Implementation of SOLT calibration for an obsolete VNA

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Introduction

Obsolete vector network analysers (VNAs) in principle allow one to create user's calibration kits, but only as analytical models including capacitances, inductances, resistances, and delay lines for coaxial terminations. Determining these parameters is a complex task. In modern VNAs, a more convenient option is available when instead of the models for each calibration standard its Touchstone s1p (SHORT, OPEN, LOAD) or s2p (THRU) file can be used. The implementation of the SOLT calibration with the s1p/s2p files for the coaxial terminations developed in the present project was intended to expand the functionality of VNA HP8753E (30 kHz – 6 GHz) in a research lab at MISiS. Experimental setup for measuring high-frequency magneto-impedance in ferromagnetic wires, see Fig. 1, was developed and then deployed for this lab by DYK in 2017-2018.

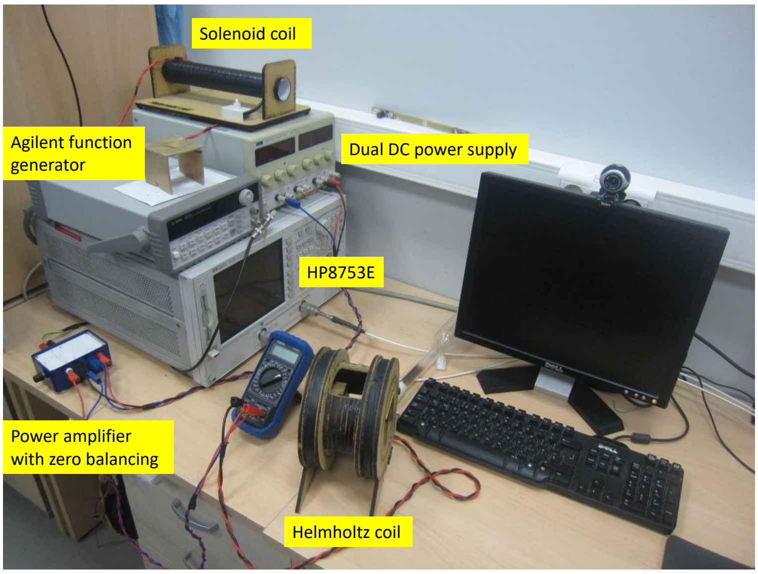


Fig. 1. Experimental setup for measuring high-frequency magneto-impedance in ferromagnetic wires. Designed and deployed for a research lab at MISiS by DYK in 2017-2018.

The measurement scheme is shown in Fig. 2. The instruments (VNA and function generator) are controlled by Agilent VEE 6.0 program. This program was written by us a long time ago and only slightly modified for the current project. The SOLT calibration was not implemented there, only acquisition of the raw S-parameters. Therefore, a separate console application (compiled executable file) was developed and compiled in Fortran 90 to correct S-parameters measured from the sample under test and saved in the csv files. The console application uses the s1p and s2p files for the SOLT terminations and additional S-parameter measurements required for the calibration. Its use is explained later in this report. Fortran and VEE programs, as well as the console application, have been stored in a repository on GitHub. Obviously, these measurement and calibration procedures are rather laborious. We are planning to upgrade the system as shown in Fig. 3, using a more powerful computer, GPIB-USB adapter, and control program written entirely in Python, including SOLT calibration and GUI. Interaction with VNA and the function generator will be carried out through PyVISA using SCPI script commands. Using these tools, we can configure instruments, receive raw data from VNA, apply error corrections, save the corrected traces in files on the computer or return them to VNA for visualization on its monitor. Through SCPI commands, we can create virtual buttons to emulate the front panel of VNA. When requested by the SCPI command, VNA can provide a monitor image dump for transmission via GPIB or parallel port as a graphic file in the HP-GL text format. There are graphical libraries in Python that allow one to work with this format. We would also like to implement the time domain option that would allow the signal integrity measurements.

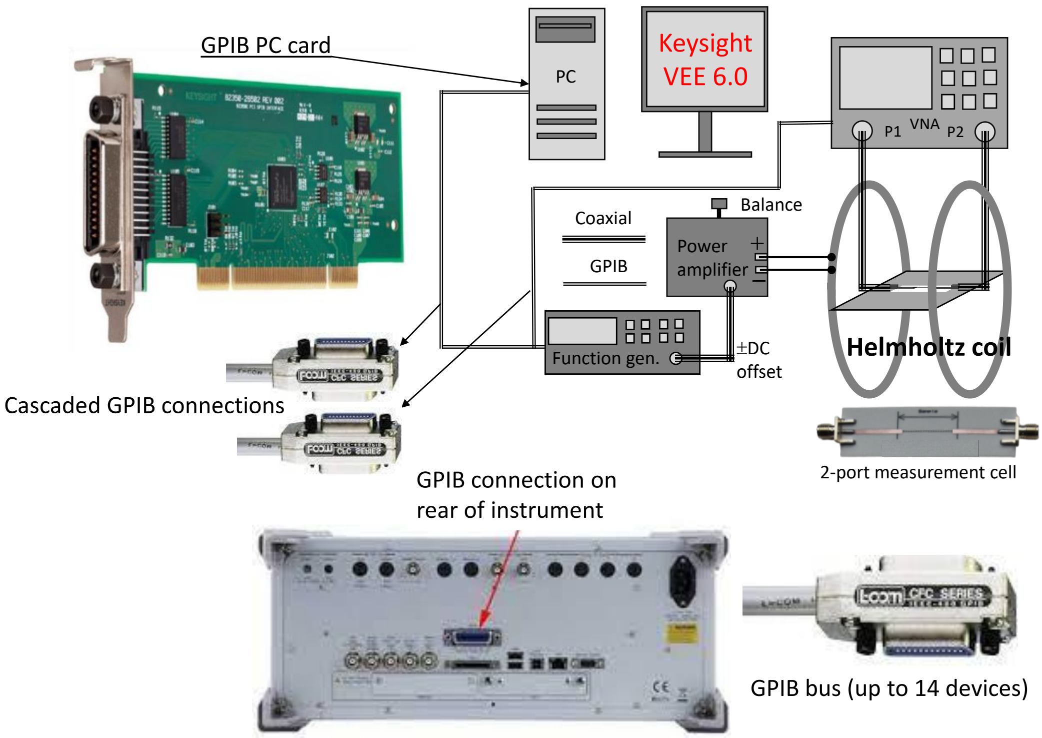


Fig. 2. Currently implemented measurement scheme at MISiS.

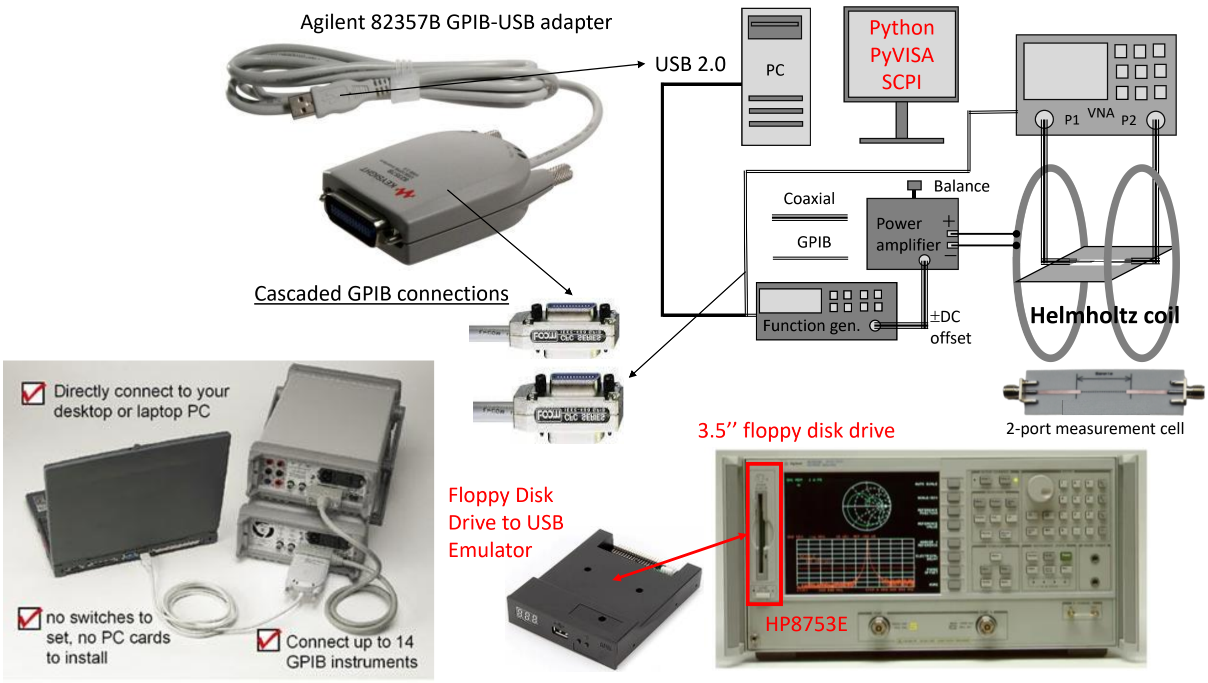


Fig. 3. Planned upgrade of the measurement system at MISiS.

VNA has a relic of the past era – 3.5-inch floppy disk drive. It will be replaced by the GOTEK emulator for connecting a USB flash drive. The emulator itself will have to be modified to make disk switching software, and not two buttons as in GOTEK.

Coaxial and non-coaxial terminations

Let us remind the format of Touchstone text files having the extensions s1p or s2p. Both files must include the header # Hz S RI R 50 which indicates that the frequency is measured in Hz, S-parameters are represented as the real and imaginary parts RI, and the characteristic impedance R is 50 Ω. The s1p file contains dispersion of the complex reflection coefficient S_{11} (or S_{22}) and consists of three columns: frequency f, $\mathrm{Re}[S_{11}(f)]$, $\mathrm{Im}[S_{11}(f)]$. The s2p text file contains dispersion of all S-parameters and consists of nine columns: f, $\mathrm{Re}[S_{11}(f)]$, $\mathrm{Im}[S_{11}(f)]$, $\mathrm{Re}[S_{21}(f)]$, $\mathrm{Im}[S_{21}(f)]$, $\mathrm{Re}[S_{12}(f)]$, $\mathrm{Im}[S_{12}(f)]$, $\mathrm{Re}[S_{22}(f)]$, $\mathrm{Im}[S_{22}(f)]$. The s1p files for the coaxial terminations SHORT, OPEN, and LOAD, and the s2p file for the THRU jumper can be accurately measured on VNA pre-calibrated with a commercial coaxial kit. The frequency range determines the type of coaxial connector: up to 20 GHz – SMA, up to 26.5 GHz – 3.5 mm, and up to 40 GHz – K-type (or 2.92 mm). All three types are mechanically compatible. The terminations SHORT and OPEN can be bought or made of the coaxial connectors, as shown in Fig. 4. The THRU jumper can be made of a coaxial adapter or a rigid/semi-rigid cable assembly. LOAD has to be bought. We recommend Chinese AliExpress (international) or Taobao (national) online shops to buy cheap SOL terminations or calibration kits up to $18-20$ GHz.

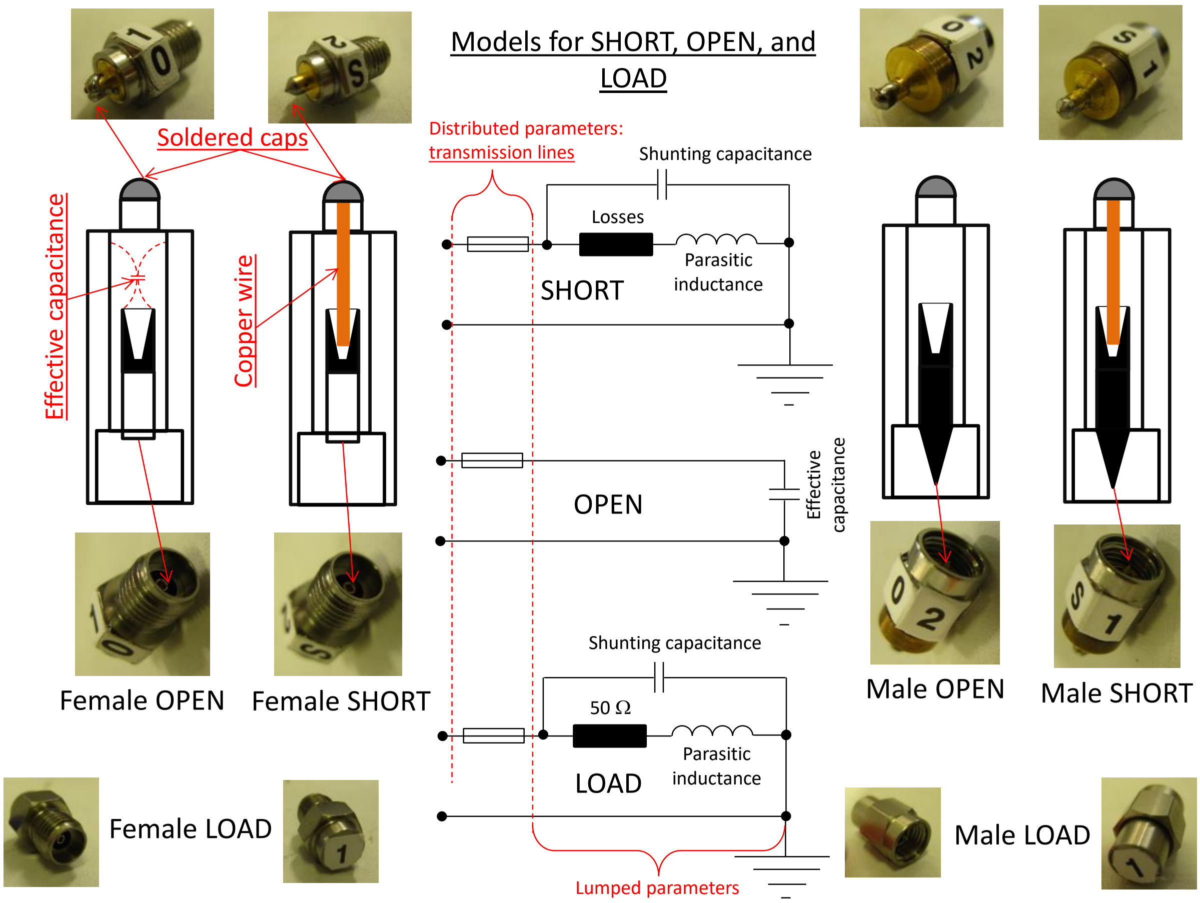


Fig. 4. Terminations SHORT, OPEN, and LOAD made of coaxial connectors (SMA/3.5 mm/2.92 mm).

The things are getting more complicated for the PCB measurement cells. For de-embedding the microstrips, they will require additional calibration cells with the microstrips of the same shape and size, but terminated with surface SHORT (via to the ground), OPEN (open end), and LOAD (two 100 Ω Vishay RF resistors connected in parallel to the ground through the vias). Fig. 5 shows such a set for a dogbone PCB cell used to measure the stress impedance in ferromagnetic wires. The test piece of wire is placed in the gap between the microstrips and connected to their ends with silver paint or epoxy resin. Tension is transferred to the wire through the cell fixed between the grippers of the testing machine. In addition to tensile stress, this cell allows the application of an external magnetic field as well as localized heating. If stress is not an external stimulus being studied, then a simpler straight cell can be used. The s1p files of the surface mount terminations cannot be measured directly. However, due to their miniature dimensions, they can be considered "almost ideal" up to 8 GHz and even higher frequencies. “Ideal” means that $S_{11\mathrm{OPEN}} \equiv 1$, $S_{11\mathrm{SHORT}} \equiv -1$, $S_{11\mathrm{LOAD}} \equiv 0$ for any frequencies (dispersionless). Since for THRU a direct connection of the microstripes is used, then $S_{21} \equiv S_{12} \equiv 1$, $S_{11} \equiv 0$, and $S_{22} \equiv 0$. Although this standard is for reference measurements only and is not used for the microstrip de-embedding.

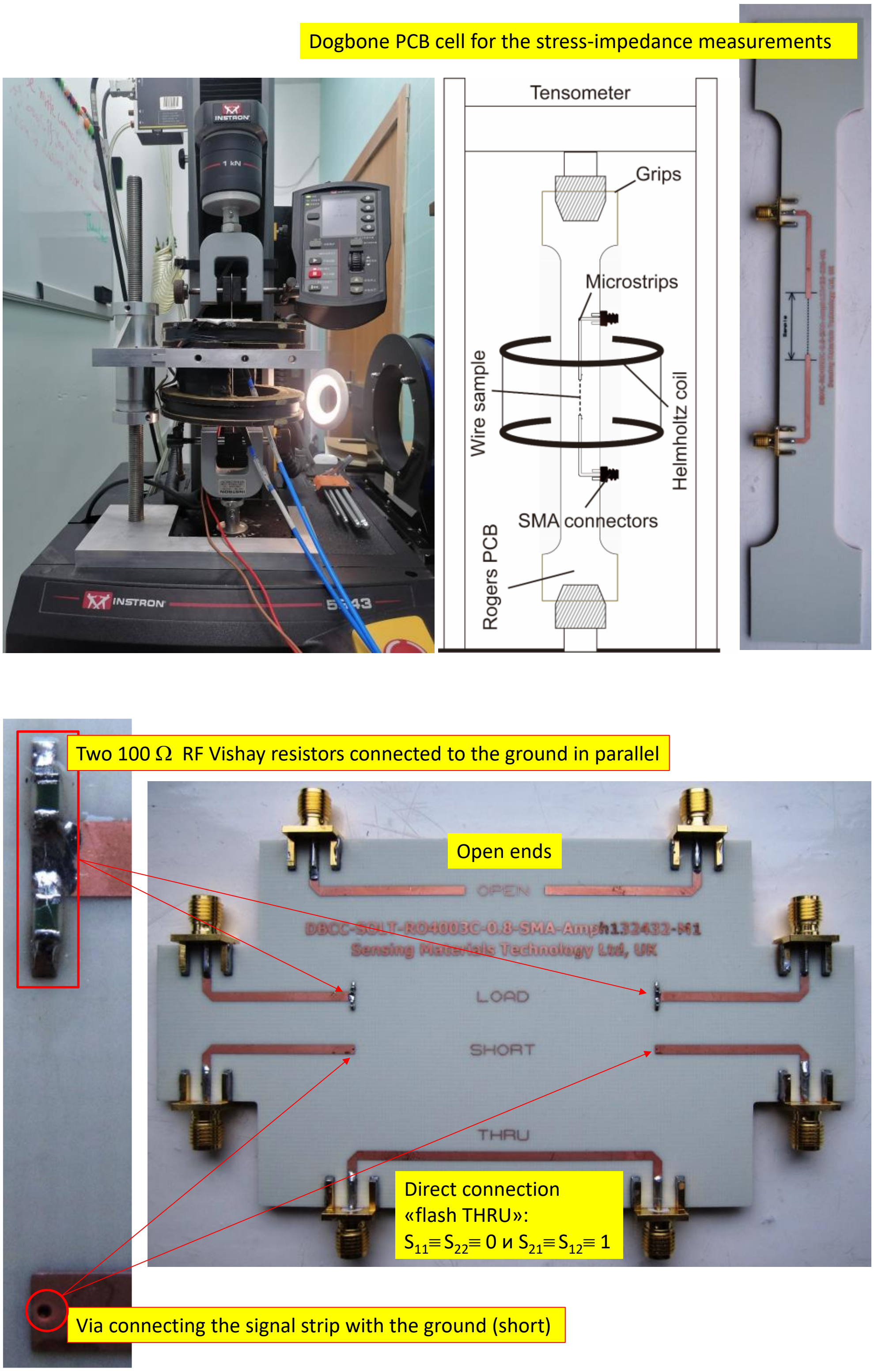


Fig. 5. The dogbone PCB measurement and calibration cells with the surface mount SOLT standards. Such cells are used for measuring the stress-dependence of the high-frequency impedance in ferromagnetic wires.

A detailed discussion of the impedance measurements on the PCB cells and the 3-stage calibration method, see Fig. 6, can be found in another report of ours. Also see our website where all reports are stored. In the present report, we only discuss the implementation of SOLT calibration for the legacy VNA HP8753E. In order to make PCB impedance measurements, we need to save several intermediate csv files that are used in several programs that perform all calibration steps, including SOLT, microstrip de-embedding, and delay compensation along a wire sample. In a future upgrade, SOLT and the next two stages in Fig. 6 will be merged into a single program.

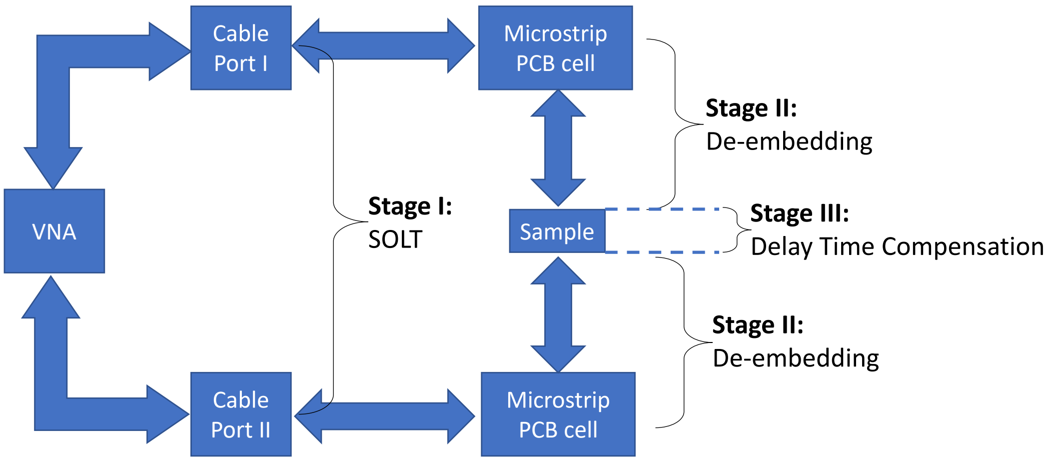


Fig. 6. 3-stage calibration method used for the impedance measurements on the PCB cells.

Origins of regular errors in a VNA

To create a realistic model of functioning of a VNA measurement port, it will be sufficient to consider its scheme shown in Fig. 7. According to this scheme, the port includes a tunable RF harmonic source, directional coupler, receiver of the test signal, and receiver of the reference signal (not explicitly shown). The receiver of reference signal registers amplitude and phase of the excitation signal from the RF source. The role of the directional coupler is to pass only the reflected or coming signal from an external device connected to the port. This signal is registered by the test receiver. At the same time, the signal from the source must not enter the test receiver bypassing the port – it is cut off by the directional coupler. However, some signal leakage is always observed from the source to the test receiver bypassing the external device. The complex ratio of the leakage signal to the reference signal is called the directivity. In addition, a signal leakage from the source of the active port to the test receiver of the passive port can be observed bypassing the external measurement track, i.e. due to interference inside of VNA. This type of leakage is called the isolation or crosstalk. In modern analysers, the isolation is so high that this type of signal leakage between the ports is usually not taken into account when calibrating.

Other two origins of regular errors are the impedance mismatches: (i) mismatch between the measurement track and the active port (signal source mismatch) and (ii) mismatch between the measurement track and the passive port (load mismatch), as shown in Fig. 8. Both mismatches result in multiple reflections that blend with the useful signal in the directional couplers. For a quantitative evaluation of these mismatches, corresponding reflection coefficients can be introduced. Next, it should be taken into account that any device transfer functions are prone to the frequency dispersion, and hence even in the absence of regular errors mentioned above the measured signal will be linearly distorted by amplitude and phase. Taking into account the frequency dispersion of the signal transfer functions is called the tracking and it can be described by the corresponding transmission coefficient.

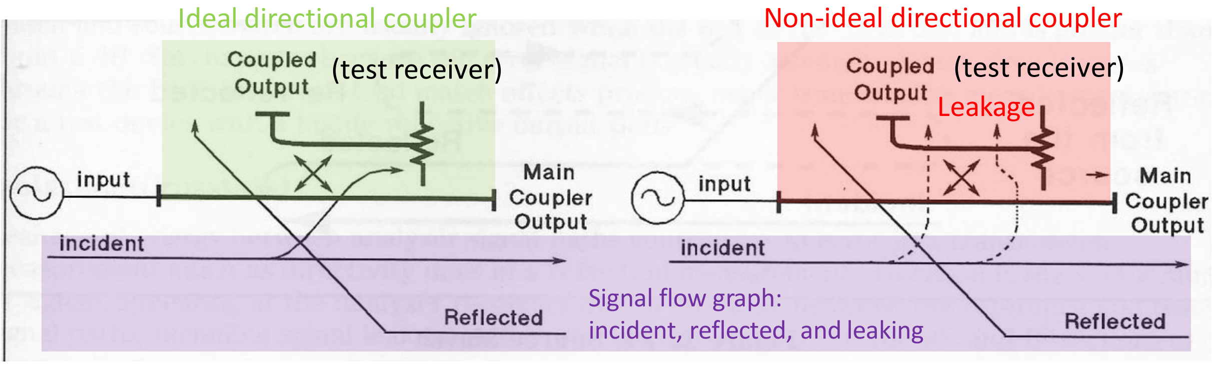
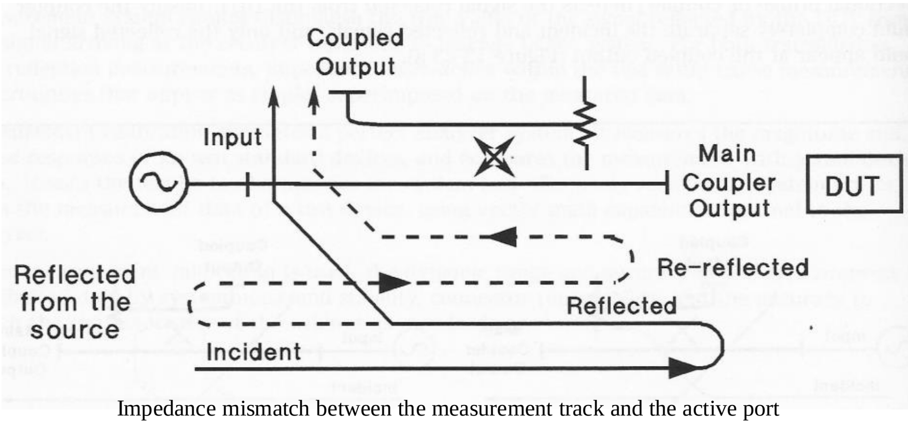
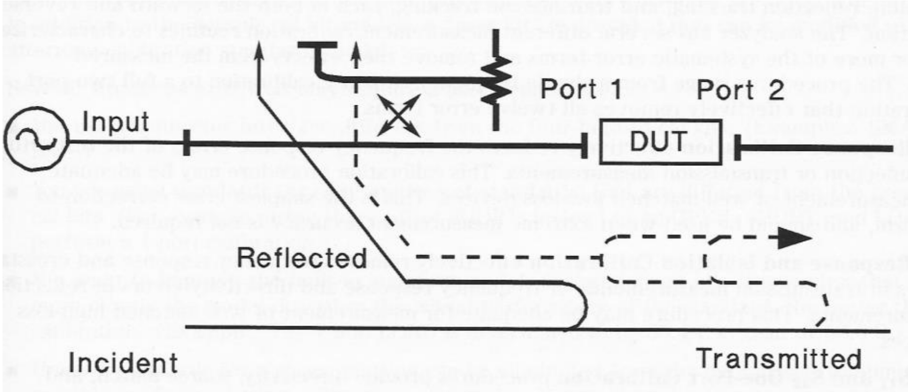


Fig. 7. Signal leakage from the RF source to the test receiver bypassing the port in a non-deal directional coupler.



Impedance mismatch between the measurement track and the active port (signal source mismatch).



Impedance mismatch between the measurement track and the passive port (load mismatch).

Fig. 8. Impedance mismatches: (i) mismatch between the measurement track and the active port and (ii) mismatch between the measurement track and the passive port.

Error models in a 1-port or 2-port VNA

In the previous section, we have identified the types of regular errors in a VNA: *directivity*, *source mismatch*, *load mismatch*, *isolation/crosstalk*, and *tracking*. Below we consider the signal flow graphs and the calibration procedures that allow one to correct S-parameters measured from a DUT. The errors will be characterised by their S-parameters, denoted as E-parameters and provided with two-letter indices. The first index will designate one of the following errors: *D-directivity*, *R-reflection*, *T-transmission*, *S-source mismatch*, *L-load mismatch*, and *X-crosstalk*. The second index will be *F-forward* when the first port is active and the second port is passive, and *R-reverse* when it is the other way around. We obtain the following list of the regular errors, 12 in total:

E_{DF} – directivity forward	E_{DR} – directivity reverse
E_{SF} – source mismatch forward	E_{SR} – source mismatch reverse
E_{RF} – reflection tracking forward	E_{RR} – reflection tracking reverse
E_{LF} – load mismatch forward	E_{LR} – load mismatch reverse
E_{TF} – transmission tracking forward	E_{TR} – transmission tracking reverse
E_{XF} – crosstalk forward	E_{XR} – crosstalk reverse

3-term error model for the 1-port measurements

Let us begin with the 1-port measurement, shown in Fig. 9, which is described by the error model consisting of three terms: E_{DF}, E_{RF}, and E_{SF}. The only measurement parameter is the reflection coefficient S_{11M}. We would like to know the actual reflection coefficient S_{11A} from DUT. By means of three additional measurements from the standards SHORT, OPEN, and LOAD, it is possible to find E_{DF}, E_{RF}, and E_{SF}, and then recover S_{11A}.

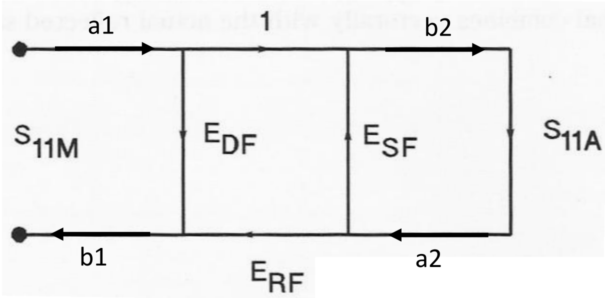


Fig. 9. 3-component error model for the 1-port measurements.

Let us consider the system of linear equations describing the signal flow graph in Fig. 9:

$$\begin{cases} b_1 = a_1 E_{DF} + a_2 E_{RF} \\ b_2 = a_1 + a_2 E_{SF} \\ a_2 = b_2 S_{11A} \end{cases} \qquad (1)$$

Here, $a_{1,2}$ and $b_{1,2}$ are some complex amplitudes. Excluding a_2 and b_2, we obtain:

$$S_{11M} = \frac{b_1}{a_1} = E_{DF} + \frac{E_{RF} S_{11A}}{1 - S_{11A} E_{SF}} \qquad (2)$$

Using (2), S_{11A} can be expressed through S_{11M}:

$$S_{11A} = \frac{S_{11M} - E_{DF}}{E_{RF} + E_{SF}(S_{11M} - E_{DF})} \qquad (3)$$

Eq. (3) is the essence of the 1-port calibration, and it allows one to recover the actual reflection coefficient from the measured one. In (3), we have three unknowns E_{DF}, E_{RF}, and E_{SF} (3-term model). To find them, we will measure the reflection coefficient S_{11M} from three known standards *S*-SHORT, *O*-OPEN, and *L*-LOAD. Using (2), we obtain:

$$\begin{cases} S_{11MS} = E_{DF} + \frac{E_{RF} S_{11S}}{1 - S_{11S} E_{SF}} \\ S_{11MO} = E_{DF} + \frac{E_{RF} S_{11O}}{1 - S_{11O} E_{SF}} \\ S_{11ML} = E_{DF} + \frac{E_{RF} S_{11L}}{1 - S_{11L} E_{SF}} \end{cases} \qquad (4)$$

where $S_{11M} = S_{11MS,O,L}$ and $S_{11A} = S_{11S,O,L}$ depending on the measured standard. Where to get $S_{11S,O,L}$ has been explained in Introduction. The system of equations (4) can be rewritten in the following form:

$$\begin{cases} E_{DF} + S_{11MS} S_{11S} E_{SF} + S_{11S}(E_{RF} - E_{DF} E_{SF}) = S_{11MS} \\ E_{DF} + S_{11MO} S_{11O} E_{SF} + S_{11O}(E_{RF} - E_{DF} E_{SF}) = S_{11MO} \\ E_{DF} + S_{11ML} S_{11L} E_{SF} + S_{11L}(E_{RF} - E_{DF} E_{SF}) = S_{11ML} \end{cases} \qquad (5)$$

which is a system of linear equations with respect to the three unknowns $x = E_{DF}$, $y = E_{SF}$, and $z = (E_{RF} - E_{DF} E_{SF})$.

Let us write (5) in a matrix form:

$$\begin{pmatrix} 1 & S_{11MS}S_{11S} & S_{11S} \\ 1 & S_{11MO}S_{11O} & S_{11O} \\ 1 & S_{11ML}S_{11L} & S_{11L} \end{pmatrix} \times \begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} S_{11MS} \\ S_{11MO} \\ S_{11ML} \end{pmatrix} \quad (6)$$

Solving (6) numerically, we will find $E_{DF} = x$, $E_{SF} = y$, and $E_{RF} = z + E_{DF}E_{SF}$ (all of them are complex). In the case of coaxial standards, the parameters S_{11S}, S_{11O}, and S_{11L} will be known from the precisely measured s1p files. We will not derive analytical formulas for the solution of (6) because it is not actual for numerical calculations.

In the case of the PCB standards in Fig. 5 which are assumed to be "ideal", i.e. $S_{11S} \equiv -1$, $S_{11O} \equiv 1$, and $S_{11L} \equiv 0$, the system (6) will take the form:

$$\begin{pmatrix} 1 & -S_{11MS} & -1 \\ 1 & S_{11MO} & 1 \\ 1 & 0 & 0 \end{pmatrix} \times \begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} S_{11MS} \\ S_{11MO} \\ S_{11ML} \end{pmatrix} \quad (7)$$

12-term error model for the 2-port measurements

For the 2-port measurements, we will use the error model shown in Fig. 10. As it has been mentioned above, the crosstalks E_{XF} and E_{XR} between the ports can be neglected for most measurements, and hence the 12-term model in Fig. 10 becomes the 10-term model that we continue to work with. To calculate the signal diagram, let us use the system of reference x and y points shown in Fig. 11.

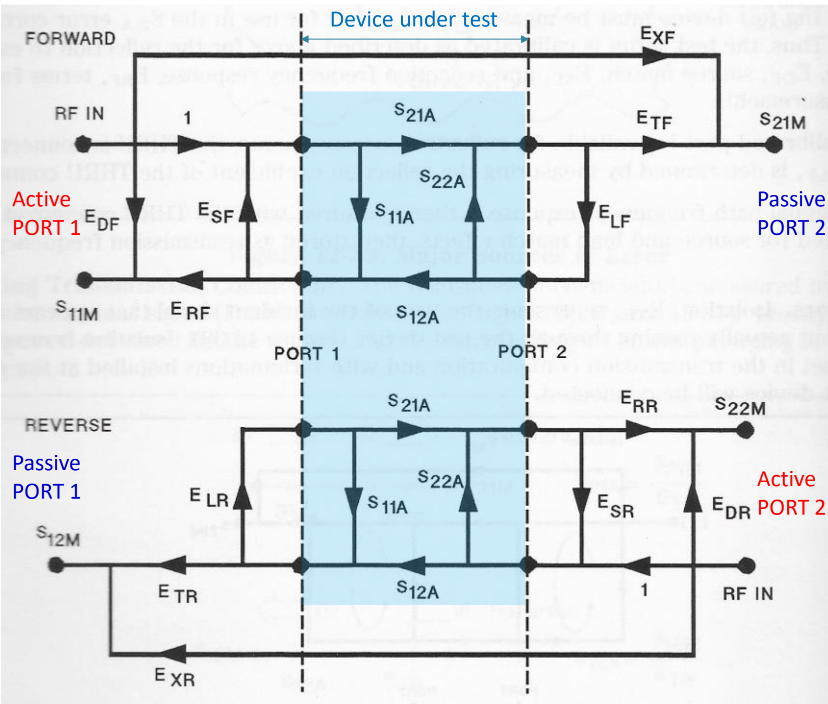


Fig. 10. 12-term error model for the 2-port measurements. For further calculations, we will neglect the crosstalks E_{XF} and E_{XR} between the ports.

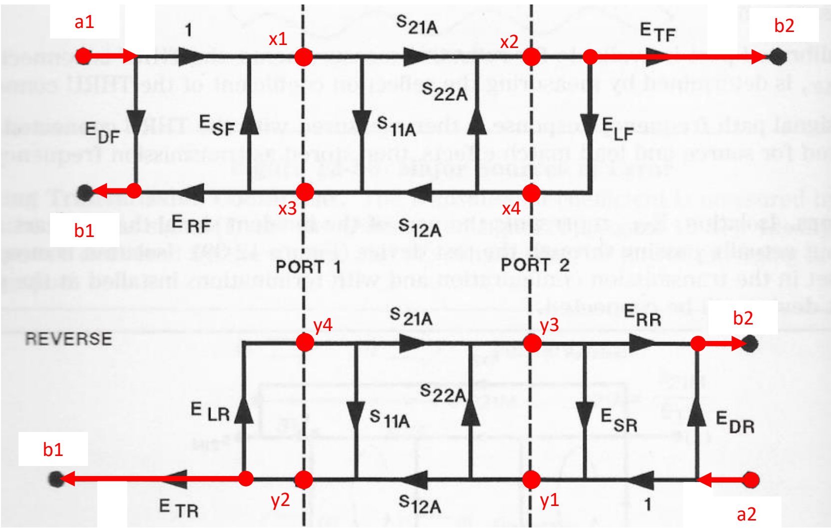


Fig. 11. The system of reference *x* and *y* points used to calculate the signal diagram.

For the signals coming into the reference points and for the network input and output signals, we obtain the following equations:

$$\begin{cases} b_1 = a_1 E_{DF} + x_3 E_{RF} \\ x_1 = a_1 + x_3 E_{SF} \\ x_3 = x_1 S_{11A} + x_4 S_{12A} \\ x_2 = x_1 S_{21A} + x_4 S_{22A} \\ x_4 = x_2 E_{LF} \\ b_2 = x_2 E_{TF} \\ \\ b_2 = a_2 E_{DR} + y_3 E_{RR} \\ y_1 = a_2 + y_3 E_{SR} \\ y_3 = y_1 S_{22A} + y_4 S_{21A} \\ y_2 = y_1 S_{12A} + y_4 S_{11A} \\ y_4 = y_2 E_{LR} \\ b_1 = y_2 E_{TR} \end{cases} \tag{8}$$

Excluding the reference points from (8), we obtain:

$$\begin{cases} S_{11M} = \frac{b_1}{a_1} = E_{DF} + \frac{S_{21M} S_{11A} E_{RF}}{S_{21A} E_{TF}} - \frac{S_{21M} S_{11A} S_{22A} E_{LF} E_{RF}}{S_{21A} E_{TF}} + \frac{S_{21M} S_{12A} E_{RF} E_{LF}}{E_{TF}} \\ \frac{1}{S_{21A} E_{TF}} - \frac{S_{22A} E_{LF}}{S_{21A} E_{TF}} = \frac{1}{S_{21M}} + \frac{S_{11A} E_{SF}}{S_{21A} E_{TF}} - \frac{S_{11A} S_{22A} E_{LF} E_{SF}}{S_{21A} E_{TF}} + \frac{S_{12A} E_{SF} E_{LF}}{E_{TF}} \\ S_{21M} = \frac{b_2}{a_1} \\ \\ S_{22M} = \frac{b_2}{a_2} = E_{DR} + \frac{S_{12M} S_{22A} E_{RR}}{S_{12A} E_{TR}} - \frac{S_{12M} S_{11A} S_{22A} E_{LR} E_{RR}}{S_{12A} E_{TR}} + \frac{S_{12M} S_{21A} E_{LR} E_{RR}}{E_{TR}} \\ \frac{1}{S_{12A} E_{TR}} - \frac{S_{11A} E_{LR}}{S_{12A} E_{TR}} = \frac{1}{S_{12M}} + \frac{S_{22A} E_{SR}}{S_{12A} E_{TR}} - \frac{S_{11A} S_{22A} E_{LR} E_{SR}}{S_{12A} E_{TR}} + \frac{S_{21A} E_{LR} E_{SR}}{E_{TR}} \\ S_{12M} = \frac{b_1}{a_2} \end{cases} \tag{9}$$

Simplifying (9), we obtain:

$$\begin{cases} S_{11M} = E_{DF} + \frac{S_{11A}E_{RF} - E_{LF}E_{RF}det_A}{1 - S_{11A}E_{SF} - S_{22A}E_{LF} + E_{LF}E_{SF}det_A} \\ S_{21M} = \frac{S_{21A}E_{TF}}{1 - S_{11A}E_{SF} - S_{22A}E_{LF} + E_{LF}E_{SF}det_A} \\ S_{22M} = E_{DR} + \frac{S_{22A}E_{RR} - E_{LR}E_{RR}det_A}{1 - S_{11A}E_{LR} - S_{22A}E_{SR} + E_{LR}E_{SR}det_A} \\ S_{12M} = \frac{S_{12A}E_{TR}}{1 - S_{11A}E_{LR} - S_{22A}E_{SR} + E_{LR}E_{SR}det_A} \end{cases} \tag{10}$$

where

$$det_A = \begin{vmatrix} S_{11A} & S_{12A} \\ S_{21A} & S_{22A} \end{vmatrix} = S_{11A}S_{22A} - S_{12A}S_{21A} \tag{11}$$

All errors in (10), with the exception of E_{TF}, E_{LF}, E_{TR}, and E_{LR}, can be found from the 1-port calibration of each port using (6), (7):

$$\begin{pmatrix} 1 & S_{11S}S_{11MS} & S_{11S} \\ 1 & S_{11O}S_{11MO} & S_{11O} \\ 1 & S_{11L}S_{11ML} & S_{11L} \end{pmatrix} \times \begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} S_{11MS} \\ S_{11MO} \\ S_{11ML} \end{pmatrix} \tag{12}$$

$E_{DF} = x$, $E_{SF} = y$, and $E_{RF} = z + E_{DF}E_{SF}$

$$\begin{pmatrix} 1 & S_{22S}S_{22MS} & S_{22S} \\ 1 & S_{22O}S_{22MO} & S_{22O} \\ 1 & S_{22L}S_{22ML} & S_{22L} \end{pmatrix} \times \begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} S_{22MS} \\ S_{22MO} \\ S_{22ML} \end{pmatrix} \tag{13}$$

$E_{DR} = x$, $E_{SR} = y$, and $E_{RR} = z + E_{DR}E_{SR}$

If the same calibration standards are used for both ports (e.g. same-sex cables), then $S_{22S} \equiv S_{11S}$, $S_{22O} \equiv S_{11O}$, and $S_{22L} \equiv S_{11L}$. However, even in this case it is not necessarily that $S_{22MS} \equiv S_{11MS}$ and etc.

To find the remaining four errors E_{TF}, E_{LF}, E_{TR}, and E_{LR}, let us make use of (10) where S_{ijT}-parameters of the THRU standard must be put instead of S_{ijA}-parameters:

$$\begin{cases} E_{LF} = \frac{S_{11T}E_{RF} + S_{11T}(S_{11MT} - E_{DF})E_{SF} - (S_{11MT} - E_{DF})}{(E_{SF}\,det_T - S_{22T})(S_{11MT} - E_{DF}) + E_{RF}det_T} \\ E_{LR} = \frac{S_{22T}E_{RR} + S_{22T}(S_{22MT} - E_{DR})E_{SR} - (S_{22MT} - E_{DR})}{(E_{SR}\,det_T - S_{11T})(S_{22MT} - E_{DR}) + E_{RR}det_T} \\ \qquad \Downarrow \\ E_{TF} = \frac{S_{21MT} + S_{21MT}E_{LF}(E_{SF}\,det_T - S_{22T}) - S_{11T}S_{21MT}E_{SF}}{S_{21T}} \\ E_{TR} = \frac{S_{12MT} + S_{12MT}E_{LR}(E_{SR}\,det_T - S_{11T}) - S_{22T}S_{12MT}E_{SR}}{S_{12T}} \end{cases} \tag{14}$$

where $det_T = S_{11T}S_{22T} - S_{21T}S_{12T}$. If a direct connection without a jumper is used for THRU – the so called “flash THRU”, then $S_{11T} \equiv S_{22T} \equiv 0$ and $S_{21T} \equiv S_{12T} \equiv 1$. For example, if two heterogeneous cables are being calibrated, they can be connected together directly. Also, we will have an ideal “flash THRU” for the PCB standards in Fig. 5.

After all the errors are already found, it is necessary to recover S_{ijA}-parameters of DUT from the measured S_{ijM}-parameters. To do this, let us make use of (10) that will be rewritten in the following form:

$$\begin{cases} S_{11A}(E_{RF}+S_{11M}E_{SF}-E_{DF}E_{SF})+S_{22A}(S_{11M}-E_{DF})E_{LF}= \\ \quad =(S_{11M}-E_{DF})+(S_{11M}E_{LF}E_{SF}-E_{DF}E_{LF}E_{SF}+E_{LF}E_{RF})det_A \\ S_{11A}S_{21M}E_{SF}+S_{22A}S_{21M}E_{LF}+S_{21A}E_{TF}=S_{21M}+S_{21M}E_{LF}E_{SF}det_A \\ S_{11A}(S_{22M}-E_{DR})E_{LR}+S_{22A}(E_{RR}+S_{22M}E_{SR}-E_{DR}E_{SR})= \\ \quad =(S_{22M}-E_{DR})+(S_{22M}E_{LR}E_{SR}-E_{DR}E_{LR}E_{SR}+E_{LR}E_{RR})det_A \\ S_{11A}S_{12M}E_{LR}+S_{22A}S_{12M}E_{SR}+S_{12A}E_{TR}=S_{12M}+S_{12M}E_{LR}E_{SR}det_A \end{cases} \tag{15}$$

With respect to S_{ijA}-parameters, the system (15) is non-linear, and we did not find an easy way to "unravel" it. Therefore, we will resort to another method of solution using the propagation P-matrices. Let us remind the formalism of S- and P-matrices in order to agree on the definitions and designations. In Fig. 12, a single 2-port network and two cascaded networks are shown.

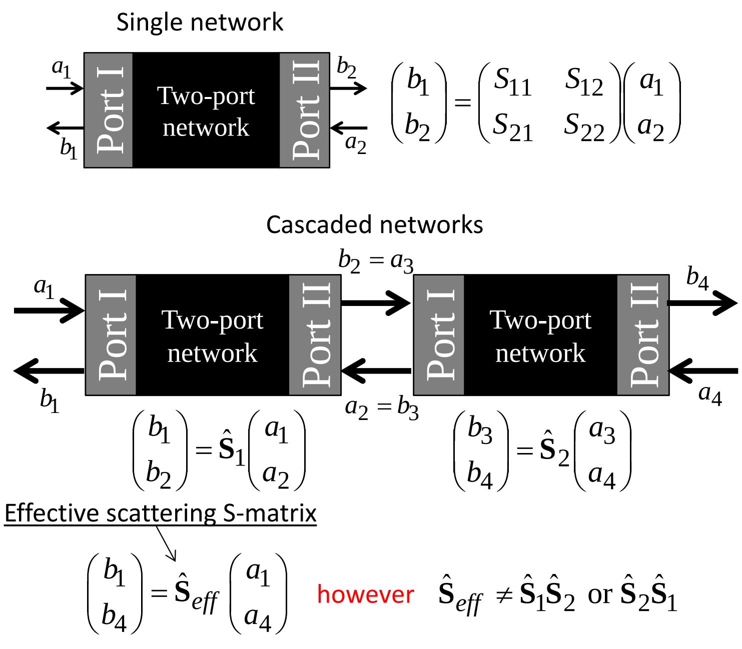


Fig. 12. 2-port linear network and cascade of two networks.

In a linear network, the input $a_{1,2}$ and output $b_{1,2}$ signals are related through linear relations. This is how S-matrix is introduced:

$$\begin{cases} b_1=S_{11}a_1+S_{12}a_2 \\ b_2=S_{21}a_1+S_{22}a_2 \end{cases} \Rightarrow \begin{pmatrix} b_1 \\ b_2 \end{pmatrix}=\begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix}\begin{pmatrix} a_1 \\ a_2 \end{pmatrix} \Rightarrow \vec{\mathbf{b}}=\hat{\mathbf{S}}\vec{\mathbf{a}} \tag{16}$$

The components of $\hat{\boldsymbol{S}}$ usually depend on the frequency, although we will not show this explicitly for the compactness of writing. S-parameters is defined as follows: $S_{11}=(b_1/a_1)_{a_2=0}$ and $S_{22}=(b_2/a_2)_{a_1=0}$ (reflection coefficients), $S_{12}=(b_1/a_2)_{a_1=0}$ and $S_{21}=(b_2/a_1)_{a_2=0}$ (transmission coefficients). Linear networks connected in series can be represented as a single effective network, but its effective S-matrix will not be a product of *S*-matrices of the connected networks. For the cascade calculations, the so-called transmission P-matrix is introduced (transmission from “the left” to “the right”):

$$\begin{pmatrix} b_2 \\ a_2 \end{pmatrix} = \widehat{\mathbf{P}} \begin{pmatrix} a_1 \\ b_1 \end{pmatrix} \tag{17}$$

where

$$\widehat{\mathbf{P}} = \begin{pmatrix} \frac{S_{12}S_{21}-S_{22}S_{11}}{S_{12}} & \frac{S_{22}}{S_{12}} \\ -\frac{S_{11}}{S_{12}} & \frac{1}{S_{12}} \end{pmatrix} = \begin{pmatrix} -\frac{det_A}{S_{12}} & \frac{S_{22}}{S_{12}} \\ -\frac{S_{11}}{S_{12}} & \frac{1}{S_{12}} \end{pmatrix} = \begin{pmatrix} P_{11} & P_{12} \\ P_{21} & P_{22} \end{pmatrix} \tag{18}$$

Let us note that in (18) as the result of action of the operator $\widehat{\mathbf{P}}$ on the vector $\begin{pmatrix} a_1 \\ b_1 \end{pmatrix}$ we obtain $\begin{pmatrix} b_2 \\ a_2 \end{pmatrix}$, and not $\begin{pmatrix} a_2 \\ b_2 \end{pmatrix}$. It is this definition of the transfer matrix that makes it possible to construct the cascade products as shown in Fig. 13. Also, the origin of $det_A = S_{22}S_{11} - S_{12}S_{21}$ in (10) now becomes clear because when working with the transmission functions just *S*-parameters cannot appear alone.

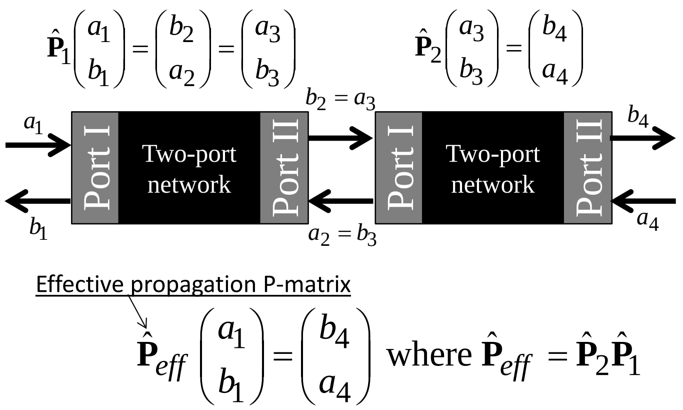


Fig. 13. Transmission matrices for the cascade network calculations.

S-matrix can be expressed through the components of P-matrix:

$$\widehat{\mathbf{S}} = \begin{pmatrix} -\frac{P_{21}}{P_{22}} & \frac{1}{P_{22}} \\ P_{11} - \frac{P_{12}P_{21}}{P_{22}} & \frac{P_{12}}{P_{22}} \end{pmatrix} \tag{19}$$

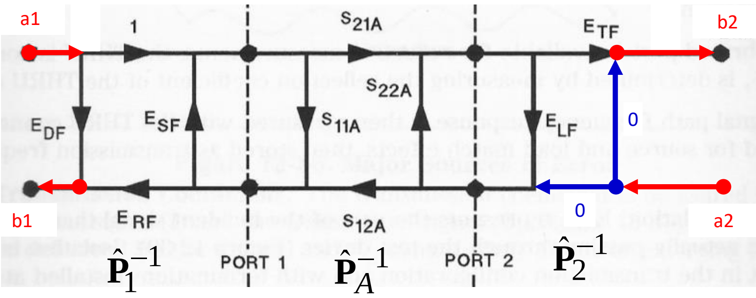
Along with the transmission “from the left to the right” in (17), P-matrix for the transmission from “the right to the left” can be introduced as well:

$$\widehat{\mathbf{P}}^{-1} \begin{pmatrix} b_2 \\ a_2 \end{pmatrix} = \begin{pmatrix} a_1 \\ b_1 \end{pmatrix} \tag{20}$$

$$\widehat{\mathbf{P}}^{-1} = \begin{pmatrix} \frac{1}{S_{21}} & -\frac{S_{22}}{S_{21}} \\ \frac{S_{11}}{S_{21}} & -\frac{det_A}{S_{21}} \end{pmatrix} \tag{21}$$

Such definition of the transmission matrix appears useful if $S_{12} = 0$ (e.g. in amplifies).

Now, let us show how first two equations in (10) and (15) can be obtained by means of the formalism of P-matrices. Let us complement the upper signal diagram in Fig. 10 up to three complete networks as shown in Fig. 14 (additional blue lines with zero transmission coefficients).



$$\begin{pmatrix} a_1 \\ b_1 \end{pmatrix} = \hat{\mathbf{P}}_1^{-1}\hat{\mathbf{P}}_A^{-1}\hat{\mathbf{P}}_2^{-1}\begin{pmatrix} b_2 \\ a_2 \end{pmatrix} \qquad \hat{\mathbf{P}}_M^{-1} = \hat{\mathbf{P}}_1^{-1}\hat{\mathbf{P}}_A^{-1}\hat{\mathbf{P}}_2^{-1}$$

Fig. 14. Upper diagram from Fig. 10 complemented up to three complete networks.

Using (21), for the networks in Fig. 14, we obtain:

$$\widehat{\mathbf{P}}_M^{-1} = \begin{pmatrix} \frac{1}{S_{21M}} & 0 \\ \frac{S_{11M}}{S_{21M}} & 0 \end{pmatrix} \tag{22}$$

$$\widehat{\mathbf{P}}_1^{-1} = \begin{pmatrix} 1 & -E_{SF} \\ E_{DF} & E_{RF} - E_{SF}E_{DF} \end{pmatrix} \tag{23}$$

$$\widehat{\mathbf{P}}_A^{-1} = \begin{pmatrix} \frac{1}{S_{21A}} & -\frac{S_{22A}}{S_{21A}} \\ \frac{S_{11A}}{S_{21A}} & -\frac{det_A}{S_{21A}} \end{pmatrix} \tag{24}$$

$$\widehat{\mathbf{P}}_2^{-1} = \begin{pmatrix} \frac{1}{E_{TF}} & 0 \\ \frac{E_{LF}}{E_{TF}} & 0 \end{pmatrix} \tag{25}$$

Multiplying the matrices in the order shown in Fig. 14 ($\widehat{\mathbf{P}}_M^{-1} = \widehat{\mathbf{P}}_1^{-1}\widehat{\mathbf{P}}_A^{-1}\widehat{\mathbf{P}}_2^{-1}$), we obtain:

$$\begin{pmatrix} \frac{1}{S_{21M}} & 0 \\ \frac{S_{11M}}{S_{21M}} & 0 \end{pmatrix} = \begin{pmatrix} 1 & -E_{SF} \\ E_{DF} & E_{RF} - E_{SF}E_{DF} \end{pmatrix} \times \begin{pmatrix} \frac{1}{S_{21A}} & -\frac{S_{22A}}{S_{21A}} \\ \frac{S_{11A}}{S_{21A}} & -\frac{det_A}{S_{21A}} \end{pmatrix} \times \begin{pmatrix} \frac{1}{E_{TF}} & 0 \\ \frac{E_{LF}}{E_{TF}} & 0 \end{pmatrix} \tag{26}$$

Simplifying, we obtain:

$$\begin{pmatrix} \frac{1}{S_{21M}} & 0 \\ \frac{S_{11M}}{S_{21M}} & 0 \end{pmatrix} = \begin{pmatrix} \frac{1}{S_{21A}E_{TF}} - \frac{S_{22A}E_{LF}}{S_{21A}E_{TF}} - E_{SF}\left(\frac{S_{11A}}{S_{21A}E_{TF}} - \frac{E_{LF}det_A}{S_{21A}E_{TF}}\right) & 0 \\ E_{DF}\left(\frac{1}{S_{21A}E_{TF}} - \frac{S_{22A}E_{LF}}{S_{21A}E_{TF}}\right) + (E_{RF} - E_{SF}E_{DF})\left(\frac{S_{11A}}{S_{21A}E_{TF}} - \frac{E_{LF}det_A}{S_{21A}E_{TF}}\right) & 0 \end{pmatrix} \tag{27}$$

Equating the nonzero components in the matrices to the left and right, we obtain:

$$\begin{cases} \frac{1}{S_{21M}} = \frac{1-S_{22A}E_{LF}-S_{11A}E_{SF}+E_{SF}E_{LF}det_A}{S_{21A}E_{TF}} \\ \frac{S_{11M}}{S_{21M}} = \frac{E_{DF}(1-S_{22A}E_{LF}-S_{11A}E_{SF}+E_{SF}E_{LF}\,det_A)+S_{11A}E_{RF}-E_{RF}E_{LF}det_A}{S_{21A}E_{TF}} \end{cases} \tag{28}$$

$$\begin{cases} S_{21M} = \frac{S_{21A}E_{TF}}{1-S_{22A}E_{LF}-S_{11A}E_{SF}+E_{SF}E_{LF}det_A} \\ S_{21M} = E_{DF} + \frac{S_{11A}E_{RF}-E_{RF}E_{LF}det_A}{1-S_{22A}E_{LF}-S_{11A}E_{SF}+E_{SF}E_{LF}det_A} \end{cases} \tag{29}$$

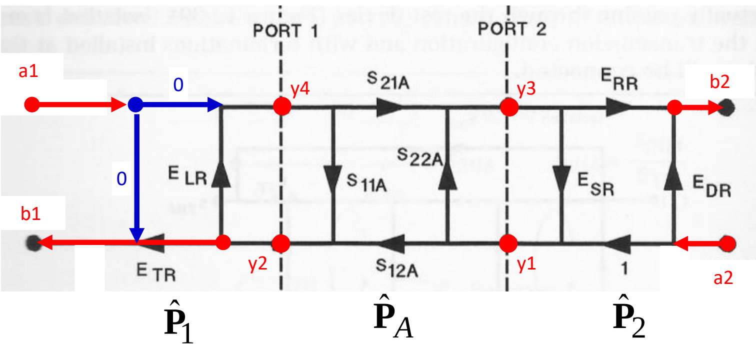
Eqs. (29) are exactly first two equations in (10) and (15). Similarly, other two equations in (10) and (15) can be obtained using the complemented diagram in Fig. 15. For it, the following matrices are used:

$$\widehat{\mathbf{P}}_M = \begin{pmatrix} 0 & \frac{S_{22M}}{S_{12M}} \\ 0 & \frac{1}{S_{12M}} \end{pmatrix} \tag{30}$$

$$\widehat{\mathbf{P}}_1 = \begin{pmatrix} 0 & \frac{E_{LR}}{E_{TR}} \\ 0 & \frac{1}{E_{TR}} \end{pmatrix} \tag{31}$$

$$\widehat{\mathbf{P}}_A = \begin{pmatrix} -\frac{det_A}{S_{12A}} & \frac{S_{22A}}{S_{12A}} \\ -\frac{S_{11A}}{S_{12A}} & \frac{1}{S_{12A}} \end{pmatrix} \tag{32}$$

$$\widehat{\mathbf{P}}_2 = \begin{pmatrix} E_{RR}-E_{DR}E_{SR} & E_{DR} \\ -E_{SR} & 1 \end{pmatrix} \tag{33}$$



$$\hat{\mathbf{P}}_2\hat{\mathbf{P}}_A\hat{\mathbf{P}}_1\begin{pmatrix} a_1 \\ b_1 \end{pmatrix} = \begin{pmatrix} b_2 \\ a_2 \end{pmatrix} \qquad \hat{\mathbf{P}}_M = \hat{\mathbf{P}}_2\hat{\mathbf{P}}_A\hat{\mathbf{P}}_1$$

Fig. 15. Lower diagram from Fig. 10 complemented up to three complete networks.

If in (15), we will try to introduce the unknowns S_{11A}, S_{12A}, S_{21A}, S_{22A}, and det_A to avoid non-linearity, their number will exceed the number of equations. Calculations with P-matrices suggest us that in the equations obtained after multiplying the transfer matrices, which constitute the cascaded networks in Figs. 14 and 15, it is possible to expose either S_{12A} or S_{21A}.

If we decide to expose S_{12A}, then rewriting the matrix equation for the network in Fig. 15 in the form $\widehat{\mathbf{P}}_A\widehat{\mathbf{P}}_1\widehat{\mathbf{P}}_M^{-1} = \widehat{\mathbf{P}}_2^{-1}$, we obtain:

$$\begin{pmatrix} -\frac{det_A}{S_{12A}} & \frac{S_{22A}}{S_{12A}} \\ -\frac{S_{11A}}{S_{12A}} & \frac{1}{S_{12A}} \end{pmatrix} \times \begin{pmatrix} \frac{E_{RF}-E_{SF}E_{DF}}{E_{RF}} & \frac{E_{SF}}{E_{RF}} \\ -\frac{E_{DF}}{E_{RF}} & \frac{1}{E_{RF}} \end{pmatrix} \times \begin{pmatrix} \frac{1}{S_{21M}} & 0 \\ \frac{S_{11M}}{S_{21M}} & 0 \end{pmatrix} = \begin{pmatrix} \frac{1}{E_{TF}} & 0 \\ \frac{E_{LF}}{E_{TF}} & 0 \end{pmatrix} \tag{34}$$

Multiplying the matrices in (34) and simplifying, we obtain:

$$\begin{pmatrix} \frac{S_{22A}(S_{11M}-E_{DF})-det_A(E_{RF}-E_{SF}E_{DF}+S_{11M}E_{SF})}{S_{12A}S_{21M}E_{RF}} & 0 \\ \frac{S_{11M}-E_{DF}-S_{11A}(E_{RF}-E_{SF}E_{DF}+S_{11M}E_{SF})}{S_{12A}S_{21M}E_{RF}} & 0 \end{pmatrix} = \begin{pmatrix} \frac{1}{E_{TF}} & 0 \\ \frac{E_{LF}}{E_{TF}} & 0 \end{pmatrix} \tag{35}$$

Equating the nonzero components in the matrices to the left and right, we obtain:

$$\begin{cases} S_{22A}(S_{11M}E_{TF} - E_{DF}E_{TF}) - S_{12A}S_{21M}E_{RF} - \\ \quad - det_A(E_{TF}E_{RF} - E_{TF}E_{SF}E_{DF} + S_{11M}E_{TF}E_{SF}) = 0 \\ \\ S_{11A}(S_{11M}E_{TF}E_{SF} - E_{TF}E_{SF}E_{DF} + E_{TF}E_{RF}) + \\ \quad +S_{12A}S_{21M}E_{RF}E_{LF} = E_{TF}(S_{11M} - E_{DF}) \end{cases} \tag{36}$$

Adding other two equations from (15) to (36), we obtain the system of linear equations with respect of the four unknowns S_{11A}, S_{22A}, S_{12A}, and det_A (no S_{21A}):

$$\begin{cases} S_{22A}(S_{11M}E_{TF} - E_{DF}E_{TF}) - S_{12A}S_{21M}E_{RF} - \\ \quad - det_A(E_{TF}E_{RF} + S_{11M}E_{TF}E_{SF} - E_{TF}E_{SF}E_{DF}) = 0 \\ \\ S_{11A}(S_{11M}E_{TF}E_{SF} - E_{TF}E_{SF}E_{DF} + E_{TF}E_{RF}) + \\ \quad +S_{12A}S_{21M}E_{RF}E_{LF} = E_{TF}(S_{11M} - E_{DF}) \\ \\ S_{11A}(S_{22M}E_{LR} - E_{DR}E_{LR}) + S_{22A}(E_{RR} + S_{22M}E_{SR} - E_{DR}E_{SR}) - \\ \quad - det_A(S_{22M}E_{LR}E_{SR} + E_{LR}E_{RR} - E_{DR}E_{LR}E_{SR}) = (S_{22M} - E_{DR}) \\ \\ S_{11A}S_{12M}E_{LR} + S_{22A}S_{12M}E_{SR} + S_{12A}E_{TR} - det_A\, S_{12M}\, E_{LR}E_{SR} = S_{12M} \end{cases} \tag{37}$$

Let us rewrite (37) in the matrix form:

$$\begin{pmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{pmatrix} \times \begin{pmatrix} S_{11A} \\ S_{22A} \\ S_{12A} \\ det_A \end{pmatrix} = \begin{pmatrix} 0 \\ E_{TF}(S_{11M} - E_{DF}) \\ (S_{22M} - E_{DR}) \\ S_{12M} \end{pmatrix} \quad (38)$$

where

$$\begin{cases} a_{11} = 0 \\ a_{21} = S_{11M}E_{TF}E_{SF} - E_{TF}E_{SF}E_{DF} + E_{TF}E_{RF} \\ a_{31} = S_{22M}E_{LR} - E_{DR}E_{LR} \\ a_{41} = S_{12M}E_{LR} \\ a_{12} = S_{11M}E_{TF} - E_{DF}E_{TF} \\ a_{22} = 0 \\ a_{32} = E_{RR} + S_{22M}E_{SR} - E_{DR}E_{SR} \\ a_{42} = S_{12M}E_{SR} \\ a_{13} = -S_{21M}E_{RF} \\ a_{23} = S_{21M}E_{RF}E_{LF} \\ a_{33} = 0 \\ a_{43} = E_{TR} \\ a_{14} = -E_{TF}E_{RF} - S_{11M}E_{TF}E_{SF} + E_{TF}E_{SF}E_{DF} \\ a_{24} = 0 \\ a_{34} = -S_{22M}E_{LR}E_{SR} - E_{LR}E_{RR} + E_{DR}E_{LR}E_{SR} \\ a_{44} = -S_{12M}E_{LR}E_{SR} \end{cases} \quad (39)$$

Then, S_{21A} can be calculated:

$$S_{21A} = \frac{S_{11A}S_{22A} - det_A}{S_{12A}} \quad (40)$$

In the case of the 2-port measurements each corrected S_{ijA}-parameter will depend on all measured S_{ijM}-parameters (see 38-40). Although explicit formulas for S_{ijA} can be found from (38)-(40), they are not necessarily optimal for calculations. Let us dwell on the system (38) that will be solved numerically using a library function. In the Fortran numerical library IMSL, high precision iterations methods are used for solving the linear systems. In the case of ill-conditioned matrices, iteration methods may provide more stable solutions, than analytical equations.

Calibration and measurement procedures

The program code for the external SOLT calibration was developed in Fortran 90 using the IMSL numerical library. From IMSL, the following subroutines were used (the first "D" in the names means double precision): spline interpolation (DCSIEZ) with recalculation to a new argument vector, and solution of a linear system of equations with complex coefficients (DLSACG).

The calibration and measured files, as well as the SOLT.exe console application that calculates the corrected S-parameters, must be located in the same folder. Below, we provide four calibration and measurement scenarios that do not appeal to the recently proposed 3-stage calibration procedure (see Fig. 6).

Scenario 1: 1-port coaxial DUT

1. Create the work folder.
2. Deactivate the error correction on VNA.
3. Copy the console application **SOLT.exe** to the work folder.
4. Copy the calibration files **S11S.csv**, **S11O.csv**, and **S11L.csv** for the coaxial SOL terminations to the work folder. Each file must contain three columns: Frequency (Hz), $\mathrm{Re}[S_{11}]$, $\mathrm{Im}[S_{11}]$. No headers.
5. Consecutively connect the coaxial calibration standards SHORT, OPEN, and LOAD to the end of cable on Port 1 and measure the dispersion of their S_{11}-parameter in a wide frequency range. Save the measured *S*-parameters in the files **S11MS.csv**, **S11MO.csv**, and **S11ML.csv**. Copy these files to the work folder.
6. Measure S_{11}-parameter from DUT, save it in the file **S11M.csv**, and copy to the work folder.
   a. If the field dependence of S_{11} is being measured, including the hysteresis, the file must contain six columns: Field (forward), $\mathrm{Re}[S_{11}]$, $\mathrm{Im}[S_{11}]$, Field (reverse), $\mathrm{Re}[S_{11}]$, $\mathrm{Im}[S_{11}]$.
   b. If the frequency dispersion of S_{11} is being measured, the file must contain three columns: Frequency (Hz), $\mathrm{Re}[S_{11}]$, $\mathrm{Im}[S_{11}]$. The file **S11M.csv** must contain the same frequency points as **S11MS.csv**.
7. Run the calculation program **SOLT.exe (Scenario 1)**.

The total number of csv files in the folder before the calculations: 7. In the prepared files, all headers must be removed – leave only the columns with values. After the calculations, there will be created two corrected files **S11corrected.csv** and **Zcorrected.csv** (impedance) in the same format as **S11M.csv** (dispersion or field dependence). If for the selected frequency range DUT cannot be considered as a lumped element, S_{11} saved in **S11corrected.csv** needs further correction to compensate for the return delay time within DUT. In this case, we cannot use **Zcorrected.csv** and the impedance must be recalculated. This procedure is not included to **SOLT.exe**. We do not discuss the compensation of the delay time here in detail, as we have finished another report to this, where the 3-stage calibration, shown in Fig. 6, has been developed.

Scenario 2: 1-port non-coaxial DUT on a PCB cell

1. Create the work folder.
1. Deactivate the error correction on VNA.
2. Copy the console application **SOLT.exe** to the work folder.
3. Consecutively connect the end of cable on Port 1 to the PCB calibration cell with the surface mount SHORT, OPEN, and LOAD terminations and measure the dispersion of their S_{11}-parameter in a wide frequency range. Save the measured S-parameters in the files **S11MS.csv**, **S11MO.csv**, and **S11ML.csv**. Copy these files to the work folder.
4. Measure S_{11}-parameter from DUT on the PCB cell, save it in the file **S11M.csv**, and copy to the work folder.
    a. If the field dependence of S_{11} is being measured, including the hysteresis, the file must contain six columns: Field (forward), Re[S_{11}], Im[S_{11}], Field (reverse), Re[S_{11}], Im[S_{11}].
    b. If the frequency dispersion of S_{11} is being measured, the file must contain three columns: Frequency (Hz), Re[S_{11}], Im[S_{11}]. The file **S11M.csv** must contain the same frequency points as **S11MS.csv**.
5. Run the calculation program **SOLT.exe (Scenario 2)**.

The total number of csv files in the folder before the calculations: 4. In the prepared files, all headers must be removed – leave only the columns with values. After the calculations, there will be created two corrected files **S11corrected.csv** and **Zcorrected.csv** in the same format as **S11M.csv** (dispersion or field dependence). If for the selected frequency range DUT cannot be considered as a lumped element, S_{11} saved in **S11corrected.csv** needs further correction to compensate for the return delay time within DUT. In this case, we cannot use **Zcorrected.csv** and the impedance must be recalculated. This procedure is not included to **SOLT.exe**.

For this scenario, VNA is calibrated together with the cables and the microstrips. The surface mount SOL terminations on the PCB calibration cell are supposed to be ideal. We now prefer a different approach shown in Fig. 6. There, the surface mount SOL terminations are also supposed to be ideal, but they are used only for de-embedding the microstrips. VNA and the cable are calibrated separately using the coaxial SOLT terminations with the Touchstone files.

Scenario 3: 2-port coaxial DUT

1. Create the work folder.
2. Deactivate the error correction on VNA.
3. Copy the console application **SOLT.exe** to the folder.
4. Copy the calibration files **S11S.csv**, **S11O.csv**, **S11L.csv** (for Port 1) and **S22S.csv**, **S22O.csv**, **S22L.csv** (for Port 2) to the work folder. Even if the cables are of the same sex and the same SOL standards are used for their calibration, it is necessary to create the two sets of files for the first and second ports.
5. If **THRU** is a jumper (not flash), copy the calibration files **S11T.csv**, **S12T.csv**, **S21T.csv**, and **S22T.csv** for **THRU** to the work folder.
6. Consecutively connect the coaxial calibration standards SHORT1, OPEN1, and LOAD1 to the end of cable on Port 1 and measure the dispersion of their S_{11}-parameter in a wide frequency range. Save the measured S-parameters in the files **S11MS.csv**, **S11MO.csv**, and **S11ML.csv**. Copy these files to the work folder.
7. Consecutively connect the coaxial calibration standards SHORT2, OPEN2, and LOAD2 to the end of cable on Port 2 and measure the dispersion of their S_{22}-parameter in a wide frequency range. Save the measured S-parameters in the files **S22MS.csv**, **S22MO.csv**, and **S22ML.csv**. Copy these files to the work folder.
8. Connect the cables together through THRU (it may be a direct connection if the cables are of different sexes) and measure all four S-parameters in a wide frequency range. Save the measured S-parameters in the files **S11MT.csv**, **S12MT.csv**, **S21MT.csv**, and **S22MT.csv**. Copy these files to the work folder.
9. Measure all four S-parameters of DUT, save them in the files **S11M.csv**, **S12M.csv**, **S21M.csv**, and **S22M.csv**, and copy to the work folder.
   a. If the filed dependence of S-parameters is being measured, including the hysteresis, each file must contain six columns: Field (forward), Re[S], Im[S], Field (reverse), Re[S], Im[S].
   b. If the frequency dispersion of S-parameters is being measured, each file must contain three columns: Frequency (Hz), Re[S], Im[S]. The files **S11M.csv**, **S12M.csv**, **S21M.csv**, and **S22M.csv** must contain the same frequency points as **S11MS.csv**.
10. Run the calculation program **SOLT.exe (Scenario 3)**.

The total number of csv files in the folder before the calculations: 24 (non-flash THRU) or 20 (flash THRU). In the prepared files, all headers must be removed – leave only the columns with values. After the calculations, there will be created five corrected files: **S11corrected.csv**, **S21corrected.csv**, **S12corrected.csv**, **S22corrected.csv**, and **Zcorrected.csv** in the same format as **S**M.csv** files (dispersion or field dependence). The impedance will be calculated from S_{21}-parameter. If for the selected frequency range DUT cannot be considered as a lumped element, S_{21} saved in **S21corrected.csv** and used for the calculation of impedance needs further correction to compensate for the transmission delay time within DUT. In this case, we cannot use **Zcorrected.csv** and the impedance must be recalculated. This procedure is not included to **SOLT.exe**.

Scenario 4: 2-port non-coaxial DUT on a PCB cell

1. Create the work folder.
2. Deactivate the error correction on VNA.
3. Copy the console application **SOLT.exe** to the work folder.
4. Consecutively connect the end of cable on Port 1 to the surface mount calibration standards SHORT1, OPEN1, and LOAD1 on the PCB cell and measure the dispersion of their S_{11}-parameter in a wide frequency range. Save the measured S-parameters in the files **S11MS.csv**, **S11MO.csv**, and **S11ML.csv**. Copy these files to the work folder.
5. Consecutively connect the end of cable on Port 2 to the surface mount calibration standards SHORT2, OPEN2, and LOAD2 on the PCB cell and measure the dispersion of their S_{22}-parameter in a wide frequency range. Save the measured S-parameters in the files **S22MS.csv**, **S22MO.csv**, and **S22ML.csv**. Copy these files to the work folder.
6. Connect the cables together through THRU on the PCB cell (it is always flash) and measure all four S-parameters in a wide frequency range. Save the measured S-parameters in the files **S11MT.csv**, **S12MT.csv**, **S21MT.csv**, and **S22MT.csv**. Copy these files to the work folder.
7. Measure all four S-parameters of DUT placed onto the PCB cell, save them in the files **S11M.csv**, **S12M.csv**, **S21M.csv**, and **S22M.csv**, and copy to the work folder.
    a. If the filed dependence of S-parameters is being measured, including the hysteresis, each file must contain six columns: Field (forward), $\mathrm{Re}[S]$, $\mathrm{Im}[S]$, Field (reverse), $\mathrm{Re}[S]$, $\mathrm{Im}[S]$.
    b. If the frequency dispersion of S-parameters is being measured, each file must contain three columns: Frequency (Hz), $\mathrm{Re}[S]$, $\mathrm{Im}[S]$. The files **S11M.csv**, **S12M.csv**, **S21M.csv**, and **S22M.csv** must contain the same frequency points as **S11MS.csv**.
8. Run the calculation program **SOLT.exe (Scenario 4)**.

The total number of csv files in the folder before the calculations: 14. In the prepared files, all headers must be removed – leave only the columns with values. After the calculations, there will be created five corrected files: **S11corrected.csv**, **S21corrected.csv**, **S12corrected.csv**, **S22corrected.csv**, and **Zcorrected.csv** in the same format as **S**M.csv** files (dispersive or field). The impedance will be calculated from S_{21}-parameter. If for the selected frequency range DUT cannot be considered as a lumped element, S_{21} saved in **S21corrected.csv** and used for the calculation of impedance needs further correction to compensate for the transmission delay time within DUT. In this case, we cannot use **Zcorrected.csv** and the impedance must be recalculated. This procedure is not included to **SOLT.exe**.

Scenarios 2 and 4 can be adapted for the new 3-stage calibration in Fig. 6, but only for the frequency dispersion measurement, not the field dependence. Algorithms for these procedures were written in Python. They are described in our resent report and stored in a public repository on GitHub (two supplementary reports can be found there). Working with several algorithms and multiple files makes measurements and calibration rather time consuming. That is why we proposed next upgrade for the measurement system at MISiS. In addition, we would like to implement the correction of field dependences using the 3-stage calibration.

Now, we can only offer some partial adaptations of Scenarios 2 and 4 to include the 3-stage calibration.

Scenario 2A: 1-port non-coaxial DUT on a PCB cell with the 3-stage calibration

1. Create two folders: “Stage_1” and “Stage_2-3”.
2. Deactivate the error correction on VNA.
3. Copy the console application **SOLT.exe** to the Stage_1 folder.
4. Copy the calibration files **S11S.csv**, **S11O.csv**, and **S11L.csv** for the coaxial SOL terminations to the Stage_1 folder. Each file must contain three columns: Frequency (Hz), Re[S_{11}], Im[S_{11}]. No headers.
5. Consecutively connect the coaxial calibration standards SHORT, OPEN, and LOAD to the end of cable on Port 1 and measure the dispersion of their S_{11}-parameter in a wide frequency range. Save the measured *S*-parameters in the files **S11MS.csv**, **S11MO.csv**, and **S11ML.csv**. Copy these files to the Stage_1 folder.
6. Connect the end of cable on Port 1 to the PCB calibration cell with the surface mount SHORT termination and measure the dispersion of its S_{11}-parameter in a wide frequency range. Save the measured S-parameter in the file **S11M.csv**.
   a. Copy **S11M.csv** to the Stage_1 folder, run **SOLT.exe (Scenario 1)**. The **S11corrected.csv** file will be created.
   b. Rename **S11corrected.csv** to **MS11S.csv** and save in the Stage_2-3 folder.
7. Connect the end of cable on Port 1 to the PCB calibration cell with the surface mount OPEN termination and measure the dispersion of its S_{11}-parameter in a wide frequency range. Save the measured S-parameter in the file **S11M.csv**.
   a. Copy **S11M.csv** to the Stage_1 folder, run **SOLT.exe (Scenario 1)**. The **S11corrected.csv** file will be created.
   b. Rename **S11corrected.csv** to **MS11O.csv** and save in the Stage_2-3 folder.
8. Connect the end of cable on Port 1 to the PCB calibration cell with the surface mount LOAD termination and measure the dispersion of its S_{11}-parameter in a wide frequency range. Save the measured S-parameter in the file **S11M.csv**.

   a. Copy **S11M.csv** to the Stage_1 folder, run **SOLT.exe (Scenario 1)**. The **S11corrected.csv** file will be created.
   b. Rename **S11corrected.csv** to **MS11L.csv** and save in the Stage_2-3 folder.
9. Measure S_{11}-parameter from DUT on the PCB cell, save it in the file **S11M.csv**. Only the frequency dispersion of S_{11} is allowed, not the field dependence. The file must contain three columns: Frequency (Hz), $\mathrm{Re}[S_{11}]$, $\mathrm{Im}[S_{11}]$.
   a. Copy **S11M.csv** to the Stage_1 folder, run **SOLT.exe (Scenario 1)**. The **S11corrected.csv** file will be created.
   b. Rename **S11corrected.csv** to **MS11.csv** and save in the Stage_2-3 folder.
10. Now, in the Stag_2-3 folder you must have the following files: **MS11S.csv**, **MS11O.csv**, **MS11L.csv**, **MS11.csv**. These files have been calculated with the SOLT correction for VNA and the cables (Stage 1 in Fig. 6).
    a. Run **main.py** in the "Probe deembedding" Python project, choose the Stage_2-3 folder for the location of files, and follow the instruction for a 1-port probe de-embedding with the ideal termination model.
    b. In the Stage_2-3 folder, the Python program will create the corrected files **S11A.csv** and **ZA_from_S11A.csv** where the microstrip have been de-embedded (Stage 2 in Fig. 6).
11. If DUT is not a lumped element, further correction will be required to compensate for the return delay time within DUT (Stage 3 in Fig. 6).
    a. Clone **S11A.csv** to the Stage_2-3 folder with the name **S.csv**. The file must contain three columns: Frequency (Hz), $\mathrm{Re}[S_{11}]$, $\mathrm{Im}[S_{11}]$.
    b. Run **main.py** in the "Delay time" Python project, choose the Stage_2-3 folder for the location of files, and follow the instruction.
    c. In the Stage_2-3 folder, the Python program will save the initial and unwrapped phases of S_{11}, and show the delay time on the screen.
    d. Run **main.py** in the "Impedance dispersion" project, choose the Stage_2-3 folder for the location of files, and follow the instruction. The program will ask the delay time already calculated at the previous step and draw the real and imaginary parts of the impedance in a while loop. Looking at these graphs, the delay time could be further adjusted based on physical principles determining the impedance dispersion behaviour (e.g., its real part must be positive for the whole frequency range). The corrected parameters will be saved in **S_corrected.csv** and **Z_corrected.csv**, which completes the Stage 3 in Fig. 6.

Steps 6-8 can only be performed once, as they are only needed to create the S-parameter model of the microstrip on the PCB cell.

Scenario 4A: 2-port non-coaxial DUT on a PCB cell with the 3-stage calibration

1. Create two folders: “Stage_1” and “Stage_2-3”.
2. Deactivate the error correction on VNA.
3. Copy the console application **SOLT.exe** to the Stage_1 folder.
4. Copy the calibration files **S11S.csv**, **S11O.csv**, **S11L.csv** (for Port 1) and **S22S.csv**, **S22O.csv**, **S22L.csv** (for Port 2) to the Stage_1 folder. For this scenario the cables must have the same sex and the same SOL standards. However, it is necessary to create the two sets of files for the first and second ports. The PCB cell also has the same connectors.
5. Copy the calibration files **S11T.csv**, **S12T.csv**, **S21T.csv**, and **S22T.csv** for the **THRU** jumper to the Stage_1 folder.
6. Consecutively connect the coaxial calibration standards SHORT, OPEN, and LOAD to the end of cable on Port 1 and measure the dispersion of their S_{11}-parameter in a wide frequency range. Save the measured S-parameters in the files **S11MS.csv**, **S11MO.csv**, and **S11ML.csv**. Copy these files to the Stage_1 folder.
7. Consecutively connect the coaxial calibration standards SHORT, OPEN, and LOAD to the end of cable on Port 2 and measure the dispersion of their S_{22}-parameter in a wide frequency range. Save the measured S-parameters in the files **S22MS.csv**, **S22MO.csv**, and **S22ML.csv**. Copy these files to the Stage_1 folder.
9. Connect the cables together through the THRU jumper and measure all four S-parameters in a wide frequency range. Save the measured S-parameters in the files **S11MT.csv**, **S12MT.csv**, **S21MT.csv**, and **S22MT.csv**. Copy these files to the Stage_1 folder.
10. Connect the end of cable on Port 1 to the PCB calibration cell with the surface mount SHORT1 termination and measure the dispersion of its S_{11}-parameter in a wide frequency range. Save the measured S-parameter in the file **S11M.csv**.
    a. Copy **S11M.csv** to the Stage_1 folder, run **SOLT.exe (Scenario 1)**. The **S11corrected.csv** file will be created.
    b. Rename **S11corrected.csv** to **MS11S.csv** and save in the Stage_2-3 folder.
11. Connect the end of cable on Port 1 to the PCB calibration cell with the surface mount OPEN1 termination and measure the dispersion of its S_{11}-parameter in a wide frequency range. Save the measured S-parameter in the file **S11M.csv**.
    a. Copy **S11M.csv** to the Stage_1 folder, run **SOLT.exe (Scenario 1)**. The **S11corrected.csv** file will be created.
    b. Rename **S11corrected.csv** to **MS11O.csv** and save in the Stage_2-3 folder.

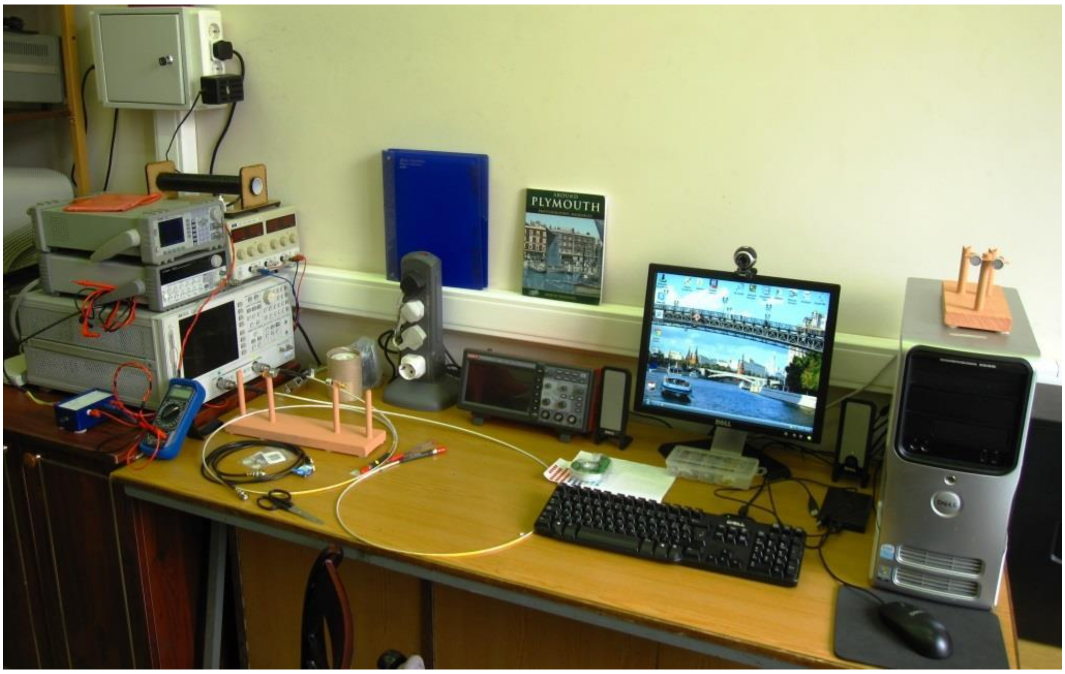
12. Connect the end of cable on Port 1 to the PCB calibration cell with the surface mount LOAD1 termination and measure the dispersion of its S_{11}-parameter in a wide frequency range. Save the measured S-parameter in the file **S11M.csv**.
    a. Copy **S11M.csv** to the Stage_1 folder, run **SOLT.exe (Scenario 1)**. The **S11corrected.csv** file will be created.
    b. Rename **S11corrected.csv** to **MS11L.csv** and save in the Stage_2-3 folder.
13. Connect the end of cable on Port 1 to the PCB calibration cell with the surface mount SHORT2 termination and measure the dispersion of its S_{11}-parameter in a wide frequency range. Save the measured S-parameter in the file **S11M.csv**. We use Port 1 and the "11" indexes since only one port correction will be used to recalculate this file.
    a. Copy **S11M.csv** to the Stage_1 folder, run **SOLT.exe (Scenario 1)**. The **S11corrected.csv** file will be created.
    b. Rename **S11corrected.csv** to **MS22S.csv** and save in the Stage_2-3 folder.
14. Connect the end of cable on Port 1 to the PCB calibration cell with the surface mount OPEN2 termination and measure the dispersion of its S_{11}-parameter in a wide frequency range. Save the measured S-parameter in the file **S11M.csv**. We use Port 1 and the "11" indexes since only one port correction will be used to recalculate this file.
    a. Copy **S11M.csv** to the Stage_1 folder, run **SOLT.exe (Scenario 1)**. The **S11corrected.csv** file will be created.
    b. Rename **S11corrected.csv** to **MS22O.csv** and save in the Stage_2-3 folder.
15. Connect the end of cable on Port 1 to the PCB calibration cell with the surface mount LOAD2 termination and measure the dispersion of its S_{11}-parameter in a wide frequency range. Save the measured S-parameter in the file **S11M.csv**. We use Port 1 and the "11" indexes since only one port correction will be used to recalculate this file.
    a. Copy **S11M.csv** to the Stage_1 folder, run **SOLT.exe (Scenario 1)**. The **S11corrected.csv** file will be created.
    b. Rename **S11corrected.csv** to **MS22L.csv** and save in the Stage_2-3 folder.
16. Measure all four S-parameters of DUT on the PCB cell (connect two cables to the cell), save them in the files **S11M.csv**, **S12M.csv**, **S21M.csv**, and **S22M.csv**. Only the frequency dispersion of S is allowed, not the field dependence. Each file must contain three columns: Frequency (Hz), $\mathrm{Re}[S]$, $\mathrm{Im}[S]$.
    a. Copy **S11M.csv**, **S12M.csv**, **S21M.csv**, and **S22M.csv** to the Stage_1 folder, run **SOLT.exe (Scenario 3)**. The **S11corrected.csv**, **S21corrected.csv**, **S12corrected.csv**, **S22corrected.csv** files will be created.

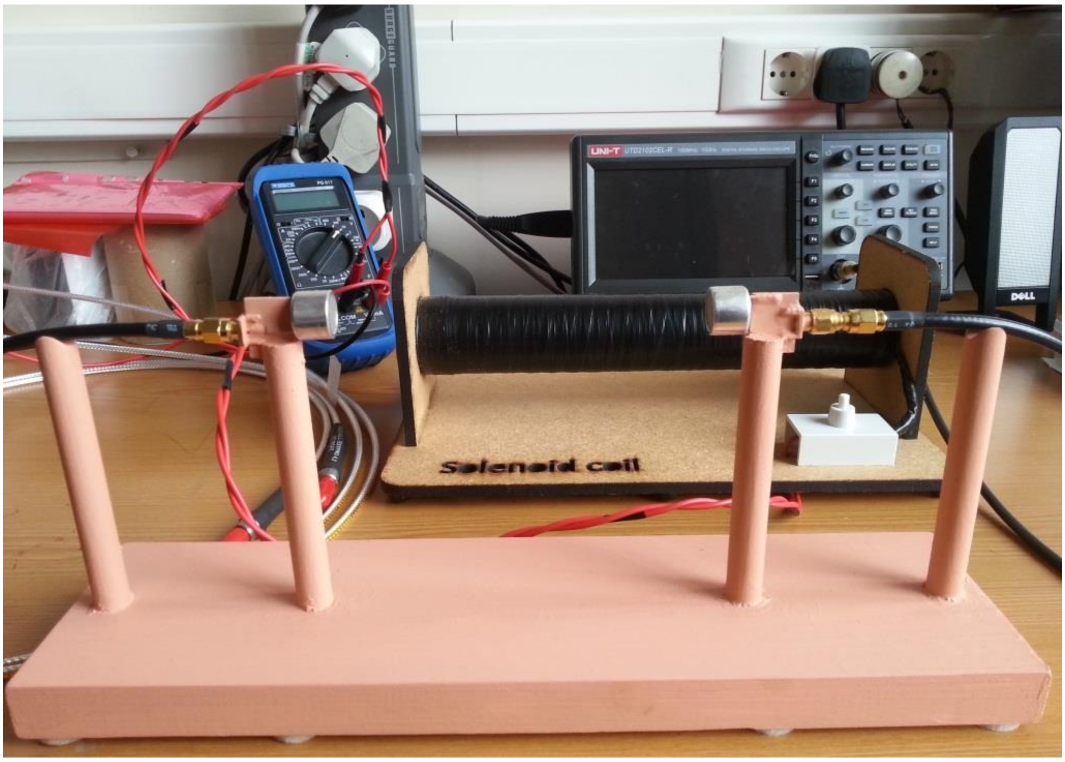
   b. Rename **S11corrected.csv** to **MS11.csv**, **S21corrected.csv** to **MS21.csv**, **S12corrected.csv** to **MS12.csv**, **S22corrected.csv** to **MS22.csv** and save them in the Stage_2-3 folder.

17. Now, in the Stag_2-3 folder you must have the following files: **MS11S.csv**, **MS11O.csv**, **MS11L.csv**, **MS22S.csv**, **MS22O.csv**, **MS22L.csv**, **MS11.csv**, **MS21.csv**, **MS12.csv**, **MS22.csv**. These files have been calculated with the SOLT correction for VNA and the cables (Stage 1 in Fig. 6).
    a. Run **main.py** in the "Probe deembedding" Python project, choose the Stage_2-3 folder for the location of files, and follow the instruction for a 2-port probe de-embedding with the ideal termination model.
    b. In the Stage_2-3 folder, the Python program will create the corrected files **S21A.csv** and **ZA_from_S21A.csv** where the microstrips have been de-embedded (Stage 2 in Fig. 6).
18. If DUT is not a lumped element, further correction will be required to compensate for the return delay time within DUT (Stage 3 in Fig. 6).
    a. Clone **S21A.csv** to the Stage_2-3 folder with the name **S.csv**. The file must contain three columns: Frequency (Hz), Re[S_{21}], Im[S_{21}].
    b. Run **main.py** in the "Delay time" Python project, choose the Stage_2-3 folder for the location of files, and follow the instruction.
    c. In the Stage_2-3 folder, the Python program will save the initial and unwrapped phases of S_{21}, and show the delay time on the screen.
    d. Run **main.py** in the "Impedance dispersion" project, choose the Stage_2-3 folder for the location of files, and follow the instruction. The program will ask the delay time already calculated at the previous step and draw the real and imaginary parts of the impedance in a while loop. Looking at these graphs, the delay time could be further adjusted based on physical principles determining the impedance dispersion behaviour (e.g., its real part must be positive for the whole frequency range). The corrected parameters will be saved in **S_corrected.csv** and **Z_corrected.csv**, which completes the Stage 3 in Fig. 6.

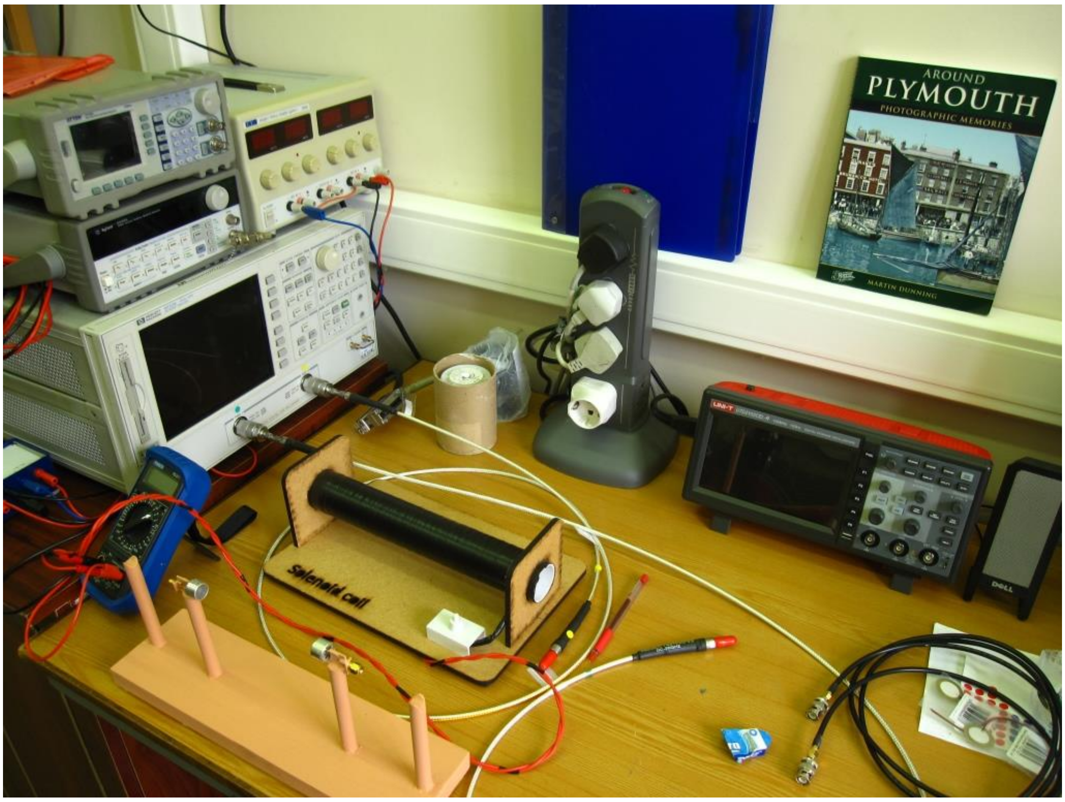
Steps 10-15 can only be performed once, as they are only needed to create the S-parameter model of the microstrips on the PCB cell.

Photo gallery of the lab at MISiS


PLYMOUTH



Measurements with ultrasonic transducers



Solenoid coil and ultrasonic transducers