Introduction to antenna measurement systems

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Outline

1. Introduction,
2. Far-field ranges,
3. Anechoic chambers,
4. Near-field systems: Spherical, planar & cylindrical,
5. Compact ranges,
6. Polarization measurements,
7. Measurement instrumentation,
8. Power and dynamic range,
9. Gain standards and Gain measurements,
10. Other measurement systems,
11. Visit to the UPM antenna test facilities.

Introduction

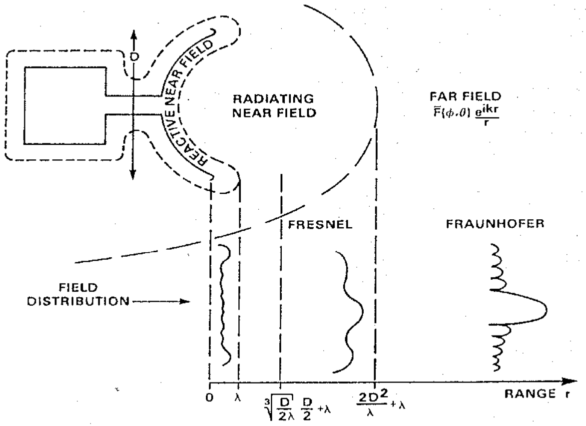
Introduction

- ***Definition of an antenna by the Webster's Dictionary:***
  → a usually metallic device for radiating or receiving radio waves.
- ***Definition of an antenna by IEEE Standard Definitions of Terms for Antenna:***
  → a mean for radiating or receiving radio waves
  → i.e. antenna is the transitional structure between free-space and a guiding device.
- ***Aims of Antenna Measurements*:**
  – Evaluation of designed antennas,
  – Empirical validation for antenna analysis methods.
- ***Antenna Parameters to be measured*:**
  – Radiation pattern parameters: directivity, cross-polar radiation...
  – Gain and antenna efficiency,
  – Impedance and port isolations.
- ***Antenna measurement systems according to field regions*:**
  – Outdoor far field ranges,
  – Anechoic chambers: planar, cylindrical, spherical near-field systems, compact ranges

Field Regions

Space surrounding an antenna is subdivided in:

- ***Reactive near field region***: that portion of the near field region immediately surrounding the antenna, where the reactive field predominates.
- ***Radiating near field region***: *(Includes Fresnel zone):* intermediate region, where the radiation fields predominate, but the angular field distribution depends upon the distance from the antenna.
- ***Far Field (Fraunhofer) region***: the region of the field of an antenna where the angular field distribution is independent of the distance from the antenna.



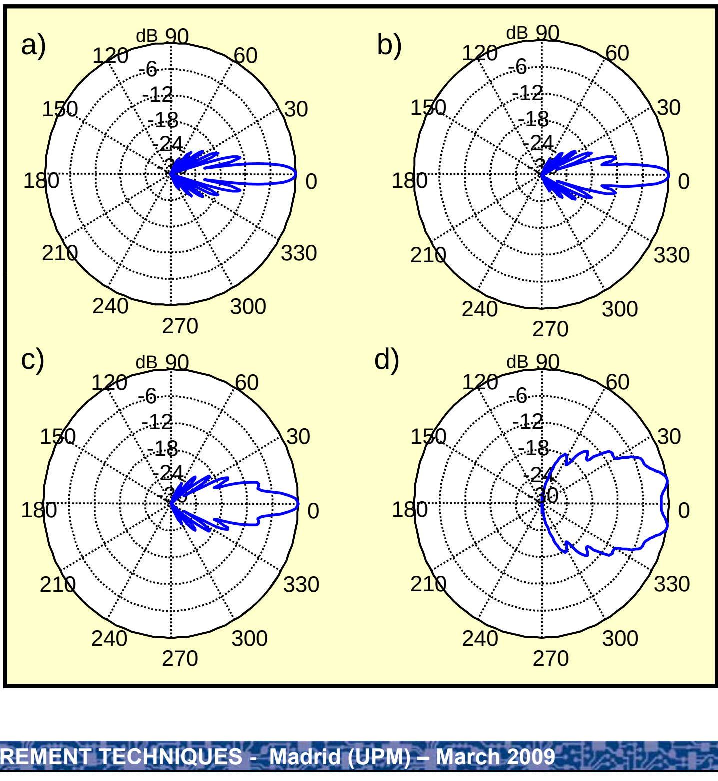
Far field distance satisfies:

$$r \geq \frac{2D^2}{\lambda} \quad y \quad r >> \lambda$$

D: Maximum dimension of the antenna

Example: radiated field of an antenna

- Simulated Vertical radiation pattern for a 9 resonant dipoles (h=210 cm) at 900 MHz.
- Far field distance = 26.7 m:
- distance d:
  - a) d = 27 m
  - b) d = 13.5 m
  - c) d = 6.75 m
  - d) d = 2.7 m

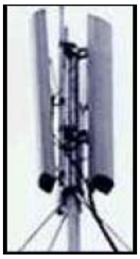


Antennas and far-field distances

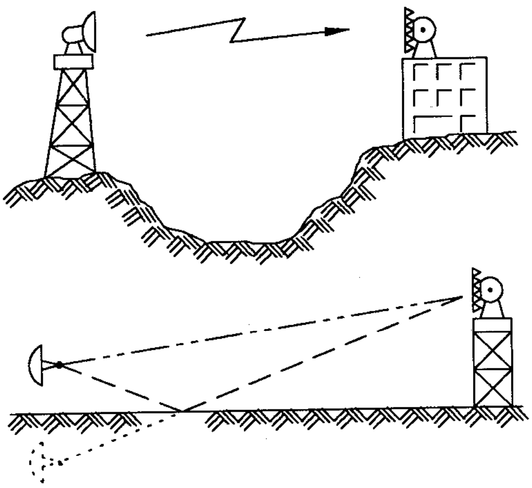
- For **monopoles** and **dipoles** (length $\leq \lambda$), **$R_{far\ field} \geq 10\lambda$** is used, because **reactive field** is **negligible**.

- For **large reflectors** in microwave band with circular aperture with $D >> \lambda$, **$R_{far\ field} \geq 2D^2/\lambda$** is used, because of the **phase errors at the aperture**.

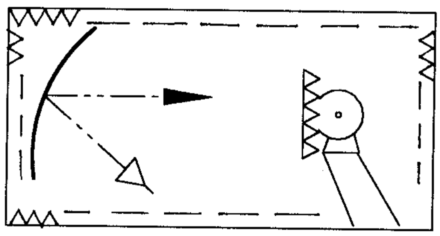
- For **base station antennas** (arrays with height $h >> \lambda$), **$R_{far\ field} \geq 2h^2/\lambda$** is used, because of the **phase errors at the aperture**.



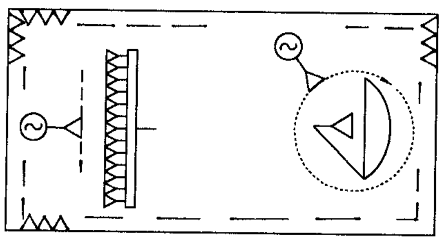
Antenna Measurement Systems



Far-Field Systems:
Elevated & Ground Reflection Ranges



Compact Systems

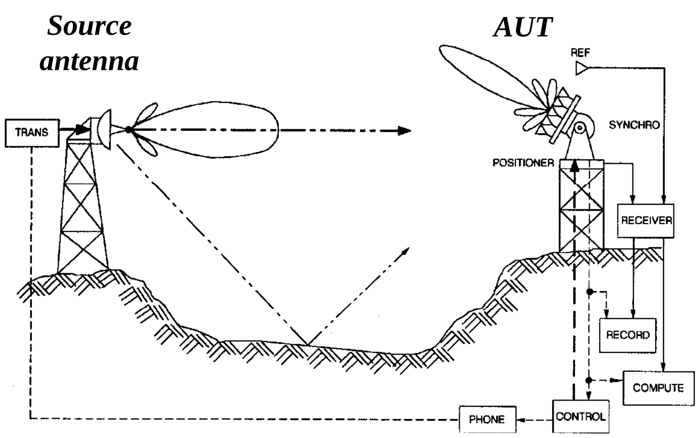


Near-Field Systems:
Planar, Cylindrical & Spherical

Far-field ranges

Far field ranges

- Antenna under test (AUT), usually in reception, is illuminated by a source (probe antenna).
  - → This antenna must be in **far field distance**.
  - → In this case, the incident wave is a **plane wave**.



• The AUT can be measured in transmission or in reception.

• Radiation patterns and parameters are the same, according to the reciprocity theorem.

Far field design: criteria

→ These criteria determine the source antenna specifications and the minimum distance R between antennas.

1- Inductive coupling between antennas.

– Important for low frequencies.

Ratio for a short dipole ⟹ $\mathbf{R \geq 10\lambda \;\Rightarrow\; \frac{E_{1/r^2}}{E_{1/r}} \leq -36dB}$

2- Spatial periodic variations in the illuminating wave front caused by reflections.

– Important for unmatched antennas or metallic supports with bad absorbers.

3- Longitudinal variation of the amplitude in the antenna.

– $R \geq 10\,L$ (L, length of the antenna) ⇔ Variation ≤ 1 dB

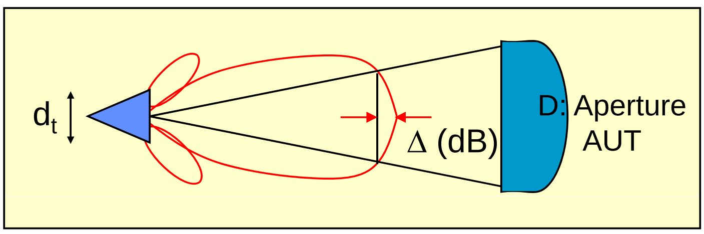
Far field design: criteria

4- Amplitude taper of the illuminating wave front.

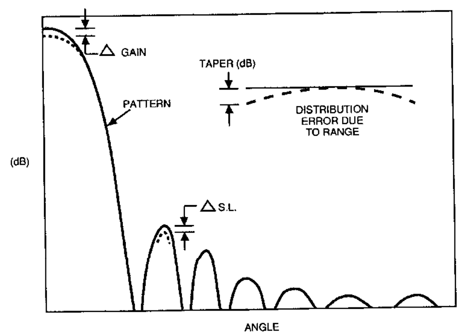
– Reduction in measured gain and SLL.

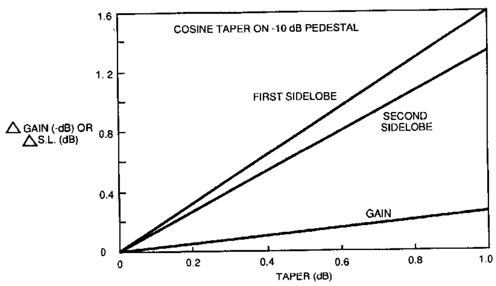
– For a typical parabolic reflector (cosine taper on –10 dB pedestal)

» Δ=-0.5 dB ⇒ ΔG=-0.15 dB.



– **CRITERIA: $\Delta \approx$ -0.25 dB⇒ d_t**





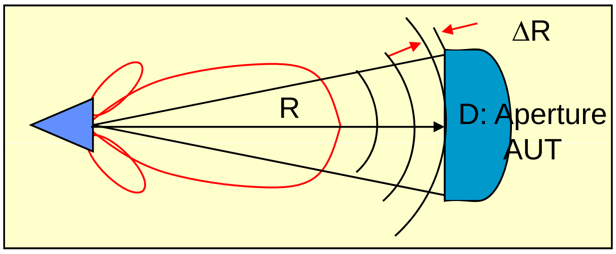
Far field design: criteria

5- Phase error/curvature of the illuminating wave front.

- Reduces the gain.
- Increases the side lobe and fills the nulls.

$$\Delta R \approx \frac{D^2}{8R} \qquad \Delta\Phi = \frac{2\pi}{\lambda}\Delta R \approx \frac{\pi D^2}{4\lambda\lambda}$$

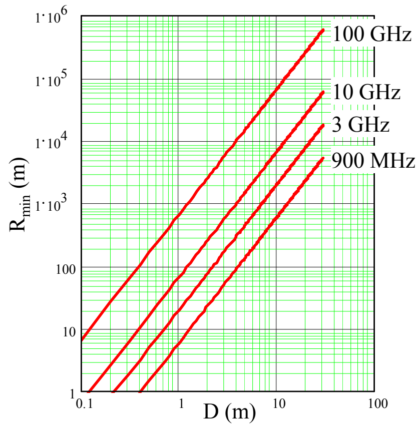
- MINIMUM DISTANCE CRITERIA: phase error = 22.5º



$$\Delta\Phi \le \frac{\pi}{8}$$

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

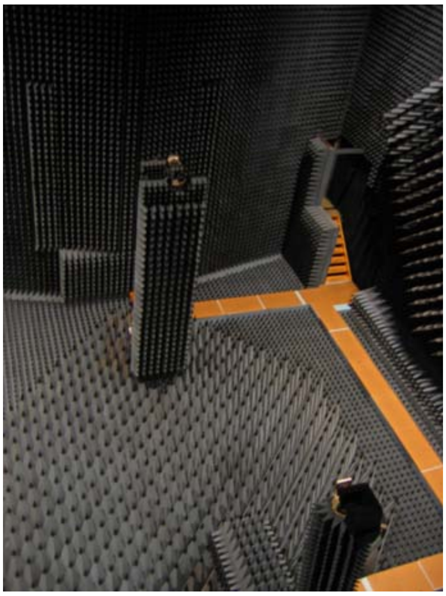
⇒ **Far field distance**



Anechoic chambers

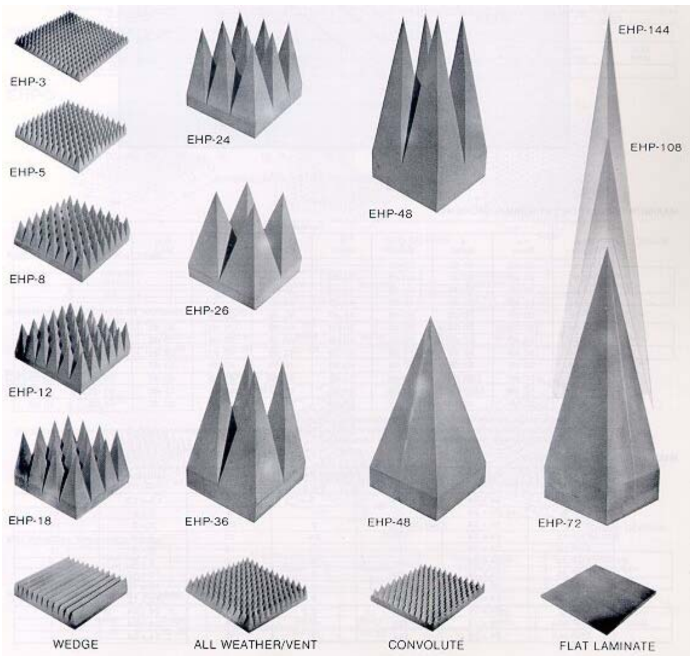
Anechoic chambers

- Close areas (normally shielded) covered by electromagnetic absorbing material, that simulate free space propagation conditions, due to the absorption of the radiation absorbing material (RAM).



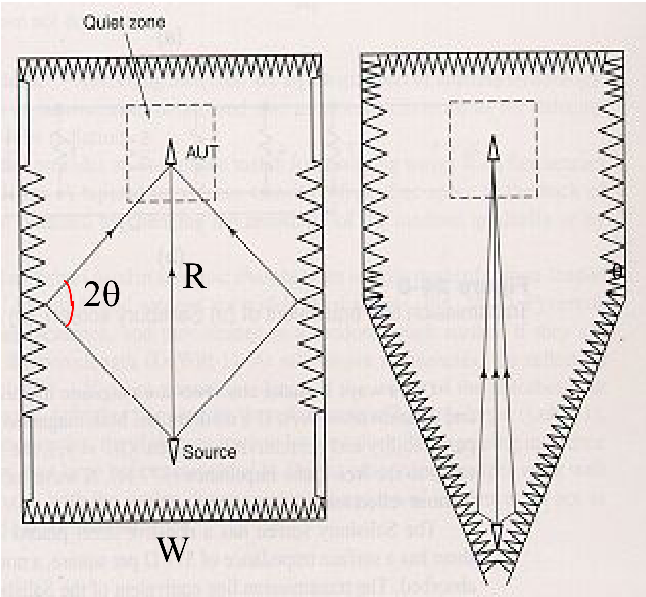
- **Advantages:**
  - *All weather operation.*
  - *Control of the environment (temperature, cleanness ...)*
  - *Security.*
  - *Freedom from interference.*

Anechoic chambers: Microwave Absorbing materials



- **Pyramidal absorbers** ($H>5\lambda$): $\rho < -50$ dB.
- **Convoluted absorbers**: $\rho < -50$ dB in mm-wavelengths.
- **Flat laminate absorbers**: $\rho < -25$ dB (towers...).
- **Walkway absorbers**: (pyramidal + foam + polystyrene laminate) .
- **Wedge absorbers**: for compact ranges.
- **All weather or vent absorbers**.

Anechoic chambers: Examples



***a) Rectangular Test chamber*:**

$\theta_{max}<70^{\circ} \Longrightarrow W/R>1/2.75$

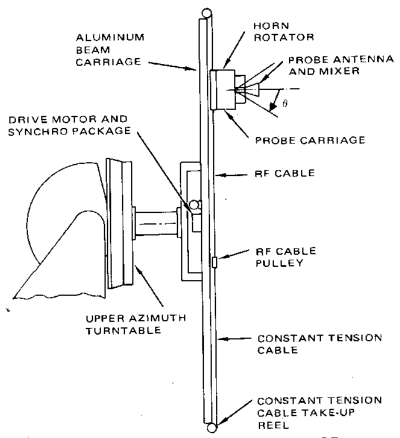
Source antenna main lobe can't illuminate the side walls, floor or ceiling.

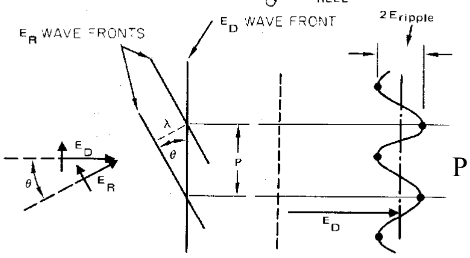
***b) Tapered Test Chamber*:**

Interference signals eliminate the ripple in quiet zone. Used in VHF and UHF.
The source is adjusted at each frequency.

***c) Semi-open chamber*:** AUT is protected by a building (without one wall). The antenna source is far away.

Anechoic chambers: Range evaluation of a planar scanner





$$P=\frac{\lambda}{\text{sen}\,\theta}$$

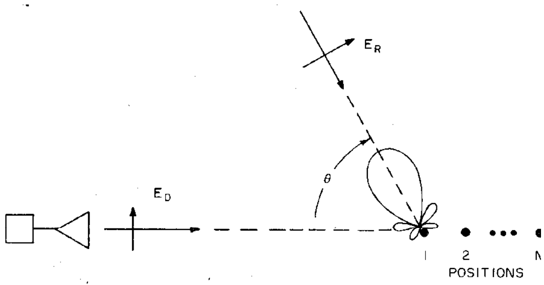
- Using a linear slide and an azimuth turntable (or a XY scanner), it is possible:
  - To test if the maximum of the antenna source is directed to the centre of the quiet zone (measurement aperture).
  - To evaluate the reflections.

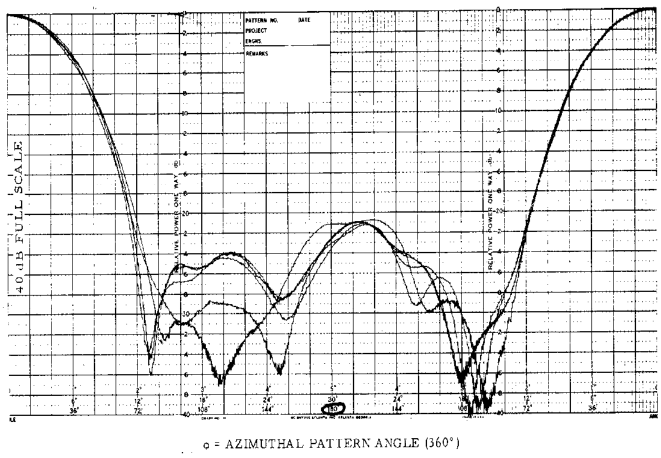
$$\frac{E_R}{E_D}(\text{dB})=20\log\left(\frac{-1+10^{\sigma/20}}{1+10^{\sigma/20}}\right)$$

σ = peak to peak ripple (dB)

Anechoic chambers: Range evaluation with a pattern comparison method

- The same antenna is measured at different distances. In this way, the direct and reflect signals add with different relative phases in AUT.
- The maximum to minimum ratio and the average allow to obtain the reflected signal level





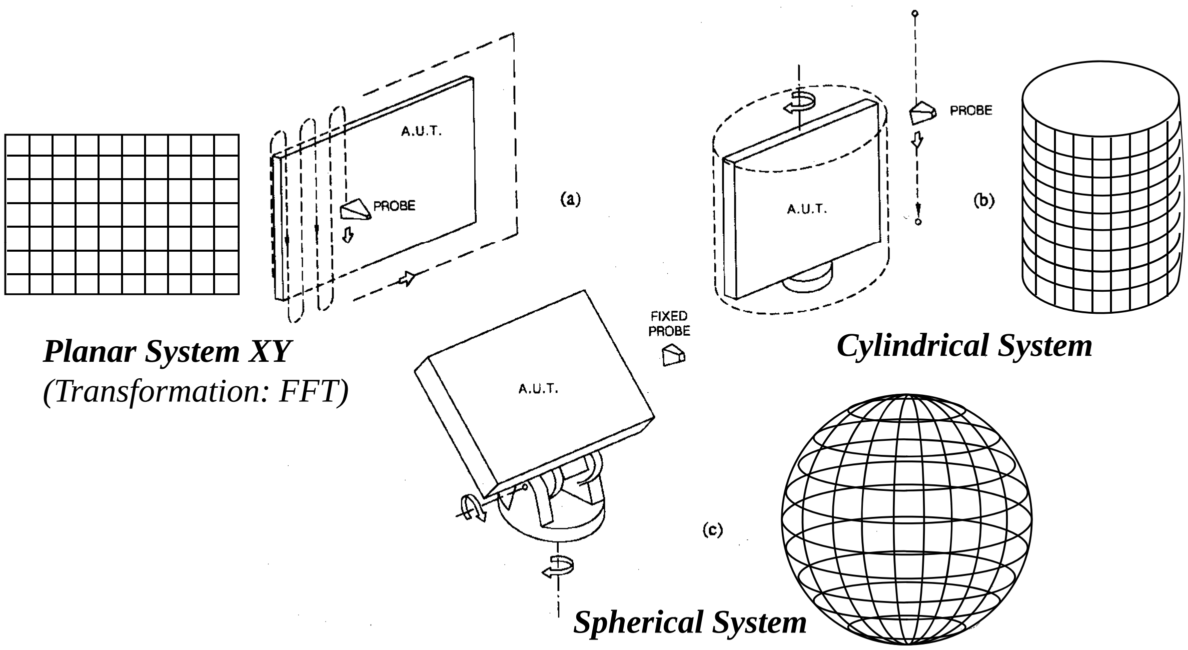
Near-field systems:

Spherical, planar, cylindrical

Near field systems

- The radiated field is **measured in a surface** (plane, cylinder or sphere) **near to the AUT**, and the far field is obtained using a **transformation** algorithm.
- **Advantages**:
  - Less use of space,
  - Indoor systems advantages (independent of weather conditions…),
  - The far field is obtained without the error due to the finite distance.
- **Drawbacks**:
  - More complex and precise exploring systems are required,
  - Transformation software based on modal analysis (with plane, cylindrical or spherical waves),
  - A probe calibration is necessary.

Types of near-field scanning



Spherical near-field system

- Any **solution** can be expressed as a **sum of the spherical vector waves** → we refer to this sum as the **spherical wave expansion (SWE)**.
- The **SWE for the AUT** (in the AUT coordinate system) can be transformed to the **probe coordinate system** using 3 rotation coefficients and 1 translation coefficient.
- Using the **probe receiving coefficients,** the **signal received by the probe** can be obtained.
- The **knowledge of the probe receiving coefficients** is obtained from a separate **probe calibration**.
- In spherical near-field measurements, a **precise optical alignment is important**:
  - The **roll over azimuth axes must intersect** to assure acquisition over a **sphere**.
  - The **probe axis must point to the cutting point of the roll and azimuth axes**.
  - The **acquisition points** must satisfy the **sampling theorem**:

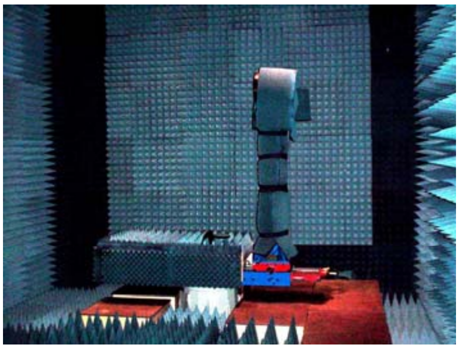
$$N_{max} = \left\lceil \frac{2\pi}{\lambda} \cdot R_0 \right\rceil + \text{Margin}, (\text{normally Margin} = 10) \quad and \quad \Delta\theta = \Delta\phi = \frac{180}{N_{max}}$$

Example of an spherical near-field system

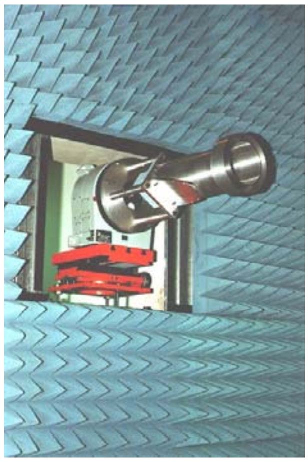
UPM antenna measurement ranges

Spherical System:

- Dimensions: **7.3 x 4.3 x 4.3 m**
- Frequency band: **1.5 – 20 GHz**
- **ORBIT Controller and positioners**
- **Agilent HP8530A VNA**
- Approved for **Space Measurements** (ESA) at 5.3 GHz using ERS panel



AUT Positioner. Roll over Azimuth on longitudinal table



Polarization Positioner

Planar near-field system: theoretical analysis

- In the planar near-field system, the **coupling equation** relates the **measured values** with the **probe correction coefficients** and the **AUT transmission coefficients**.
- Since they are related by **a Fourier Transform**, it can be solved applying an Inverse Fourier Transform.

Measured Values

$$D(k_x,k_y)=\sum_{s=M,N} S_s(k_x,-k_y)T_s(k_x,k_y)=\frac{(1-\Gamma_s\Gamma_l)\exp(-j\gamma z_0)}{(2\pi)^4 a_0}\frac{kZ}{\gamma}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} b'_0(\vec{r}_0)\exp(-j\{k_x x+k_y y\})\,dx\,dy$$

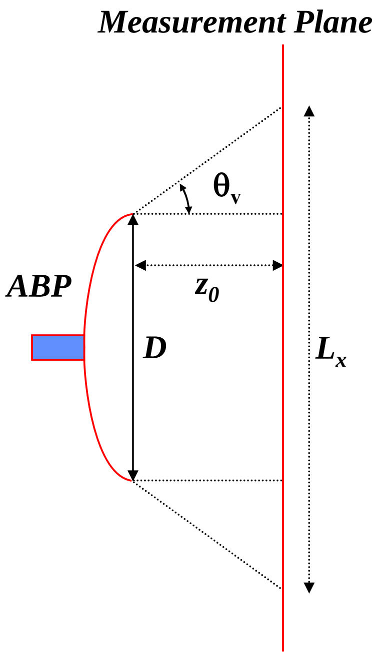
Probe Correction

AUT Transmission Properties

Planar near-field system: practical aspects

- **Angular validity of the measurement**:
  - → Sampling acquisitions has to be limited to a **finite rectangle** in the measurement plane.
  - → This truncation **limits the validity** of measurement result in far field to **angles lower to θ_v**.

$$\theta_v = \text{atan}\left(\frac{L_x - D}{2z_0}\right)$$



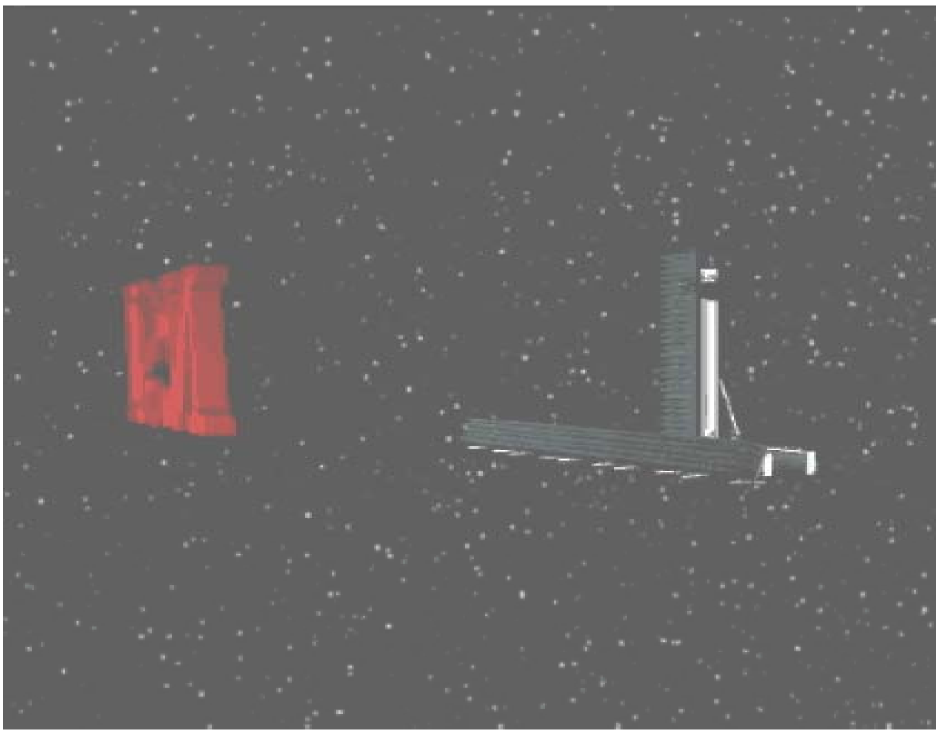
  - → If **$E(L_x/2)$ < -40 dB**, the **truncation error** is **negligible**.
- **Maximum sampling rate** → **Sampling Theorem**

$$\Delta_x \le \frac{2\pi}{2k} = \frac{\lambda}{2}$$

$$\Delta_y \le \frac{\lambda}{2}$$

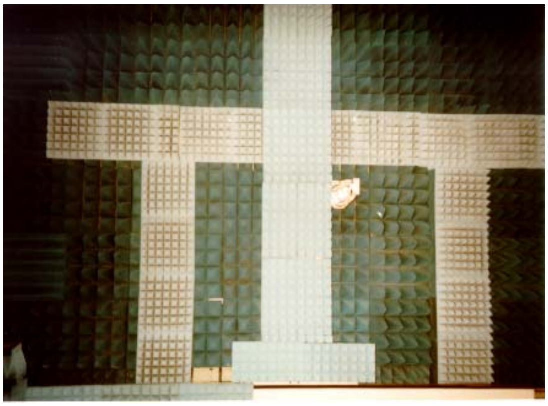
(In some conditions, it can be higher)

Planar near-field system



UPM antenna measurement ranges

Planar System:



- 3 high precision linear elements assure the **scanner high precision**.
- The lower horizontal guide is a **linear ball spline**, that allows a free rotation of the vertical tower.
- The tower leans on the upper horizontal guide.
- Scan area: **4.75 x 4.75 meters**
- Frequency band: **0.8 – 40 GHz**
- Horizontal axis velocity: **10 cm/sec**
- Vertical axis velocity: **33 cm/sec**
- **z errors < 0,34mm** peak to peak in the scan area

Dimensions: **6 meters lower horizontal guide**
1 meter supporting cart
5.5 meters tower
upper horizontal guide at 2 meters

Cylindrical near-field system

- In the cylindrical near-field system, the **coupling equation** relates the measured values with the **probe correction coefficients** and the **AUT transmission coefficients**.
- With **2 set of measured values for each polarization** & the probe **correction coefficients**, the **AUT transmission coefficients** could be derived.
- Then, with these **AUT transmission coefficients**, the **θ-components & φ-components** of the far-field can be obtained.

→ **Far-field:**

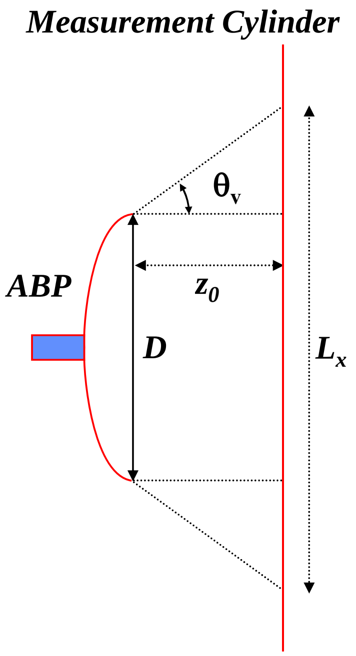
$$E_\phi(\theta,\phi) = \sin\theta \sum_{n=-\infty}^{\infty} j^n a_n (k\cos\theta)\cdot e^{jn\phi}$$

$$E_\theta(\theta,\phi) = j\sin\theta \sum_{n=-\infty}^{\infty} j^n b_n (k\cos\theta)\cdot e^{jn\phi}$$

Cylindrical near-field system: practical aspects

- **Angular validity of the measurement**:
  - → Sampling acquisitions has to be limited to a **finite rectangle** in the measurement plane.
  - → This truncation **limits the validity** of measurement result in far field to **angles lower to θ_v**.

$$\theta_v = \mathrm{atan}\left(\frac{L_x - D}{2z_0}\right)$$



  - → If **$E(L_x/2) < -40$ dB**, the **truncation error** is **negligible**.
- **Maximum sampling rate** → **Sampling Theorem**
  - Vertical direction: **the same than planar system**,
  - Horizontal direction: **the same than the spherical system**.

Cylindrical near-field system

UPM antenna measurement ranges

Cylindrical and Spherical System:

- **Sharing elements with the planar system**.
- Cylindrical: **AUT on Azimuth positioner** and **probe on scanner y-axis**.
- Spherical system: **AUT on Roll over Azimuth**
- Frequency band: **1 – 40 GHz**
- **Linear slide to adjust measurement distance**.

CYLINDRICAL SYSTEM

Compact ranges

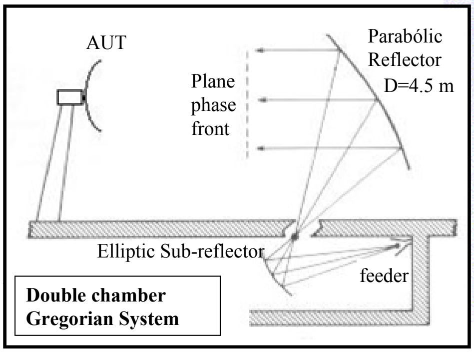
Compact ranges

- The idea is to form a **planar wave** around the AUT using **reflector** systems.
- They are used for **measuring antennas in far field** and for measuring object **RCS**.
- **Don't need field transformation**, the measurements are obtained in **far-field**.
- LIMITATIONS:
  - → **Complex & big structures** needed, so the chamber **dimensions** must be **higher**.
  - → Their **precisions** are, in general, **lower** than in near field systems.
  - → Mainly related with the **flatness of the field in the quiet zone:**
    - – Desired amplitude constant to a fraction of a dB,
    - – Desired phase flat to few degrees.
  - → **At higher frequencies, limited by the tolerances of the reflectors surfaces.**
  - → **At lower frequencies, limited by the electrical size of the absorber pyramids.**

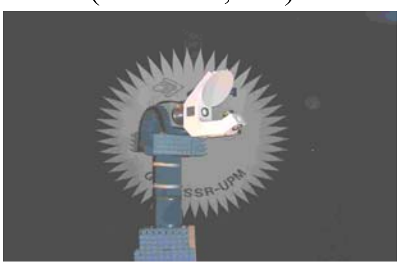
UPM antenna measurement ranges

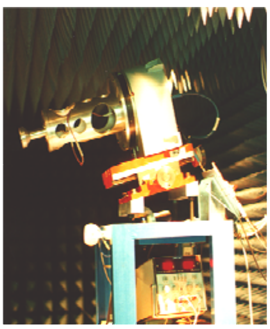
Compact Range System:

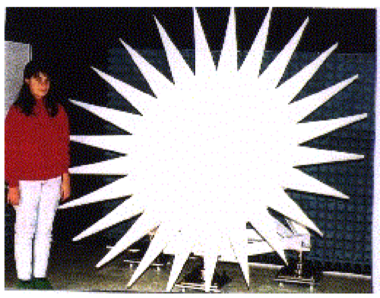
Gregorian System
Measurements of **Antennas** and **RCS**
Dimensions:
Main chamber: **15.2 x 7.9 x 7.3 m**
Subreflector chamber: **6 x 3 x 2.4 m**
Frequency band: **6 – 60 GHz**
Rotary joints at 40 GHz
Quiet zone at X band: **2.5 m.diameter**
(±0.25 dB, ±3º)



Main Reflector

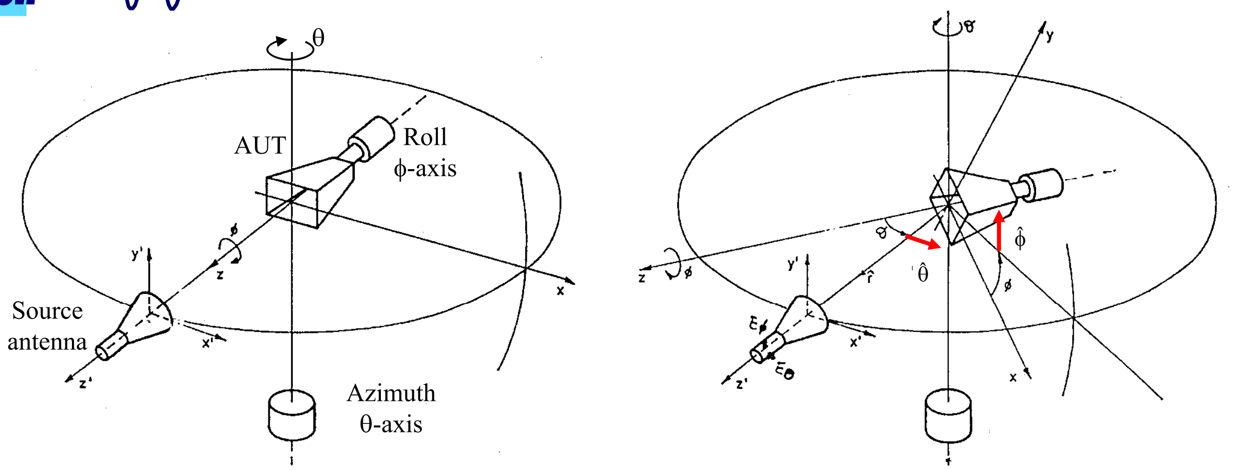



Feeder


Subreflector

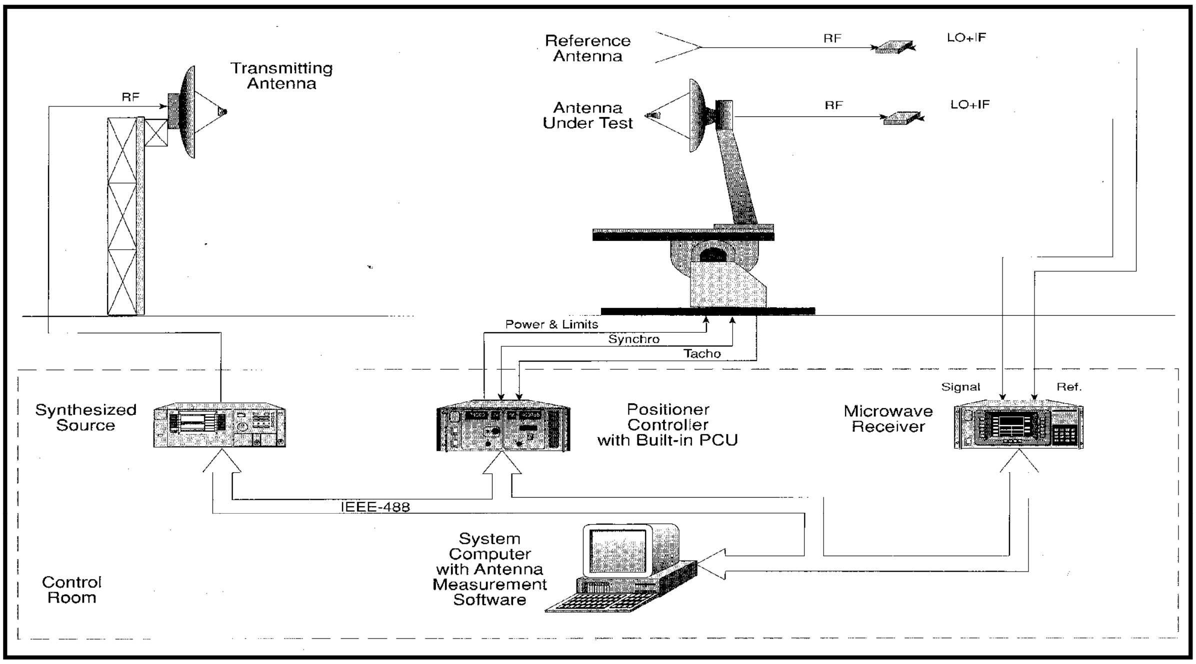
- Polarization measurements,
- Measurement instrumentation,
- Power and dynamic range.

Polarization measurements



- With a double polarization probe, it is possible to obtain E_θ y E_ϕ simultaneously, but an accurate calibration of both channels is required.
- With a single polarization probe, each component is acquired in one scan with a 90º rotation of source antenna.
- Components CP-XP, CPC-XPC are obtained with field expressions.

Measurement instrumentation

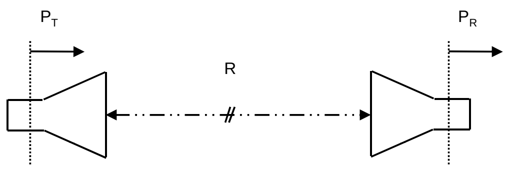


Power and dynamic range

$$P_{Rmax}(dBm) = P_T(dBm) + 20\log\left(\frac{\lambda}{4\pi \cdot R}\right) + G_T(dBi) + G_R(dBi) \leq P_{Sat}$$

$$P_{Rmin}(dBm) = S_{Rx}(dBm) + (S/N)(dB)$$

$$DR(dB) = P_{Rmax}(dBm) - P_{Rmin}(dBm)$$



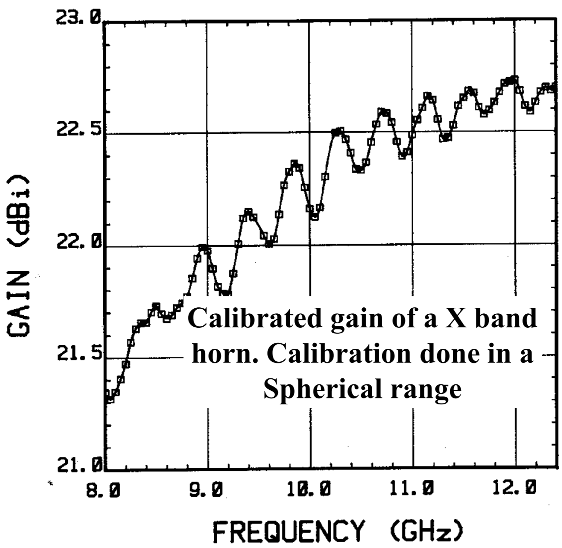
P_{sat} = Saturation of the transmitter
S_{Rx} = Sensitivity of the receiver
S/N = Required signal to noise (measurement errors)
DR = dynamic range of the measurement (SLL or XP requirements)

S/N	Amp. error	Phase error
20 dB	±0.9 dB	±5.7 º
30 dB	±0.28 dB	±1.8º
40 dB	±0.09 dB	±0.57º

Gain measurements

Gain standards

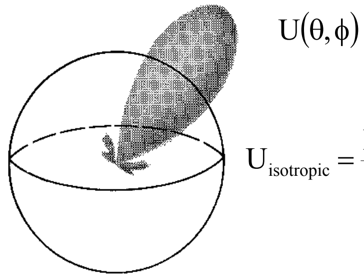
- **In microwave bands, rectangular horns are used as gain standards.**
- **The gain is almost equal to the directivity given by the manufacturer.**
  - The error of this value uses to be in 0.3 dB
- **If a better precision is required, it is necessary to calibrate the gain standard, using:**
  - Absolute gain measurement.
  - Integrating the radiation pattern to obtain the directivity



Gain measurements

- ***IEEE Standard Definitions of Terms for Antennas***:
  → **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".

$$G = \frac{r^2 \Re\{1/2 \cdot \mathbf{E} \cdot \mathbf{H}^*\}}{P_{accepted}/4\pi}$$



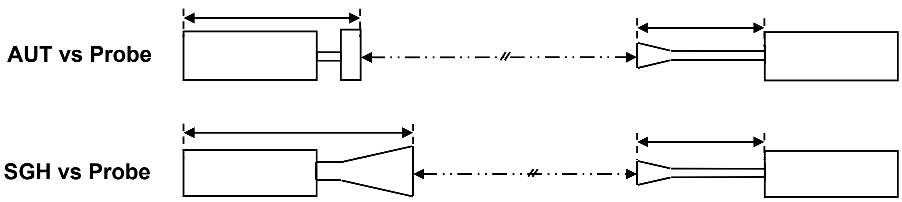
$$U_{isotropic} = \frac{P_{radiated}}{4\pi}$$

→ **REALIZED GAIN**:
"The gain of an antenna reduced by the losses due to the mismatch of the antenna input impedance to a specified impedance".

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

Gain measurements

- The most classical method is **gain substitution technique**, illuminating the **AUT** and a **gain standard** (usually, a Standard Gain Horn, **SGH**) with the same source antenna, for example a **probe**.



- **Far-field substitution technique**:

$$(G_{aut})_{dB} = 20\log\left(\frac{d_{aut-prb}}{d_{sgh-prb}}\right) + (G_{sgh})_{dB} + 10\log\left(\frac{P_{R\,aut-prb}}{P_{R\,sgh-prb}}\right) + 10\log\left|\frac{\left(1-|\Gamma_{sgh}|^2\right)}{\left(1-|\Gamma_{aut}|^2\right)}\right|$$

Gain measurements

- Correction for impedance mismatch:

$$\Delta_Z = -10\log\left|\frac{\left(1-|\Gamma_{aut}|^2\right)\left(1-|\Gamma_{rx}|^2\right)}{|1-\Gamma_{aut}\Gamma_{rx}|^2}\right| + 10\log\left|\frac{\left(1-|\Gamma_{sgh}|^2\right)\left(1-|\Gamma_{rx}|^2\right)}{|1-\Gamma_{sgh}\Gamma_{rx}|^2}\right|$$

- To improve the impedance matching, an attenuator after the AUT is used. In this case: $\Gamma_{rx} \approx 0$.

$$\Rightarrow \Delta_Z = 10\log\left|\frac{\left(1-|\Gamma_{sgh}|^2\right)}{\left(1-|\Gamma_{aut}|^2\right)}\right|$$

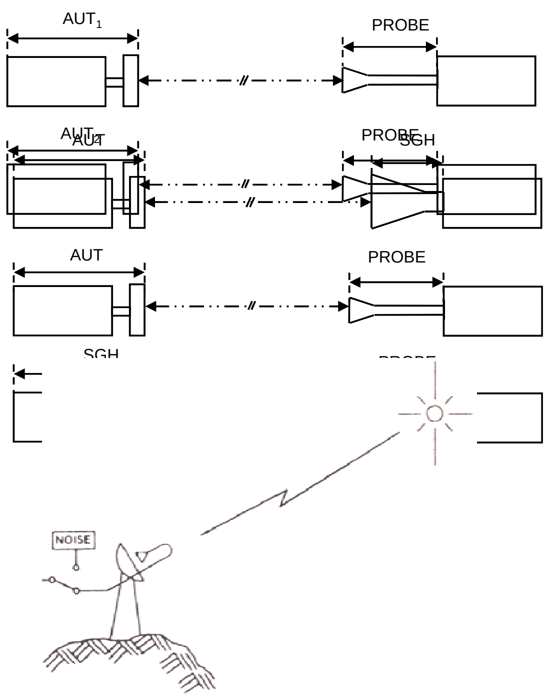
Absolute gain measurements

3 main types → Two antenna method,
→ Three antenna method,
→ Radio source technique

A) Two antennas method: based on using identical antennas and the Friis transmission formula.

B) Three antennas method eliminates the need for identical antennas by making three measurements and solving the three equations.

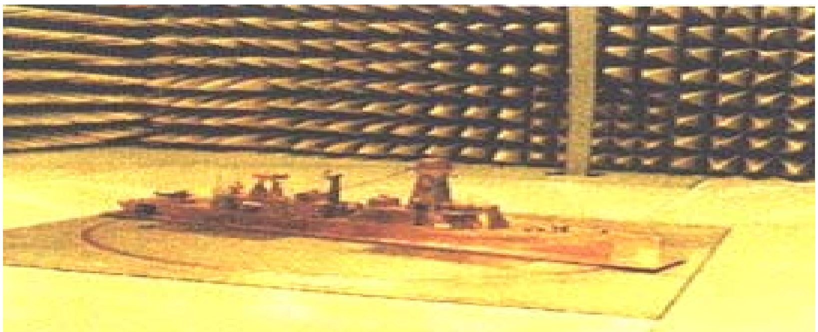
C) Radio source is suited to very large, high gain antennas that cannot be measured any other way. The gain can be calculated either by comparing the level to a known noise source or by compution from the known noise figure and bandwidth of the receiver.



Others measurement systems

UPM antenna measurement ranges

Arc System: Semi-Anechoic chamber



- **Measurements of Antennas on scaled ships** (1:50 and 1:100 models)
- Dimensions: **6.5 x 5.5 x 2.7 m**
- Frequency band: **200 MHz – 3 GHz**
- Positioning system: **azimuth for ship and elevation for probe**.

Systems based on thermographical techniques

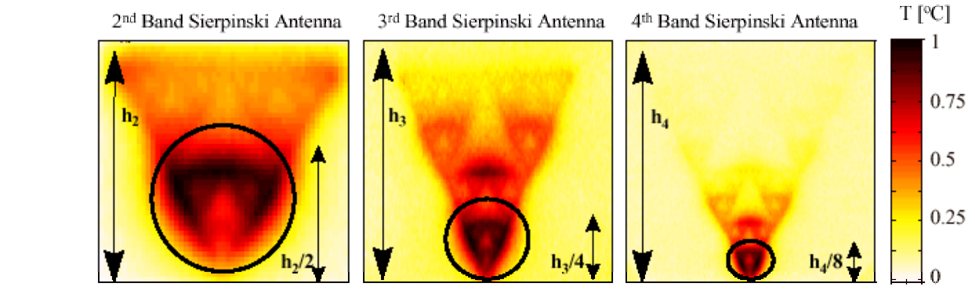
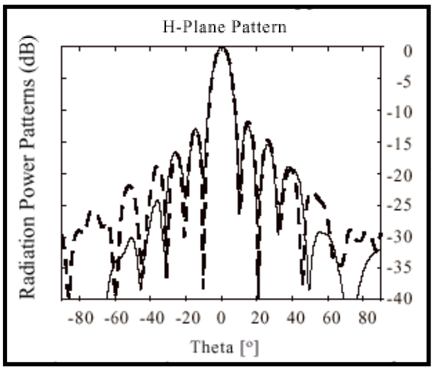


Fig. 5. Thermograms of Fractal-Sierpinki Antennas of 2nd, 3rd, and 4th band: h_2=6 cm; h_3=12 cm and h_4=22 cm.



- **Thermal intensity measurement in the planar system,**
- **Phase reconstruction,**
- **Radiation pattern extraction.**

Systems for small antennas (mobile)

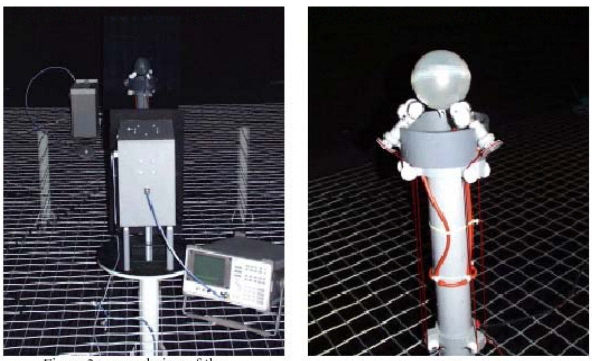


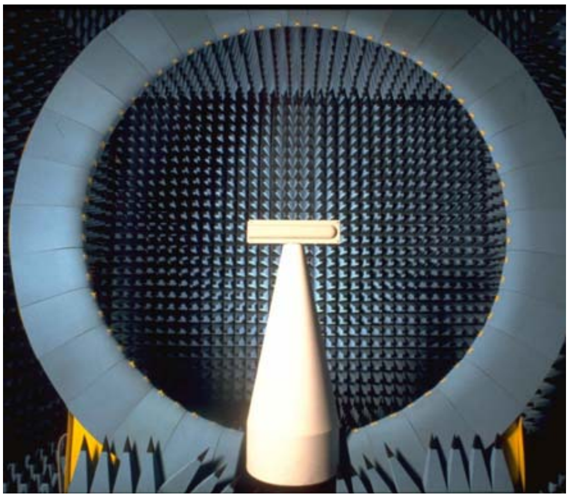
Figure 2 : general view of the measurement

Figure 3 : view of the positionner

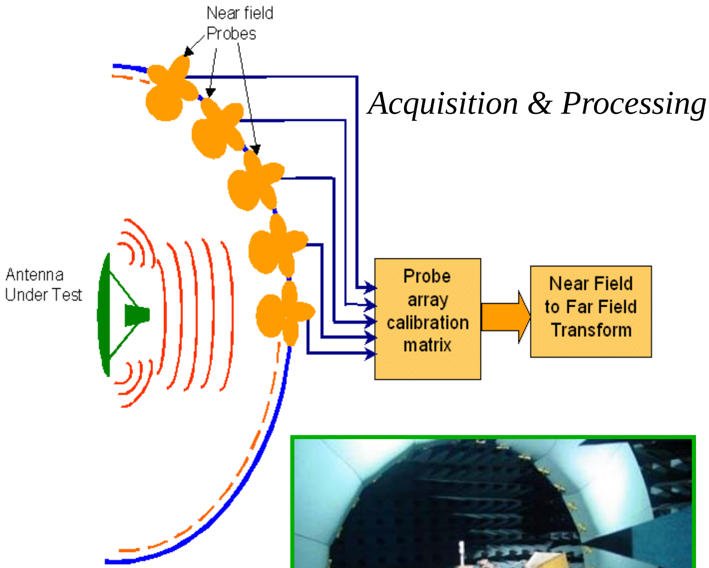
Sistema de EPFL-LEMA (Lausanne - Suiza)

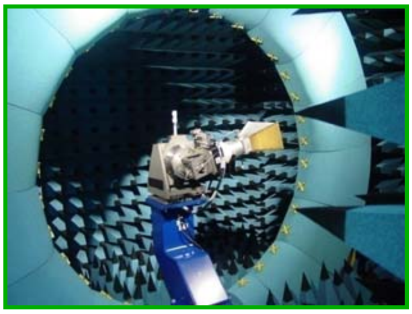
Sistema de Chalmers-Bluetest (Göteborg – Suecia)

SATIMO Stargate System



Stargate system made of 64 probes

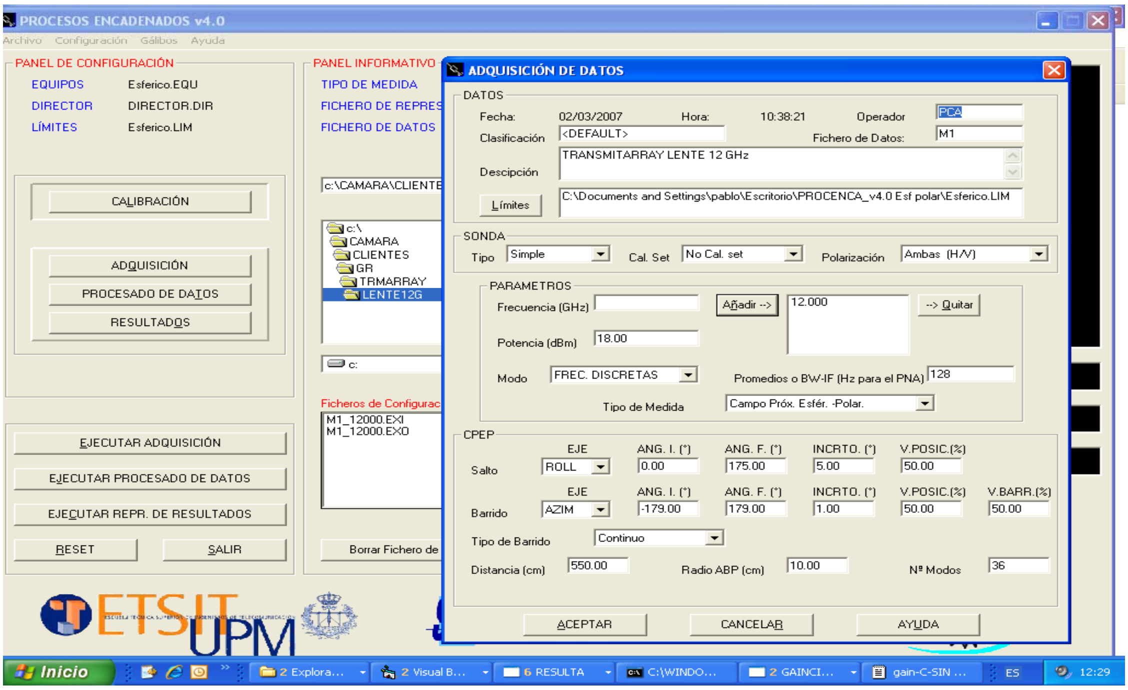




Probe Calibration

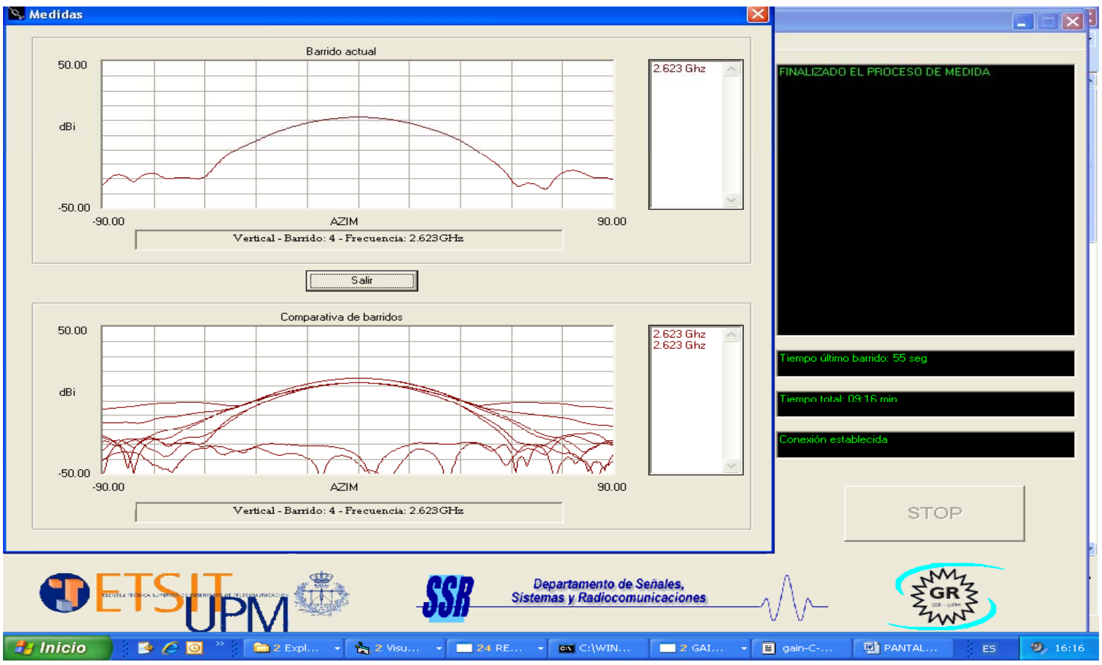
Acquisition, Processing and Representation Software

Software PROCENCA (GR-UPM)



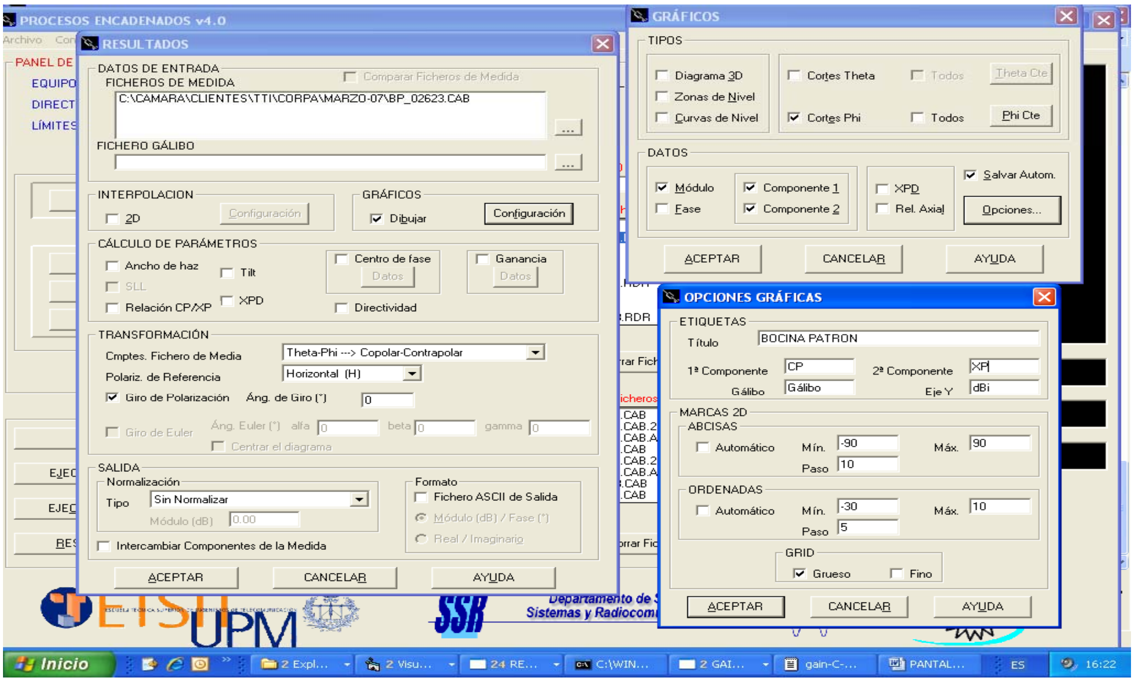
Measurement definition

Software PROCENCA (GR-UPM)



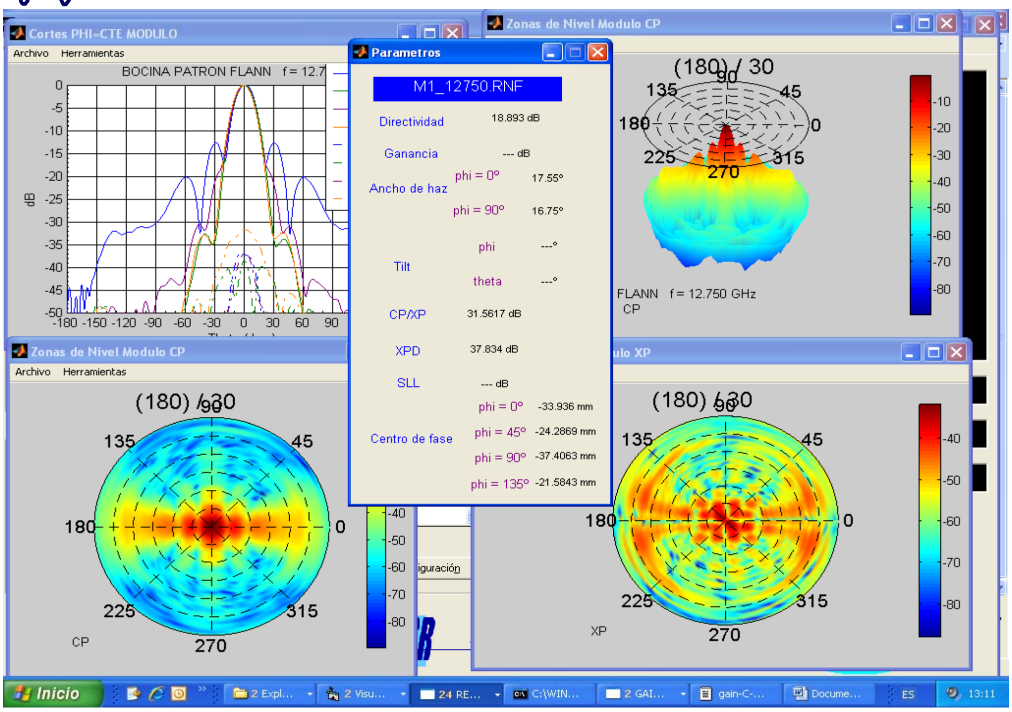
Acquisition

Software PROCENCA (GR-UPM)



Results definition

Software PROCENCA (GR-UPM)



Results

And now…

→ Visit to the UPM antenna test facilities…