浙江大學
ZHEJIANG UNIVERSITY

ACCM 12
Hangzhou, China 25–28 April, 2023
12th Asian–Australasian Conference on Composite Materials

Modern free-space facility for testing microwave scattering properties of composite materials

Institute for Composites Science Innovation (InCSI), School of Materials Science & Engineering, Zhejiang University, 38 Zheda Road, Hangzhou, 310027, PR China

功能复合材料与结构研究所
Institute for Composites Science Innovation

Contributors to the project

Zhejiang University, China

- Dr. Dmitriy Makhnovskiy (project architect, microwave design, automation)
- Dr. Huan Wang (composite materials)
- Dr. Azim Uddin (technical assistance)
- Dr. Diana Estevez (technical assistance)
- Mengyue Peng (technical assistance)
- Prof. Faxiang Qin (research supervisor)

University of St. Andrews, Scotland

- Dr. Yujie Zhao (CAD design)

Lisi Aerospace, England

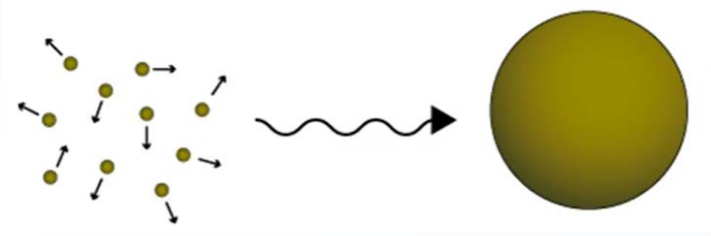
- Konstantin Gorbatov (Node Red GUI, Kollmorgen robotics)

Outline of project

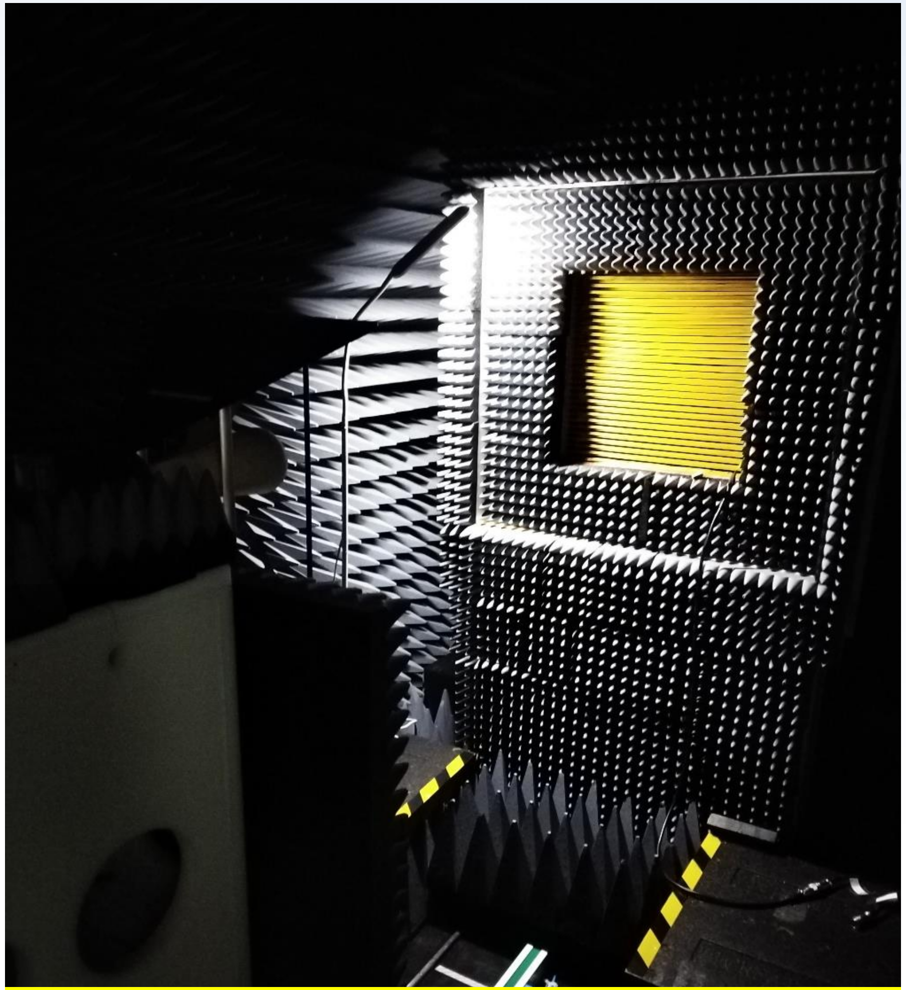
- From microscopic to macroscopic EM properties
- Hybrid approach in modelling microwave scattering properties
- Bench measurements of EM properties of inclusions under external stimuli
- Free space measurements of composites under external stimuli
- Technical aspects of building microwave facilities for material measurements

From microscopic to macroscopic electromagnetic properties

Bench measurements under external stimuli: magnetic field, tensile stress, and heating



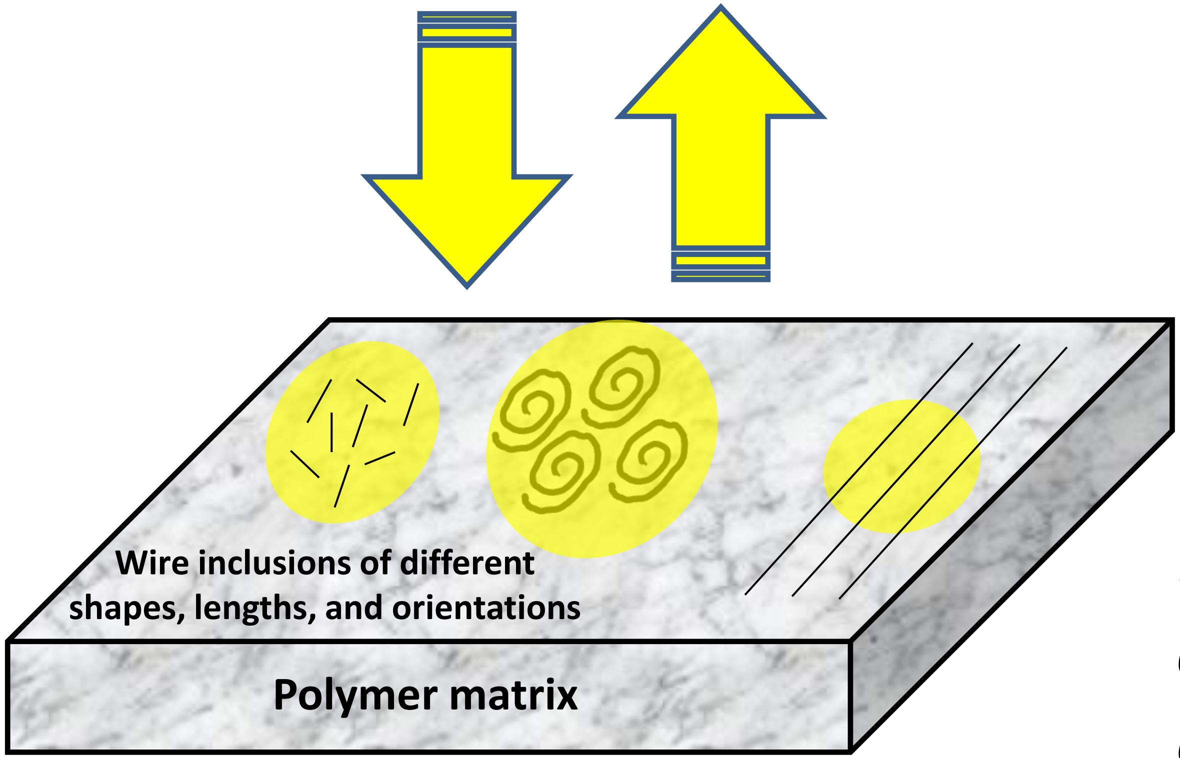
Fabrication of 2D/3D composite structures



Free space measurements under external stimuli: magnetic field, tensile stress, and heating

Hybrid approach in modeling microwave response of wire-filled composites

Microwave response measurement and simulation (CST studio or other solvers) with **the impedance boundary condition on the wire surface**



$\bar{E}_x = \varsigma_{xx}\bar{H}_\varphi$ - impedance boundary condition

$$\varsigma_{xx}^{\mathrm{SI}}[\Omega/\mathrm{sq}] = Z[\Omega] \times \frac{2\pi a}{l}$$

Experimentally measured impedance

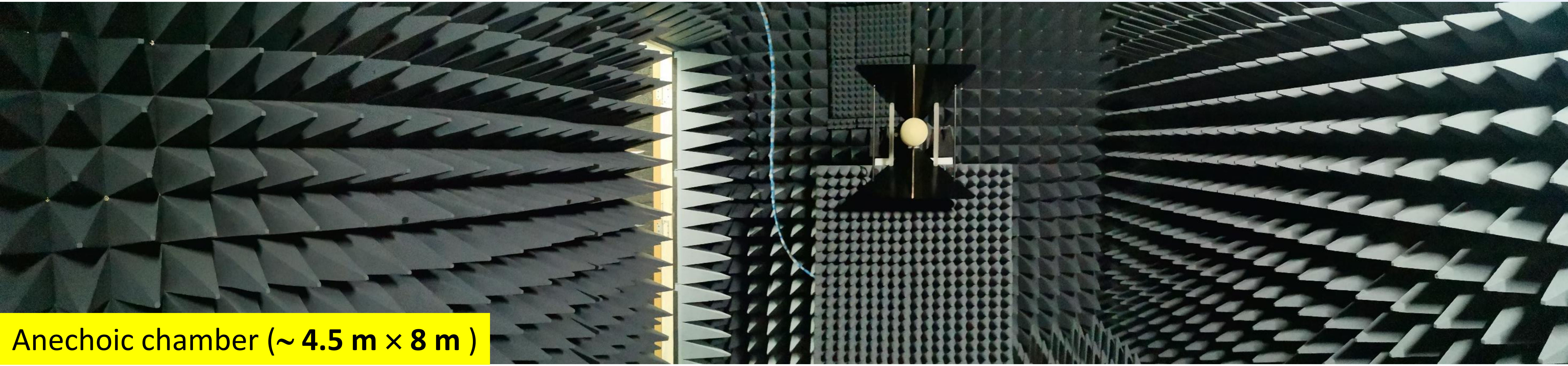
$$\varsigma_{xx}^{\mathrm{cgs}}[(\mathrm{s/cm})/\mathrm{sq}] = Z[\Omega] \times \frac{10^9 a}{2lc}$$

l – wire length on the PCB cell

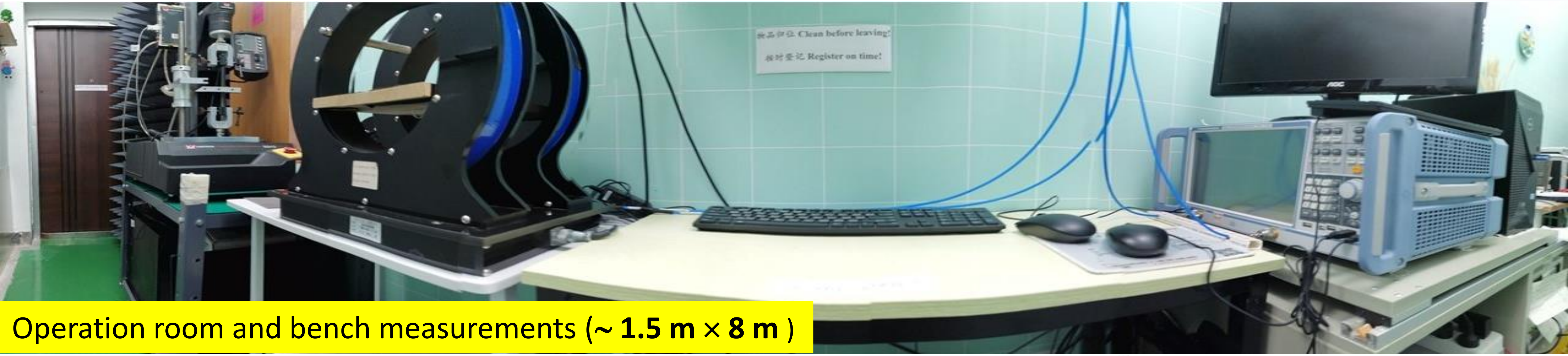
a – wire radius (same units as l)

c – speed of light (cm/s)

Room partitioning

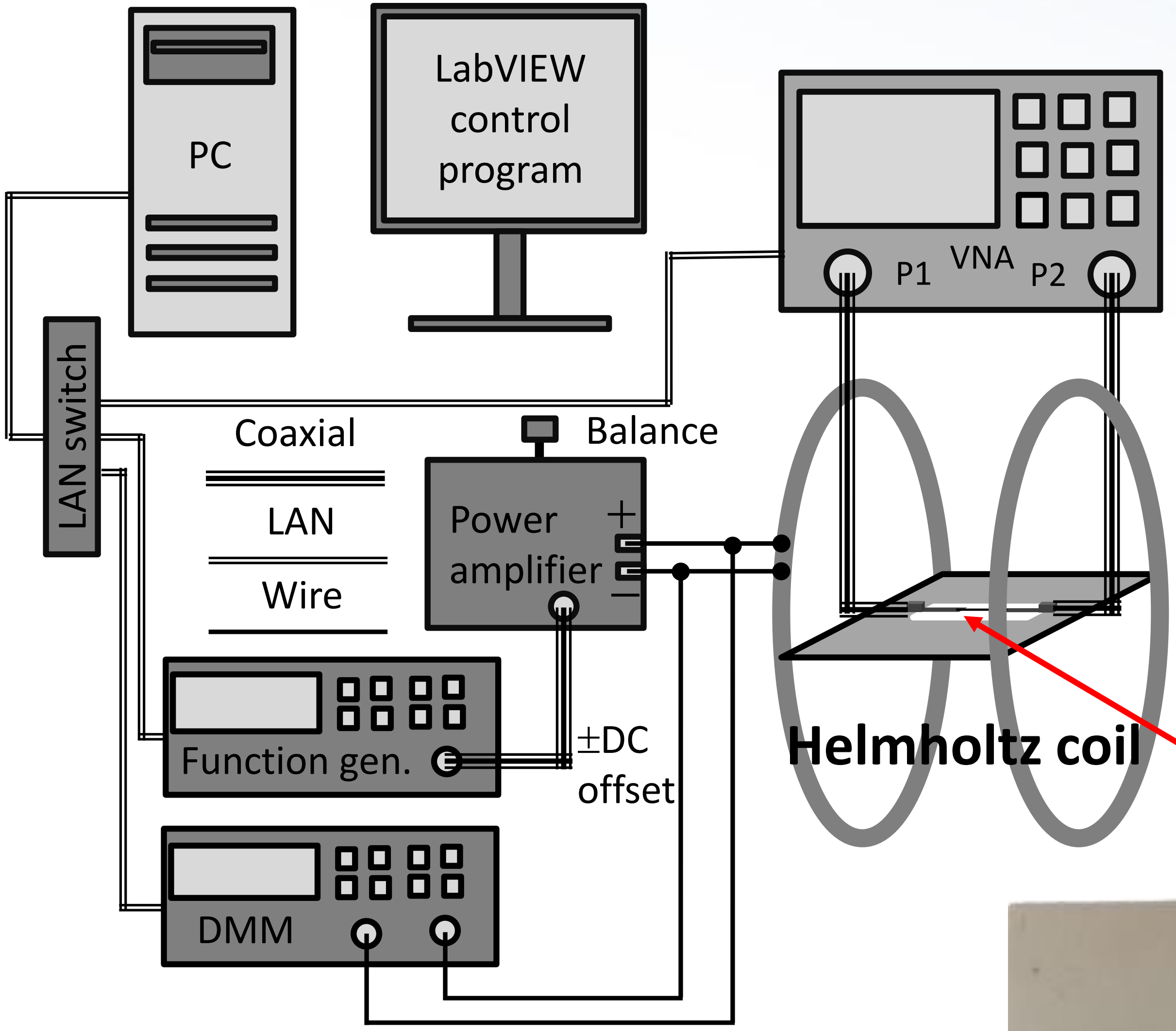


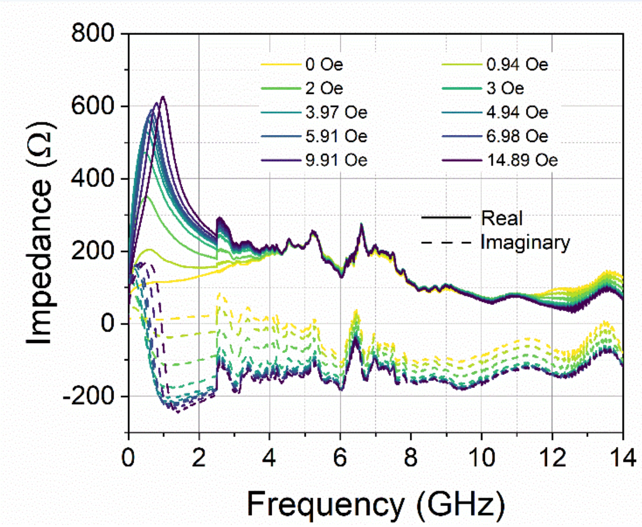
Anechoic chamber (~ **4.5 m × 8 m**)

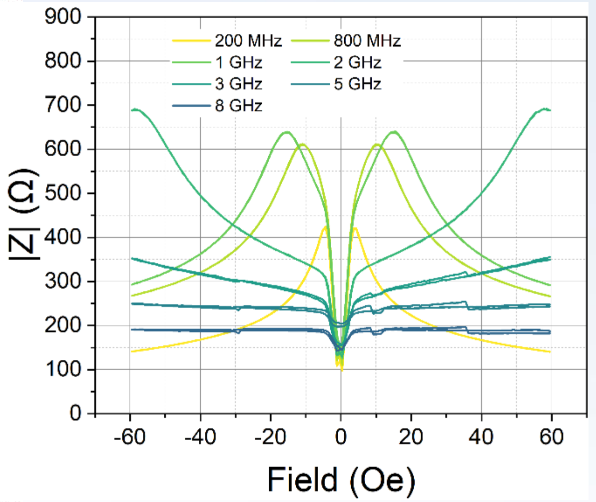


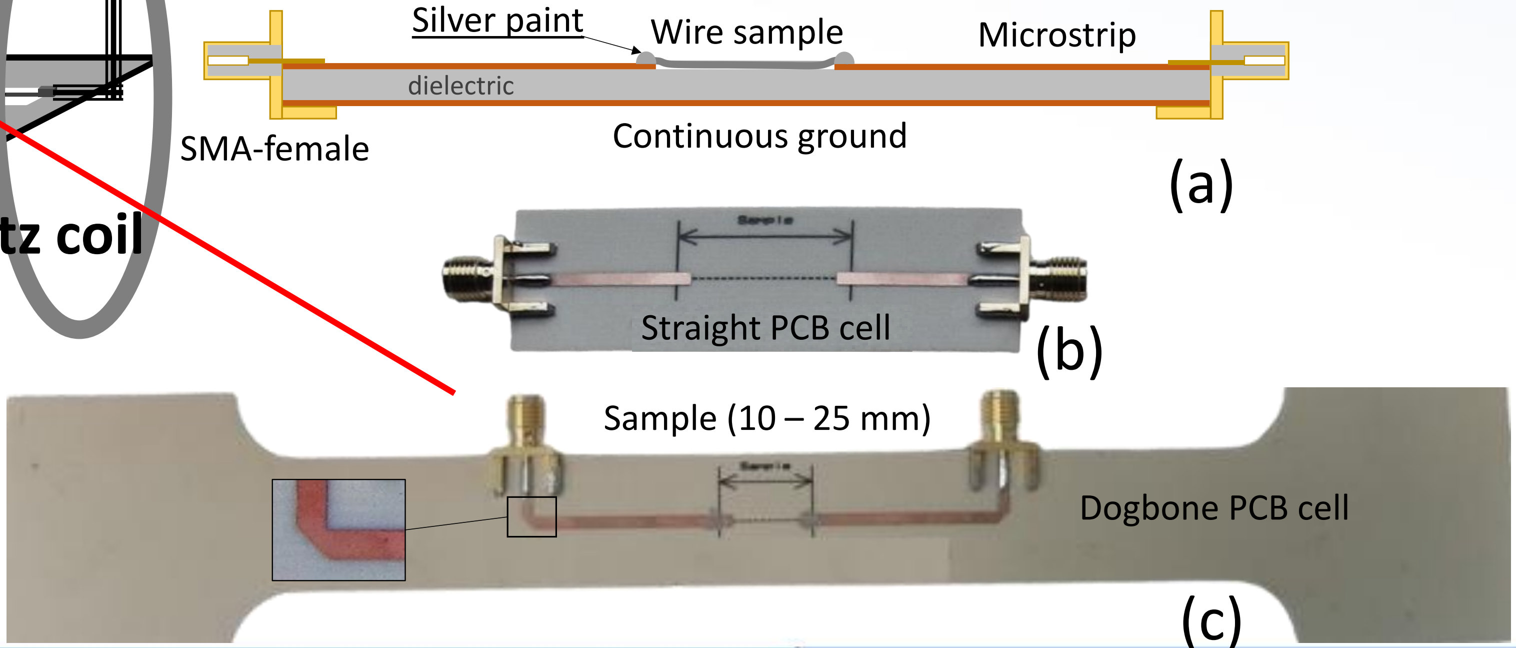
Operation room and bench measurements (~ **1.5 m × 8 m**)

Bench measurements of the wire impedance: magnetic field



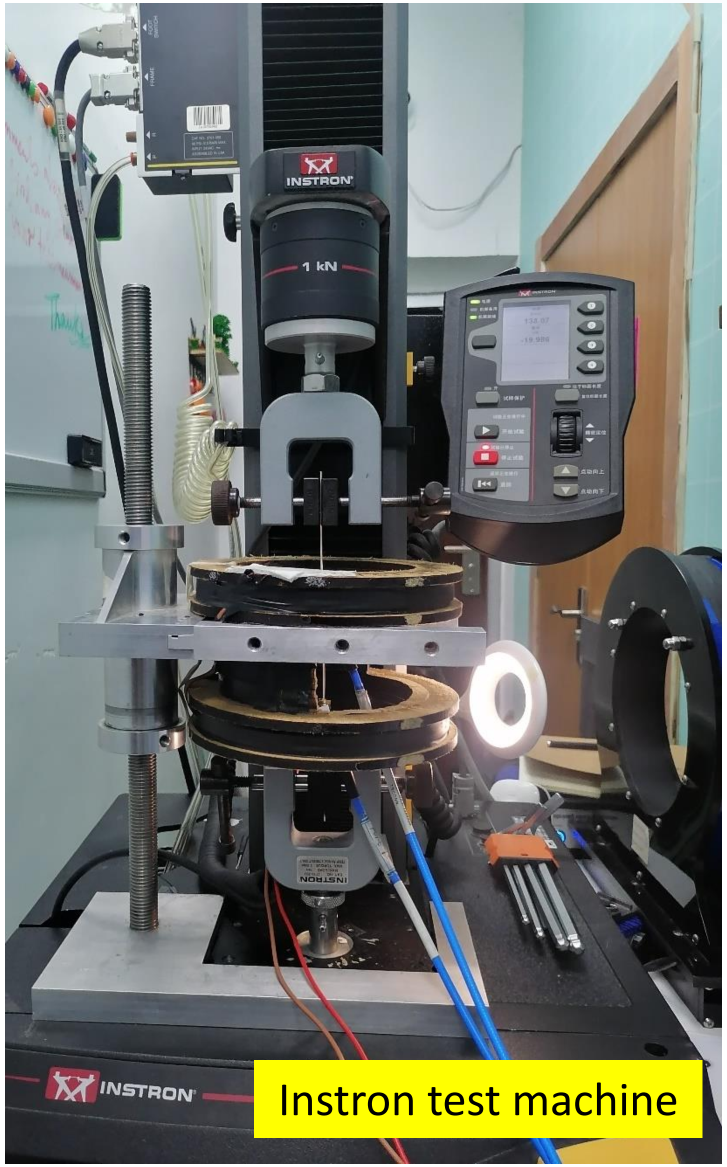


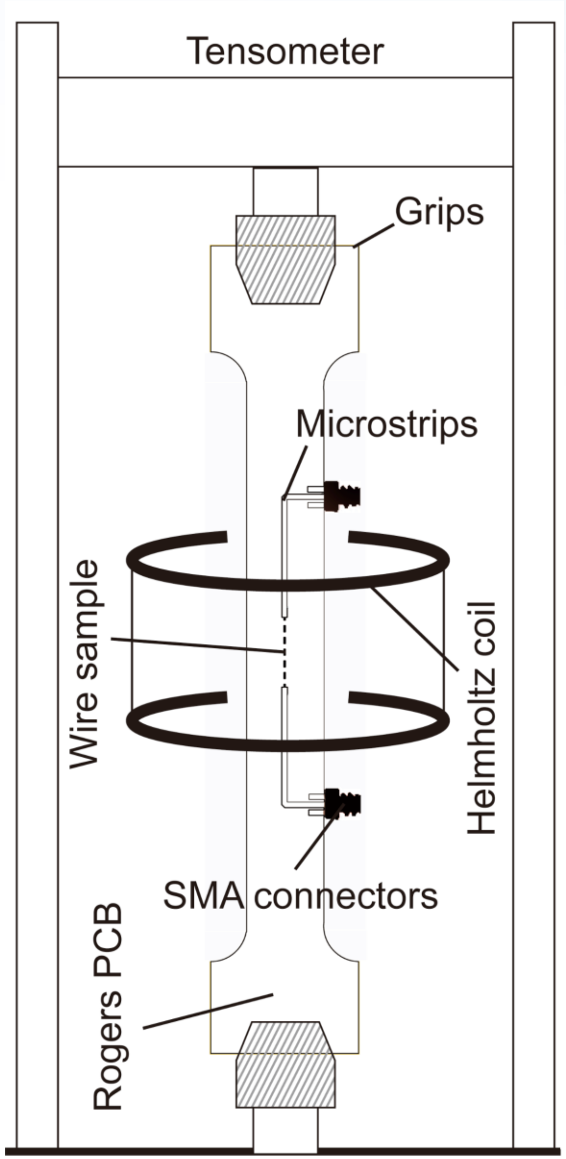




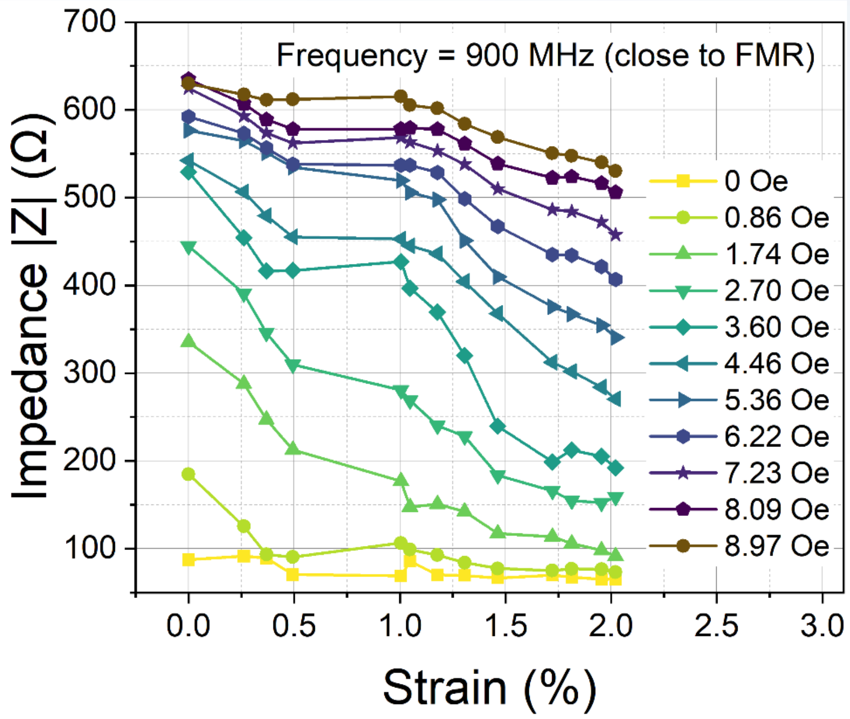
Broadband Measurements of the Surface Impedance

Bench measurements of the wire impedance: tensile stress

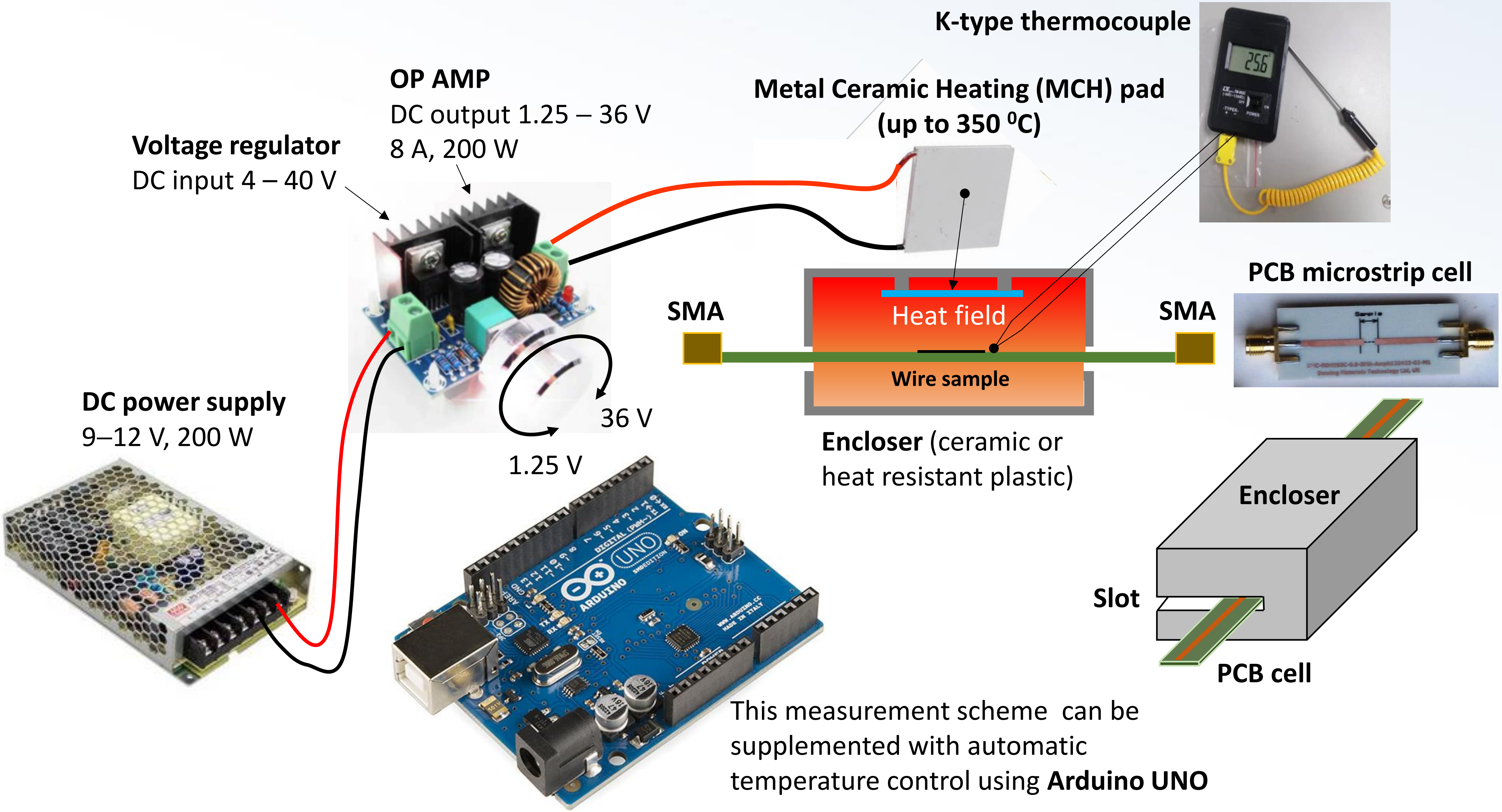




Dogbone PCB
measurement cell

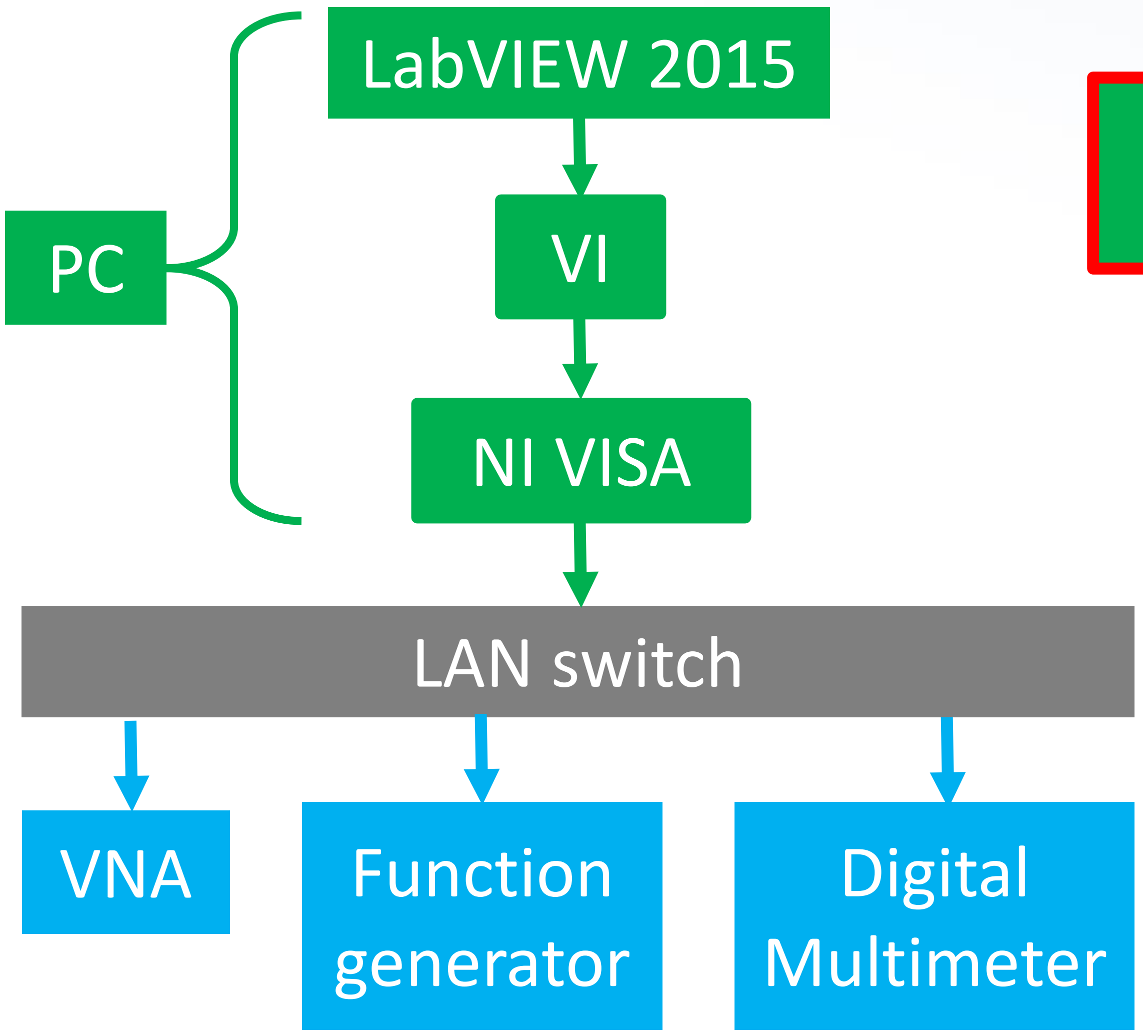


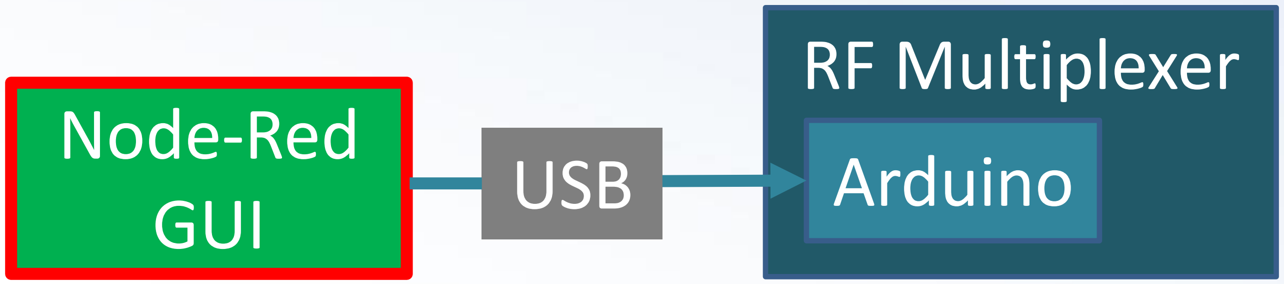
Bench measurements of wire impedance: heating



This measurement scheme can be supplemented with automatic temperature control using **Arduino UNO**

Instrument control for bench measurements



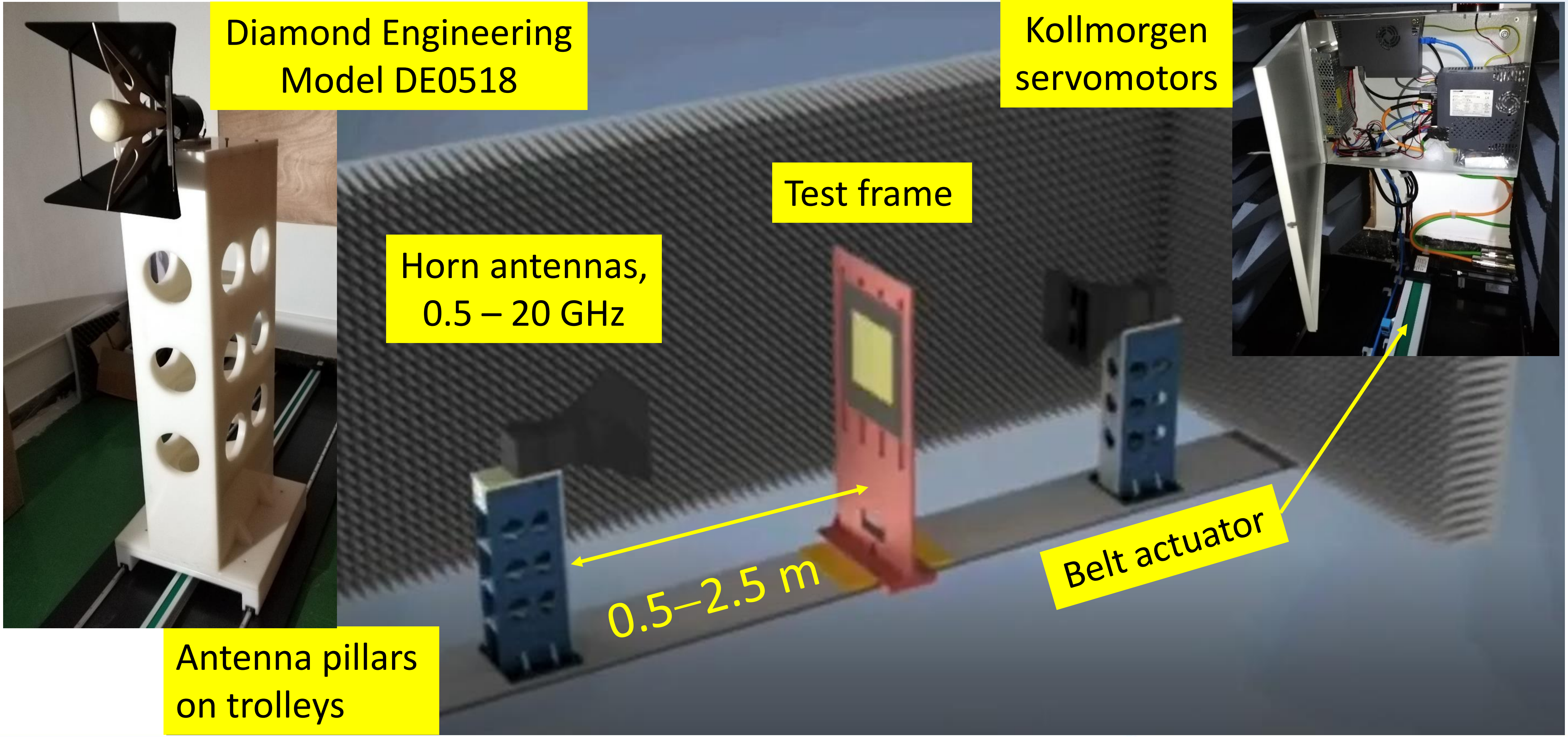


VI – Virtual Instruments are the basic building blocks of LabVIEW programs

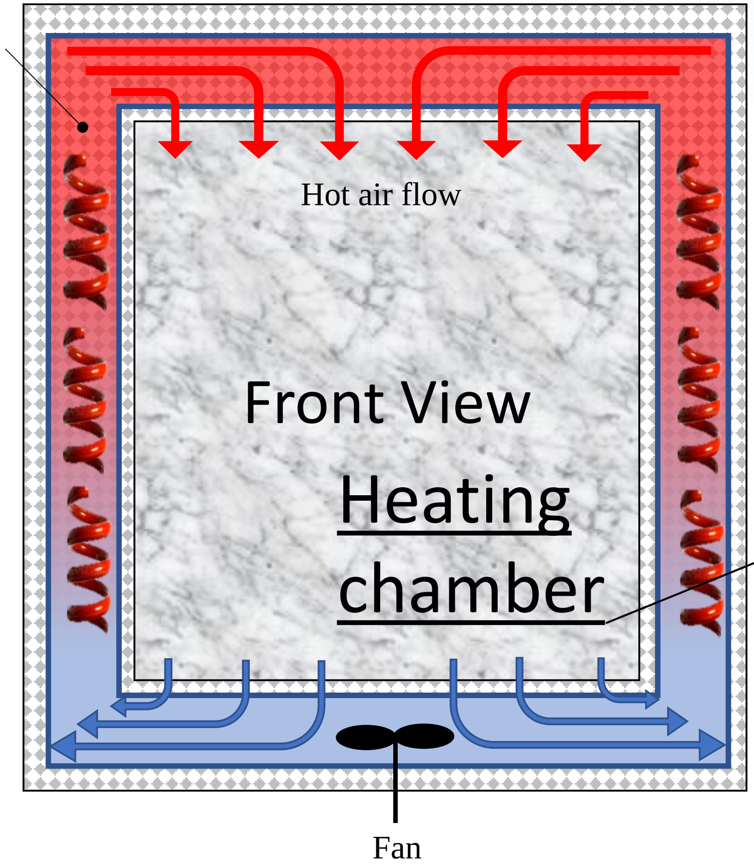
NI VISA – National Instrument VISA

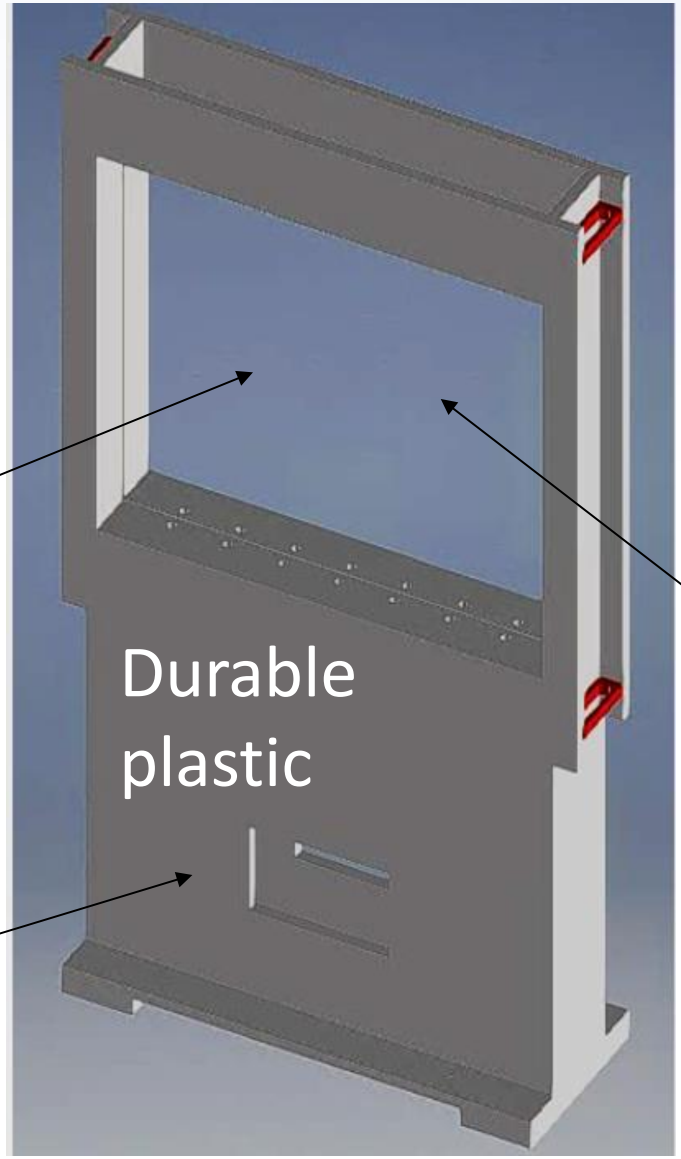
VISA – Virtual Instrument Software Architecture

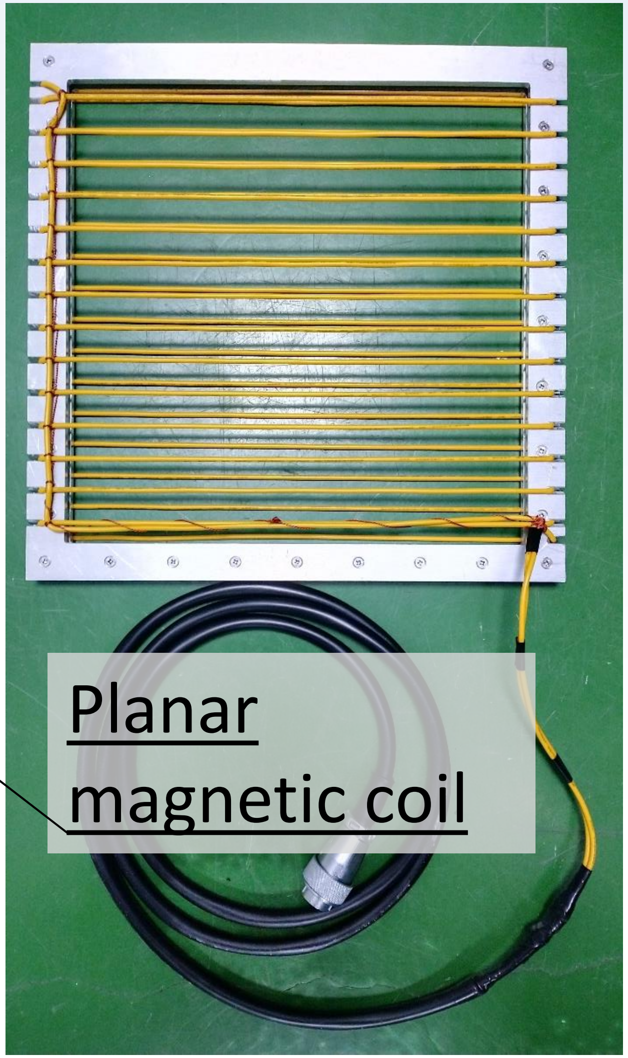
Anechoic chamber



Universal test frame for mounting samples and providing external stimuli

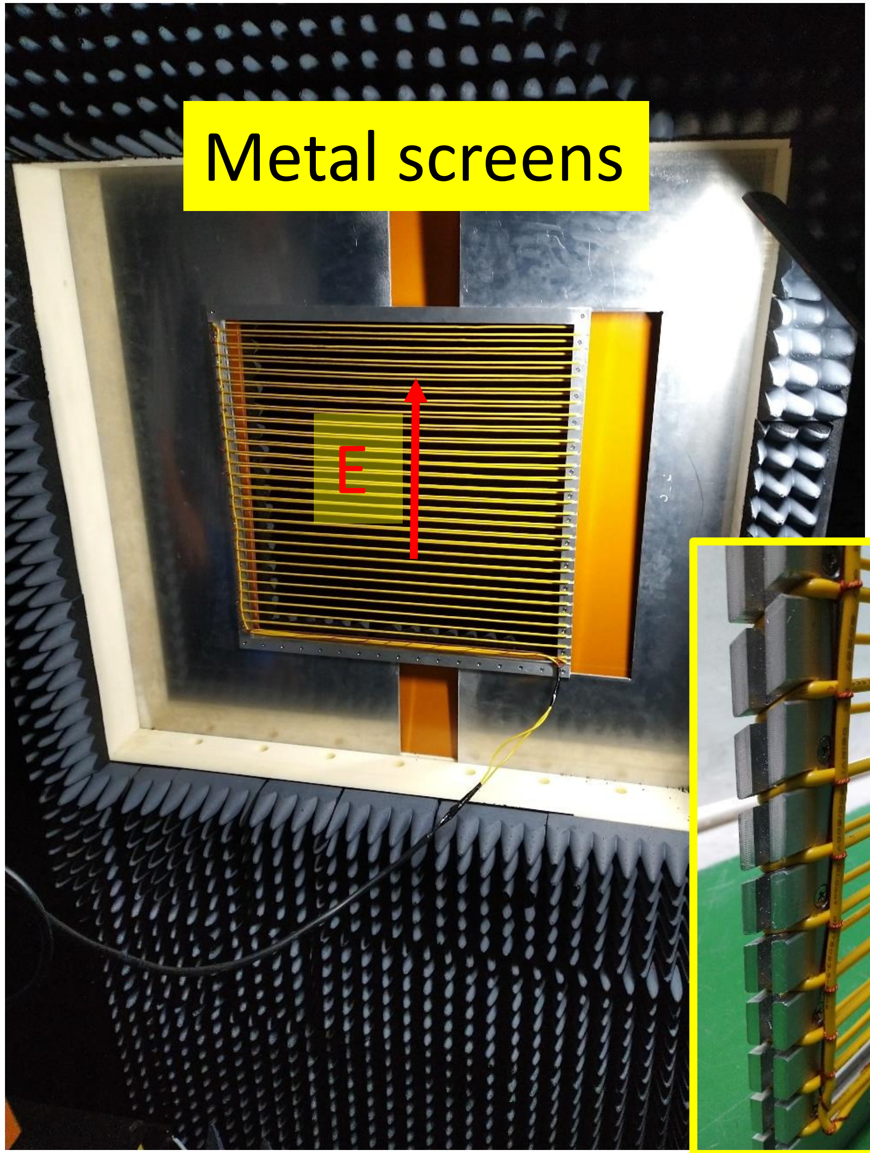




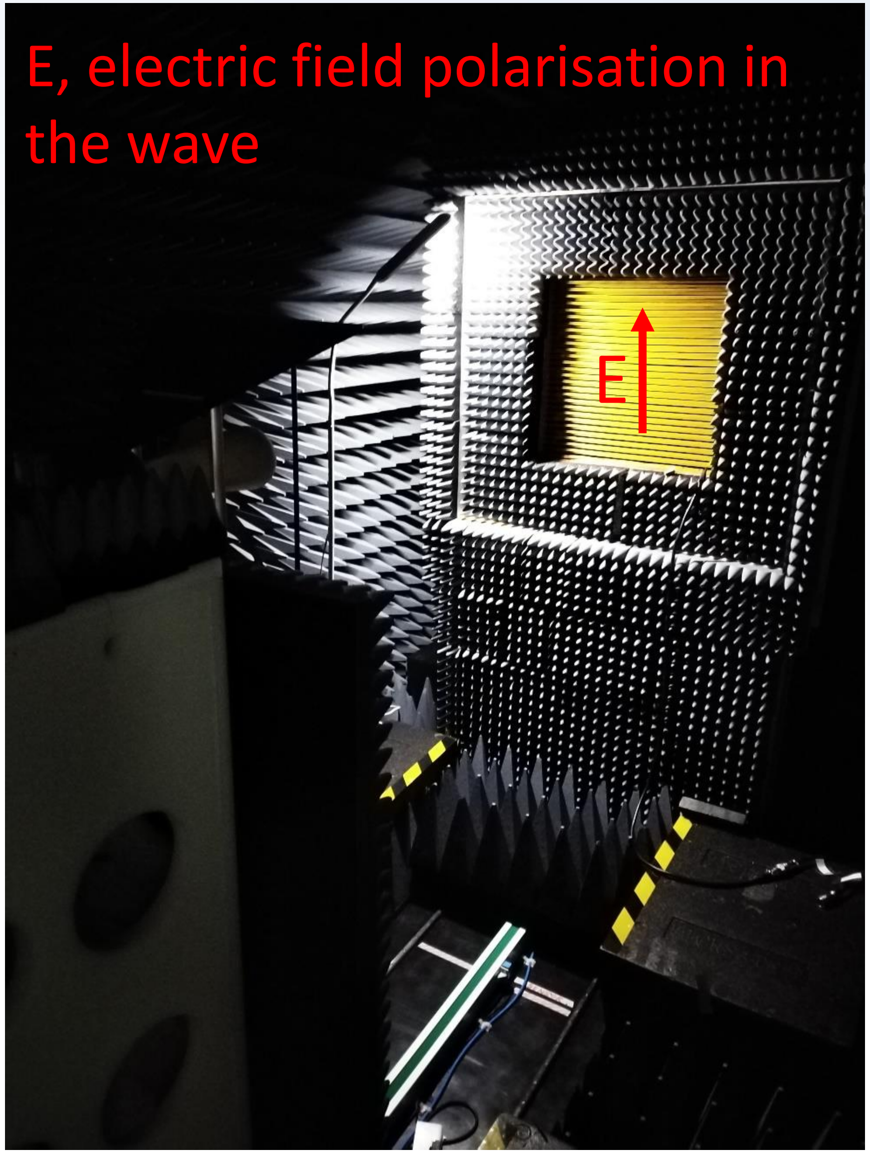


Cavity for a stretching mechanism

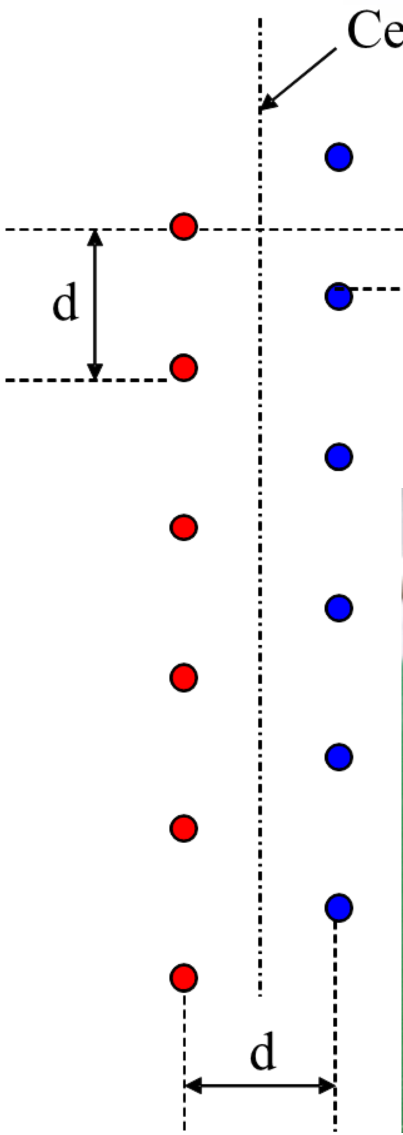
Test frame: measurements with magnetic field

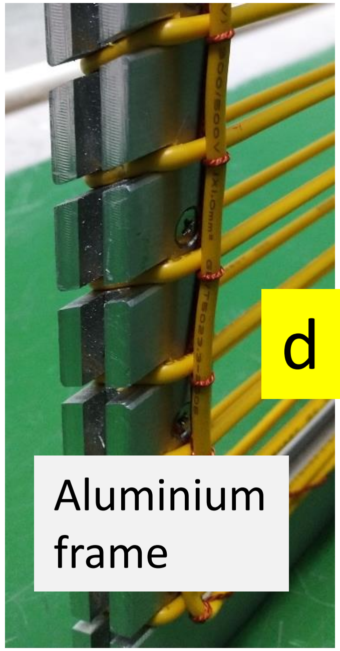


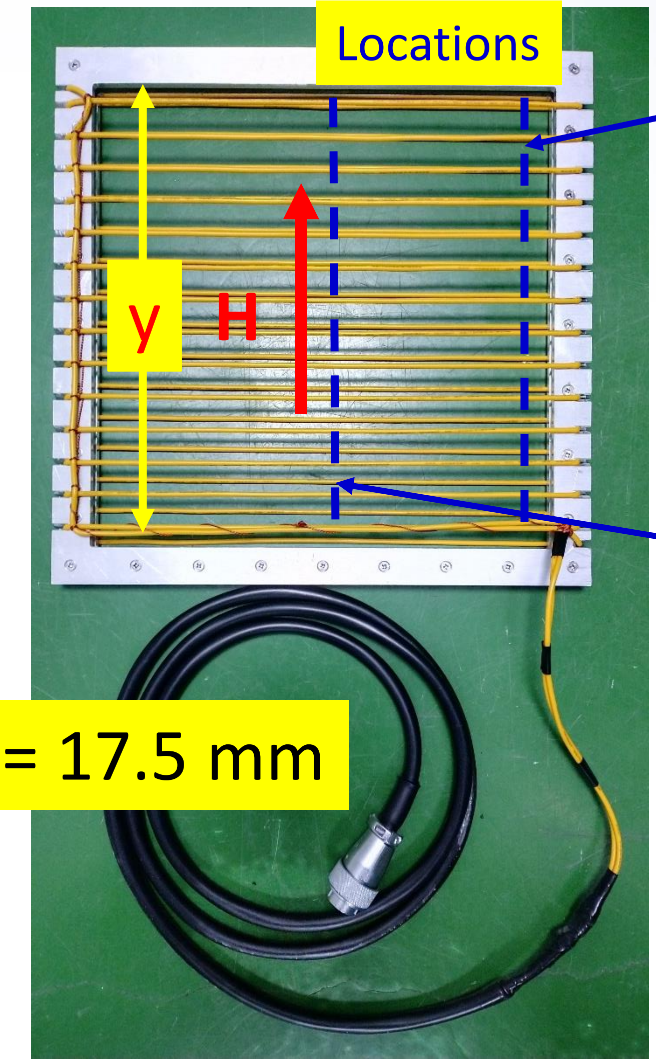
Planar magnetic coil

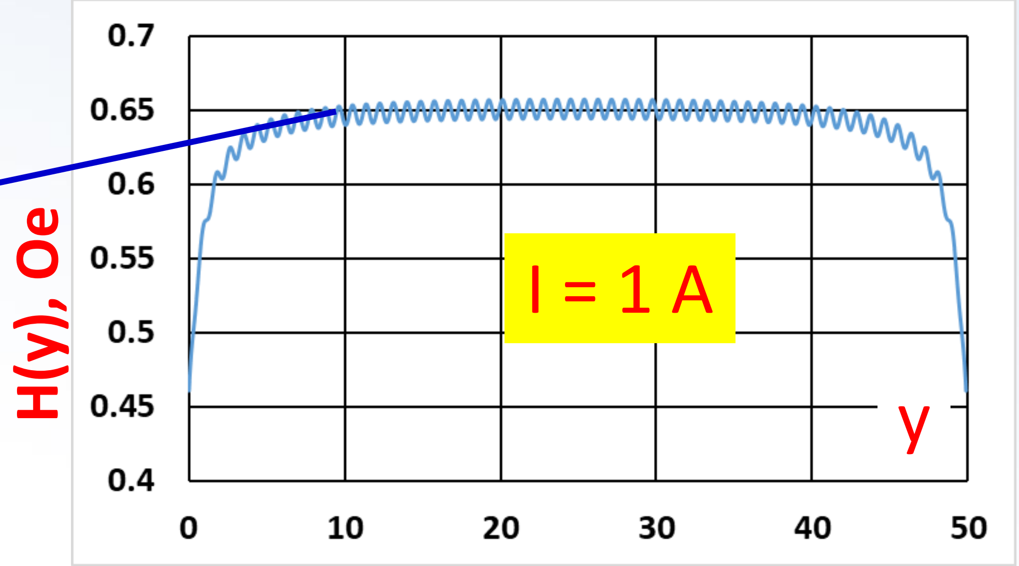


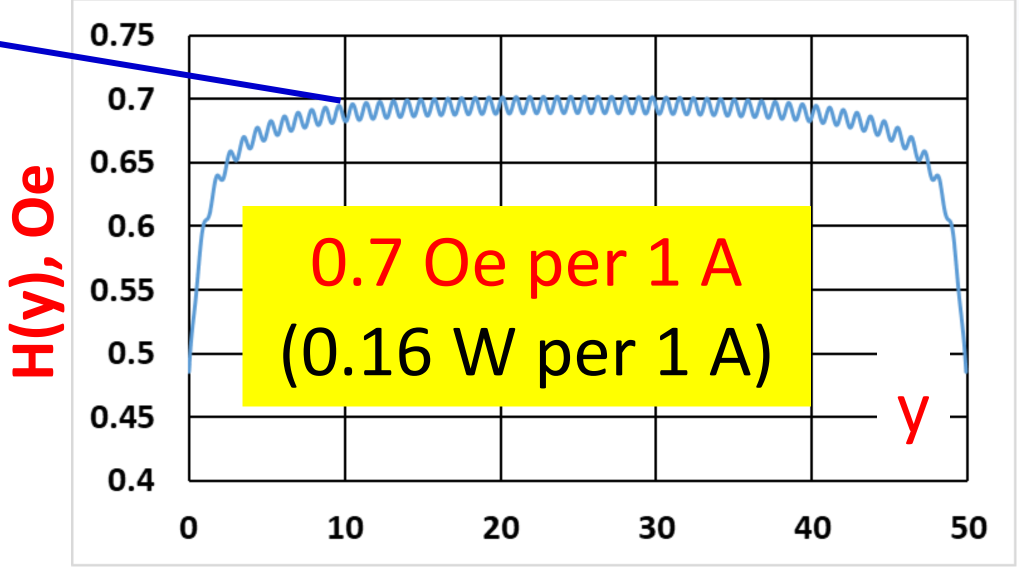
Planar magnetic coil



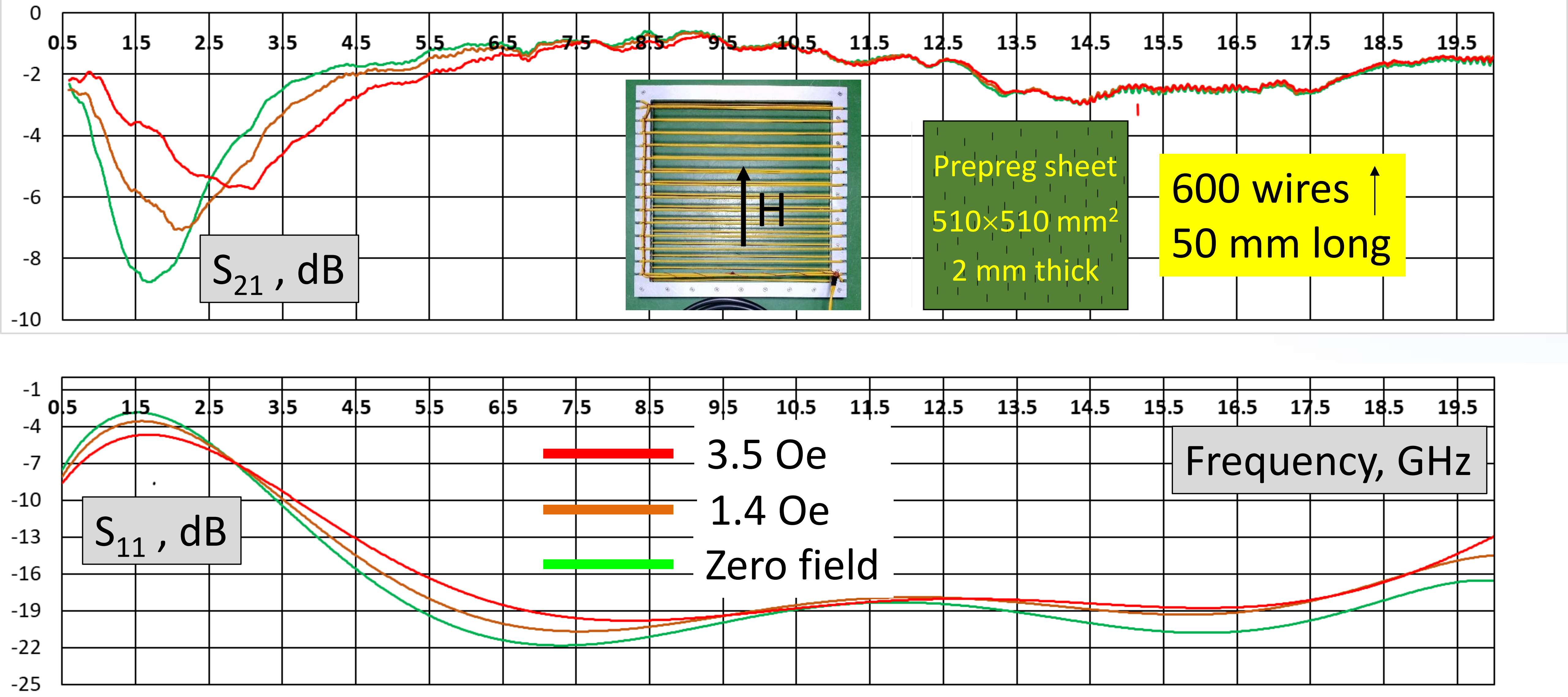






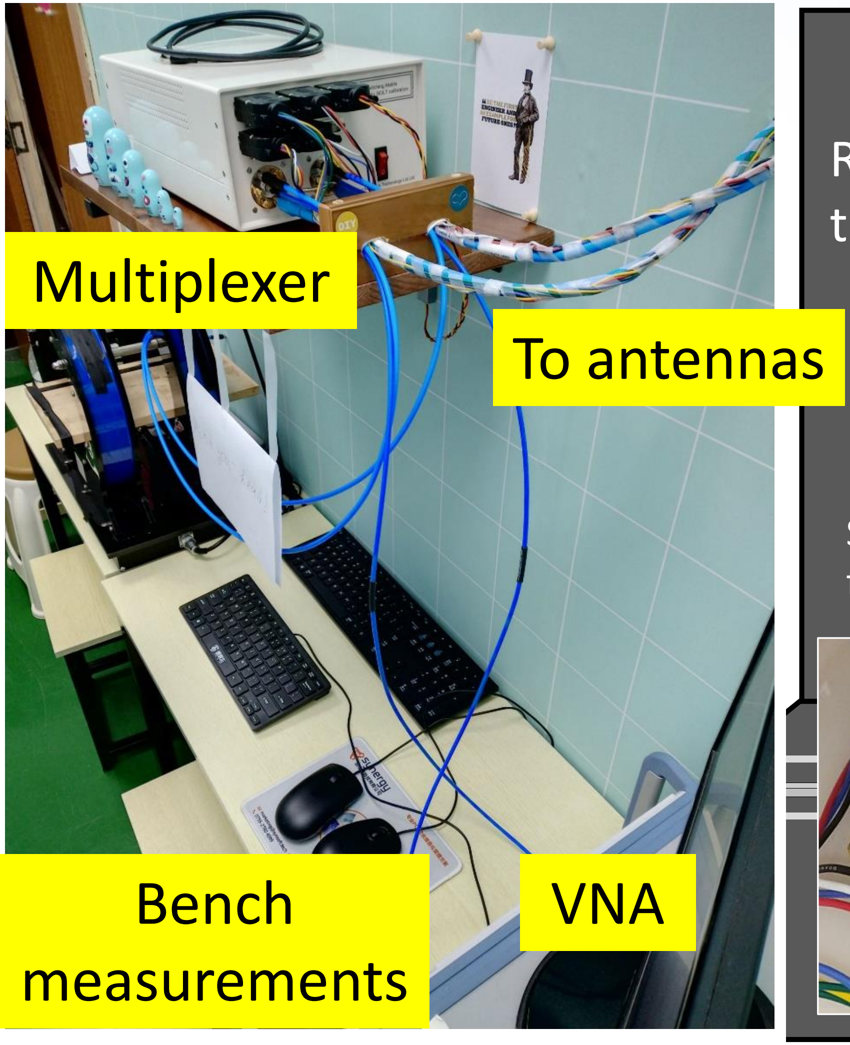


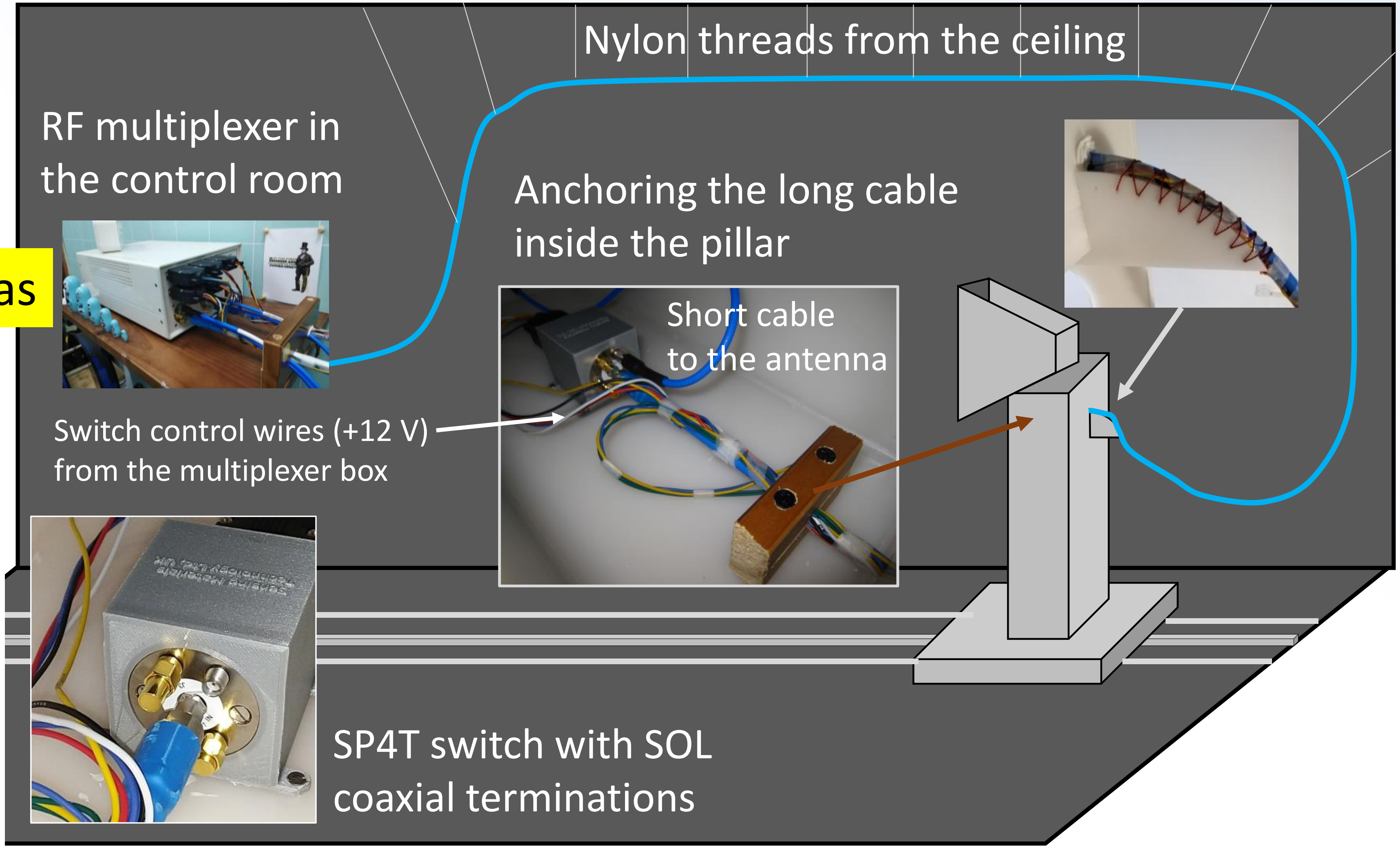
Field tunable composites: unidirectional ferromagnetic wire dipoles



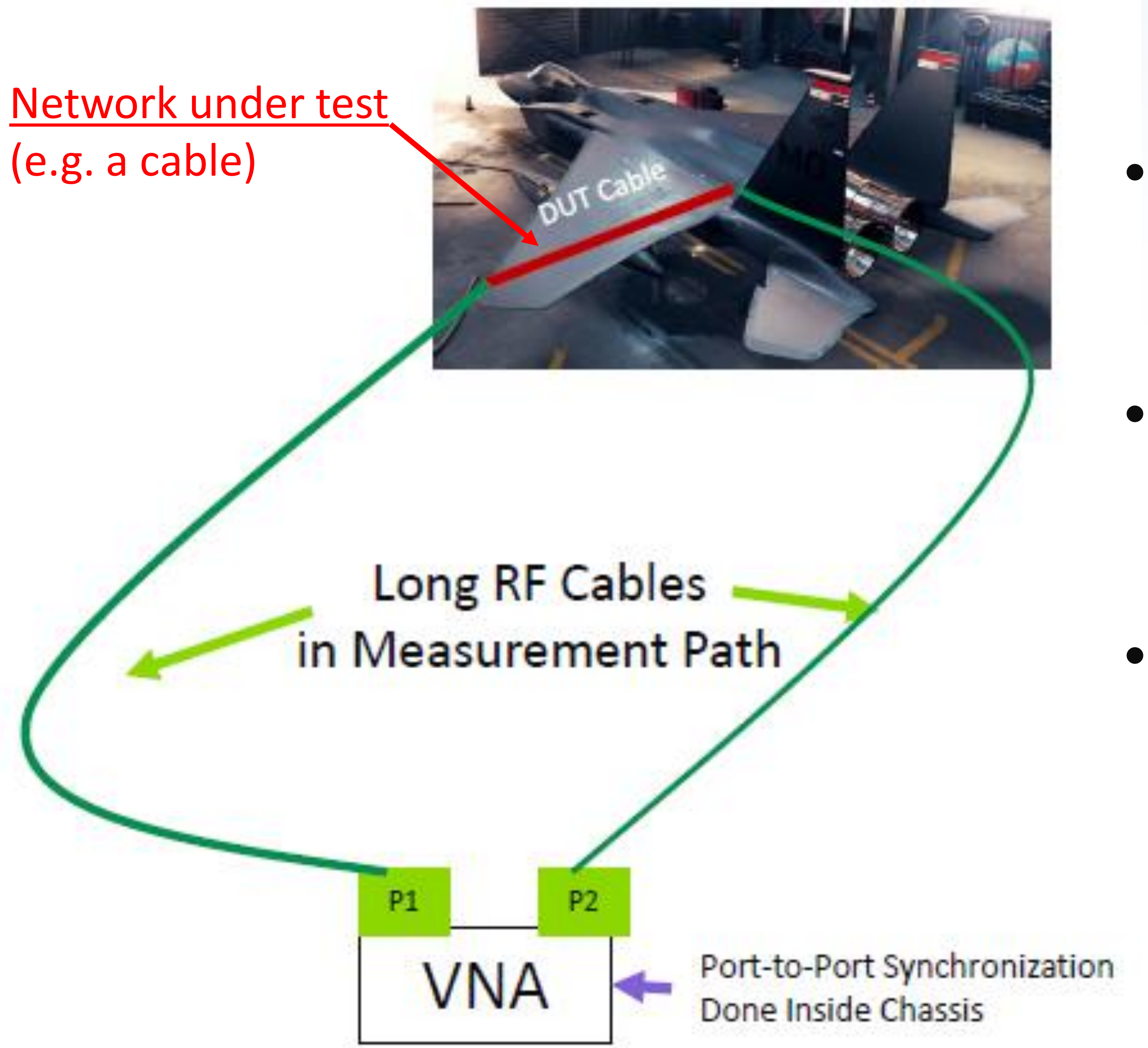
Technical aspects of building microwave laboratory for material measurements…

Cable suspension in the anechoic chamber



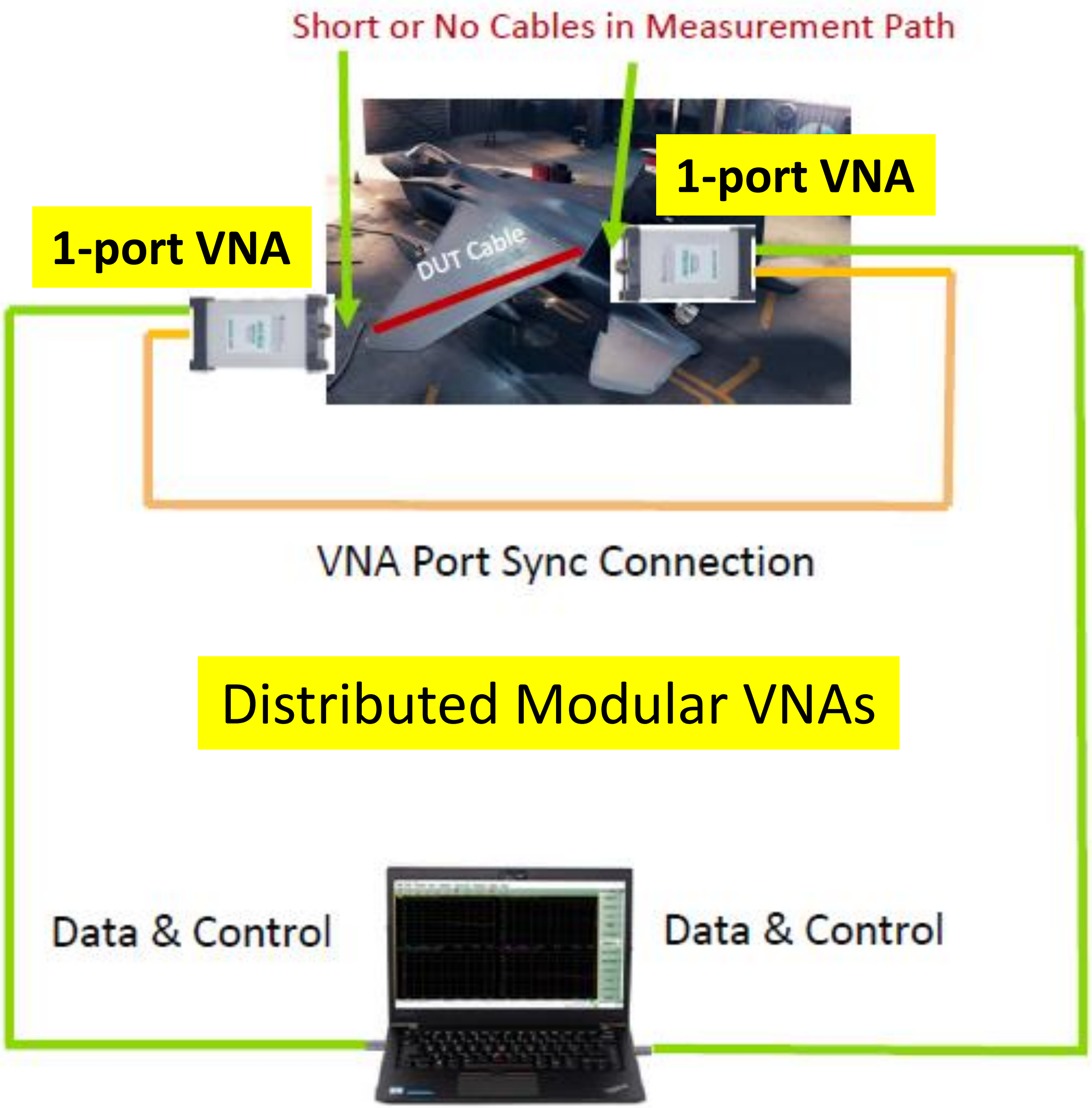


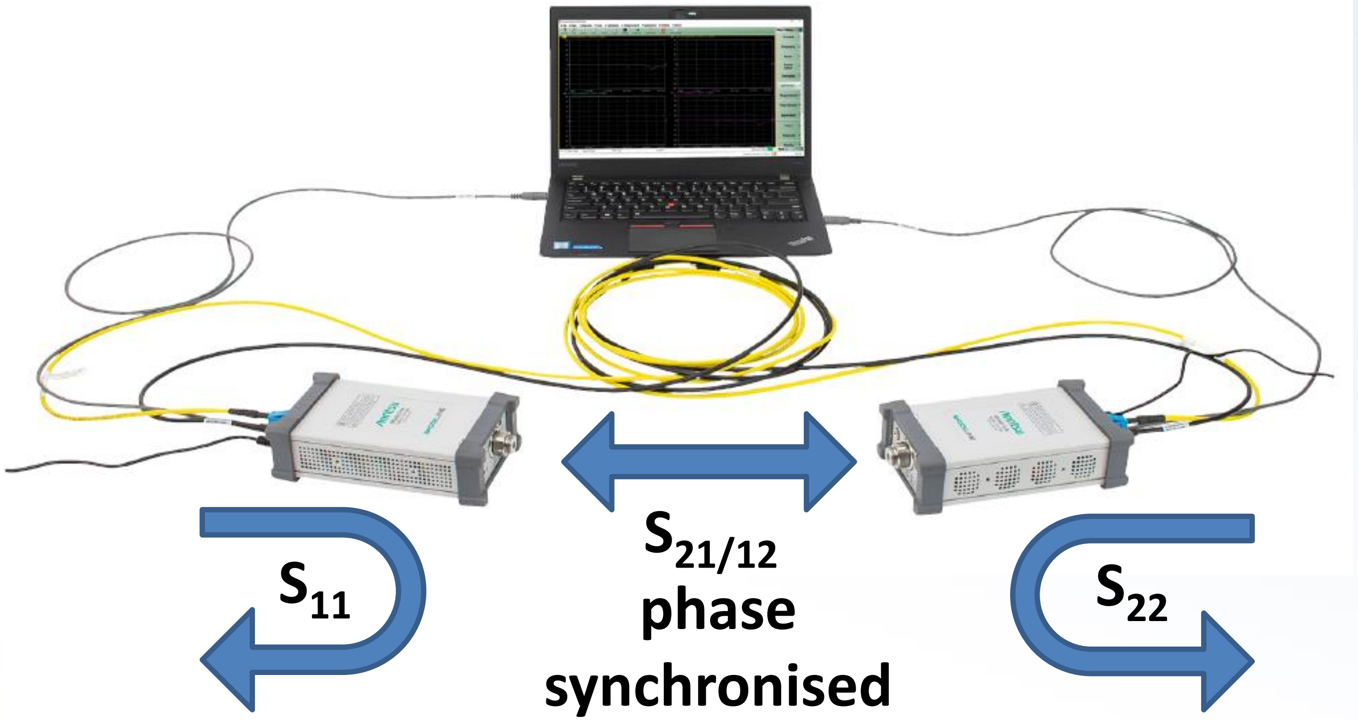
Problem of long cables for network measurements



- VNA must have enough dynamic range performance to overcome cable insertion loss
- Small deviations in cable electrical length cause deviations in phase measurement results
- Electrical length affected by changes in environmental temperature and cable movement

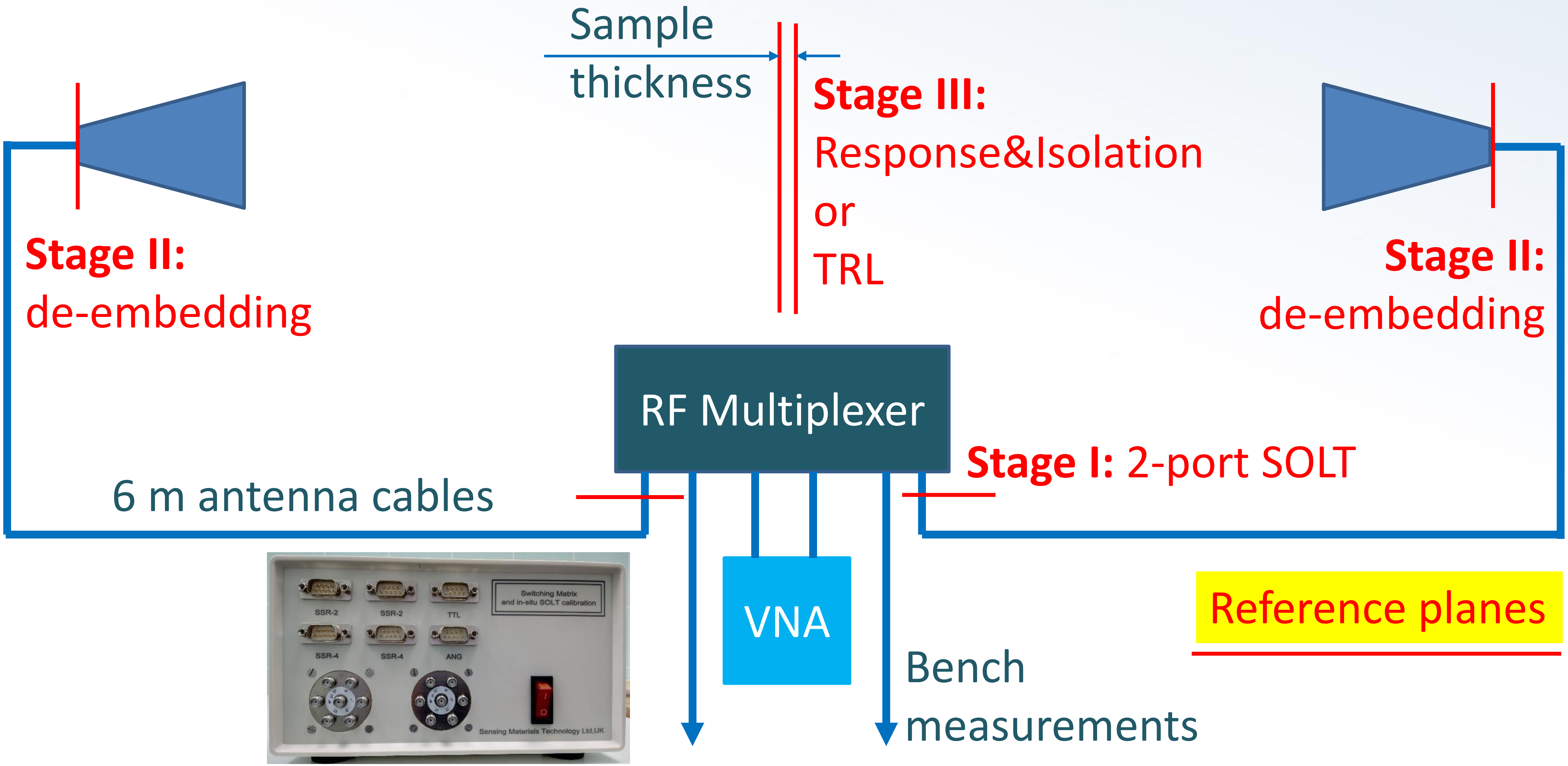
Anritsu's solution of the problem of long cables



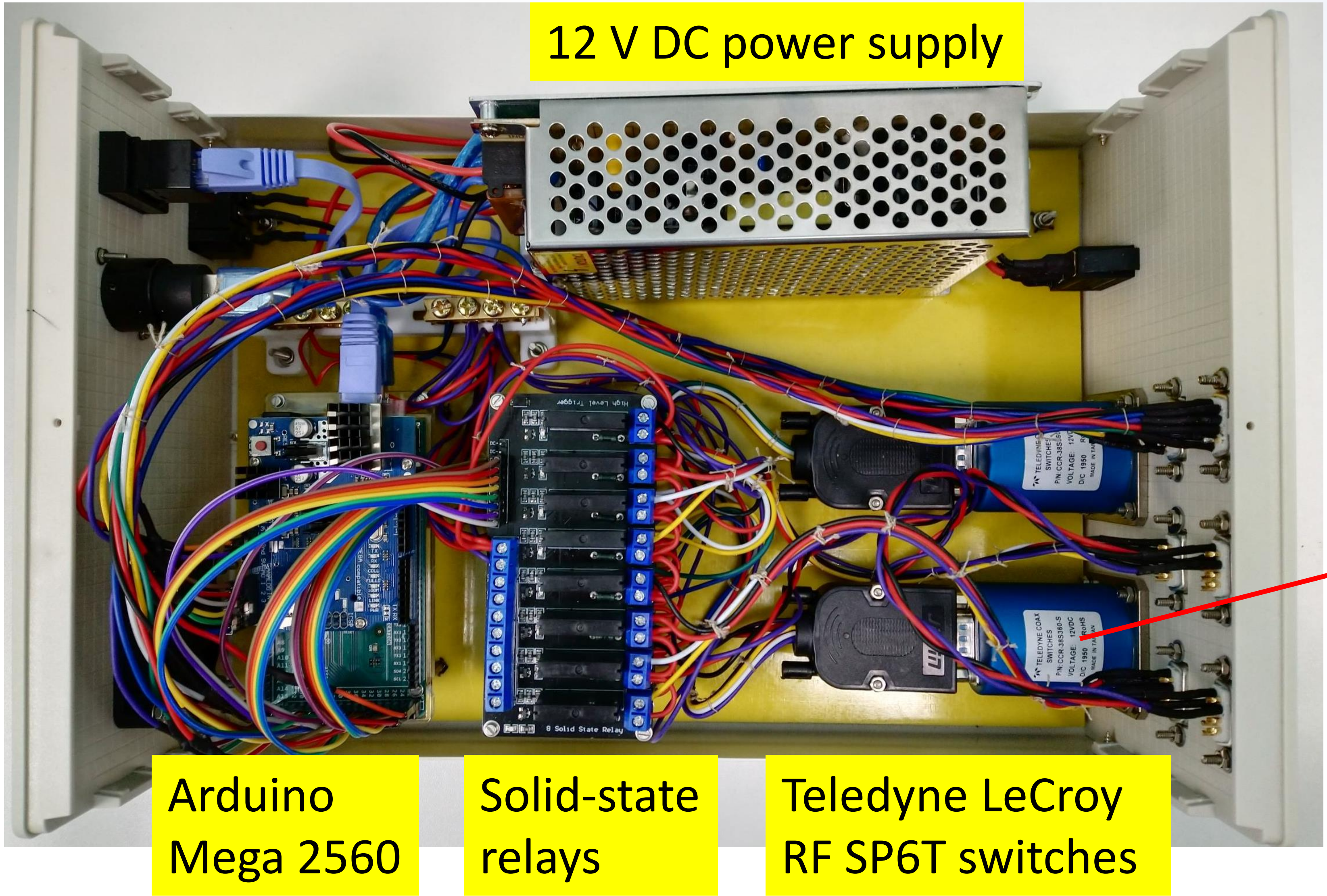


- A new VNA architecture was proposed that includes two independent VNAs with complete source and measurement capability that do not rely on signal sourcing or processing back in a mainframe.
- Phase synchronization between two independent VNAs allows the 2-port S-parameter measurements.

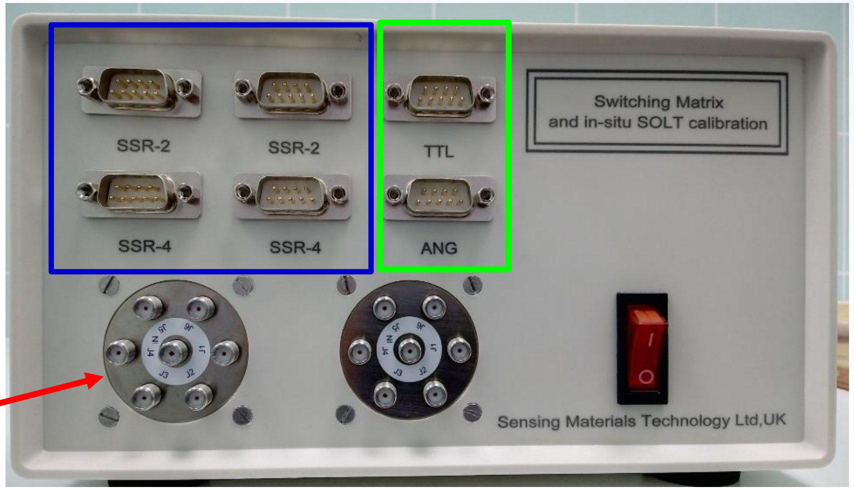
Our solution of the problem of long cables: 3-stage calibration procedure



Bespoke programable RF multiplexer



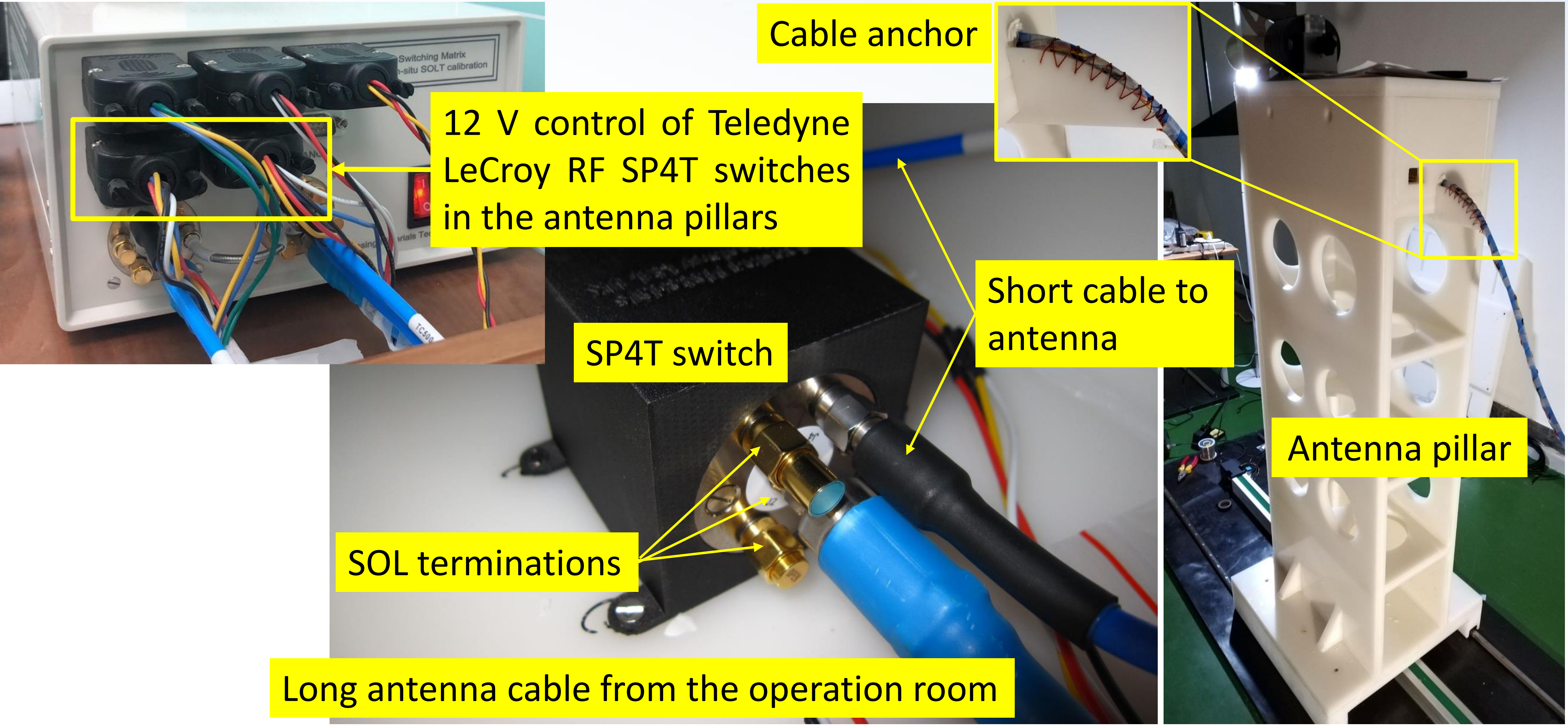
12 V outputs for controlling external SP2T and SP4T switches



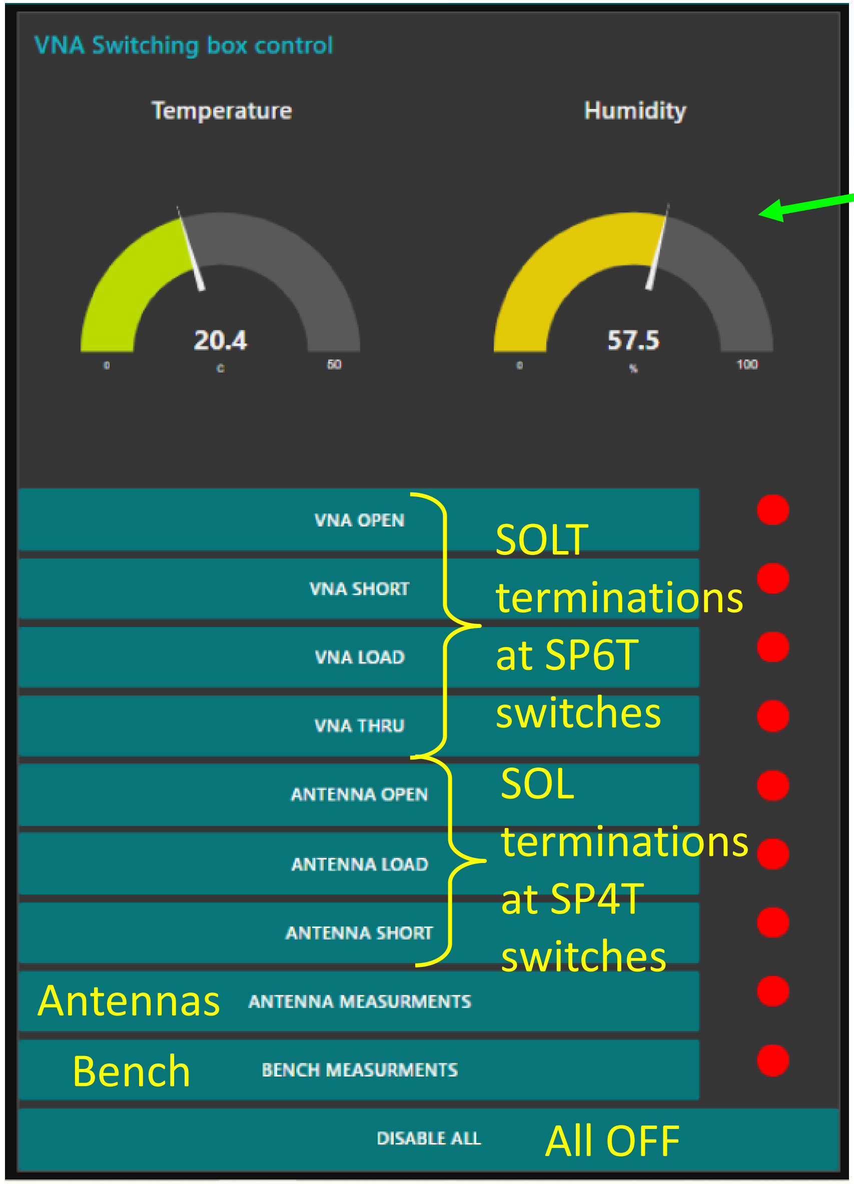
TTL GPIO

Analog input, 0-5 V, 10 bit

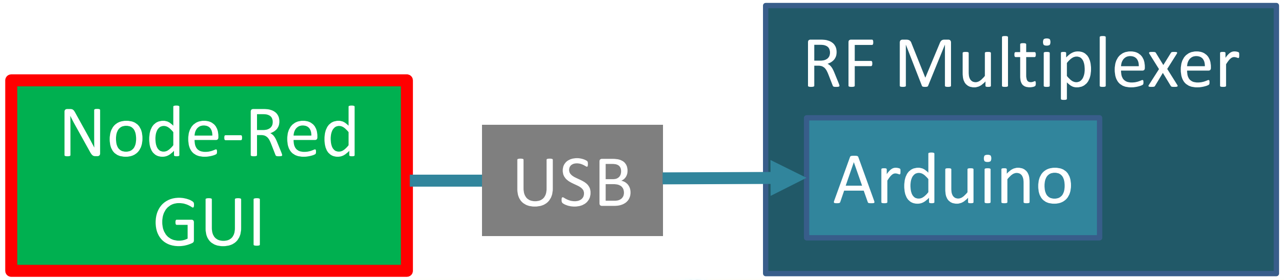
RF SP4T switches inside the antenna pillars



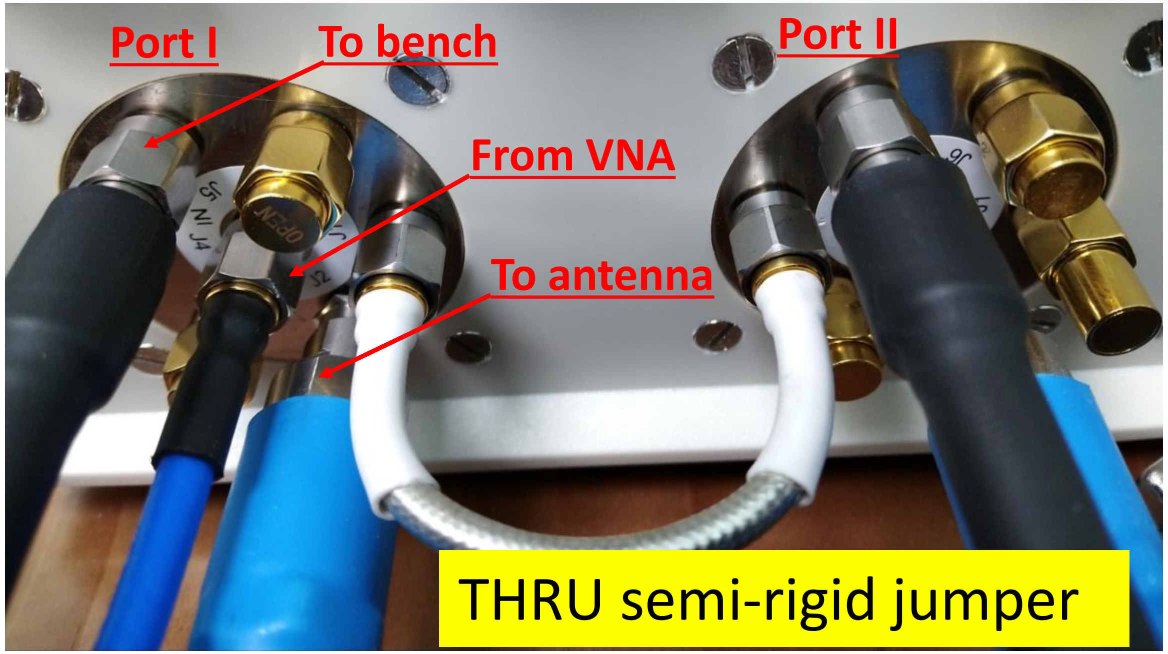
Node-Red GUI for controlling the multiplexer

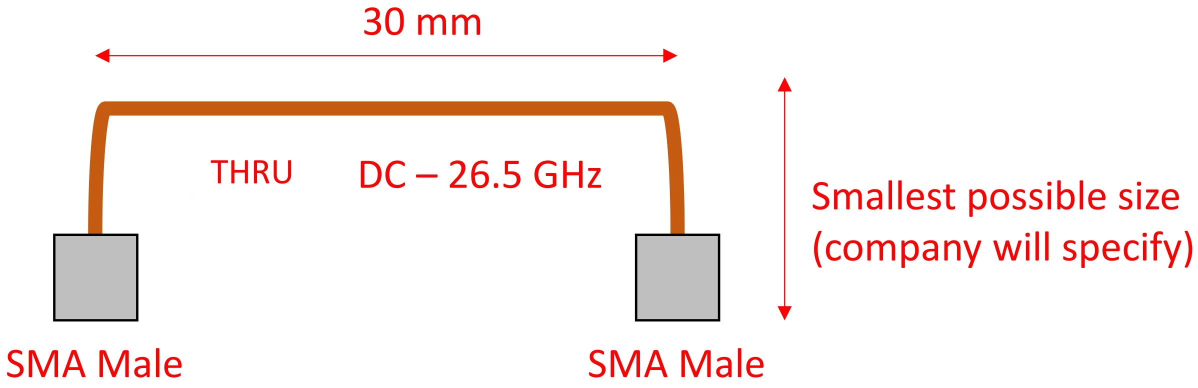


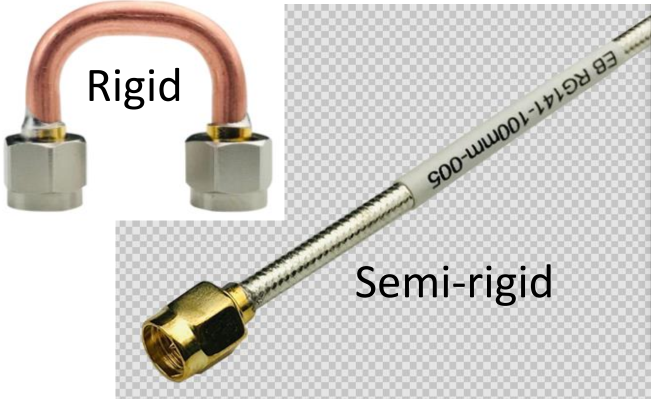
Temperature and humidity sensor
for controlling the calibration conditions



RF multiplexer: automatic 2-port SOLT calibration of VNA (Stage I)

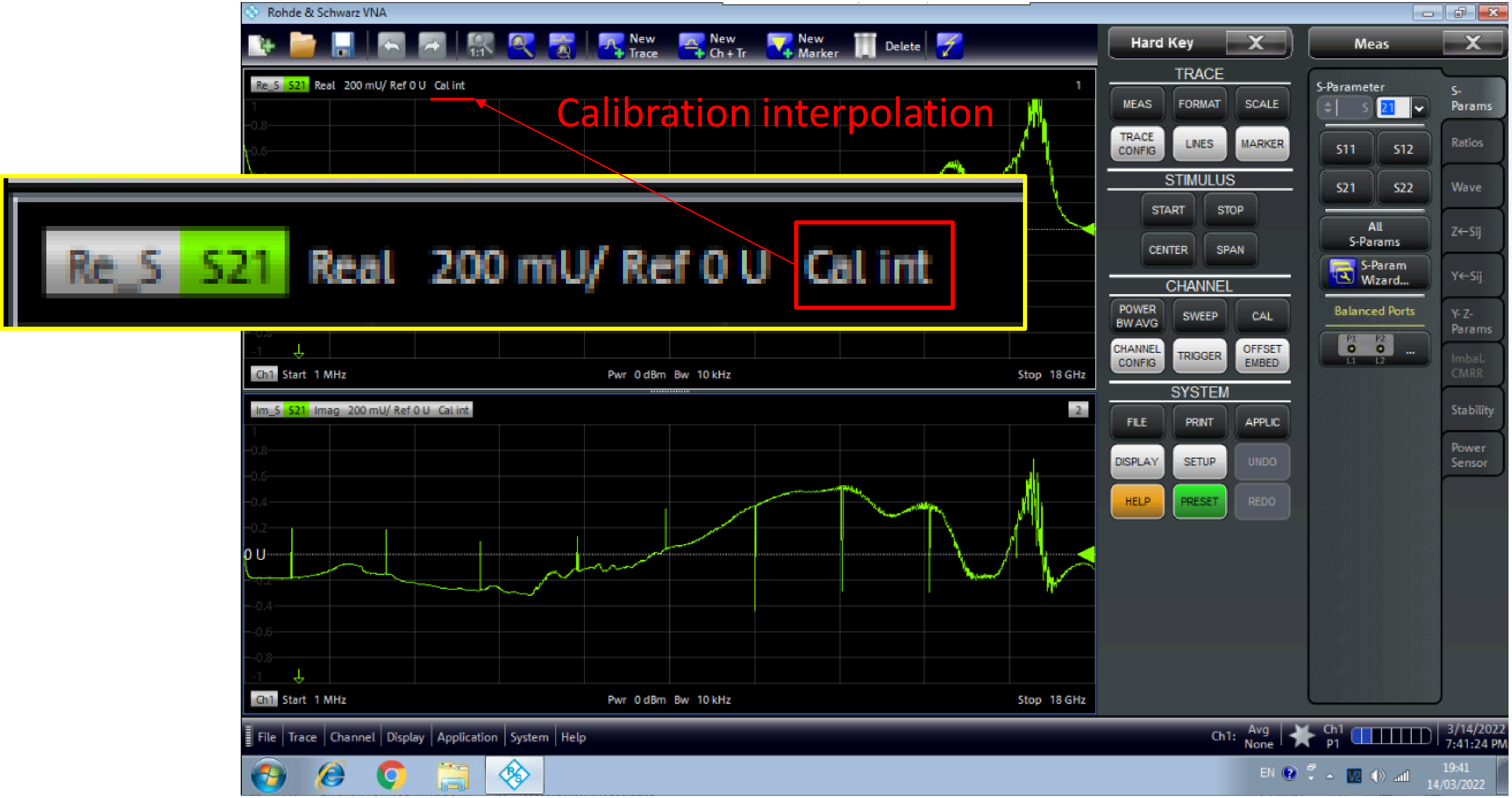






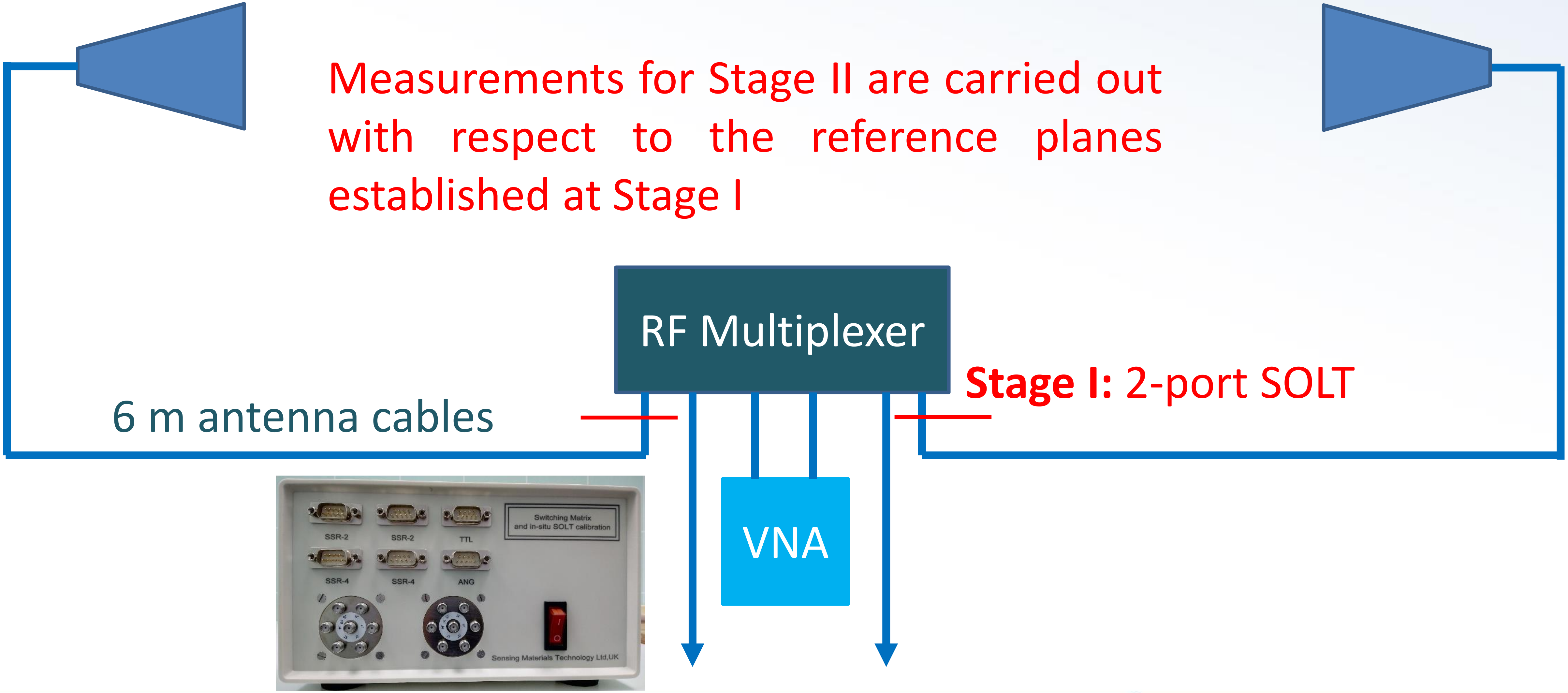
1. Automatic 2-port SOLT calibration of VNA
2. Multiplexing between the bench and free space measurements
3. Controlling SP4T RF switches in the antenna pillars

Activation of the 2-port SOLT calibration (Stage I)



Reference planes after Stage I

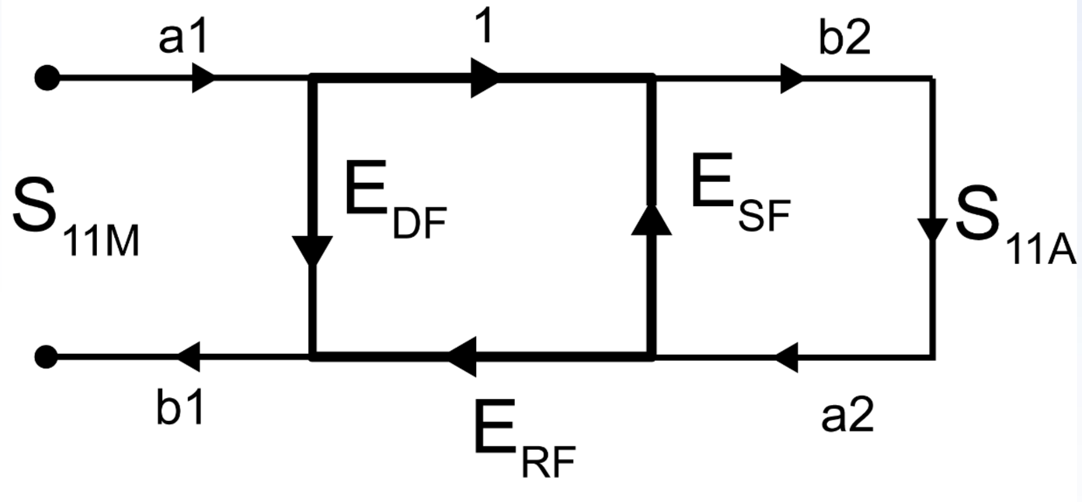
Measurements for Stage II are carried out with respect to the reference planes established at Stage I



Automatic creation of the cable S-parameter model

SOL terminations at RF SP4T switches inside the antenna pillars

3-term model



$$\begin{cases} E_{DF} + S_{11MS}\boxed{S_{11S}}E_{SF} + \boxed{S_{11S}}(E_{RF} - E_{DF}E_{SF}) = \boxed{S_{11MS}} \\ E_{DF} + S_{11MO}\boxed{S_{11O}}E_{SF} + \boxed{S_{11O}}(E_{RF} - E_{DF}E_{SF}) = \boxed{S_{11MO}} \\ E_{DF} + S_{11ML}\boxed{S_{11L}}E_{SF} + \boxed{S_{11L}}(E_{RF} - E_{DF}E_{SF}) = \boxed{S_{11ML}} \end{cases}$$

Reflection coefficients measured at the multiplexer output after SOLT calibration (Stage I)

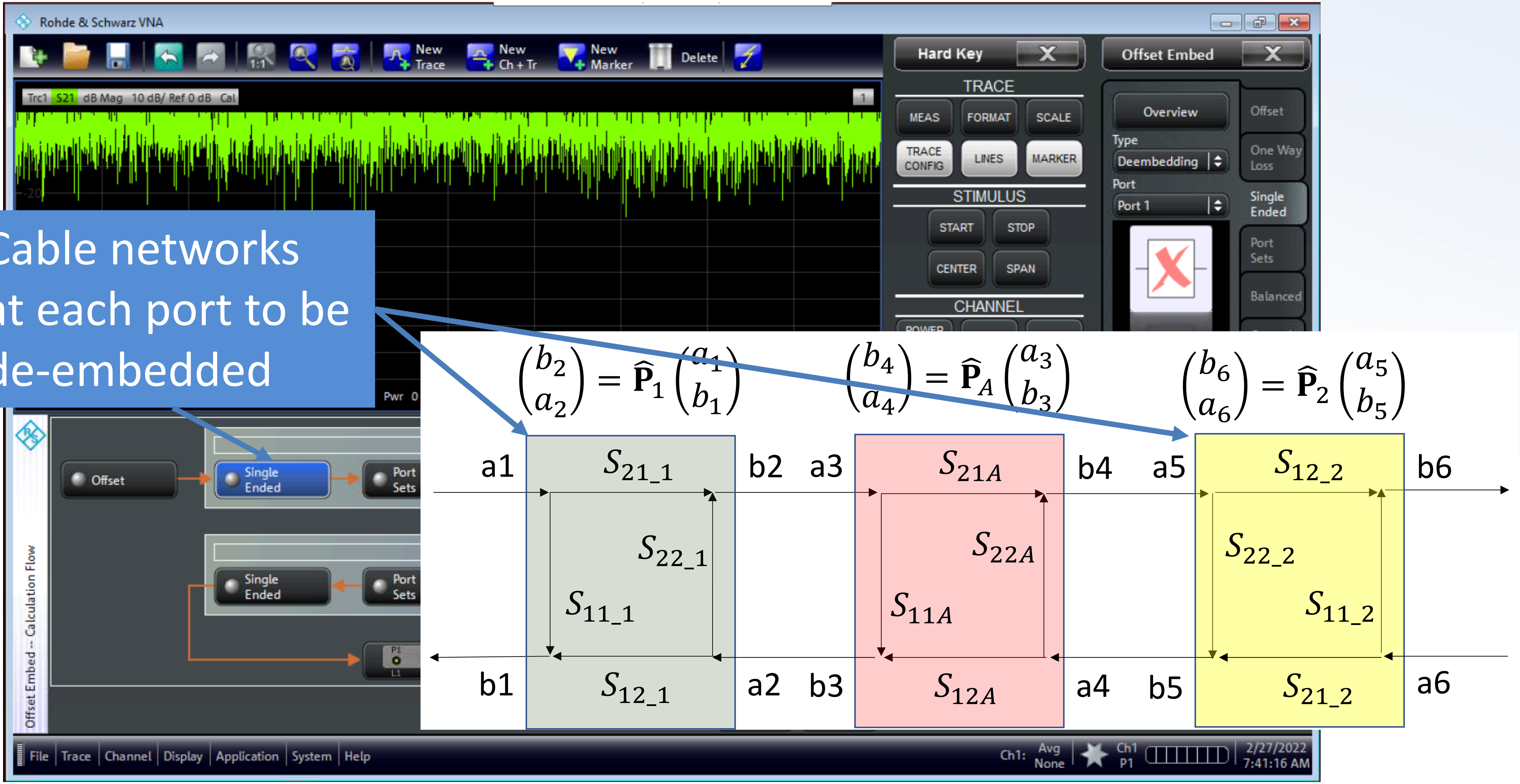
$$S_{11} = E_{DF}, S_{22} = E_{SF}, \text{ and } S_{21} = S_{12} = \sqrt{E_{RF}}$$

Recovered cable S-parameters (s2p files)

Uploading the cable s2p files to VNA for automatic de-embedding (Stage II)

Cable networks at each port to be de-embedded

$$\begin{pmatrix} b_2 \\ a_2 \end{pmatrix} = \widehat{\mathbf{P}}_1 \begin{pmatrix} a_1 \\ b_1 \end{pmatrix} \quad \begin{pmatrix} b_4 \\ a_4 \end{pmatrix} = \widehat{\mathbf{P}}_A \begin{pmatrix} a_3 \\ b_3 \end{pmatrix} \quad \begin{pmatrix} b_6 \\ a_6 \end{pmatrix} = \widehat{\mathbf{P}}_2 \begin{pmatrix} a_5 \\ b_5 \end{pmatrix}$$



Reference planes after Stage II

Measurements for Stage III are carried out with respect to the reference planes established at Stage II

Stage II:
de-embedding

Stage II:
de-embedding

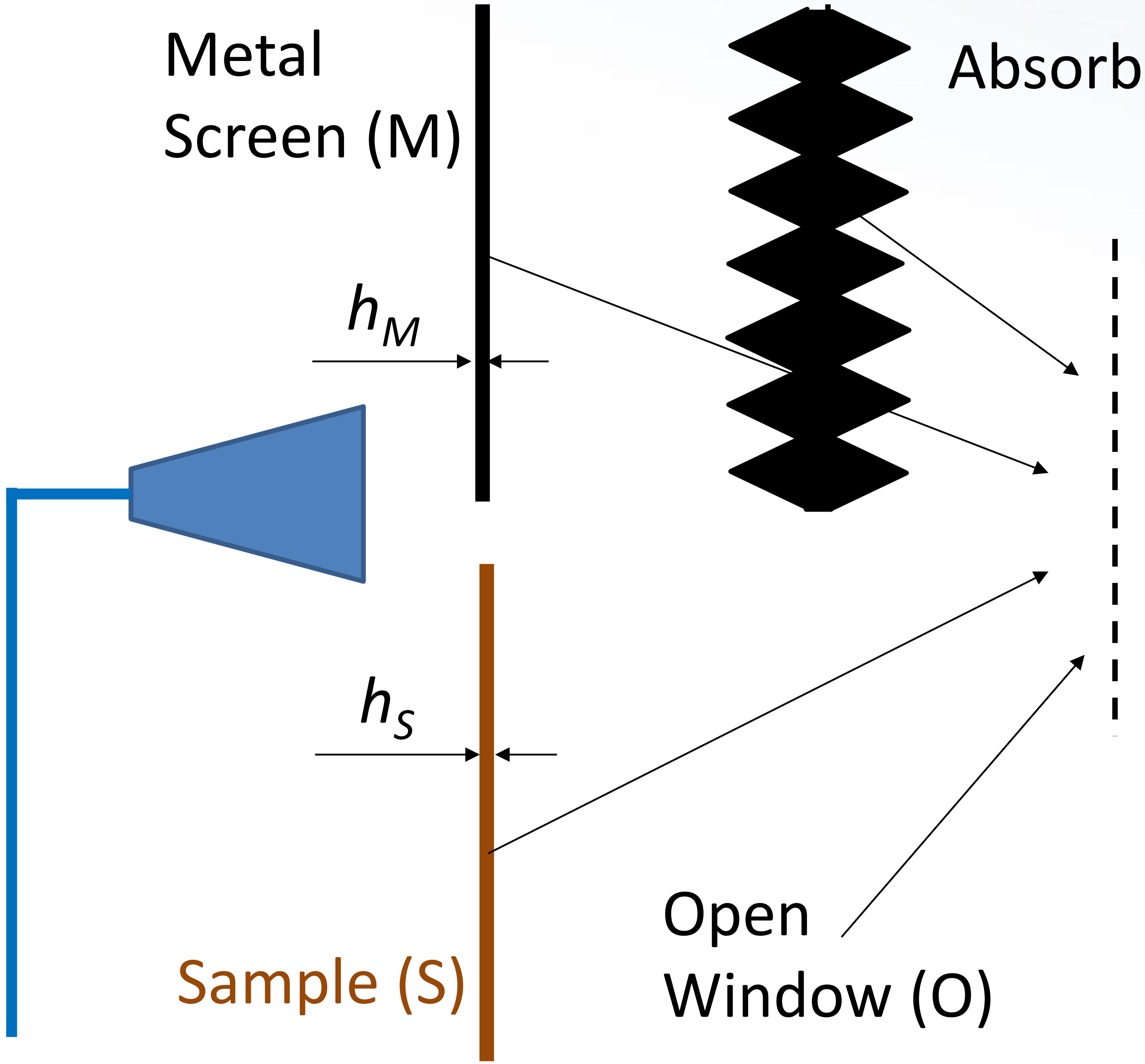
RF Multiplexer

6 m antenna cables

VNA

Bench measurements

Response&Isolation (Stage III): metal screen and absorber



Antennas remain stationary

$S_{kkM}, S_{kkL}, S_{klO}, S_{kkS}$ are S-parameters measured for two screens (**M, L**), open window (**O**), and the sample under test (**S**), where $k = \overline{1,2}$; $l = \overline{1,2}$; $k \neq l$

Response&Isolation as a normalisation procedure:

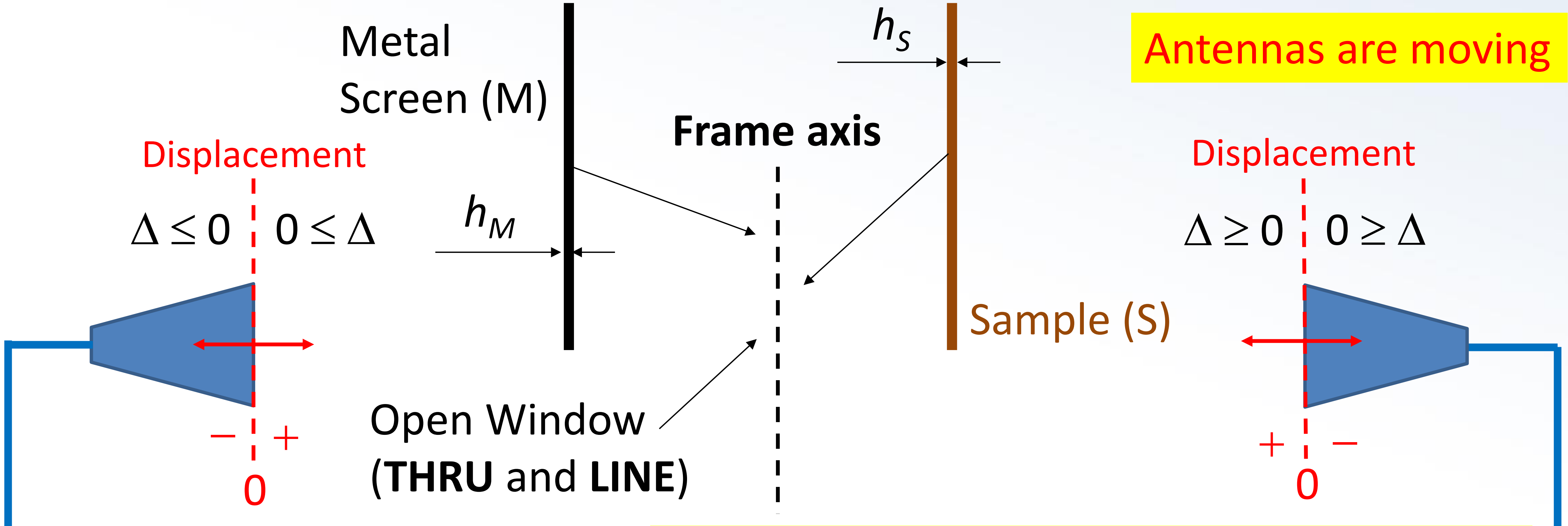
$$\tilde{S}_{kkM}(\omega_n) = S_{kkM}(\omega_n) \times exp\left(i\frac{\omega_n}{c}(h_S - h_M)\right)$$

$$\tilde{S}_{klO}(\omega_n) = S_{klO}(\omega_n) \times exp\left(i\frac{\omega_n}{c}h_S\right)$$

ω_n – frequency sweep points (rad/s)

$$\tilde{S}_{kkS}(\omega_n) = \frac{S_{kkS} - S_{kkL}}{\tilde{S}_{kkM} - S_{kkL}} \qquad \tilde{S}_{klS}(\omega_n) = \frac{S_{klS} - S_{klM}}{\tilde{S}_{klO} - S_{klM}}$$

TRL calibration (Stage III): metal screen and line standards



Initial position: $\Delta = 0$

THRU: $\Delta_T = h_S/2, \boldsymbol{S_{klT}}, k = \overline{1,2}; l = \overline{1,2}$

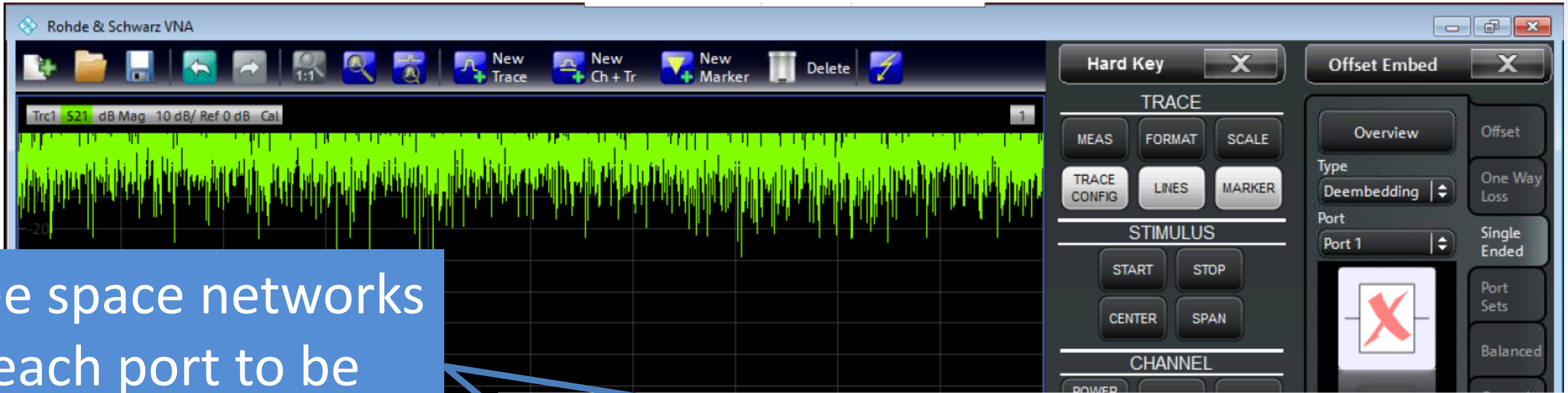
REFLECT: $\Delta_M = (h_S - h_M)/2, \boldsymbol{S_{kkM}}$

LINES (several): $\Delta_L = (h_S - h_i)/2, \boldsymbol{S_{klL}}, k = \overline{1,2}; l = \overline{1,2}$

$$h_i: 20^0 \leq \left| arg\left(\frac{S_{21T}}{S_{21L}}\right)\right| \leq 160^0 \text{ for } f \in [f_i^{start}, f_i^{stop}]$$

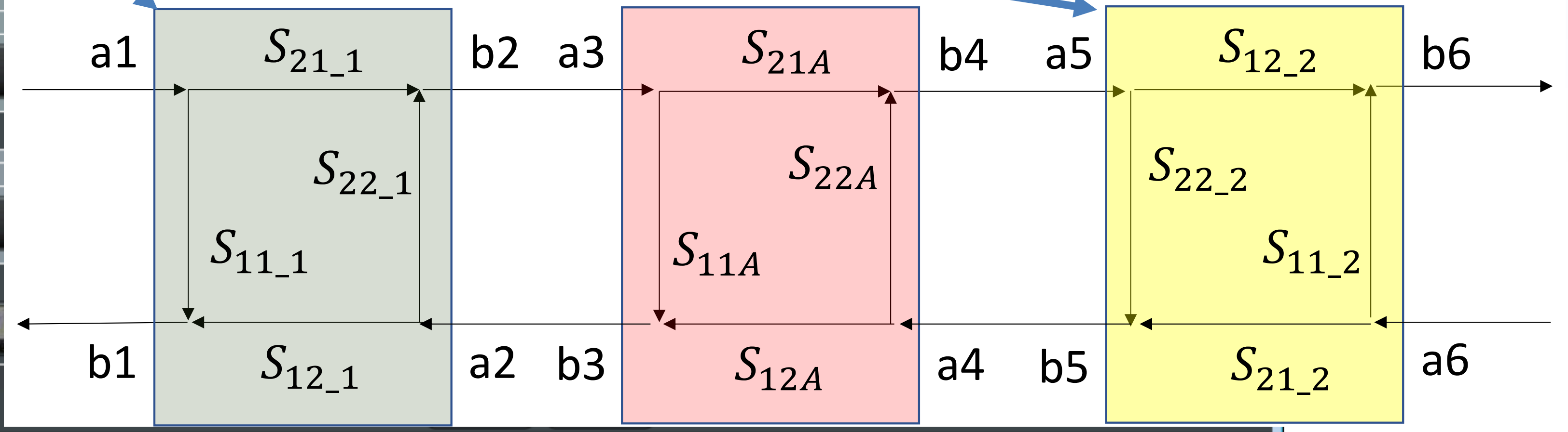
Sample: $\Delta = 0, \boldsymbol{S_{klS}} \rightarrow \widetilde{\boldsymbol{S}}_{\boldsymbol{klS}}$ (TRL mathematics)

TRL: s2p files of the free space can be uploaded to VNA for automatic de-embedding



Free space networks at each port to be de-embedded

$$\begin{pmatrix} b_2 \\ a_2 \end{pmatrix} = \widehat{\mathbf{P}}_1 \begin{pmatrix} a_1 \\ b_1 \end{pmatrix} \quad \begin{pmatrix} b_4 \\ a_4 \end{pmatrix} = \widehat{\mathbf{P}}_A \begin{pmatrix} a_3 \\ b_3 \end{pmatrix} \quad \begin{pmatrix} b_6 \\ a_6 \end{pmatrix} = \widehat{\mathbf{P}}_2 \begin{pmatrix} a_5 \\ b_5 \end{pmatrix}$$



Reference planes after Stage III

Sample thickness

Stage III:
Response&Isolation
or
TRL

Measurements of the sample under test are carried out with respect to the reference planes established at Stage III

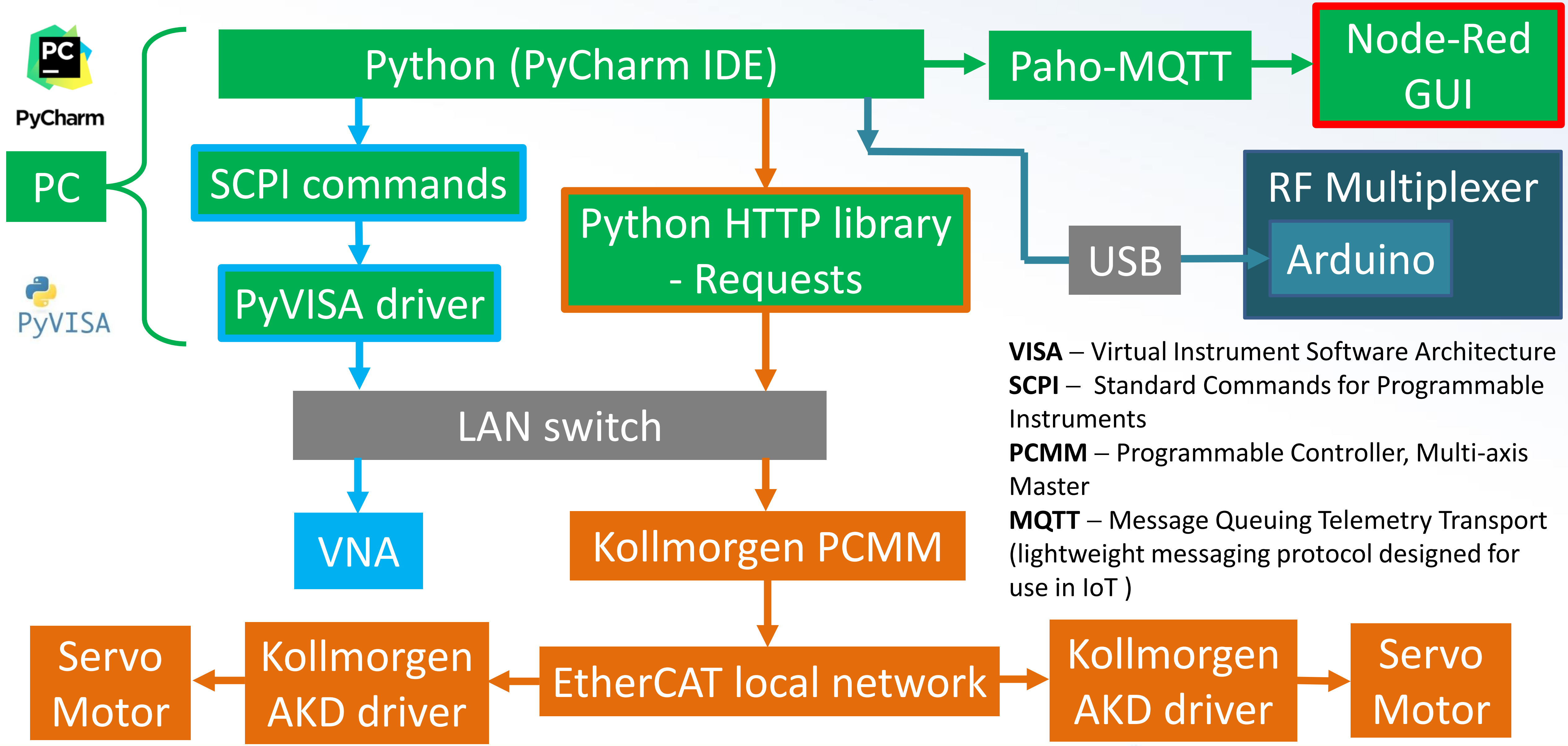
RF Multiplexer

6 m antenna cables

VNA

Bench measurements

Instrument control for free space measurements



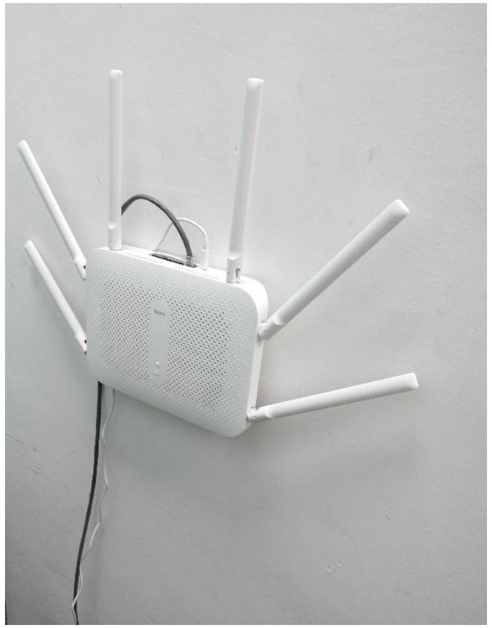
VISA – Virtual Instrument Software Architecture

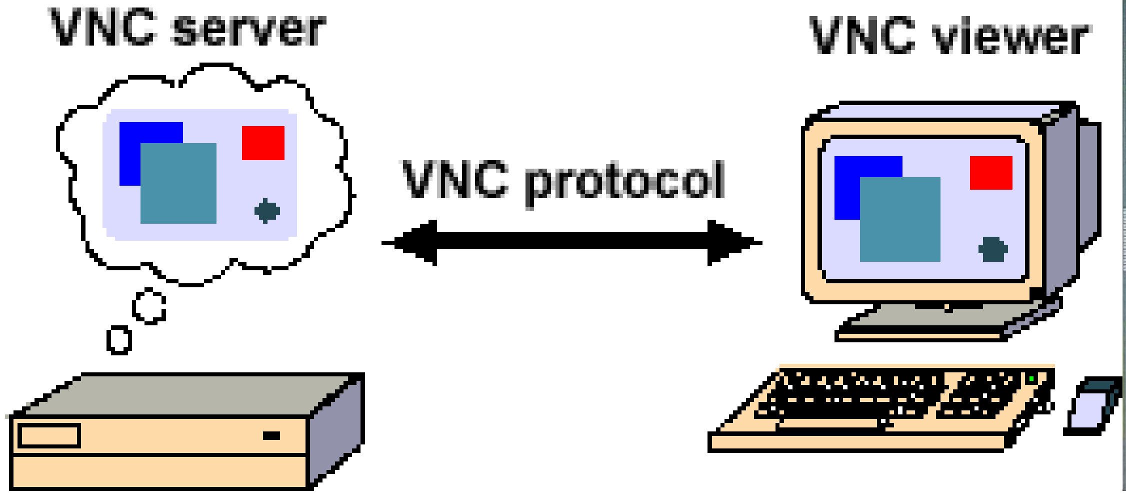
SCPI – Standard Commands for Programmable Instruments

PCMM – Programmable Controller, Multi-axis Master

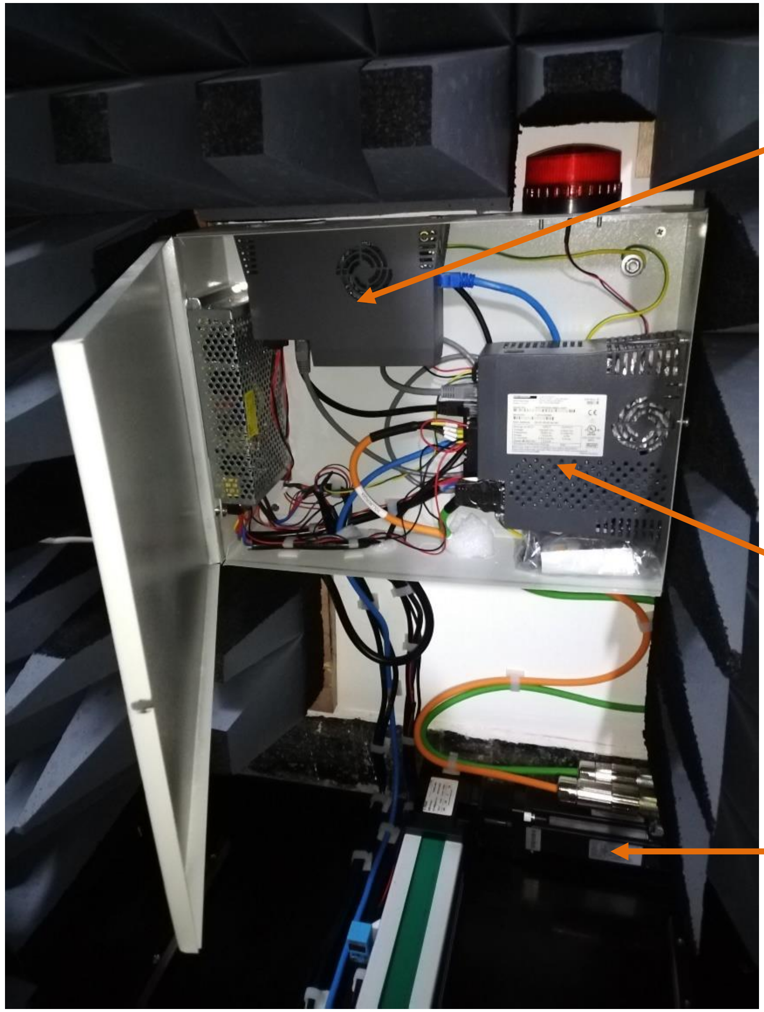
MQTT – Message Queuing Telemetry Transport (lightweight messaging protocol designed for use in IoT)

Lab Metaverse: remote programming and measurements





Robotics for antenna movement



Kollmorgen PCMM

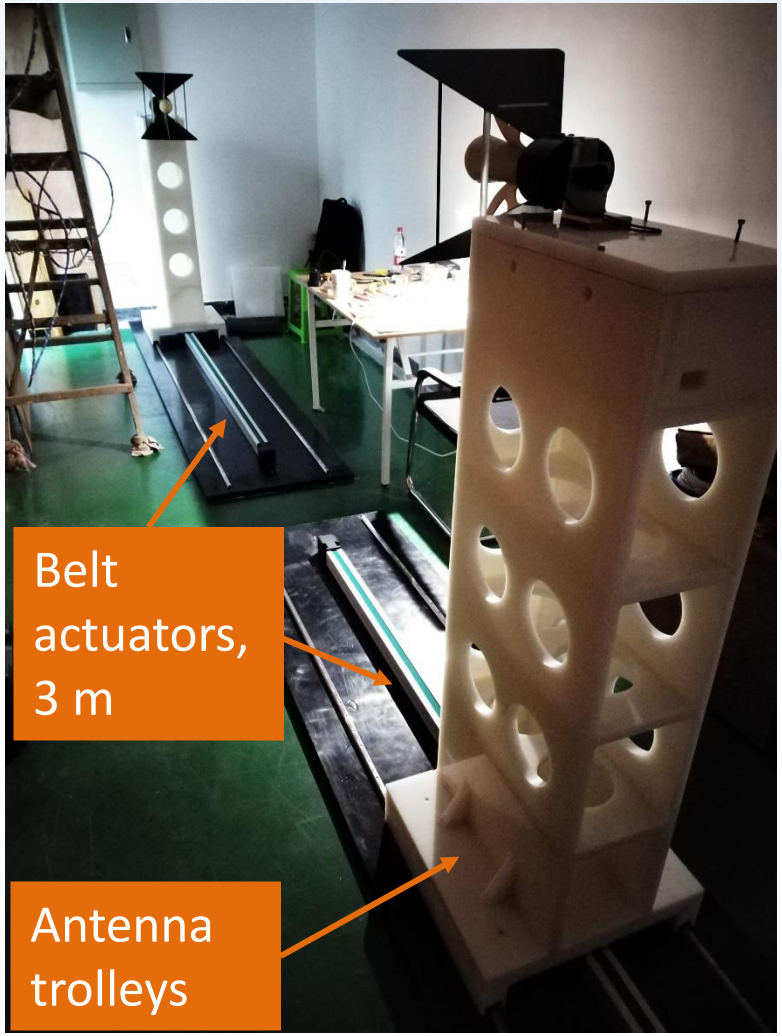
EtherCAT local network

Kollmorgen AKD driver

Kollmorgen AKD driver

Servo Motor

Servo Motor



Belt actuators, 3 m

Antenna trolleys

Conclusions

- Multi-stage calibration provides accurate S-parameter measurements of composite samples in free space
- External stimuli can be applied during microwave scattering measurements
- Automation and robotics are important for complex microwave measurements

Outlook

- Developing scattering theory based on the hybrid approach and its experimental verification
- Designing and building a heating chamber and stretcher for microwave measurements in free space under external stimuli

Slide captions…

Preparing an oral presentation using PowerPoint involves several steps. Here's a general guide:

1. **Define the topic and purpose of your presentation:** Start by identifying the main topic of your presentation and what you want to achieve. This will help you structure your content and create an outline.
2. **Create an outline:** Create an outline that includes the main points you want to cover in your presentation. Organize your ideas in a logical order and try to keep your outline simple and easy to follow.
3. **Gather and organize your content:** Collect all the information, data, images, and other resources that you will use in your presentation. Organize them into different sections based on your outline.
4. **Choose a template:** Choose a PowerPoint template that matches the topic and purpose of your presentation. You can either use a built-in template or download one from the internet.
5. **Add content to your slides:** Start adding content to your slides based on your outline and the resources you gathered. Use bullet points, short sentences, and visual aids to keep your slides simple and easy to read.
6. **Use visuals:** Use visuals such as charts, graphs, and images to illustrate your points and make your presentation more engaging.
7. **Practice your presentation:** Practice your presentation several times before delivering it. This will help you identify areas that need improvement and make you more confident.
8. **Present with confidence:** On the day of your presentation, be confident and speak clearly. Use your slides as a guide, but don't read from them word-for-word. Make eye contact with your audience and engage them by asking questions or soliciting feedback.

Remember, the goal of a PowerPoint presentation is to enhance your oral presentation, not replace it. Keep your slides simple and easy to follow, and focus on delivering a clear and engaging message to your audience.

Slide 1

Firstly, we would like to express our gratitude to the Organizing Committee for giving us the opportunity to deliver this talk. Our presentation today aims to share our experience in building a research laboratory dedicated to testing the microwave properties of composite materials under different external stimuli.

Slide 2

ZHEJIANG UNIVERSITY

- **From microscopic to macroscopic EM properties:** *Our goal is to develop methods that allow for the qualitative and quantitative description of macroscopic properties by characterizing the constituent elements of the system*
- **Hybrid approach in modelling microwave scattering properties:** *Our approach involves leveraging experimental data from individual components to simulate their electromagnetic response in free space. Currently, we are implementing this technique for wire inclusions*
- **Bench measurements of EM properties of inclusions under external stimuli:** *As per our proposed methodology, the design of a composite system should begin with an assessment of the electromagnetic properties of its individual components. For example, it's important to measure the high-frequency impedance of wire inclusions*
- **Free space measurements of composites under external stimuli:** *When investigating the microwave response of composite systems in free space, it can be challenging to explore the influence of external stimuli like magnetic fields, heat, or mechanical stress*
- **Technical aspects of building microwave facilities for material measurements:** *This presentation will cover the fundamental principles of building such systems*

Slide 3

The practical application of composite systems with electromagnetic functionality is feasible when their properties can be predicted based on the electrodynamics of their constituent elements and appropriate manufacturing processes can be developed. To confirm the accuracy of these models, it is necessary to validate the system's response in free space for a specific polarization of electromagnetic radiation.

Slide 4

浙江大學 ZHEJIANG UNIVERSITY

Our research has led to significant advancements in modelling and measuring the microwave response of composite systems that contain ferromagnetic wire inclusions. The hybrid approach involves measuring the wire impedance over a wide frequency range of up to 15-20 GHz, which we then convert into an impedance boundary condition to simulate the microwave behaviour of the composite material. This allows us to measure the impedance under different external stimuli, including the application of a magnetic field, heat, or tensile stress. CST Studio enables us to simulate the microwave response of microelements that have impedance boundary conditions instead of simple conductivity properties. Additionally, we are currently working on developing our own solver based on the antenna equation to further enhance modelling capabilities.

Building our laboratory posed significant challenges due to the limited available space. To facilitate both benchtop and free space measurements, we divided the area into two sections: a control room and an anechoic chamber. The dimensions of these two sections are shown on the slide. The control room serves as the central hub for multiplexing between benchtop and antenna measurements and for controlling antenna movements. Additionally, we were able to accommodate a compact Instron stress machine within the control room.

Slide 6

To measure the high-frequency impedance of ferromagnetic wires under an external magnetic field, we use programmable instruments from Rohde&Schwarz, such as the ZNB20 2-port Vector Network Analyzer (VNA) covering a frequency range from 100 kHz to 20 GHz, a Function Generator, and a Digital Multimeter. The Helmholtz magnetic coil is driven by the Function Generator through a power amplifier that provides the necessary voltage levels and the current. The actual voltage applied to the coil, after amplification, is measured with the Digital Multimeter. For each field value, VNA performs a frequency sweep and measures S21-parameter of the wire sample mounted onto a PCB cell. The cell comprises two microstrip lines with a continuous ground plane on the reverse side, and the wire sample is fixed in the gap between the lines with conductive silver paint. A program on PC converts S21-parameter into the wire impedance. The synchronization of the devices is carried out using a LabVIEW program on PC. We can measure both the dispersion of the impedance at a fixed bias magnetic field and its field dependencies at a fixed frequency. These measurements are shown on the slides.

Slide 7

To investigate the relationship between wire impedance and tensile stress under a bias magnetic field, we use a specially designed dogbone PCB cell. The Instron stress machine securely clamps the cell between its grippers, thereby applying stress to the wire sample. The PCB cell is positioned within a Helmholtz coil, and the sample's strain can be monitored using an optical camera, as shown in the photograph, or with tensiometers attached to the cell on the ground plane's side.

Slide 8

ZHEJIANG UNIVERSITY

To measure impedance as a function of temperature, the PCB cell can be placed in a slot within a mini-heating chamber, which is currently in the developmental stage. While the sample is heated, it can be magnetized and subjected to mechanical stress. Temperature regulation within the heating chamber is expected to be achieved through an Arduino microcontroller.

浙江大學 ZHEJIANG UNIVERSITY

To control and synchronize devices connected to a PC via a LAN switch, we use a single LabVIEW program that leverages the National Instruments VISA driver. In addition, we've developed a user-friendly graphical interface using Node-Red, an IoT programming tool. This interface enables effortless switching of the multiplexer between bench and free space measurements.

浙江大學 ZHEJIANG UNIVERSITY

Our anechoic chamber is compact yet functional. It contains two wideband horn antennas mounted on pillars, which can be easily moved along rails using belt actuators and Kollmorgen servomotors. Additionally, a universal test frame is located at the centre of the chamber, which allows us to affix samples for testing. To minimize reflections, the walls, ceiling, and floor of the chamber are covered with cone-shaped absorbers.

ZHEJIANG UNIVERSITY

The universal test frame is a versatile tool constructed from durable plastic that serves multiple purposes, such as performing microwave calibrations in free space, securing the sample under test, and applying external stimuli to it. At present, we have implemented the application of an external magnetic field, while the development of the heating chamber and stretching mechanism is still underway. The heating chamber will be inserted into the upper window, and the stretching mechanism will be situated in the base cavity.

Slide 12

By using a planar coil, a uniform magnetic field can be applied over the entire area of a thin composite sheet, except for narrow areas around the edges. To insert the sample into the coil, a top slot is provided. The coil is firmly fixed within the frame using two interlocking metal screens, and the entire installation is lined with radio absorbers. The electric field of the wave emitted from the horn antenna is polarized perpendicular to the coil's turns, minimizing any disruption to the wave's propagation.

The planar Helmholtz coil is mounted on to a thin aluminium frame that features slots for the turns. Thick insulated wire, capable of carrying a large current, is wound in layers across two planes, with the layers shifted relative to each other by half the interturn distance. The distance between the layers equals the interturn distance, which closely resembles the design of the Helmholtz coil. As a result, we refer to it as a planar Helmholtz coil. While it's true that creating a magnetic field may require significant currents, the power dissipated by the coil can still remain quite small. This is because a wire with a larger cross-sectional area can be used, which allows for better conductivity and reduces resistance.

Slide 14

ZHEJIANG UNIVERSITY

In this study, we demonstrate measurements in free space using a thin composite sample consisting of two layers of prepreg with ferromagnetic wire pieces randomly distributed between them. The sample contained 600 wire dipoles, each 50 mm in length, all oriented along the magnetic field in the planar coil. We measured S21- and S11-parameters over a frequency range of 0.5 to 20 GHz at different bias magnetic fields. The S-parameter dispersions showed resonant behaviour, with S21 exhibiting the most sensitivity to the magnetic field, affecting both the magnitude and frequency of the resonance. Although S11 may not be as tunable as S21, the observed changes in the resonance region could still be adequate for sensory applications, particularly when tensile stress is used as a control parameter. To enhance sensitivity to external stimuli, we suggest using quarter-wave thickness multilayer structures. While we won't go into detail on the numerous possible applications here, the results of this study have promising implications for various fields.

Slide 15

In the upcoming slides, we'll cover the key technical factors to consider when constructing a free space measurement system for characterizing microwave materials. These considerations are essential to ensure accurate and reliable results. So, let's dive in.

Slide 16

Creating a bench measurement system for characterizing microwave materials is impractical due to several factors, including the need to measure individual elements and large composite samples, the broad frequency range (0.5 – 20 GHz), and the requirement to account for external stimuli. To overcome these challenges, we've positioned the antennas away from the VNA and connected them to it via six-meter cables and a multiplexer. To allow for free movement of the antennas on trolleys, the cables are suspended from the ceiling using nylon threads. However, the long cables present a calibration challenge, which we address with an in-situ de-embedding method that we'll explain in the following slides. The antenna pillars contain RF switches that we use to de-embed the long cables coming from VNA, and the multiplexer controls all of the RF switches.

浙江大學
ZHEJIANG UNIVERSITY

When dealing with long cables, it is crucial to ensure that the VNA has sufficient dynamic range performance to account for the insertion loss, as this can significantly impact reflection measurements. Furthermore, even small changes in the electrical length of the cables can lead to deviations in the phase measurement results, which can be caused by environmental temperature fluctuations or cable movement.

A new VNA architecture, proposed by Anritsu, includes two independent VNAs with complete source and measurement capabilities that do not rely on signal sourcing or processing back in a mainframe. The phase synchronization between these two independent VNAs through an optical fibre enables 2-port S-parameter measurements.

Slide 19

The proposed Anritsu scheme enables S-parameter measurements of networks located at a considerable distance from the VNA. However, it has a major drawback that these measurements cannot be multiplexed between benchtop and free space. To overcome this limitation, we have developed and implemented our own 3-stage calibration scheme that involves moving the reference planes to the surface of the sample. In the first stage, the VNA is automatically calibrated using full 2-port SOLT calibration. In the second stage, the cables are de-embedded. Finally, in the third stage, we compensate for the amplitude and phase distortions in free space.

Slide 20

Our custom-designed programable multiplexer consists of a DC power supply, two RF SP6T switches, solid-state relays, and an Arduino 2560 microprocessor. In addition to controlling the internal SP6T switches, the multiplexer also controls RF SP4T switches located inside the antenna pillars, which are used to de-embed the long antenna cables. On the front panel, there are 12 V outputs for controlling external switches, as well as a digital GPIO and a 10-bit analog input for 0-5 V.

浙江大學
ZHEJIANG UNIVERSITY

SP4T switches located inside the antenna pillars are used to terminate the antenna cables with SOL coaxial standards. These standards are necessary to create a cable S-parameter model and to perform its automatic de-embedding. The SP4T switches are controlled by wires coming from the multiplexer, along with the antenna cables. After measuring the SOL reflections from the cables, they are switched to enable the antenna measurements.

During automatic measurements, the multiplexer is controlled by a Python program. For benchtop measurements, we have created a separate graphical user interface (GUI) using the Nord-Red programming language, which is commonly used in Internet of Things (IoT) applications.

SP6T switches in the multiplexer are terminated using coaxial SOL standards - that is, a SHORT, OPEN, and LOAD - and are also connected by a short cable jumper that represents the THRU standard. In the first stage, the full 2-port SOLT calibration of the VNA is conducted, which also includes calibrating the short cables from VNA to the multiplexer. Once calibrated, the reference planes are set at the outputs of the switches, and all subsequent measurements are taken relative to these reference planes. This calibration process is fully automated, with the Python program controlling the multiplexer.

Slide 24

Once the calibration process is complete, it is saved and activated on the VNA. This ensures that the calibration is applied to all subsequent measurements.

All measurements in Stage II are carried out with respect to the reference planes established at the outputs of SP6T switches in the multiplexer.

A complete S-parameter model of a long antenna cable is created using what is known as the 3-term model. To achieve this, we need to measure three reflection coefficients (S11-parameters) when the cable is terminated by SOL coaxial standards on SP4T switches inside the antenna pillar. This process is fully automated and controlled by the multiplexer.

The S-parameter model of each cable is automatically uploaded to the VNA for de-embedding. In this process, each cable is treated as an additional network after the reference plane that was established in Stage I. De-embedding involves virtually removing these networks, which effectively moves the reference planes up to the outputs of the SP4T switches inside the antenna pillars.

All measurements in Stage III are carried out with respect to the reference planes established at the outputs of SP4T switches inside the antenna pillars.

Slide 29

In the final Stage III of the calibration process, the amplitude and phase distortions are eliminated that are introduced by antennas and free space. There are two ways to achieve this: Response&Isolation and TRL calibration. For Response&Isolation procedure, the antennas remain stationary while the transmission and reflection coefficients are measured from and through the open window, metal screen, and absorber. Based on these measurements, the S-parameters measured from the sample under test can be normalised to obtain their undistorted values. This normalization procedure involves some mathematics, which we will not delve into explaining in this presentation. It's important to note that while the Response&Isolation procedure is effective in eliminating amplitude and phase distortions, it is not a complete calibration method. This is because it does not recreate S-parameters of the networks associated with the antennas and free space. Since this stage involves manipulation with the screens, it cannot be fully automated.

浙江大學
ZHEJIANG UNIVERSITY

TRL, or THRU, REFLECT, LINE, is a complete calibration technique that allows for the recreation of all the S-parameters of the network, including the antenna and free space. This calibration method involves the use of the open window, a metal screen, and a few linear standards, which require the movement of the antennas in order to introduce some phase incursion compared to THRU standard with the open window. Since this stage involves manipulation with the screens, it cannot be fully automated.

When it comes to TRL calibration, the reconstructed S-parameter model of the free space network can be merged with the cable network derived in the previous stage for automatic de-embedding. This will enable us to visualize the results of corrected measurements directly on the VNA's screen.

After Stage III of calibration, the reference planes will be shifted to the surface of the sample under test, and measurements of the sample will be conducted with respect to these reference planes.

The system architecture is displayed on this slide. The software part includes a Python program and two Python libraries, PyVISA and HTTP, which are utilized to communicate with VNA and Kollmorgen servo controller, respectively. These devices are connected via a LAN switch. Two servo motors for the left and right antennas, controlled by a common controller and individual motor drivers, are connected to the local EtherCAT network. The free space measurements are controlled through a graphical user interface (GUI) written in Node-Red, an IoT programming tool. GUI communicates with the rest of the program through the MQTT protocol. The multiplexer is controlled by the Python program and connected to PC via USB.

浙江大學
ZHEJIANG UNIVERSITY

We have enabled remote programming and laboratory management through the use of RealVNC cloud technology. This wonderful tool has allowed us to continue the project even during the pandemic. Additionally, we organized a webinar for students, in which we were able to broadcast measurements directly from the laboratory.

Automation and robotics have made their way into many fields of study, including microwave technology. However, it should be recognized that combining these technologies can present significant challenges for research groups, as our own experience has demonstrated. Currently, antenna movement is only used for TRL calibration, but there may be other measurement schemes that require precise positioning. Our robotics system consists of two belt actuators that drive the antenna trolleys, a single motor controller, and two Kollmorgen servo motors with drivers. The motors are connected to each other via a local EtherCAT network, and we have developed our own Python software to control them.