IEEE Std 1720-2012

Recommended practice for near-field measurements

Theory of 3 near-field techniques is described, including probes, uncertainty analysis, and some special topics

Field Regions



- Reactive zone: portion of the region surrounding the Antenna Under Test (AUT), where the reactive fields predominate
- Near-field zone: intermediate region, where the radiation fields predominate, but the angular field distribution depends on the distance from the AUT
- Far-field zone: that region where the angular field distribution does not depend on the distance from the AUT

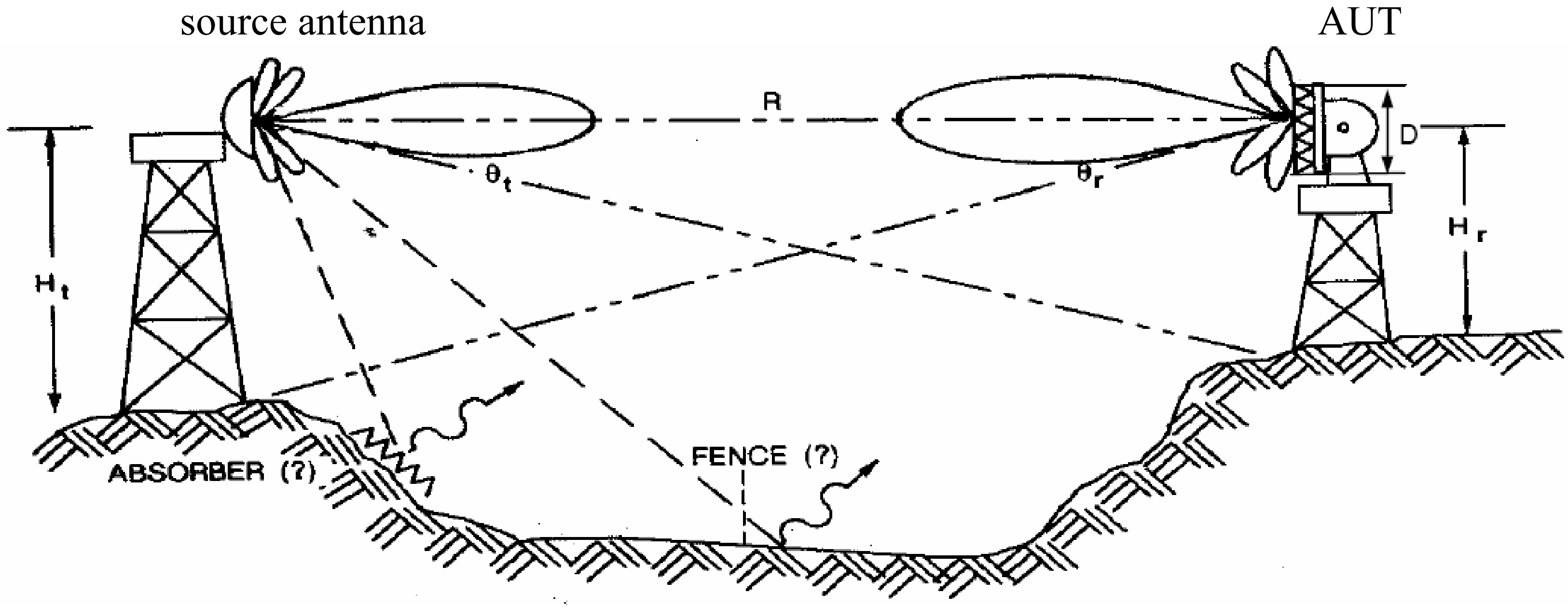
Classification of Measurement Ranges

- ➢ Radiation pattern, directivity, gain, etc. – are the far-field parameters
- Test conditions imply that the field radiated by AUT should closely approximate ”plane wave” when probed at the far-field distance
- Alternatively, ”plane wave” illumination of AUT is required in receiving mode

- ➢ The measurement ranges can be classified by the far-field condition:
  - Far-field ranges (free-space, reflection, compact range)
  - Near-field ranges (planar, cylindrical, spherical) + tranformation to the far field

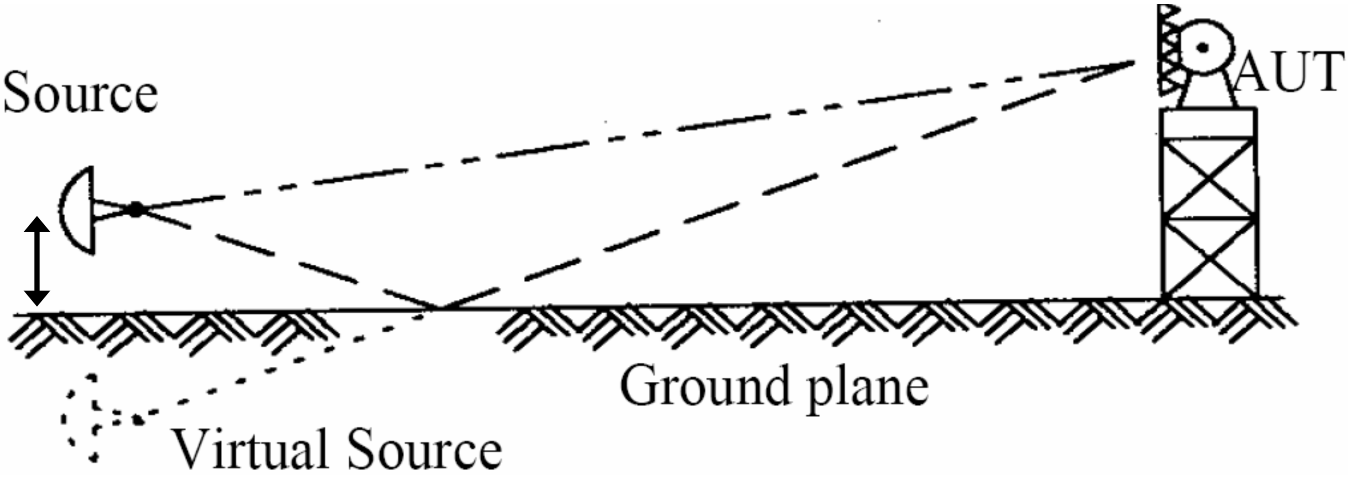
- There are also exceptions, e.g. reverberation chamber allows measurement of many useful antenna and communication system parameters in a closed metal box

Far-Field Ranges – Outdoor: Elevated Range



- The source and AUT are elevated by H_t and H_r above the terrain
- Directive source antennas with low sidelobes are used to minimize ground reflections
- Water-proof absorbers and resistive fences are used to reduce ground reflections
- Special signal processing is used to extract the desired signal
- Use of short pulses to isolate the desired signal
- ➢ Disadvantages: external interference, influence of environment, etc.

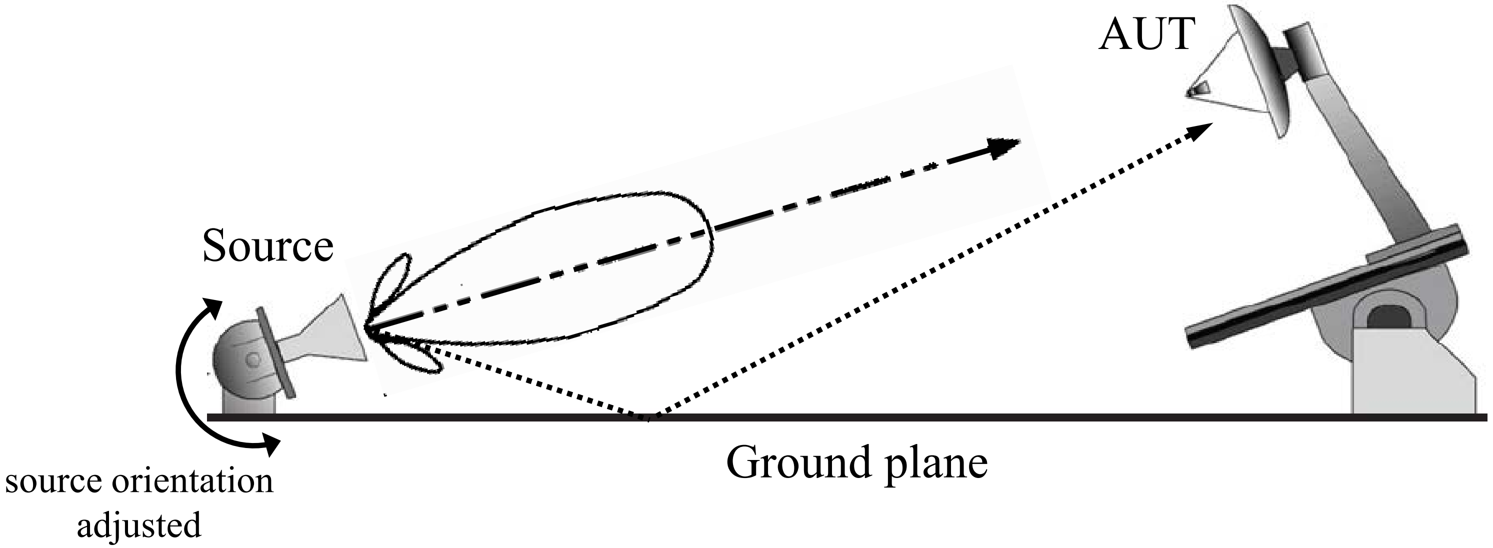
Far-Field Ranges – Outdoor: Ground-Reflection Range



source hight adjusted

- *The height of the source* is adjusted to make use of reflected wave in constructive interference
- The ground plane should be flat and its reflectivity should not depend on weather conditions
- The source antenna pattern should be low-directive
- This configuration is useful in UHF and VHF bands, where the reflections cannot be avoided
- ➢ Disadvantages: external interference, influence of environment, frequency dependence, etc.

Far-Field Ranges – Outdoor: Slanted Range



- *The orientation of the source* is adjusted to minimize the reflected wave
- The source pattern should have low sidelobes or nulls outside the main lobe
- The source pattern should be frequency independent
- Water-proof absorbers and resistive fences can also be used to reduce ground reflections
- ➢ Disadvantages: external interference, influence of environment, frequency dependence, etc.

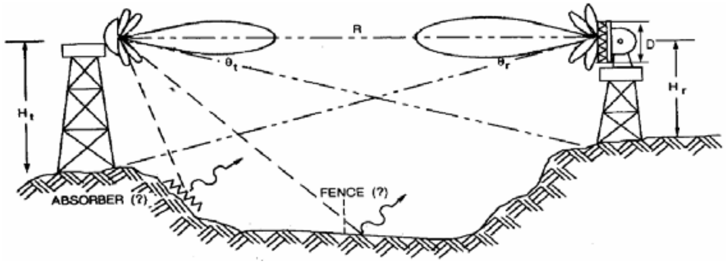
Example: Far-field distance and FF range power budget

- ➢ Our AUT is a usual commercial reflector for satellite TV reception: diameter is 80 cm, operation frequency is 12 GHz

FF distance for this antenna ($2D^2/\lambda$) ≈ 50 m

- ➢ Transmitter power for a FF test range (12 GHz):

- the source antenna has gain of 20 dBi,
- a typical AUT will be a 30 dBi antenna,
- the receiver has sensitivity of –100 dBm,
- the distance between the towers is 600 m
- the desired dynamic range is ≥ 60 dB



Signal generator power level (using $P_r = P_t \cdot G_t \cdot G_r \, (\lambda/4\pi R)^2$) → +20 dBm = 100 mW

Anechoic Chambers

Shielded room covered inside by absorbing material to simulate free-space conditions

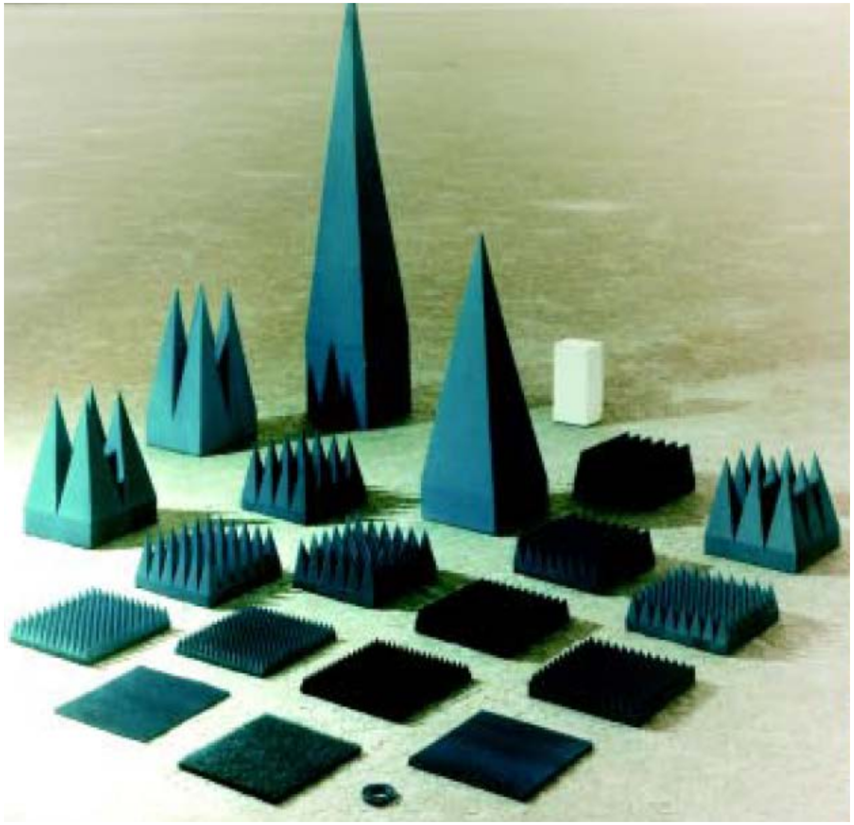
Advantages:

- All weather operation
- Control of environment (temperature, humidity, cleanliness)
- Security
- Free from interference

Disadvantages:

- Limited dimensions, typically < 10 m

Microwave Absorbers I

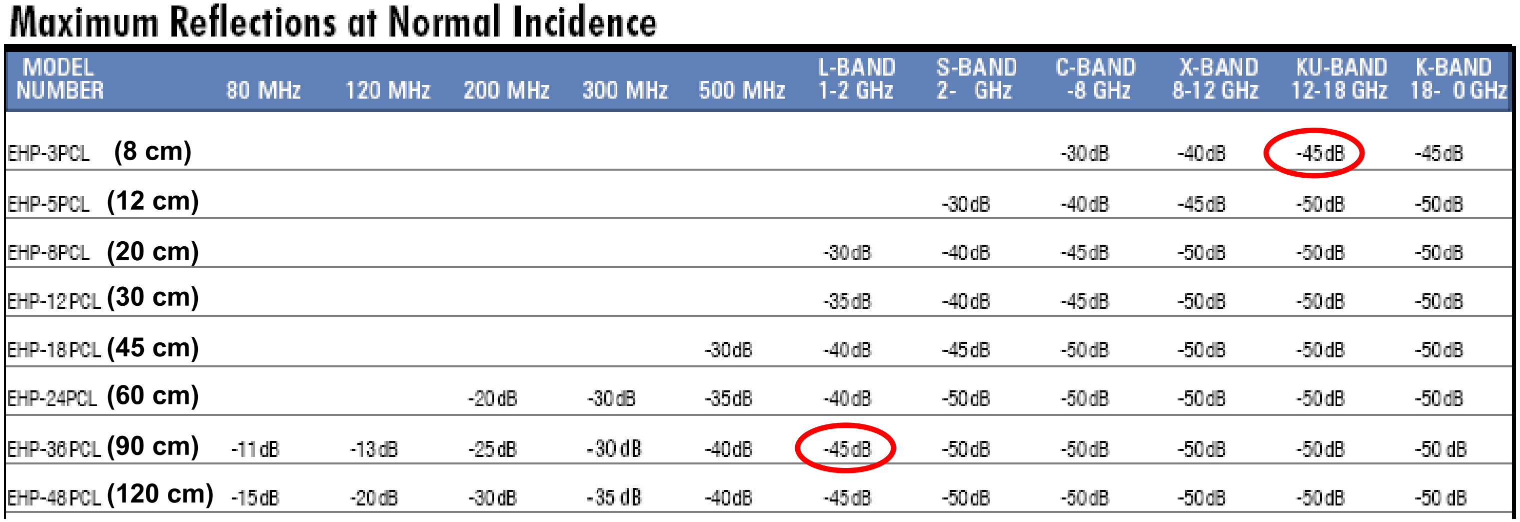


- Material of various size and shape to absorb microwave energy
- Typically made of foam filled with carbon powder

Basic types are:

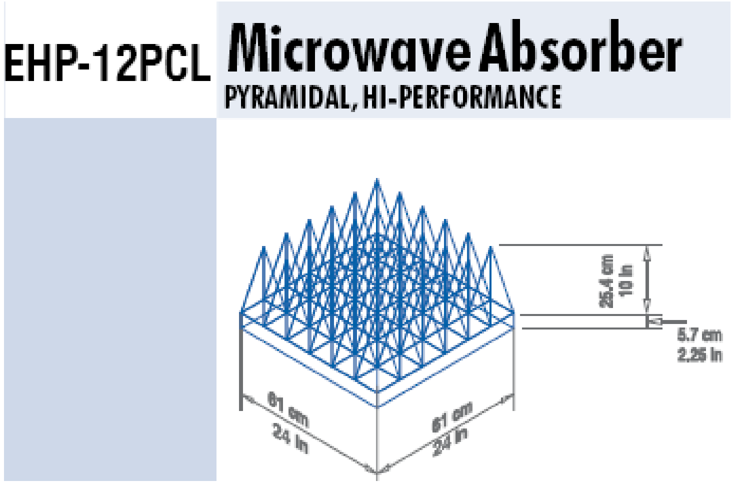
- Pyramidal absorbers: $h > 2.5\lambda$, $\rho < -45$ dB
- Convoluted absorbers – for mm-waves
- Flat laminate absorbers: $\rho \leq -20$ dB, $h > \lambda/4$
- Walkway absorbers
- High-power absorbers
- Resonant thin resistive films ($h \sim 0.1\lambda$)
- Ferrite tiles, typically for 20...200 MHz

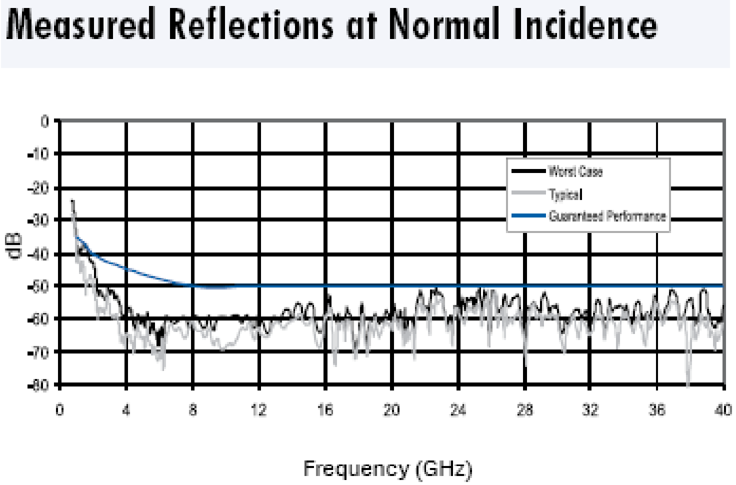
Microwave Absorbers II



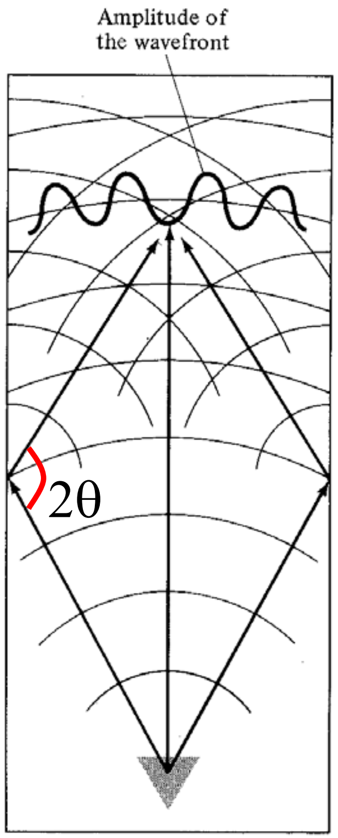
Maximum Reflections at Normal Incidence

MODEL NUMBER	80 MHz	120 MHz	200 MHz	300 MHz	500 MHz	L-BAND 1-2 GHz	S-BAND 2- GHz	C-BAND -8 GHz	X-BAND 8-12 GHz	KU-BAND 12-18 GHz	K-BAND 18- 0 GHz
EHP-3PCL **(8 cm)**								-30dB	-40dB	-45dB	-45dB
EHP-5PCL **(12 cm)**							-30dB	-40dB	-45dB	-50dB	-50dB
EHP-8PCL **(20 cm)**						-30dB	-40dB	-45dB	-50dB	-50dB	-50dB
EHP-12PCL **(30 cm)**						-35dB	-40dB	-45dB	-50dB	-50dB	-50dB
EHP-18PCL **(45 cm)**					-30dB	-40dB	-45dB	-50dB	-50dB	-50dB	-50dB
EHP-24PCL **(60 cm)**			-20dB	-30dB	-35dB	-40dB	-50dB	-50dB	-50dB	-50dB	-50dB
EHP-36PCL **(90 cm)**	-11dB	-13dB	-25dB	-30 dB	-40dB	-45dB	-50dB	-50dB	-50dB	-50dB	-50 dB
EHP-48PCL **(120 cm)**	-15dB	-20dB	-30dB	-35 dB	-40dB	-45dB	-50dB	-50dB	-50dB	-50dB	-50 dB

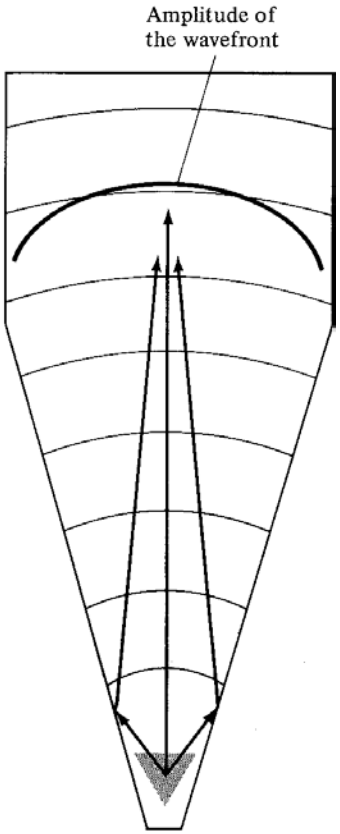

EHP-12PCL **Microwave Absorber**
PYRAMIDAL, HI-PERFORMANCE


Measured Reflections at Normal Incidence

Types of Anechoic Chambers



(a) Rectangular chamber



(b) Tapered chamber

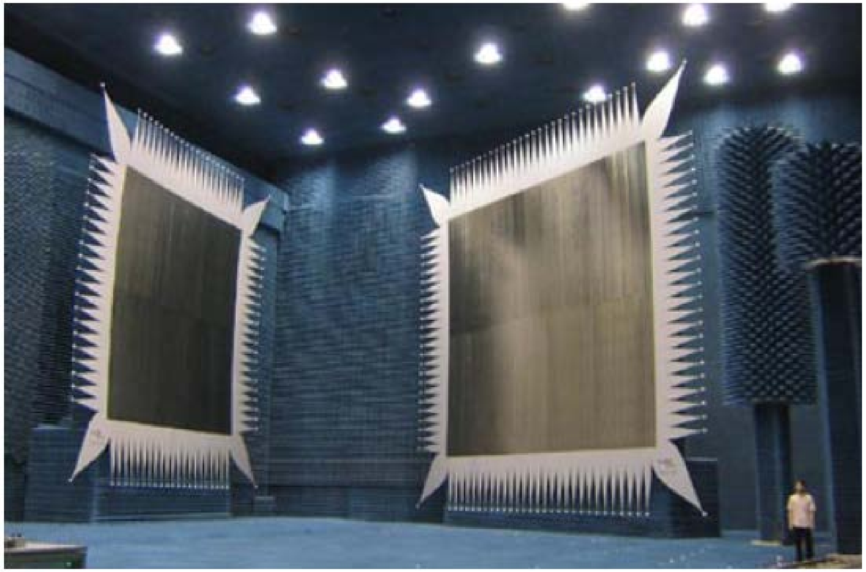
Rectangular anechoic chamber

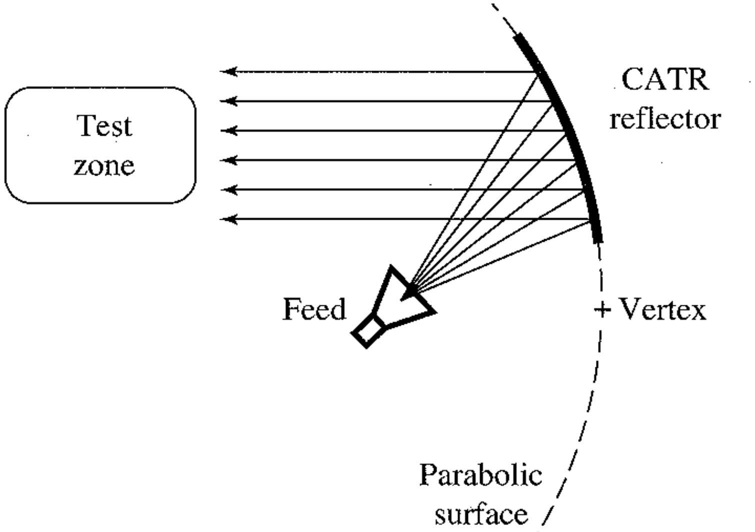
- Specular reflection points are covered with the best (largest) absorbers
- Maximum incidence angle θ < 50°

Tapered anechoic chamber

- Reflections from the side walls interfere constructively in the test zone
- Source position is adjusted at each frequency
- Used mainly at lower frequencues (UHF), where absorbers performance decreases

Compact Ranges – Indoor Far-Field for Large AUT





- ➢ Condition of plane-wave illumination is fulfilled at short distance

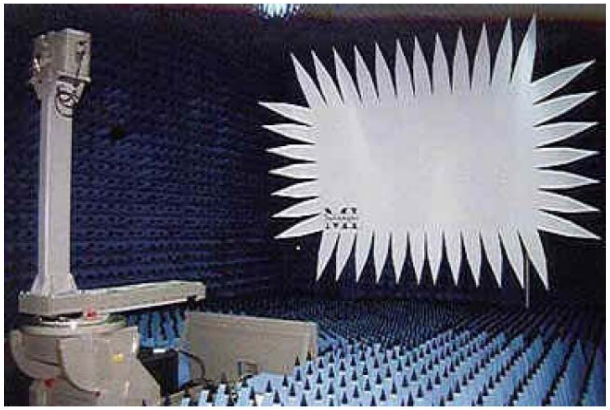
Advantages

- Indoor: controlled, secure environment
- Direct far-field pattern measurements
- Wide bandwidth, typically 3...40 GHz

Disadvantages

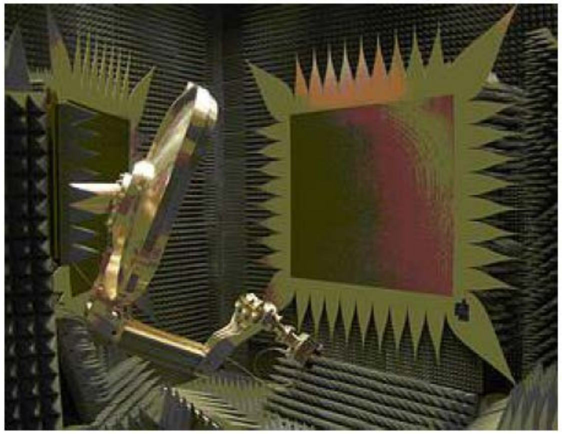
- High cost - because of large reflectors and expensive feeds
- Test zone quality has limitations

Types of Compact Ranges



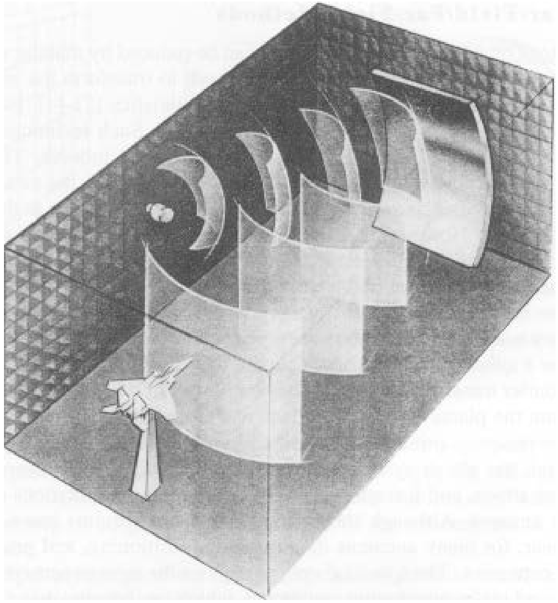
Single parabolic reflector CR

Dual parabolic-cylinder CR



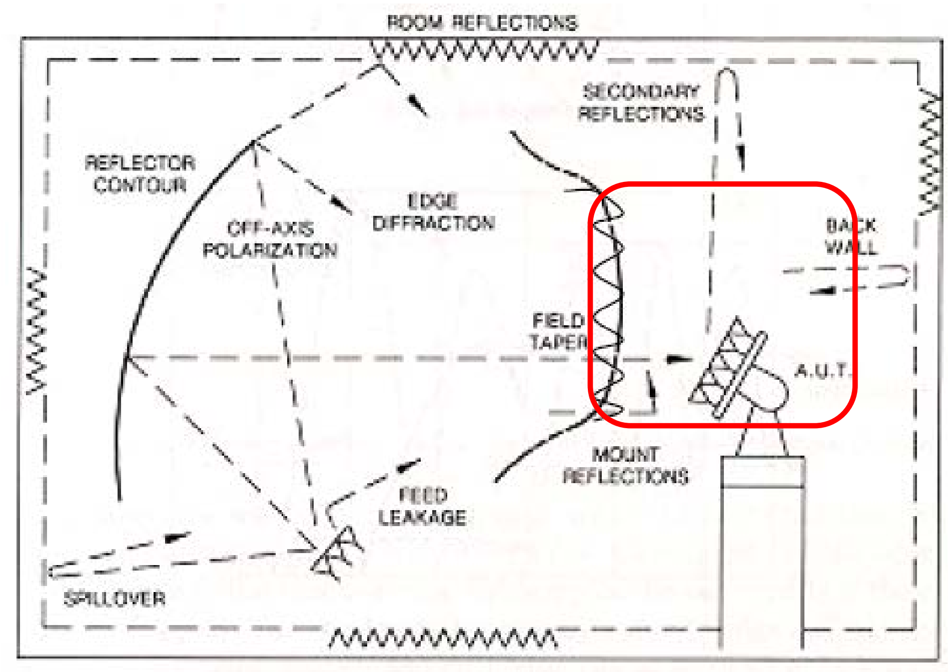
Dual offset Cassegrain CR

Single plane collimating range



Quiet Zone

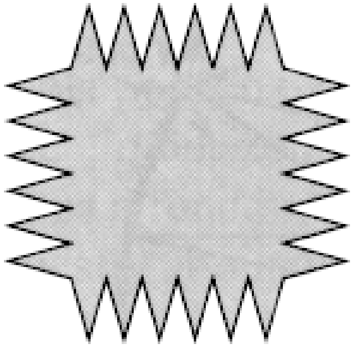
Quiet zone: volume, where the AUT is located, in which the illuminating field amplitude and phase differs from those of a plane wave by less than a pre-established amount



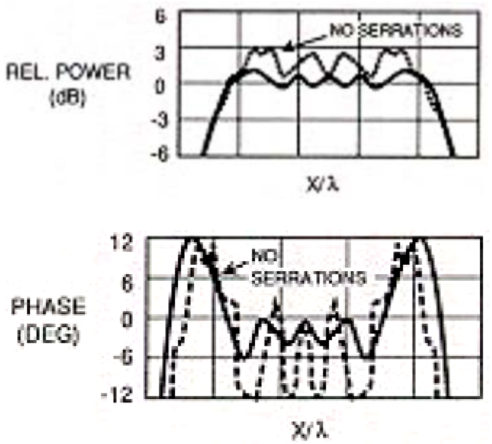
Taper: amplitude variation in the quiet zone border induced by the feed pattern and path lengths to the reflector surface. Typical specs are from –0.5 dB to –1dB

Ripple: field variations produced by edge reflector diffractions and reflections from the room walls. Typical specs are ±0.5 dB in amplitude and ±10º in phase

Edge Diffraction

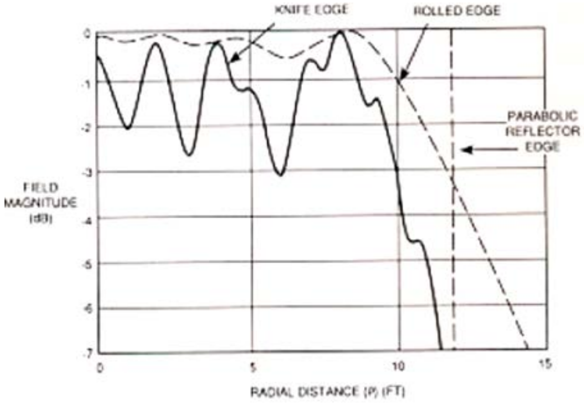


(a) Front view of a serrated-edge CATR reflector.



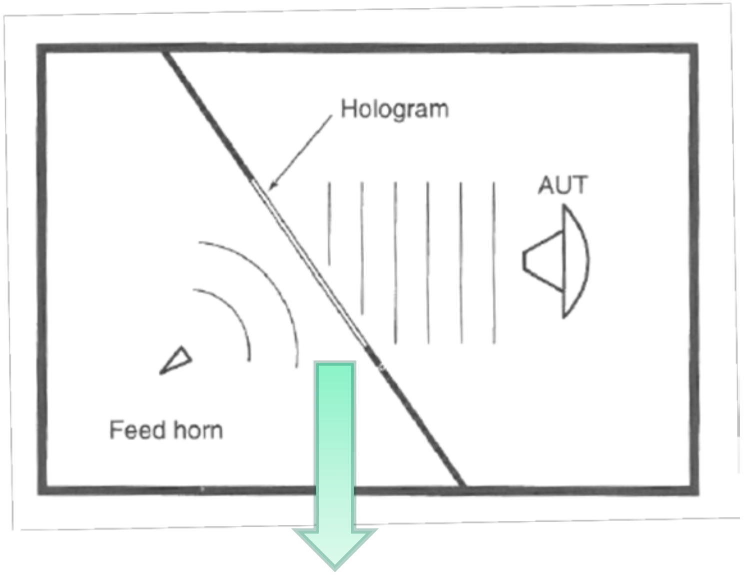
- Serrated edge tapers the amplitude of the reflected field near the edge
- Reflector size is increased by about 30%, which increases the cost

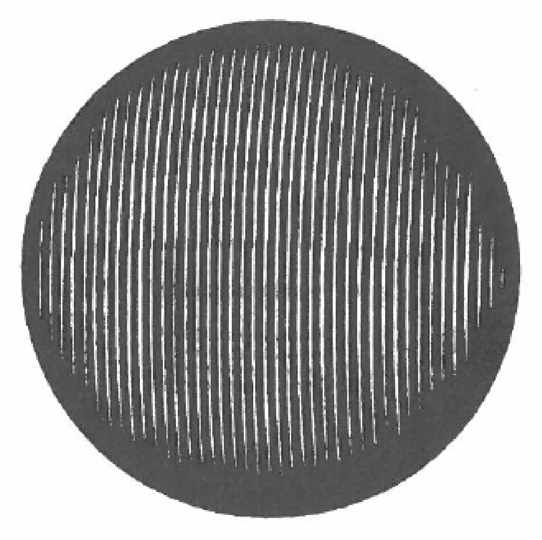
(b) Side view of a rolled-edge CATR reflector.



- Rolled edge gradually re-direct the reflected energy away from the quiet zone
- Reflector size is increased by 10-20%
- Wall absorbers must be better (larger)

Hologram Compact Range





Applied at frequencies 100..600 GHz

Amplitude hologram: etched thin metallic layer of a dielectric film

It modulates the spherical wave so that a plane wave is created on the other side

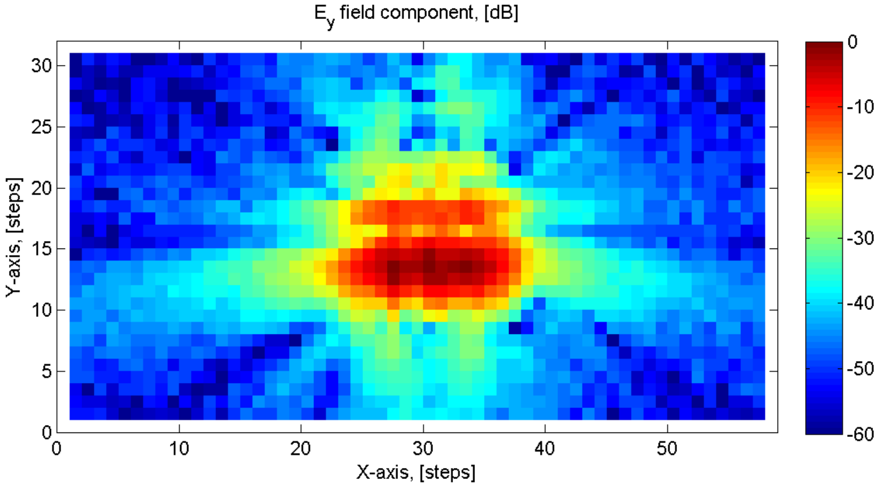
Advantages:

- Rather easy and cheap to make
- Quiet zone of 1..2 m are possible

Disadvantages:

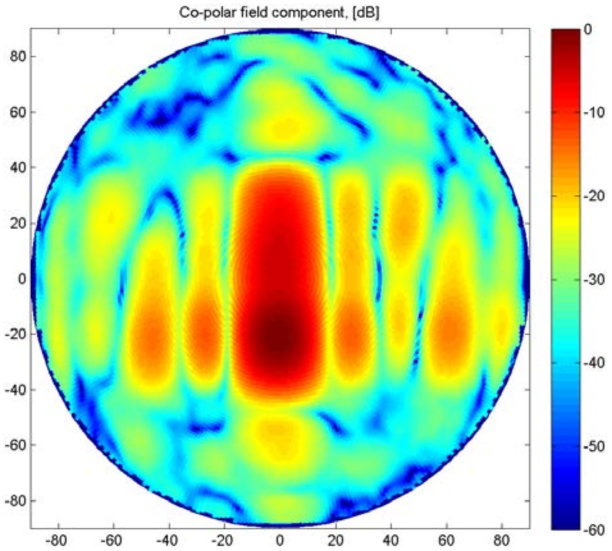
- Narrow frequency range
- One polarization

Near-Field Measurement Techniques



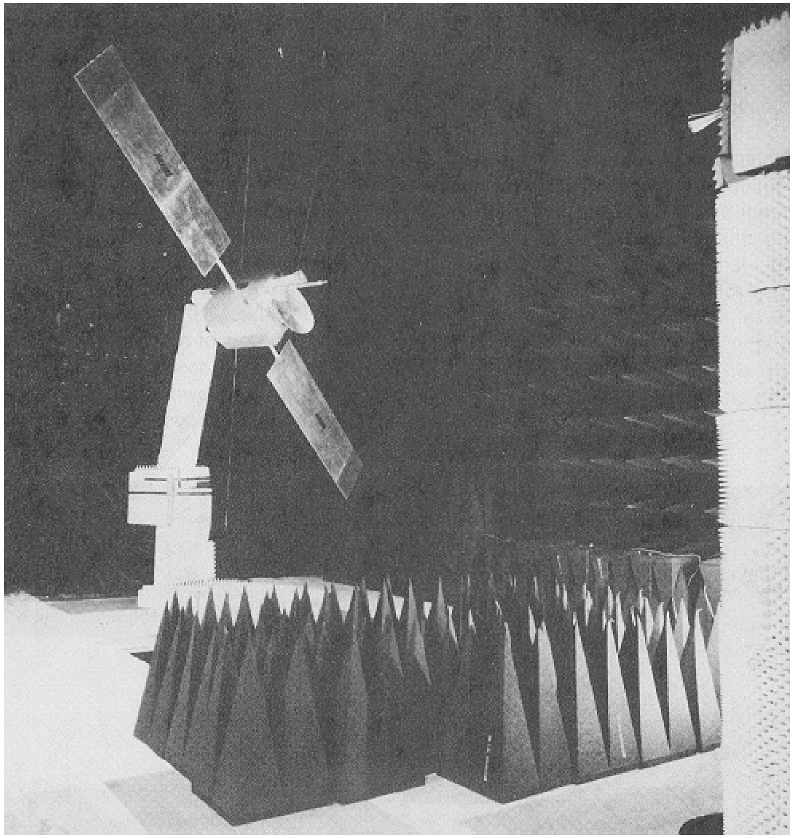
Measured near field

Near-field to far-field transformation algorithm ?

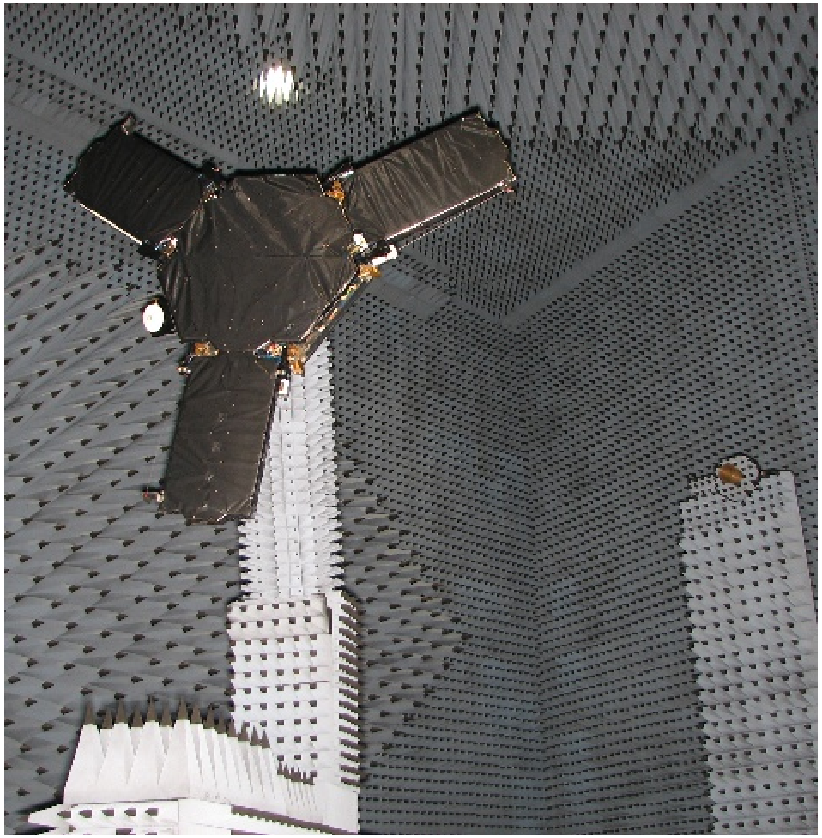


Calculated far field

Near-Field Measurements at DTU

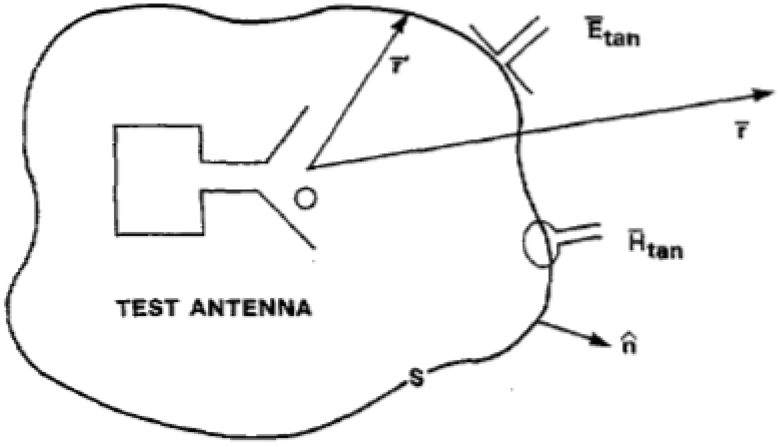


Measurement of telemetry antenna on 1/2.5 scale model of DFS-Kopernikus satellite in 1984



Measurement of antenna patterns on the MIRAS space radiometer for ESA’s SMOS mission in 2006

NF techniques: general problem



$$\bar{E}(\bar{r}) \underset{r\to\infty}{=} \frac{-ike^{ikr}}{4\pi r}\,\hat{r}\times\oint_S(\bar{K}_m + Z_o\,\hat{r}\times\bar{K}_e)\,e^{-ik\hat{r}\cdot\bar{r}'}\,dS'$$

$$\bar{K}_e = \hat{n}\times\bar{H} \qquad \bar{K}_m = -\hat{n}\times\bar{E}$$

$$\bar{E}(\bar{r}) = \oint_S[\hat{n}'\times\bar{E}(\bar{r}')]\cdot\bar{\bar{G}}(\bar{r}',\bar{r})\,dS'$$

Assume we have ideal probes that measure the electric and magnetic field tangential to an arbitrary surface S enclosing the test antenna

The far field is then given by vector Kirckhoff integral of the equivalent electric and magnetic currents

It can be derived in terms of tangential electric or magnetic field alone: expression with dyadic Green's function $\bar{\bar{G}}$

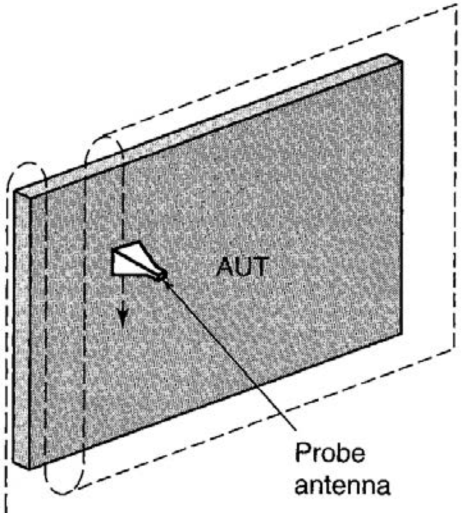
However, $\bar{\bar{G}}$ is impractical to find, unless the surface S supports orthogonal vector wave functions

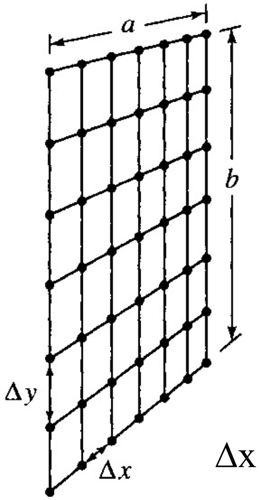
Three coordinate systems offer mechanically convenient scanning possibilities:
planar, cylindrical, and spherical

A.D. Yaghjian, "An overview of near-field antenna measurements", *IEEE Trans. Antennas Propagat.*, vol. 34, no. 1, 1986, pp. 30-45.

Scanning Geometries I

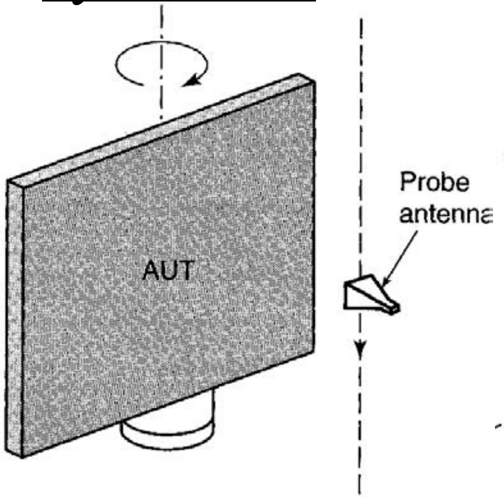
<u>planar</u>

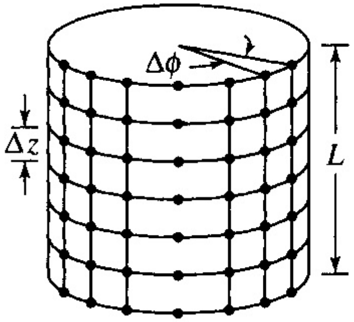




$\Delta x = \Delta y \le \lambda/2$

<u>cylindrical</u>

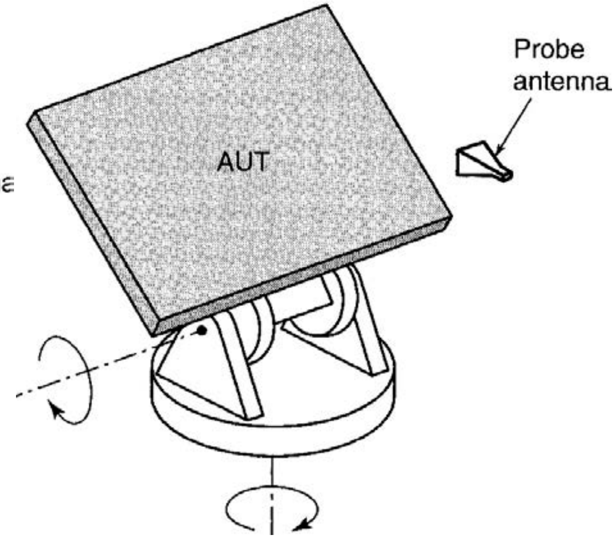


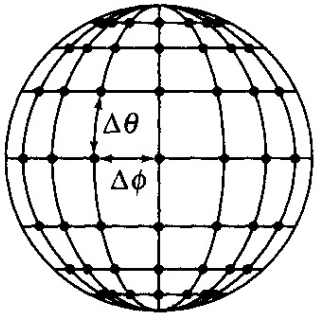


$\Delta z \le \lambda/2$

$\Delta\phi = \lambda/2(a+\lambda)$

<u>spherical</u>

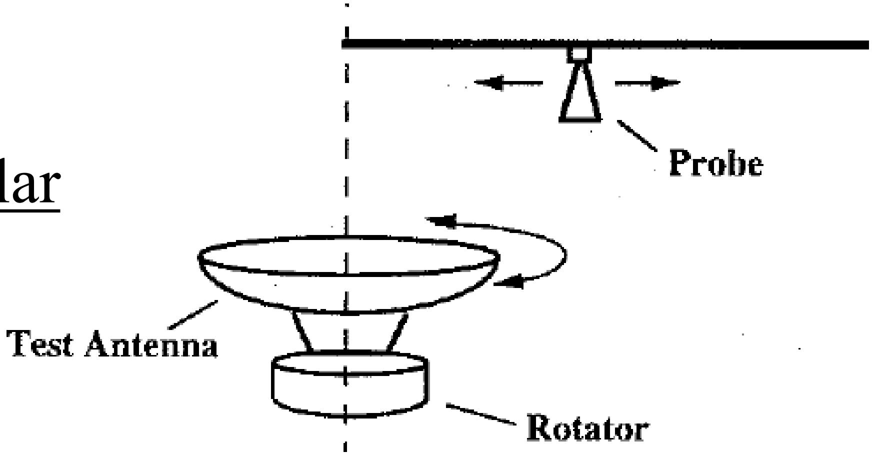


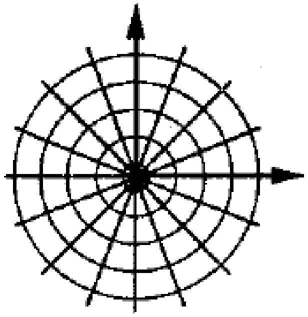


$\Delta\phi = \Delta\theta = \lambda/2(a+\lambda)$

Scanning Geometries II

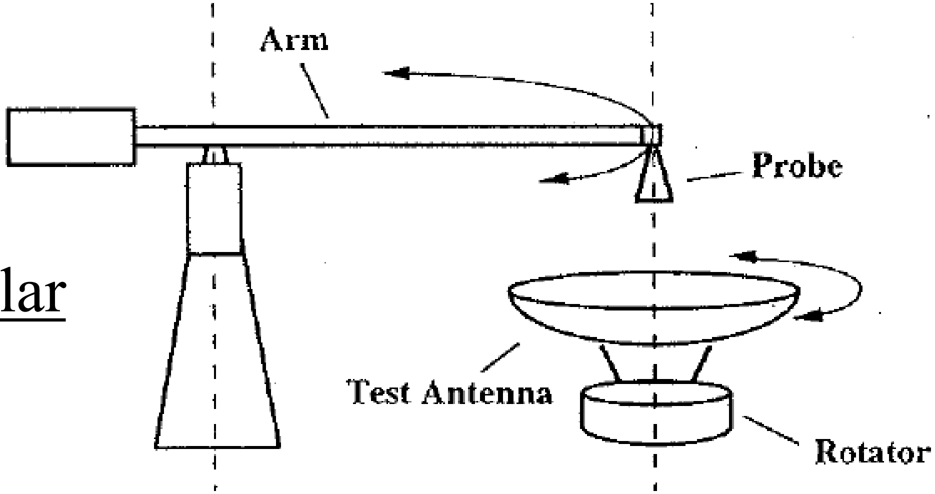
plane-polar

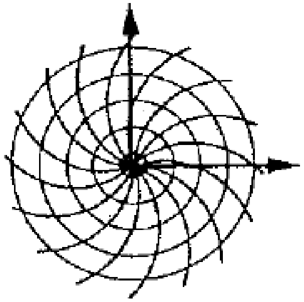




Plane-Polar
Data Grid

plane-bi-polar





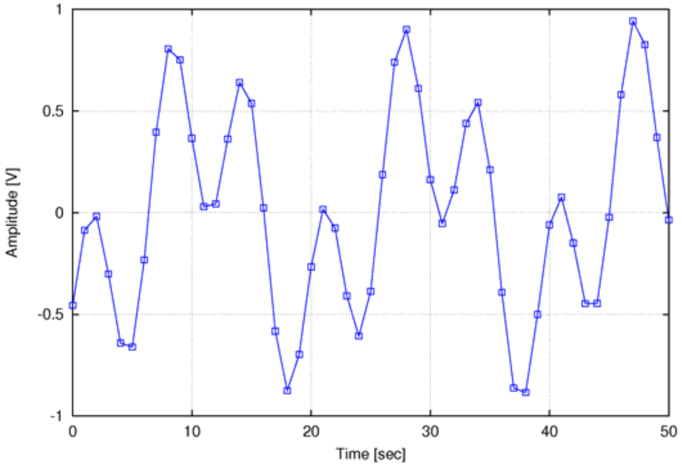
Bi-Polar
Data Grid

Domain Transformation I

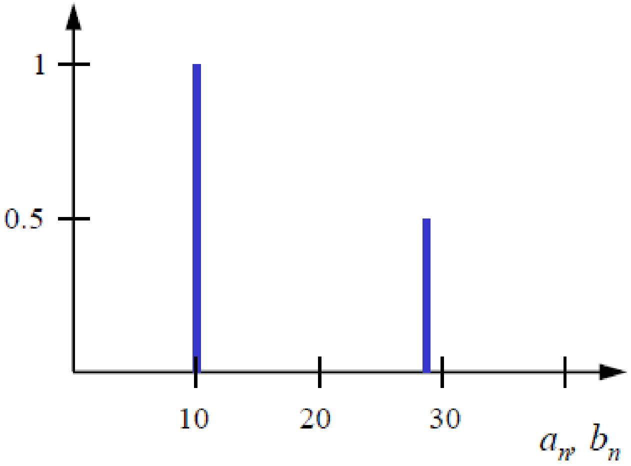
The Fourier Series: *f*(*t*) is a periodic signal with period *T*

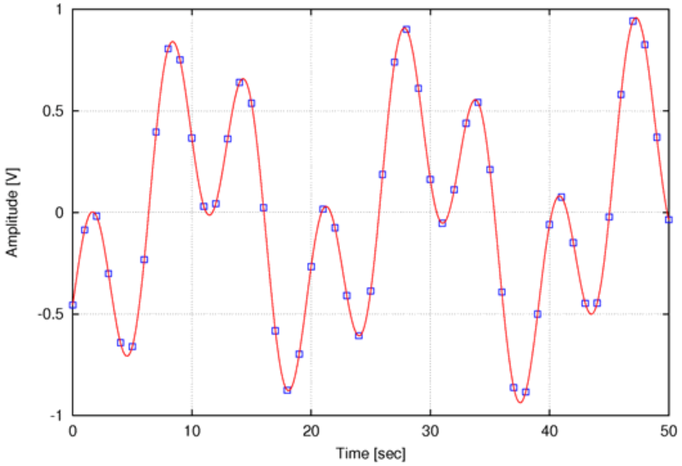
$$f(t)=\sum_{n=0}^{\infty}\left(a_n\cos(n\pi\frac{t}{T})+b_n\sin(n\pi\frac{t}{T})\right)$$

Signal domain



Spectral domain

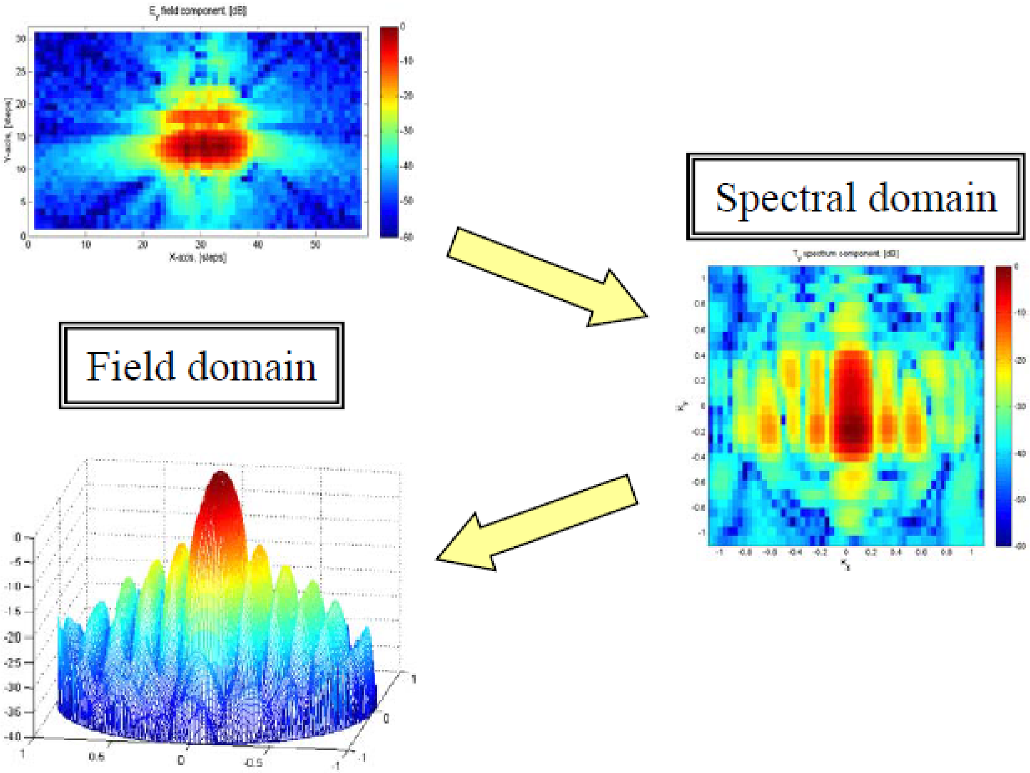




Domain Transformation II

The Plane Wave Expansion: ***E*** is a divergence-free electromagnetic field

$$\mathbf{T}_s(k_x,k_y)=\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\mathbf{E}_a(x,y,0)e^{-i(k_x x+k_y y)}dxdy \qquad \boldsymbol{E}(\boldsymbol{r})=\frac{1}{4\pi^2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\boldsymbol{T}(k_x,k_y)e^{i(k_x x+k_y y+\sqrt{k^2-k_x^2-k_y^2}\,z)}dk_x dk_y$$



Spectral domain

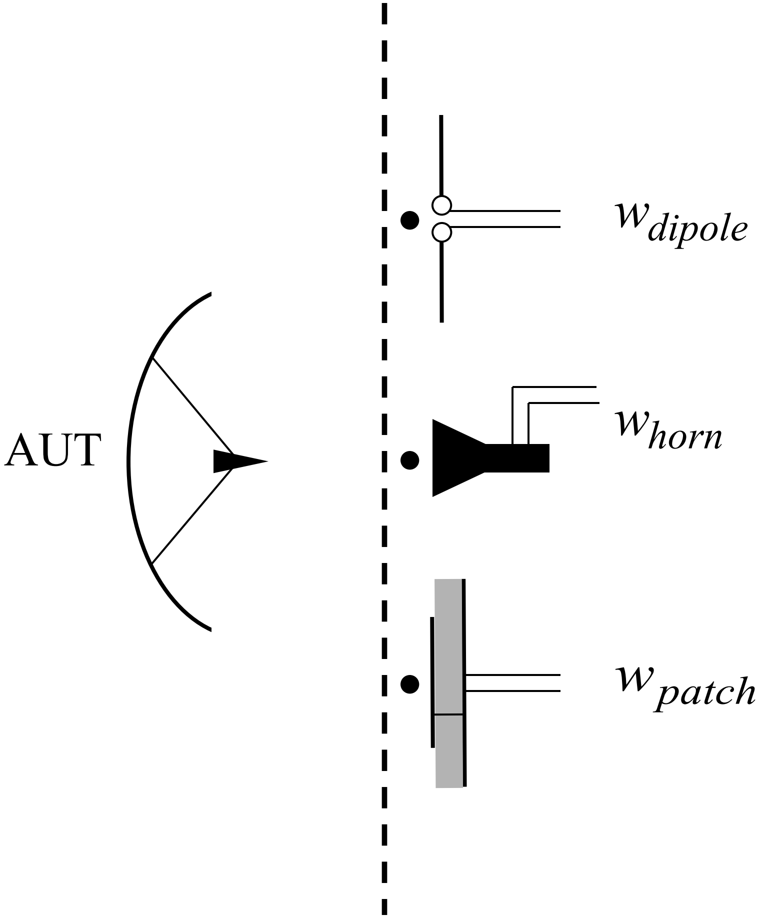
Field domain

We choose the known **expansion functions**

We determine the unknown **expansion coefficients** from measurements/samples of the signal or field according to some **sampling criterion**

We determine the **far field** from the found expansion coefficients

Probe Correction



The signal measured by the probe w_{probe} is not equal to the electric field $\boldsymbol{E}$

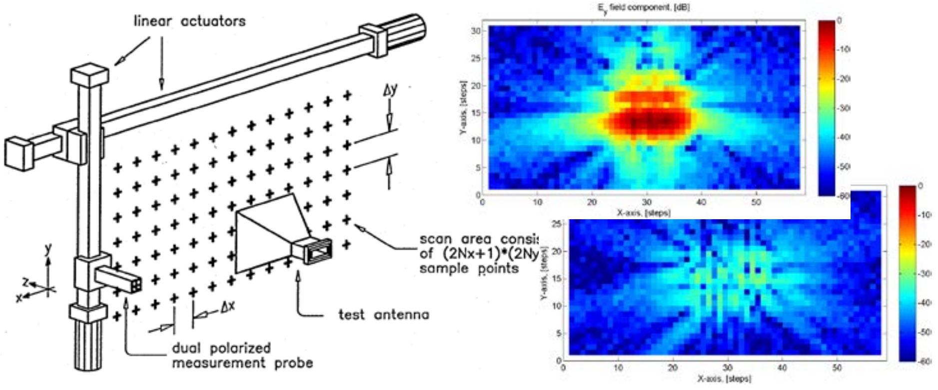
Different probes give different measured signals

$$w_{dipole} \neq w_{horn} \neq w_{patch}$$

To determine the electric field we need to compensate for the influence of the probe – hence we need to know the characteristics of the probe

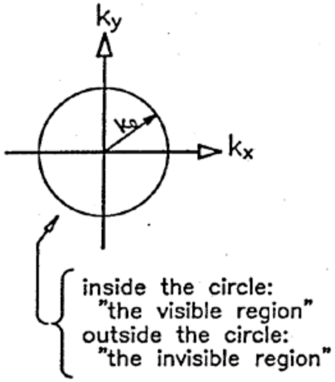
Planar Near-Field Antenna Measurement

Step 1: Measurement of near field

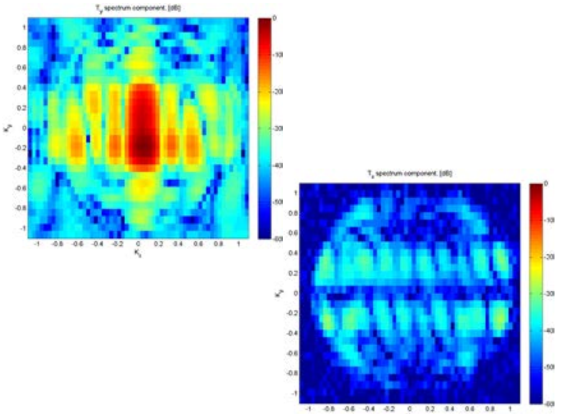


Step 2: Calculation of the spectrum

$$\sum_{x,y} \mathbf{T}_s \mathbf{P}_s = e^{-ik_z z_0} \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \mathbf{E}_a(x,y,z_0)\, e^{-i(k_x x + k_y y)}\, dxdy$$



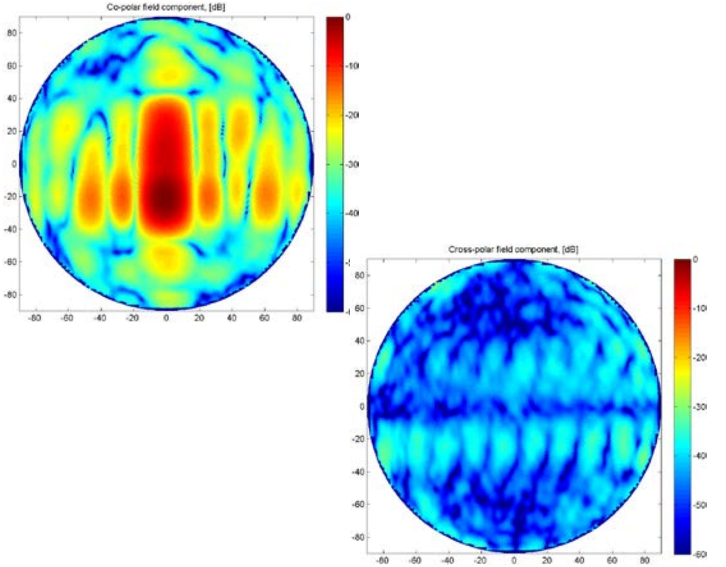
inside the circle:
"the visible region"
outside the circle:
"the invisible region"



Step 3: Applying probe correction, calculation of the far field

$$\mathbf{T}_x \approx \sum_{x,y} \mathbf{T}_s \mathbf{P}_{s,1} \Big/ \mathbf{P}_{x,1} \qquad \mathbf{T}_y \approx \sum_{x,y} \mathbf{T}_s \mathbf{P}_{s,2} \Big/ \mathbf{P}_{y,2} - \sum_{x,y} \mathbf{T}_s \mathbf{P}_{s,1} \Big/ \mathbf{P}_{x,1}\, \rho_2$$

$$\mathbf{E}(r,\theta,\phi) \approx \frac{-ik}{2\pi} \cos\theta \frac{e^{ikr}}{r} \mathbf{T}_s(k_{x0}, k_{y0})$$



Near-Field vs. Far-Field

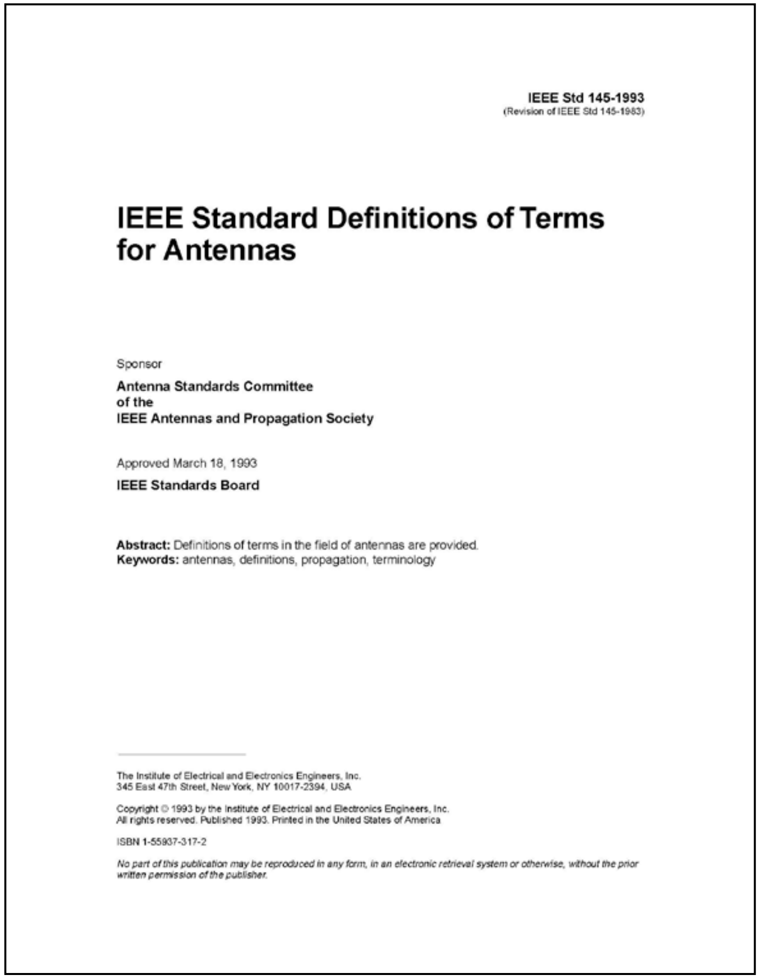
Near-Field Techniques

- Measurement indoors
  - controlled environment, shielding, security
  - small size facility compared to AUT size
- Transformation is necessary
  - amplitude and phase are required
  - essentially more data are required
  - probe characterization is required
  - precise alignment is required
  - long measurement time
  - field is calculated everywhere
  - diagnostics is possible
- Highest accuracy is achievable

Far-Field Techniques

- Measurement outdoors
  - reflections, RF interference, weather
- Measurement indoors
  - controlled environment, shielding, security
  - AUT size limitation ($2D^2/\lambda$)
  - quality of the plane wave (CR)
- Far-field is measured directly
  - only necessary data are measured
  - short measurement time
- Moderate accuracy is achievable

Gain Measurement: Definitions



IEEE Std 145-1993
(Revision of IEEE Std 145-1983)

IEEE Standard Definitions of Terms for Antennas

Sponsor

Antenna Standards Committee
of the
IEEE Antennas and Propagation Society

Approved March 18, 1993

IEEE Standards Board

Abstract: Definitions of terms in the field of antennas are provided.

Keywords: antennas, definitions, propagation, terminology

The Institute of Electrical and Electronics Engineers, Inc.
345 East 47th Street, New York, NY 10017-2394, USA

ISBN 1-55937-317-2

2.107 directivity (of an antenna) (in a given direction). The ratio of the radiation intensity in a given direction from the antenna to the radiation intensity averaged over all directions.

$$D = \frac{r^2 \,\mathrm{Re}\left\{\frac{1}{2}\boldsymbol{E}\cdot\boldsymbol{H}*\right\}}{P_{rad}/4\pi}$$

2.165 gain (in a given direction). The ratio of the radiation intensity, in a given direction, to the radiation intensity that would be obtained if the power accepted by the antenna were radiated isotropically.

$$G = \frac{r^2 \,\mathrm{Re}\left\{\frac{1}{2}\boldsymbol{E}\cdot\boldsymbol{H}*\right\}}{P_{acc}/4\pi}$$

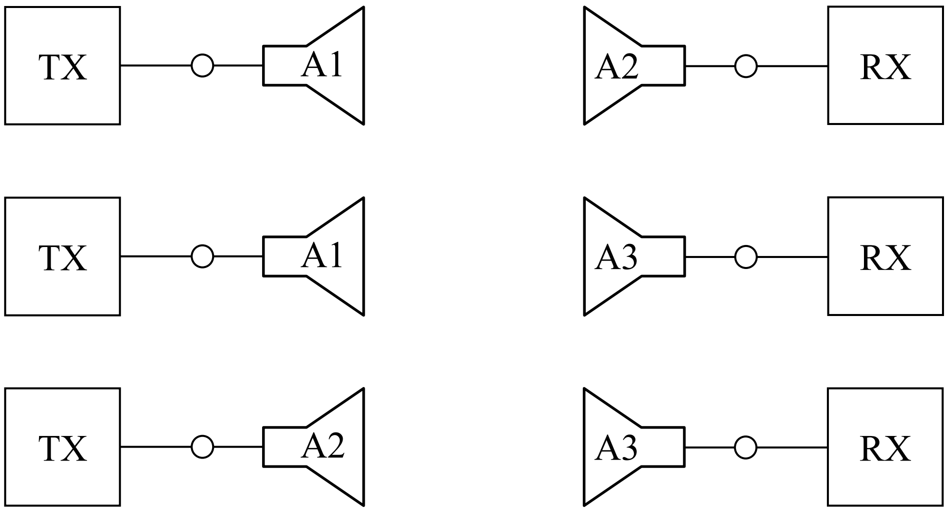
2.321 realized gain. The gain of an antenna reduced by the losses due to the mismatch of the antenna input impedance to a specified impedance.

$$G_R = G\left(1-\left|\Gamma_{in}\right|^2\right)$$

Three-Antenna Technique

Friis transmission formula

$$P_{RX} = P_{TX} G_{A1} G_{A2} \left(\frac{\lambda}{4\pi R} \right)^2 M_{A1} M_{A2}$$



- P_{TX} must be stable and known (*)
- R must be far-field distance

Three equations with three(*) unknowns

$$G_{A1} G_{A2} = \frac{P_{A2}}{P_{TX}} \left(\frac{4\pi R}{\lambda} \right)^2 \frac{1}{M_{A1} M_{A2}}$$

$$G_{A1} G_{A3} = \frac{P_{A3}}{P_{TX}} \left(\frac{4\pi R}{\lambda} \right)^2 \frac{1}{M_{A1} M_{A3}}$$

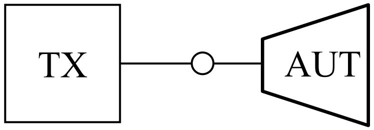
$$G_{A2} G_{A3} = \frac{P_{A3}}{P_{TX}} \left(\frac{4\pi R}{\lambda} \right)^2 \frac{1}{M_{A2} M_{A3}}$$

M_x is impedance mismatch correction

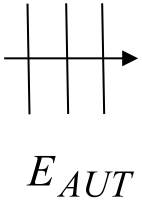
Solution

$$\boxed{G_{A1} = \sqrt{\frac{G_{A1} G_{A2} \cdot G_{A1} G_{A3}}{G_{A2} G_{A3}}}}$$

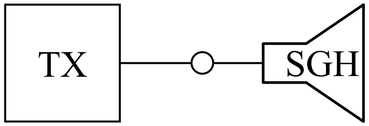
Gain-Transfer (Gain Substitution) Technique



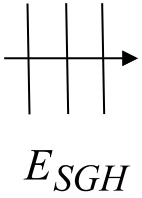
$$P_{acc,AUT} = \frac{1-|\Gamma_{AUT}|^2}{|1-\Gamma_{AUT}\Gamma_g|^2}|v_g|^2$$



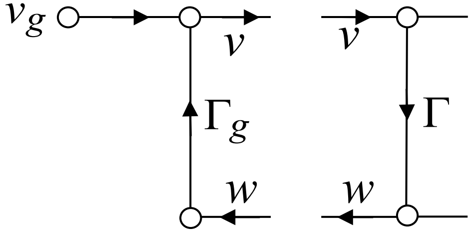
$$|E_{AUT}|^2 \propto G_{AUT} P_{acc,AUT}$$



$$P_{acc,SGH} = \frac{1-|\Gamma_{SGH}|^2}{|1-\Gamma_{SGH}\Gamma_g|^2}|v_g|^2$$



$$|E_{SGH}|^2 \propto G_{SGH} P_{acc,SGH}$$



$$P \propto |v|^2 - |w|^2$$

$$\left.\begin{aligned} v &= v_g + \Gamma_g w \\ w &= \Gamma v \end{aligned}\right\} \Rightarrow v = \frac{v_g}{1-\Gamma\Gamma_g}$$

$$\boxed{G_{AUT} = G_{SGH} \frac{|E_{AUT}|^2}{|E_{SGH}|^2} \frac{P_{acc,SGH}}{P_{acc,AUT}}}$$

For near-field antenna measurements this procedure becomes somewhat more complicated…

…but in any case we need to know G_{SGH}

Gain-Transfer Technique – Near-Field Measurement

1. Formula with signals

$$G_{AUT} = G_{SGH} \frac{|E_{AUT}|^2}{|E_{SGH}|^2} \frac{P_{acc,SGH}}{P_{acc,AUT}} = G_{SGH} \frac{|E_{AUT}|^2}{|E_{SGH}|^2} \frac{M_{SGH}}{M_{AUT}}$$

E_{AUT}, E_{SGH} are obtained from measured near-field signals through NF-FF transformation

2. Formula with total power

$$\eta_{AUT} = \eta_{SGH} \frac{P_{AUT}^{rad}}{P_{SGH}^{rad}} \frac{M_{SGH}}{M_{AUT}}$$

$$G_{AUT} = D_{AUT}\, \eta_{AUT}$$

η_{AUT} is AUT radiation efficiency

In the case of spherical near-field measurement

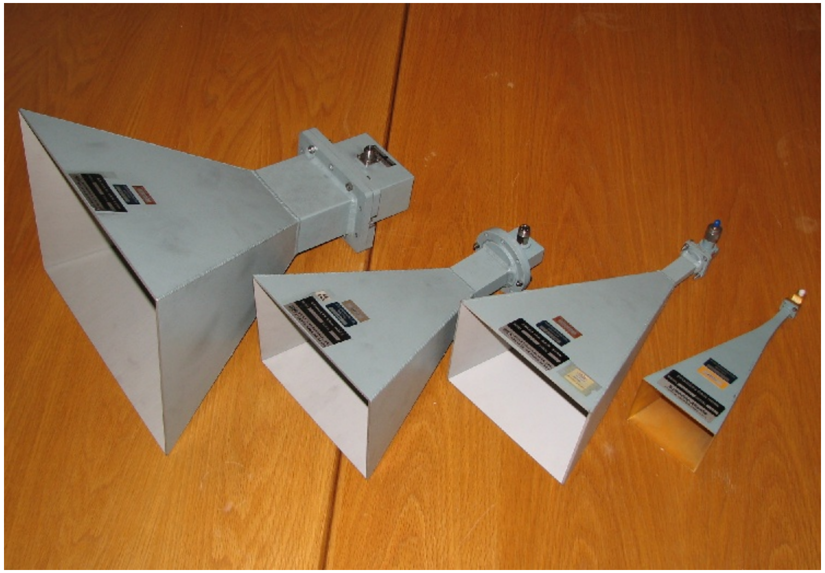
$$P^{rad} = \frac{1}{2} \sum_{smn} \left| Q_{smn}^{(3)} \right|^2$$

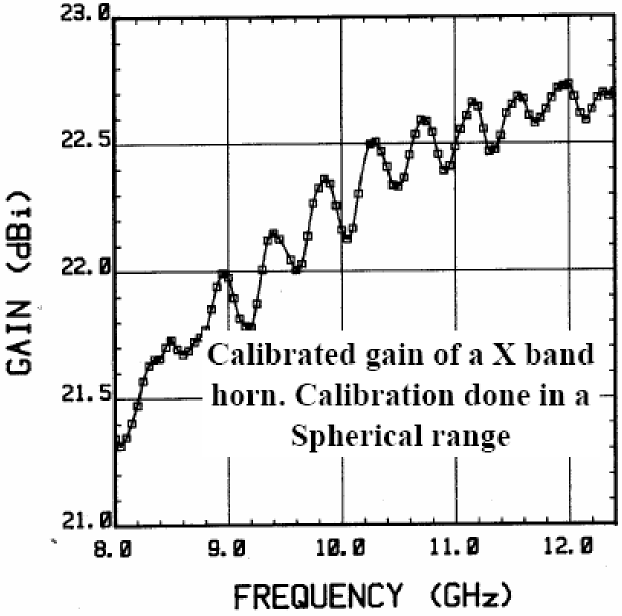
Gain determination procedure

- Full-sphere measurement of AUT
- Full-sphere measurement of SGH
- Measurement of Γ_{AUT} and Γ_{SGH}
- Calculation of G_{AUT} or η_{AUT}

Gain Standards

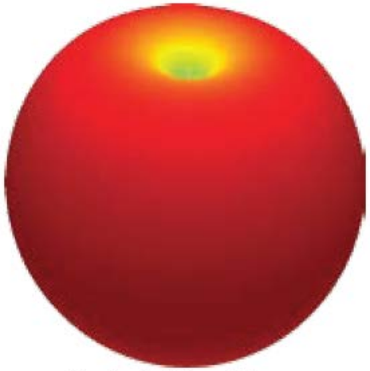
Standard Gain Horns





Calibrated gain of a X band horn. Calibration done in a Spherical range

Standard Dipoles



Typical 3D pattern

Measurement Uncertainty

Typical inaccuracies and errors

Pattern, Directivity

- Mechanical: pointing, axes intersection, probe orientation
- Electrical: noise, drift, non-linearity, leakage
- Probe-related: polarization, channel balance, pattern knowledge
- Stray signals: wall/terrain scattering, multiple reflections, interference
- Acquisition: scan area truncation, sampling point offset
- Processing: NF-FF transformation, filtering, interpolation

Gain, Efficiency

- AUT directivity
- SGH gain or efficiency
- Total radiated power (AUT, SGH)
- Mismatch correction (AUT, SGH)
- Amplitude drift
- Cable variations
- Scattering effects

Influence of each item is evaluated either by experiments or by simulations and *standard uncertainty* is estimated. *Combined standard uncertainty* is calculated as root sum square (RSS) of all standard uncertainties. *Expanded uncertainty* is calculated applying an *expansion factor* for the corresponding *confidence level*.

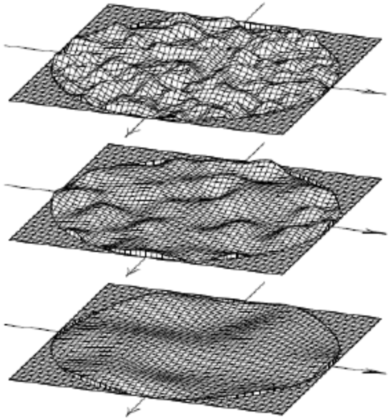
"**Guide to the Expression of Uncertainty in Measurement**", Intern. Organization for Standardization, Geneva, Switzerland, 1995.

Application Dependent Aspects

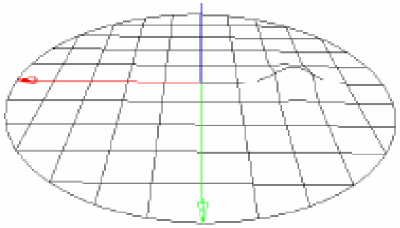
- Measurement of small antennas
  - Omni-directional pattern, influence of feed cable, integrated generator/receiver
  - Reverberation chamber measurements, Wheeler cup method
- Measurement of mm-wave antennas
  - Very large antennas, amplitude and phase instability
  - Phase drift compensation, phase-less measurements, holographic compact range
- Measurement of antennas located at/on user
  - Influence of user: absorption and scattering, instability
  - Specific Absorption Rate (SAR), Effective Isotropic Radiated Power (EIRP), etc.
- Measurement of antennas on satellites, aircrafts, ships, cars, etc.
  - Scattering from closely located and very big conductive body
  - Truncated measurements, measurements on scaled models
- Measurement of MIMO systems and smart antennas
  - New parameters: diversity gain, available capacity, total isotropic sensitivity, etc.
  - New techniques are required and being developed

Antenna Diagnostics I

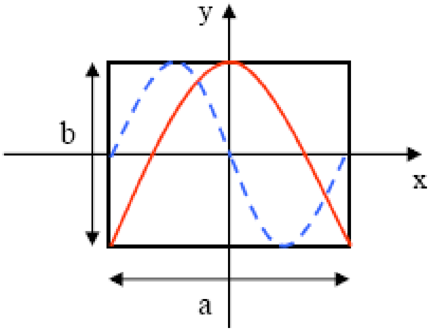
Identification of the unwanted mechanical and/or electrical errors in an antenna which modify the antenna performance



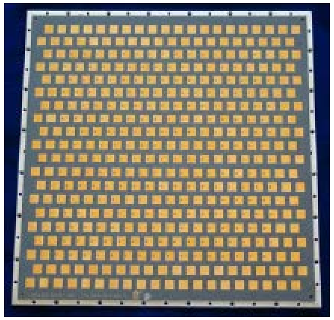
Surface distortions



Unwanted mode excitation

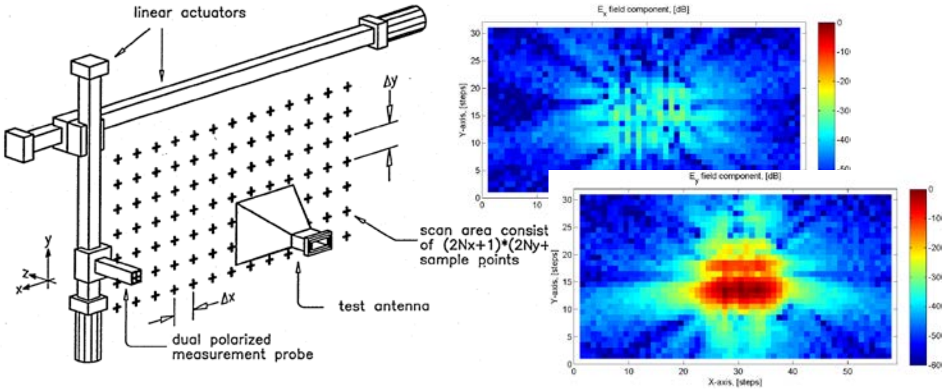


Feed network problems



Antenna Diagnostics II

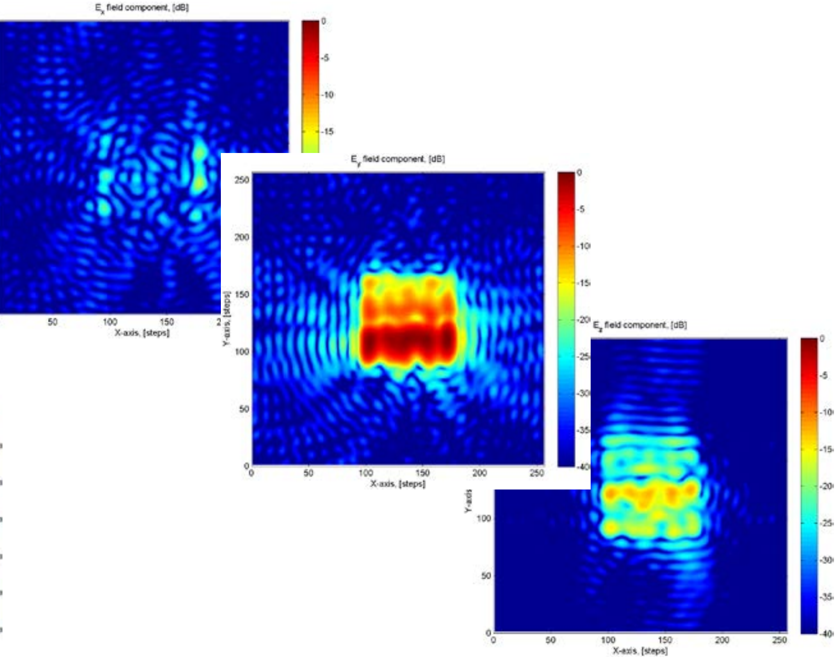
Step 1: Measurement of the near field or the far field



Step 3: Applying probe correction, calculation of the near field

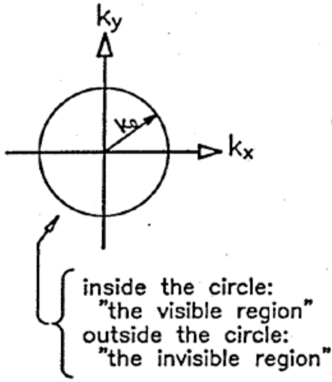
$$\mathbf{T}_x \approx \sum_{x,y} \mathbf{T}_s \mathbf{P}_{s,1} \Big/ \mathbf{P}_{x,1} \qquad \mathbf{T}_y \approx \sum_{x,y} \mathbf{T}_s \mathbf{P}_{s,2} \Big/ \mathbf{P}_{y,2} - \sum_{x,y} \mathbf{T}_s \mathbf{P}_{s,1} \Big/ \mathbf{P}_{x,1}\, \rho_2$$

$$\mathbf{E}_t(x,y,z) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \mathbf{T}_s(k_x, k_y) e^{i\gamma z} e^{i(k_x x + k_y y)} dk_x dk_y$$



Step 2: Calculation of the spectrum

$$\sum_{x,y} \mathbf{T}_s \mathbf{P}_s = \frac{e^{-i\gamma z_0}}{2\pi} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \mathbf{E}_t(x,y,z_0) e^{-i(k_x x + k_y y)} dxdy$$



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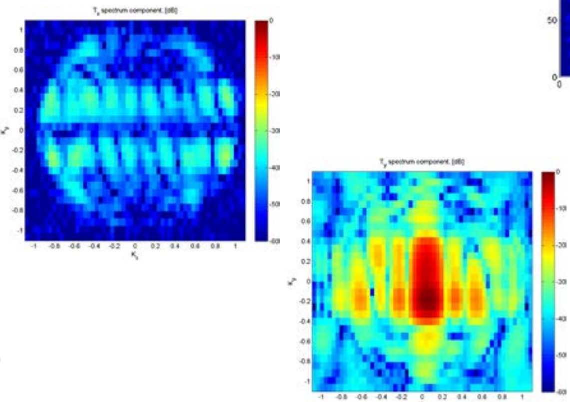

Advanced Spherical Near-Field Antenna Measurements

European School of Antennas

ESoA course held every second year around end-of-June at DTU

Advanced theory in few lectures

Practical exercises including

- Mechanical alignment
- Probe calibration
- NF antenna measurement
- S-parameters measurements
- Antenna diagnostics

Data processing and presentation

Literature

The following literature is suggested for reading:

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- A.D. Yaghjian. "An overview of near-field antenna measurements", *IEEE Trans. Antennas Propagat.*, vol. 34, no. 1, 1986, pp. 30-45.
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