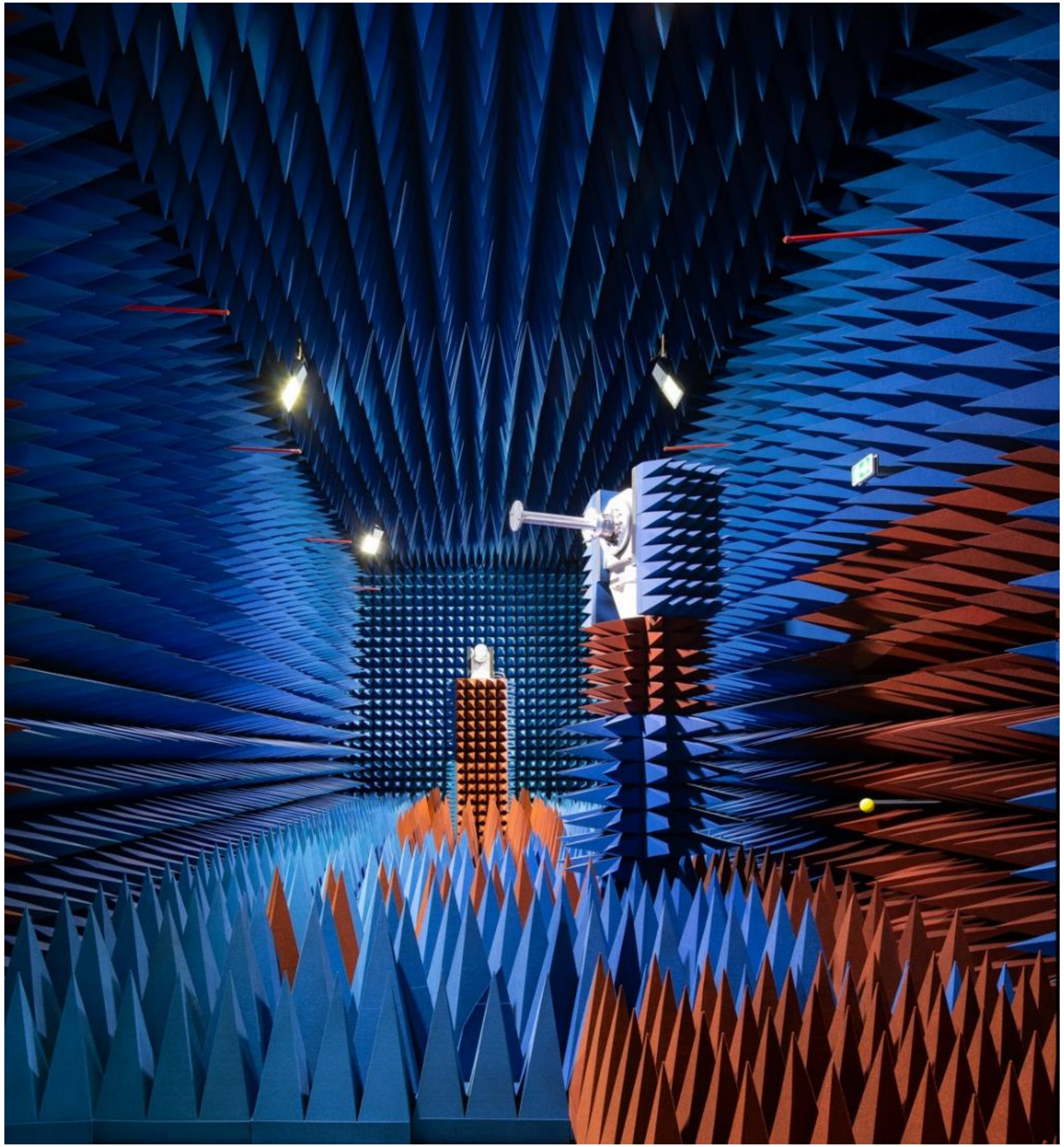

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Introduction to Antenna Measurements

Réseaux des Electroniciens du CNRS
Journées Radar, 17 au 19 Octobre 2023, IETR, Rennes

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plate-forme M²ARS (Manufacturing Measurement and Analysis of Radiating Systems)

Institut d'Electronique et des Technologies du numéRique

Outline

Introduction

Introduction

What is an antenna?

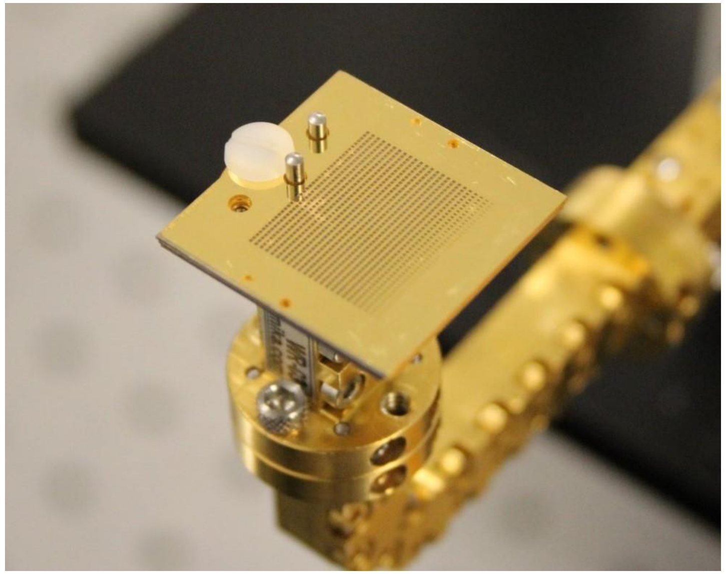
- Transducer transforming guided on wave into wave propagating in free space.
- Device focusing radiated field in the space.
- Component used as emitter or receiver.
- Active or passive device.
- System for signal transmission between fixed or moving points.
- System for signal emission and reception for imaging purposes.

Introduction

What are the different kind of characterization needs?

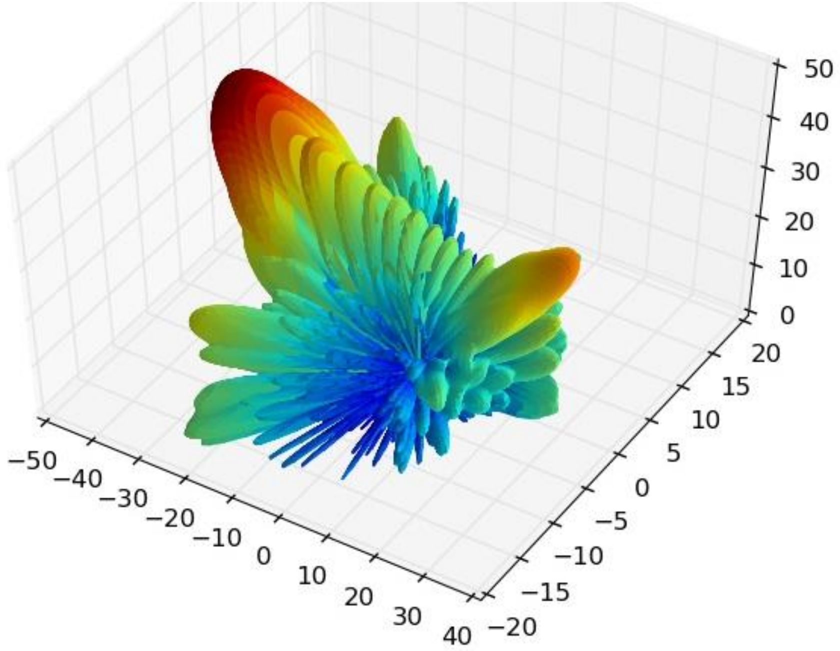
Circuit characterization : Reflection coefficient ; Access coupling

> Scalar or Vector Network Analyser



Radiation characterization : beam characterisitics (direction, size) ; gain ; polarization

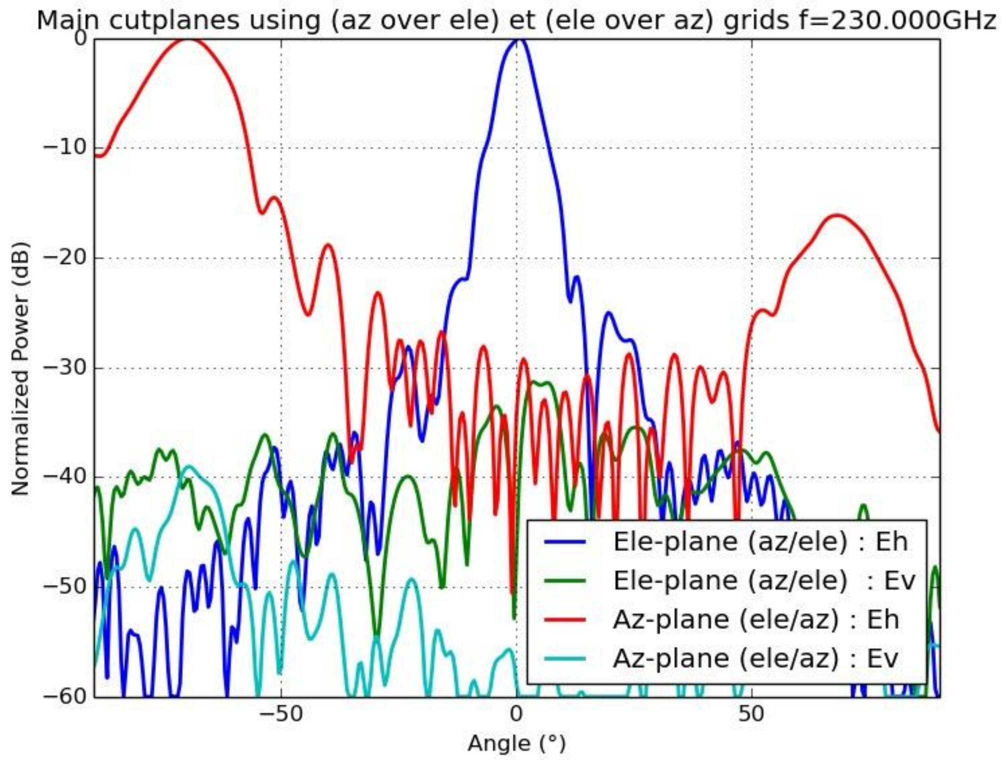
> Antenna Test Facility

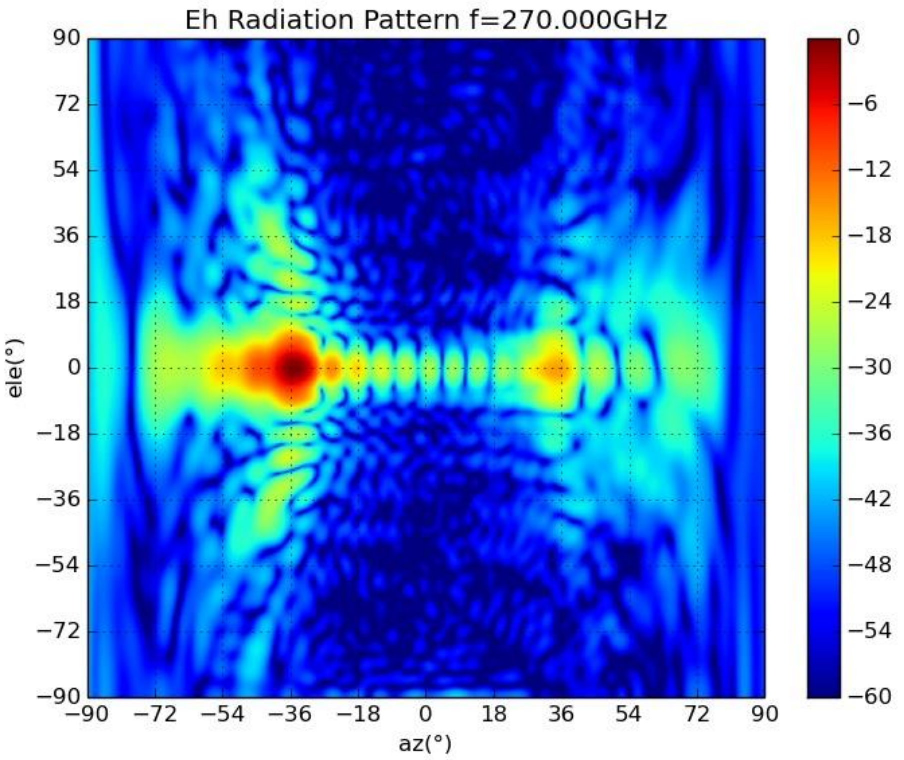


Introduction

What are the different kind of radiation characterizations?

- 2D or 3D characterization ie cutting planes defined in the Antenna Under Test coordinates system
    - Choice of the representation space : angular grid ; uv grid ; cartesian grid
    - Choice of data to be represented : gain, normalized power (copolar? Crosspolar? total?), axial ratio…





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Introduction

What are the parameters of interest?

- Characteristics of the main lobe pointing angle, half-power beamwidth, polarization ellipse main axis.
- Side lobes level.
- Gain value.
- Directivity value.
- Polarization characteristics : axial ratio, polarization rejection.

Basics

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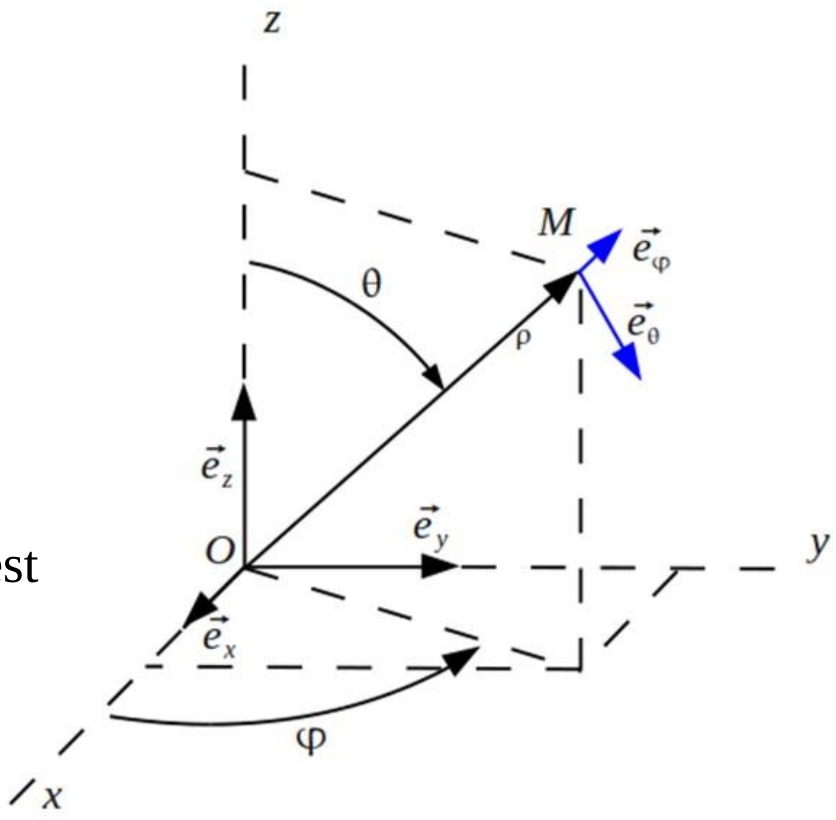
Basics

O : - center of coordinate system Oxyz .
- radiation point source.
- reception point of the radiation.

M : - observation point (when source at O).
- point source (when reception at O).

Oxyz : - direct orthonormed system.
- Ox : horizontal axis.
- Oy : vertical axis.
- Oz : horizontal axis, exiting the antenna under test



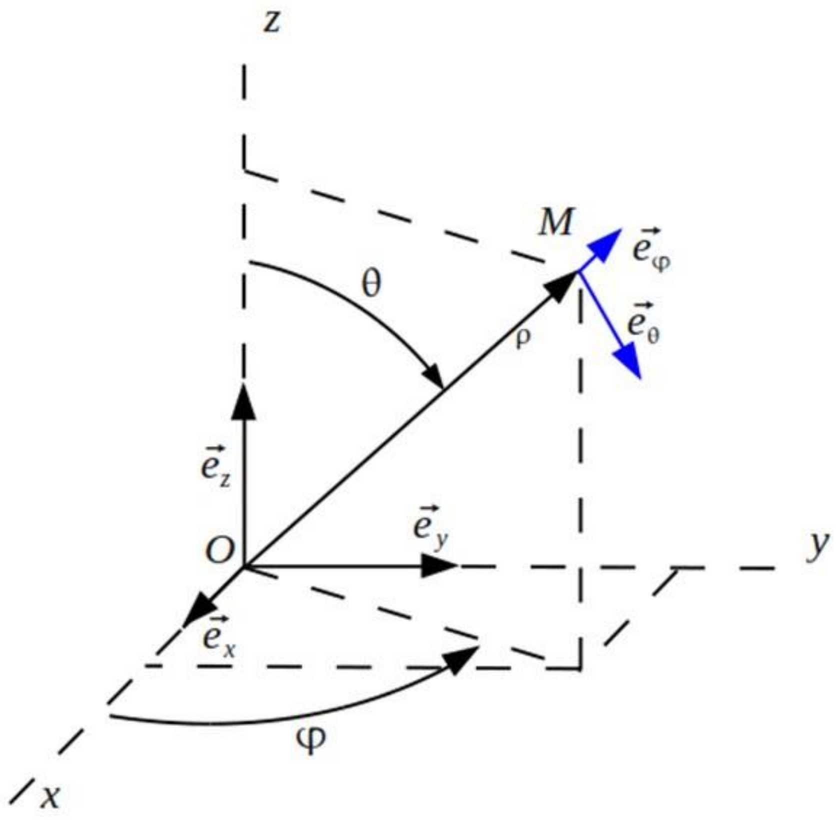
Basics

Plane wave

- electromagnetic field orthogonal to the propagation direction
- the propagation direction is constant
- electric and magnetic fields are orthogonal and with a quadrature phase shift.
- no attenuation, phase varies linearly with the distance
- no variation in amplitude as a function of the position

$$\vec{E}(M)=\left(E_\theta \vec{e}_\theta + E_\varphi \vec{e}_\varphi\right) e^{-j\vec{k}.\vec{OM}}$$

$$\vec{k}=\frac{2\pi}{\lambda}\vec{u}$$



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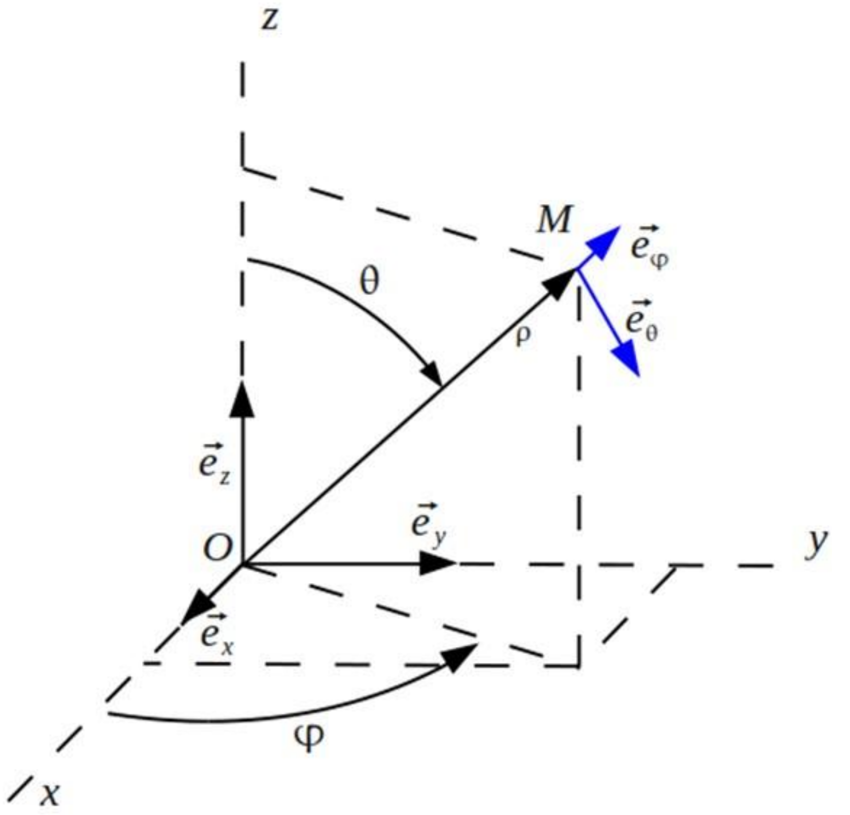
Basics

Spherical wave

- electromagnetic field orthogonal to the propagation direction
- electric and magnetic fields are orthogonal and with a quadrature phase shift.
- Isotropic propagation with a 1/r attenuation and a phase varying linearly with the distance

$$\vec{E}(M)=\left(E_\theta \vec{e}_\theta+E_\varphi \vec{e}_\varphi\right)\frac{1}{|\vec{OM}|}e^{-j\vec{k}.\vec{OM}}$$

$$\vec{k}=\frac{2\pi}{\lambda}\frac{\vec{OM}}{|\vec{OM}|}$$



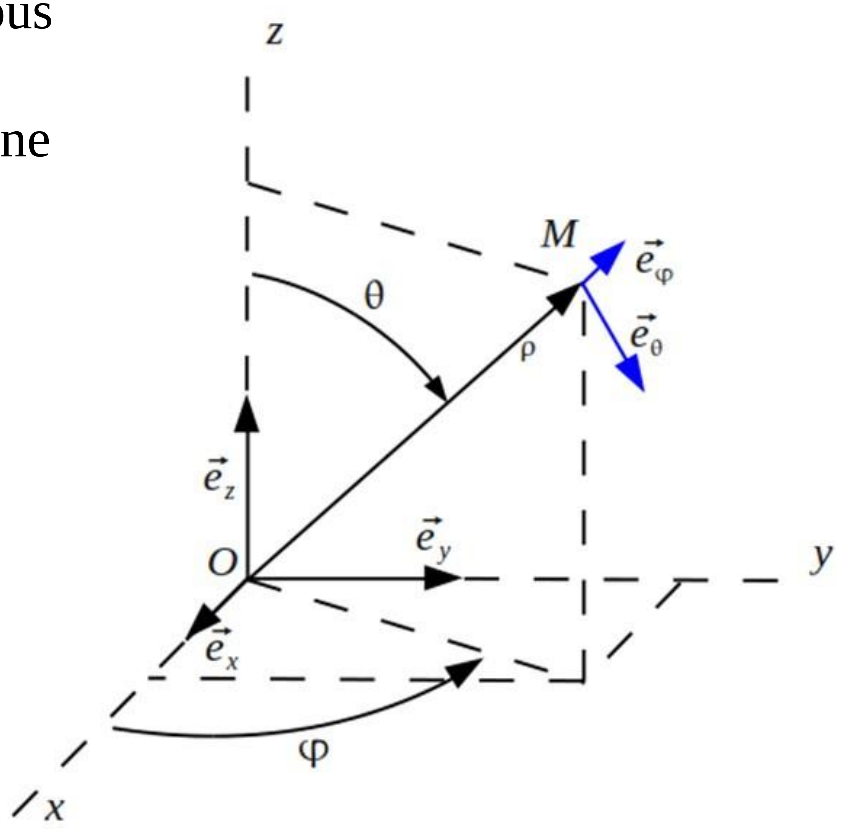
Basics

Far field

- the observed wave is planar
- antenna : set of isotropic sources > radiation is homogeneous to a summation of spherical waves
- criteria to consider locally the spherical wave as a planar one

$$\vec{E}(M) = \left(E_\theta \vec{e}_\theta + E_\varphi \vec{e}_\varphi\right) \frac{1}{|\vec{OM}|} e^{-j\vec{k}.\vec{OM}}$$

$$\vec{k} = \frac{2\pi}{\lambda} \frac{\vec{OM}}{|\vec{OM}|}$$

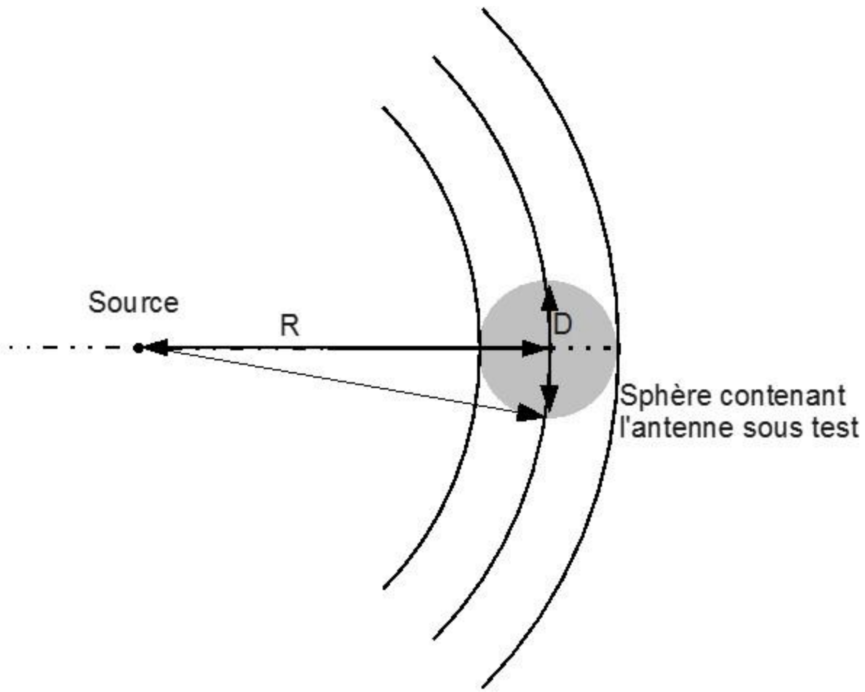


Basics

Far field : criteria of lateral phase variation
- defined for a sphere of diameter D.
- the phase front variation must be lower than 22.5°.

$$k\left(\sqrt{R^2+(D/2)^2}-R\right)\le\frac{\pi}{8}$$

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



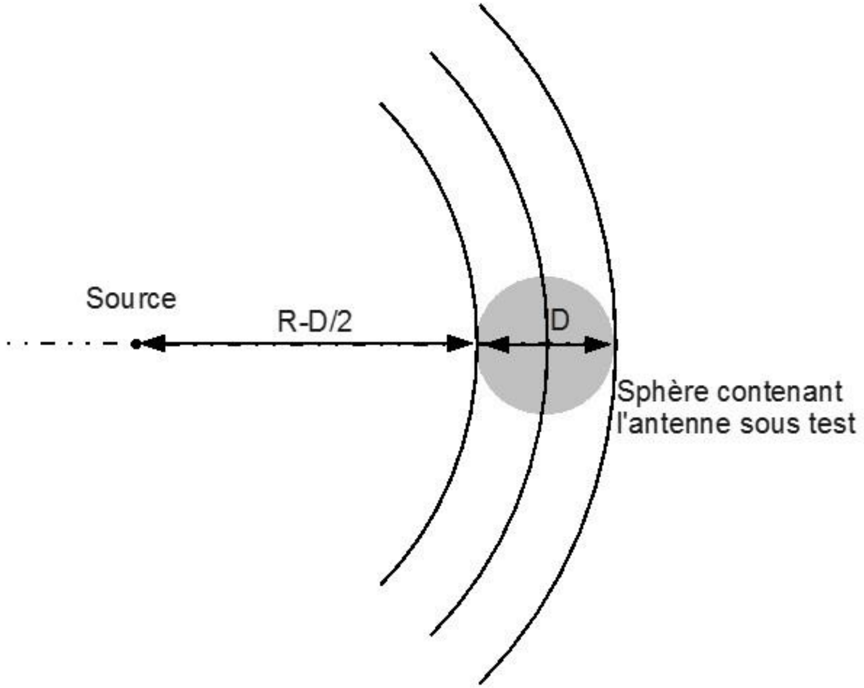
Basics

Far field : criteria of longitudinal magnitude variation

- defined for a sphere of diameter D.
- the longitudinal magnitude variation must be lower than 0.5dB (ie linear ±5%).

$$\frac{R+\frac{D}{2}}{R} \leq 10^{(0.5/20)} \quad et \quad \frac{R-\frac{D}{2}}{R} \geq 10^{(-0.5/20)}$$

$$\boxed{R \geq 10\,D}$$



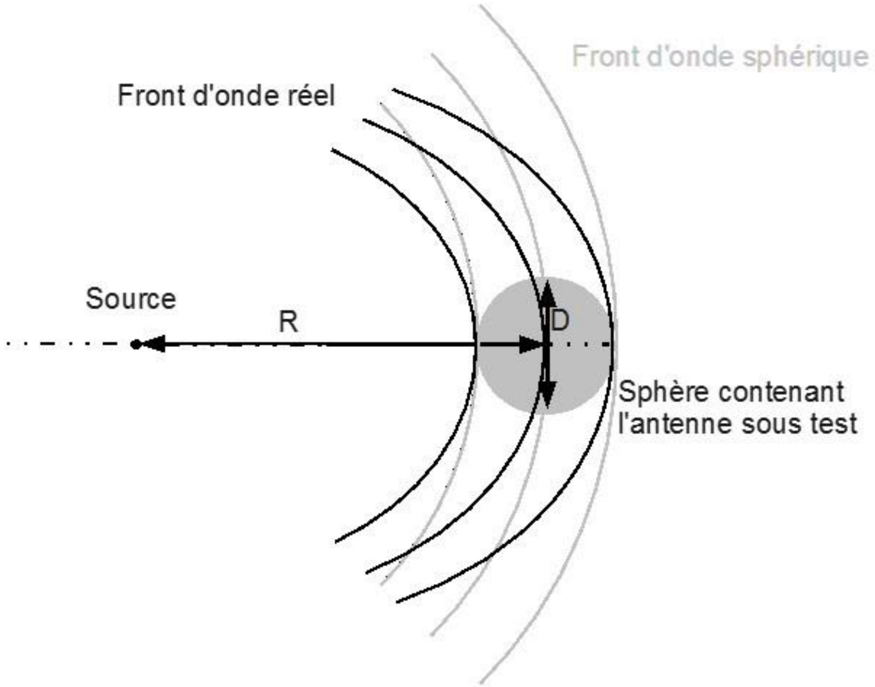
Basics

Far field : criteria of lateral magnitude variation

- defined for a sphere of diameter D.
- the lateral magnitude variation must be lower than 0.5dB.

$$\frac{f(\vec{OM})/|\vec{OM}|}{f(\vec{OM}')/|\vec{OM}'|} \leq \varepsilon \qquad f(\vec{OM}') \leq f(\vec{OM})$$

$$\boxed{\frac{\sqrt{R^2+\left(\frac{D}{2}\right)^2}}{R} \leq \varepsilon \frac{f(\vec{OM}')}{f(\vec{OM})}}$$



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Basics

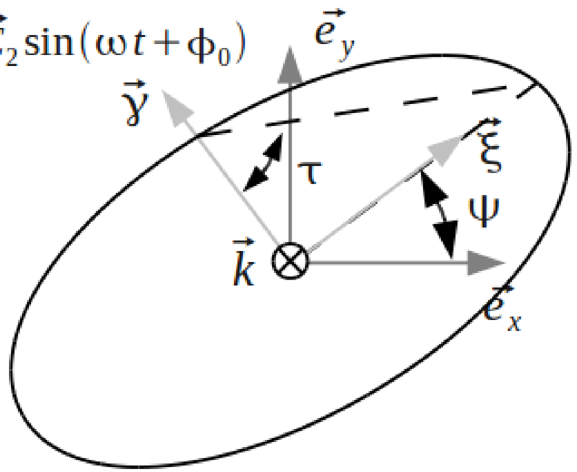
Polarization ellipse :

- far field.
- contour plotted by the temporal variation of the field vector, in the plane orthogonal to the direction of propagation.
- characterized by:
  - ➢its sense of rotation (observer looking in the direction of propagation).
  - ➢the tilt of its main axis in the observation system.
  - ➢the ratio of its major to its minor axis.

$$\vec{E}=E_1.\cos(\omega t+\phi_0)\vec{\xi}+E_2.\sin(\omega t+\phi_0)\vec{\gamma}=\vec{E}_1\cos(\omega t+\phi_0)+\vec{E}_2\sin(\omega t+\phi_0)$$

⬇

$$\vec{E}=A\vec{\xi}+jB\vec{\gamma}$$



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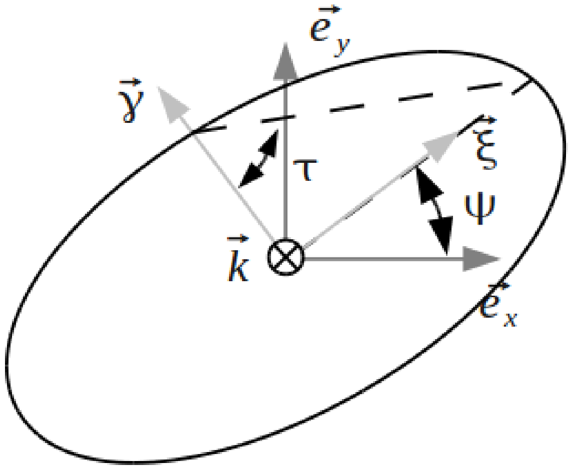
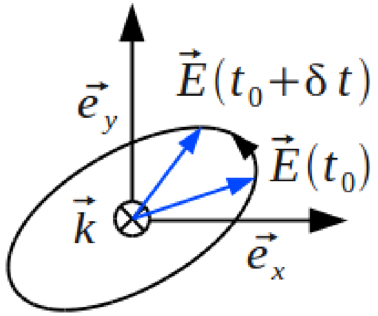
Basics

Polarization ellipse :

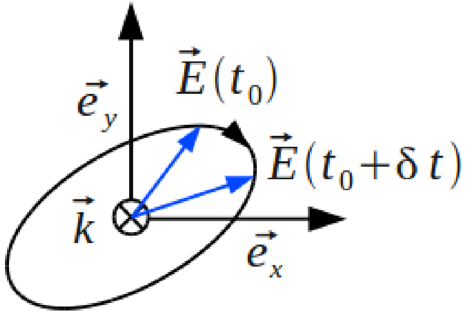
$$\vec{E} = A\vec{\xi} + jB\vec{\gamma}$$





Polarisation gauche

$signe(A.B) > 0$



Polarisation droite

$signe(A.B) < 0$

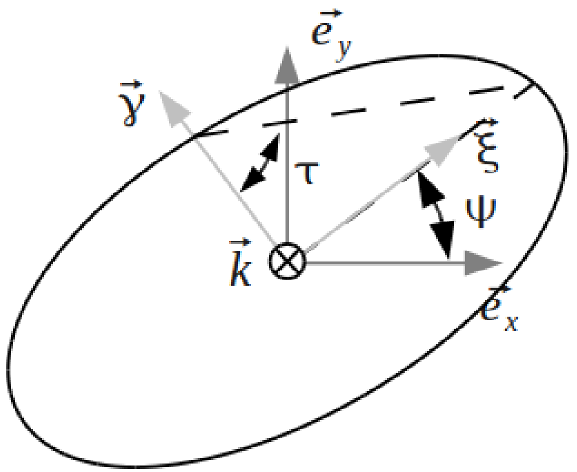
Basics

Polarization ellipse :

- Elliptical polarization : $\vec{E} = A\vec{\xi} + jB\vec{\gamma}$

- Linear polarization : $\vec{E} = A\vec{\xi}$

- Circular polarization : $\vec{E} = A\{\vec{\xi} \pm j\vec{\gamma}\}$



Expansion :

- a circular polarization can be expanded into 2 equal linear polarization that are orthogonal and of 90° phase shift.
- a linear polarization can be expanded into 2 circular polarizations right and left hands of same magnitude

$$\vec{E} = A\vec{\xi} = \frac{A}{2}(\vec{\xi} + j\vec{\gamma}) + \frac{A}{2}(\vec{\xi} - j\vec{\gamma})$$

- an elliptical polarization can be expanded into 2 circular polarization right and left hands, whose magnitude ratio is called polarization rejection

$$\vec{E} = A\vec{\xi} + jB\vec{\gamma} = \frac{A+B}{2}(\vec{\xi} + j\vec{\gamma}) + \frac{A-B}{2}(\vec{\xi} - j\vec{\gamma})$$

Basics

Gain (absolute gain) :

- ratio between the radiation intensity at the observation point and the one that would be achieved if the power accepted by the antenna is isotropically radiated

$$G(\theta,\varphi)=\frac{\phi(\theta,\varphi)}{P_0/4\pi}$$

- translate the capability of an antenna to focus the energy into space

Realized Gain :

- ratio between the radiation intensity at the observation point and the one that would be achieved if the power delivered to the antenna would be isotropically radiated

$$G_{realisé}(\theta,\varphi)=\frac{\phi(\theta,\varphi)}{P_M/4\pi}=(1-|\Gamma^2|)G(\theta,\varphi)$$

- express the capability of an antenna to focus the energy into space
- take into account the mismatch losses

Basics

Directivity :

- Ratio between the radiation intensity of the antenna at a given point and the average radiation intensity of the antenna

$$D(\theta,\varphi)=\frac{\phi(\theta,\varphi)}{\frac{1}{4\pi}\int_0^{\pi}\int_0^{2\pi}\phi(\theta',\varphi')\sin\theta' d\theta' d\varphi'}=\frac{\phi(\theta,\varphi)}{\frac{1}{4\pi}P_T}$$

Partial directivity : case of an antenna with elliptical polarization

$$D(\theta,\varphi)=\frac{\phi_1(\theta,\varphi)+\phi_2(\theta,\varphi)}{\frac{1}{4\pi}\int_0^{\pi}\int_0^{2\pi}(\phi_1(\theta',\varphi')+\phi_2(\theta',\varphi'))\sin\theta' d\theta' d\varphi'}=\frac{\phi_1(\theta,\varphi)+\phi_2(\theta,\varphi)}{\frac{1}{4\pi}(P_{T_1}+P_{T_2})}$$

$$D(\theta,\varphi)=\frac{\phi_1(\theta,\varphi)}{\frac{1}{4\pi}P_T}+\frac{\phi_2(\theta,\varphi)}{\frac{1}{4\pi}P_T}=D_1(\theta,\varphi)+D_2(\theta,\varphi)$$

Radiation efficiency :

- Ratio between the total power radiated by an antenna, and the power accepted by this antenna

$$\eta=\frac{P_T}{P_0}=\frac{G(\theta,\varphi)}{D(\theta,\varphi)}$$

Antenna Radiation Measurement

Antenna Radiation Measurement – Measurement Systems

Measurement of radiation patterns

- relative measurement of the spatial distribution of the electromagnetic energy emitted or received by an antenna under test

- scalar measurement: only the magnitude is measured.

- vectorial measurement: magnitude and phase are measured

- **the representation of the radiation patterns is mainly done in far field**:

  > coherent with the use of the antenna within a realistic configuration

  > enables to use the plan waves formalism:

  >> simplification of the representation : electric and magnetic fields are orthogonal between them and to the propagation direction

  >> one field only can then be represented

  >> the radial component is zero: for each observation point the field is completely determined by the representation of the magnitude and phase of its projection in a orthonormed system defined in the plane orthogonal to the propagation direction at the observation point.

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Antenna Radiation Measurement – Measurement Systems

Measurements in near field :

- the measurement of the radiated field is done at a distance that **do not respect the far field criteria**.
- require the use of a near field / far field transform.
- discretization of the measurement's domain: planar, cylindrical, spherical
- discretization of the domain is linked to the antenna size
- require to master various elements playing a role in the measurement (characteristics of the probes, positionning errors minimization) and to understand the technique in order to anticipate potential post-processing aberations
- of great interest to characterize high gain antennas, to perform 3D measurements without the need of time consuming measurement compaigns
- enables to extract rich and useful information for the the directivity computation and to perform antenna diagnostic.

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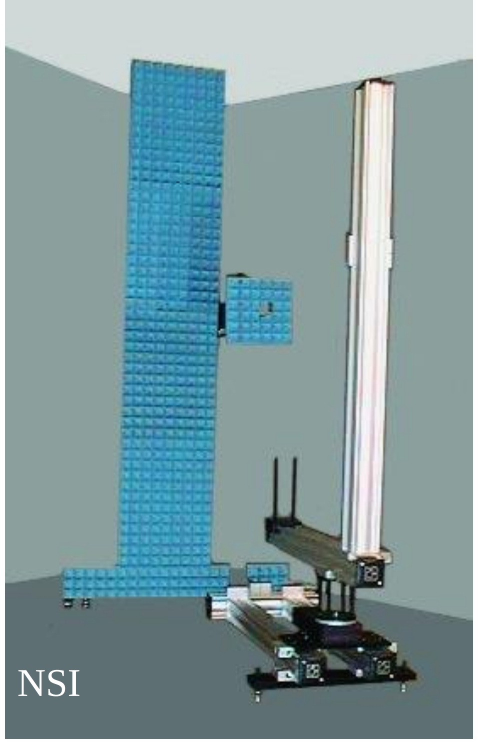
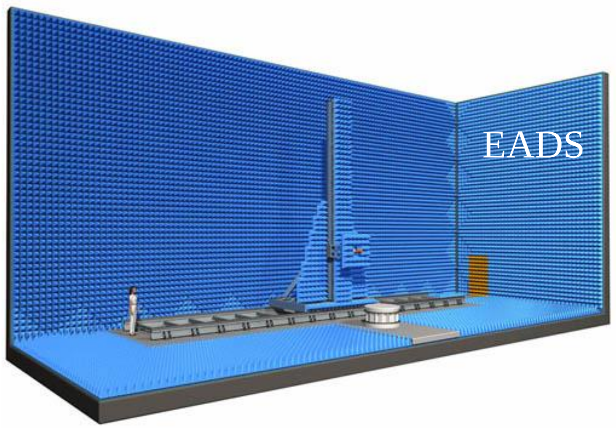
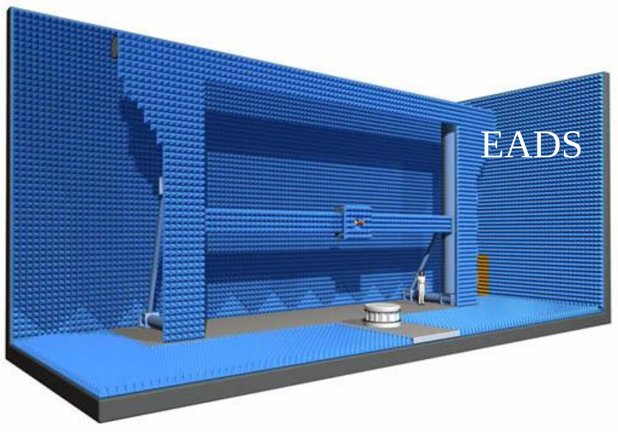
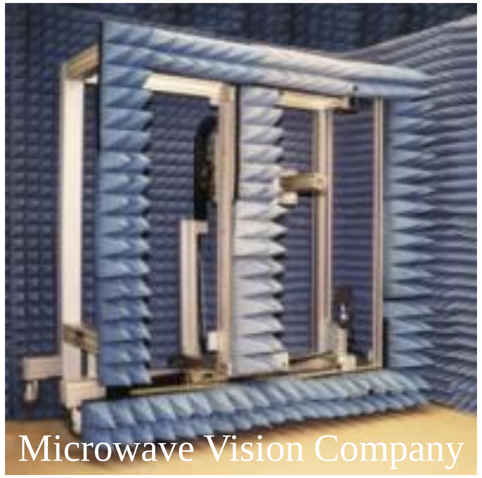
Antenna Radiation Measurement – Measurement Systems

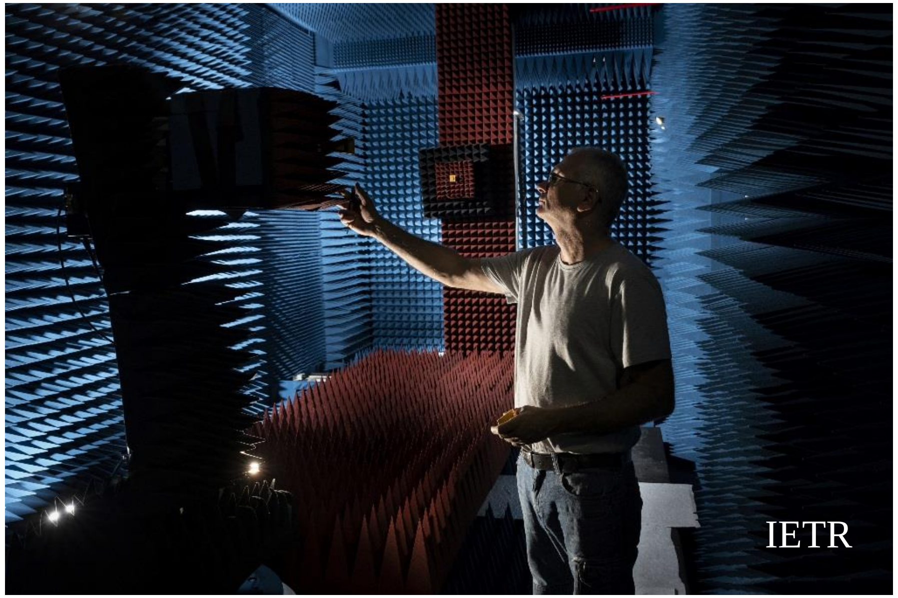
Near field measurements:





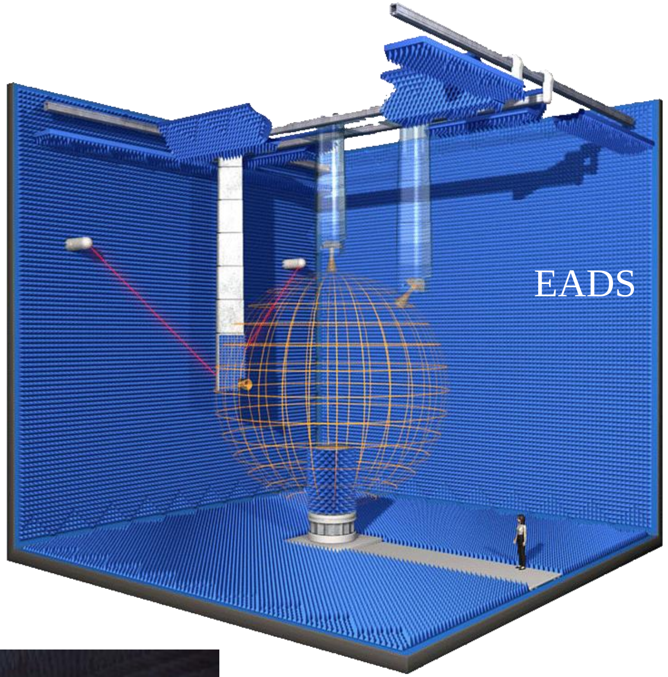


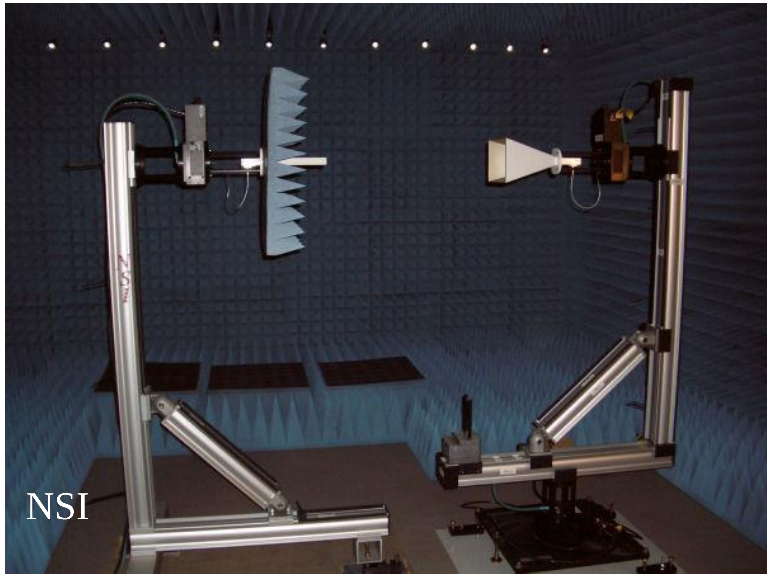




Antenna Radiation Measurement – Measurement Systems

Near field measurements:





Antenna Radiation Measurement – Measurement Systems

Far field measurements: direct illumination

- the illumination probe (or the measurement one) is placed in the line of sight of the antenna under test, at a distance that respects the far field criteria (for the probe and the antenna under test).

- the probe is placed on the optical axis of the chamber, as well as the antenna under test, in order to impose the symmetry of the measurement configuration with respect to the chamber.

- the maximum size of antenna that can be characterized is limited in terms of wavelength because of the application of the far field criteria and the physical maximum distance between emission and reception.

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Antenna Radiation Measurement – Measurement Systems

Far field measurements: indirect illumination

- the illumination probe (or the measurement one) is not placed in the line of sight of the antenna under test.

- the probe illuminates a parabolic reflector that generates a region in which the field can be considered as a plane wave

- the size of this plane wave volume, and its location with respect to the reflector, are determined by the geometry of the reflector, the radiation characteristics of the probe, and the localization of the probe with respect to the reflector

- technique of the « compact range »: the measurement volume and location are fixed, therefore the maximum antenna size that can be characterized are not in wavelengths but in length units.

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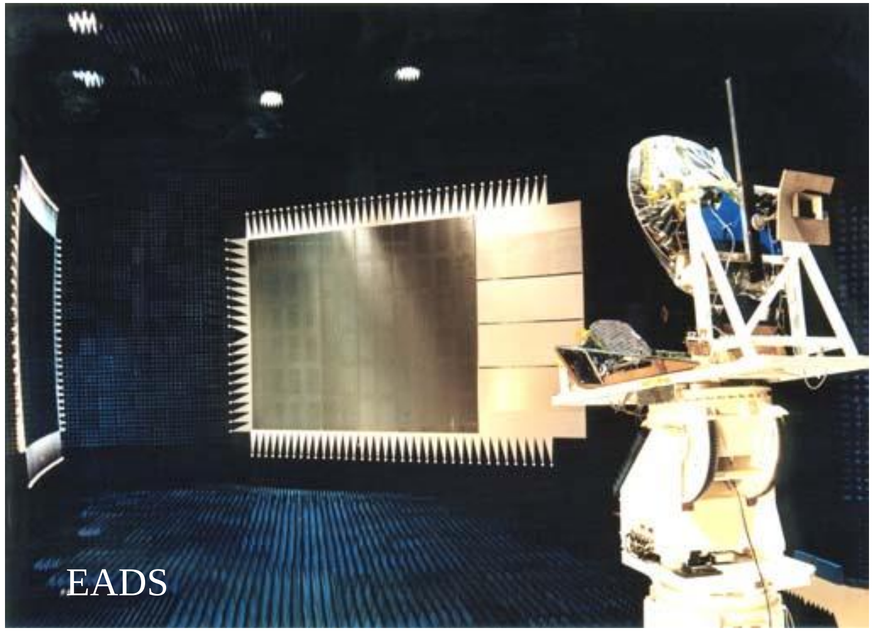
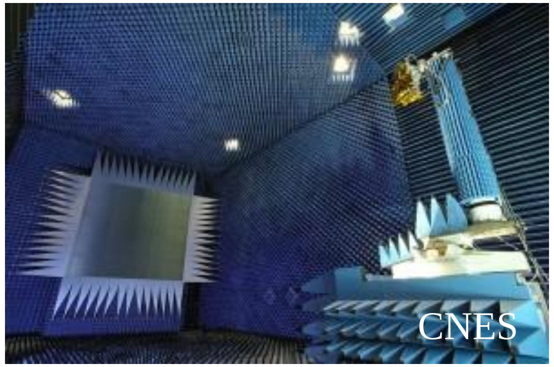
Antenna Radiation Measurement – Measurement Systems

Far field measurements: indirect illumination





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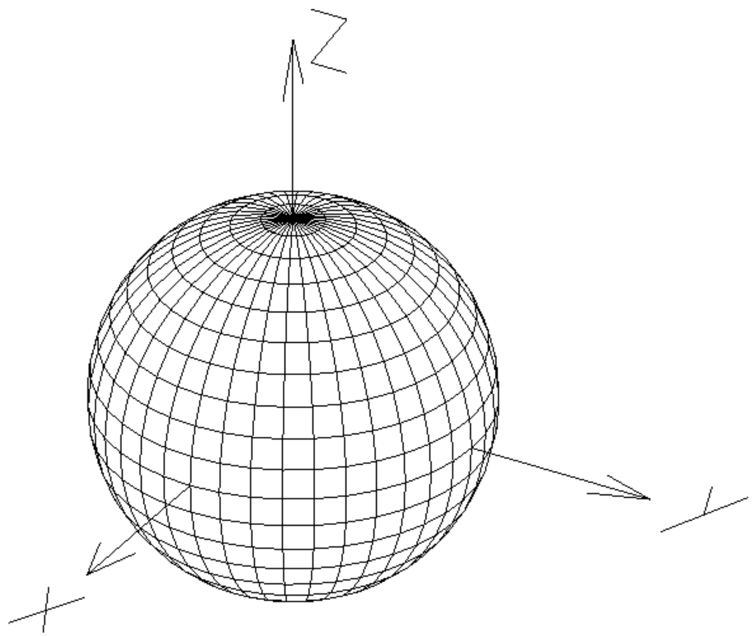
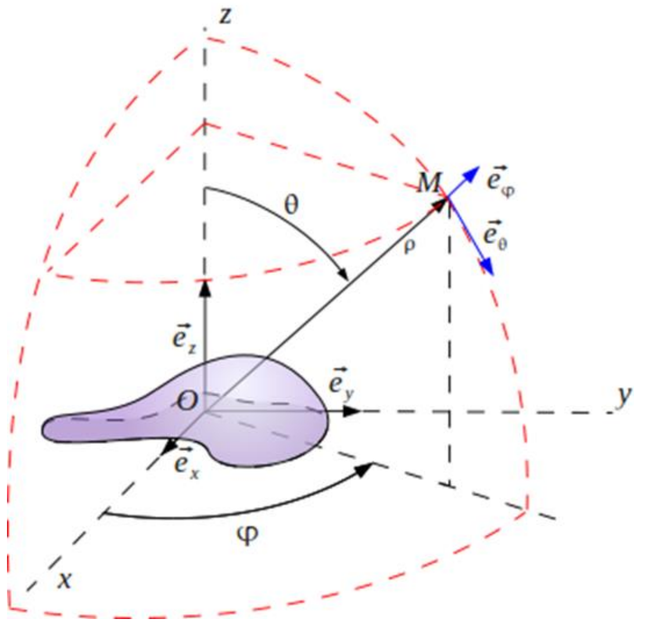
Antenna Radiation Measurement – Measurement Systems

Spherical coordinate system: latitude longitude





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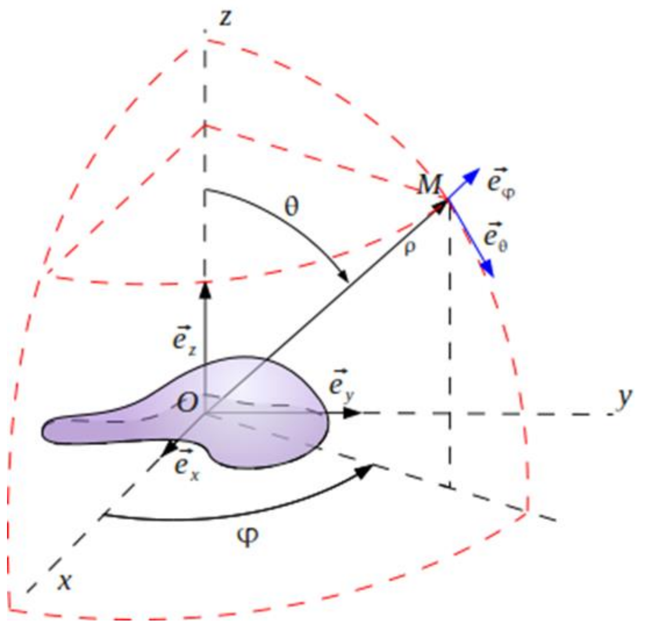
Antenna Radiation Measurement – Measurement Systems

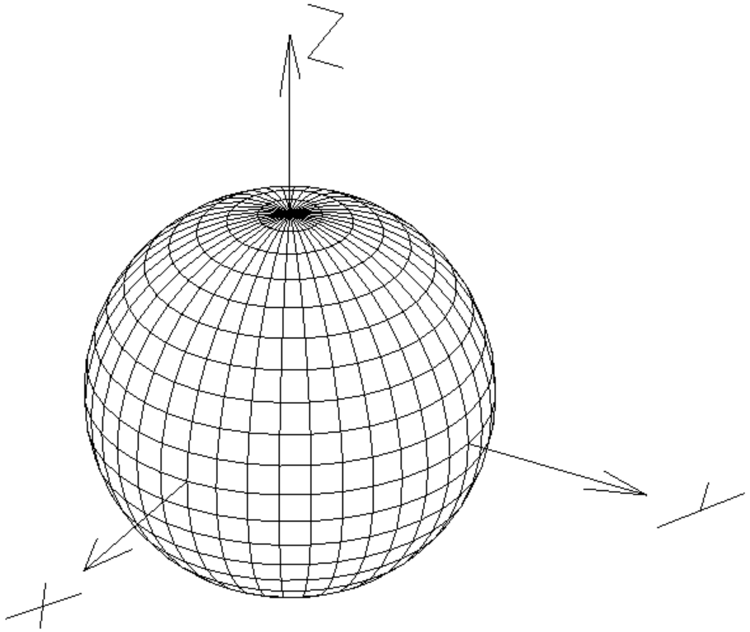
Spherical coordinate system: latitude longitude
- antenna positioning: two orthogonal rotation axis.
- Azimuthal axis :
  > rotation according to (Oy)
  > sweep in φ
- Roll axis :
  > rotation according to (Oz)
  > sweep in θ

-Measurements of components in the system $(\vec{e}_\theta, \vec{e}_\varphi)$
  > rotation axis for the measurement probe
  > rotation axis according to (Oz).

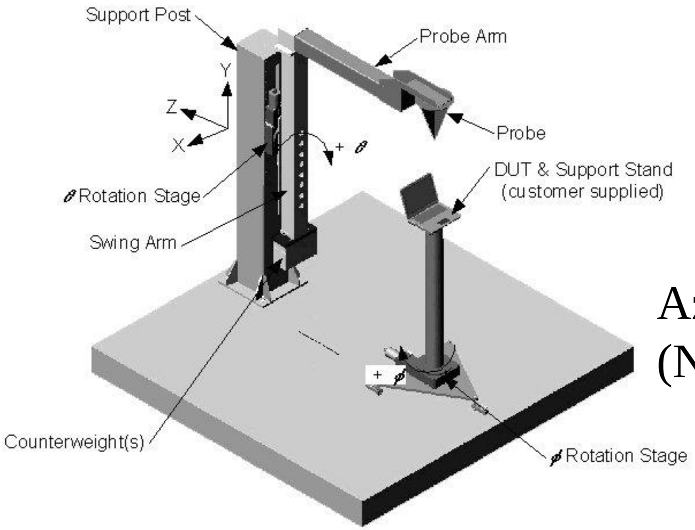


Antenna Radiation Measurement – Measurement Systems

Spherical coordinate system: latitude longitude



Roll over Azimuth
(NSI picture)



Azimuth / Roll
(NSI picture)

Antenna Radiation Measurement – Measurement Systems

Spherical coordinate system: latitude longitude

- advantages :

> possibility to merge the coordinate systems of the antenna and imposed by the rotation axis.

> high point density near the poles: interesting for antennas with broadside focusing.

> coordinate system is natural for most users.

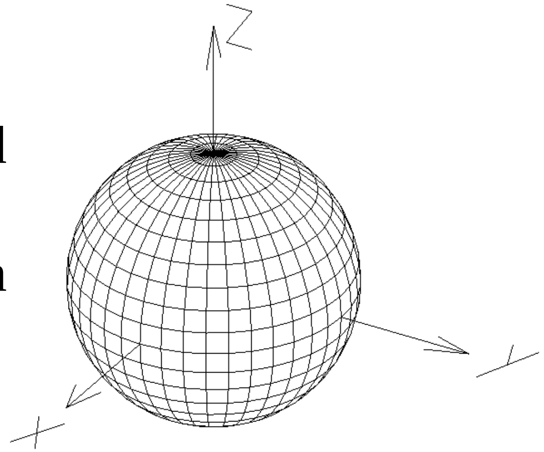
> representation of information in polar coordinate is easy.

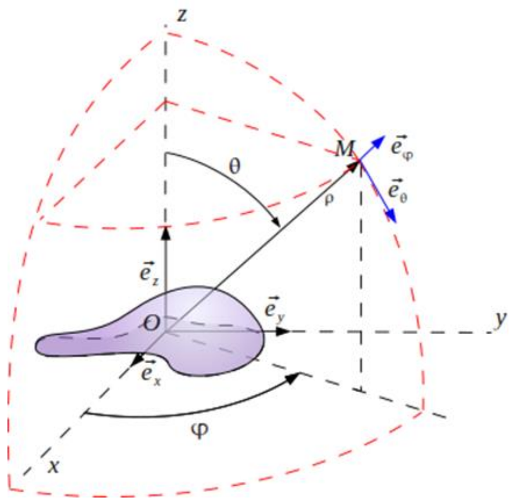
- drawbacks :

> not well suited for antennas with tilted main beam,

> rotation of both main and cross polar components during acquisition.

> grid hard to exploit for mapping purposes.





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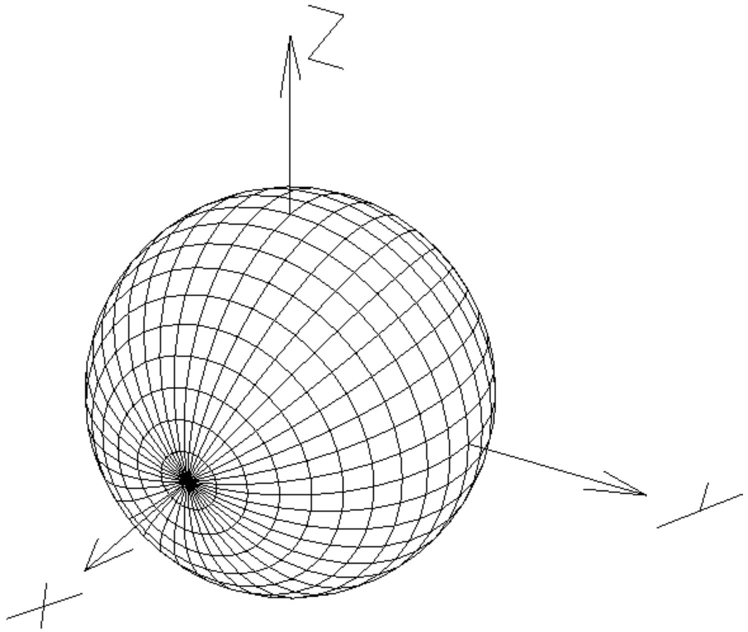
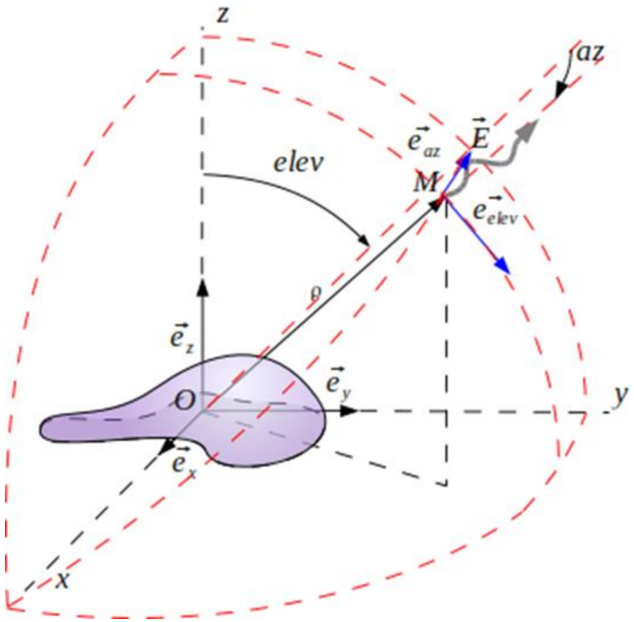
Antenna Radiation Measurement – Measurement Systems

Spherical coordinate system: azimuth elevation





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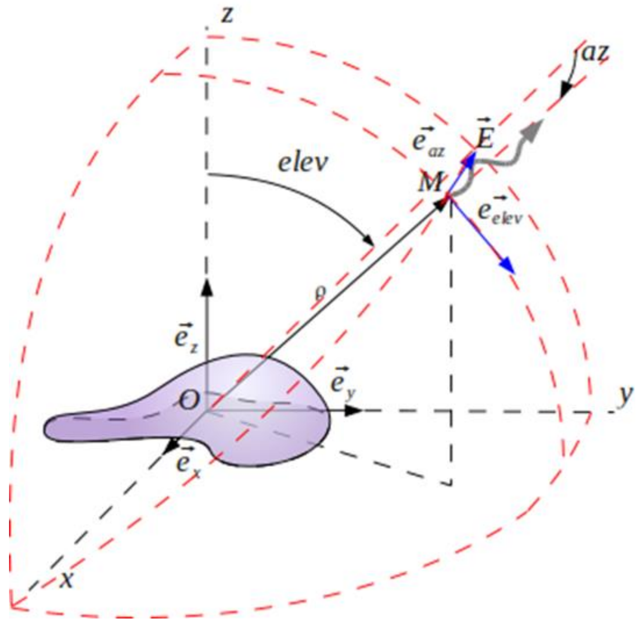
Antenna Radiation Measurement – Measurement Systems

Spherical coordinate system: azimuth elevation

- Antenna positioning: two orthogonal rotation axis.
- Azimuthal axis:
  > rotation according to (Oy)
- Elevation axis:
  > rotation according to (Ox)

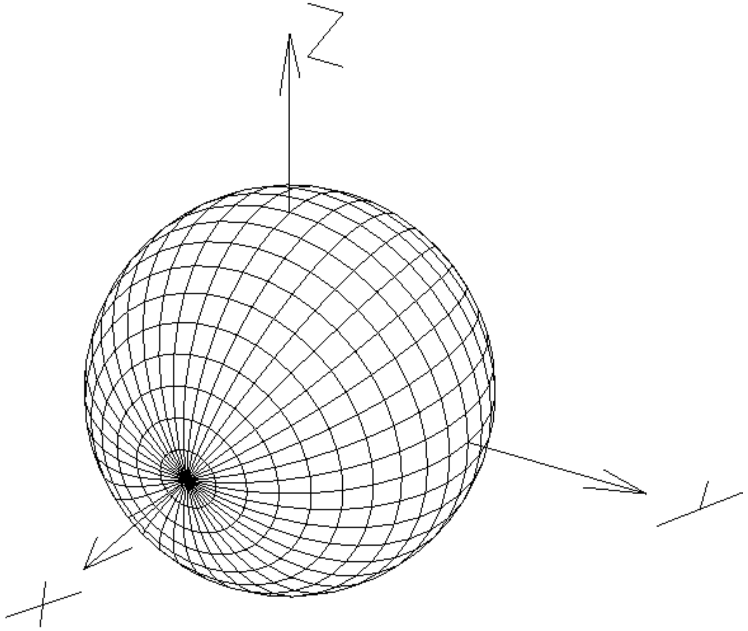
- Measurements of components in the system
  > rotation axis for measurement probe.
  > rotation axis according to (Oz).

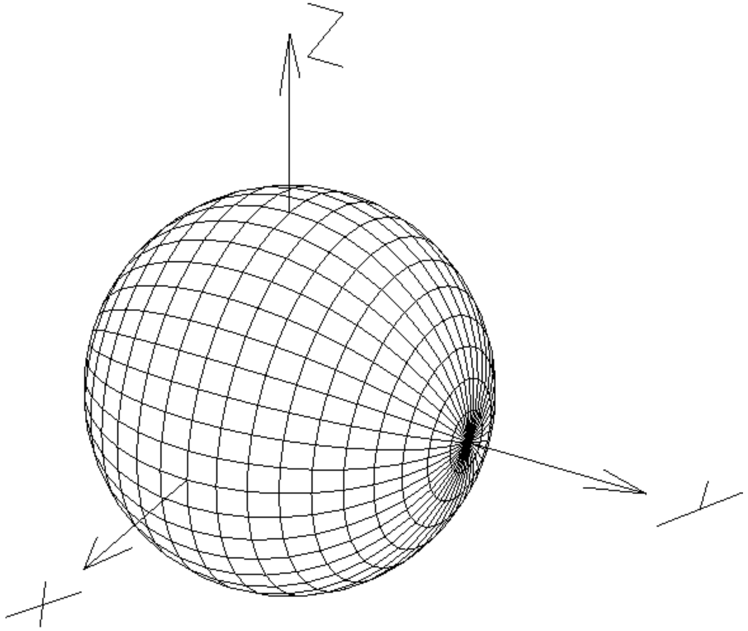
$(\vec{e}_\theta, \vec{e}_\varphi)$



Antenna Radiation Measurement – Measurement Systems

Spherical coordinate system: azimuth elevation





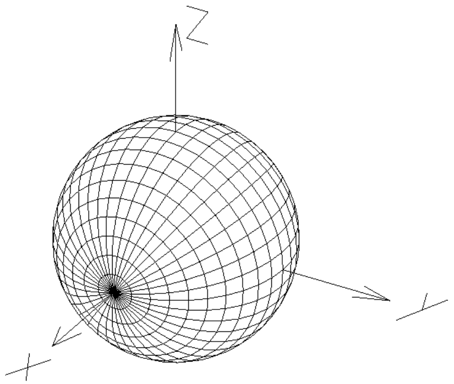
Elevation over azimuth
(picture Orbit FR)

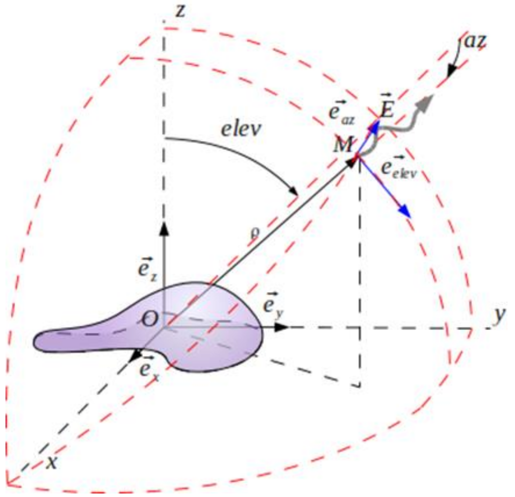
Azimuth over elevation
(picture Orbit FR)

Antenna Radiation Measurement – Measurement Systems

Spherical coordinate system: azimuth elevation

- advantages:
  > coordinate system natural for on site exploitation of the characterized antenna.
  > characterization of antennas with tilted main beam is more easy: in the case of a beam tilt according to both axis, the use of an additional azimuthal axis located in the elevation plane is interesting.
  > grid can be easily exploited for mapping purposes.
- drawbacks:
  > the coordinate systems linked to the antenna and imposed by the rotation axis cannot by merged without important shadowing effects.





Antenna Radiation Measurement – Quiet Zone

- the quiet zone is the volume in which is placed the antenna under test, and for which the uniformity of the incident field complies to predefined specifications.
- these specifications are related to the level of the total field due to the reflections inside the chamber, with respect to the level of the incident field obtained at the observation point.
- These quantities are related to both the magnitude and the phase of the field, even if in general the attention is focused on the magnitude and more specifically on the mean level of reflectivity in the quiet zone.
- reflectivity: magnitude of the ratio between the total field due to reflections and the incident field

$$r(\theta,\varphi)=max\frac{|\sum \vec{E}^s(\theta,\varphi)|}{|\vec{E}(\theta,\varphi)|}$$

- reflectivity of the quiet zone:

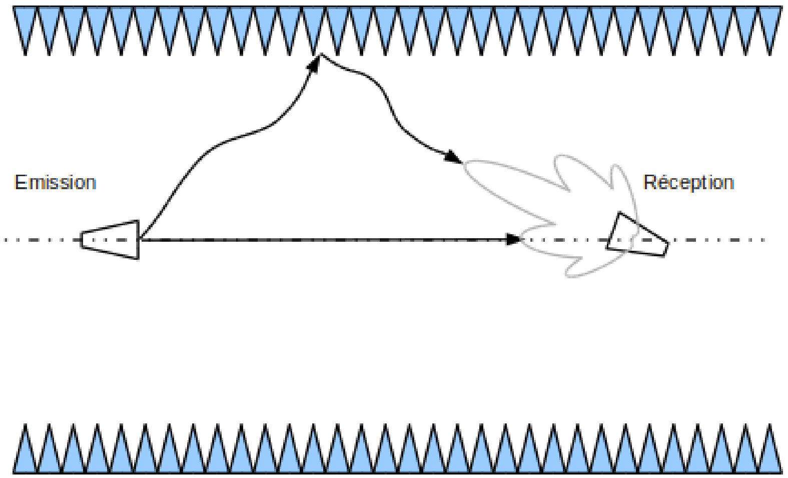
$$R=mean(r(\theta,\varphi))$$

Antenna Radiation Measurement – Quiet Zone

- Hypothesis : reflections on the sides of the chamber

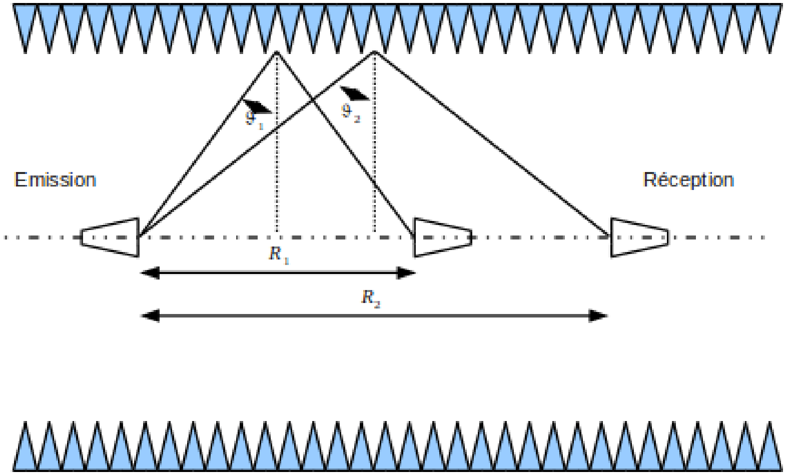
- Normalized pattern (max at 0): $$\phi_r(\theta,\varphi)=\frac{\phi(\theta,\varphi)}{max(\phi(\theta,\varphi))}=\frac{\phi(\theta,\varphi)}{\phi(0,0)}$$

- Interference magnitude: $$\Delta(\theta,\varphi)=\frac{(\phi_r(\theta,\varphi)+R)}{(\phi_r(\theta,\varphi)-R)}$$



Antenna Radiation Measurement – Quiet Zone

- Reflectivity of absorbers:
  > level inversely proportional to frequency.
  > level proportional to the incident wave (minimal reflectivity when the incident wave is normal to the absorber, maximal when the incident wave is grazing).
- variation of reflectivity in the quiet zone:
  > for a given frequency: degradation when the distance E/R increases.
  > for a given E/R distance: improvement when the frequency increases.



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Antenna Radiation Measurement – Quiet Zone

Antenna Pattern Comparison Method

- hypothesis : reflections on the sides of the chamber
- Measurements of the same pattern for various distances transmitter/receiver

> low variation of the reflectivity

> variation of the difference between direct and indirect paths:

>> variation of the relative phase

>> fluctuation of the level of the side lobes

>> averaging of the patterns to minimize the effects of the reflections

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Antenna Radiation Measurement – Quiet Zone

Time gating

- Hypothesis : reflections on the sides of the chamber
- Measurement of the same pattern for a frequency band enables:
  - > a blind distance larger than the indirect path
  - > a sufficient temporal resolution
- the transfer function of the antenna is a limitation of this technique
- idea :
  - > frequential measurements
  - > localization of echoes in time domain
  - > filtering in time domain
  - > transformation back in frequency domain

Antenna Radiation Measurement – Cutting Planes

Cuttings planes:

- Trajectory used to measure the EM field.

- Case of the radius latitude longitude :
  - Roll axis set to fixed value, and motion control apply on the Azimuth axis > cutting plane = longitude.
  - Azimut axis set to fixed value, and motion control apply on the Roll axis > cutting plane = latitude.
  - Motion control on both axis : definition of a specific cutting plane in a grid defined by another motion axis architecture, another orientation of the Antenna Under Test (AUT).

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Antenna Radiation Measurement – Cutting Planes

Data acquisition :

- Step by step :
  - positioning system stop for acqusition at each point of the sampling grid ;
  - data acquisition can not be performed during the displacement time between two samples (cinematic constraints; number of frequencies ; dynamic range constraint…).

- On the fly : positioning system never stop.

Antenna Radiation Measurement – Cutting Planes

Type of data :

- Electrical field for at least one probe polarisation orientation :
  - linear polarisation :
    - 1 orientation ;
    - two orthogonal orientations defined in the chamber cartesian coordinate system, fixed during the measurement process.
    - two orthogonal orientations defined in the AUT coordinate system (ie tracking in the chamber coordinates system) >> Ludwig 3 : tracking of the orientation defined by the main axis of the ellipse of the E-field at the main beam maximum location.
  - Circular polarisation : LHCP and/or RHCP.

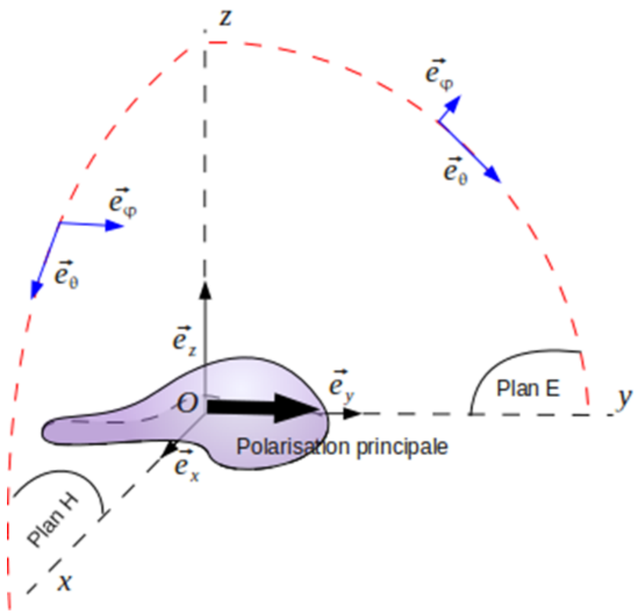
- Magnitude or Magnitude and phase.

Antenna Radiation Measurement – Cutting Planes

Cuttings planes: main beam in the axis
- main planes: orthogonal cutting planes containing the maximum of the main beam.

- Antenna with linear polarization:
> E-plane: cutting plane parallel to the polarization of the antenna.
> H-plane: cutting plane orthogonal to the polarization of the antenna.

- antenna with elliptical polarization: Ludwig 3 formalism
> main polarization: projection of the field on the main axis of the ellipse obtained for the maximum of the beam.
> cross polarisation: projection of the field on the minor axis of the ellipse obtained for the maximum of the beam.

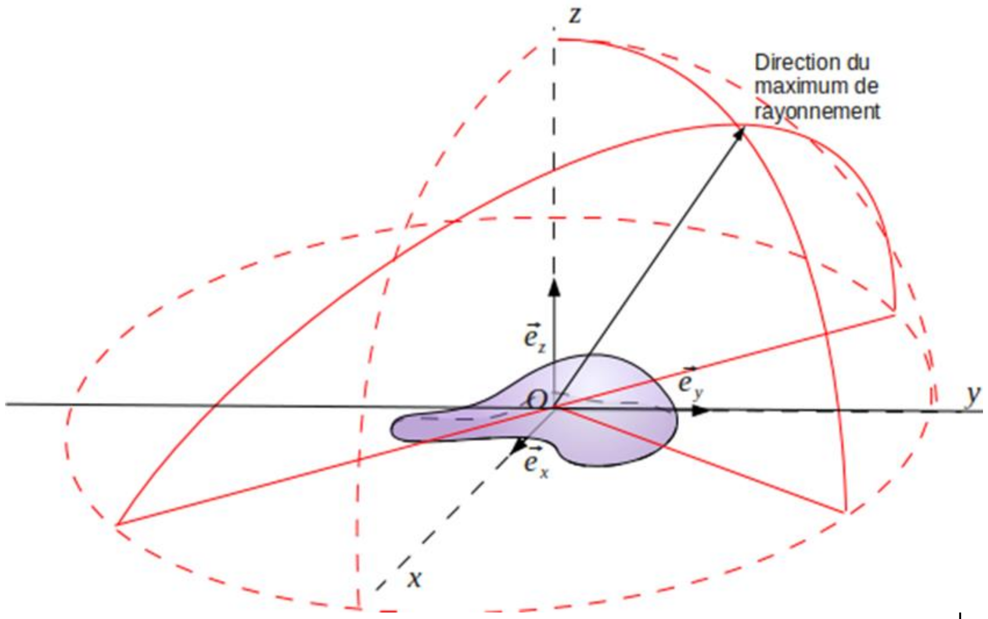


Antenna Radiation Measurement – Cutting Planes

Cutting planes: tilted main beam

- main planes: orthogonal cutting planes containing the maximum of the main beam.

- application Ludwig 3 formalism
  > main polarization: projection of the field on the main axis of the ellipse obtained for the maximum of the beam.
  > cross polarization: projection of the field on the minor axis of the ellipse obtained for the maximum of the beam.



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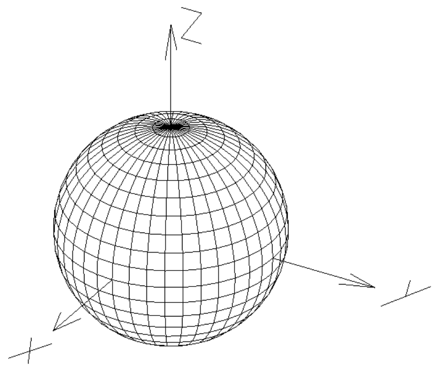
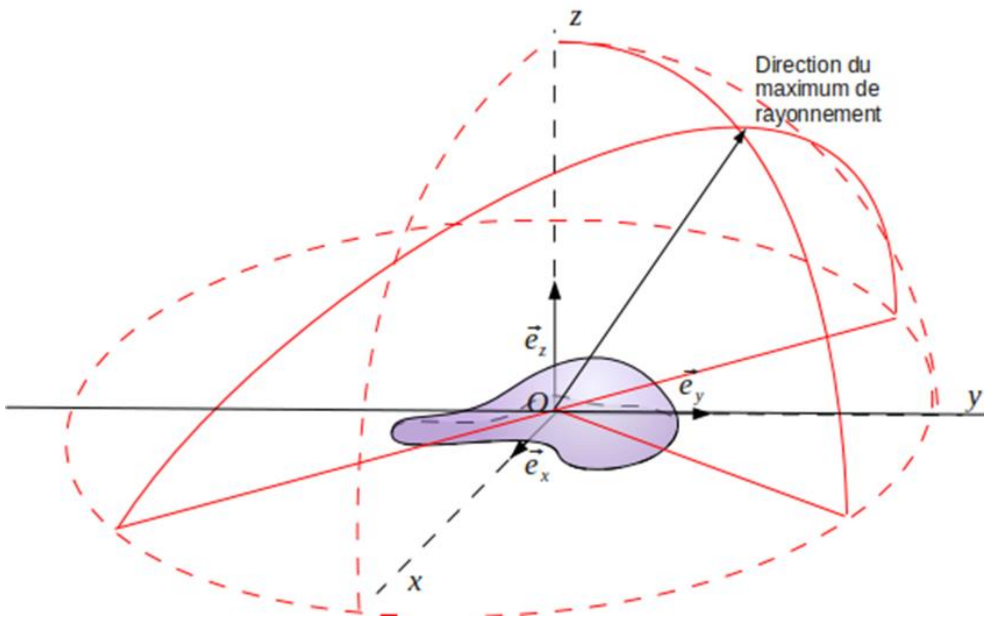
Antenna Radiation Measurement – Cutting Planes

Cutting planes: tilted main beam
measurement system latitude/longitude

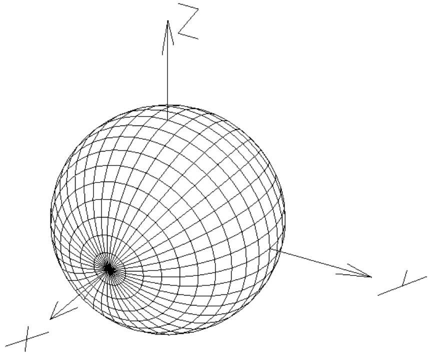
- Capability to move both axis before each measurement:
  > computation of the path of each cutting plane
  > projection of the field in the system basis defined by the maximum of the beam (Ludwig 3).

- Not able to move both axis before each measurement:
  > 3D acquisition.
  > interpolation to reconstruct the field in both cutting planes.
  > projection of the field in the basis defined by the maximum of the main beam (Ludwig 3).





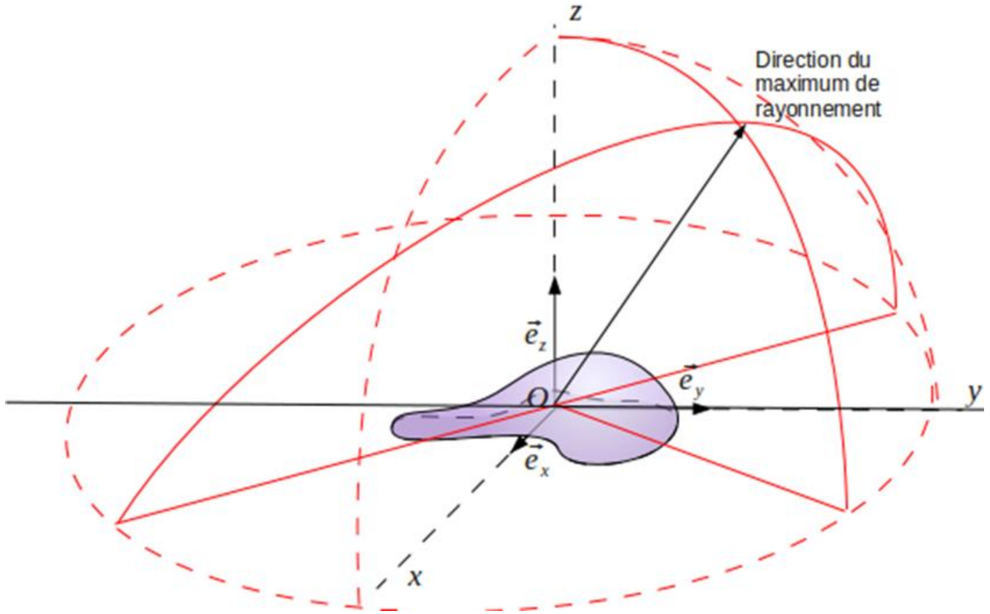
Antenna Radiation Measurement – Cutting Planes



Cutting planes: tilted main beam
measurement system azimuth/elevation

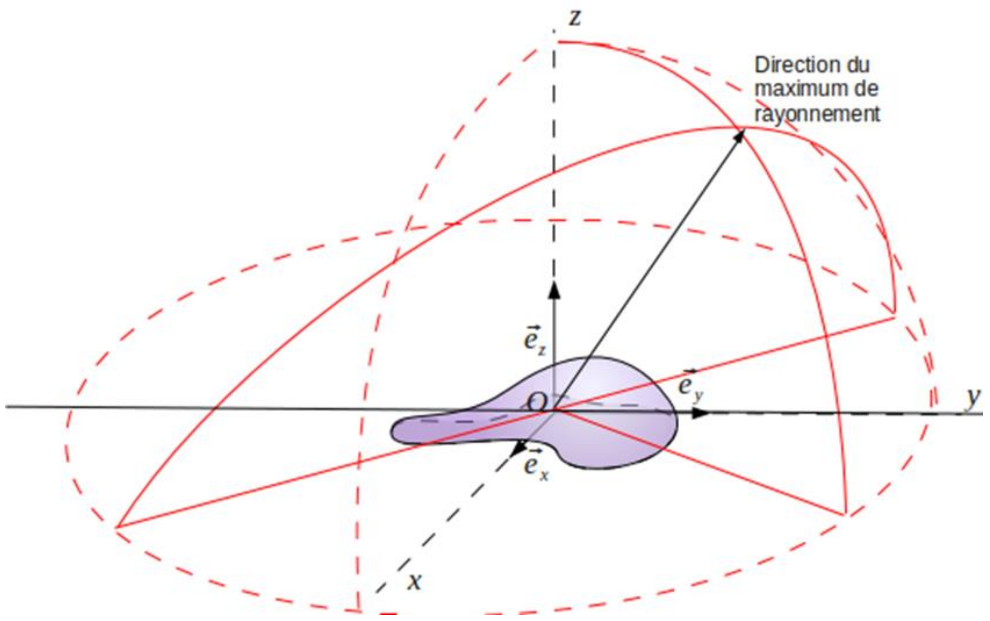
- tilt according to x or y :
  > classical acquisition in azimuth/elevation.
  > use of probe locations in accordance to the main and minor axis of the polarization ellipse obtained at the beam maximum.

- tilt according to x and y :
  > general case: procedure similar to the latitude/longitude case.
  > mounting of the antenna under test such that there is only one tilt: azimuth/elevation/azimuth



Antenna Radiation Measurement – Cutting Planes

Cutting planes: tilted main beam



Interest of such cutting planes :

- homogeneous to E- and H-plane;
- enable antenna analysis as a 2D array when their two azimut angles are fitting to the AUT axis.

Limitation of this definition :

- do not correspond to positioning system sampling grid.
- 3D representation is using a different grid for each main component :
  - ➢ considering Oz orientation in the main beam direction,
  - ➢ Considering Ox and Oy in the direction of the co- and cross-polar component,
  - ➢ then each component is represented respectively in an elevation/azimuth and azimuth/elevation grid.

Antenna Radiation Measurement – Gain, Polarization, Phase Centre

Measurement of the gain: link budget
- measurement of two antennas face to face.
- application of the Friis formula

$$|S|^2 = G_{réception} G_{émission} A_{el} \left(1 - |\Gamma_{émission}|^2\right)\left(1 - |\Gamma_{réception}|^2\right) \qquad A_{el} = \left(\frac{\lambda}{4\pi D}\right)^2$$

- calibrated measurement system:
  > compensation of the mismatchs at the input and output.
  > compensation of the cable losses.
- gain of the probe is known.
- Measurement of the mismatch between two antennas.
- distance between measured antennas.

Antenna Radiation Measurement – Gain, Polarization, Phase Centre

Measurement of the gain: technique of the three antennas

- measurements of three antennas per couple (3 measurements of 2 antennas placed face to face)

- application of Friis formula

$$|S_{12}|^2 = G_1 G_2 A_{el} A_{syst} \left(1-|\Gamma_1|^2\right)\left(1-|\Gamma_2|^2\right)$$
$$|S_{13}|^2 = G_1 G_3 A_{el} A_{syst} \left(1-|\Gamma_1|^2\right)\left(1-|\Gamma_3|^2\right)$$
$$|S_{23}|^2 = G_2 G_3 A_{el} A_{syst} \left(1-|\Gamma_2|^2\right)\left(1-|\Gamma_3|^2\right)$$

$$G_1 = \frac{|S_{12}||S_{13}|}{|S_{23}|} \frac{1}{1-|\Gamma_1|^2}$$
$$G_2 = \frac{|S_{12}||S_{23}|}{|S_{13}|} \frac{1}{1-|\Gamma_2|^2}$$
$$G_3 = \frac{|S_{13}||S_{23}|}{|S_{12}|} \frac{1}{1-|\Gamma_3|^2}$$

- measurement system matched otherwise compensation of the mismatches at the input and output.

- measurement of the matching of each antenna.

- distance between antennas measured.

Antenna Radiation Measurement – Gain, Polarization, Phase Centre

Measurement of the gain: substitution technique

- measurement of the antenna under test and then of a reference antenna

- application of Friis formula

$$|S_{AUT}|^2 = G_{AUT} A_{el} A_{syst} \left(1 - |\Gamma_{AUT}|^2\right)$$
$$|S_{étalon}|^2 = G_{étalon} A_{el} A_{syst} \left(1 - |\Gamma_{étalon}|^2\right)$$

$$G_{AUT} = G_{étalon} \frac{|S_{AUT}|^2}{|S_{étalon}|^2} \frac{1 - |\Gamma_{étalon}|^2}{1 - |\Gamma_{AUT}|^2}$$

- measurement system matched otherwise compensation of the mismatches at the input and output.

- measurement of the matching of each antenna.

Antenna Radiation Measurement – Gain, Polarization, Phase Centre

Measurement of the gain: technique of the three antennas in near field
- measurements of three antennas per couple (3 measurements of 2 antennas placed face to face)
- each measurement is carried out for a variation of the distance between then ranging from $0.2\,D^2/\lambda$ to $2\,D^2/\lambda$
- approximation by regression polynomials

$$S_{ij}(d)=\frac{1}{d}\left(\alpha_0^{ij}+\alpha_1^{ij}\frac{1}{d}++\alpha_2^{ij}\frac{1}{d^2}+\ldots\right)\left(\sqrt{1-|\Gamma_i|^2}\right)\left(\sqrt{1-|\Gamma_j|^2}\right)$$

- the first term corresponds to the far field: we apply the formula used the the technique of the three antennas.
- measurement system matched otherwise compensation of the mismatches at the input and output.
- measurement of the matching of each antenna.
- distance between antennas measured.

Antenna Radiation Measurement – Gain, Polarization, Phase Centre

Polarization: scalar measurements

Incomplete information, the determination of the polarization characteristics are done:

- use of a probe of right or left hand circular polarization

  > determination of the weightings used for the expansion of the polarization ellipse into right and left hand circular polarization.

  > direction of travel of the obtained ellipse.

  > the tilt of the ellipse cannot be determined.

- use of a probe of linear polarization:

  > measurement in spining polarization

  > for each position of the antenna under test, a set of various tilts of the probe is used in order to determine the main and minor axis of the polarization ellipse of the AUT.

  > simplification when applying a continuous rotation of the probe.

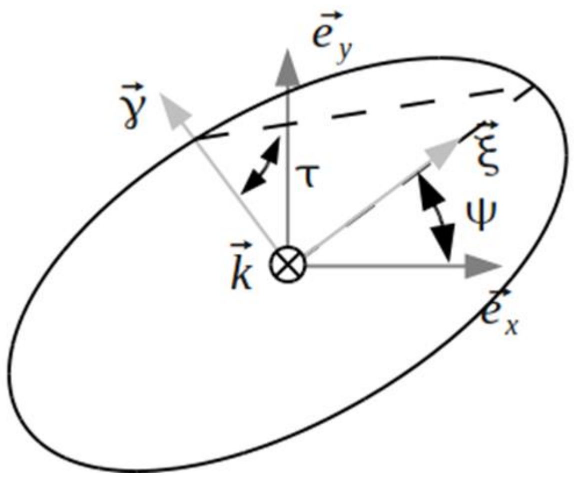
  > visualisation of the envelop corresponding to the main and minor axis of the ellipse.

  > the position of the probe enables to determine the tilt of the ellipse.

  > no information about the direction of travel of the ellipse.

Antenna Radiation Measurement – Gain, Polarization, Phase Centre

Polarization : vectorial measurements
- use of a probe of linear polarization
- measurements magnitude/phase for two orthogonal probe positions
- the measured fields can be expressed in compact form (probe according to x and y):



$$E_x = \left(A\vec{\xi} + jB\vec{\gamma}\right).\vec{e}_x e^{j\varphi_0}$$
$$E_y = \left(A\vec{\xi} + jB\vec{\gamma}\right).\vec{e}_y e^{j\varphi_0}$$

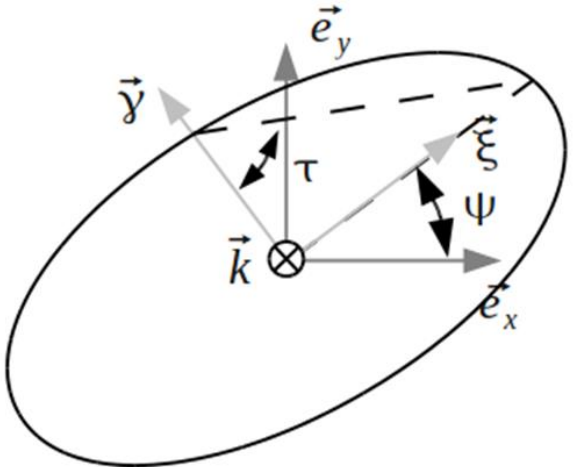
$$E_x = \left(A\cos(\psi) - jB\sin(\psi)\right)e^{j\varphi_0}$$
$$E_y = \left(A\sin(\psi) + jB\cos(\psi)\right)e^{j\varphi_0}$$

$$E_x = \frac{A+B}{2}\left(\cos(\psi) - j\sin(\psi)\right)e^{j\varphi_0} + \frac{A-B}{2}\left(\cos(\psi) + j\sin(\psi)\right)e^{j\varphi_0}$$
$$E_y = \frac{A+B}{2}\left(\sin(\psi) + j\cos(\psi)\right)e^{j\varphi_0} + \frac{A-B}{2}\left(\sin(\psi) - j\cos(\psi)\right)e^{j\varphi_0}$$

Antenna Radiation Measurement – Gain, Polarization, Phase Centre

Polarization : vectorial measurements

$$E_x=\frac{A+B}{2}(\cos(\psi)-j\sin(\psi))e^{j\varphi_0}+\frac{A-B}{2}(\cos(\psi)+j\sin(\psi))e^{j\varphi_0}$$
$$E_y=\frac{A+B}{2}(\sin(\psi)+j\cos(\psi))e^{j\varphi_0}+\frac{A-B}{2}(\sin(\psi)-j\cos(\psi))e^{j\varphi_0}$$



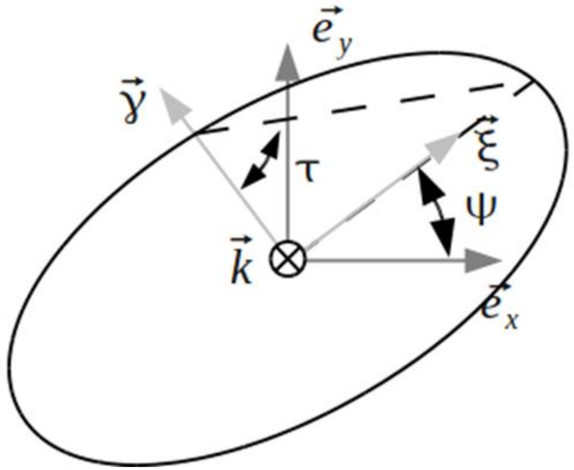
$$E_x=\frac{A+B}{2}e^{-j\psi}e^{j\varphi_0}+\frac{A-B}{2}e^{j\psi}e^{j\varphi_0}$$
$$E_y=j\frac{A+B}{2}e^{-j\psi}e^{j\varphi_0}-j\frac{A-B}{2}e^{j\psi}e^{j\varphi_0}$$

$$E_x+jE_y=(A-B)e^{j\psi}e^{j\varphi_0}$$
$$E_x-jE_y=(A+B)e^{-j\psi}e^{j\varphi_0}$$

$$|E_x+jE_y|=|A-B| \qquad |E_x-jE_y|=|A+B|$$

Antenna Radiation Measurement – Gain, Polarization, Phase Centre

Polarization : vectorial measurements



$$|E_x + jE_y| = |A - B| \qquad |E_x - jE_y| = |A + B|$$

$|E_x + jE_y| > |E_x - jE_y|$ Right hand polarization

$|E_x + jE_y| < |E_x - jE_y|$ Left hand polarization

$$e^{2j\psi} = \left(\frac{E_x + jE_y}{E_x - jE_y}\right)\left(\frac{A+B}{A-B}\right)$$

$$AR = \tan(\tau) = |max(A,B)| / |min(A,B)|$$

… be careful if the probe has an elliptical polarization!

Antenna Radiation Measurement – Gain, Polarization, Phase Centre

Phase center

- definition of the phase center: comes from the modeling of the antenna radiation as a superposition of spherical waves

- simplest case: isotropic antenna > if this source is placed exactly at the center of the coordinate system, then the phase is constant for all positions of the observation point (at a fixed distance).

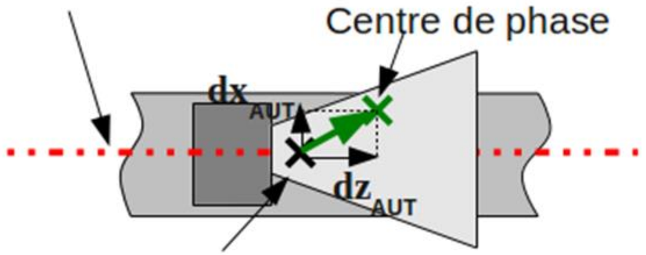
- generalization: the phase center is the point from which is produced the radiation of the antenna.

- when the antenna is placed such as this point is located at the center of the coordinate system then a constant phase pattern is obtained for a finite angular sweep.

Antenna Radiation Measurement – Gain, Polarization, Phase Centre

Phase center: computation

- the search for the phase center is carried out over a part of the main beam of the radiation pattern.



$$dx_{AUT} = \vec{OP}.\vec{e}_x = \Delta \sin(\varphi_0)$$
$$dz_{AUT} = \vec{OP}.\vec{e}_z = \Delta \cos(\varphi_0)$$

$$\Phi = \Phi_0 - k\left(dz\cos(\theta) - dx\sin(\theta)\right)$$

Antenna Radiation Measurement – Gain, Polarization, Phase Centre

Phase center: computation

- Determination of the lateral and longitudinal shifts: least square method

$$\delta=\sum_{i=-N}^{N}\left(\Phi_i^{mes}-\left(\Phi_0-k\left(d_z\cos(\theta_i)-d_x\sin(\theta_i)\right)\right)\right)^2$$

- Sum of the squares of the difference between measurements and modeling is minimum if:

$$\frac{d\delta}{dx}=\sum_{i=-N}^{N}\left(2\left(\Phi_i^{mes}-\left(\Phi_0-k\left(d_z\cos(\theta_i)-d_x\sin(\theta_i)\right)\right)\right)\left(-k\sin(\theta_i)\right)\right)=0$$

$$\frac{d\delta}{dz}=\sum_{i=-N}^{N}\left(2\left(\Phi_i^{mes}-\left(\Phi_0-k\left(d_z\cos(\theta_i)-d_x\sin(\theta_i)\right)\right)\right)\left(k\cos(\theta_i)\right)\right)=0$$

$$\frac{d\delta}{d\Phi_0}=\sum_{i=-N}^{N}\left(2\left(\Phi_i^{mes}-\left(\Phi_0-k\left(d_z\cos(\theta_i)-d_x\sin(\theta_i)\right)\right)\right)(-1)\right)=0$$

Antenna Radiation Measurement – Gain, Polarization, Phase Centre

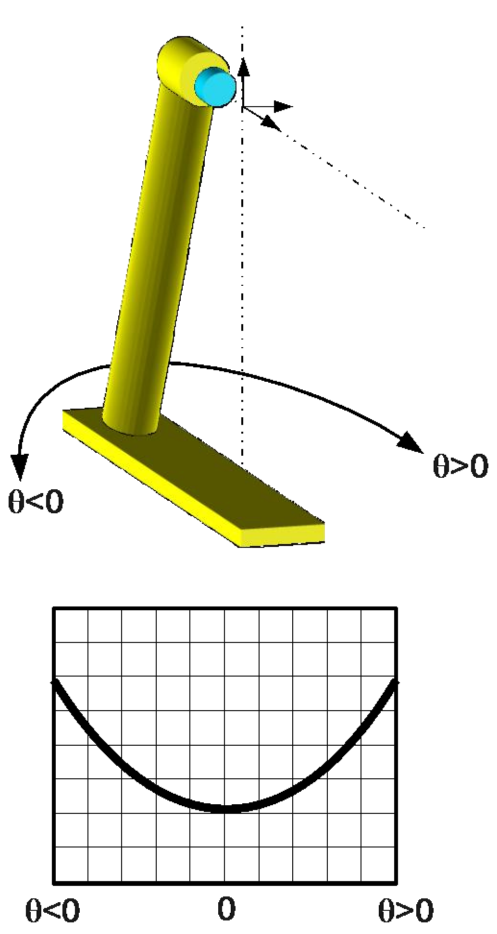
Phase center: computation

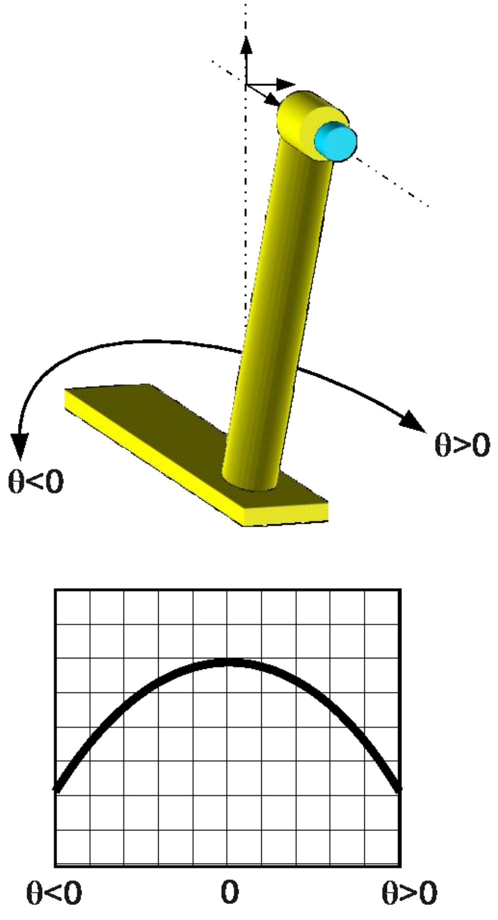
$$\begin{bmatrix} -k\sum_{i=-N}^{N}\sin^2(\theta_i) & k\sum_{i=-N}^{N}\sin(\theta_i)\cos(\theta_i) & -\sum_{i=-N}^{N}\sin(\theta_i) \\ -k\sum_{i=-N}^{N}\sin(\theta_i)\cos(\theta_i) & k\sum_{i=-N}^{N}\cos^2(\theta_i) & -\sum_{i=-N}^{N}\cos(\theta_i) \\ -k\sum_{i=-N}^{N}\sin(\theta_i) & k\sum_{i=-N}^{N}\cos(\theta_i) & -(2N+1) \end{bmatrix} \begin{bmatrix} dx \\ dz \\ \Phi_0 \end{bmatrix} = \begin{bmatrix} -\sum_{i=-N}^{N}\Phi_i^{mes}\sin(\theta_i) \\ -\sum_{i=-N}^{N}\Phi_i^{mes}\cos(\theta_i) \\ -\sum_{i=-N}^{N}\Phi_i \end{bmatrix}$$

- determination assumes that the used beam is not tilted
- in the case of a beam with tilt:
  > compensation of this tilt to determine the phase center
  > the phase center is projected in the reference coordinate system

Antenna Radiation Measurement – Gain, Polarization, Phase Centre

Phase center: intuitive approach





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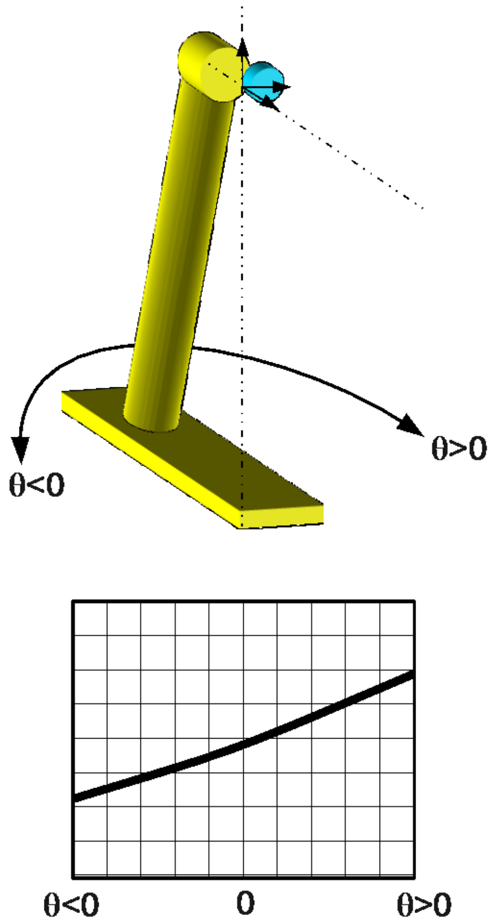
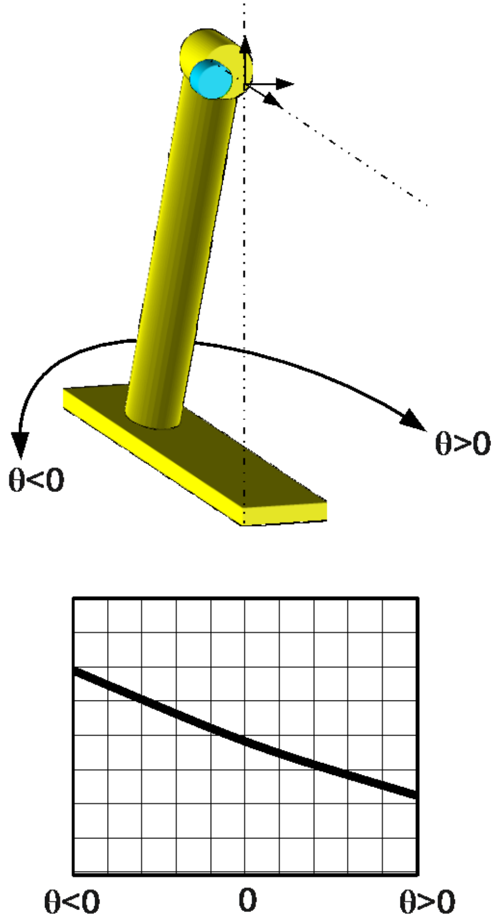
Antenna Radiation Measurement – Gain, Polarization, Phase Centre

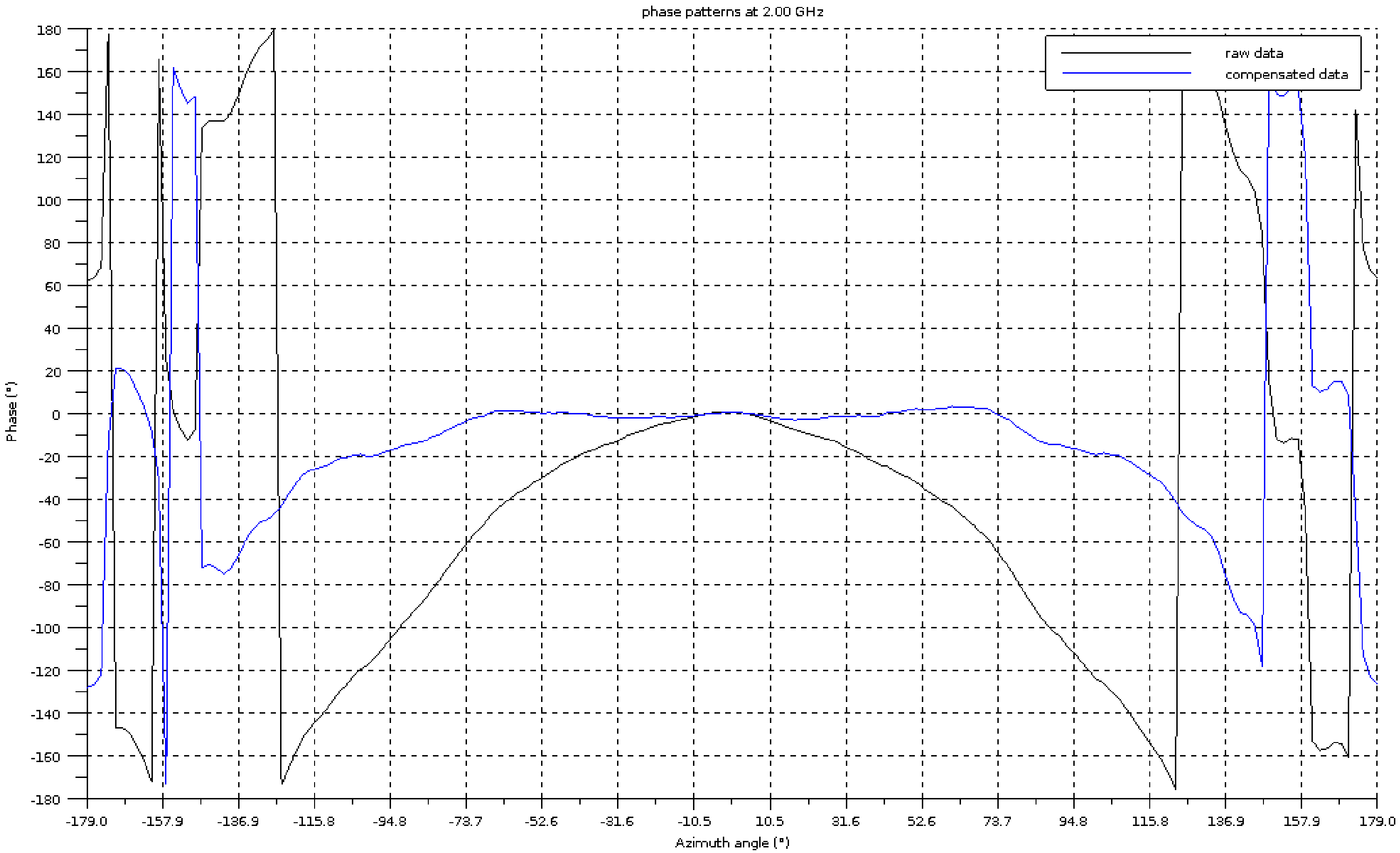
Phase center: intuitive approach





Antenna Radiation Measurement – Gain, Polarization, Phase Centre

Phase center: example



Antenna Radiation Measurement – Data Processing

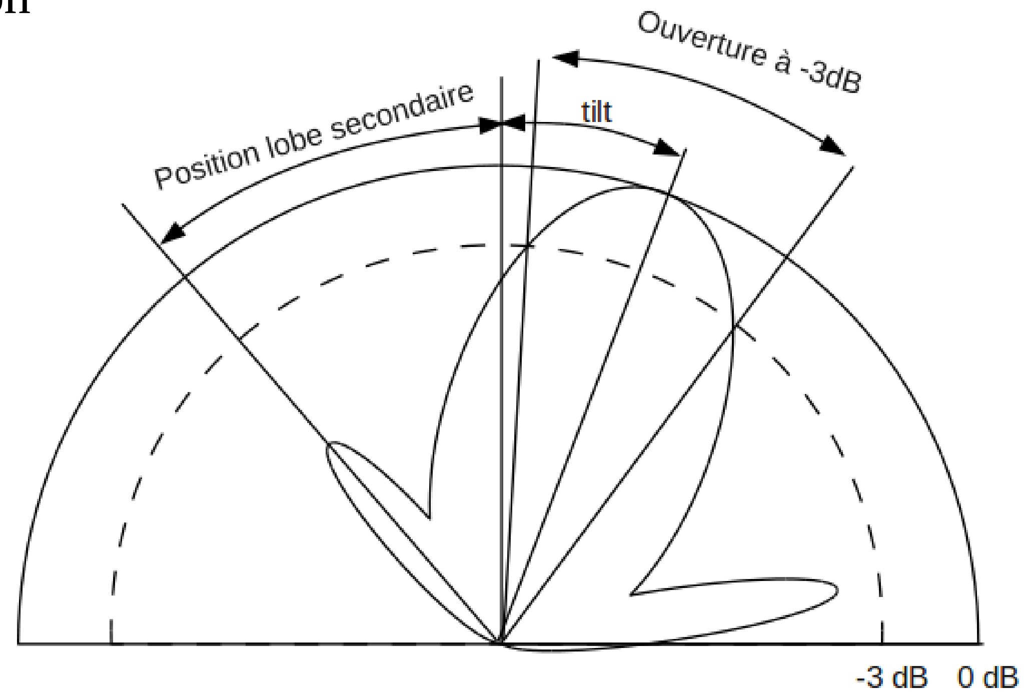
Basic rules:

- measurement representation: what is the goal?
  - > to proceed to results analysis
    - >> easy to exploit
    - >> topic of discussion (especially when the antenna is not working)
  - > to show that the antenna works properly (or not)
    - >> easy to understand
    - >> fit your language to your interlocutor…

- Simple things to be applied :
  - > choice of scaling
    - >> coherent with the capabilities of the measurement system and the pattern levels
    - >> fixed to ease comparisons
  - > choice of representation format: essential to be understood by users

Antenna Radiation Measurement – Data Processing

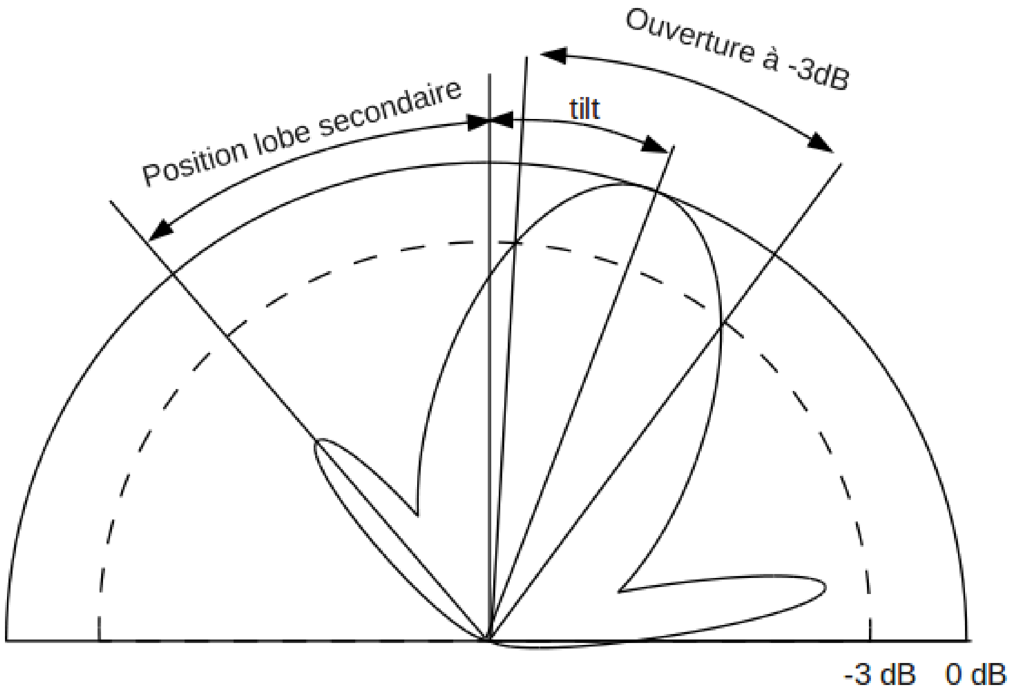
Cutting planes: data exploitation



Computation of the aperture:
- linear interpolation of the points located from both side of the circle used to define the aperture.
- polynomial interpolation (regression polynomial) of the part of the beam cutting the circle used to define the aperture. An approximation of parabolic kind is in general good enough, but in the case of deformed beams a higher polynomial order must be used.

Antenna Radiation Measurement – Data Processing

Cutting planes: data exploitation



Computation of the tilt angle:

- linear interpolation of the points located from both sides of the maximum of the beam.
- polynomial interpolation (regression polynomial) of the upper part of the beam, then computation of the poles of the polynomial derivative.

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Antenna Radiation Measurement – Data Processing

Types of representation : 2D representation (cutting planes)

- cartesian :
  - > ideal for accurate analysis, if the scaling is well chosen...
  - > not always understood by beginners.
  - > modification of the scaling
    - >> scaling factor
    - >> enables zoom in abscissa and ordinate.

- polar :
  - > very visual so easy to understand.
  - > less appropriated for accurate analysis (which can be convenient!).
  - > modification of scaling
    - >> scaling factor induces a pattern « deformation ».
    - >> enables zoom in ordinates (radius).
    - >> do not necessarily enable zoom in abscissa (angle) : use a sweep of [-180:180]° or [-90:90]° do not enable an enlargment…

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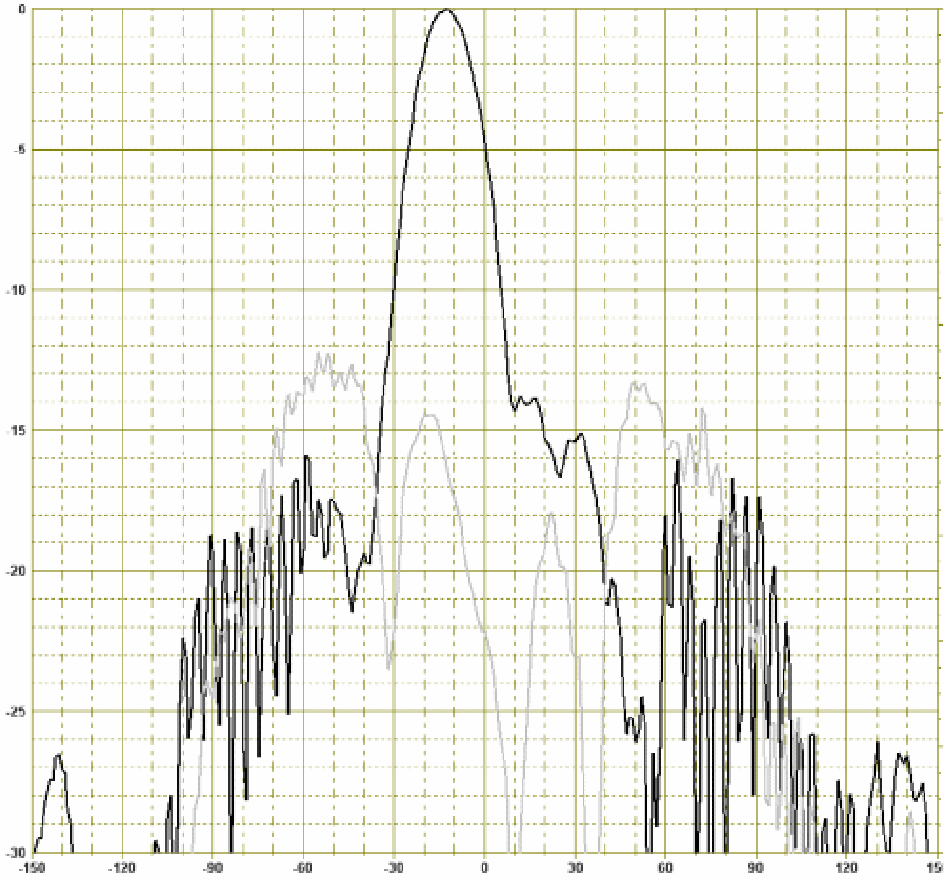
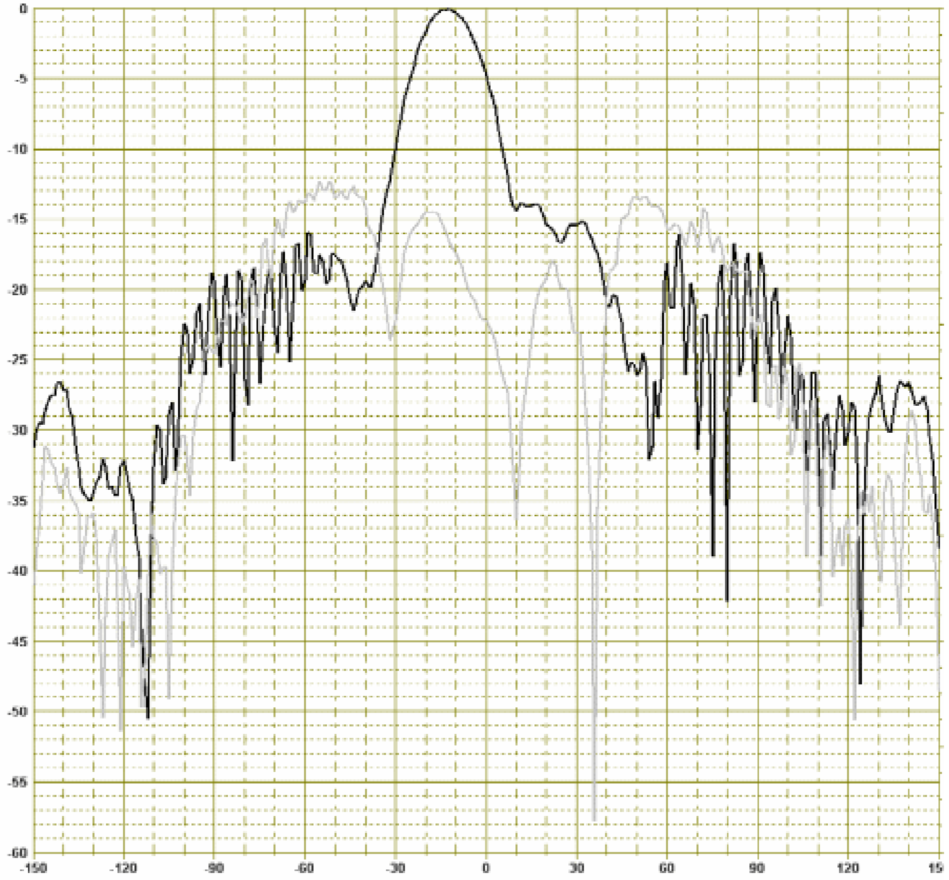
Antenna Radiation Measurement – Data Processing

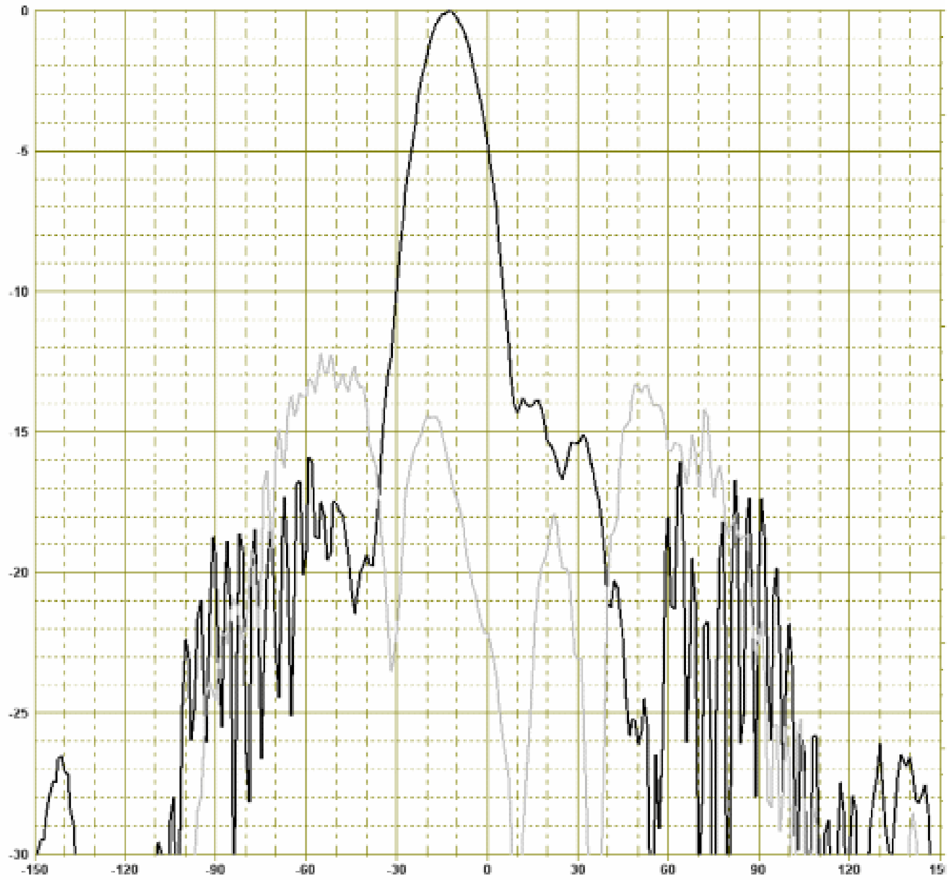
Types de representation: 2D representation

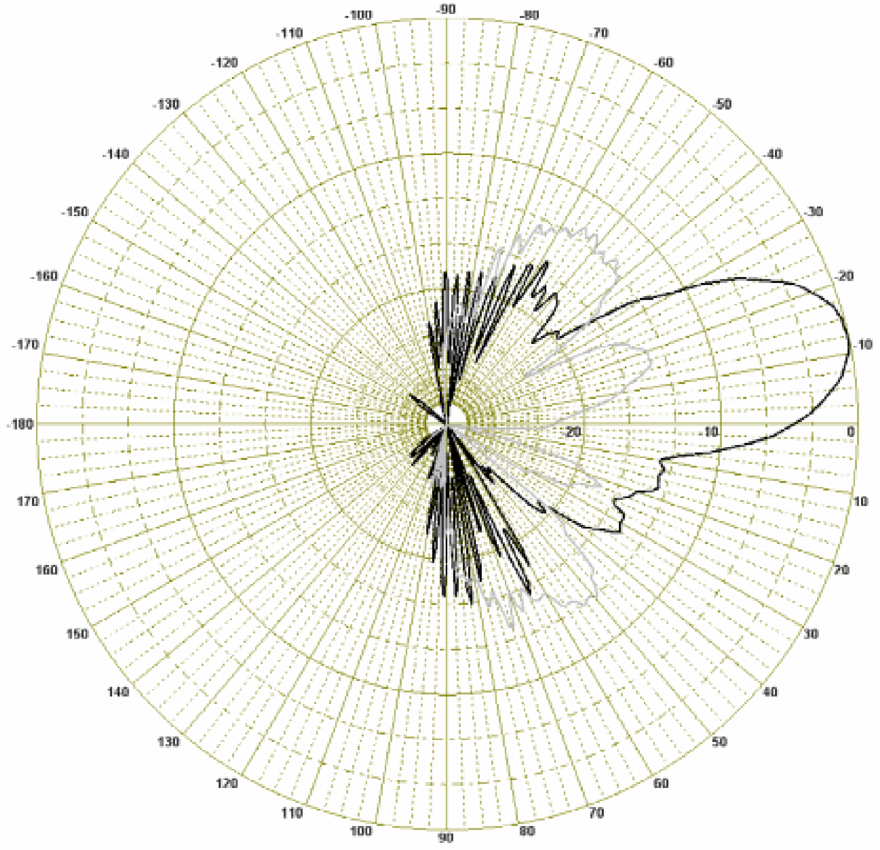




Antenna Radiation Measurement – Data Processing

Types de representation: 2D representation





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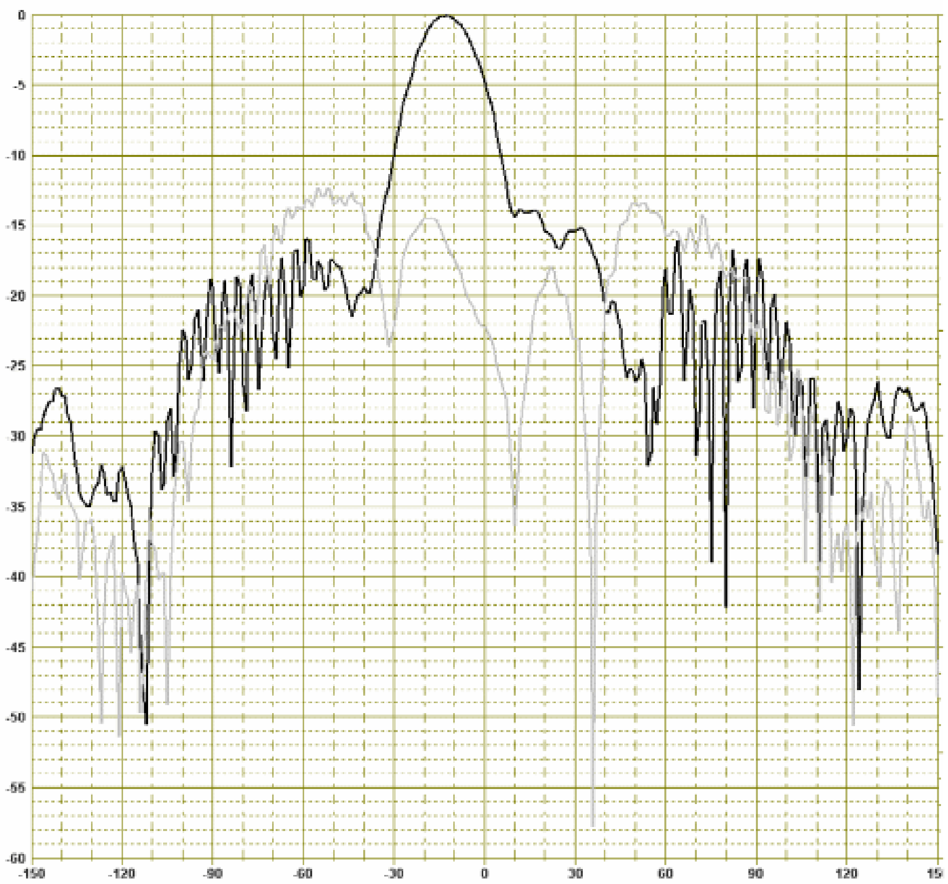
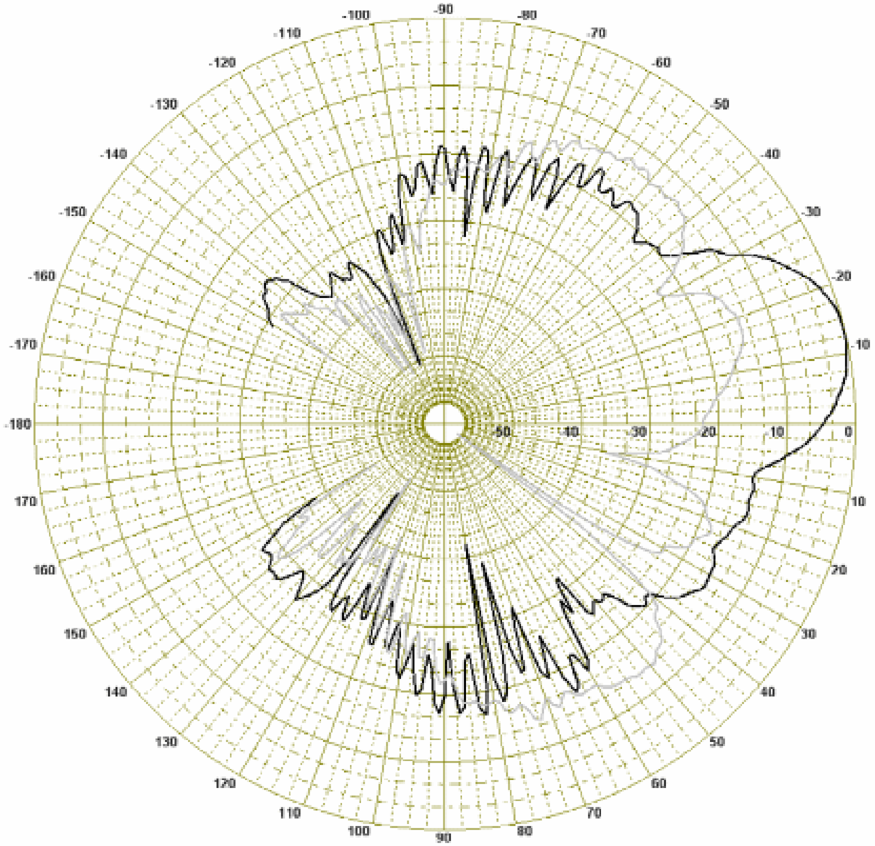
Antenna Radiation Measurement – Data Processing

Types de representation: 2D representation





Antenna Radiation Measurement – Data Processing

Types de representation: 3D representation
- spherical :
  > natural visualisation, so easy to understand!
  > not appropriate to accurate analysis
  > deformation when projected

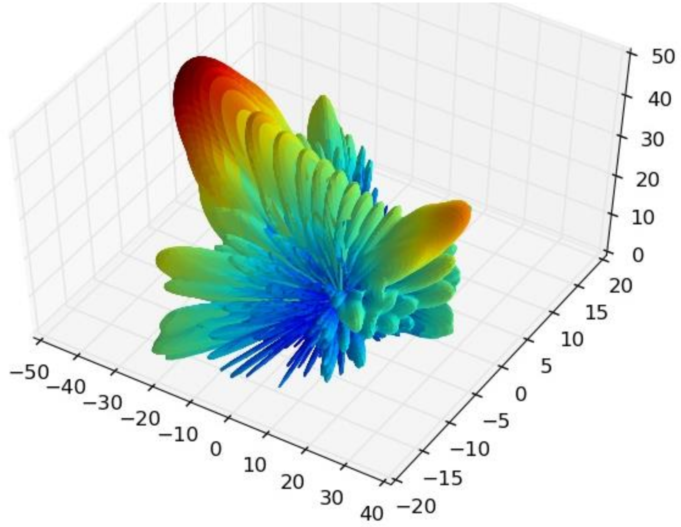
- mapping: field intensity is represented by a color code
  > cartesian grid:
    >> the choice of the grid is essential (theta/phi, azimuth/elevation)
    >> not so easy to understand for beginners
    >> well suited for analysis
  > polar grid:
    >> visually better than cartesian grid
    >> less appropriated than cartesian grid for analysis

Antenna Radiation Measurement – Data Processing

Spherical 3D representation
- Full sphere representation :
  - Sampling of the sphere according to a $(\theta;\varphi)$ grid.
  - For each sample, definition of a vector $\vec{V}$ contaning the information V to represent :

$$\vec{V} = V\,\vec{e}_\rho = V\begin{bmatrix} sin\theta cos\phi \\ sin\theta sin\phi \\ cos\theta \end{bmatrix}$$

  - Choice of the axis scale and color map is of main interest…



Antenna Radiation Measurement – Data Processing

Spherical 3D representation

- Hemisphere sphere representation :
  - Sampling of the sphere according to a $(\theta;\varphi)$ grid.
  - On each hemisphere, for each sample, definition of a vector $\vec{V}$ contaning the information V to represent :

$$\vec{V} = \begin{bmatrix} sin\theta cos\phi \\ sin\theta sin\phi \\ V \end{bmatrix}$$

  - Scale definition for each axis is simple, understanding of representation is not natural.

Antenna Radiation Measurement – Data Processing

3D mapping representation

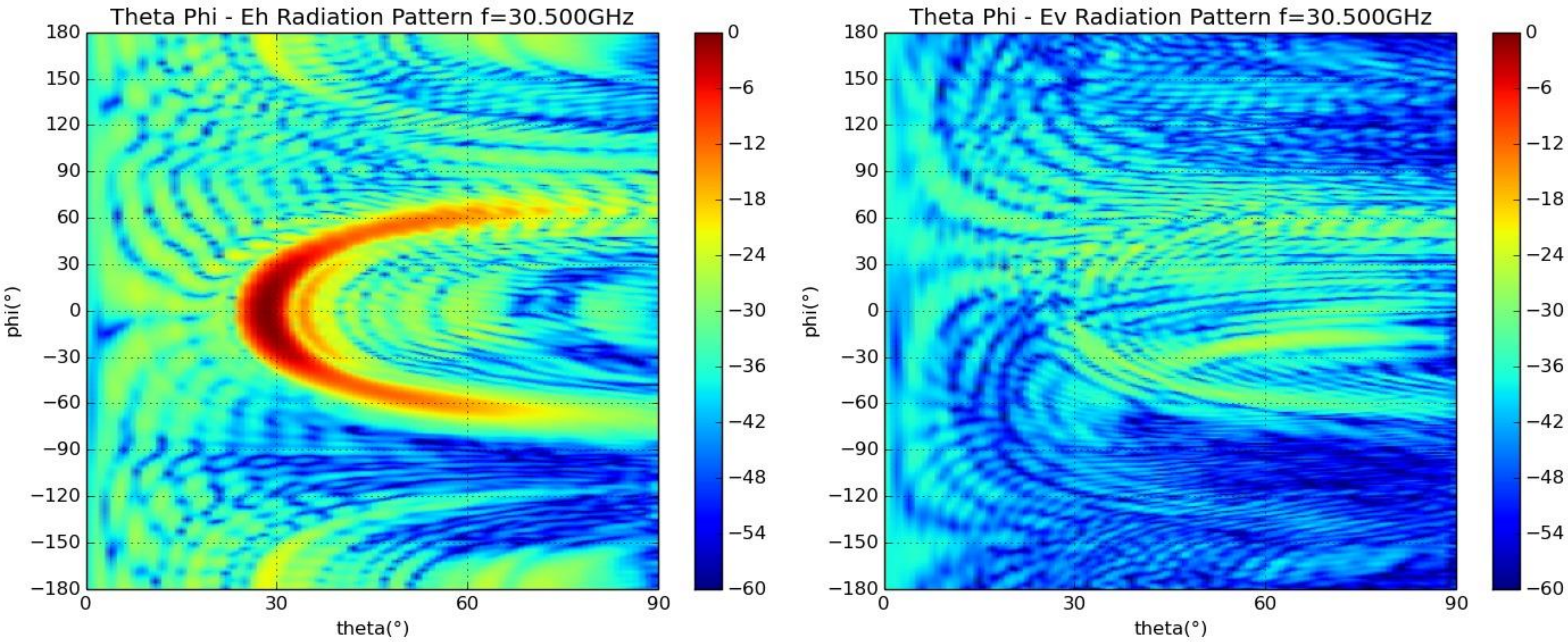
- Cartography of the parameter of interest, on a specific sampling grid :
  - A color map is used to give information on the parameter value variation
  - The grid can be a cartesian or polar one.

- Cartesian grid :
  - The (θ, φ) grid is not easy to understand and not well suited for $(\overrightarrow{e_\theta}, \overrightarrow{e_\varphi})$ representation (singularity on the poles).
  - The elevation/azimuth and azimuth/elevation is easy to understand, but deformation near the poles are obvious.
  - The uv grid definition is not easy to understand, but the visual representation is efficient, even if deformation occured near radius=1.

- Polar grid :
  - The grid is easy to understand, but the analysis is not easy due to deformation near outer circle.

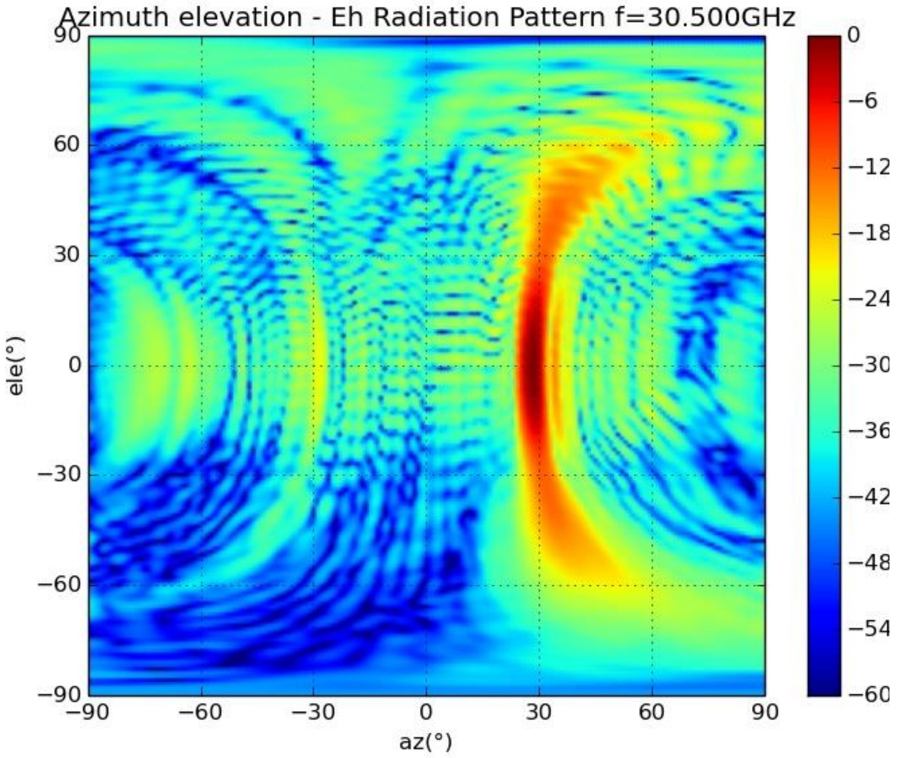
Antenna Radiation Measurement – Data Processing

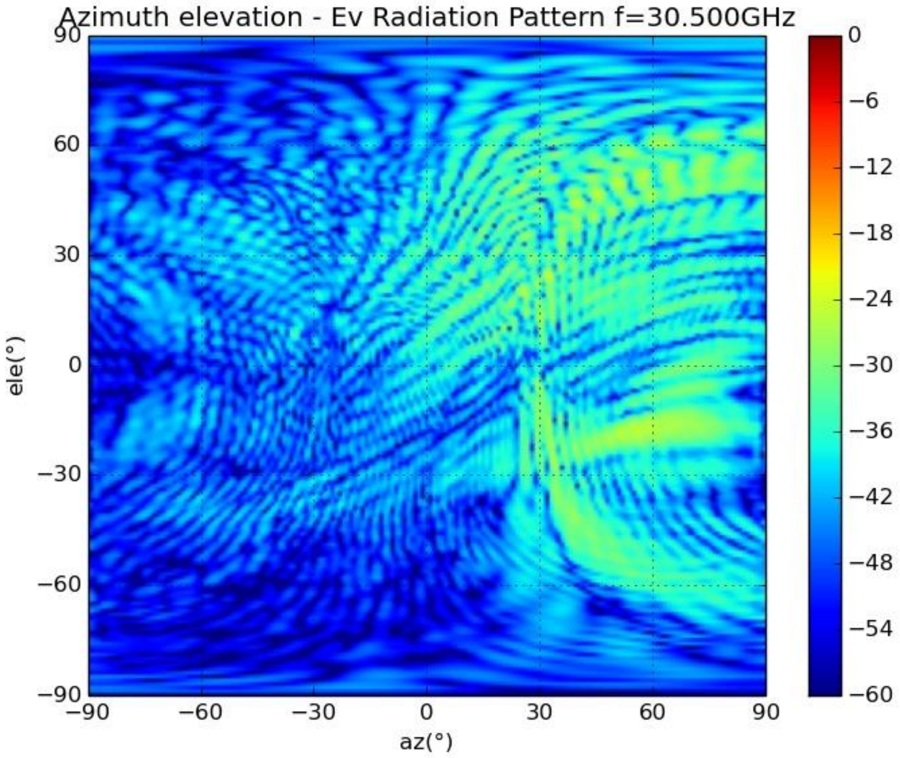
Types of representation : examples



Antenna Radiation Measurement – Data Processing

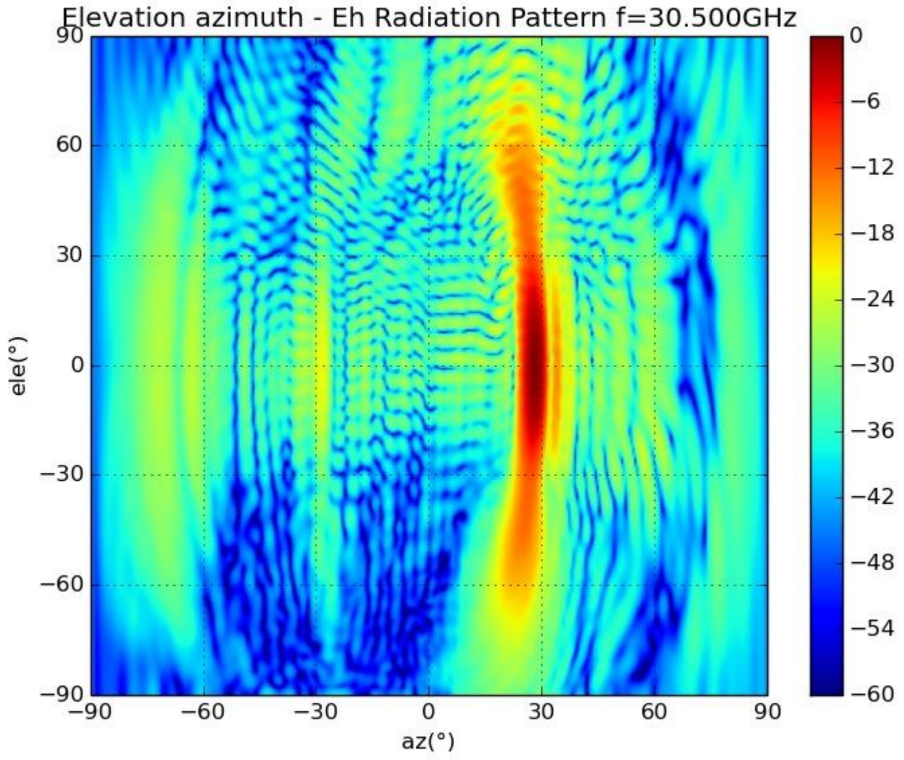
Types of representation : examples

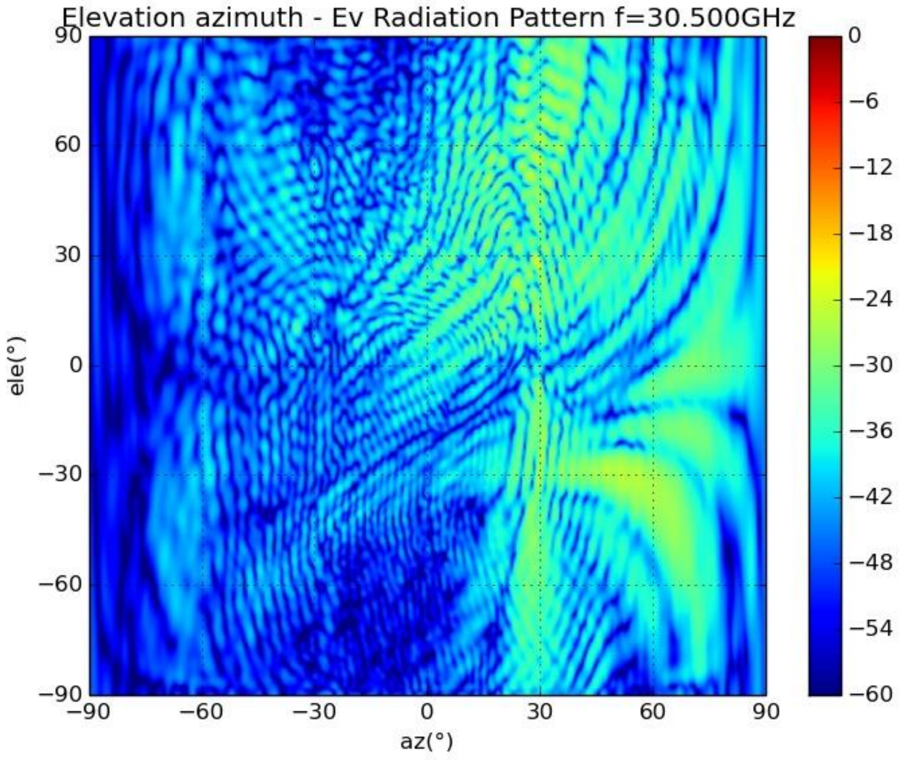




Antenna Radiation Measurement – Data Processing

Types of representation : examples





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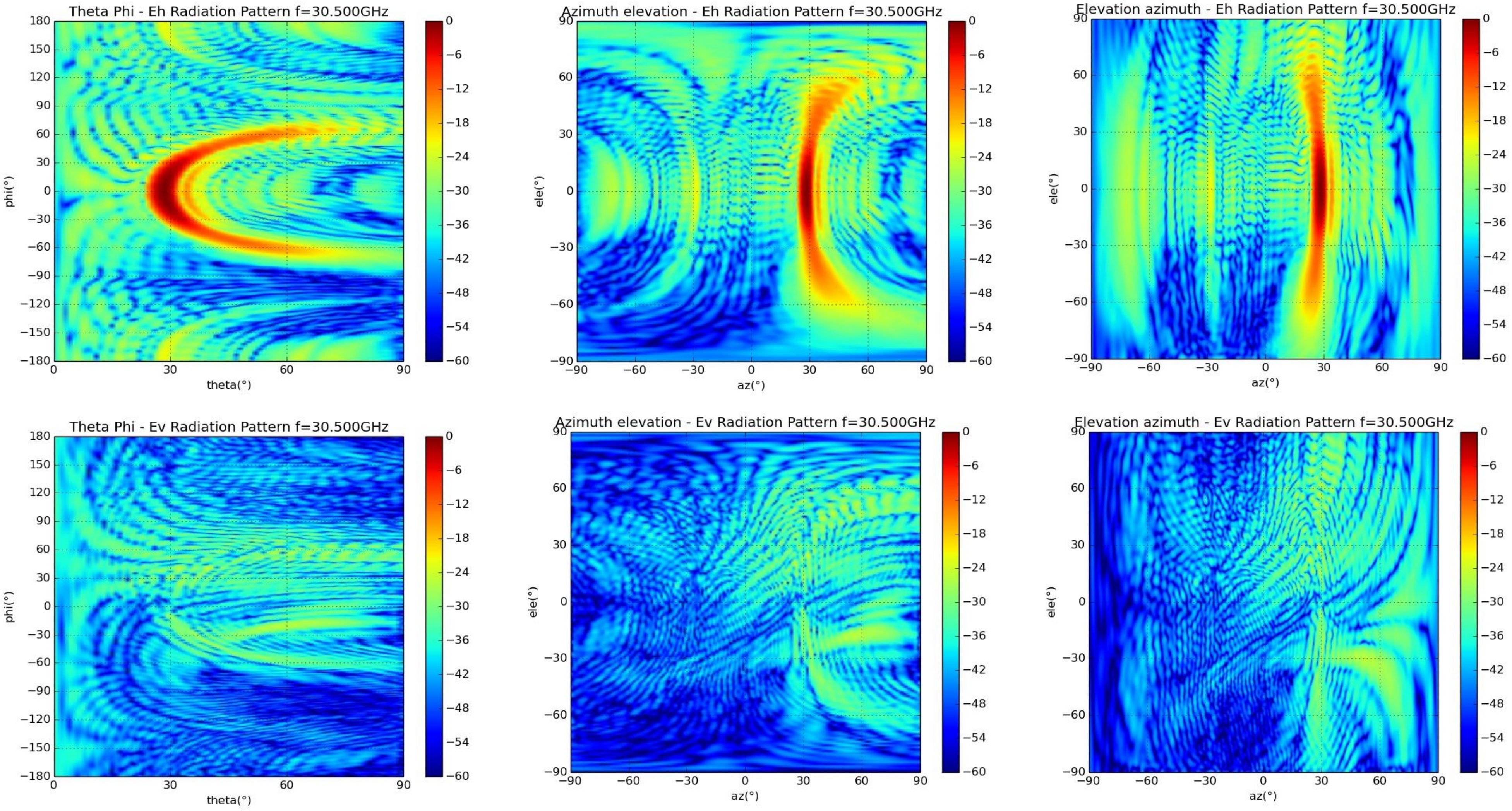
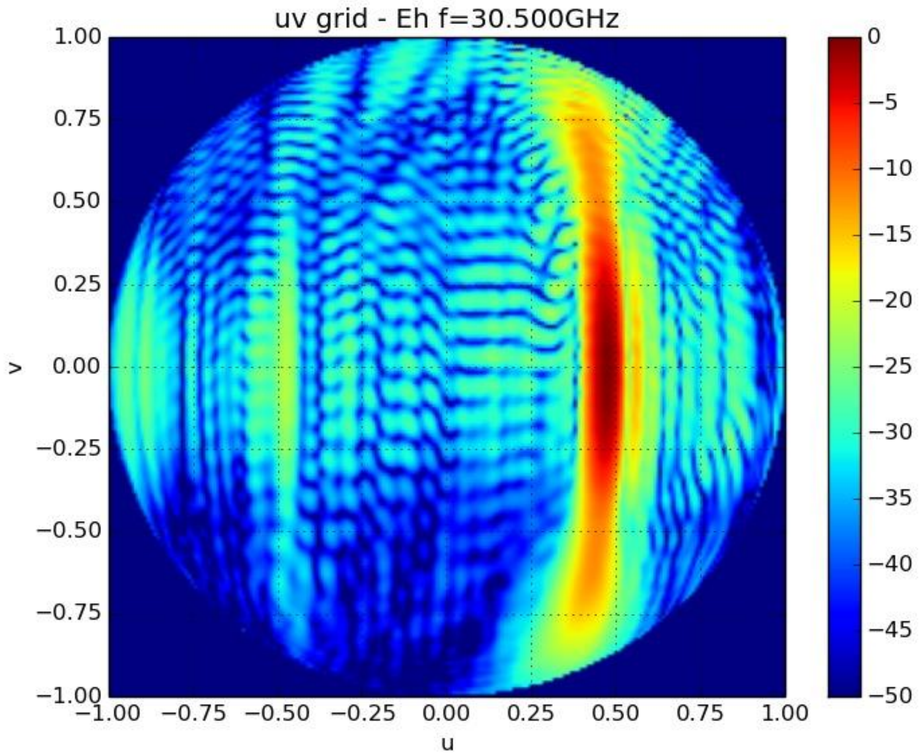
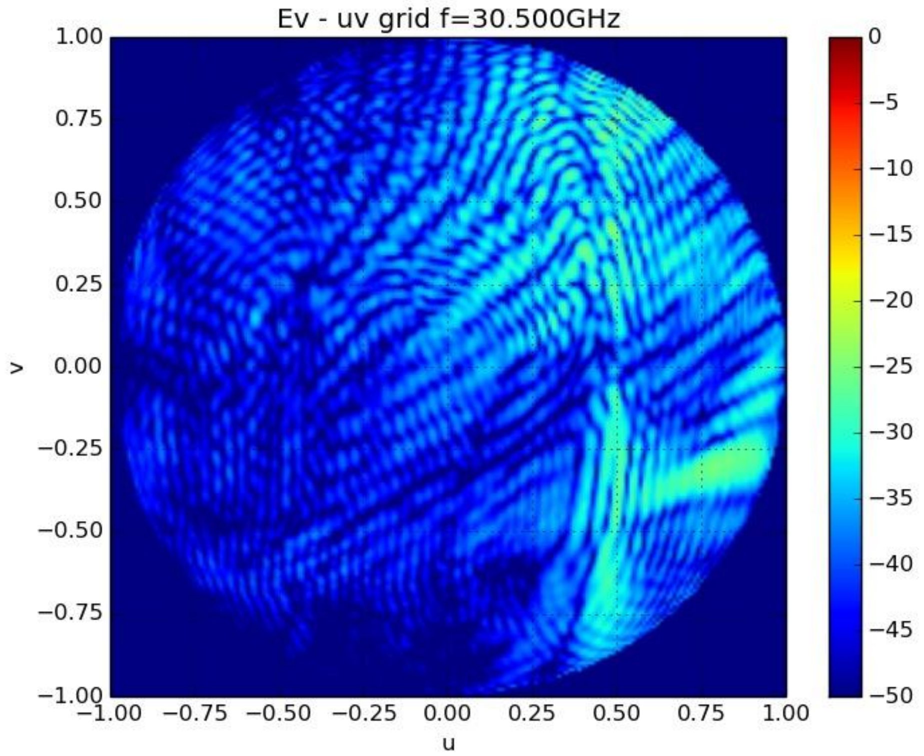
Antenna Radiation Measurement – Data Processing



Antenna Radiation Measurement – Data Processing

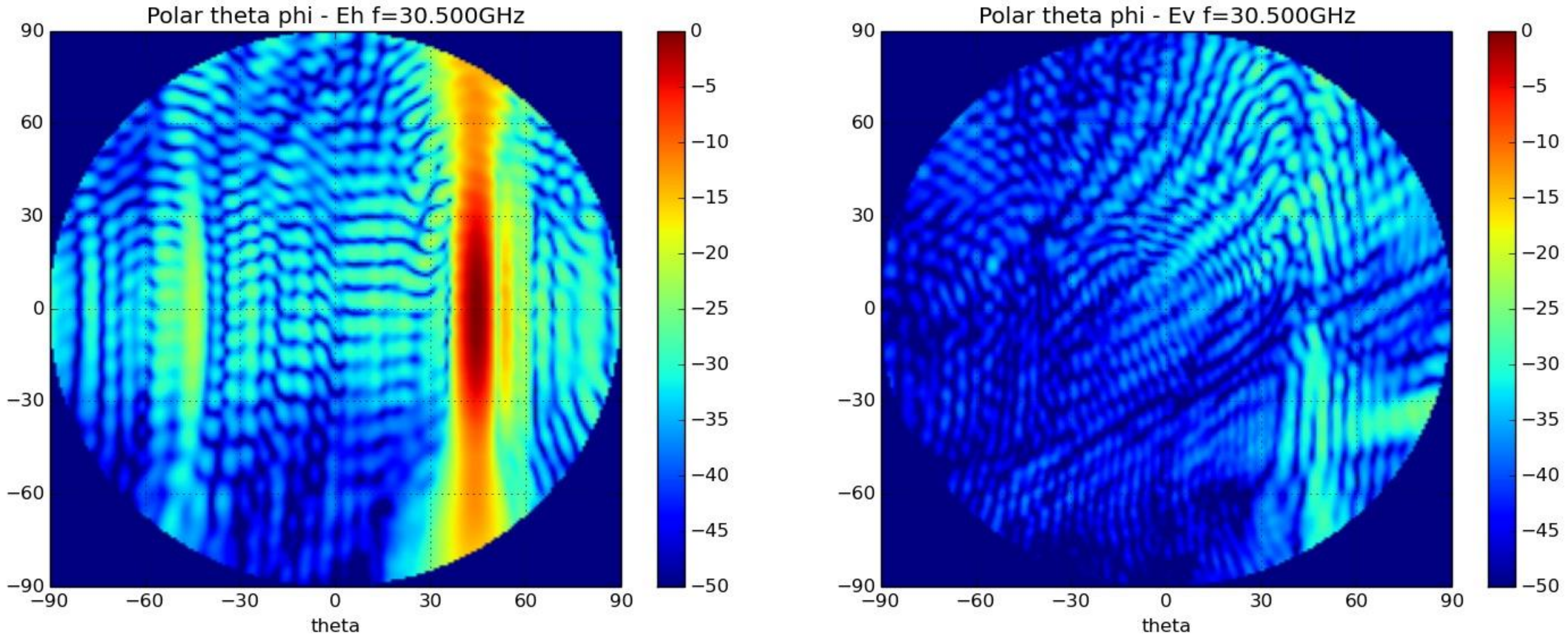
Types of representation : examples





Antenna Radiation Measurement – Data Processing

Types of representation : examples



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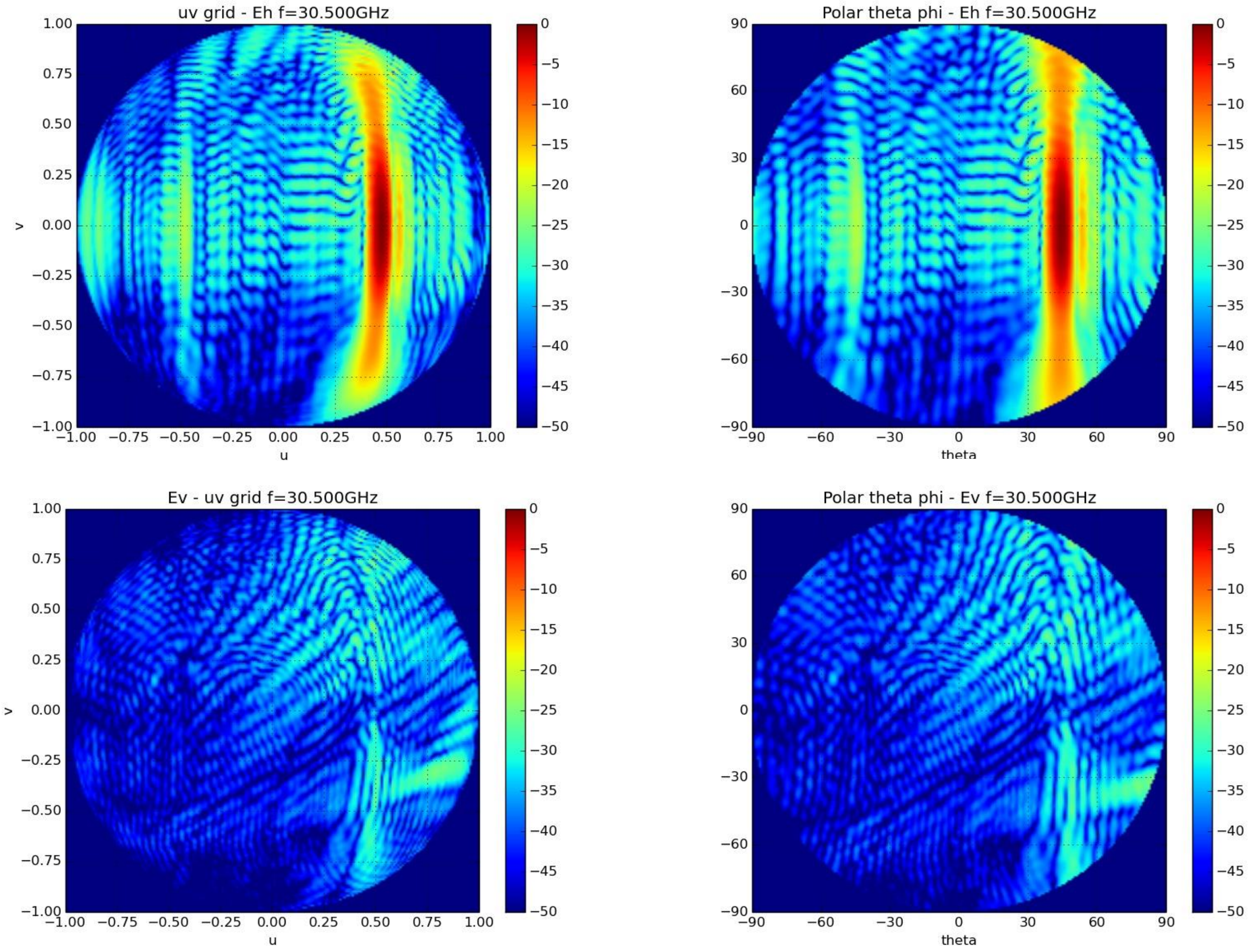
Antenna Radiation Measurement – Data Processing



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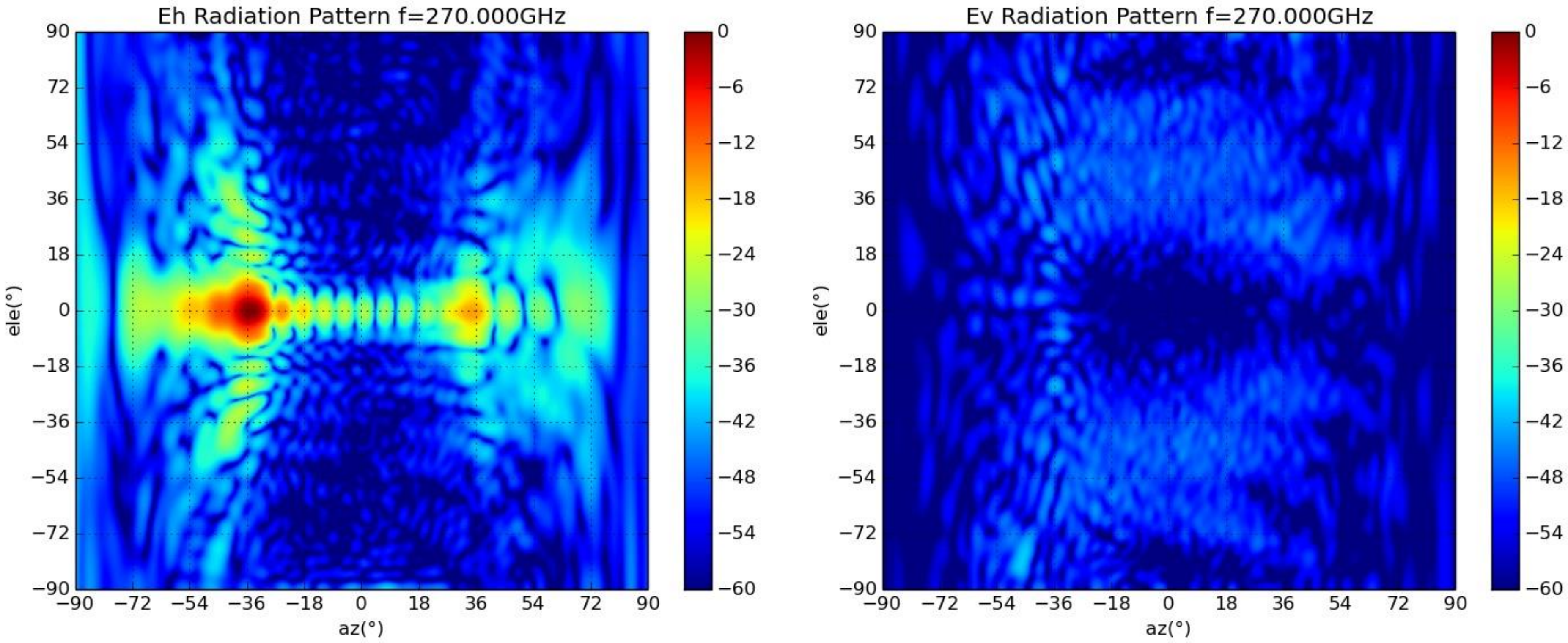

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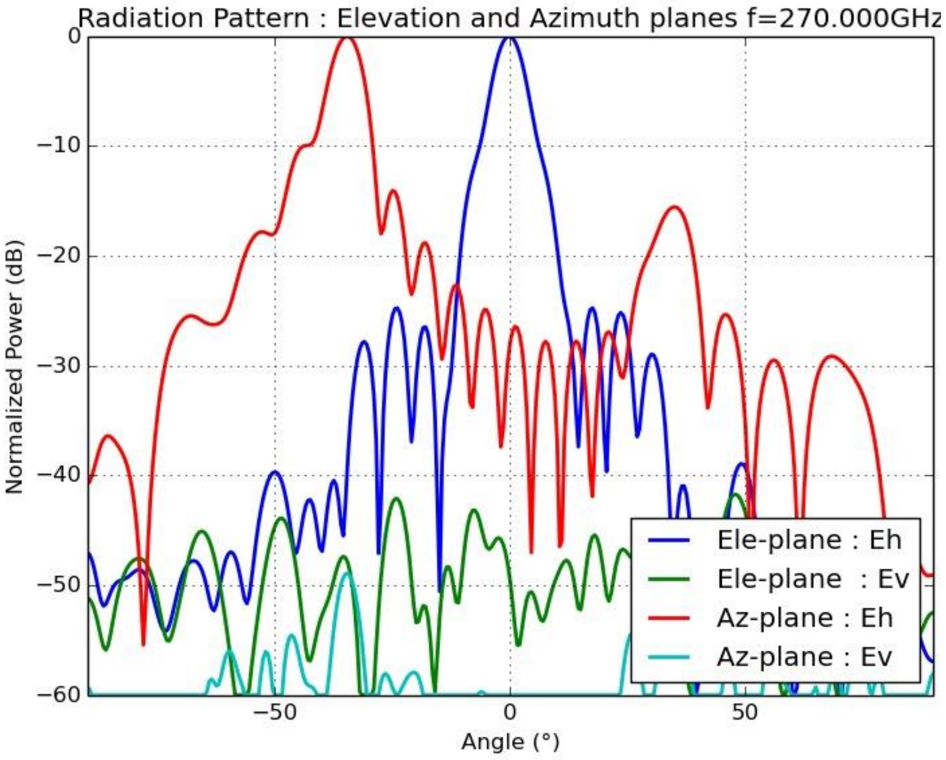

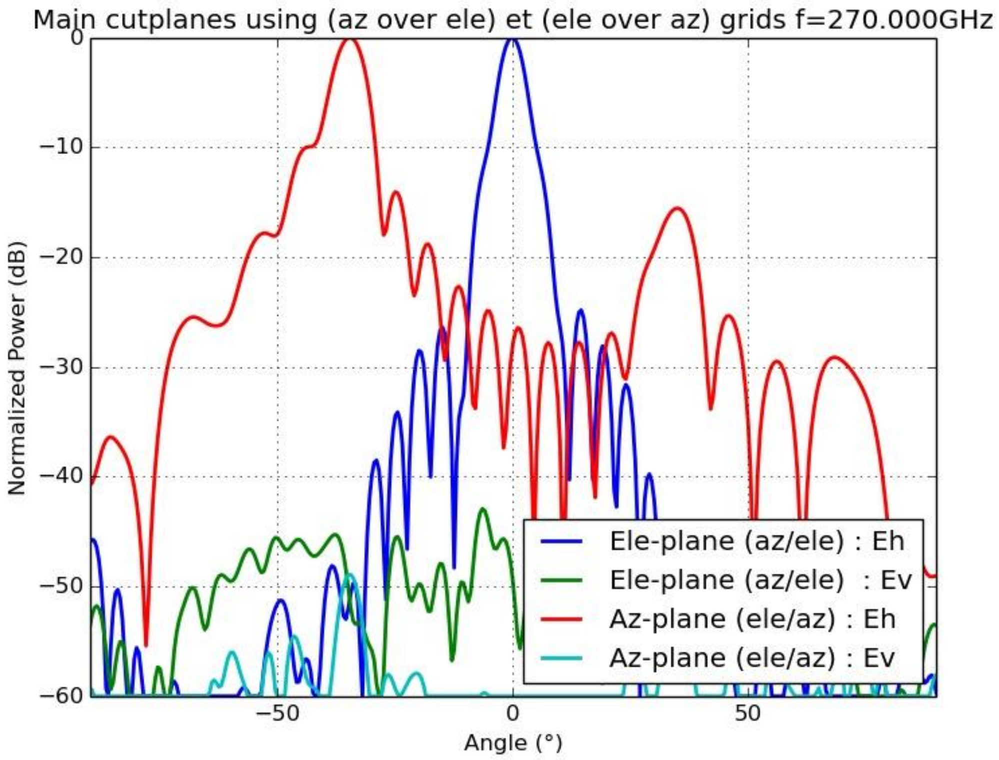

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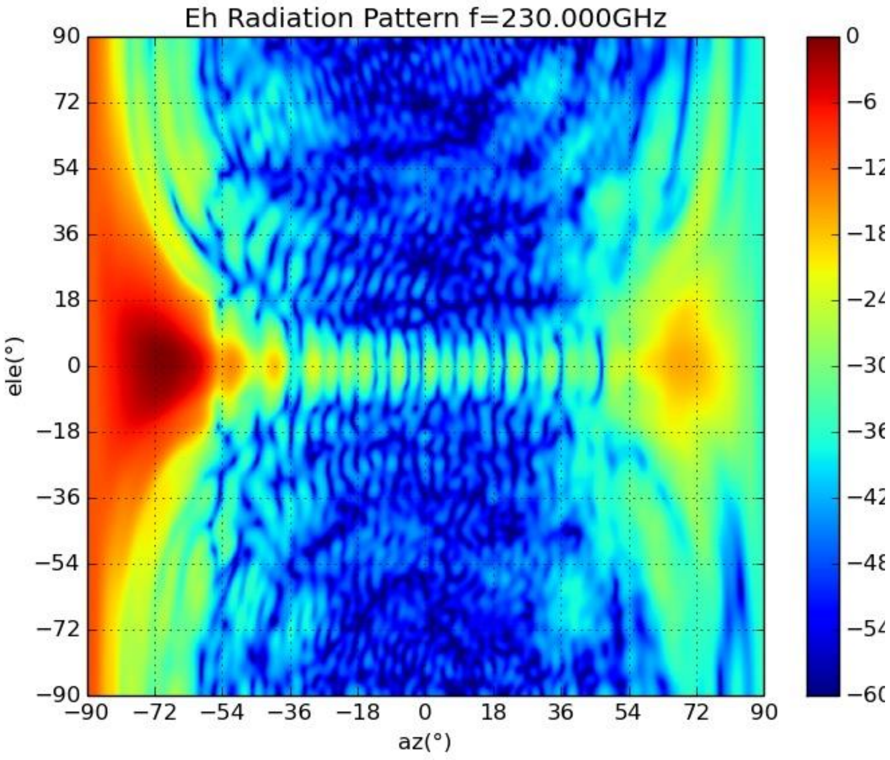
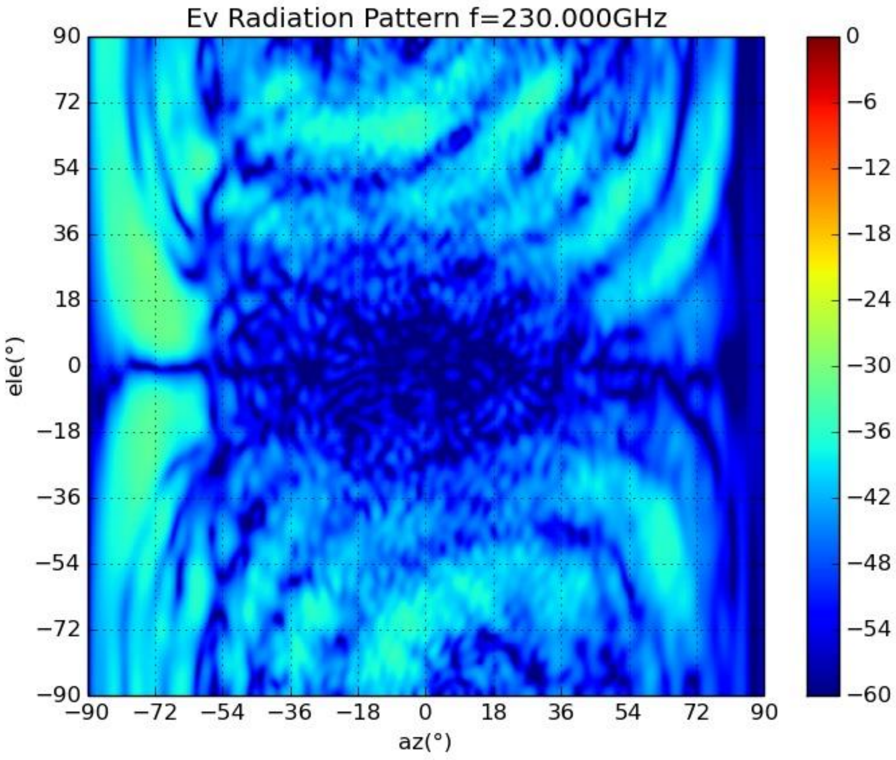
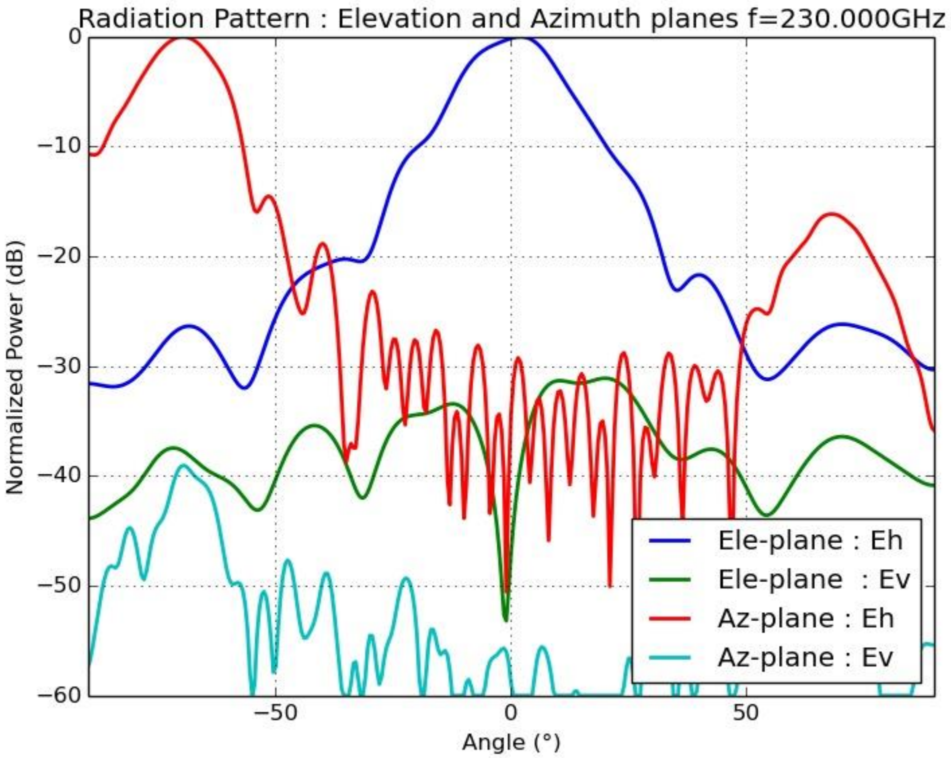
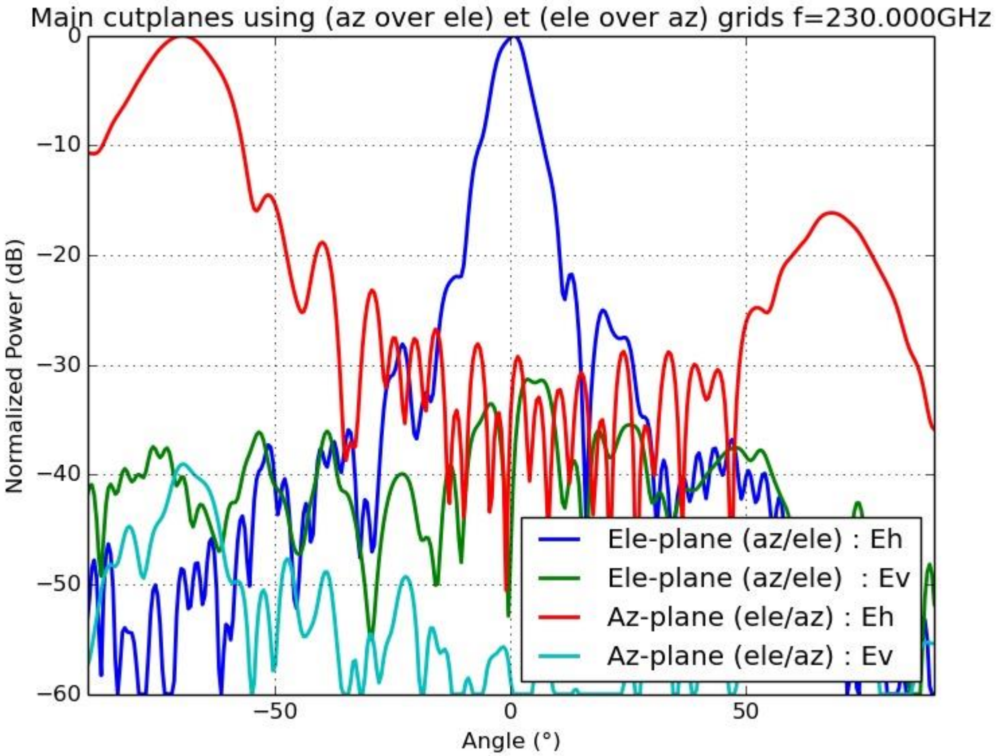




Antenna Radiation Measurement – Data Processing





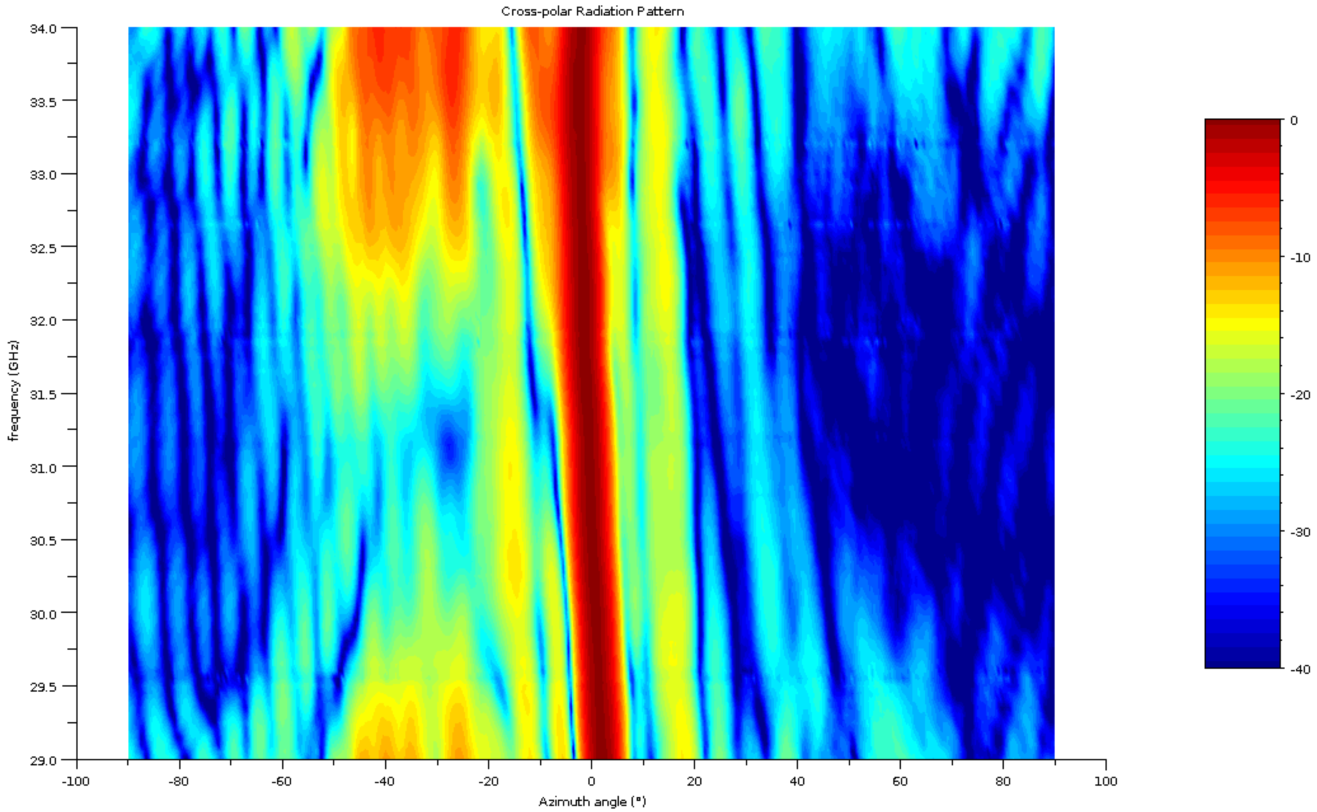
Antenna Radiation Measurement – Data Processing

Types of representation: 3D representation

- mapping representation on a grid frequency/angle
  - > for normalized patterns:
    - >> visualization of the side lobe levels
    - >> visualization of the tilt evolution
  - > for gain patterns:
    - >> visualization of the gain evolution...

Antenna Radiation Measurement – Data Processing

Types of representation: 3D representation



Antenna Radiation Measurement – Data Processing

Keypoint : Discussion between Design and Characterization Teams : mandatory to avoid misunderstanding :

- « I want to measure my antenna » : it is out of understanding! Do you need a ruler?
- Antenna characterization needs have to be defined :
  - Overall goal of this characterization
  - Type of characterization : 2D? 3D?
  - Data of interest : cutting planes? Full sphere data? Gain? Directivity? Polarization? Beam tilt? Half Power Beam Width? Phase centre? …
  - Number of beams
  - Number of configurations
  - Frequency range and frequency step
  - Antenna coordinates system
  - Data coordinate system
- Antenna under Test constraints have to be defined :
  - Geometrical size ; Weight
  - Type of connector
  - Specific mounting part have to be developped?

Coordinate System

Coordinate System

Rotation matrix in the Cartesian coordinate system :

- Rotation matrix around (Ox) axis :

$$Q_x(\phi) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & -\sin\phi \\ 0 & \sin\phi & \cos\phi \end{bmatrix}$$

- Rotation matrix around (Oy) axis :

$$Q_y(\phi) = \begin{bmatrix} \cos\phi & 0 & \sin\phi \\ 0 & 1 & 0 \\ -\sin\phi & 0 & \cos\phi \end{bmatrix}$$

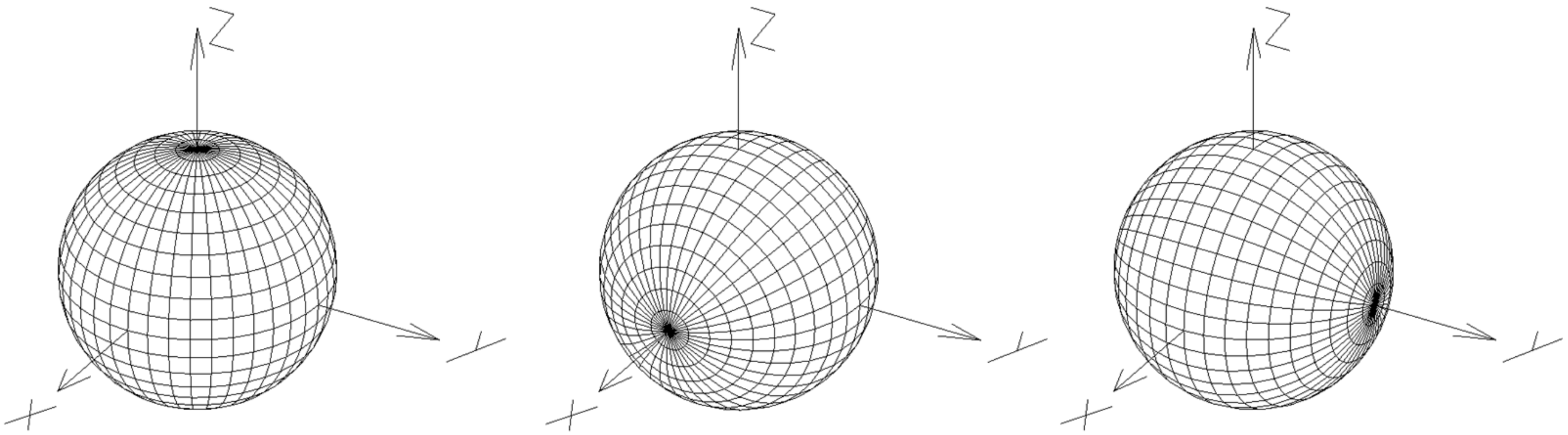
- Rotation matrix around (Oz) axis :

$$Q_z(\phi) = \begin{bmatrix} \cos\phi & -\sin\phi & 0 \\ \sin\phi & \cos\phi & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Coordinate System

Transform from Cartesian to Spherical coordinate systems :

Latitude-Longitude ((θ, ϕ) grid) Elevation-Azimuth Azimuth-Elevation



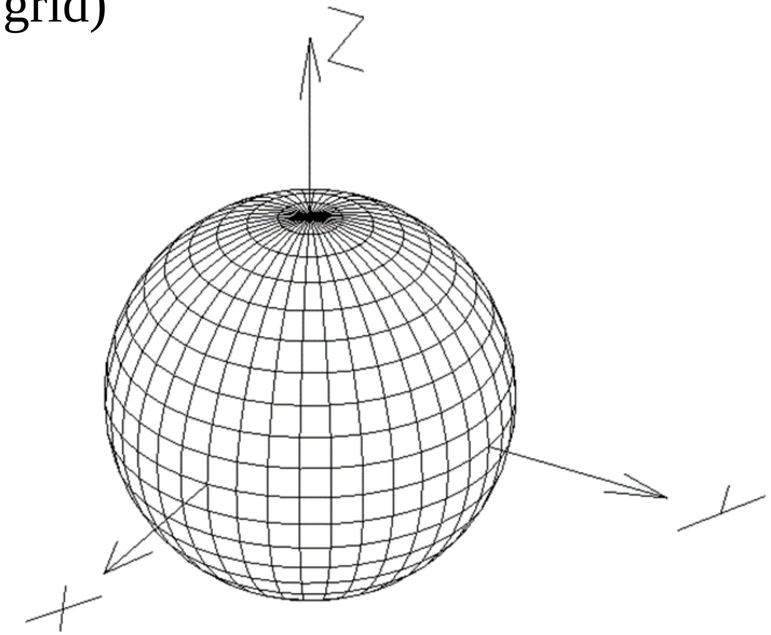
Statements for measurements :

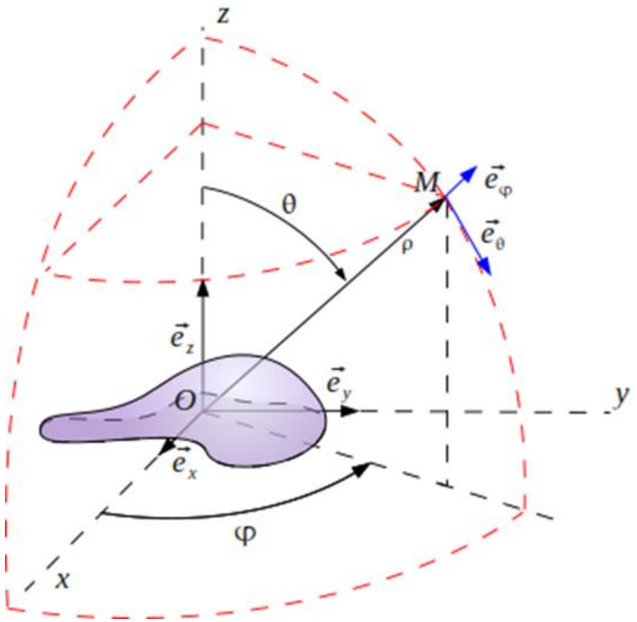
- Antenna aperture is in the (xOy) plane,
- (Ox) is horizontal,
- (Oy) is vertical.

Coordinate System

Transform from Cartesian to Spherical coordinate systems :

Latitude-Longitude ((θ, ϕ) grid)





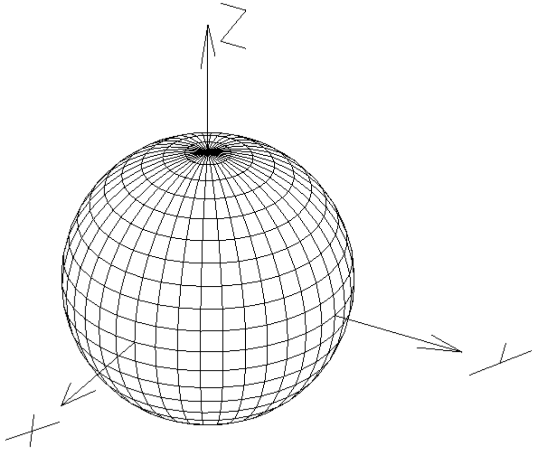
Statements for measurements :

- Antenna aperture is in the (xOy) plane,
- (Ox) is horizontal,
- (Oy) is vertical.

Coordinate System

Transform between Cartesian and polar spherical coordinate coordinates:

- φ angle :
  - related to a rotation according to a horizontal axis.
  - Range : $[-\varphi_{max}\ ;+\varphi_{max}]°$.
- θ angle :
  - related to a rotation according to the vertical axis.
  - Range : $[-\theta_{max}\ ;+\theta_{max}]°$.
- Optical axis : $\theta = 0\ ;\ \varphi = 0$



$$\begin{bmatrix} A_x \\ A_y \\ A_z \end{bmatrix} = \begin{bmatrix} \sin\theta\cos\phi & \cos\theta\cos\phi & -\sin\phi \\ \sin\theta\sin\phi & \cos\theta\sin\phi & \cos\phi \\ \cos\theta & -\sin\theta & 0 \end{bmatrix} \begin{bmatrix} A_\rho \\ A_\theta \\ A_\varphi \end{bmatrix}$$

$$\begin{bmatrix} A_\rho \\ A_\theta \\ A_\varphi \end{bmatrix} = \begin{bmatrix} \sin\theta\cos\phi & \sin\theta\sin\phi & \cos\theta \\ \cos\theta\cos\phi & \cos\theta\sin\phi & -\sin\theta \\ -\sin\phi & \cos\phi & 0 \end{bmatrix} \begin{bmatrix} A_x \\ A_y \\ A_z \end{bmatrix}$$

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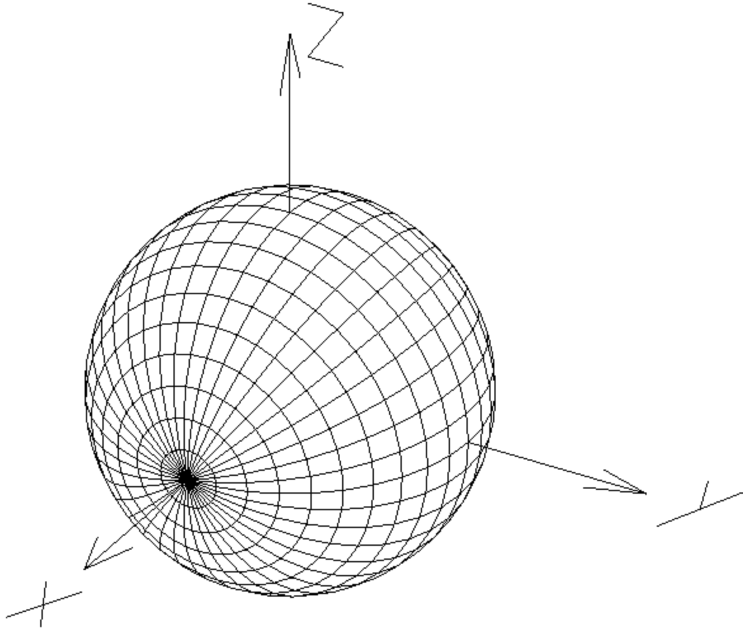
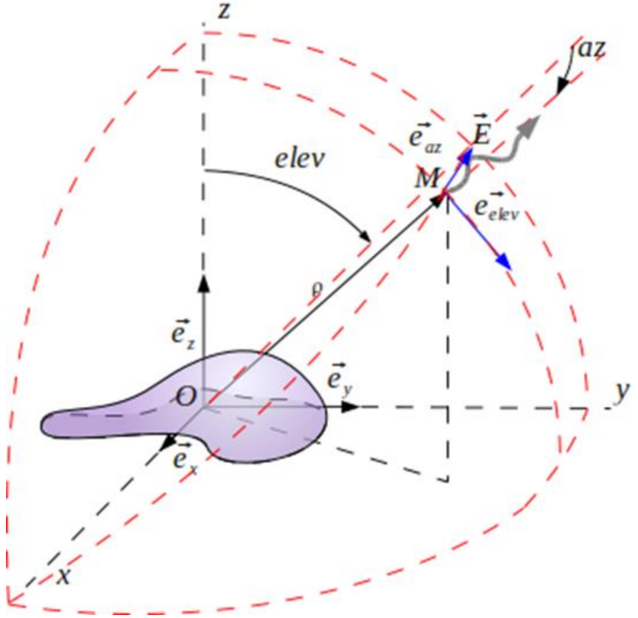
Coordinate System

Transform from Cartesian to Spherical coordinate systems :

Elevation-Azimuth





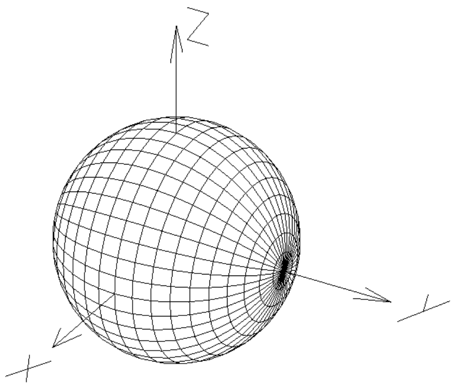
Statements for measurements :

- Antenna aperture is in the (xOy) plane,
- (Ox) is horizontal,
- (Oy) is vertical.

Coordinate System

Transform between Cartesian to Spherical radius-azimuth-elevation coordinates:

- Elevation angle :
  - related to a rotation according to the horizontal axis.
  - Range : [-elev_max ; elev_max]°.
- Azimuth angle :
  - related to a rotation according to the vertical axis.
  - Range : [-az_max ; az_max]°.
- Optical axis : elev=0° ; az = 0°.



$$\begin{bmatrix} A_x \\ A_y \\ A_z \end{bmatrix} = \begin{bmatrix} \cos elev \sin az & \sin elev \sin az & \cos az \\ \sin elev & -\cos elev & 0 \\ \cos elev \cos az & \sin elev \cos az & -\sin az \end{bmatrix} \begin{bmatrix} A_\rho \\ A_{az} \\ A_{elev} \end{bmatrix}$$

$$\begin{bmatrix} A_\rho \\ A_{az} \\ A_{elev} \end{bmatrix} = \begin{bmatrix} \cos elev \sin az & \sin elev & \cos elev \cos az \\ \sin elev \sin az & -\cos elev & \sin elev \cos az \\ \cos az & 0 & -\sin az \end{bmatrix} \begin{bmatrix} A_x \\ A_y \\ A_z \end{bmatrix}$$

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Coordinate System

Transform between Cartesian to Spherical radius-elevation-azimuth coordinates:

- Elevation angle :
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  - Range : [-elev_max ; elev_max]°.
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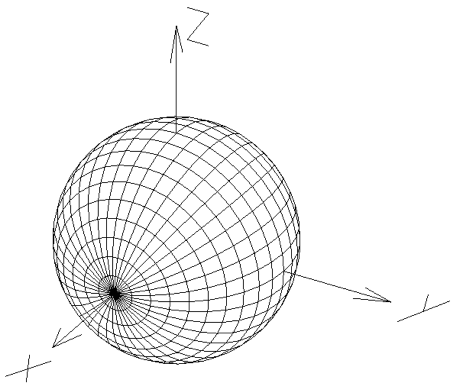
  - related to a rotation according to the vertical axis.
  - Range : [-az_max ; az_max]°.
- Optical axis : elev=0° ; az = 0°.



$$\begin{bmatrix} A_x \\ A_y \\ A_z \end{bmatrix} = \begin{bmatrix} \sin az & -\cos az & 0 \\ \cos az \sin elev & \sin az \sin elev & -\cos elev \\ \cos az \cos elev & \sin az \cos elev & \sin elev \end{bmatrix} \begin{bmatrix} A_\rho \\ A_{az} \\ A_{elev} \end{bmatrix}$$

$$\begin{bmatrix} A_\rho \\ A_{az} \\ A_{elev} \end{bmatrix} = \begin{bmatrix} \sin az & \cos az \sin elev & \cos az \cos elev \\ -\cos az & \sin az \sin elev & \sin az \cos elev \\ 0 & -\cos elev & \sin elev \end{bmatrix} \begin{bmatrix} A_x \\ A_y \\ A_z \end{bmatrix}$$

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Coordinate System

Direction cosine grid / uv grid:

- based on the direction of the observation/illumination points :

$$\begin{bmatrix} u \\ v \\ w \end{bmatrix} = \begin{bmatrix} \sin\theta\cos\varphi \\ \sin\theta\sin\varphi \\ \cos\theta \end{bmatrix}$$

- Representation of the field strength on a uv grid is homogeneous to represent the field strength on the grid obtained by projecting of the observation point defined on a unit radius sphere, on the xOy plane.

- An equiangular uv-grid corresponds to an irregular grid in the angular domain.

- linked with the k-space as : $u = {}^{k_x}/_{k_0}$; $\mathrm{v} = {}^{k_y}/_{k_0}$; $\mathrm{w} = {}^{k_z}/_{k_0}$

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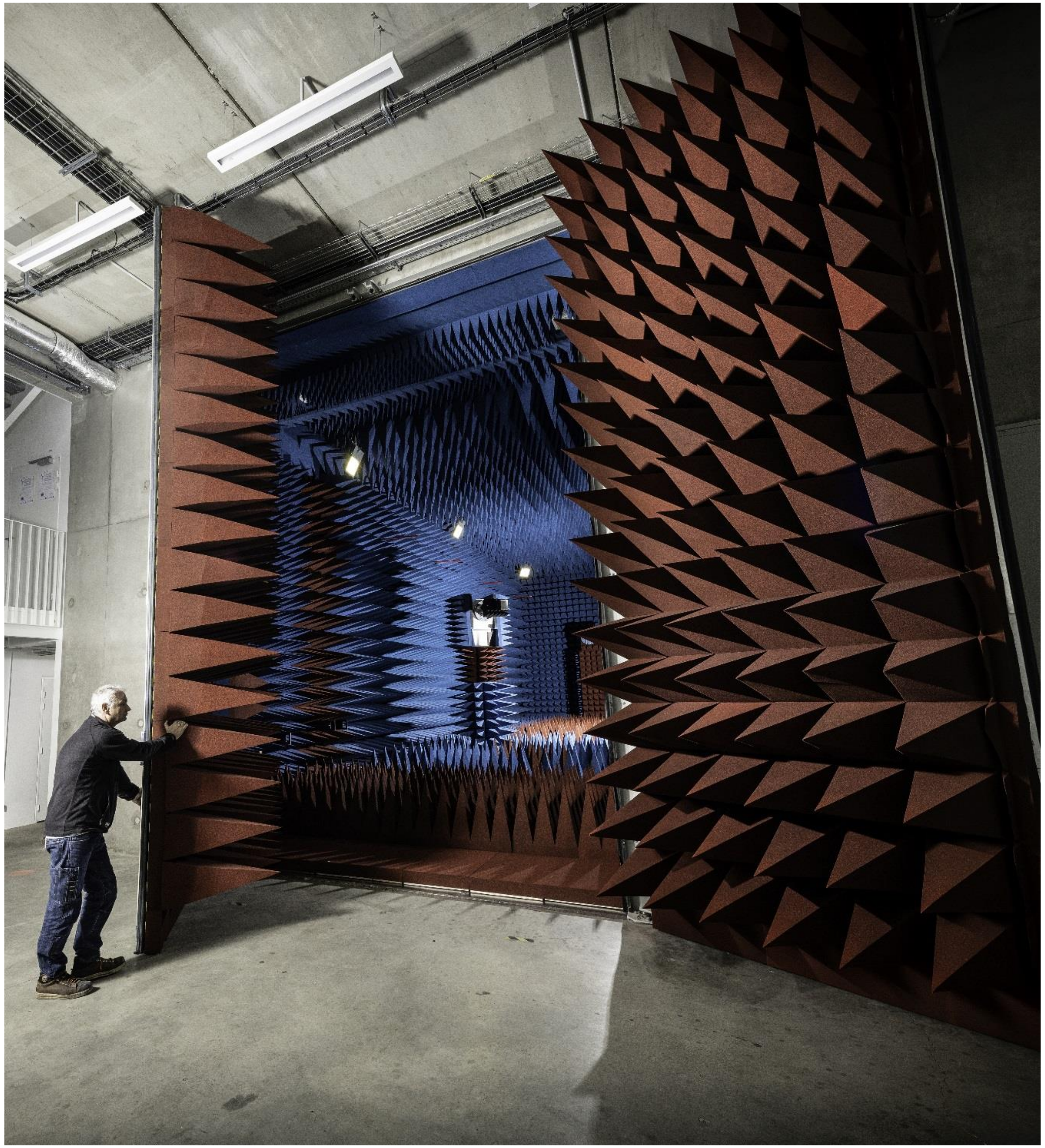

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Thanks for your attention

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plate-forme M^2ARS (Manufacturing Measurement and Analysis of Radiating Systems)

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