Course on Microwave Measurements

Antenna measurements

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Summary

• Why antenna measurements?
• What do we measure?
• How do we measure?
Why antenna measurements?

- To verify the design
- To tune the antenna components
- To evaluate the production yield
- To routinely check the antenna performance

AUT = Antenna Under Test
Parameters of interest

Radiation characteristics

- Radiation pattern: main lobe beamwidth, main lobe direction, side lobes levels/directions, gain
- Polarization: axial ratio, cross polarization

Input characteristics

- Reflection coefficient

System parameters

- Equivalent Isotropic Radiater Power (EIRP), Gain to antenna temperature ratio (G/T)

Mechanical properties
Radiation pattern

The radiation pattern represents the normalized spatial power distribution radiated by the antenna.

- **Radiation intensity:**
  \[ K(\theta, \phi) = \frac{dP_{irr}}{d\Omega} \]  
  [W/sterad]

- **Directivity:**
  \[ D(\theta, \phi) = \frac{K(\theta, \phi)}{K_{\text{mean}}} = \frac{dP_{irr}}{d\Omega} \frac{P_{irr}}{P_{\text{in}}} \frac{1}{4\pi} \]

- **Gain:**
  \[ G(\theta, \phi) = \eta D(\theta, \phi) = \frac{dP_{irr}}{d\Omega} \frac{P_{irr}}{P_{\text{in}}} \frac{1}{4\pi} \]

The radiation pattern is the plot of \( G(\theta, \phi)/G_{\text{max}} \) (equivalent to \( K(\theta, \phi)/K_{\text{max}} \)).
Radiation pattern

Polar representation (2D)

Logarithmic (dB)  Linear
Radiation pattern

Cartesian representation (2D)

Logarithmic (dB)  Linear
Radiation pattern

Spherical representation (3D)
Radiation pattern

Cartesian representation (3D)
Radiation pattern

Contour plot (3D)
Radiation pattern

Relevant parameters
Radiation pattern

International Telecommunication Union (ITU) masks
Polarization

Linear polarization

Locus of tips of instantaneous $E$

Elliptical polarization

Circular polarization
Relevant field zones

Azimuth angle

-θ

0°

+θ

Distance (r)

\( \frac{\lambda}{2\pi} \)

\( \frac{2D^2}{\lambda} \)

Reactive near-field

Radiated near-field

Radiated far-field (Fraunhofer region)
Friis formula

$$\frac{P_{RX}}{P_{TX}} = \left( \frac{\lambda}{4\pi r} \right)^2 G_1 G_2 \tau$$
Antenna measurement setup

Outdoor far-field
- Elevated range
- Ground reflection range

Indoor (anechoic chamber) far-field
- Standard AUT-probe system
- Compact antenna test range (CATR)

Indoor (anechoic chamber) near-field
- Planar scanning system
- Cylindrical scanning system
- Spherical scanning system
Outdoor far-field

Elevated range

- Flat land
- AUT/probe mounted on high towers/buildings at far-field distance
- Probe must guarantee uniform field distribution on AUT (not critical)
- If possible, scatterers placed on the ground reflection area
Outdoor far-field

Elevated range
Outdoor far-field

Elevated range
Outdoor far-field

Ground reflection range

- Flat land
- The ground reflection enhances phase uniformity on the AUT
- AUT/probe mounted on high towers/buildings at far-field distance
- The AUT is positioned on the first interference lobe between the probe and the ground mirror reflection
Outdoor far-field

Ground reflection range
Calibration methods

Reference antenna method
- Difference of received power / voltage
- Arbitrary transmit antenna
- Replacement (once) of antennas: Risk of misalignment
- Calibrated reference antenna needed

Three antenna method
- Three arbitrary antennas
- Replacement (twice) of antennas: risk of misalignment
- Change of test set-up

Two antenna method
- No motion of the test set-up
- Straight forward measurement / calculation
- Two identical antennas needed
# Outdoor far-field

## Pros/Cons

<table>
<thead>
<tr>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Smiley" /> Convenient test site for &quot;low-frequency&quot; antennas (30 MHz – 1000 MHz), even covering those antennas that don’t fit into the anechoic chamber</td>
<td><img src="image" alt="Sad face" /> Large measurement distance between antennas (up to 10 m)</td>
</tr>
<tr>
<td><img src="image" alt="Smiley" /> Large measurement distance between antennas (up to 10 m)</td>
<td><img src="image" alt="Sad face" /> Influence of ground plane: Ground reflection, impedance, …</td>
</tr>
<tr>
<td><img src="image" alt="Smiley" /> External interferences can affect the calibration measurements</td>
<td><img src="image" alt="Sad face" /> Calibration measurements can cause interferences to other services</td>
</tr>
<tr>
<td><img src="image" alt="Green arrow" /> Sufficient signal levels during calibration</td>
<td><img src="image" alt="Green arrow" /> Minimization of required signal levels (link budget)</td>
</tr>
<tr>
<td><img src="image" alt="Green arrow" /> Avoidance of &quot;busy&quot; frequencies for calibration</td>
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</tr>
<tr>
<td><img src="image" alt="Green arrow" /> Minimization of transmitting periods</td>
<td><img src="image" alt="Green arrow" /> Minimization of transmitting periods</td>
</tr>
</tbody>
</table>
Indoor far-field

Anechoic chamber

Completely shielded environment covered by electromagnetic absorbing panels
Indoor far-field

Anechoic chamber
Indoor far-field

Pyramidal Anechoic chamber
Indoor far-field

Pyramidal Anechoic chamber

ETS-Lindgren Wireless Test Chambers
(400 MHz to 6000 MHz)

Sat Com Electronics Antenna Tapered Chamber
(500 MHZ 40 GHz)
Indoor far-field

Semi-Anechoic chamber
Indoor far-field

Semi-Anechoic chamber

Antenna 100MHz

U_{antenna}=50V

Measurement

Simulation-FDTD
Indoor far-field

Semi-Anechoic chamber

Between Antenna (100 MHz) and Antenna (450 MHz)

![Graph showing S12 dB vs Frequency for two antennas.](image)
Indoor far-field measurement details

Frequency constraints

\[ f_{\text{min}} < f < f_{\text{max}} \]

- Dimensions of the anechoic chamber
- Reflection of the anechoic material
- Attenuation
- Instrumentation
- Antenna probe
Indoor far-field measurement details

Frequency constraints

\[ f_{\text{min}} < f < f_{\text{max}} \]

- Dimensions of the anechoic chamber: \( 4 \text{m} \times 3 \text{m} \times 3 \text{m} \)
- Reflection of the anechoic material
- Attenuation
- Instrumentation
- Antenna probe

small antennas: \( r \gg \lambda \) \quad \Rightarrow \quad f_{\text{min}} = 750 \text{ MHz} \\
large antennas: \( r \gg 2D^2/\lambda, D=10\lambda \) \quad \Rightarrow \quad f_{\text{min}} = 15 \text{ GHz}
Indoor far-field measurement details

Frequency constraints

\[ f_{\text{min}} < f < f_{\text{max}} \]

- Dimensions of the anechoic chamber
- Reflection of the anechoic material
- Attenuation
- Instrumentation
- Antenna probe

ECCOSORB VHP-NRL: \(<-30 \text{ dB} @ 3-4 \text{ GHz}\)
# Indoor far-field measurement details

## Guanteed Maximum Reflectivity of ECCOSORB® VHP Grades

<table>
<thead>
<tr>
<th></th>
<th>120 MHz</th>
<th>200 MHz</th>
<th>300 MHz</th>
<th>500 MHz</th>
<th>1 GHz</th>
<th>3 GHz</th>
<th>5 GHz</th>
<th>10 GHz</th>
<th>15 GHz</th>
<th>24 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>VHP-2-NRL</td>
<td>-30</td>
<td>-40</td>
<td>-45</td>
<td>-50</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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**Typical Reflectivity**

ECCOSORB VHP-2-NRL / VHP-4-NRL / VHP-8-NRL / VHP-12-NRL

Frequency in MHz

Reflectivity in dB

-80  -70  -60  -50  -40  -30  -20  -10  0  10  20  30  40  50  60  70  80

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- Guanteed Maximum Reflectivity of ECCOSORB® VHP Grades
- Indoor far-field measurement details


Indoor far-field measurement details

Frequency constraints

- Dimensions of the anechoic chamber
- Reflection of the anechoic material
- Attenuation
- Instrumentation
- Antenna probe

\[ f_{\text{min}} < f < f_{\text{max}} \]

ECCOSORB VHP-NRL: what about \( f > 24 \text{ GHz} \)
Indoor far-field measurement details

Frequency constraints

\[ f_{\text{min}} < f < f_{\text{max}} \]

- Dimensions of the anechoic chamber
- Reflection of the anechoic material
- Attenuation
- Instrumentation
- Antenna probe

\[ r = 4\text{m}, f = 50 \text{ GHz}, \text{ free-space propagation: -80 dB} \]

\[ \text{cables’ attenuation: tens of dB} \]
Indoor far-field measurement details

Frequency constraints

\[ f_{\text{min}} < f < f_{\text{max}} \]

- Dimensions of the anechoic chamber
- Reflection of the anechoic material
- Attenuation
- Instrumentation
- Antenna probe

Cables and connectors limitations

frequency range and sensitivity of transmitter/receiver (e.g., VNA)
Indoor far-field measurement details

Frequency constraints

\[ f_{\text{min}} < f < f_{\text{max}} \]

- Dimensions of the anechoic chamber
- Reflection of the anechoic material
- Attenuation
- Instrumentation
- Antenna probe

antenna horn in band X: \( f_{\text{min}} = 7 \text{ GHz} \)
Indoor far-field measurement details

Frequency constraints

\( f_{\text{min}} < f < f_{\text{max}} \)

- Dimensions of the anechoic chamber
- Reflection of the anechoic material
- Attenuation
- Instrumentation
- Antenna probe

Taking all the constraints into account:

4m x 3m x 3m \[\rightarrow\] 3 GHz < f < 25 GHz
Indoor far-field measurement details

Antenna phase center

Phase center?
Indoor far-field measurement details

TX/RX antennas alignment problem

Solution: use laser pointers
Indoor far-field measurement details

TX/RX antennas alignment problem

Solution: exploit directly the radiation pattern
Indoor far-field measurement details

Example of measurement result (UNIPV near-field system)

![Graph showing S12 [dB] vs. angolo [deg]]
Due to the double reflector system, the AUT is illuminated by a uniform plane wave in spite of the limited distance.
Indoor far-field

Compact antenna test range (CATR)
Indoor far-field

Compact antenna test range (CATR)

- Parabolic reflector
- Hyperbolic reflector
- Calibrated probe (TX)
- AUT (RX)
- AUT moving system
Indoor far-field

Compact antenna test range (CATR)
Indoor far-field

Compact antenna test range (CATR)
Indoor far-field

Compact antenna test range (CATR)

Figure 3. Amplitude and Phase at 26.5 GHz
Indoor far-field

Compact antenna test range (CATR)

Figure 4. Amplitude and Phase at 40 GHz
Indoor far-field

Compact antenna test range (CATR)

Figure 5. Amplitude and Phase at 94 GHz
Indoor near-field

Planar scanning system

Calibrated probe (RX)

AUT (TX)
Indoor near-field

Planar scanning system
Indoor near-field

Planar scanning system
Indoor near-field

Cylindrical scanning system

Calibrated probe (RX)

AUT (TX)
Indoor near-field

Cylindrical scanning system
Indoor near-field

Spherical scanning system
Indoor near-field

Spherical scanning system
Indoor near-field

Spherical scanning system

Calibrated probe (RX)

AUT (TX)
Indoor near-field measurement details
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Indoor near-field measurement details
Indoor near-field measurement details

\[ \Delta x < \frac{\lambda}{2} \]

\[ \Delta y < \frac{\lambda}{2} \]
Indoor near-field measurement details

\[ \Delta \phi < \frac{\lambda}{2(a + \lambda)} \]

\[ \Delta z < \frac{\lambda}{2} \]
Indoor near-field measurement details

\[ \Delta \phi < \frac{\lambda}{2(a + \lambda)}; \Delta \theta < \frac{\lambda}{2(a + \lambda)} \]
Indoor near-field measurement details

\[ \overline{E}(x, y, z) \]

\[ \overline{E}(x, y, z = 0) \]

\[ E_x(x, y, z = 0); E_y(x, y, z = 0) \]
Indoor near-field measurement details

\[ f_x(k_x, k_y) \approx \int_{-b/2}^{b/2} \int_{-a/2}^{a/2} E_x(x, y, z = 0)e^{j(k_xx+k_yy)} \, dx \, dy \]

\[ \overline{E_{ff}}(r, \theta, \phi) \approx j \frac{ke^{-jkr}}{2\pi r} \left( \cos \theta \overline{f}(k_x, k_y) \right) \]
Indoor near-field measurement details

\[ M = \frac{a}{\Delta x} + 1 \]

\[ \Delta x = \frac{\pi}{k_{x,\text{max}}} \]

\[ k_x = \frac{2\pi}{a} m \]

\[ k_x^2 + k_y^2 \leq k^2 \]

zero-padding
Indoor near-field measurement details

Horn @ 10 GHz

\[
 k = \frac{2\pi}{\lambda} \approx 210 \ [m^{-1}]
\]

\[
 k_x = k \sin \theta \cos \varphi \rightarrow k_{x}^{\text{max}} = k \sin 30^\circ \approx 105 \ [m^{-1}]
\]

\[
 \Delta x \approx 3 \ [cm]
\]

\[
 \Delta \theta = 0.5^\circ \rightarrow \Delta k_x = 1.8 \ [m^{-1}] \rightarrow a \approx 3.5 \ [m]
\]

\[
 a \approx 2 \ [m]
\]

\[
 M = \frac{a}{\Delta x} + 1 \approx 67 \rightarrow M = 64
\]
Indoor near-field measurement details

Horn @ 10 GHz

\[ M = 64 \rightarrow M \times N = 4096 \]

\[ T \approx 5 \times 4096 \approx 6 \text{ [h]} \]

\[ M = \frac{a}{\Delta x} + 1 \]

\[ \Delta x = \frac{\pi}{k_x^{\text{max}}} \]

\[ k_x = \frac{2\pi}{a} m \]
Indoor near-field measurement details

Probe radiation pattern correction needed
## Outdoor vs indoor

<table>
<thead>
<tr>
<th>Outdoor (far-field)</th>
<th>Indoor (far-field/near-field)</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ Simple measurement technique</td>
<td>+ Controlled environment (temperature, humidity, …)</td>
</tr>
<tr>
<td>+ Limited post-processing</td>
<td>+ No electromagnetic interferences</td>
</tr>
<tr>
<td>– Large measurement field</td>
<td>+ Accuracy</td>
</tr>
<tr>
<td>– High signal attenuation</td>
<td>– antenna dimension/frequency limitation (far-field)</td>
</tr>
<tr>
<td>– Environmental/climate changes</td>
<td>– Frequency and dimension limitation</td>
</tr>
<tr>
<td>– Electromagnetic interferences</td>
<td>– Strong post-processing (near-field)</td>
</tr>
<tr>
<td></td>
<td>– Large number of samples (near-field)</td>
</tr>
<tr>
<td></td>
<td>– Measurement of amplitude and phase (near-field)</td>
</tr>
</tbody>
</table>
## Outdoor vs indoor

<table>
<thead>
<tr>
<th></th>
<th>Near-Field</th>
<th>Far-Field</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Planar</td>
<td>Cylindrical</td>
</tr>
<tr>
<td>High gain antenna</td>
<td>Excellent</td>
<td>Good</td>
</tr>
<tr>
<td>Low gain antenna</td>
<td>Poor</td>
<td>Good</td>
</tr>
<tr>
<td>High frequency</td>
<td>Excellent</td>
<td>Excellent</td>
</tr>
<tr>
<td>Low frequency</td>
<td>Poor</td>
<td>Poor</td>
</tr>
<tr>
<td>Gain measurement</td>
<td>Excellent</td>
<td>Good</td>
</tr>
<tr>
<td>Close sidelobes</td>
<td>Excellent</td>
<td>Excellent</td>
</tr>
<tr>
<td>Far sidelobes</td>
<td>Adequate</td>
<td>Excellent</td>
</tr>
<tr>
<td>Low sidelobes</td>
<td>Excellent</td>
<td>Excellent</td>
</tr>
<tr>
<td>Axial ratio</td>
<td>Excellent</td>
<td>Excellent</td>
</tr>
<tr>
<td>Zero G effects (horizontal mode)</td>
<td>Poor</td>
<td>Good (horizontal mode)</td>
</tr>
<tr>
<td>Multipath</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>Weather</td>
<td>Excellent</td>
<td>Excellent</td>
</tr>
<tr>
<td>Security</td>
<td>Excellent</td>
<td>Excellent</td>
</tr>
<tr>
<td>Facility cost</td>
<td>Low</td>
<td>Moderate</td>
</tr>
<tr>
<td>Operating cost</td>
<td>Moderate</td>
<td>Moderate</td>
</tr>
<tr>
<td>Speed (complete measures)</td>
<td>Excellent</td>
<td>Good</td>
</tr>
<tr>
<td>Speed (simple cuts)</td>
<td>Good</td>
<td>Fair</td>
</tr>
<tr>
<td>Complexity</td>
<td>Moderate</td>
<td>Moderate</td>
</tr>
<tr>
<td>Mechanical surface measurements</td>
<td>Excellent</td>
<td>No</td>
</tr>
<tr>
<td>Antenna access</td>
<td>Excellent</td>
<td>Excellent</td>
</tr>
<tr>
<td>Antenna alignment</td>
<td>Easy</td>
<td>Moderate</td>
</tr>
</tbody>
</table>
Possible source of errors

Errors due to the measurement equipment

- Instrumentation
- Connection cables
- Control/acquisition/processing software
- Inaccurate placement of the probe

Errors due to the measurement setup

- Multiple reflection in the measurement region
- Undersampling and/or limited sampling surface
- Non ideality of the probe