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EURAMET project 1426: S-parameter measurement comparison conducted with the help of *VNA Tools*

Comparison Report

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ABSTRACT

This inter-laboratory comparison took place in the framework of the EMPIR project 15RPT01 RFMicrowave. The participants measured S-parameters in the coaxial line system for a set of Type-N 50 Ohm devices up to 18 GHz with the help of the VNA metrology software *VNA Tools*. This report compares and discusses results.

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1 INTRODUCTION

In the framework of the EMPIR project 15RPT01 RFMicrowave (Development of RF and Microwave Metrology Capability) the collaborators have been trained to use the VNA metrology software *VNA Tools* [1–3] to perform VNA measurements. The software supports data taking, VNA calibration and error correction and the evaluation of measurement uncertainties in accordance with relevant standards [4,5]. The concluding activity of the task 1.2 named "software capabilities for measurement uncertainty evaluation" is a measurement comparison in Type-N 50 Ohm up to 18 GHz as a EURAMET project.

The technical protocol [6] has been prepared and the participants have been asked to characterize their measurement systems to populate the *VNA Tools* database with the necessary information. This is an essential step to reliably evaluate measurement uncertainties. In the measurement loop the participants used *VNA Tools* to perform the measurements of a selected set of traveling standards. Results have been submitted to the pilot laboratory in the *VNA Tools* data format. The pilot laboratory has calculated reference values and degrees of equivalence and derived summary statements for compliance with the reference values. Setup of the comparison, analysis and results are presented in this report.

2 PARTICIPANTS

The participants are all from European national metrology institutes. They are listed in table 1. The comparison was piloted by METAS.

3 TRAVELING STANDARDS AND MEASUREMENT SCHEDULE

The following traveling standards were measured in the comparison.

- Type-N female Load, Suhner 6500.17.B, SN: LNF1
- Type-N female Open, HP 85054-60028, SN: 41645
- Type-N female Short, SN: CNF2
- Type-N male Load, Suhner 6500.17.A, SN: LNM1
- Type-N male Open, MMC 8810B1, SN: 212
- Type-N male Short, Inmet 7001, SN: 64671
- Type-N Adapter, Agilent 85032-60020, SN: 50618
- Type-N Attenuator 6 dB, HP 8491B, SN: 21224
- Type-N Power Splitter, Keysight 11667A, SN: MY51357676

The traveling standards have been pre-selected for stability by performing repeated measurements at different connector orientations.

Measurements were performed in a single loop, whereas the pilot laboratory performed the first, one intermediate and the last measurement to evaluate the stability of the standards. The schedule of the measurement loop is listed in table 2.

The traceability schemes of the individual laboratories are shown in table 3.

Acronym	Institute	Country
CMI	Cesky Metrologicky Institut	Czech Republic
GUM	Central Office of Measures	Poland
INTA	Instituto Nacional de Técnica Aeroespacial	Spain
METAS	Eidgenössisches Institut für Metrologie	Switzerland
NIS	National Institute for Standards	Egypt
NQIS	National Quality Infrastructure System	Greece
RISE	Research Institutes of Sweden AB	Sweden
SIQ	Slovenski Institut za Kakovost in Meroslovje	Slovenia
UME	Ulusal Metroloji Enstitüsü	Turkey

Table 1: Participants

Figure 1: Female one-port traveling standards (short, open, load)

Figure 2: Male one-port traveling standards (short, open, load)

Figure 3: Multi-port traveling standards (adapter, 6 dB attenuator, power splitter)

Institute	Measurement period
METAS	26.07.2017 to 27.07.2017
RISE	01.08.2017 to 21.08.2017
CMI	18.09.2017 to 19.09.2017, 21.09.2017
SIQ	13.11.2017 to 24.11.2017
GUM	05.01.2018 to 10.01.2018
NQIS	15.01.2018 to 06.02.2018
INTA	15.02.2018 to 16.02.2018 one-ports, 09.03.2018 two-ports, 13.03.2018 splitter
METAS	26.03.2018 to 27.03.2018
NIS	07.06.2018
UME	31.07.2018 to 16.08.2018
METAS	28.08.2018 to 30.08.2018

Table 2: Measurement schedule

Institute	Traceability scheme
CMI	Own primary realization. Air-dielectric lines and short characterized by CMI length laboratory. Own characterization of step attenuator for VNA linearity.
GUM	Traceability through transfer standards. Calibration kit Agilent 85054B (OSL and sliding loads) characterized by NPL.
INTA	Traceability through transfer standards. Agilent OSL standards characterized by METAS for VNA calibration and attenuators (20 dB and 50 dB) characterized by METAS for VNA verification.
METAS	Own primary realization. Characterization of primary standards (air-dielectric lines and offset shorts). Details described in [7].
NIS	Traceability through transfer standards. Calibration kit Agilent 85054B. Manufacturer generic data, which is claimed to be traceable to NIST.
NQIS	Traceability through transfer standards. Calibration kit Agilent 85054B (OSL and sliding loads) characterized by METAS. However, it seems that the METAS calibration was not used, because no correlation with METAS has been found in the data set. Verification kit Agilent 85055A characterized by NPL.
RISE	Traceability through transfer standards. Dimensonally characterized air-dielectric lines (by NPL) and characterized step attenuators (by METAS) for VNA linearity.
SIQ	Traceability through transfer standards. OSL kit characterized by METAS and step attenuator characterized by METAS for VNA linearity.
UME	Traceability through transfer standards. Agilent 85055A Verification kit characterized by PTB.

Table 3: Traceability schemes

4 MEASUREMENT QUANTITIES

The following quantities had to be measured in this comparison.

- One-ports:
  - 8 measurements with different connector orientation.
  - Mean S-parameter data (S11).
- Two-ports:
  - 8 measurements with different connector orientation.
  - Mean S-parameter data (S11, S21, S12, S22).
- Three-ports:
  - Reflection coefficient of port 1 (S11).
  - Equivalent reflection coefficient for port 2 $\left(S22 - \frac{S32 \cdot S21}{S31}\right)$.
  - Equivalent reflection coefficient for port 3 $\left(S33 - \frac{S32 \cdot S31}{S21}\right)$.
  - Insertion loss port 1 to port 2 (S21).
  - Insertion loss port 1 to port 3 (S31).
  - Transmission tracking (S21/S31).
  - All 9 S-parameters (optional).
- Frequencies:
  - 50 MHz
  - 100 MHz to 18 GHz in 100 MHz steps
- Additional mechanical parameter:
  - pin depth of the traveling standards and used test ports.

5 DATA ANALYSIS

The data analysis follows the principles laid out in [8]. No specific frequency points have been defined beforehand for the analysis. But we strongly believe that it is anyway more informative to analyze the full data set and to derive summary statements for the report, whereas the full data set is made available to the participants in electronic form for a more detailed inspection.

5.1 Drift correction

The repeated measurements at METAS did not reveal significant drift of the traveling standards. No drift correction is therefore applied.

5.2 Outlier removal

It is good practice to exclude NMIs that have common traceability paths and are thus correlated from the calculation of the CRV. INTA and SIQ are traceable to METAS and are therefore excluded from the calculation of the CRV. NQIS is claiming to be traceable to METAS as well, but this is not apparent from the data that has been submitted. See as well discussion on correlation between laboratories in section 5.3.1.

Furthermore, the data sets of RISE and GUM are not used for the calculation of the comparison reference value (CRV) due to dubious features in their data sets:

RISE The uncertainty associated with S11 of the male load is unrealistically low. In contrast, the uncertainty associated with S11 of the female load is much larger. There is no reasonable explanation for such a large difference.

GUM For male open and short, the ripple in the phase of S11 is larger than the specified associated measurement uncertainty.

5.3 Comparison reference value (CRV)

The CRV of the one-ports and two-ports is determined as a consensus value by taking the weighted mean of the data sets. The weights used are the normalized inverse of the 2x2 covariance matrices associated with the individual S-parameters. The correlation information between laboratories, which is in principle available, has been ignored in this calculation, see 5.3.1 for an explanation. For S11 this leads to the following equation for the CRV $S11_{CRV}$

$$S11_{CRV} = V_T^{-1} \sum_i V_i^{-1} S11_i \qquad V_T = \sum_i V_i^{-1} \tag{1}$$

with the covariance matrix V_i associated with $S11_i$ and the index i denoting the participants. The result is a bivariate CRV with real and imaginary components. The calculation (1) is done at each frequency point for each S-parameter of each traveling standard. .

For the power splitter, only two participants supplied the full three-port S-parameters, CMI and METAS. Therefore, the unweighted mean of the datasets from CMI and METAS is taken as CRV.

The uncertainty associated with the CRV is calculated using linear uncertainty propagation. This is done automatically with the help of the generic uncertainty calculator *METAS UncLib* [9].

5.3.1 *A note on inter-laboratory correlation*

Because the *VNA Tools* data format also keeps track of inter-laboratory correlations, it would in principle even be possible to include laboratories, which are correlated, e.g. due to a common traceability route. For instance INTA and SIQ fall into this category, because they obtain traceability from METAS. In this case the inverse of the full covariance matrix including inter-laboratory off-diagonal elements could be used as weights. However, an attempt to do so produced strange results for the CRV. A closer inspection of the data sets revealed that the data of UME, NQIS and NIS is highly correlated. We can safely assume that this correlation is not real and that it was probably introduced by using the same uncertainty IDs for the calibration standards in the VNA Tools database. It is known that the use of wrong correlation effects in the calculation of covariance weighted means can cause a bias in the result. It was therefore decided to omit any inter-laboratory correlation information in the analysis and instead exclude INTA and SIQ from the calculation of the CRV, as pointed out in section 5.2.

5.4 Degrees of equivalence and compliance rates with CRV

The degree of equivalence (DoE) is calculated as the difference between the participants data point and the CRV. Compliance is usually declared if this difference is covered by the associated expanded uncertainty (95% coverage). In the present case we have calculated bivariate (real and imaginary components) CRVs for each S-parameter at each frequency point. From this bivariate DoEs for each frequency point can be calculated. The associated uncertainty of a bivariate DoE

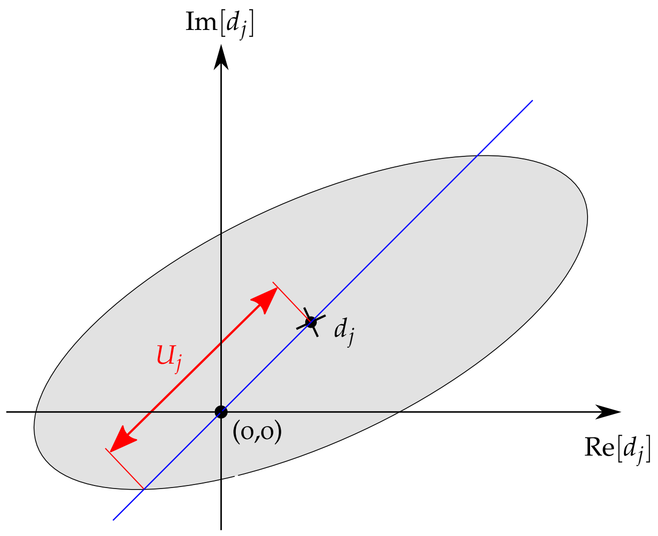

Figure 4: Graphical interpretation of the compliance criterion given by the equations (3) and (4). The elliptically bounded gray area corresponds to the 95% uncertainty region associated with the estimate of the DoE d_j at an arbitrary frequency point. U_j is the distance (in red) between d_j and the intersection with the elliptical boundary, given by the straight blue line through d_j and (0,0). The compliance rate $DoE_{95\,\%}$ corresponds to the fraction of data points over frequency for which the point (0,0) is covered by the elliptical uncertainty region.

is a 2x2 coviariance matrix, which is automatically calculated with the help of *METAS UncLib*. For 95% coverage the covariance matrix is expanded with the square root of the upper 95% point of the χ^2-distribution, i.e. with a factor 2.45. The corresponding elliptical region (assuming an underlying bivariate Gaussian distribution) should cover the point $d_j = (0,0)$ for compliance with the CRV. As a summary statement we have calculated the percentage ratio of compliance over the entire frequency range for each laboratory and for each S-parameter of each traveling standard.

As an example the formalism for S11 is shown here for an arbitrary laboratory. The bivariate degree of equivalence d_j is calculated for each frequency $j = (1...N_{freq})$ as the difference between S11 and the CRV.

$$d_j = S11_j - S11_{CRV_j} \tag{2}$$

The percentage ratio of compliance $DoE_{95\%}$ for the particular laboratory is calculated using

$$DoE_{95\,\%} = \frac{1}{N_{freq}} \sum_{j=1}^{N_{freq}} \left(|d_j|/U_j \leq 1 \right) \tag{3}$$

with

$$U_j = 2.45 \frac{|d_j|}{\sqrt{d_j' V_{d_j}^{-1} d_j}}. \tag{4}$$

Equation (4) is based on [8] and a graphical interpretation is given in figure 4. The condition $|d_j|/U_j \leq 1$ used in equation (3) corresponds to a generalization of the well-known normalized error criterion. Equation (3) gives therefore the fraction of data points over frequency for which the criterion is fulfilled. For compliance with the CRV $DoE_{95\,\%} \geq 0.95$ is expected. In section 6 the results are shown graphically with bar graphs for each S-parameter and each traveling standard.

5.5 Calculation of the averaged uncertainty

As a further summary statement we calculated a measure for the expanded uncertainty of each participant averaged over the entire frequency range for each S-parameter and each traveling standard. The analysis determines the average size of major and minor axis of the elliptical region associated with the 2x2 covariance matrix. The chosen formalism is as follow (shown for S11 of one of the traveling standards and an arbitrary participant)

$$\begin{pmatrix}\lambda_1\\ \lambda_2\end{pmatrix} = \mathrm{Eig}\left(V_j\right) \tag{5}$$

$$U_{mean_j} = \frac{1}{2}\cdot\left(\sqrt{\lambda_1}+\sqrt{\lambda_2}\right) \tag{6}$$

$$U_{mean\,95\,\%} = \frac{1}{N_{freq}}\sum_{j=1}^{N_{freq}} 2.45\cdot U_{mean_j} \tag{7}$$

The eigenvalues of the covariance matrix associated with S11 are calculated in (5) for each frequency point j. As a measure for the average uncertainty the mean of the semi-minor and semi-major axis (square roots of the eigenvalues) of the corresponding elliptical region is calculated in (6). The average over all frequency points multiplied with 2.45 in (7) leads to $U_{mean\,95\,\%}$ as a measure for the average expanded uncertainty for each participant.

These results are also shown next to the figures with the average compliance rates in section 6.

6 RESULTS

The data sets used in the analysis together with the calculated CRVs are made available to the participants of the comparison in electronic form. The electronic data set corresponds to the averaged values (based on up to eight repetitions under different connector orientations) submitted by the participants. In some cases the pilot had to make some formal adjustments for the analysis. Some one-port data was reported as S22 and had to be renamed to S11. The data submitted for the splitter was not very consistent. Some measurements were lacking or the wrong quantity was measured and some port assignments were wrong and had to be corrected. Not all data sets followed the frequency list prescribed in the technical protocol.

The following figures show the summary quantities calculated in section 5, notably the percentage ratio of compliance with the CRV calculated in 5.4 and the averaged uncertainty calculated in 5.5. These figures provide a quick evaluation of the performance of each lab. For a more in-depth understanding it is recommended to consult the electronic data set.

Finally, figure 21 shows an overview of the pin depth measurements without any further analysis.

6.1 One-ports

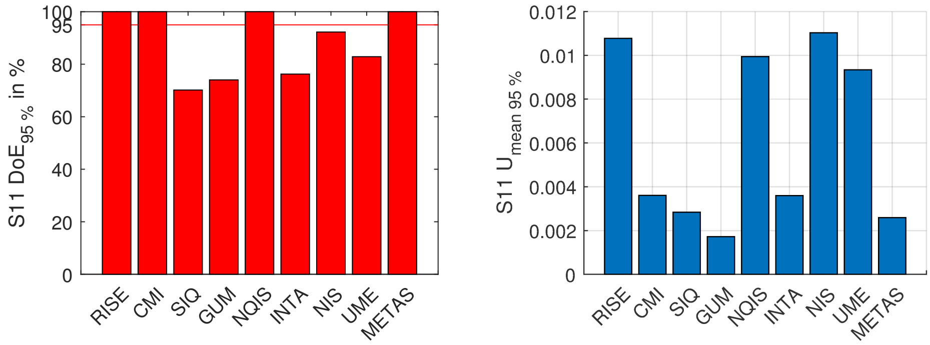

Figure 5: Female load: compliance rate with CRV (left) and averaged uncertainty (right) for S11.

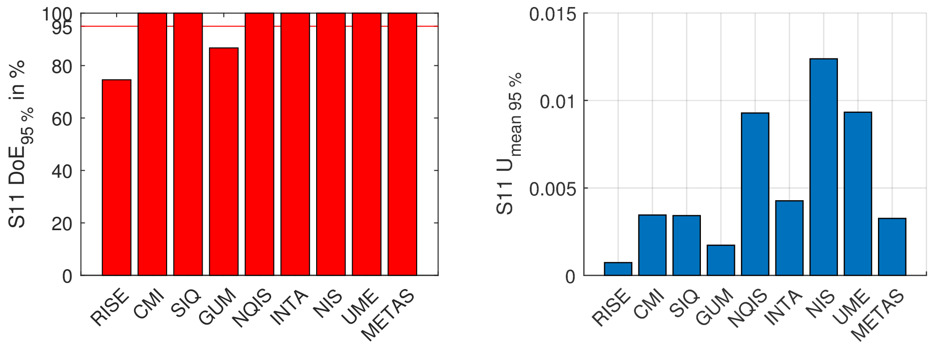

Figure 6: Male load: compliance rate with CRV (left) and averaged uncertainty (right) for S11.

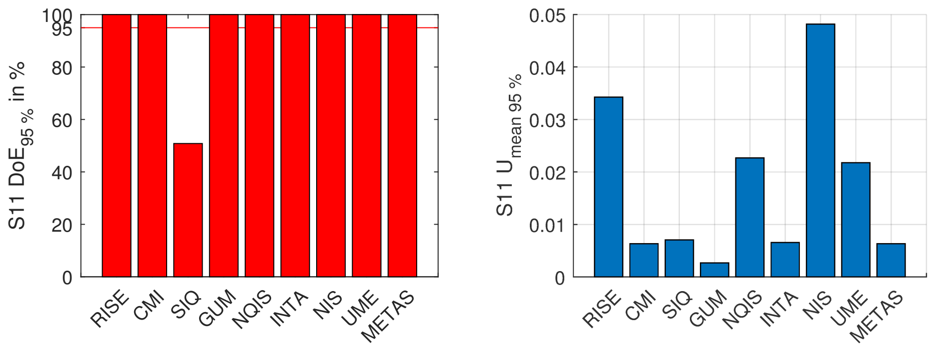

Figure 7: Female open: compliance rate with CRV (left) and averaged uncertainty (right) for S11.

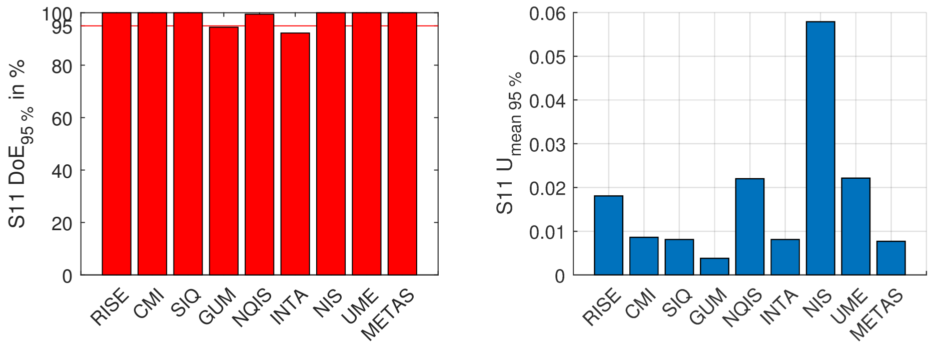

Figure 8: Male open: compliance rate with CRV (left) and averaged uncertainty (right) for S11.

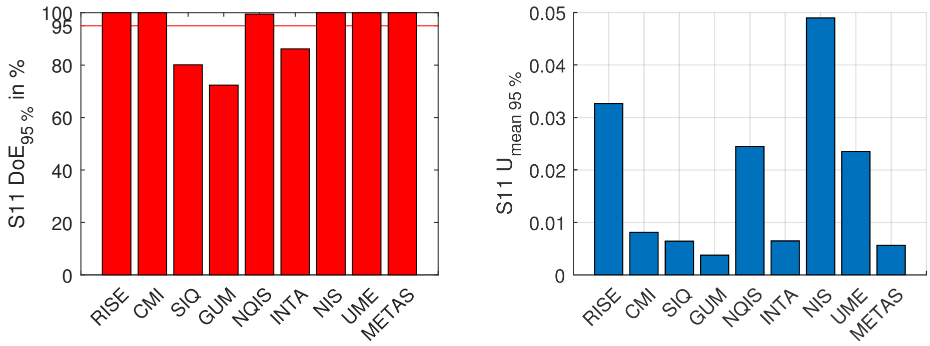

Figure 9: Female short: compliance rate with CRV (left) and averaged uncertainty (right) for S11.

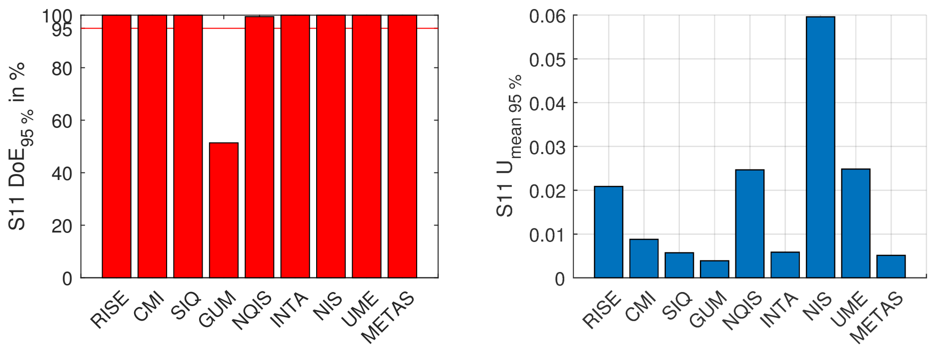

Figure 10: Male short: compliance rate with CRV (left) and averaged uncertainty (right) for S11.

6.2 Two-ports

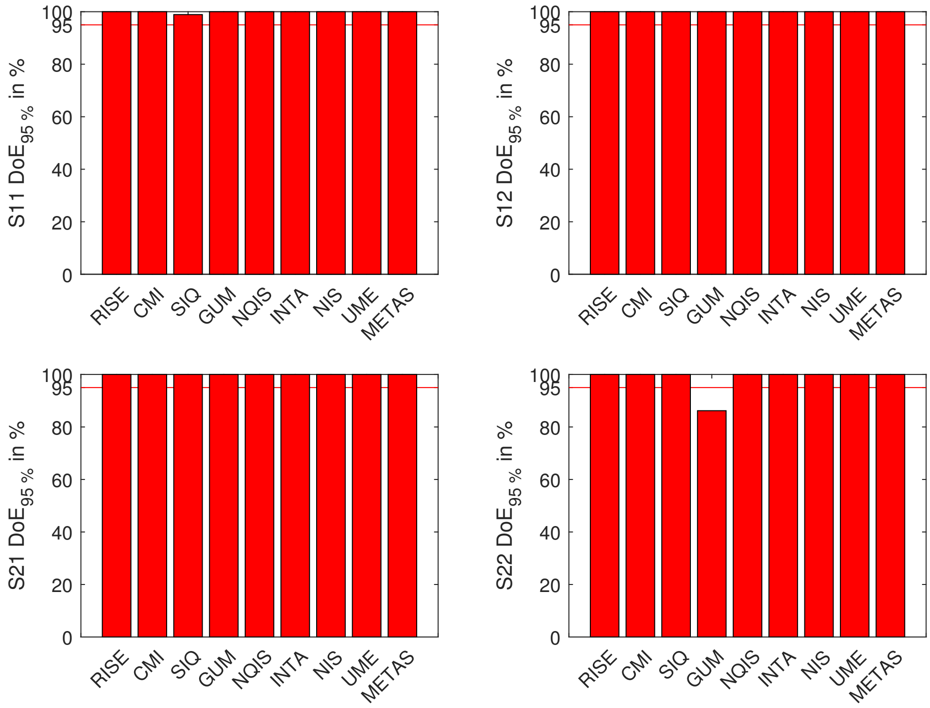

Figure 11: Adapter: compliance rate with CRV for S11, S12, S21 and S22.

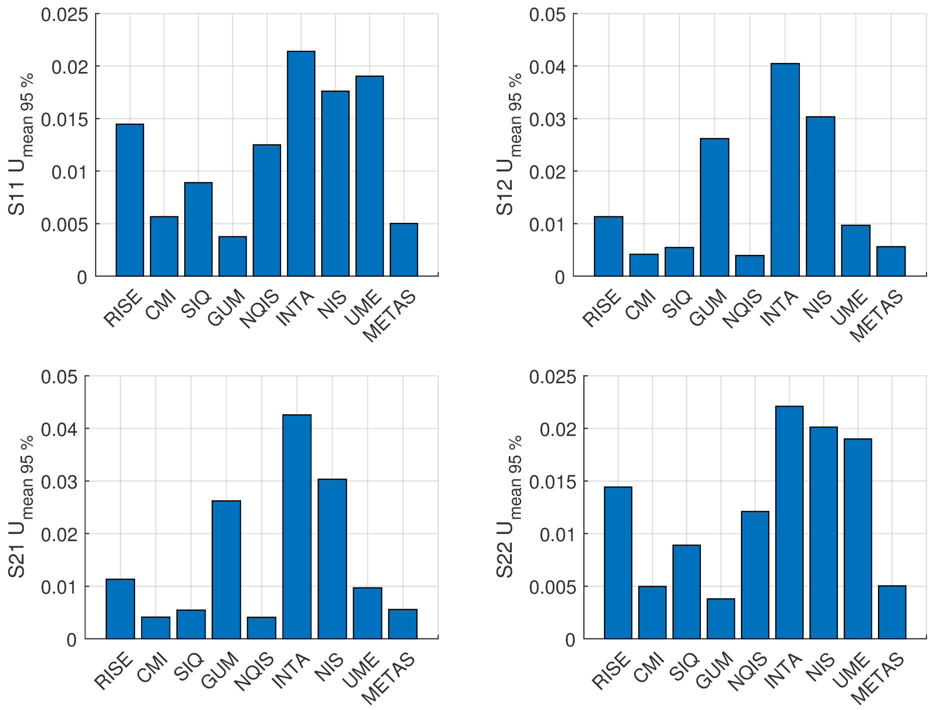

Figure 12: Adapter: averaged uncertainty for S11, S12, S21 and S22.

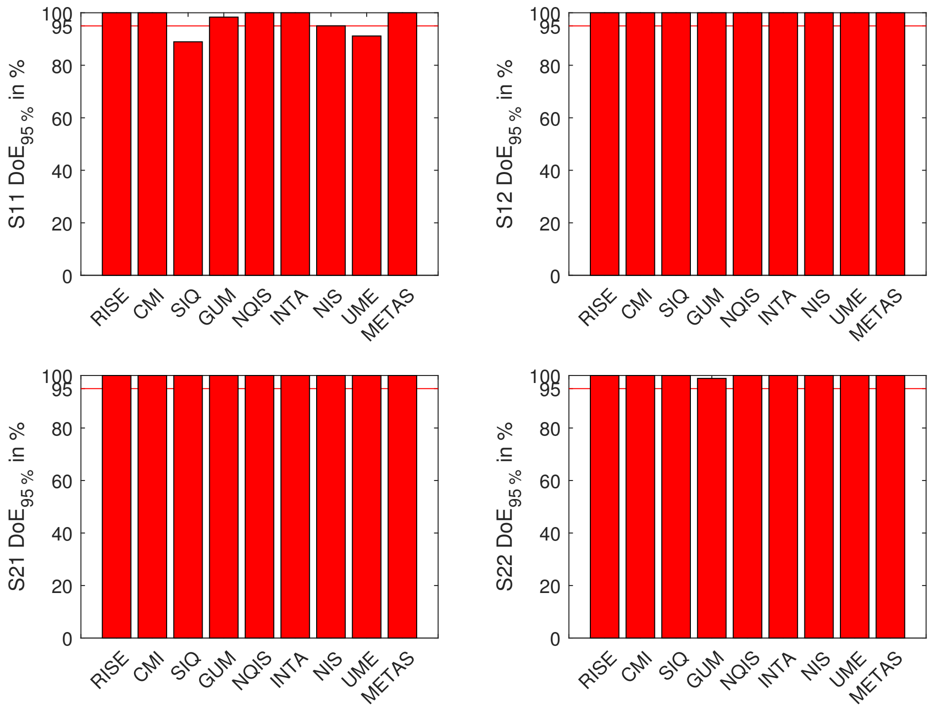

Figure 13: 6 dB Attenuator: compliance rate with CRV for S11, S12, S21 and S22.

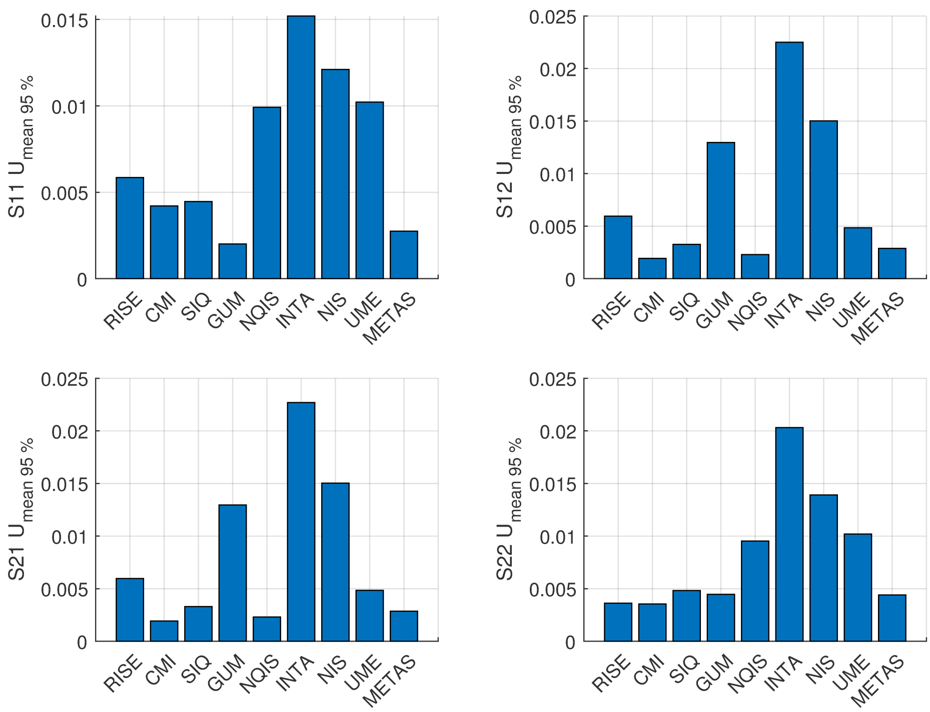

Figure 14: 6 dB Attenuator: averaged uncertainty for S11, S12, S21 and S22.

6.3 Three-port

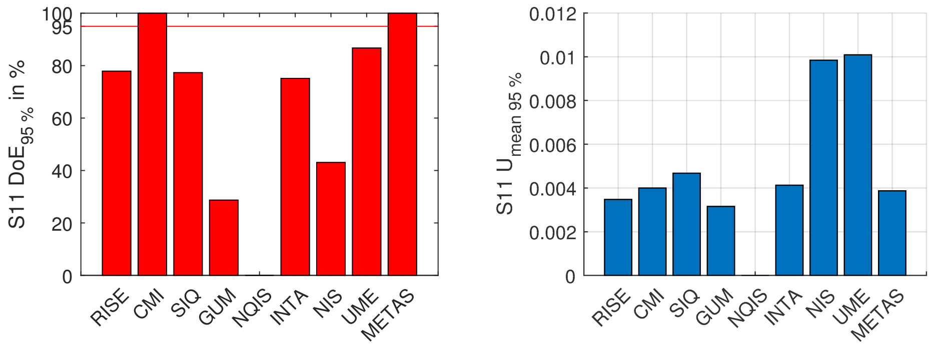

Figure 15: Power splitter: compliance rate with CRV (left) and averaged uncertainty (right) for S11. No data from NQIS.

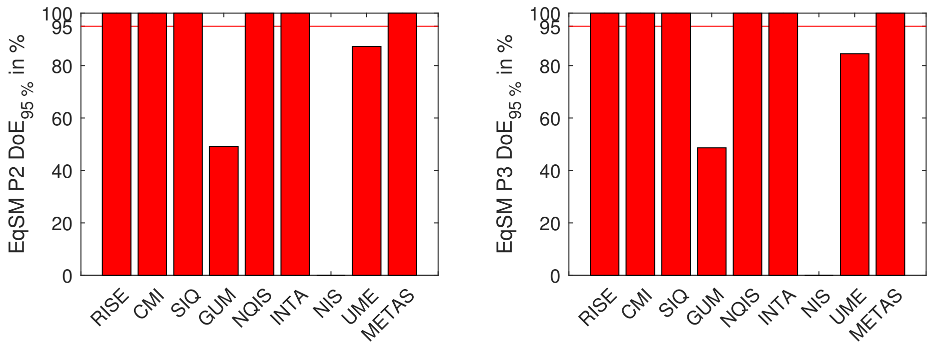

Figure 16: Power splitter: compliance rate with CRV for equivalent reflection coefficients at port 2 (left) and port 3 (right). No data from NIS.

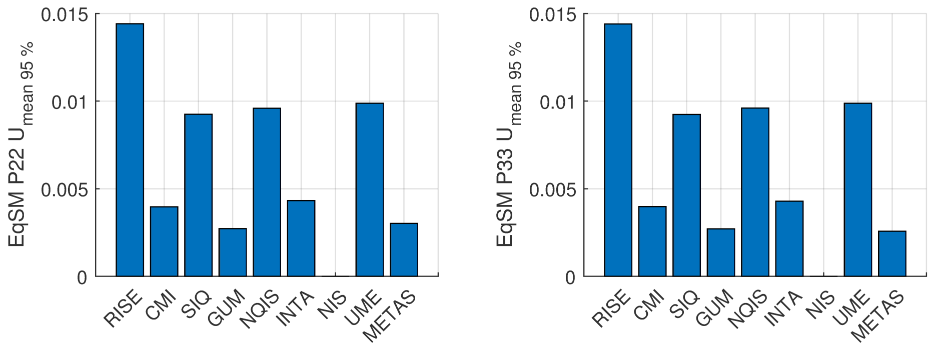

Figure 17: Power splitter: averaged uncertainty for equivalent reflection coefficient at port 2 (left) and port 3 (right). No data from NIS.

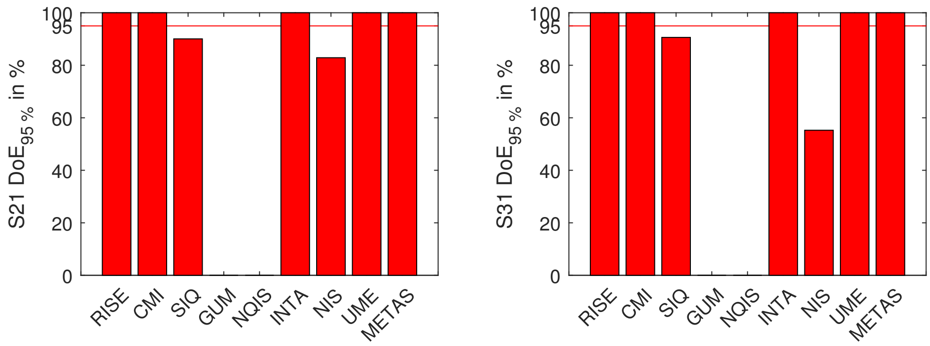

Figure 18: Power splitter: compliance rate with CRV for insertion loss at port 2 (left) and port 3 (right). No data from NQIS. The compliance rate of GUM is indeed zero.

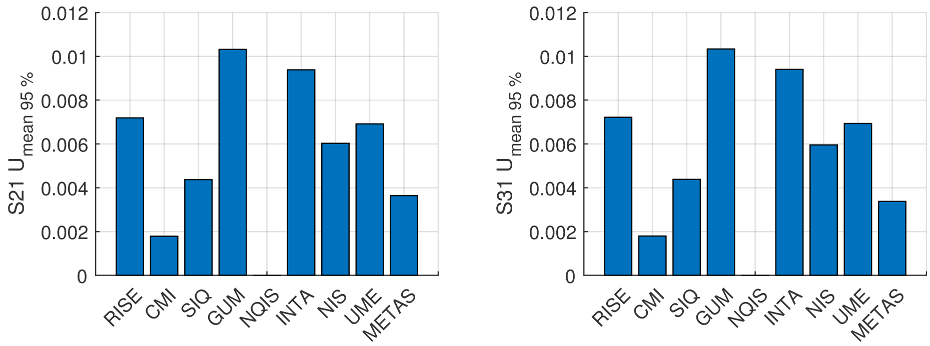

Figure 19: Power splitter: averaged uncertainty for insertion loss at port 2 (left) and port 3 (right). No data from NQIS.

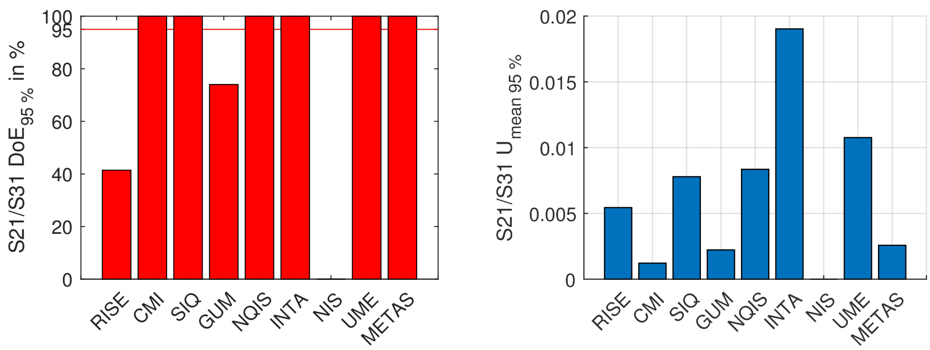

Figure 20: Power splitter: compliance rate with CRV (left) and averaged uncertainty (right) for transmission tracking. No data from NIS.

6.4 Pin depth measurements

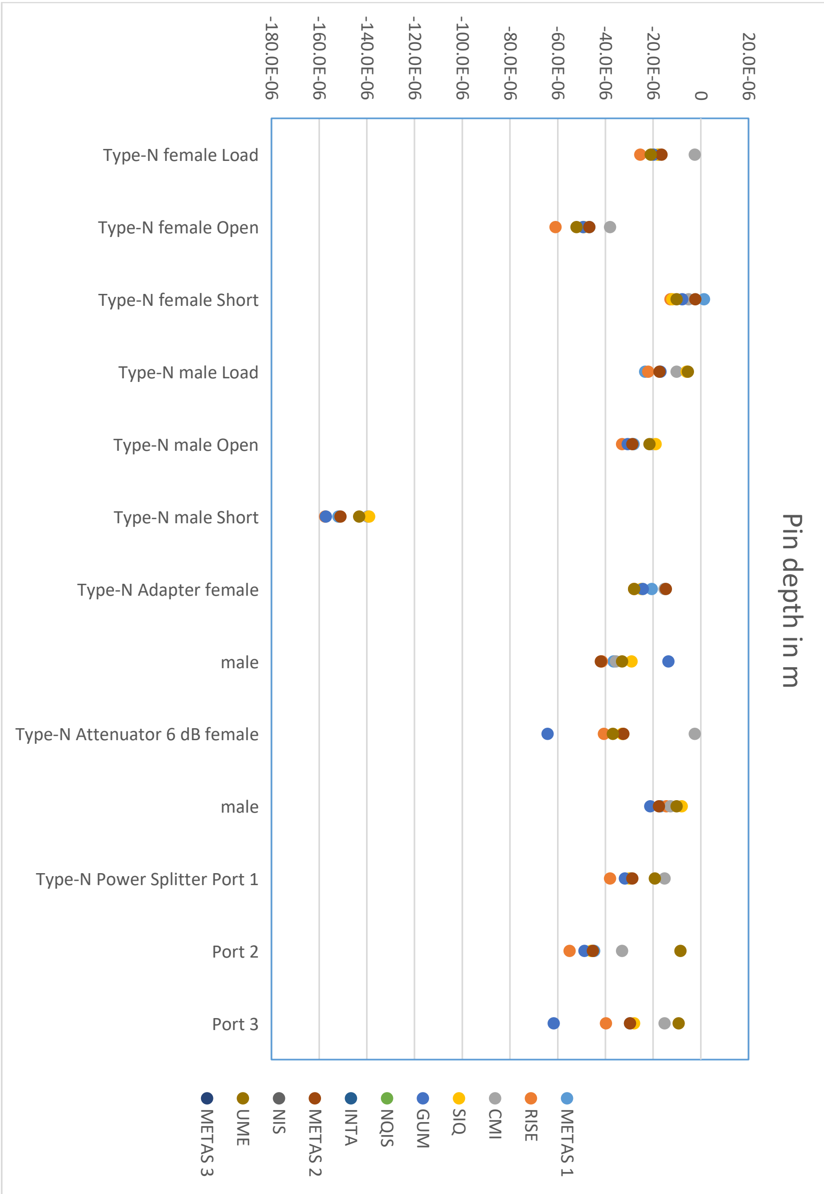

Figure 21: Pin depth measurements

7 DISCUSSION AND SUMMARY

With a few exceptions the agreement of the data was reasonable. Full compliance with the CRV at the 95% level for all traveling standards has been reached by CMI, NQIS and METAS, although NQIS has not submitted all requested splitter data. The pilot made an inspection of the data submitted by the participants and the findings are summarized below

- Female one-ports show a slightly bigger spread than male one-ports. One reason might be the slotted interface. A variation in the diameter of the male pin at the test port will cause slightly different spreading of the female fingers of the device under test.
- The two-ports generally show a conservative estimation of the uncertainty if compared to the spread of the data. This is introduced by the dominating uncertainty due to cable movement. The default values are relatively large. With a careful evaluation of the cable effect, e.g before the measurement, the uncertainty could be reduced.
- For the splitter measurements, the participants were generally less careful in following the directions in the technical protocol regarding measurements and calculations.
- Not all participants have collected measurements at 8 different connector orientations.
- A large difference in uncertainty between female and male component is unrealistic and is likely due to a configuration error.
- In some cases large ripples can be seen in the data sets. A very likely source for such behavior is an instability in the measurement setup.
- The large correlation that can be observed between some data sets from different participants is not real. It is probably caused by accidentally applying the same uncertainty ID (unique identifier of uncertainty object) to physically different things.

8 ACKNOWLEDGEMENT

The pilot laboratory would like to thank the participants for the largely smooth course of this comparison and for their constructive participation.

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