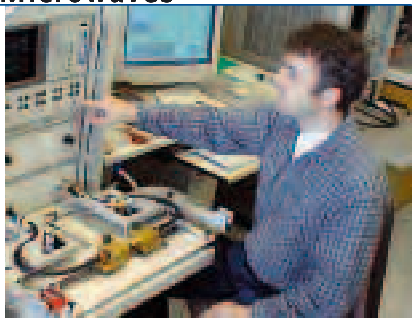

Scattering Parameter Measurements in the Coaxial 2.4 mm Line System

METAS acted as the pilot laboratory in this first formal S-parameter comparison of the coaxial 2.4 mm line system. Nine national metrology institutes and three commercial laboratories participated. The agreement between laboratories is generally good, METAS results in particular comply with all reference values.

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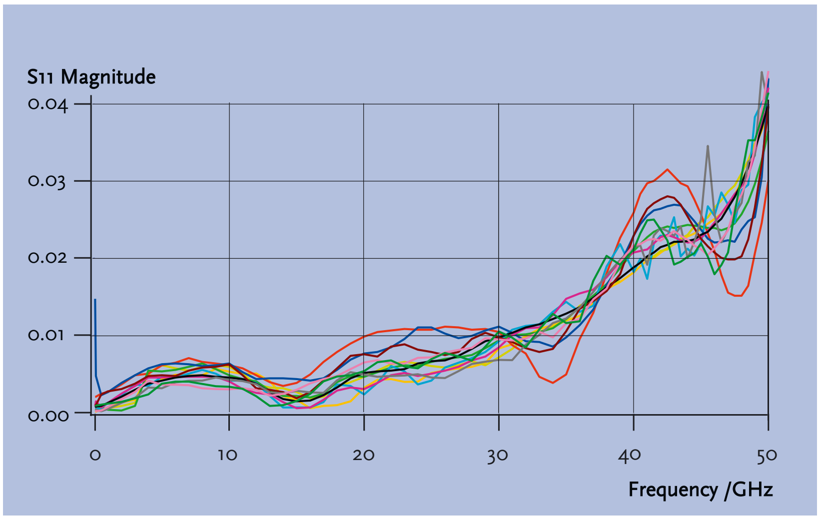
1: Travelling standards: Three attenuators (top) and four terminations (below) with coaxial 2.4 mm connectors.



2: Magnitude of S11 as a function of frequency for one particular travelling standard: The different colours represent the participants. The deviation of e. g. the red curve is not just a constant offset. Depending on the phasing of the additional component, the interference is either constructive or deconstructive and leads to a deviation that oscillates with frequency. The full frequency information provides valuable insight in such a case.

During the last decade, devices equipped with 2.4 mm coaxial connectors, which are designed for frequencies up to 50 GHz, were introduced to the market. Measurements at these high frequencies show strong sensitivity to deviations from the ideal coaxial geometry, as e. g. caused by the movement of cables or mechanical stress, and demand a great deal of the operator's capabilities.

METAS as Pilot Laboratory

In 1996, METAS initiated an informal bilateral comparison with the commercial Agilent calibration laboratory in Winnersh, UK, to measure scattering parameters in the coaxial 2.4 mm system. This experiment led to a proposal for a EUROMET supplementary comparison at the EUROMET RF experts meeting 1998 at Physikalisch-Technische Bundesanstalt (PTB), Braunschweig (Germany). After a trial round, which tested the stability of the travelling standards, the main loop took place between April 2001 and June 2003. Nine national metrology institutes (NMI's) and three commercial laboratories participated in the comparison.

METAS acted as pilot laboratory and provided a technical protocol to define the measurement and organisational details. During the loop it performed regularly control measurements of the travelling standards and it collected the data, analysed it and wrote the comparison reports. The final report [1] is available in the key comparison data base of the BIPM and can be found through the electronic abstract [2].

Large Quantity of Data

The S-parameters of four terminations and three attenuators (Picture 1) were measured in the frequency range from 50 MHz to 50 GHz at 63 different frequencies. For a subset of seven frequencies («Annex Data»), the participants were asked to quote measurement uncertainties. In addition, the participants repeated the measurements at different connector orientations («Connector Orientation Data»). All laboratories used an Agilent 8510C Vector Network Analyser (VNA) to perform the measurements.

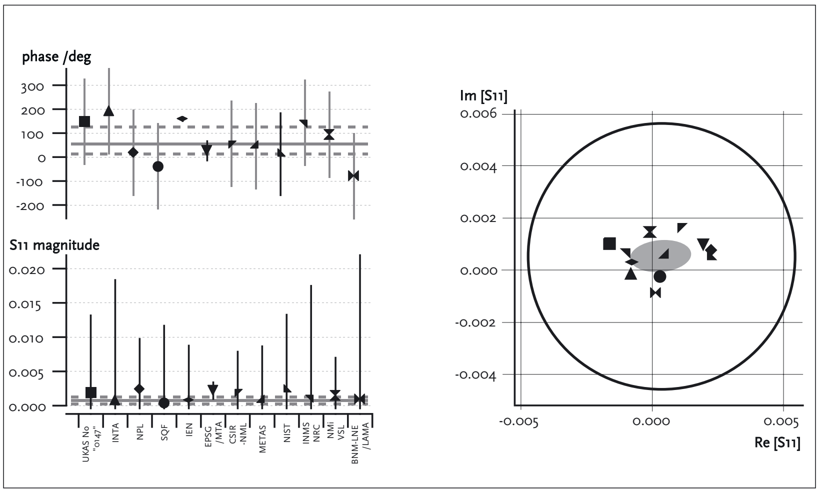
It lies in the nature of S-parameter measurements to produce large quantities of data. It has been argued in the past that a comparison should be restricted to only a few measurements at selected frequency points. Diagram 2 however is a good example that the full frequency response contains important information. Therefore the full data set together with a visualisation tool was made available to the participants on a CD-ROM. «Annex Data» and «Connector Orientation Data» were subject to further analysis, the results of which can be found in the final report.

Data Analysis

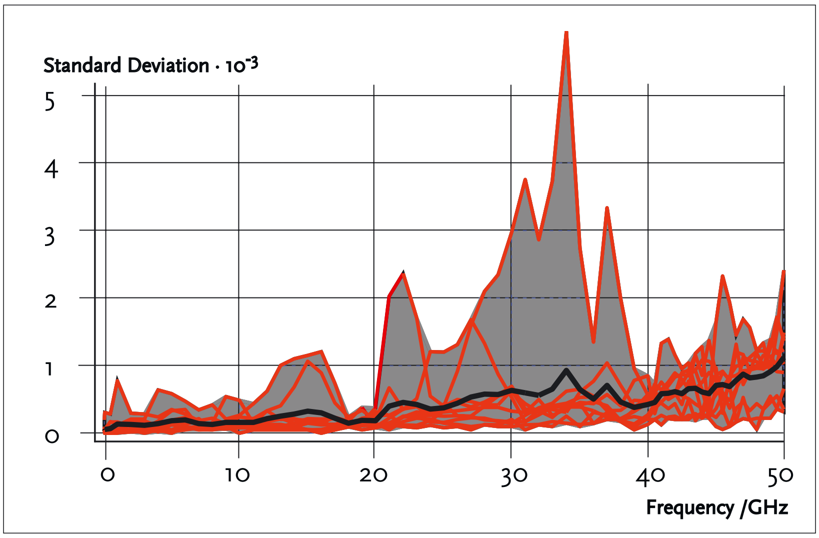
Guidelines are available for the analysis of measurement comparisons with scalar-valued measurands. For complex-valued quantities, as S-parameters, however the situation is different. No truly established method or directive exists. In this comparison additional difficulties occurred: One finding was the large differences in the quoted uncertainties between laboratories (Diagram 3). This reflects the limited experience of the laboratories with the 2.4 mm system and the fact that the uncertainty evaluation for the VNA measurement process is generally not very well established. We concluded that the quoted uncertainties do not necessarily reflect the actual measurement capabilities.

Another problem: For these measurements most laboratories have traceability to the same NMI (National Institute of Standards and Technology, NIST). It remains unclear to what extent the determination of the comparison reference value has been biased due to correlations between the participants.

Techniques of multivariate statistics can be used to analyse samples of multidimensional



3: The results of the analysis of the «Annex Data» for one device at 1 GHz.
Left: Data points with uncertainties as submitted by the participants displayed as magnitude and phase. The grey lines indicate the reference value (solid) and its 95 % confidence interval (dashed).
Right: Data points in the complex plane. Shown are the grey shaded ellipse, which covers the 95 % confidence region of the reference value and the grey circle of outlier boundary.



4: Results of the analysis of the «Connector Orientation Data». The red lines show the standard deviations in S-parameter measurements due to different connector orientations for each laboratory. The black line is the mean of all standard deviations.

data. How to apply these methods to complex-valued S-parameter data has been discussed rather recently in the literature. The analysis of the «Annex Data» was done accordingly to determine a comparison reference value and its 95 % confidence region. Additionally robust statistics was used to eliminate outliers and a Monte Carlo technique was applied to propagate the confidence region between coordinate systems. References and details of the whole procedure can be found in the final report.

Due to the large amount of data it was decided to automate the analysis and software was written for the purpose. A wise decision considering that the whole analysis had to be redone after the release of draft A report because some laboratories required changes to their data or even retracted part of their measurements.

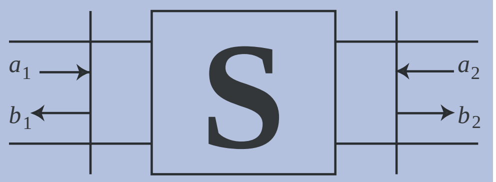
Good Agreement of Results

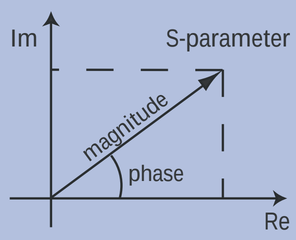
Diagram 4 is an example of «Annex Data» results as shown in the report. All together the graphical and tabular presentation of the «Annex data» covers more than 60 pages. In general the agreement between laboratories is good. In some cases significant deviation from the reference value can be observed. To our knowledge in most of these cases the cause of the problems has been identified. METAS results comply with the reference values of all travelling standards at all frequencies.

For the «Connector Orientation Data» a simple statistical analysis was done. Of interest were not absolute values but the spread that was caused due to different orientations of the connector. As a measure of this scatter the standard deviation was calculated for the measurements of each laboratory and plotted vs. frequency (Diagram 4). One finds that the variation between laboratories is quite significant. Notable is also the strong dependence on frequency, a finding which requires further studies.

Scattering Parameters (S-Parameters)

S-parameters are used to characterise reflective and transmissive behaviour of a device upon impact of a high frequency electromagnetic signal. The figure schematically represents the situation for a 2-port device (e. g. an attenuator) with input signals applied to both ports. If the device is linear, the output signals can be defined in terms of the input signals. Thus,





$$b_1 = S_{11}a_1 + S_{12}a_2$$
$$b_2 = S_{21}a_1 + S_{22}a_2$$

with the signal amplitudes a1, a2 , b1 and b2 and the scattering parameters Sij. The scheme can be generalised to n ports and the equations can be written more economically in matrix form b = S · a with the S-parameters contained in the scattering matrix S and the column vectors a and b containing input and output signal amplitudes, respectively. S-parameters are two-dimensional quantities either described in polar coordinates with magnitude and
phase or as complex numbers with real (Re) and imaginary (Im) parts.

Lessons Learned

This supplementary comparison was beneficial to all participants, allowing them to compare their measurement capabilities in the not so well established coaxial 2.4 mm system. A large amount of data was produced, which invites for further studies. The results reveal that additional effort is needed to improve uncertainty evaluation for VNA measurements. In this regard we also refer to the article on page 20, which describes the current development of software tools for VNA uncertainty evaluation at METAS. Still lacking are binding guidelines on how to analyse a comparison with multidimensional measurands. However the approach used by METAS was successful and points into the right direction. The work load for METAS as a pilot laboratory was significantly larger than originally expected, but in summary the lead in this comparison was a valuable experience and the impedance laboratory gained much competence in this particular measurement field.

References

[1] Juerg Ruefenacht and Markus Zeier, «EUROMET.EM.RF-S16: Comparison of scattering parameter measurements in the coaxial 2.4 mm line system», Metrologia, 2005, 42, Tech. Suppl., 01001
[2] www.iop.org/EJ/abstract/0026-1394/42/1A/01001/