

EE 117B/217B Microwave and Wireless Measurements

Lab 6 - Antenna Measurements

Fall 2026

CAUTION: READ THIS PAGE CAREFULLY BEFORE STARTING THE LAB

This lab uses the FieldFox Microwave Analyzer N9918B in its **Network Analyzer (NA)** and **Spectrum Analyzer (SA)** modes, a set of microwave horn antennas, a custom microstrip patch array, motorized and manual positioning stages, and the Keysight **Compact Antenna Test Range (CATR)** chamber. Please handle the instruments very carefully as they are very expensive and delicate. The most vulnerable parts of the instruments are the RF PORTS (APC-3.5 connectors). These connectors are protected by the small Female-Female Port Savers. **DO NOT REMOVE THE PORT SAVERS FROM THE FIELDFOX PORTS FOR ANY EXPERIMENT.**

All connections are to be made through these Port Saver Connectors. If you have never handled RF instrumentation before, ask the instructor to demonstrate how to make connections. Always hold the cable with one hand and rotate the end nuts of the SMA cables with the other. Once you make a soft connection by hand, use the torque wrench provided to complete the connection. Only rotate the end nuts, never the components.

Caution for this particular lab

Motor controllers: Be very careful when connecting the DC power supplies to the motor controllers. Applying the reverse polarity or the wrong voltage will damage the controllers.

Cables on moving stages: Before starting any motorized rotation, route the cable so that it cannot wrap around the stage or be pulled taut at the end of the sweep.

Connector types: The RF ports on the chamber use 2.4 mm connectors. We have attached 2.4 mm-to-2.92 mm adapters so that SMA cables can be connected. Please do not remove these adapters. Handle this experiment extra carefully.

CATR chamber: Do not open the chamber door or reach into the chamber while the positioner is moving. The DUT roll stage is mechanically limited to $\pm 360^\circ$; do not command it beyond this range. Do not change any cable connections inside the chamber, and do not disconnect the positioner USB cable from the control PC.

Introduction

In this lab you will measure the two quantities that describe how an antenna radiates: its gain and its radiation pattern. The lab is divided into three experiments: (1) antenna gain measurements with a vector network analyzer, (2) far-field radiation pattern measurements over the air, and (3) radiation pattern measurements in a compact antenna test range (CATR) chamber.

In the first experiment you will use the FieldFox in NA mode to measure the transmission coefficient S_{21} between pairs of antennas and extract their gain from the Friis transmission formula. A full 2-port calibration with the Keysight 85052D calibration kit moves the reference planes to the ends of the cables, so the cable losses do not enter the measurement, and RF absorbers and time gating suppress the stray radiation that reaches the antennas by paths other than the direct one. You will measure the gain of two WR-75 standard gain horns and a broadband ridged horn with the three-antenna method, compare it with the simpler two identical antenna method, and with the image method, where a single antenna faces a flat metal plate and the plate creates an image of the antenna. The theory for this experiment is collected in Appendices A and B.

In the second experiment you will assemble a simple far-field antenna range. One FieldFox will act as a CW source driving a transmit horn, and a second FieldFox in SA mode will measure the power received by the antenna under test (AUT), a custom 4×4 microstrip patch array mounted on a motorized rotation stage controlled from MATLAB. You will measure the return loss of the array, its co- and cross-polarized E-plane and H-plane radiation patterns, and its gain from the Friis equation, using the measured received power and cable losses and the gain of the transmit horn that you measured in the first experiment. The pattern definitions are collected in Appendix C.

In the third experiment you will use the Keysight CATR chamber, controlled by the over the air (OTA) Chamber Control software, with the FieldFox in VNA mode. In a CATR, a parabolic reflector converts the spherical wave of a feed horn into a plane wave in a small region called the quiet zone, so that far-field patterns can be measured at a distance much shorter than $2D^2/\lambda$. You will calibrate the FieldFox, connect it to the chamber, use the chamber calibration files to remove the path loss of the range, and measure the gain, the principal-plane cuts and a 2D (polar) radiation pattern of a standard gain horn. The CATR theory is described in Appendix D, and the complete connection and software setup procedure is described in Appendix E.

Objectives

At the end of this lab you will:

1. Measure the absolute gain of antennas with the three-antenna, two identical antenna and image methods, and understand the assumptions and error sources of each.
2. Use RF absorbers and time-domain gating to suppress stray radiation and isolate the direct path or a single reflection in an antenna measurement.
3. Set up a far-field antenna range and measure the return loss and the co- and cross-polarized E- and H-plane radiation patterns of an antenna array.
4. Determine the gain of an antenna from the Friis equation using a calibrated link.
5. Operate a compact antenna test range: connect the instrument, perform the mechanical boresight alignment, calibrate out the range path loss, and measure 1D and 2D radiation patterns.

Since students are performing the lab together, please ensure that you **take turns performing the experiments.**

Equipment List

The equipment used in this lab is listed in Table 1. The antennas are labeled as follows throughout this manual: **A** and **B** are the two Fairview Microwave FM9855B/SF-15 horns, **C** is the UWB ridged horn, **SGH** is the Eravant SAR-2018-90NF-R3 standard gain horn, and **AUT** is the 4×4 patch array.

Lab Report

Each lab comes with a Lab Questionnaire. As you go through this Lab Manual, you will encounter several questions along the way. When you do, go over to that question in the Lab Questionnaire and answer it accordingly. All students in one lab group will submit one combined lab report. **It is recommended that you complete the post-processing parts of the lab also during the designated lab hours so you can work together with your team.**

Equipment	Part Number	Qty
Keysight FieldFox Microwave Analyzer (NA / SA modes)	N9918B	2
WR-75 horn antenna, 10–15 GHz, 15 dBi nominal, SMA(f) (A , B)	Fairview Microwave FM9855B/SF-15	2
UWB double-ridged horn antenna (C)		1
WR-90 standard gain horn, 8.2–12.4 GHz, 20 dBi nominal, N(f) (SGH)	Eravant SAR-2018-90NF-R3	1
Custom 4×4 microstrip patch array (AUT)	NA	1
N(m)-to-3.5 mm adapter (for the SGH)	NA	1
Antenna mounting brackets	NA	3
Two pedestals (platforms) for the far-field range	NA	2
Motorized rotation stage (Pololu Tic stepper controller) and PC with MATLAB	NA	1
DC power supply for the motor controller (12 V, 1 A limit)	NA	1
USB to micro-USB cable (motor controller to PC)	NA	1
SMA right-angle adapter (AUT cable on the rotation stage)	NA	1
Flat aluminum plate (ground plane for the image method)	NA	1
Leveler and two vices (to hold the metal plate)	NA	1 / 2
RF absorbers (several panels)	NA	–
3.5 mm mechanical calibration kit	Keysight 85052D	1
Flexible SMA/3.5 mm coaxial test cables (including one long cable for the far-field range)	NA	2
Tape measure / ruler	NA	1
Keysight Compact Antenna Test Range with OTA Chamber Control software and control PC	CATR	1
WR-28 standard gain horn, 26.5–40 GHz, 20 dBi nominal, 2.4 mm(f) (CATR AUT, installed in the chamber)	Eravant SAR-2013-282F-E2	1
SMA cables (FieldFox to the 2.92 mm adapters on the chamber back panel)	NA	2
Ethernet cable and Ethernet-USB adapter	NA	1 each
Torque wrench	(shared)	1

Table 1: Equipment used in the Antenna Measurements Lab 6 experiments.

1 Antenna Gain Measurements (60 mins)

In this experiment you will measure the absolute gain of antennas from the transmission coefficient between two antennas, using the FieldFox in NA mode. All the methods in this section are based on the Friis transmission formula,

$$|S_{21}|^2 = G_1 G_2 \left(\frac{\lambda}{4\pi R} \right)^2, \quad (1)$$

where G_1 and G_2 are the (realized) gains of the two antennas, R is the distance between them and λ is the free-space wavelength. Equation (1) assumes that the antennas are in each other's far field, aligned on boresight, polarization matched, and that only the direct path contributes to S_{21} . The derivation and the formulas for each method are given in Appendix A. The measurement setup is shown in Fig. 1.

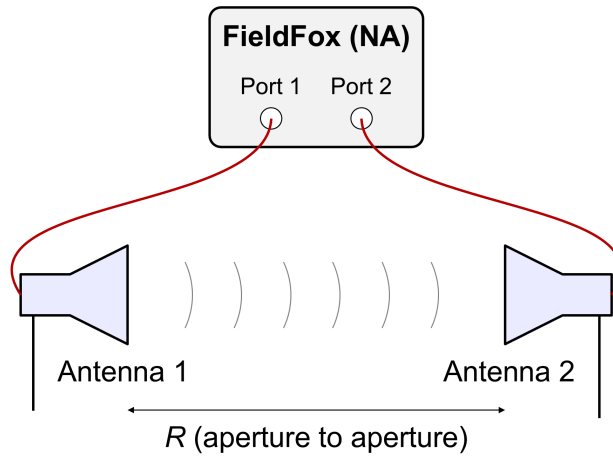


Figure 1: Setup for the gain measurements: the two antennas are connected to the two ports of the FieldFox in NA mode and face each other on boresight at a distance R . RF absorber on the table between the antennas suppresses the reflection from the table.

1.1 Three-Antenna Method (35 mins)

1. Measure the aperture dimensions of antennas A, B and C with the ruler, and compute the far-field distance $2D^2/\lambda$ of each antenna at 15 GHz, where D is the largest dimension (the diagonal) of the aperture. Choose a separation R that satisfies the far-field condition for every pair of antennas, or that is as close to it as the bench allows (**Q1.1.1**). Note that this criterion is conservative when the two antennas are different; see Appendix B.
2. Preset the FieldFox and select NA mode. Set the start frequency to 8.5 GHz, the stop frequency to 15 GHz, the number of points (**Sweep** $\rightarrow$ **Resolution**) to 401, the IF bandwidth to 1 kHz and the output power to **High**. Select the S_{21} measurement with **Log Mag** format. Antennas A and B are specified from 10 to 15 GHz; the sweep starts below 10 GHz (but above the 7.87 GHz cutoff of WR-75) because you will need the gain of antenna A at the far-field measurement frequency $f_0 = 9$ GHz in Section 2.
3. Connect the two coaxial test cables to Port 1 and Port 2. Perform a full 2-port calibration at the ends of the two cables with the Keysight **85052D** 3.5 mm calibration kit, following the

procedure from Lab 1 (select the 85052D kit in the FieldFox calibration menu). From now on, the reference planes are the cable ends, which will connect directly to the antennas, so the loss of the cables is removed from the measured S_{21} and you do not need to account for it. **Do not move or flex the cables more than necessary after the calibration.**

4. Mount antennas A and B on the brackets, facing each other on boresight at the separation R (aperture to aperture) that you chose. Both antennas must be at the same height, their boresight axes must coincide, and their polarizations must be aligned. The E-field of a rectangular waveguide horn is parallel to the *short* side of the waveguide; orient both horns with the short side vertical (vertical polarization). Keep the region between and around the antennas clear of objects, including yourselves.
5. Place RF absorbers on the table/floor between the two antennas, and in front of any nearby objects (walls, instruments, metal parts of the bench) that the antennas can see, to suppress stray reflections. The absorbers must not block the direct path between the apertures.
6. Connect antenna A to Port 1 and antenna B to Port 2. Fine-tune the alignment (rotate one horn slightly in azimuth and elevation) to maximize $|S_{21}|$.
7. Turn on the time-domain transform of S_{21} as in Lab 2, in **band-pass** mode (the measurement does not include frequencies near DC). Identify the direct-path response, which arrives after a delay of about R/c plus the delay of the two horns, and the later responses: reflections from the surroundings and the multiply scattered wave between the two antennas, which arrives $2R/c$ after the direct path. Save the time-domain response (**Q1.1.2**).
8. Set a gate around the direct-path response, wide enough to include the whole response but narrower than $2R/c$, so that the multiply scattered wave and the later reflections are excluded. Turn on the gate and transform back to the frequency domain. Save both the gated and the ungated S_{21} traces as .csv files (**Save/Recall**). Record R . Since gating distorts the response near the edges of the sweep, discard the first and last few hundred MHz of the gated data.
9. Without changing R , replace antenna B with antenna C, align, and save the gated and ungated S_{21} for the pair A–C. Then replace antenna A with antenna B, align, and save the gated and ungated S_{21} for the pair B–C. If the aperture of C is not in the same plane as the aperture of A and B, adjust the bracket position so that the aperture-to-aperture distance remains R . Adjust the gate position for each pair if needed.
10. Plot the gated and ungated $|S_{21}|$ (dB) versus frequency for the three pairs (**Q1.1.3**). Use the three-antenna equations (Appendix A.1) and the gated data to compute and plot the gains G_A , G_B and G_C versus frequency, and compare G_A and G_B to the nominal gain of 15 dBi (**Q1.1.4**). Record G_A at $f_0 = 9$ GHz; you will need it in Section 2. Identify the sources of error in this measurement (**Q1.1.5**).

1.2 Two Identical Antenna Method (0 mins, post process later)

1. If two antennas are identical, a single transmission measurement is sufficient to determine their gain. Use the gated S_{21} data of the pair A–B from Section 1.1 and the two-antenna formula (Appendix A.2) to compute the gain versus frequency. Compare it with G_A and G_B from the three-antenna method. How large is the error if the two antennas are not exactly identical (**Q1.2.1**)?

1.3 Image Method (25 mins)

In the image method, a single antenna faces a large flat metal plate. By image theory, the plate together with the antenna is equivalent to the antenna and its mirror image at a distance $2d$, where d is the distance between the antenna and the plate. The reflection from the plate is therefore equivalent to a two identical antenna measurement over a distance $2d$, and the gain follows from S_{11} alone (Appendix A.3). The plate reflection must be separated from the reflection of the antenna itself, so **time gating is required** for this method. The setup is shown in Fig. 2.

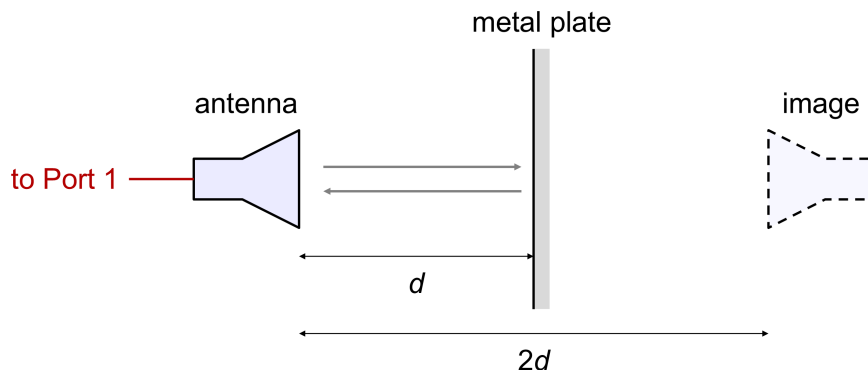


Figure 2: Image method: the reflection of an antenna from a large metal plate at distance d is equivalent to the transmission between the antenna and its image at distance $2d$.

1. Keep the NA settings and the full 2-port calibration from Section 1.1; the 2-port calibration is also valid for S_{11} . Disconnect the antennas and select the S_{11} measurement.
2. Clamp the metal plate upright with the two vices, and use the leveler to check that the plate is vertical. Mount antenna A facing the plate, with its boresight perpendicular to the plate and at the height of the plate center, at a distance of about $d = 30\text{--}40$ cm, and connect it to Port 1. Place absorbers on the table between the antenna and the plate. The antenna must be in the far field of its image, $2d > 2D^2/\lambda$. Measure the distance d between the antenna aperture and the plate with the ruler. What is the minimum d and the minimum size of the plate (**Q1.3.1**)?
3. Turn on the time-domain transform in **band-pass** mode. You should see a first response near $t = 0$ caused by the mismatch of the coaxial-to-waveguide transition and the horn aperture, followed by a second response from the plate. To locate the antenna aperture in the time-domain response, temporarily cover the aperture with a piece of aluminum foil (or a small metal sheet) and place a marker on the resulting peak. Place a second marker on the plate response, and compute d from the time difference. Compare it with the value measured with the ruler (**Q1.3.2**). Save the time-domain response.
4. Set a gate around the plate response, wide enough to include the entire plate response but excluding the response of the antenna itself and the later multiple reflections between the antenna and the plate. Turn on the gate and transform back to the frequency domain. While watching the gated $|S_{11}|$, rotate the plate slightly about its vertical axis (adjust it horizontally in the vices) until the signal is maximized; the plate is then perpendicular to the boresight. Save the gated S_{11} . Also save the ungated S_{11} for the same setup (which you can use as an estimate of the antenna return loss).

5. Compute the gain of antenna A versus frequency with the image method (Appendix A.3). Compare it with the results of Sections 1.1 and 1.2 (**Q1.3.3**). Could this method be used to measure the gain of a narrowband antenna, or of an antenna with a very narrow beam (**Q1.3.4**)?

Reminder: Take turns in doing the experiments.

2 Antenna Far-Field Measurements (60 mins)

In this experiment you will measure the radiation patterns of the 4×4 patch array (AUT) at its design frequency $f_0 = 9$ GHz on a make-shift range using the two pedestals. One FieldFox (FieldFox 1) is used as a CW source in Pulse Generator mode and drives the transmit antenna A, which stays fixed. The AUT is the receiving antenna; it is mounted on the motorized rotation stage and connected to a second FieldFox (FieldFox 2) in SA mode. A MATLAB script on the PC rotates the stage in steps, reads the received power from FieldFox 2 at each angle, and saves the pattern. By reciprocity, the receiving pattern of the AUT is identical to its transmitting pattern. The setup is shown in Fig. 3, and the pattern definitions are given in Appendix C.

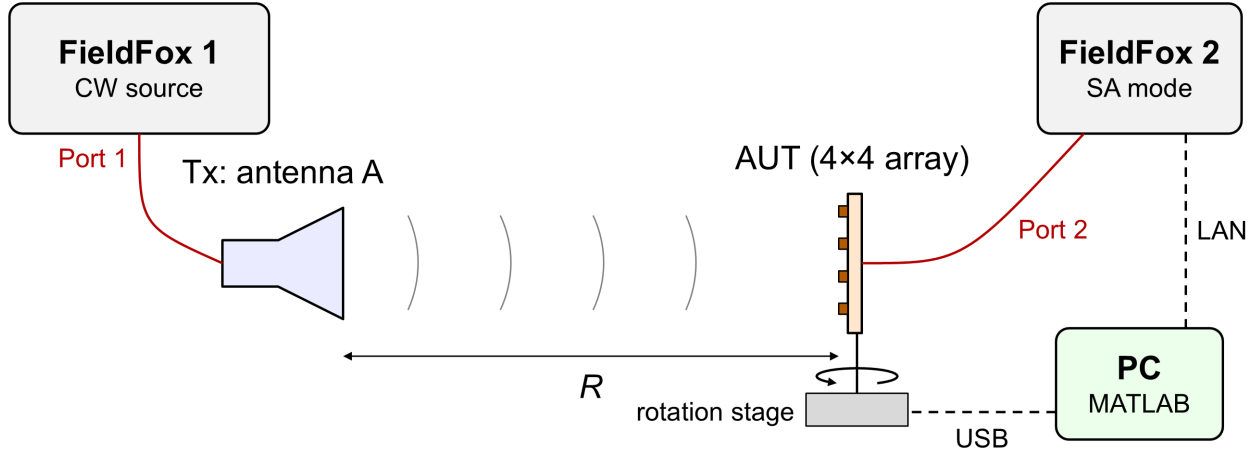


Figure 3: Far-field range: FieldFox 1 provides a CW signal to the fixed transmit horn; the AUT on the rotation stage receives, and FieldFox 2 measures the received power. MATLAB controls the stage over USB and reads FieldFox 2 over LAN.

2.1 Range Setup (20 mins)

1. Download the datasheet of the Eravant SAR-2018-90NF-R3 standard gain horn (SGH) and note its frequency range, its gain at f_0 (from the gain versus frequency curve), and its E- and H-plane half-power beamwidths. Measure the aperture dimensions of the AUT and of the SGH, and compute their far-field distances at f_0 . Choose the range length R accordingly. Typically, this should be at least twice the far-field distance of the SGH. Why (**Q2.1.1**)?
2. Calculate the received power you expect at boresight using the Friis formula, assuming a source power of 0 dBm, the nominal gains of antenna A and the AUT (estimate the AUT gain from its aperture area, assuming that the physical aperture area and the effective aperture area are equal), and the cable losses L_{tx} and L_{rx} of the transmit and receive cables at f_0 , which you measure as $-20 \log_{10} |S_{21}|$ of each cable with the FieldFox in NA mode after a full 2-port calibration with the 85052D kit. Record L_{tx} and L_{rx} ; you will need them in Section 2.3. Compare it with the noise floor of FieldFox 2 for a resolution bandwidth of 1 kHz, and estimate the dynamic range of the link (**Q2.1.2**).
3. Mount the AUT on the rotation stage so that the center of its aperture lies on the rotation axis, and so that its *boresight* is horizontal. Route the cable from the AUT to Port 2 of FieldFox 2 so that it does not flex or get pulled during the rotation. Use the provided SMA

right-angle adapter at the AUT connector. Align the AUT so that its polarization is vertical, adjusting the orientation of the antenna visually. When the motor rotates are you measuring the E-plane or the H-plane (**Q2.1.3**)?

4. Connect the motor controller to the PC using the USB to micro-USB cable. Also, connect the motor DC pins to the DC power supply set to 12 V (1 A current limit). Make sure you have connected the right polarity (red is 12 V and brown is GND). Turn on the DC power supply.
5. Mount antenna A on a fixed bracket on the second platform. Secure the antenna well and make sure its aperture goes beyond the edge of the platform. Position it at a distance R from the AUT, at the same height as the center of the AUT, pointing at the AUT. You can bring the two platforms close to align the antenna centers. Connect it to Port 1 of FieldFox 1. Set up FieldFox 1 in **Pulse Gen** mode with a CW output at 9 GHz and 0 dBm. Place an absorber on the floor between the two antennas.
6. On FieldFox 2, preset and select SA mode. Set the center frequency to 9 GHz, the span to 100 kHz and the RBW to 1 kHz. You should see the CW tone. Turn on a marker with **Peak Search**. Connect FieldFox 2 to the PC with the Ethernet cable, and check its connection in the Keysight Connection Expert software. If the instrument is not listed, add it (see also Appendix E.4):

Add → LAN Instrument → Manually Enter Address

Enter the static IP address of the FieldFox, click **Test This VISA Address**, and then **Add**. Copy the VISA resource string of the instrument (e.g. TCPIP0::192.168.1.1::inst0::INSTR); the MATLAB scripts use it as the VISA address to connect to FieldFox 2.

2.2 Return Loss of the AUT (10 mins)

1. Disconnect the long SMA cable that connects the AUT from FieldFox 2 and connect it to Port 1 of a FieldFox in NA mode. Set the start frequency to 8 GHz, the stop frequency to 10 GHz and the number of points to 401.
2. Disconnect the cable from the AUT and perform a 1-port calibration at the AUT end of the long SMA cable with the 85052D calibration kit. The reference plane is now at the end of the cable.
3. Reconnect the AUT and measure S_{11} in **Log Mag** and **Smith Chart** formats, with nothing in front of the AUT. Save the data and plot $|S_{11}|$ in dB versus frequency. Report the frequency of minimum $|S_{11}|$, the -10 dB impedance bandwidth, and the mismatch loss $-10 \log_{10}(1 - |S_{11}|^2)$ at f_0 (**Q2.2.1**).
4. Reconnect the cable to Port 2 of FieldFox 2 in SA mode.

2.3 E- and H-Plane Co- and Cross-Polarized Patterns (30 mins)

The rotation stage rotates the AUT in the horizontal plane, so every measurement is a horizontal cut through the pattern. To measure the H-plane pattern, the E-field of the AUT must be vertical (perpendicular to the plane of rotation); to measure the E-plane pattern, the E-field of the AUT

must be horizontal (in the plane of rotation). For the co-polarized pattern, the transmit horn must be polarized parallel to the E-field of the AUT; for the cross-polarized pattern it must be rotated by 90° about its boresight. The four measurements are summarized in Table 2.

Measurement	AUT E-field	Antenna A E-field	File name
H-plane, co-pol	vertical	vertical	<code>H_co.csv</code>
H-plane, cross-pol	vertical	horizontal	<code>H_x.csv</code>
E-plane, co-pol	horizontal	horizontal	<code>E_co.csv</code>
E-plane, cross-pol	horizontal	vertical	<code>E_x.csv</code>

Table 2: Orientations of the AUT and of the transmit horn for the four pattern cuts.

1. Identify the polarization of the AUT: the E-field of a microstrip patch is parallel to its resonant length, i.e. along the direction of the microstrip feed into the patch. Mount the AUT with its E-field vertical, and antenna A with its E-field vertical (short side of the waveguide vertical).
2. On the PC, open MATLAB and download the provided scripts. The script `main_pattern_measurement` conducts the full measurement. Manually adjust the motor position using the dial on the motor to maximize the received power at boresight, and set this position as home with `motor_home`. Then proceed with the pattern measurements.
3. Set the sweep from -90° to $+90^\circ$ in steps of 2° and the file name to `H_co.csv`, and run the script. The stage will rotate to each angle, read the peak marker of FieldFox 2, save the data, and return to 0° at the end. Stand away from the range during the measurement.
4. Rotate antenna A by 90° about its boresight (E-field horizontal) and measure the H-plane cross-polarized pattern (`H_x.csv`).
5. Rotate the AUT by 90° about its boresight (E-field horizontal), keeping its aperture center on the rotation axis. Re-find boresight, and measure the E-plane co-polarized (antenna A horizontal) and cross-polarized (antenna A vertical) patterns (`E_co.csv`, `E_x.csv`).
6. Plot the E-plane and H-plane patterns, with the co- and cross-polarized patterns on the same axes, normalized to the co-polarized peak, in both polar and rectangular (dB versus angle) format (**Q2.3.1**). From the co-polarized patterns, report the half-power beamwidth, the first-null positions and the first side lobe level in both planes (**Q2.3.2**). Report the cross-polarization discrimination (XPD, defined in Appendix C) at boresight in both planes. What limits the cross-polarization level you can measure on this range (**Q2.3.3**)?
7. Finally, measure the gain of the AUT directly with the Friis equation. Rotate the AUT back to 0° (boresight) in the co-polarized H-plane orientation (AUT and antenna A both vertical), and record the received power P_r (dBm) with the peak marker of FieldFox 2. Measure the range length R between the apertures. Using the transmit power P_t of FieldFox 1, the cable losses L_{tx} and L_{rx} from Section 2.1, and the gain G_A of antenna A at f_0 from Section 1.1, compute the gain of the AUT (Appendix A.4). Compare it with the aperture estimate of **Q2.1.2**. Estimate the directivity of the AUT from the measured half-power beamwidths (Appendix C), and from the ratio of gain to directivity estimate the efficiency of the array. Is the gain you measured the gain or the realized gain of the AUT? Use the S_{11} from Section 2.2 to convert between the two (**Q2.3.4**).

8. Turn off the RF output of FieldFox 1 and the DC power supply of the motor controller.

Reminder: Take turns in doing the experiments.

3 Antenna Measurements Using the Keysight CATR Chamber (60 mins)

In this experiment you will measure the gain and the radiation pattern of a standard gain horn, the Eravant SAR-2013-282F-E2 (the AUT in this section), in the Keysight Compact Antenna Test Range (CATR). The AUT, the dual-polarized feed horn and all the cables inside the chamber are already installed. The chamber is controlled by the **OTA Chamber Control** software on the chamber control PC, which moves the positioner and controls the FieldFox, which is used as a vector network analyzer to measure the transmission between the AUT and the feed. The CATR principle and the coordinate system of the positioner are described in Appendix D. **The complete connection and software setup procedure is described step by step in Appendix E; read it before you start, and follow it for each step below.**

3.1 Connecting the FieldFox to the Chamber (15 mins)

1. Read Appendix D. Download the datasheet of the Eravant SAR-2013-282F-E2 horn and note its frequency range, gain, E- and H-plane half-power beamwidths and aperture dimensions. Estimate the far-field distance $2D^2/\lambda$ of the AUT at 25 GHz and compare it with the size of the chamber. Explain how the CATR makes it possible to measure the far-field pattern inside the chamber (**Q3.1.1**).
2. Before connecting the FieldFox to the chamber, calibrate it with the two RF cables you will use. Preset the FieldFox and select NA mode. Set the start frequency to 24 GHz, the stop frequency to 26.5 GHz, the number of points to 101 and the IF bandwidth to 300 Hz. Connect the two RF cables to Port 1 and Port 2 and perform a full 2-port calibration at the ends of the cables with the 85052D calibration kit. The reference planes are now at the ends of the cables, so the cables are removed from the measurement. **Do not preset the FieldFox after this step.**
3. Follow Appendix E.1 to connect the calibrated cables to the RF ports on the back panel of the chamber: FieldFox Port 1 to chamber Port 1 (AUT), and FieldFox Port 2 to chamber Port 2 (feed, vertical polarization). Only the vertical port of the feed is used in this experiment.
4. Follow Appendices E.2–E.5 to connect the FieldFox to the chamber control PC over Ethernet, and to configure the FieldFox and the chamber positioner in the OTA Chamber Control software.

3.2 Mechanical Boresight Alignment and Positioning (10 mins)

1. Perform the mechanical boresight alignment (**Mechanical** $\rightarrow$ **Find Home**) as described in Appendix E.6. This takes a few minutes. When it is complete, record the motor offsets reported at the bottom of the window (**Q3.2.1**), and set the current position as the origin (**Set As Origin**).
2. Use the **Direct Move** tab (Appendix E.7) to move the azimuth stage to 30° and the roll stage to 45° , and observe the movement of the positioner through the chamber window. Return all the stages to 0° .

3.3 Measurement Setup and Gain Measurement (10 mins)

The transmission measured between Port 1 and Port 2 includes the loss of the chamber cables, the rotary joint and the feed horn, and the path loss of the range, about 50–55 dB. The chamber was characterized with a reference horn as the AUT, and the calibration files allow the software to remove the total path between the two ports, or parts of it (Appendix E.10). The reference horn is not available in this lab; instead, with **Enable** and **Subtract Horn** both checked, the software removes everything except the gain of the antenna on the positioner, so the measured amplitude is directly the gain of the AUT in dBi.

1. In the **Measurement/Cal** tab, set the measurement type to **PAvT** (phase and amplitude versus time), the source and receiver frequencies both to 25 GHz, the source power to 0 dBm, and the receiver (IF) bandwidth to 300 Hz (Appendix E.8).
2. Load the path loss calibration files for the **Vertical1** path as described in Appendix E.11.
3. In the **System Loss** section, select the **Vertical1** path and **UserTotalPath** as the source, and check **Enable** and **Subtract Horn** (Appendix E.12).
4. In the **Sweep** tab, set up an **Azimuth only** sweep from -30° to $+30^\circ$ in steps of 5° with the roll at 0° , check **Measurement** and **Enable Plotting**, and run it (Appendix E.9). Read the gain of the AUT at 0° azimuth (boresight) and compare it with the datasheet. Note that 25 GHz is slightly below the specified band of the horn. Why is there a small difference between your measurement and the datasheet? Consider, for example, the 2.4 mm-to-2.92 mm adapters on the chamber ports, which are included neither in the FieldFox calibration nor in the chamber calibration files (**Q3.3.1**).

3.4 Principal-Plane Pattern Cuts (10 mins)

The vertically polarized feed measures the field component perpendicular to the horizontal plane of the azimuth cut. To measure the co-polarized pattern in both principal planes with the vertical port only, the feed is rotated together with the AUT using the feed roll axis (Appendix D.1).

1. With the roll and the feed roll at 0° , set up an **Azimuth only** sweep from -90° to $+90^\circ$ in steps of 2° . Run the sweep and save the data (**Save Data**).
2. Use **Direct Move** to set both the roll and the feed roll to 90° , so that the AUT and the feed are both rotated by 90° and remain co-polarized. Repeat the azimuth sweep and save the data. Return the roll and the feed roll to 0° .
3. The E-field of the horn is parallel to the short side of its waveguide. From the orientation of the AUT, identify which of the two cuts is the E-plane and which is the H-plane. Plot both cuts (gain in dBi versus azimuth). Report the half-power beamwidths and side lobe levels, and compare them with the datasheet. Estimate the directivity from the two half-power beamwidths (Appendix C), and compare it with the gain measured in Section 3.3 (**Q3.4.1**).

3.5 2D Radiation Pattern (15 mins)

1. Check that the roll and the feed roll are at 0° , that FieldFox Port 2 is connected to chamber Port 2 (vertical), and that the **Vertical1** path is selected in the system loss correction.

2. In the **Sweep** tab, select the sweep type **Azimuth for each Roll**. Set the azimuth from -90° to $+90^\circ$ in steps of 5° , and the roll from 0° to 150° in steps of 30° . Check **Measurement**, run the sweep, and save the data. Record the duration of the sweep.
3. Convert the azimuth and roll angles to the spherical coordinates (θ, ϕ) of the AUT (Appendix D.1); the saved files also contain the DUT θ and ϕ computed by the software. Make a 2D polar plot of the pattern, with θ as the radial coordinate (0 to 90°), ϕ as the angular coordinate, and the amplitude in dB as the color. In this sweep the feed stays vertical while the AUT rolls, so the vertical port measures E_ϕ of the AUT. Using the Ludwig-3 definitions (Appendix C), explain the shape of the measured 2D pattern, in particular near $\phi = 90^\circ$, and check that the cut at $\phi = 0^\circ$ agrees with the corresponding principal-plane cut of Section 3.4 (**Q3.5.1**).
4. Move all the stages to 0° , disable the measurement, and close the OTA Chamber Control software. Disconnect the FieldFox cables from the chamber back panel, put the protective caps back on the chamber ports, and return the FieldFox to a preset state.

Congratulations! You have completed the lab. Please power down all the instruments, and return all components safely to the box just as you received them. Get checked off by the instructor before you leave.

Appendix

A The Friis Formula and Antenna Gain Measurement Methods

Friis transmission formula. Consider a transmitting antenna with gain G_t and a receiving antenna with gain G_r , separated by a distance R in the far field of each other, aligned on boresight. If the transmitting antenna accepts the power P_t , it produces the power density $S = P_t G_t / (4\pi R^2)$ at the receiving antenna, whose effective area is $A_e = G_r \lambda^2 / (4\pi)$. The received power is therefore

$$\frac{P_r}{P_t} = G_t G_r \left(\frac{\lambda}{4\pi R} \right)^2. \quad (2)$$

The factor $(4\pi R/\lambda)^2$ is the free-space path loss. In general, the right-hand side is also multiplied by the polarization mismatch factor $|\hat{\rho}_t \cdot \hat{\rho}_r^*|^2$, which is 1 for aligned linear polarizations and 0 for orthogonal polarizations.

Gain and realized gain. When the antennas are connected to a calibrated VNA, $|S_{21}|^2$ is the ratio of the power delivered to the matched receiver to the power incident from the source. If the antennas have reflection coefficients Γ_t and Γ_r , only the fraction $(1 - |\Gamma_t|^2)$ of the incident power is accepted by the transmitting antenna, and only the fraction $(1 - |\Gamma_r|^2)$ of the available received power is delivered to the receiver, so that

$$|S_{21}|^2 = (1 - |\Gamma_t|^2) G_t (1 - |\Gamma_r|^2) G_r \left(\frac{\lambda}{4\pi R} \right)^2 = G_t^{\text{re}} G_r^{\text{re}} \left(\frac{\lambda}{4\pi R} \right)^2, \quad (3)$$

where $G^{\text{re}} = (1 - |\Gamma|^2)G$ is the *realized gain*. The methods below measure realized gain; the gain follows by dividing out the mismatch factor measured with S_{11} .

Notation. In dB, Eq. (3) becomes

$$G_1 + G_2 = 20 \log_{10} |S_{21}| + 20 \log_{10} \left(\frac{4\pi R}{\lambda} \right) \equiv M_{12},$$

where the gains are in dBi and M_{12} is the measured transmission corrected for the free-space path loss.

A.1 Three-Antenna Method

With three antennas A, B and C, none of which has a known gain, three transmission measurements at the same distance R give three equations for three unknowns:

$$G_A + G_B = M_{AB}, \quad G_A + G_C = M_{AC}, \quad G_B + G_C = M_{BC}.$$

The solution is

$$\begin{aligned} G_A &= \frac{1}{2} (M_{AB} + M_{AC} - M_{BC}), \\ G_B &= \frac{1}{2} (M_{AB} + M_{BC} - M_{AC}), \\ G_C &= \frac{1}{2} (M_{AC} + M_{BC} - M_{AB}). \end{aligned} \quad (4)$$

The method requires only that all three pairs are in the far field and polarization matched; no antenna needs to be known. It is the method used to calibrate standard gain horns.

A.2 Two Identical Antenna Method

If antennas A and B are identical, $G_A = G_B = G$ and a single measurement is sufficient:

$$G = \frac{1}{2}M_{AB} = 10 \log_{10} |S_{21}| + 10 \log_{10} \left(\frac{4\pi R}{\lambda} \right). \quad (5)$$

If the antennas actually differ by ΔG dB, this formula returns their average, so each gain is in error by $\pm \Delta G/2$.

A.3 Image Method

A perfectly conducting infinite plate at a distance d in front of the antenna creates an image of the antenna at a distance $2d$. The wave reflected by the plate and received by the antenna is equivalent to the transmission between two identical antennas (the antenna and its image) separated by $2d$. Hence, with S_{11}^g the time-gated reflection from the plate,

$$|S_{11}^g| = G \frac{\lambda}{4\pi(2d)} \implies G = \frac{8\pi d}{\lambda} |S_{11}^g|, \quad (6)$$

$$G [\text{dBi}] = 10 \log_{10} |S_{11}^g| + 10 \log_{10} \left(\frac{8\pi d}{\lambda} \right).$$

The antenna must be in the far field of its image ($2d > 2D^2/\lambda$), the plate must be large enough to intercept the main beam over the first few Fresnel zones (a plate much smaller than the beam footprint at distance d underestimates the gain), and the plate must be accurately perpendicular to the boresight. Time gating is needed to separate the plate reflection from the reflection of the antenna itself. The round-trip delay of the plate response relative to the aperture is $\tau = 2d/c$.

A.4 Gain from a Calibrated Friis Link

If the gain G_t of the transmit antenna is known, the gain of the receiving antenna follows from a single received power measurement. Writing the Friis formula in dB, with the transmit power P_t at the source output, the received power P_r at the receiver input, and the losses L_{tx} and L_{rx} (in dB, positive) of the transmit and receive cables,

$$G_{\text{AUT}} [\text{dBi}] = P_r [\text{dBm}] - P_t [\text{dBm}] + L_{\text{tx}} + L_{\text{rx}} + 20 \log_{10} \left(\frac{4\pi R}{\lambda} \right) - G_t [\text{dBi}]. \quad (7)$$

The antennas must be in each other's far field, aligned on boresight and polarization matched. Since the source and receiver are not mismatch-corrected, the result is the realized gain of the AUT (if G_t is also a realized gain); dividing by $1 - |S_{11}|^2$ of the AUT gives its gain. The uncertainty of the result includes the uncertainties of G_t , of the cable losses, of the absolute power accuracy of the source and the receiver, and of R .

B Far-Field Distance

Far-field criterion. An antenna of maximum dimension D illuminated from a source at distance R sees a spherical wavefront. The path length from the source to the edge of the aperture exceeds

the path to the center by approximately $(D/2)^2/(2R) = D^2/(8R)$. The far-field (Fraunhofer) criterion requires this phase error to be smaller than $\pi/8$ (22.5°), i.e. $kD^2/(8R) \leq \pi/8$, which gives

$$R \geq \frac{2D^2}{\lambda}. \quad (8)$$

In addition, $R \gg D$ and $R \gg \lambda$ are required. For two different antennas, a more conservative criterion is $R \geq 2(D_1 + D_2)^2/\lambda$; the criterion $R \geq 2D_1^2/\lambda + 2D_2^2/\lambda$ is often used in practice. If R is too short, the measured gain is lower than the far-field gain.

C Radiation Pattern Definitions

Principal planes. For a linearly polarized antenna, the *E-plane* is the plane containing the boresight direction and the electric field vector, and the *H-plane* is the plane containing the boresight direction and the magnetic field vector. The E- and H-plane patterns are the principal-plane cuts of the radiation pattern.

Co- and cross-polarization. The *co-polarized* pattern is the pattern of the field component parallel to the intended (reference) polarization, and the *cross-polarized* pattern is the pattern of the orthogonal component. According to Ludwig's third definition, which corresponds to the usual measurement practice of rotating the polarization of the probe together with the cut angle ϕ , for an antenna polarized along $\hat{y}$:

$$E_{\text{co}} = E_\theta \sin \phi + E_\phi \cos \phi, \quad E_{\text{cross}} = E_\theta \cos \phi - E_\phi \sin \phi.$$

In the principal planes ($\phi = 0^\circ$ and 90°) these reduce to E_θ and E_ϕ . The *cross-polarization discrimination* (XPD) is the ratio of the co-polarized to the cross-polarized level, usually quoted at boresight.

Pattern parameters.

- **Half-power beamwidth (HPBW):** the angular width of the main beam between the points where the power is 3 dB below the peak.
- **First nulls and first-null beamwidth (FNBW):** the angles of the first minima on either side of the main beam.
- **Side lobe level (SLL):** the level of the highest side lobe relative to the main beam peak, in dB.
- **Directivity estimate:** for a single main beam with half-power beamwidths θ_E and θ_H (in degrees) in the two principal planes, $D \approx 41,253/(\theta_E \theta_H)$ (Kraus), or $D \approx 32,400/(\theta_E \theta_H)$ for patterns with typical side lobes. The radiation efficiency is $e = G/D$.
- **Directivity from a measured pattern:** with the normalized power pattern $P(\theta, \phi)$,

$$D = \frac{4\pi}{\int_0^{2\pi} \int_0^\pi P(\theta, \phi) \sin \theta \, d\theta \, d\phi}.$$

Array factor of a uniform planar array. By pattern multiplication, the pattern of an array of identical elements is the element pattern times the array factor. For a uniform, in-phase $N \times N$ array with element spacing d , the array factor in a principal plane is

$$AF(\theta) = \frac{\sin(N\psi/2)}{N \sin(\psi/2)}, \quad \psi = kd \sin \theta. \quad (9)$$

The nulls occur at $\sin \theta = m\lambda/(Nd)$, $m = 1, 2, \dots$, and the first side lobe of a uniform array is about -11.3 dB for $N = 4$ (-13.3 dB for large N). The element pattern of a patch broadens the E-plane pattern and modifies the side lobe levels.

D The Compact Antenna Test Range

Principle. The far-field distance $2D^2/\lambda$ of electrically large antennas at millimeter-wave frequencies can be several meters to tens of meters, which would require a very large anechoic chamber. A compact antenna test range (CATR) avoids this with an offset parabolic reflector. The feed horn is placed at the focal point of the reflector, so the spherical wave radiated by the feed is converted by the reflector into a plane wave, i.e. the rays leaving the reflector are parallel and in phase over a plane. The region where the field is a good approximation of a plane wave (uniform amplitude and phase within specified limits) is the *quiet zone*; the AUT is placed in the quiet zone, so it is effectively illuminated by a source at infinite distance. The edges of the reflector are rolled or serrated to reduce edge diffraction into the quiet zone. In this chamber the feed is dual polarized (vertical and horizontal ports), and the AUT is mounted on a roll-over-azimuth positioner.

Path loss. Because the wave in the quiet zone is a plane wave, the path loss between the feed port and an antenna in the quiet zone does not follow $(4\pi R/\lambda)^2$ with the physical distance; it is a property of the range (feed, reflector and quiet zone size) that must be measured. This is done once with a reference horn of known gain, which yields the calibration files of Appendix E.10. For this chamber the path loss is in the range of about 50–55 dB.

D.1 Positioner Axes and Coordinate System

The positioner has three motorized axes:

- **Azimuth:** the large turntable at the bottom of the positioner, which rotates the whole positioner about the vertical axis of the chamber.
- **Roll (DUT roll):** the stage on top of the azimuth stage, which rotates the AUT about its own boresight axis. Its range is limited to $\pm 360^\circ$.
- **Feed roll:** rotates the feed horn about its axis; a 90° feed roll interchanges the vertical and horizontal polarizations.

This chamber has a roll stage instead of an elevation stage, so the sweep types that involve elevation are not supported. Azimuth and roll together are sufficient to cover the whole sphere.

Let the boresight of the AUT be its z -axis. A roll angle ϕ_r selects the plane through the boresight that lies in the horizontal plane of the chamber, and the azimuth sweep then rotates the AUT within this plane. An azimuth sweep at roll ϕ_r therefore traces the great-circle cut

$$\theta = |\text{az}|, \quad \phi = \begin{cases} \phi_r, & \text{az} \geq 0 \\ \phi_r + 180^\circ, & \text{az} < 0 \end{cases}$$

(up to the sign conventions of the software, which also reports the DUT θ and ϕ in the saved files). A set of azimuth sweeps from -90° to $+90^\circ$ at roll angles from 0° to 180° therefore covers the front hemisphere.

Since the cut plane is horizontal, the **horizontally polarized** feed measures the field component in the plane of the cut and perpendicular to the direction of propagation, which is E_θ of the AUT; the **vertically polarized** feed measures the component perpendicular to the plane of the cut, which is E_ϕ .

E CATR Connection and Software Setup

This appendix describes the complete procedure to connect the FieldFox to the CATR chamber and to set up the OTA Chamber Control software. The AUT, the feed and all the cables inside the chamber are already installed; only the FieldFox needs to be connected. The positioner is connected to the chamber control PC through a USB serial port (COM port), and the FieldFox is connected to the PC over Ethernet (LAN).

E.1 RF Connections

The RF ports on the back panel of the chamber are connected as listed in Table 3. The FieldFox has only two ports, so only one feed polarization can be measured at a time. To change the polarization, either move the FieldFox Port 2 cable between chamber Port 2 and Port 3 (preferred, since each path has its own calibration file), or rotate the feed by 90° with the feed roll axis.

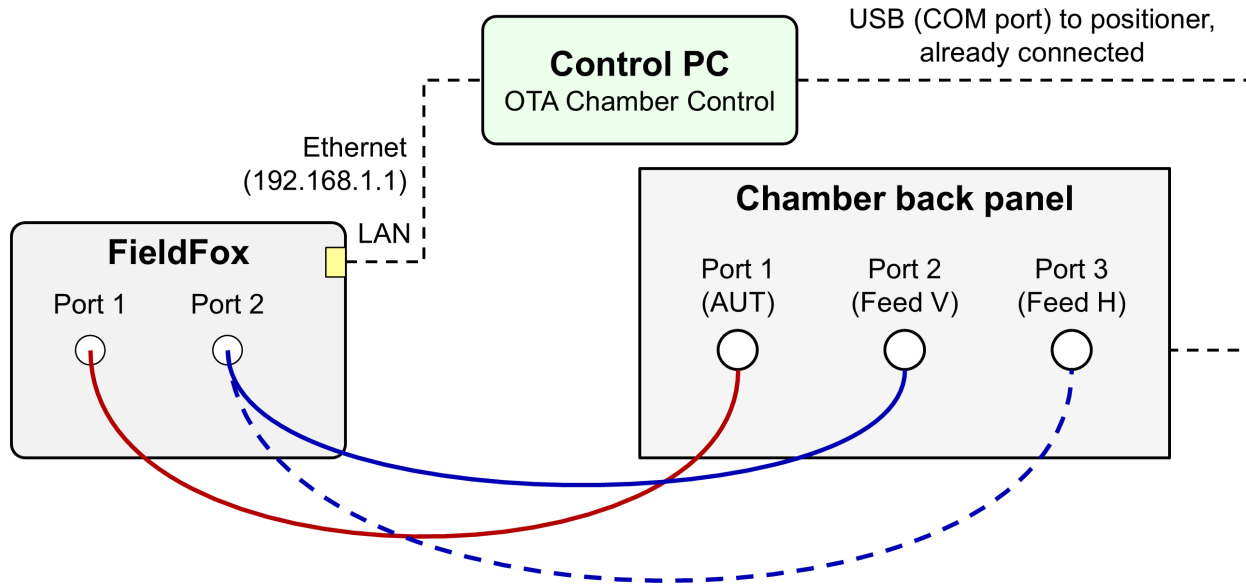
Chamber port	Connected inside the chamber to	Path name	FieldFox port
Port 1	AUT (DUT) on the positioner, through the rotary joint	–	Port 1
Port 2	Feed horn, vertical polarization	Vertical1	Port 2
Port 3	Feed horn, horizontal polarization	Horizontal1	(Port 2)

Table 3: Chamber back-panel RF ports.

1. Make sure that the FieldFox is off and that no measurement is running in the OTA Chamber Control software.
2. Using the dedicated chamber cables, connect FieldFox Port 1 to chamber Port 1 (AUT) and FieldFox Port 2 to chamber Port 2 (feed, vertical). The chamber ports are 2.4 mm connectors fitted with 2.4 mm-to-2.92 mm adapters; connect the SMA cables to these adapters and **do not remove the adapters**. Never mate a 3.5 mm or SMA connector directly to a 2.4 mm connector.
3. Leave the protective cap on chamber Port 3 when it is not in use.

E.2 Connecting the FieldFox over LAN

1. Connect the Ethernet cable between the FieldFox Ethernet port (right panel) and the Ethernet port (or Ethernet-USB adapter) of the chamber control PC. Turn on the FieldFox.
2. On the FieldFox select:



Dashed: alternative connection of Port 2 for horizontal polarization

Figure 4: Connections between the FieldFox, the chamber back panel and the control PC.

System → System Configuration → More → LAN

Read the IP address. If **Obtain IP** is set to **DHCP**, the address cannot be edited: change **Obtain IP** to **Static** first. Set **Static IP Address** to 192.168.1.1 and set **Apply Settings** to **Now**.

3. On the PC, open a terminal and run `ping 192.168.1.1`. If you see a reply, the connection is established.

E.3 Identifying the Positioner COM Port

The positioner is connected to the PC by a USB serial (COM) port, which the software addresses with the VISA resource name `ASRLn`, where n is the COM port number.

1. On the PC, open the **Windows Device Manager** and expand **Ports (COM & LPT)**.
2. Note the COM port to which the chamber positioner is attached. During the setup of this chamber, the positioner was on **COM4**, i.e. the VISA resource `ASRL4`. Two COM ports may be listed; if you are not sure which one is the positioner, ask the instructor.

E.4 Adding the FieldFox in Keysight Connection Expert

1. Open **Keysight Connection Expert** (Keysight IO Libraries Suite).
2. Click **Add** (**Add Instrument**) and select **LAN instrument**.
3. Select **Manually Enter Address** and enter the FieldFox IP address 192.168.1.1.
4. Click **Test This VISA Address**. The test should report that the address is verified.

5. Click **OK** to add the instrument. The FieldFox now appears in the instrument list with a VISA resource string such as `TCPIP0::192.168.1.1::inst0::INSTR`. Copy this resource string.

E.5 Equipment Setup in OTA Chamber Control

1. Open the **OTA Chamber Control** software and go to **Setup** → **Equipment Selection**.
2. For the Chamber/Positioner, select **CATR Positioner 2.xRo/Az** and in **Address** enter (**ASRL4**).
3. For the Test Equipment, select the FieldFox and paste the VISA resource string copied from **Connection Expert**. Click **OK**.
4. The software now connects to the positioner and to the FieldFox.

E.6 Mechanical Boresight Alignment (Find Home)

1. Open the **Boresight** tab and click **Mechanical** → **Find Home**. Look inside the chamber.
2. The positioner searches for its mechanical home (zero) position, at which the AUT points directly at the reflector and the roll is at zero. The azimuth, roll and feed roll stages will all move. This takes a few minutes. The cable joint on the roll stage is designed to move; this is normal.
3. When the search is complete, the status bar at the bottom of the window shows **Found mechanical boresight**, together with the motor offsets (e.g. for azimuth and roll), i.e. the difference between the position before the search and the mechanical home.
4. The origin of the user coordinate system is not necessarily the mechanical home. Set the current (mechanical home) position as the origin by clicking **Set As Origin**.

E.7 Direct Moves

1. Open the **Direct Move** tab. The relevant axes are **Theta (Azimuth)**, **Phi (Roll)** and **Feed Roll**.
2. To test the positioner, enter a couple of target angles and click **Move**. Pressing **Enter** alone does not move the positioner.
3. The roll stage can only go from -360° to $+360^\circ$. The rotary joint protects the RF path, but the roll motor is not designed for continuous rotation, even if the software accepts larger angles.
4. A 90° feed roll changes the polarization of the feed.
5. Use **Go to Zero** to return all the axes to the origin.

E.8 Measurement Settings

In the **Measurement/Cal** tab, set the VNA settings:

- **Measurement type:** **PAvT** (phase and amplitude versus time). The alternative **Power** measures amplitude only.

- **Receiver frequency** and **source frequency**: set both to the same value, 25 GHz (they differ only for frequency-converting devices, e.g. mixers).
- **Source power level**: as high as supported at the measurement frequency (about 0 dBm for the FieldFox).
- **Receiver bandwidth**: the IF bandwidth of the measurement. A lower bandwidth gives a lower noise floor (more dynamic range) but makes each measurement slower.
- Check that the output (source) port of the instrument is Port 1 and the input (receiver) port is Port 2, i.e. the software measures S_{21} from the AUT to the feed.

The software measures only the transmission (S_{21}) at each position; it does not record S_{11} or S_{22} . These can be measured by controlling the chamber and the FieldFox directly over SCPI but we will not do this for this lab (Appendix E.13).

E.9 Sweep Settings and Saving Data

1. Open the **Sweep** tab in the **Positioner Movement** tab.
2. **Sweep mode: Start/Stop/Step**. The positioner stops at every angle and the instrument takes a measurement. (A faster **Continuous** mode exists for some instruments, such as the PNA-X, but is not available with the FieldFox.)
3. **Sweep type: Azimuth only, Roll only, Azimuth for each Roll or Roll for each Azimuth**. In **Azimuth for each Roll**, azimuth is the inner loop: a complete azimuth sweep is made at each roll angle. The sweep types involving elevation are not supported by this chamber.
4. Enter the start, stop and step angles of each swept axis. For example, start -30° , stop 30° , step 5° gives 13 points.
5. Check **Measurement** to take measurements during the sweep. With **Measurement** unchecked, the positioner moves through the sweep without measuring, which is useful to check the motion.
6. Check **Enable Plotting** to plot the results during the sweep.
7. Click **Run**. The sweep time is proportional to the number of points; sweeps with a step of 1° or less take much longer.
8. Save the results with **Save Data**. The file contains the amplitude (dB) and phase (degrees), the azimuth and roll angles, and the corresponding DUT ϕ and θ coordinates.

E.10 Calibration Files

The chamber was characterized at installation, and the calibration data are stored in the folder **Calibration Data** on the control PC. There is one set of files for each feed path (horizontal and vertical). The files are listed in Table 4. All the quantities are transmission (gain) versus frequency in dB.

The over-the-air path loss between the quiet zone and the feed port is obtained by removing the horn and the DUT cable from the total path, $L = T - H - C$. Since L still contains the rotary joint, the rotary joint must additionally be removed in post-processing, $L' = L - J$, if it is needed.

File (one per path, H and V)	What it contains	Used by software
User total path, $T(f)$	Everything from chamber Port 1 to Port 2 (V) or Port 3 (H), measured with the reference horn as the AUT: DUT cable, rotary joint, reference horn, range path loss, feed and feed cables	Yes
DUT horn, $H(f)$	Gain of the reference horn only	Yes
DUT cable, $C(f)$	From chamber Port 1 to the end of the DUT cable, starting before the rotary joint (does not include the horn)	Yes
Rotary joint, $J(f)$	Insertion loss of the rotary joint (measured manually, not in the software file format)	No (post-processing)
Horizontal / vertical path loss, $L(f)$	Over-the-air path loss: $L = T - H - C$; not corrected for the rotary joint; about 50–55 dB	No (reference)

Table 4: Chamber calibration files. T , H , C , J and L are in dB.

E.11 Loading the Calibration Files

1. In OTA Chamber Control, open the **Calibration** menu at the top and select **Path Loss Correction**.
2. Select the path **Horizontal1**. For each user data entry (**User Total Path**, **DUT Horn**, **DUT Cable**), click **Load From File** and select the corresponding horizontal file from the **Calibration Data** folder.
3. Select the path **Vertical1** and repeat with the vertical files.
4. Do not load the rotary joint file; it is not in the format expected by the software.
5. Click **Close**.

E.12 System Loss Correction

In the **Measurement/Cal** tab, the **System Loss** section selects how the measured data are corrected:

- **Path and Source:** select the feed path (**Vertical1** or **Horizontal1**, matching the chamber port connected to the FieldFox Port 2, see Fig. 4) and the source of the correction data (**UserTotalPath**). Never use the factory correction.
- **Enable:** subtracts the total path T from the measurement. With the reference horn as the AUT, the corrected boresight reading is therefore close to 0 dB.
- **Subtract Horn:** subtracts the horn correction H from the total correction, i.e. adds the horn gain back into the measurement. With **Enable** and **Subtract Horn** checked, the measurement is $M - (T - H)$: since both M and T contain the DUT cable, the rotary joint, the range path loss and the feed, only the gain of the AUT remains, i.e. the absolute gain (in dBi) of the AUT.

- **Subtract Cable:** subtracts the DUT cable correction C from the total correction, i.e. adds the cable loss back into the measurement.

Subtract Horn and Subtract Cable only have an effect when **Enable** is checked. With only **Enable** checked, the measurement is the gain of the AUT relative to the reference horn used to characterize the chamber (the reference horn itself would read 0 dB); the reference horn is not available in this lab.

E.13 SCPI Remote Control

The OTA Chamber Control software has a SCPI interface, which can be used to control the positioner and run sweeps from your own Python code, in parallel with direct SCPI control of the FieldFox. The software must be running.

1. In Keysight Connection Expert, click **Add** and select **LAN instrument**, then **Manually Enter Address**.
2. Enter the address 127.0.0.1 (the PC itself). Change the connection protocol from the default **Instrument (VXI-11, inst0)** to **HiSLIP**. Change the HiSLIP device name from **hislip0** to **hislip200**.
3. Click **Test This VISA Address**, then add the instrument. The chamber is now available at the VISA address

TCPIP0::127.0.0.1::hislip200::INSTR

(equivalently TCPIP0::localhost::hislip200::INSTR), and responds to *IDN?.

The move and sweep commands are non-blocking: they return immediately. To wait for a move or sweep to finish, poll the operation condition register with **STAT:OPER:COND?**; bit value 4 is set while the positioner is moving, and bit value 16 while a sweep is running. Some useful commands are listed in Table 5. A minimal Python example (using pyvisa):

```
import time, pyvisa
rm = pyvisa.ResourceManager()
ch = rm.open_resource("TCPIP0::localhost::hislip200::INSTR")
ch.timeout = 200000
ch.write_termination = ch.read_termination = "\n"
print(ch.query("*IDN?"))

def wait(bitmask):
    # 4 = moving, 16 = sweeping
    while int(ch.query("STAT:OPER:COND?")) & bitmask:
        time.sleep(0.25)

ch.write("POS:MOVE:AZIM 30;ROLL 0"); ch.write("POS:MOVE:INIT"); wait(4)
ch.write("POS:SWE:AZIM:STAR -60;STOP 60;STEP 5")
ch.write("POS:SWE:TYPE AZIM"); ch.write("MEAS:TYPE PAVT")
ch.write("MEAS:ENAB 1"); ch.write("POS:SWE:INIT"); wait(16)
az = [float(x) for x in ch.query("FETC:AZIM?").split(",")]
pwr = [float(x) for x in ch.query("FETC:POW?").split(",")]
print(ch.query("SYST:ERR?"))
```

Command	Function
*IDN?, POS:IDN?	Identify the software and the positioner
SYST:ERR?	Read the next error
POS:BOR:INIT	Mechanical boresight alignment (find home)
POS:ZERO:RES, POS:ZERO:GOTO	Set current position as zero; go to zero
POS:MOVE:AZIM <a>; ROLL <a>; ROLL:FEED <a>	Set direct-move targets (degrees)
POS:MOVE:INIT	Start the direct move
POS:Curr:MOT?	Current azimuth, roll
POS:SWE:TYPE AZIM ROLL AZR ROAZ	Sweep type (AZR: azimuth for each roll)
POS:SWE:AZIM:STAR STOP STEP <a>	Azimuth sweep start/stop/step
POS:SWE:ROLL:STAR STOP STEP <a>	Roll sweep start/stop/step
POS:SWE:INIT, POS:SWE:ABOR	Start / abort a sweep
MEAS:TYPE PAVT, MEAS:ENAB 1	Measurement type; enable measurement
SOUR:FREQ <f>, SOUR:POW <p>, SENS:BAND 	Source frequency, power; IF bandwidth
SENS:CORR:SYST:ENAB SHOR SCAB <0 1>	Enable correction; subtract horn; subtract cable
STAT:OPER:COND?	Operation status (4 = moving, 16 = sweeping)
FETC:AZIM?, FETC:ROLL?	Angles of the last sweep
FETC:DUT:THET?, FETC:DUT:PHI?	DUT coordinates of the last sweep
FETC:POW?, FETC:PHAS?	Measured amplitude (dB) and phase (degrees)

Table 5: Selected SCPI commands of the OTA Chamber Control software (see the OTA Chamber Control SCPI Manual for the complete list).