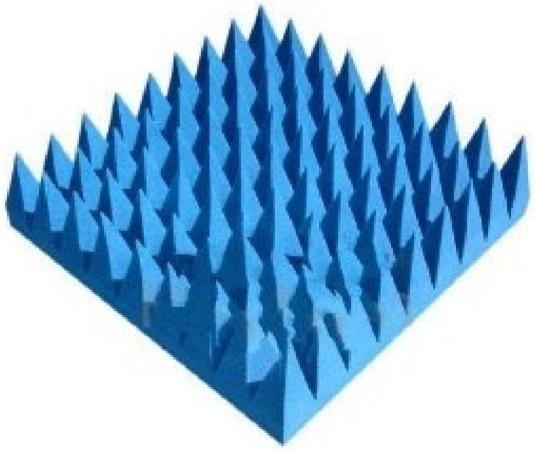
ELEC-E4450 Antennas



Topic 5: Antenna measurements

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This week's learning outcomes and content

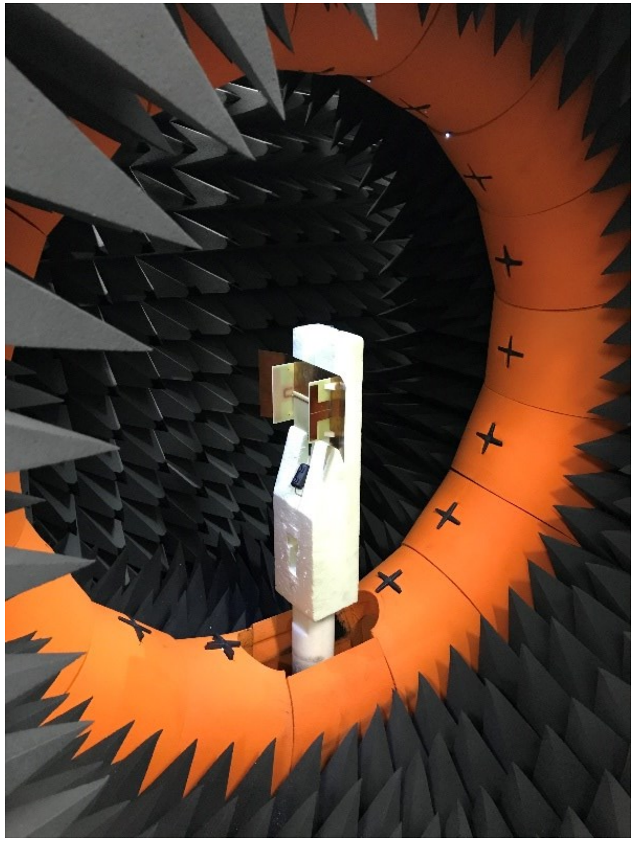
- The student has a *readiness* to **perform** basic antenna measurements such as the antenna impedance and radiation pattern measurements.
- The student can **analyze** the measurement results and **estimate** the error sources.
- Hidden agenda: introduce our state-of-the-art Electronics-ICT research facilities, e.g., ↓ Starlab

- *Hint: traditionally one exam problem is from measurements*

TUESDAY

- Input impedance / reflection coefficient measurements
- Radiation pattern and gain measurements ← FRIDAY

Teaching is based on the coursebook Chapter 7: Antenna measurements



Antenna measurements vocabulary – combine pairs!

1. Vector network analyzer (VNA)
2. Test antenna (AUT = "antenna under test")
3. Standard antenna
4. Measurement ("transmit") antenna
5. "Normal" gain
6. Realized gain
7. Partial gain
8. Anechoic chamber
9. Starlab
10. Spherical coordinate system

a. State-of-the-art antenna measurement device of Aalto University

b. Equals directivity reduced by the radiation losses $G = \eta \cdot D$

c. Device that is needed both in impedance and radiation pattern measurements

d. Gain component for a given polarization, e.g., vertical (theta) or horizontal (phi)

e. Is a geometrical system needed for displaying the spatial performance of an antenna in a particular direction

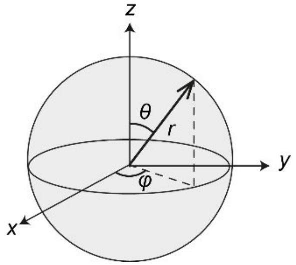
f. The antenna whose performance is already known accurately

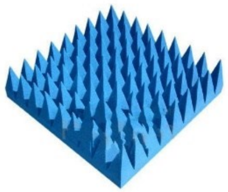
g. The antenna which typically has two orthogonal polarization – vertical (theta) and horizontal (phi)

h. Gain that is reduced by the impedance mismatch factor

i. The antenna whose performance we want to find out

j. A particular space where walls are covered with absorbers





$$G_r = \underbrace{(1 - |\Gamma|^2)}_{<1} G$$

8.9. You have an antenna, but you do not know much about its performance. To figure out, what purpose the antenna could be used, which antenna parameter would you measure first. Justify your answer with a few sentences. Aalto Electronics-ICT facilities allow you to measure any major antenna parameter.

Reflection coefficient: 4, radiation pattern: 5, gain: 2

- I would first measure its **reflection coefficient** across different frequencies using a VNA. Measuring this parameter is straightforward and by knowing its frequency of operation can reveal its purpose as frequencies are usually allocated for specific applications.
- I would measure **radiation pattern** because we can calculate directivity from it. Directivity is important because it tells the usage of an antenna.
- I would measure the **input reflection coefficient** with VNA, since otherwise it is hard to know what is the frequency band where the antenna should be used (unless it is a half-wave dipole or other basic antenna).
- The first parameter to be determined should be the **radiation pattern and directivity**. These properties are perhaps the most integral when deciding the appropriate application and use-case for the antenna.
- Because of the reciprocity theorem, the radiation and the receive patterns of an antenna are the same . So, the **radiation pattern** can be measured in the transmit or the receive operation mode, which is very useful when we have an unknown antenna.
- I propose to measure the far-field **radiation pattern** on different frequencies.
- I would measure **the matching [reflection coefficient]** of the antenna first, since we need to know the frequency range the antenna operates in.
- The **gain** would also define the purpose for which antenna is suitable.
- Using the receive mode, I would measure the **Gain**, since gain holds the information about most of the antenna parameters.
- If there were no datasheets available, I would first measure the **reflection coefficient** (S11) as a function of frequency in order to know the matching of the antenna, i.e., where does it resonate with respect to a Z0 of 50ohms.
- The **radiation pattern**. It provides a lot of information about e.g. the field amplitude, phase, polarization and power.

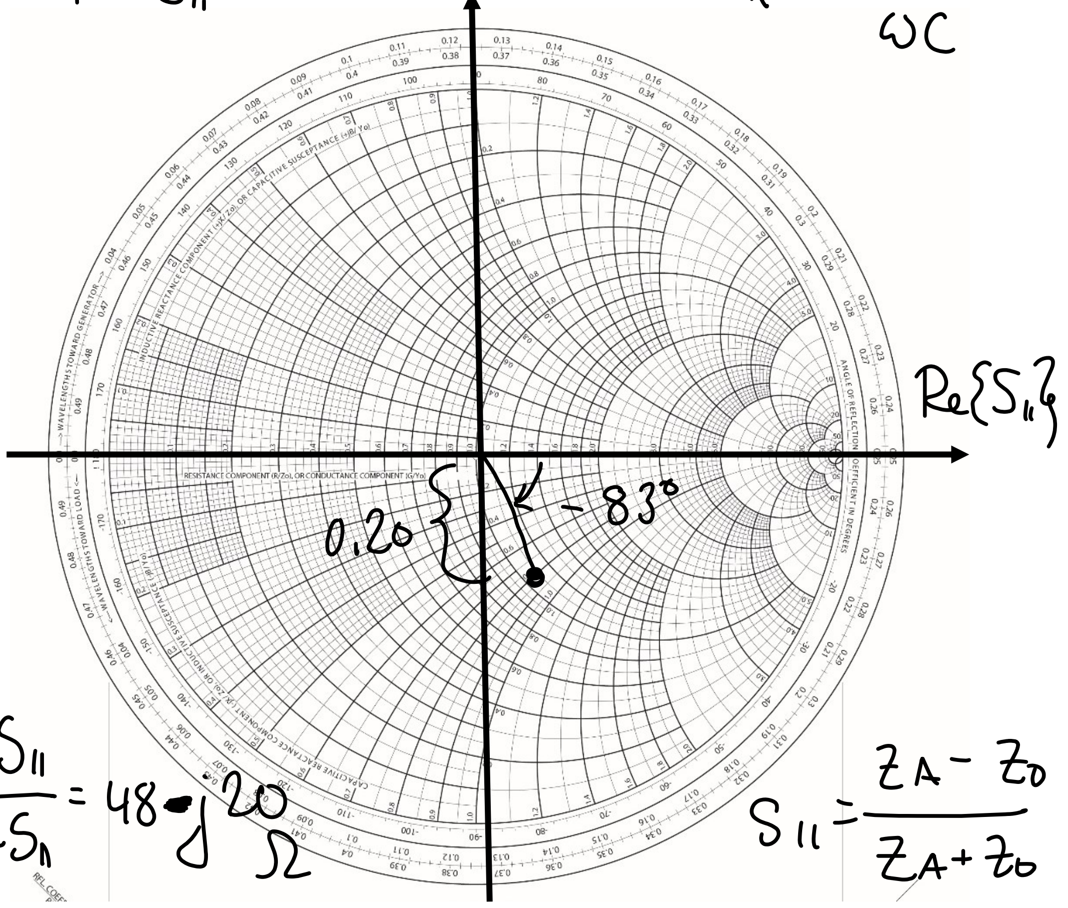
The reflection coefficient measurements are performed with a calibrated vector network analyzer whose reference impedance is 50 Ω. Also, the measurement cable has the characteristic impedance of 50 Ω. In one measurement at single frequency: $\boldsymbol{S_{11} = 0.20\angle -83°}$. Select one or more correct alternatives.

$\log_{10} 0.20 = -0.70$

1. The reflection coefficient in the dB scale is $|\Gamma| = -7$ dB
2. Less than 10% of the power is reflected at the input of the antenna.
3. The input impedance of the antenna has a capacitive reactance.

$\Gamma = S_{11}$

$X = -\frac{1}{\omega C}$



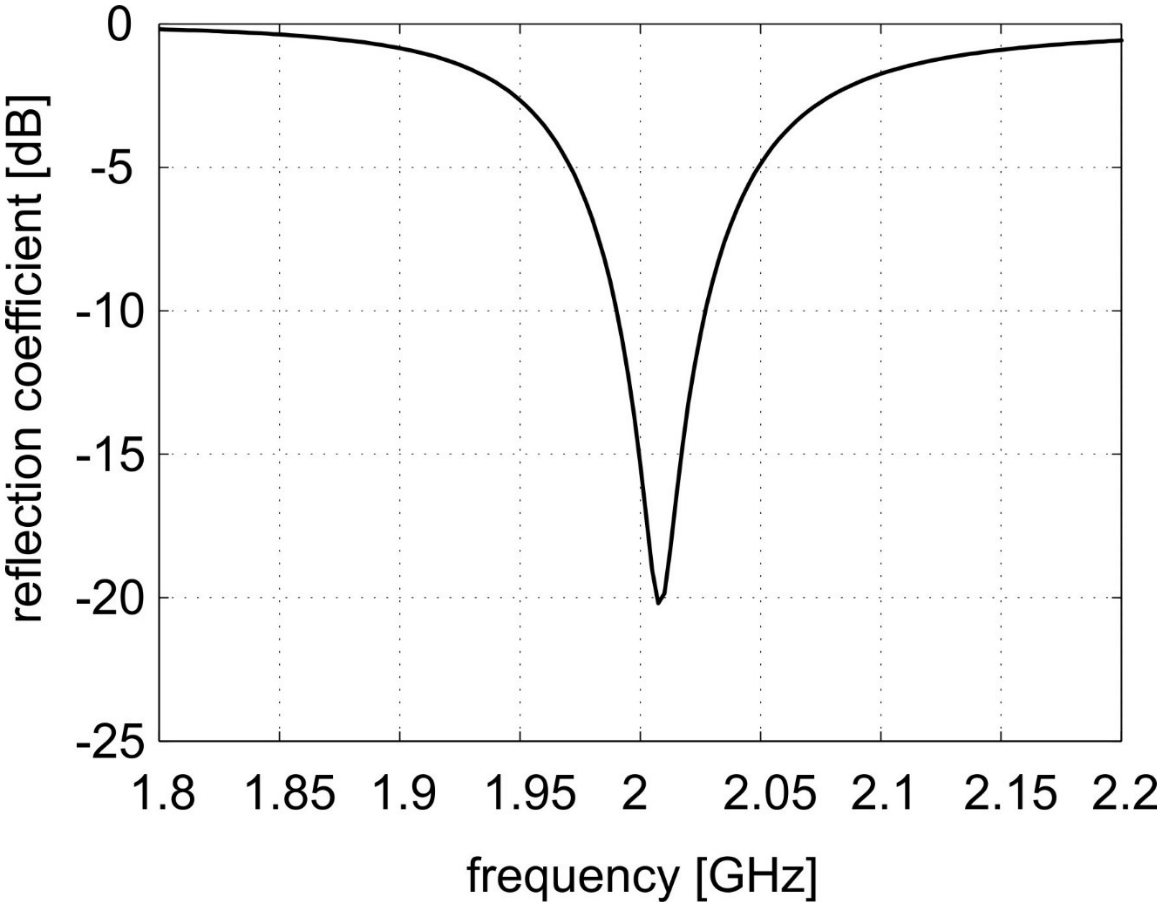
$S_{11dB} = 10 \cdot \log_{10} |S_{11}|^2 = 20 \log_{10} 0{,}20 = -14$ dB

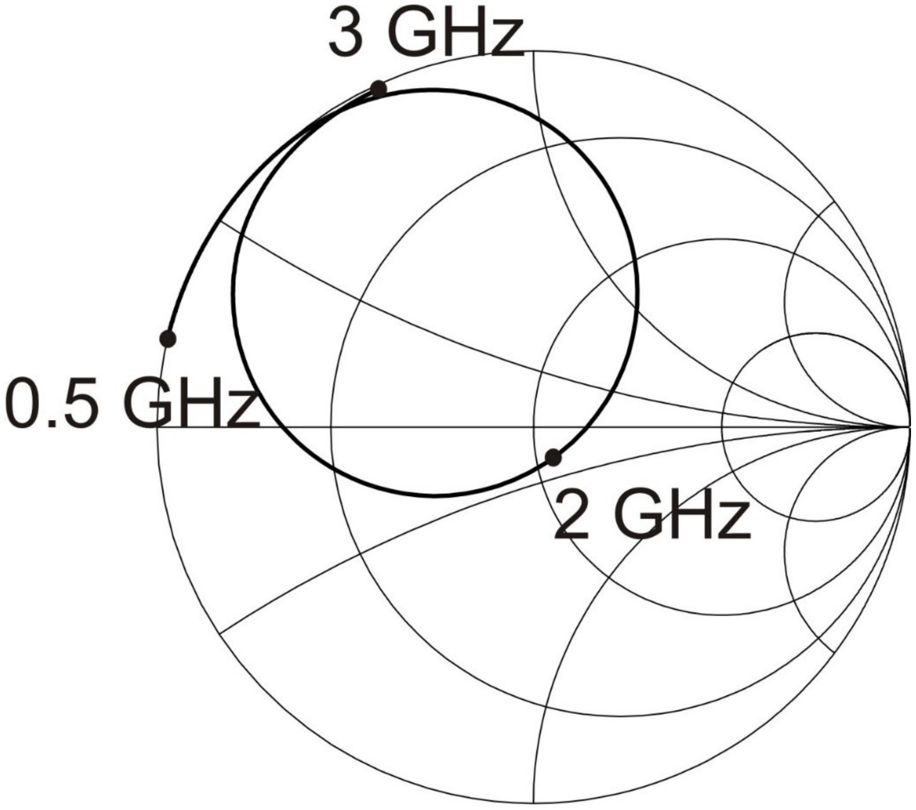
$|S_{11}|^2 = 0{,}20^2 = 0{,}04$ is reflected

$Z_A = Z_0 \frac{1+S_{11}}{1-S_{11}} = 48 - j20\ \Omega$

$S_{11} = \frac{Z_A - Z_0}{Z_A + Z_0}$

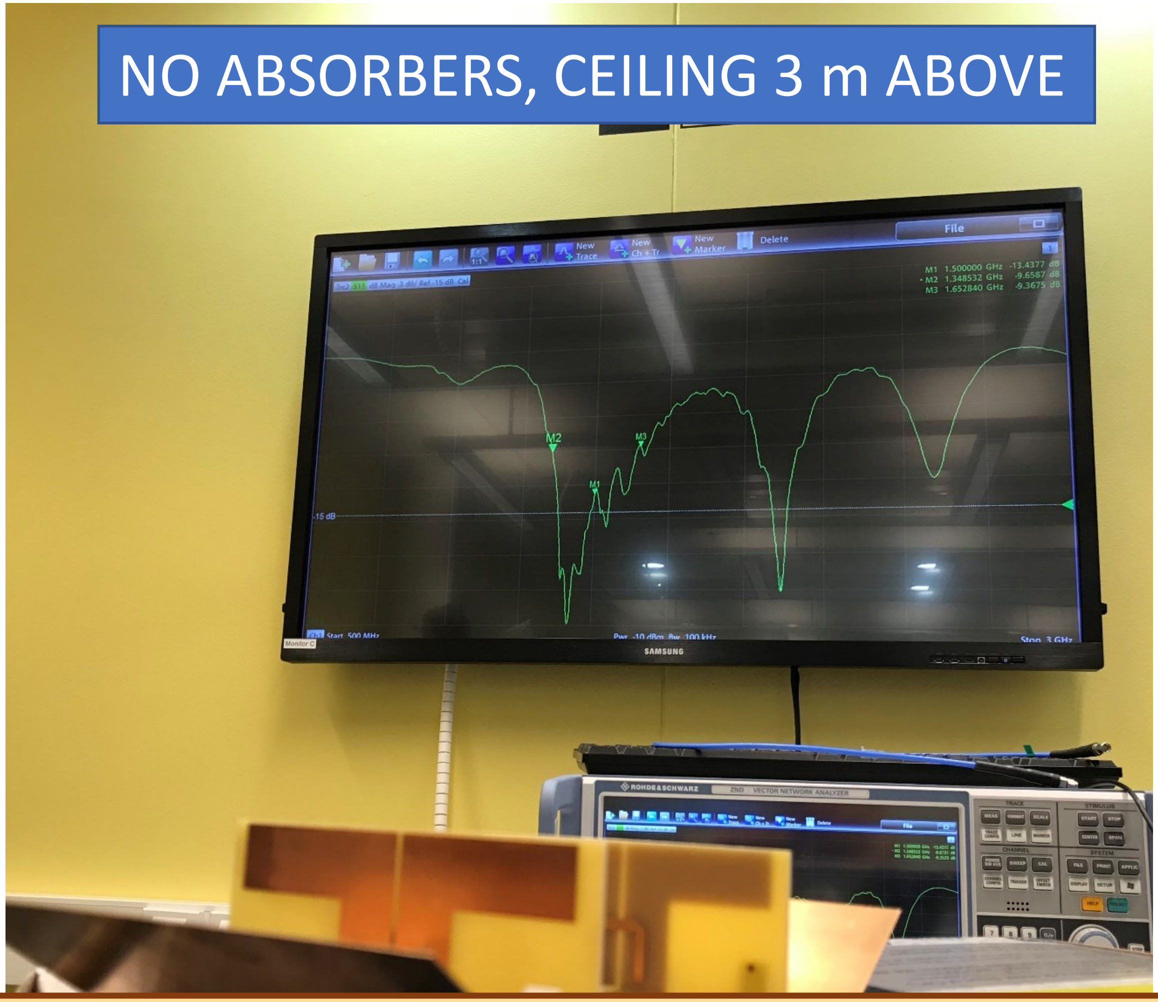
Example of authentic measurement results





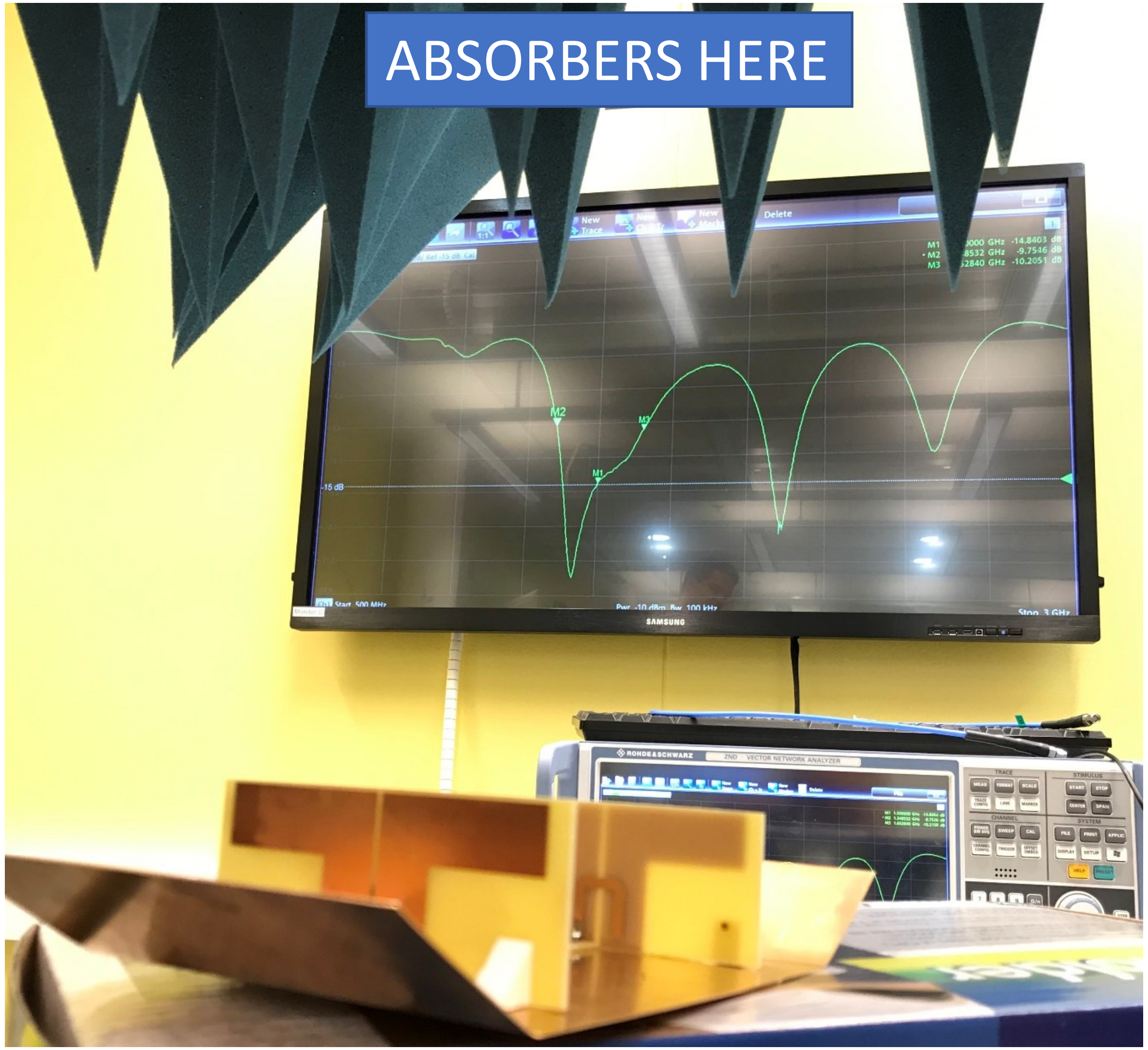
Absorbers are essential to eliminate unwanted reflection from walls, ceiling and floor

NO ABSORBERS, CEILING 3 m ABOVE

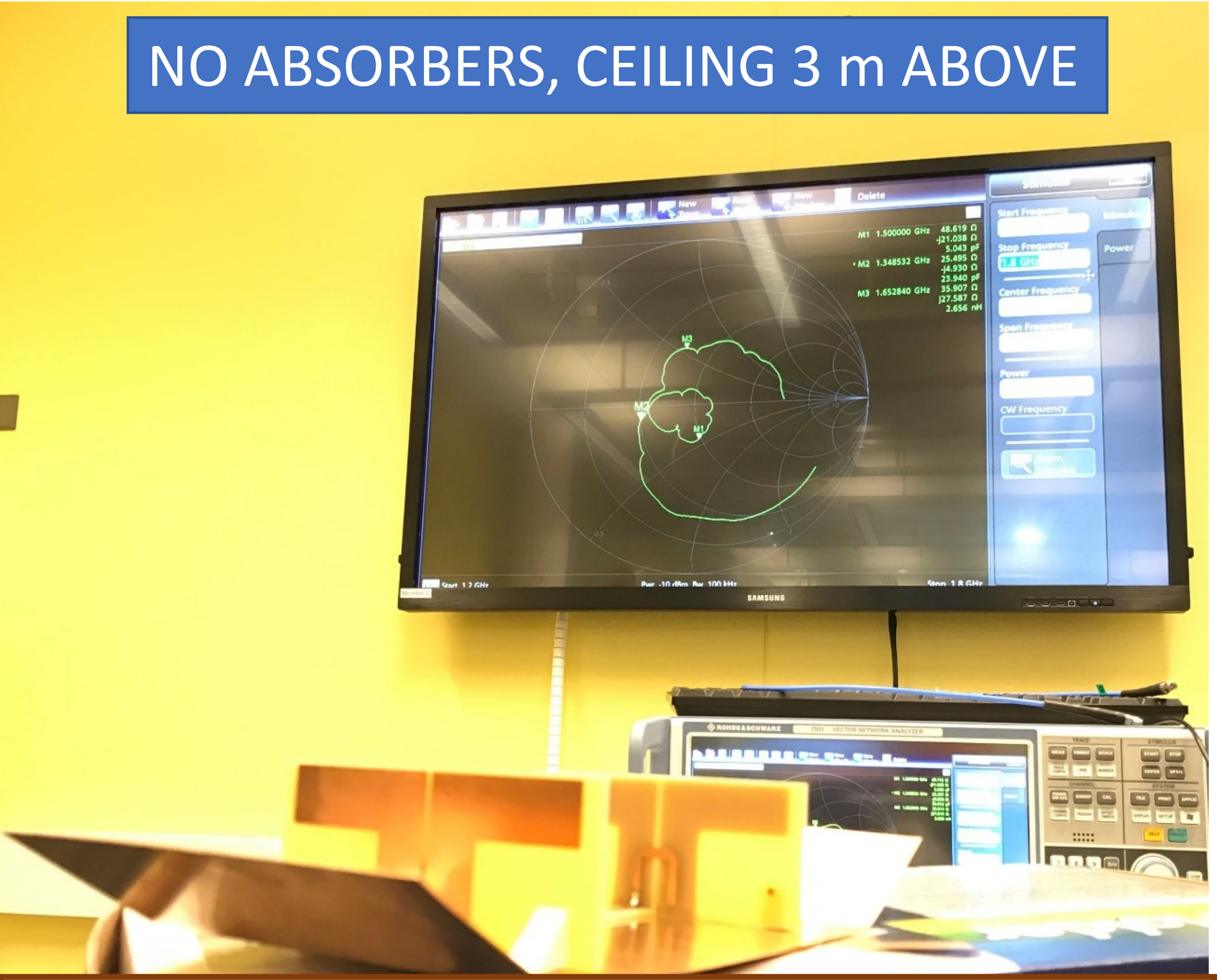


DIRECTIVE ANTENNA – MAIN LOBE UPWARDS

ABSORBERS HERE



Absorbers are essential to eliminate unwanted reflection from walls, ceiling and floor

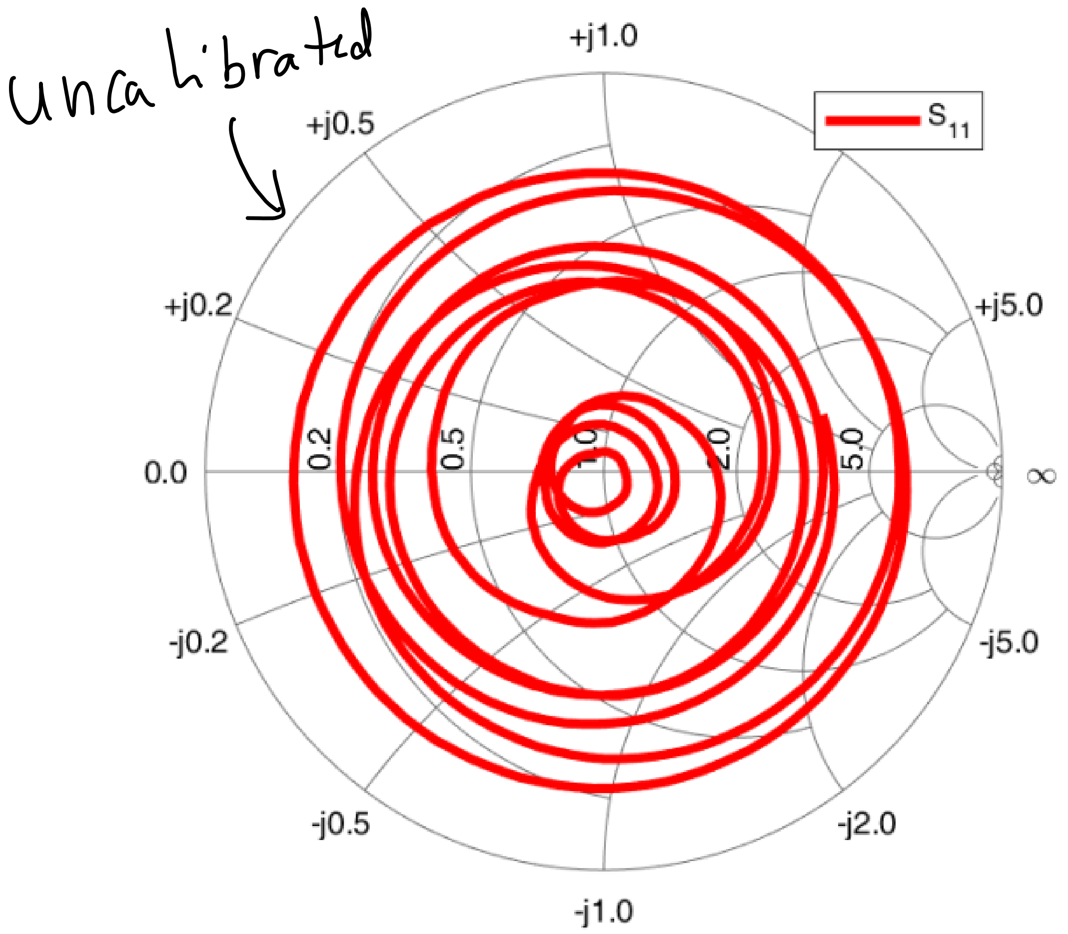


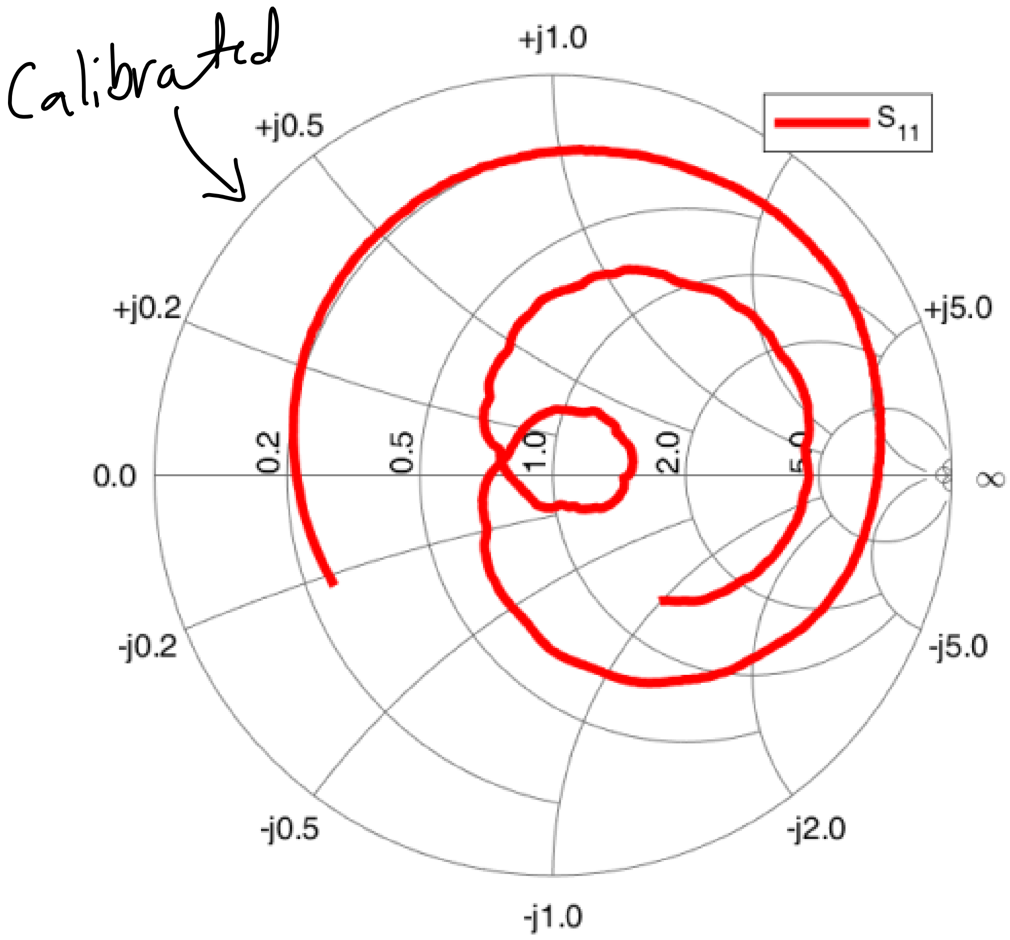
DIRECTIVE ANTENNA – MAIN LOBE UPWARDS

Reflection coefficient (“S_{11}”) measurement is performed with a calibrated vector network analyzer

1) Which result (~~LEFT or~~ RIGHT) is measured with a calibrated vector network analyzer?

2) Why the result measured with an uncalibrated vector network analyzer is like that?





8.1. Why are the impedance and far-field radiation pattern of an antenna most preferably measured in an *anechoic chamber*? Select one or more reasons of the essence.

Correct answer by **67%**

1. The radio wave reflections from the walls of an anechoic chamber are typically small and hence it allows to perform the measurements nearly under the free-space condition.
2. Radio wave reflection-free environment is very typical usage environment of antennas.
3. The chamber is shielded; hence, external radio wave interferences are small.
4. It is rather simple to move and place physically large-sized and weighty antennas, such as reflector-type antennas, in the chamber.
5. Because of the non-reflective environment, the far-field distance can be kept smaller in the chamber than in open-space measurement environment.
6. It is preferred that there is only one incident plane wave at the receiving antenna.

Questions by you: 1. How to introduce large antennas into the chamber? 2. When are outdoor ranges used for measurements? How does one control unwanted noise from other transmitters in this case? 3. What is the most prevalent source of error in antenna measurements?

8.2. The maximum dimension of an antenna perpendicular to the radiation direction is L = 0.150 m. The antenna is used within the frequency range of 6.00 – 12.0 GHz. What is the **minimum** distance R (from the antenna) at which the radiation pattern could be **directly** measured?

1. $\frac{\lambda_{max}}{2\pi} = 0.0080\ \text{m}$
2. $\frac{2L^2}{\lambda_{max}} = 0.90\ \text{m}$
3. $\frac{2L^2}{\lambda_{min}} = 1.8\ \text{m}$
4. $5L = 0.75\ \text{m}$
5. $2\lambda_{max} = 0.1\ \text{m}$

$$f = [6.00\ \text{GHz}, 12.0\ \text{GHz}]$$
$$\lambda = [0.0250\ \text{m}, 0.0500\ \text{m}]$$

Correct answer by **75%**

$$\frac{L}{\lambda_{min}} = \frac{0.150\text{m}}{0.0250\text{m}} = 6 \gg 1$$

$$\frac{L}{\lambda_{max}} = 3 \gg 1 \rightarrow \text{"large" in comp. to } \lambda$$

Questions by you: 1. How do you determine the largest transverse dimension L of irregularly-shaped antennas e.g., meandered antenna? 2. When measuring antenna arrays in an anechoic chamber, the length of the array and the individual elements play a crucial factor for determining R. Are there any other methods for determining this, besides from the effective aperture area?

8.3. The maximum dimension of an antenna perpendicular to the radiation direction is L = 0.050 m. The antenna is used in a narrow frequency range around 1.0 GHz. What is the **minimum** distance (from the antenna) at which the radiation pattern could be directly measured (*)? (*) without using the near-to-far-field transformation

$$f = 1.0\ \text{GHz}$$
$$\lambda = 0.30\ \text{m}$$

1. try: correct answer by 0%

2. try: correct answer by 50%

1. $\dfrac{\lambda}{2\pi} = 0.17\ \text{m}$
2. $\dfrac{2L^2}{\lambda} = 0.017\ \text{m}$
3. $5L = 0.25\ \text{m}$
4. $2\lambda = 0.60\ \text{m}$

Electric fields of a short dipole antenna: $\mathbf{E} = E_r \mathbf{u}_r + E_\theta \mathbf{u}_\theta$

$$E_r = \mathrm{j}\omega\mu 2IL\cos\theta \frac{e^{-\mathrm{j}kr}}{4\pi r}\left[\frac{1}{\mathrm{j}kr} + \frac{1}{(\mathrm{j}kr)^2}\right]$$

$$E_\theta = \mathrm{j}\omega\mu IL\sin\theta \frac{e^{-\mathrm{j}kr}}{4\pi r}\left[1 + \frac{1}{\mathrm{j}kr} + \frac{1}{(\mathrm{j}kr)^2}\right]$$

near-field: $kr < 1$

$\frac{2\pi}{\lambda} \cdot r < 1$

$r < \frac{\lambda}{2\pi}$

far-field: $kr > 1$

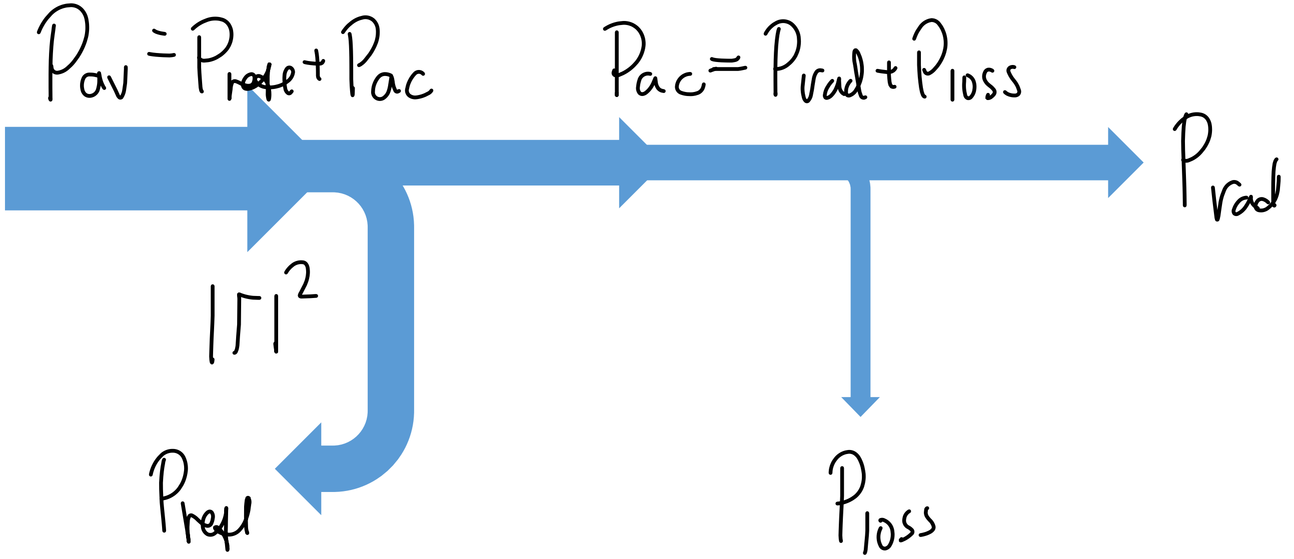
$r > \frac{\lambda}{2\pi}$

8.4. Which of the following antenna parameters has the **smallest** numeric value in the absolute scaling? The definition of the parameters follows the coursebook convention. Additionally, P_{av} stands for the available power (e.g., from the generator).

Correct answer by **67%**

1. directivity, D
2. "normal" gain, G
3. realized gain, G_r

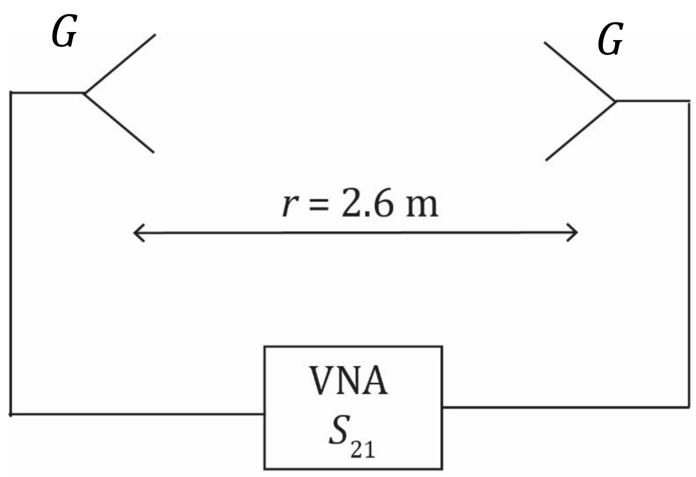
$$D = \frac{U_{max}}{U_{avg,iso}} = 4\pi \frac{U_{max}}{P_{rad}} \qquad G = 4\pi \frac{U_{max}}{P_{acc}} \qquad G_r = 4\pi \frac{U_{max}}{P_{av}}$$



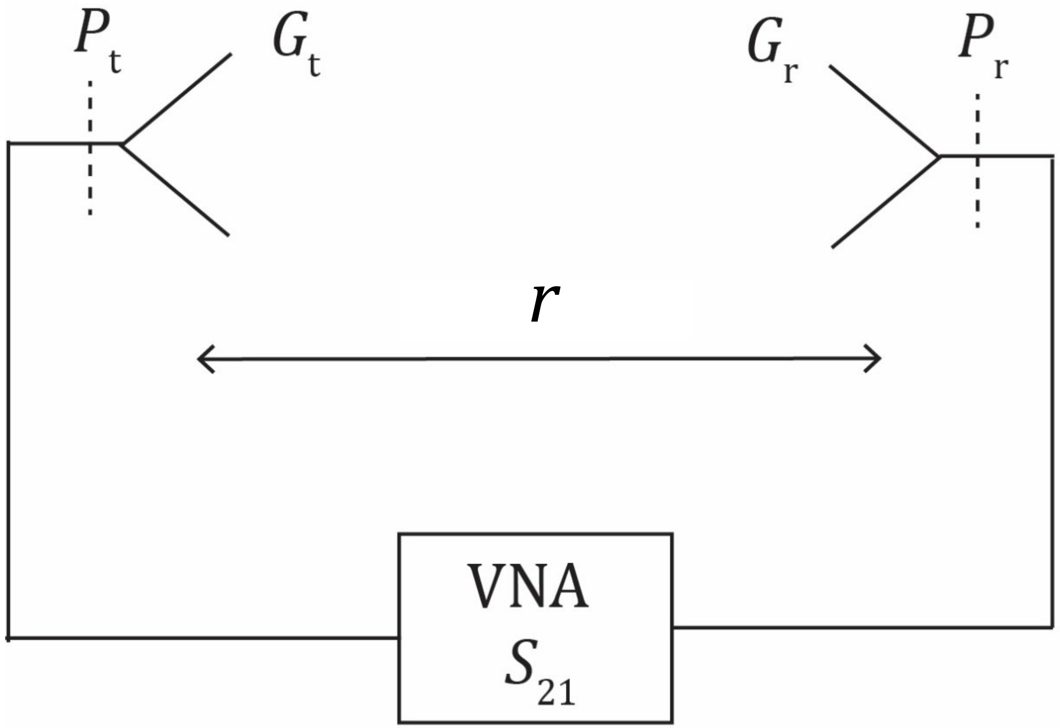
8.5. This question deals with the “absolute gain method”, see the coursebook chapter 7.3.1. Two antennas are identical, one is transmitting and one receiving. The antennas are separated by a 2.60 m distance. A calibrated vector network analyzer measures the numerical value of the power transmission coefficient (i.e., $|S_{21}|^2 = \frac{P_r}{P_t}$) between the antennas at 2.4 GHz: $|S_{21}|^2 = 0.0059 = -22.3$ dB. Assume the free-space and far-field conditions and perfect polarization and impedance matching. What is the gain of the antennas?

Correct answer by **67%**

1. $G = 13$ dB
2. $G = 23$ dB
3. $G = 26$ dB
4. The gain cannot be defined based on the given information.



Absolute-gain method is prone to measurement errors



$$P_r = G_t \cdot G_r \left(\frac{\lambda}{4\pi r}\right)^2 P_t$$

$$\frac{P_r}{P_t} = |S_{21}|^2 = G_t \cdot G_r \cdot \left(\frac{\lambda}{4\pi r}\right)^2$$

8.6. This question deals with the "gain transfer method", see coursebook chapter 7.3.2. The standard ("S") antenna has the realized gain of 13 dBi. The power transmission coefficient (i.e., $|S_{21}|^2 = \frac{P_r}{P_t}$) between standard/test antenna and the measurement antenna was measured with an **uncalibrated** vector network analyzer: with standard antenna: $S_{21dB}^{S} = -22.3$ dB, test antenna: $S_{21dB}^{T} = -25.3$ dB. Assume free-space condition and perfect polarization matching. What is the realized gain of the test antenna ("T")?

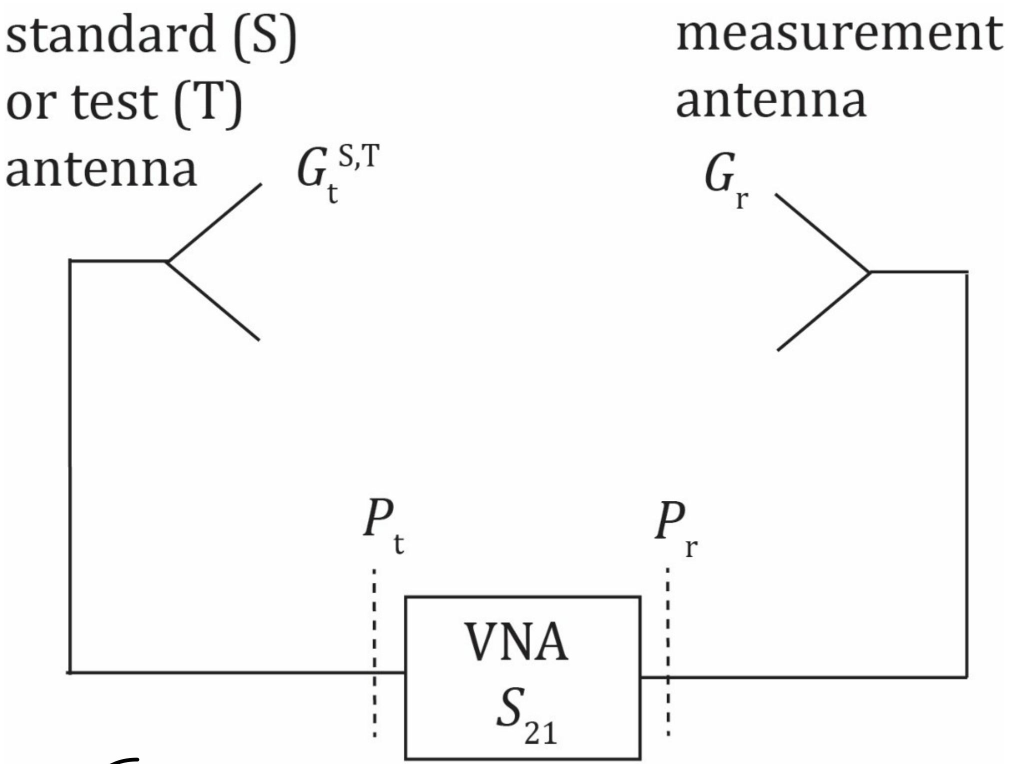
1. try: correct answer by 58%
2. try: correct answer by 100%

1. The vector network analyzer is not calibrated; hence we cannot define the gain accurately enough.
2. $G = 3.0$ dBi
3. $G = 10$ dBi
4. $G = 13$ dBi
5. $G = 16$ dBi
6. The gain cannot be defined based on the given information.

$$G^T = G^S_{dB} + S^T_{21dB} - S^S_{21dB} = 13\,\text{dBi} - 25{,}3\,\text{dB} - (-22{,}3\,\text{dB})$$

$$= 10\,\text{dBi}$$

Gain-transfer method is a relative measurement – it can be performed with an uncalibrated VNA



1) standard antenna

$$|S_{21}^S|^2 = \frac{P_r^S}{P_t^S} = G_t^S \cdot G_r \left(\frac{\lambda}{4\pi r}\right)^2$$

2) test antenna

$$|S_{21}^T|^2 = G_t^T \cdot G_r \left(\frac{\lambda}{4\pi r}\right)^2$$

$$\frac{|S_{21}^T|^2}{|S_{21}^S|^2} = \frac{G_t^T \cdot G_r \cdot \left(\frac{\lambda}{4\pi r}\right)^2}{G_t^S \cdot G_r \left(\frac{\lambda}{4\pi r}\right)^2} = \frac{G_t^T}{G_t^S} \Rightarrow$$

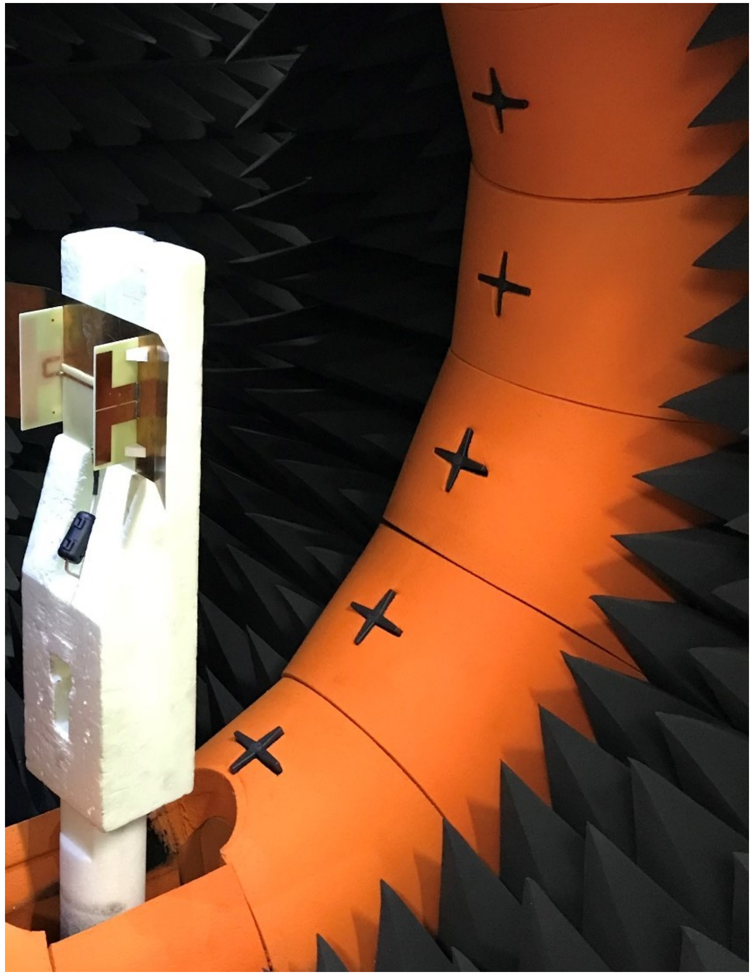
$$G_t^T = G_t^S \cdot \left|\frac{S_{21}^T}{S_{21}^S}\right|^2$$

$$\rightarrow G_{dB}^T = G_{t\,dB}^S + S_{21\,dB}^T - S_{21\,dB}^S$$

8.8. The measurement antennas (e.g., two crossed dipoles, see figure) can have two orthogonal linear polarizations: vertical (V) and horizontal (H). As the result of a measurement, we get two orthogonal **partial** gain components: $\boldsymbol{G_V}$ **= 23 dBi** and $\boldsymbol{G_H = -10}$ **dBi**. Select the correct statement.

Correct answer by **83%**

1. The total gain of the test antenna is G_T = 13 dBi.
2. The total gain cannot be defined based on the given information.
3. The polarization state of the test antenna is in practice linear.



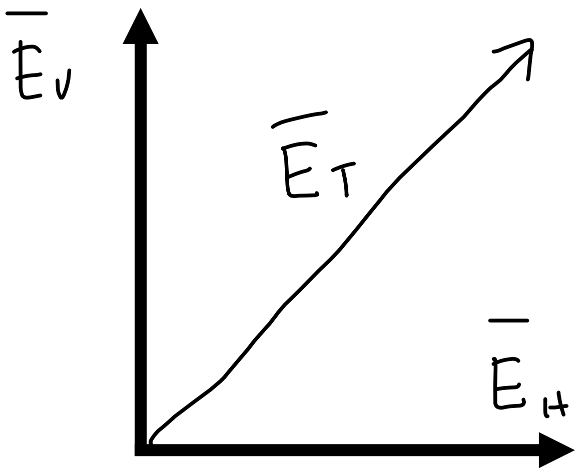
$G_V = 23\,dBi = 200 \qquad G_H = -10\,dBi = 0{,}10$

$G_T = G_V + G_H = 200 + 0{,}10 = 200{,}10$

$= 10 \log 200{,}1 = 23\,dBi$

The total gain is the sum of the orthogonal partial gain components when the absolute values are used

The coursebook formula: $G_T = G_V + G_H$



$$E_T^2 = E_V^2 + E_H^2$$

$$G_T = 4\pi r^2 \frac{S_T}{P_{av}} \leftarrow S_T = \frac{|\bar{E}_T|^2}{2\eta_0} = \frac{E_V^2 + E_H^2}{2\eta_0}$$

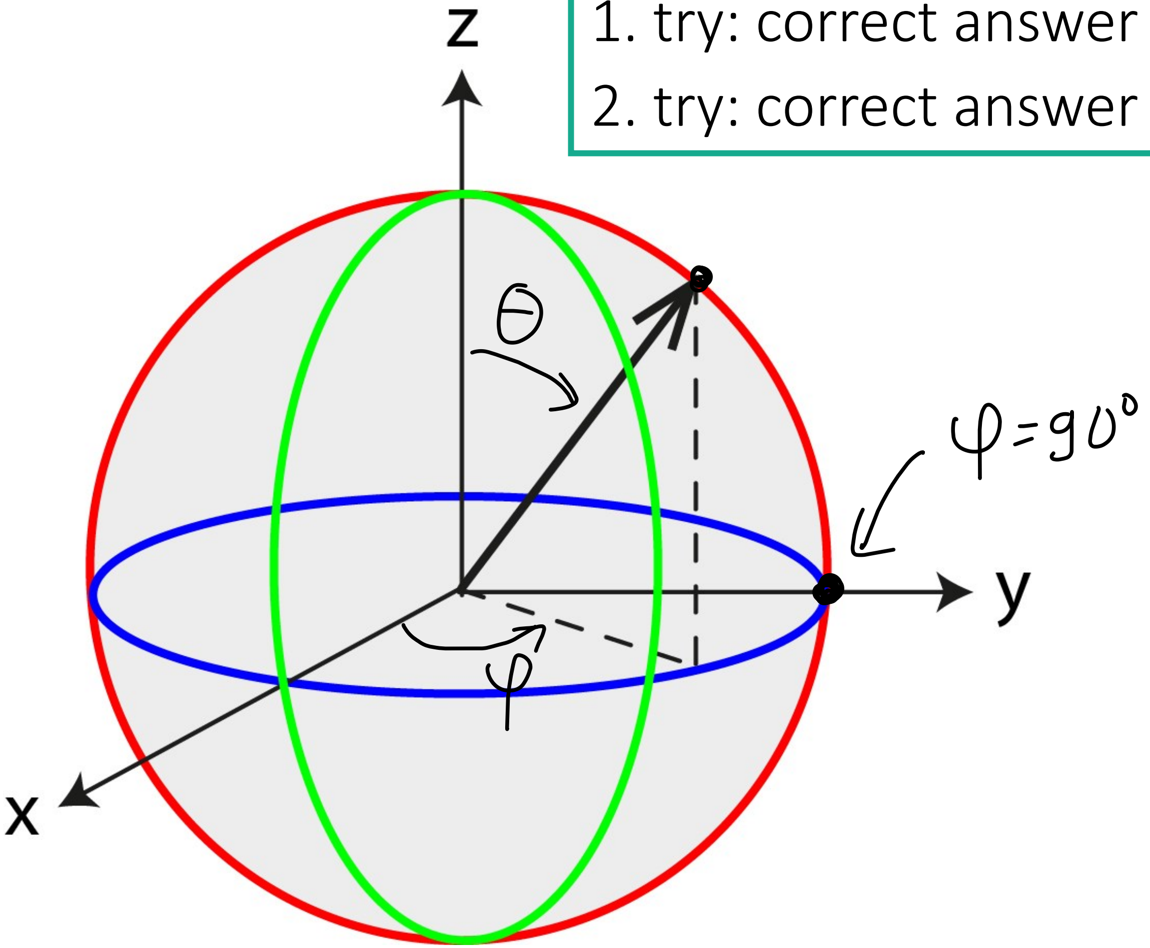
$$= 4\pi r^2 \frac{S_V + S_H}{P_{av}}$$

$$G_T = G_V + G_H$$ ← absolute values

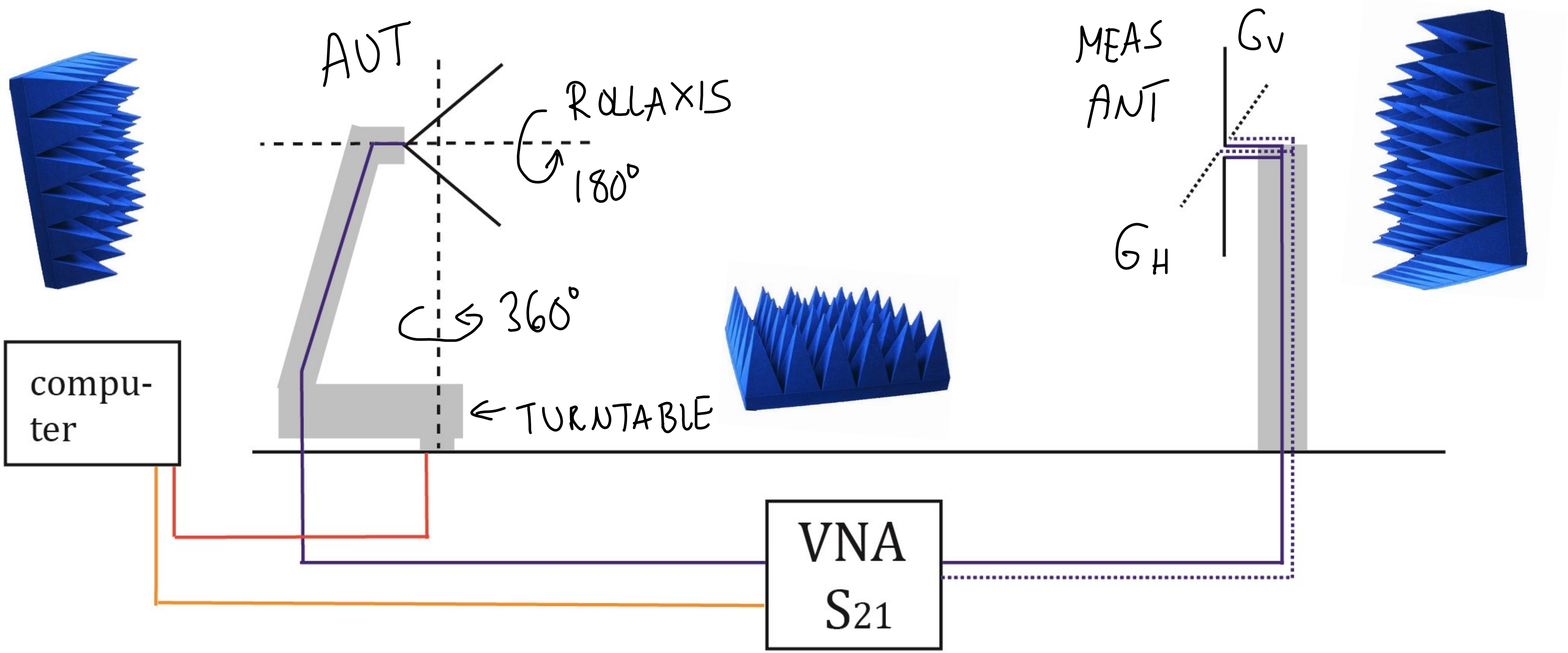
8.7. The antenna radiation pattern is the display of the radiation properties of the antenna as a function of the spherical coordinates (θ, φ). The full-3D pattern is measured, but it is typically shown for the **principal pattern cuts** in a polar or Cartesian plot. The **red**, **blue** and **green** circles illustrate the three principal cuts/planes of the standard spherical coordinates system. What is the range of the elevation θ and azimuth φ angles illustrated with the **red circle**?

1. try: correct answer by 75%
2. try: correct answer by 100%

1. $\varphi = 0°$ or $180°$ and
   θ varies from $0°$ to $180°$
2. $\varphi = 90°$ or $270°$ and
   θ varies from $0°$ to $180°$
3. $\theta = 90°$ and
   φ varies from $0°$ to $360°$

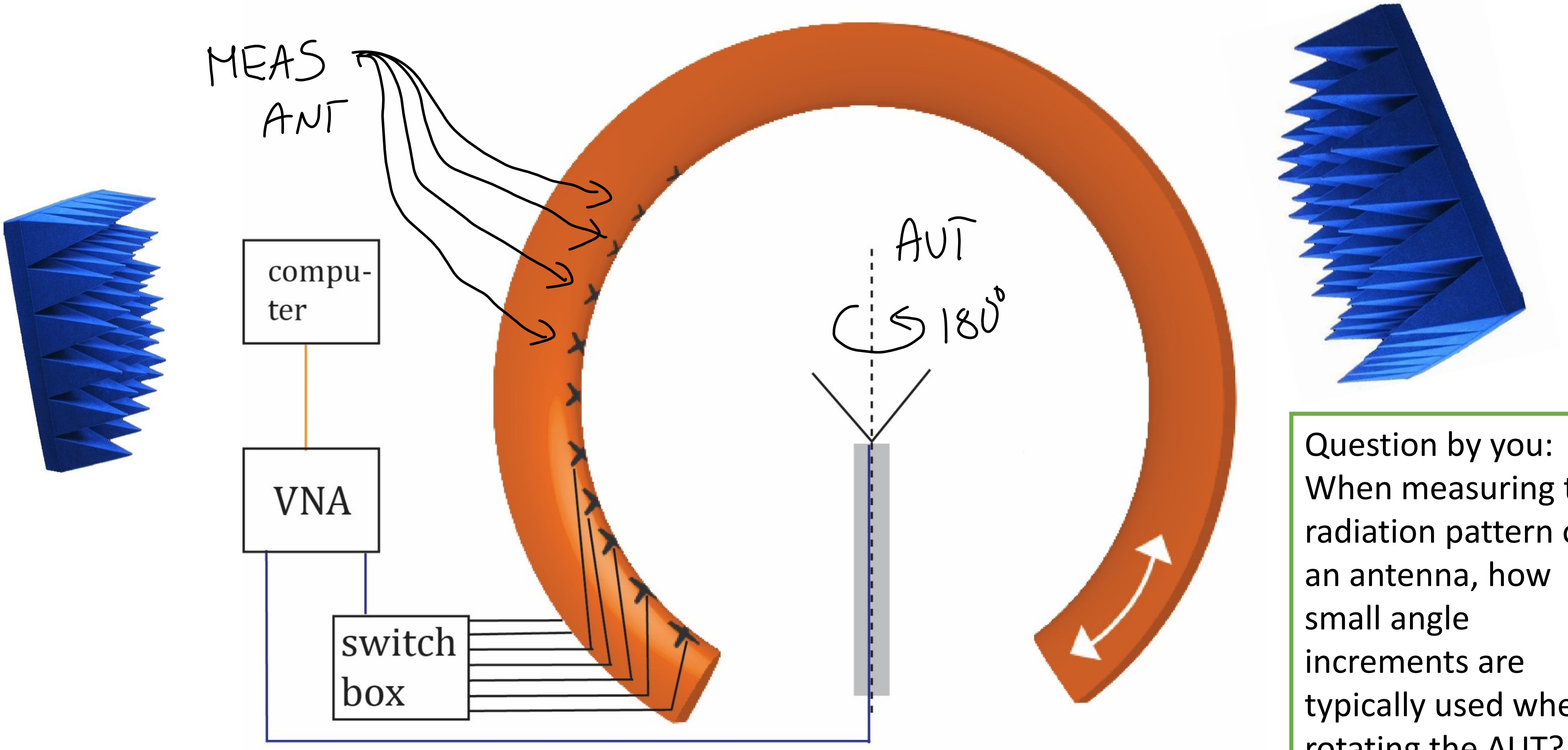


To define the full-3D radiation pattern, traditional measurement systems have <u>two</u> axes of rotation



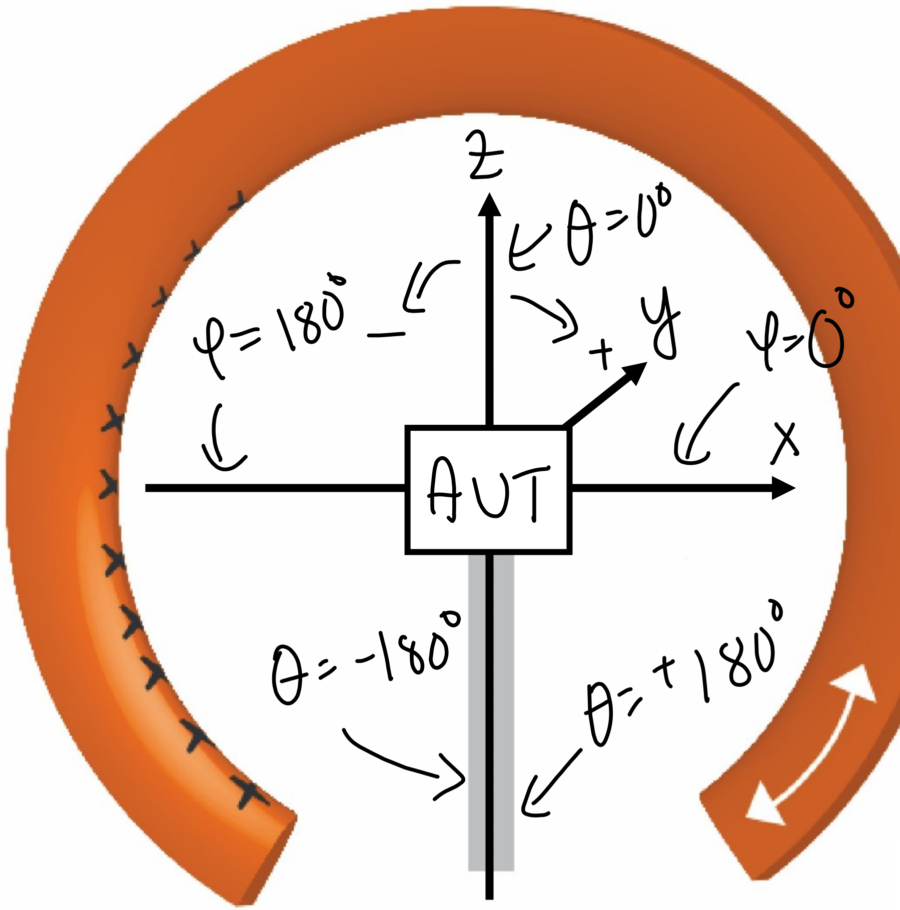
Questions by you: **1.** Does Aalto Electronics-ICT facilities allow to perform measurement on radio astronomy antenna in some way directly or indirectly? **2.** How to introduce large antennas into the chamber?

Modern measurement systems have only <u>one</u> axis of rotation – measurements can be fast!



Question by you: When measuring the radiation pattern of an antenna, how small angle increments are typically used when rotating the AUT?

Starlab has a different angle definition than the standard system



STANDARD SCS:

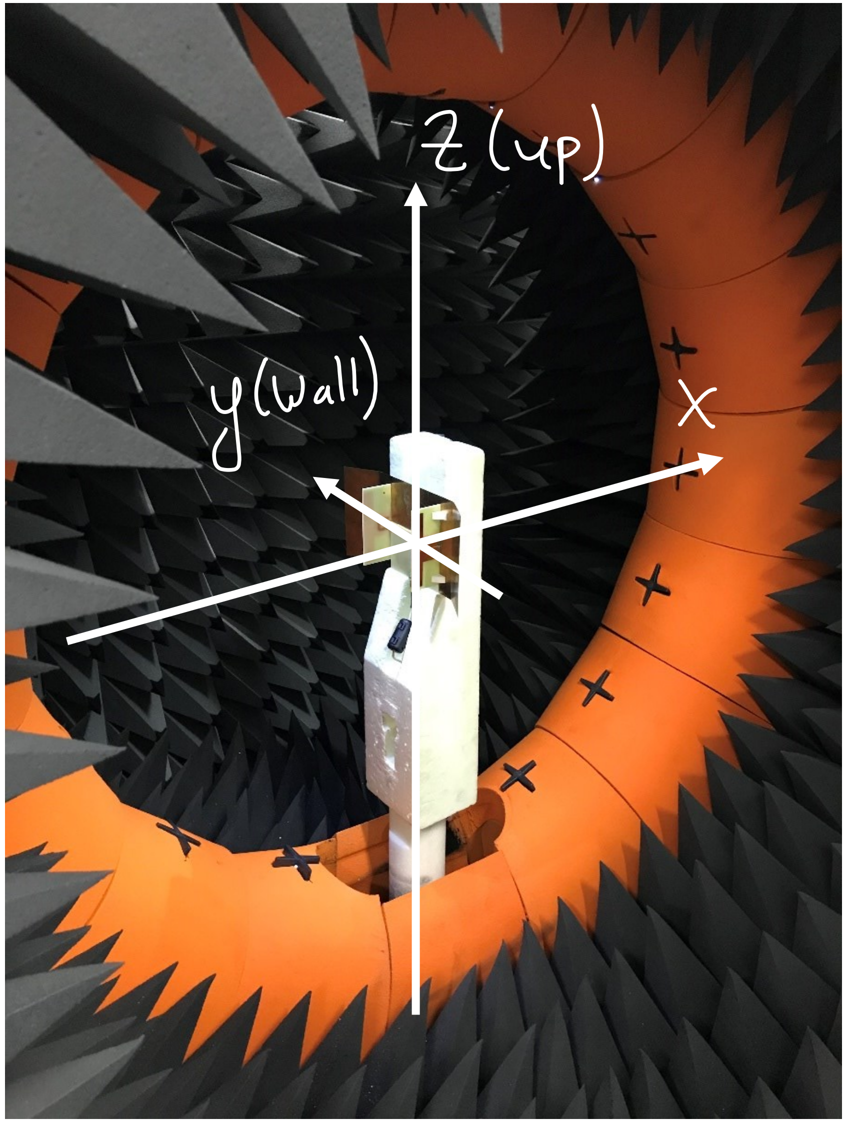
$\theta = 0° \ldots 180°$

$\varphi = 0° \ldots 360°$

STARLAB:

$\varphi = 0° \ldots 180°$

$\theta = -180° \ldots 180°$



Measurement results are served as text files

Partial realized gain (dBi), theta [vertical] component

2022 AUT = patch array - Realised Gain dBi - Theta component - 1.5 GHz.txt - Notepad

File Edit Format View Help

2
Frequency=1500(MHz)

Phi	Theta	Realized Gain Theta Component dB
0	-3.1415926536	-12.6738407345471
0	-3.1241393611	-12.5091465936221
0	-3.1066860685	-12.3280797167615
0	-3.089232776	-12.135671627083
0	-3.0717794835	-11.9354301389591
0	-3.054326191	-11.7296615226075
0	-3.0368728985	-11.5198002944844
0	-3.019419606	-11.3067046388367
0	-3.0019663134	-11.0909034417572
0	-2.9845130209	-10.8727970724858
0	-2.9670597284	-10.6528001695017
0	-2.9496064359	-10.4314373187619
0	-2.9321531434	-10.2093985667059
0	-2.9146998508	-9.98755422420394
0	-2.8972465583	-9.766947817249
0	-2.8797932658	-9.54876479397584
0	-2.8623399733	-9.33429268055274
0	-2.8448866808	-9.12487627898743
0	-2.8274333882	-8.92187128101127

Ln 4, Col 10 | 100% | Windov

Partial realized gain (dBi), phi [horizontal] component

2022 AUT = patch array - Realised Gain dBi - Phi component - 1.5 GHz.txt - Notepad

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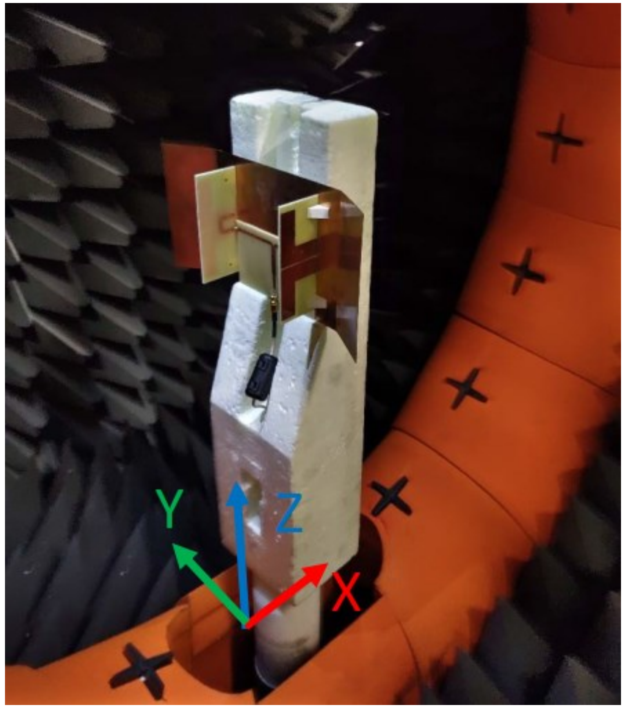
2
Frequency=1500(MHz)

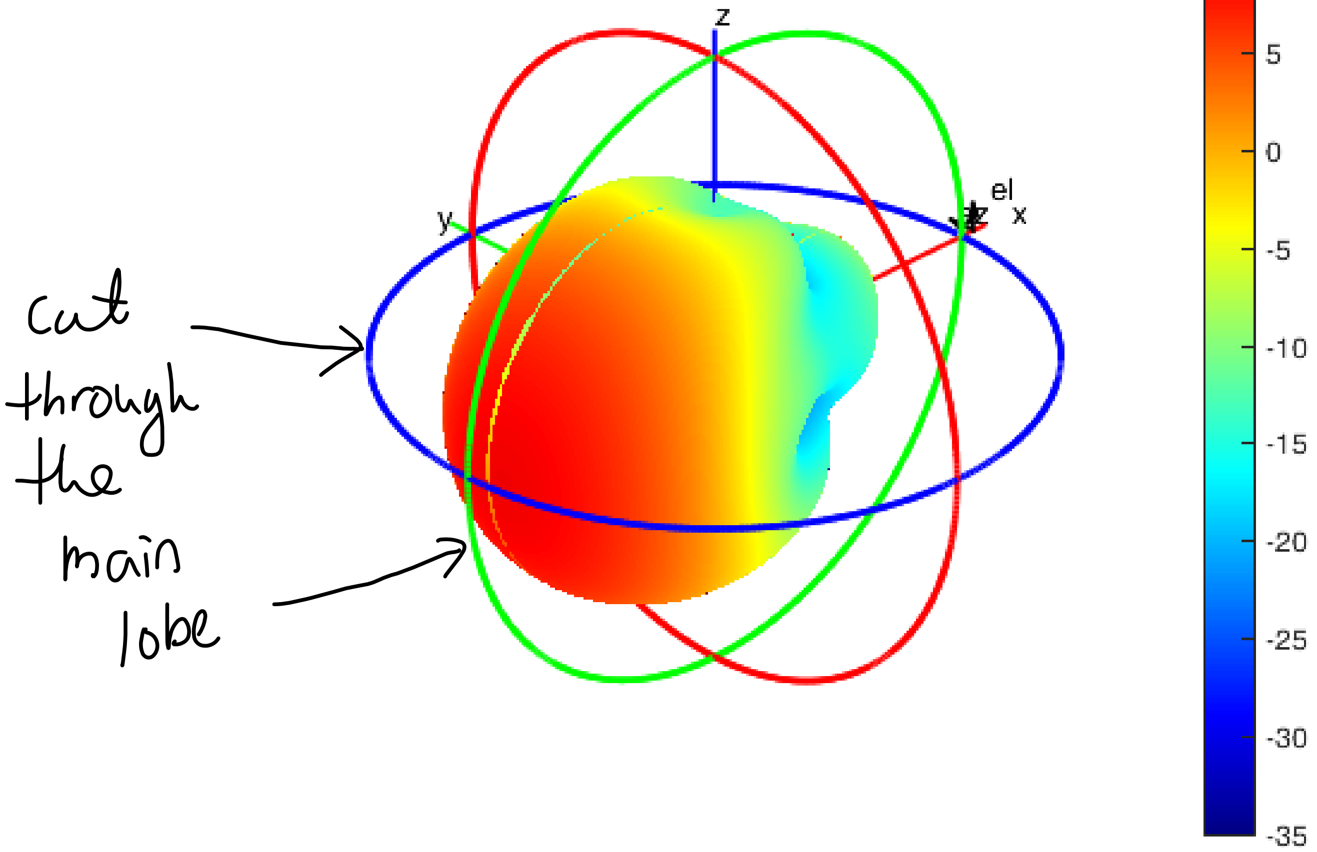
Phi	Theta	Realized Gain Phi Component dBi
0	-3.1415926536	-19.1297786342541
0	-3.1241393611	-19.2812085845786
0	-3.1066860685	-19.4392621572484
0	-3.089232776	-19.6044079107553
0	-3.0717794835	-19.7770064912632
0	-3.054326191	-19.9573024481827
0	-3.0368728985	-20.1454152860781
0	-3.019419606	-20.3413336180313
0	-3.0019663134	-20.5449005648769
0	-2.9845130209	-20.7558087451344
0	-2.9670597284	-20.9735858680129
0	-2.9496064359	-21.1975867585189
0	-2.9321531434	-21.4269785067495
0	-2.9146998508	-21.6607314944707
0	-2.8972465583	-21.897611811658
0	-2.8797932658	-22.1361763677839
0	-2.8623399733	-22.3747706932113
0	-2.8448866808	-22.61154326449
0	-2.8274333882	-22.8444611659983

Ln 4, Col 43 | 100% | Windows (CRLF) | UTF-8

Example: full-3D pattern as total realized gain (dBi) presented in standard spherical coordinate system

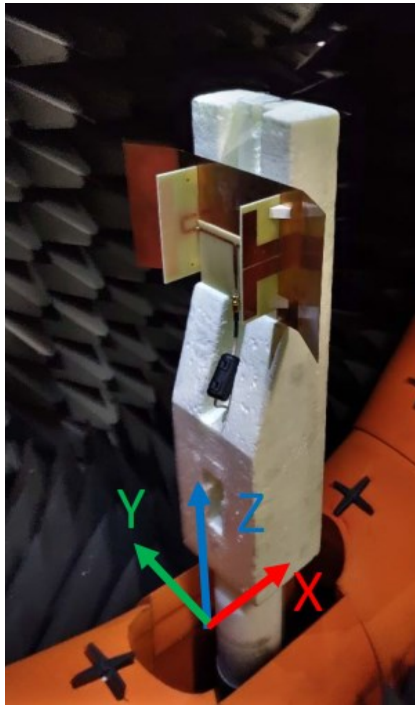


Which **two** of the three principal pattern cuts (blue, green, ~~red~~) are the most interesting?

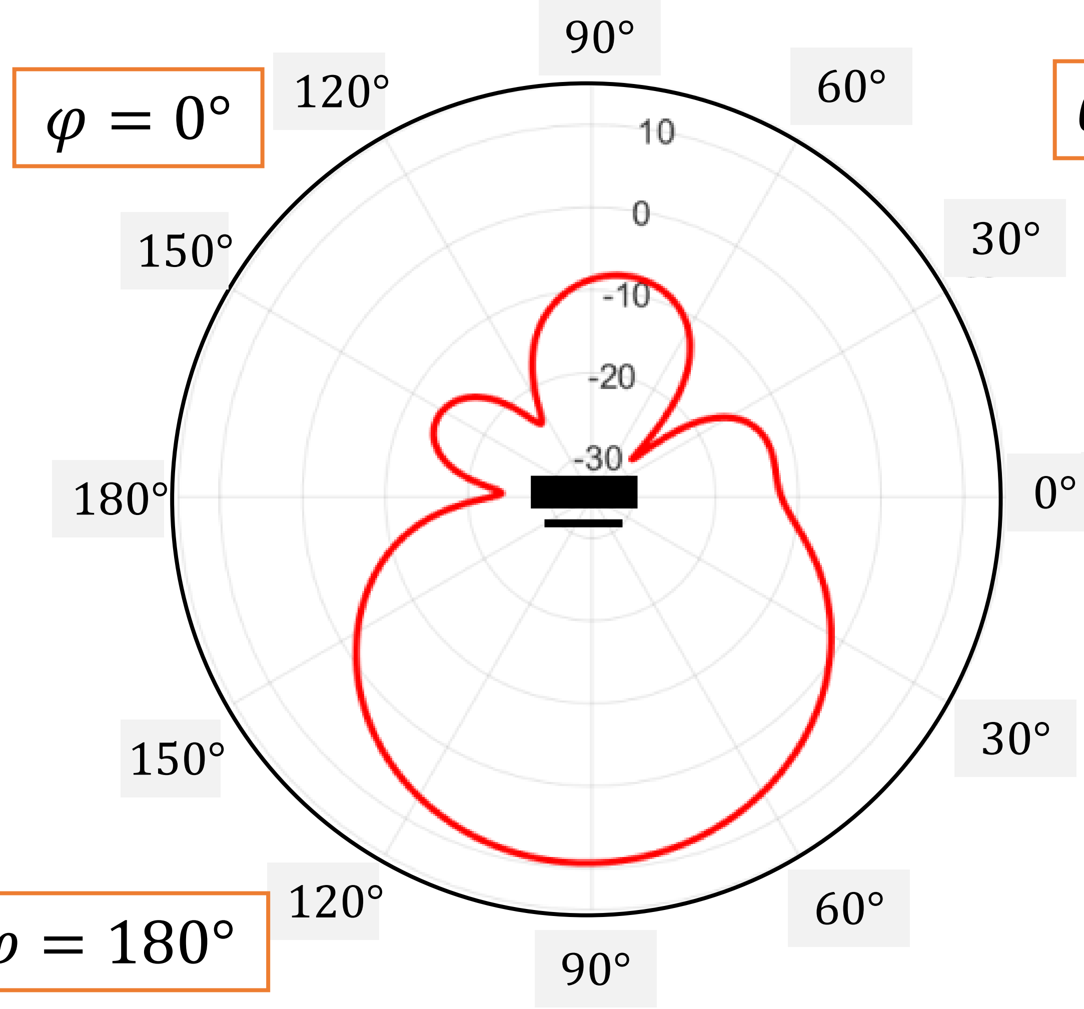


Question by you: What is the most prevalent source of error in antenna measurements?

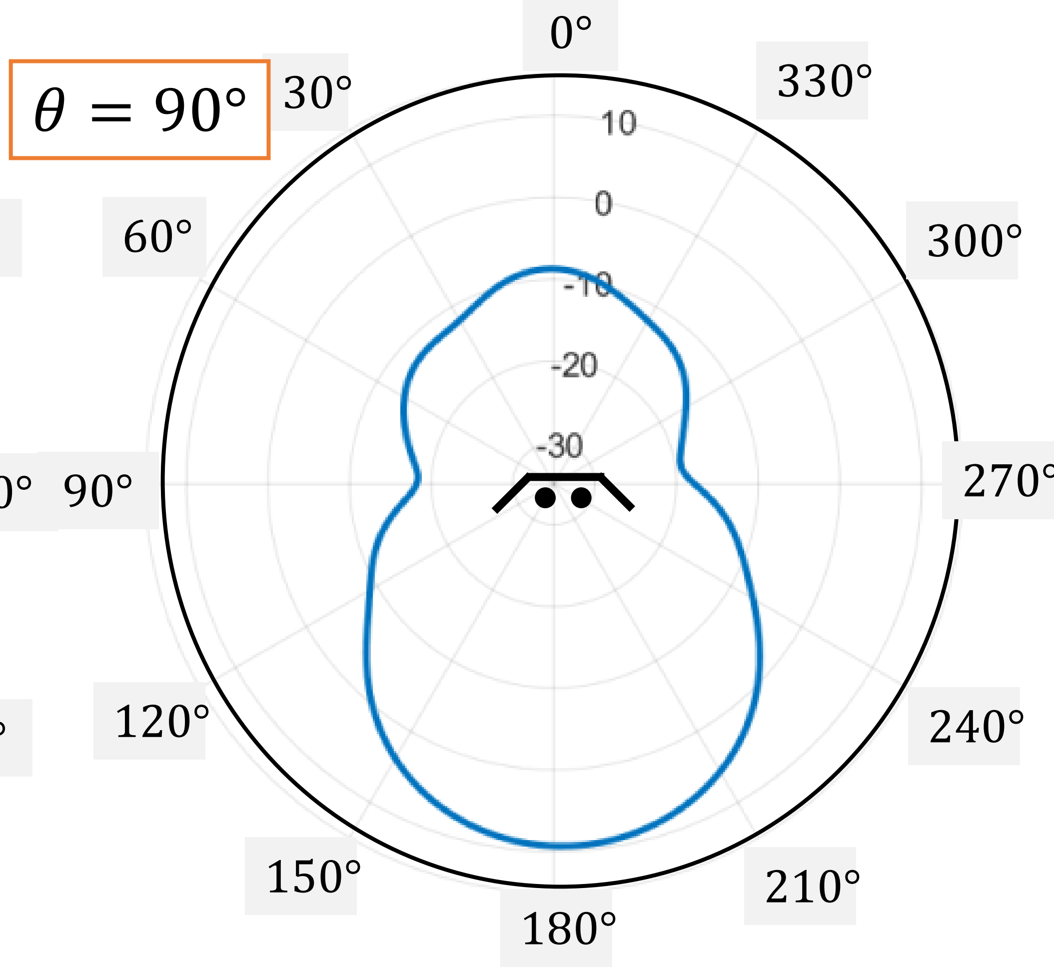
Example: two principal pattern cuts as total realized gain (dBi) are presented in polar plots of standard spherical coordinate system



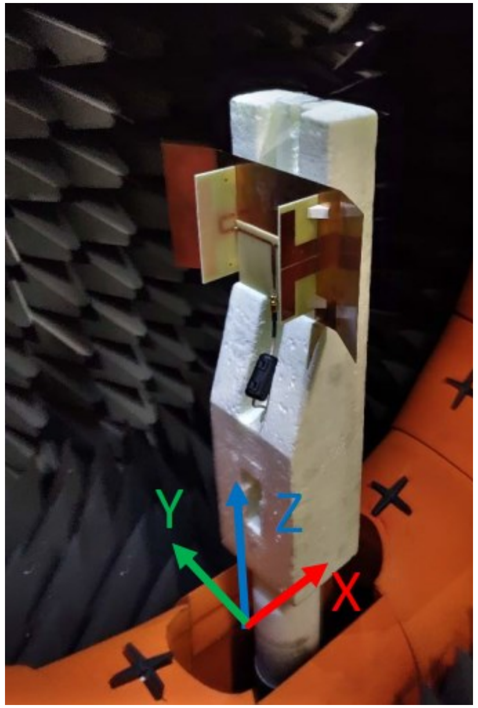
XZ-plane: θ variable

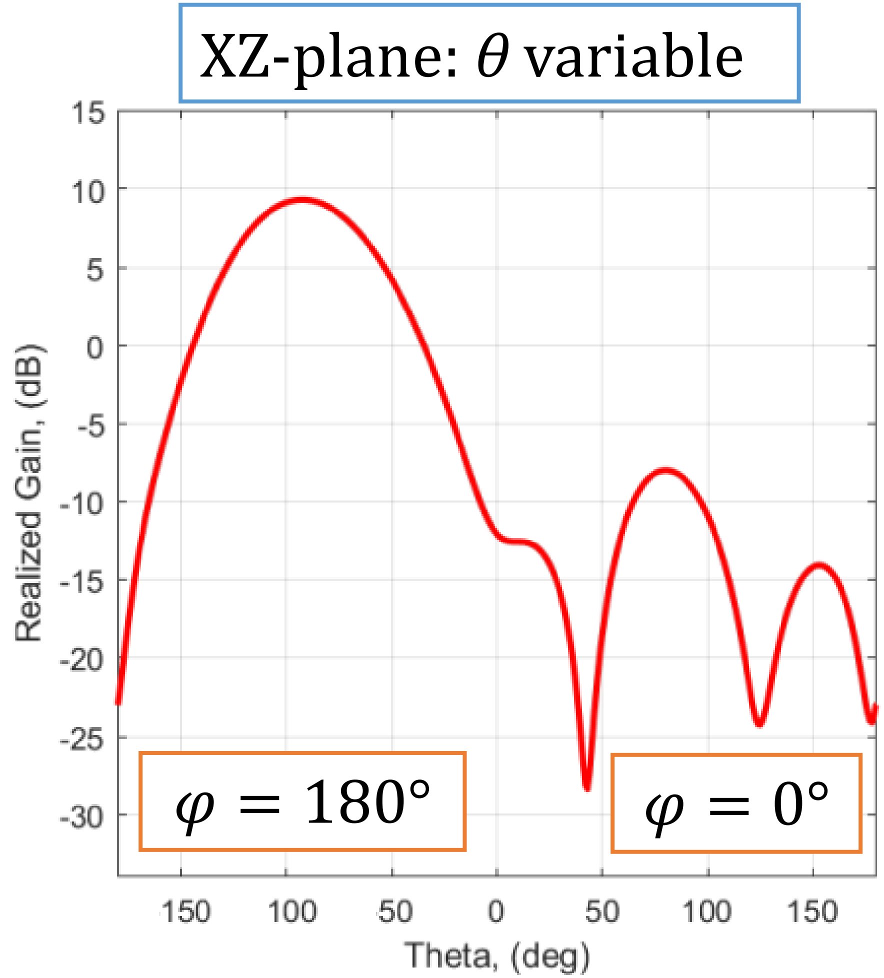


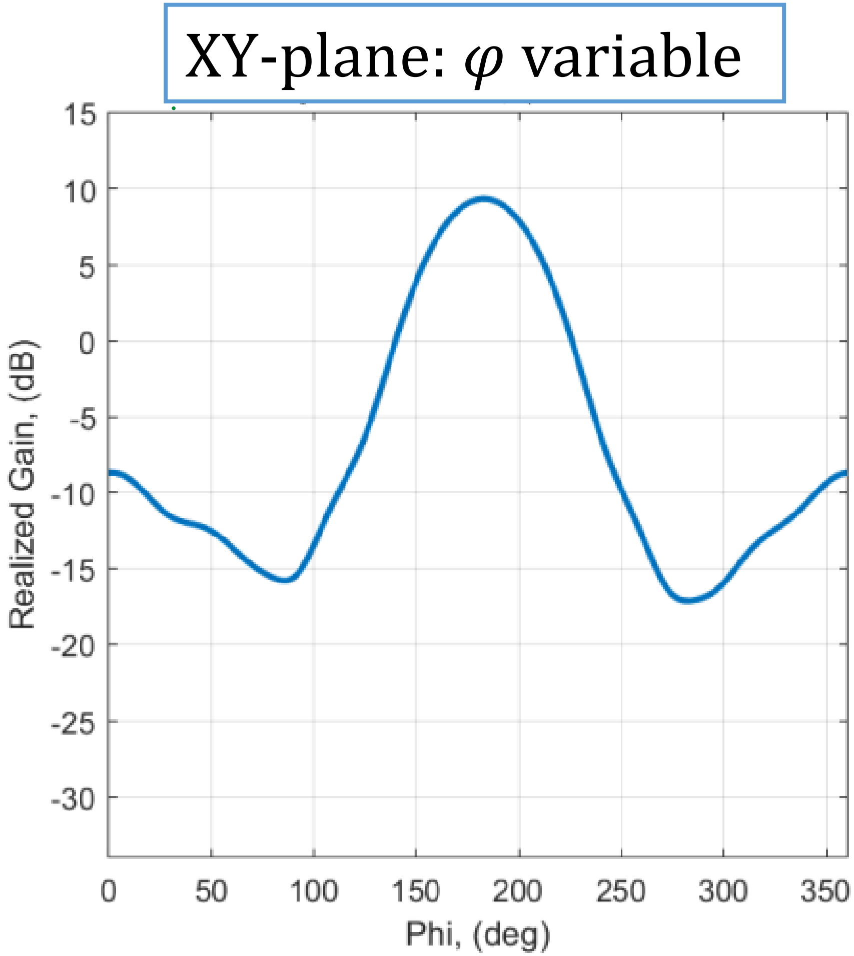
XY-plane: φ variable



Example: two principal pattern cuts as total realized gain (dBi) presented in standard Cartesian coordinate system







HPBW: 63 degrees

HPBW: 49 degrees

Home exercise: handle, display and analyze the Starlab measurement results

1. You participate(d) in **performing** a real-time measurement with the Starlab measurement system.
2. We measure the radiation pattern (*) as a function of the elevation and azimuth angles at a single frequency (1.5 GHz).

   (*) partial realized gain with orthogonal vertical (in Starlab: Theta) and horizontal (Phi) components
3. The measurement data is delivered as two text files in MyCourses.
4. Your task will be to 1) **handle** and **present** the measurement results graphically (e.g., with Matlab or Mathematica) and 2) **analyze** the results using written observations. Further details available in the exercise sheet.
5. Should you need any help for handling & presenting the results, contact Jan
6. The DL is Tuesday, 17 May. Your contributions will be compared and discussed in a review & assessment session on Friday, 20 May at 10.

Hints for compiling the measurement assignment

Pay attention to the following (i.e., affects the assessment):

- The orientation of the test antenna in the coordinate system
- Stylish-looking plot of radiation patterns (i.e., plotted with Matlab, Mathematica or equivalent)
- Clarity of the radiation patterns, e.g., main lobe direction is clearly shown
- The labels and scaling of the coordinate axes and reasonable font size
- Preferably, an authentic foto of the antenna in the measurement device
- Explanation (and possible further analysis) of the main results