Final Report

EUROMET PROJECT 633
CALIBRATION FACTOR OF THERMISTOR MOUNTS

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September 2006

Abstract:

From August 2001 to July 2002 the measurements for a Euromet project 633 (KCDB-code EUROMET.EM.RF-K8.CL) were carried out.
Two travelling standards were measured by 7 national standard institutes. The results at all selected frequencies in the range from 10 MHz to 18 GHz show a good agreement between the participants. The maximum stated uncertainty for the calibration factor ranges from 0.3 % at 50 MHz to more than 4.0 % at 18 GHz, independent of the type of connector on the DUT. Almost all results are consistent within the claimed uncertainty. The uncertainty stated for the reflection coefficient was up to 0.03 in almost all cases. Most of the results are consistent within the claimed uncertainty. SP did not measure at 10 MHz. NRC and IEN got results at 10 MHz that significantly deviate from the others. Both laboratories took actions after the distribution of the Draft A report.

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1. Introduction

During the Euromet HF experts meeting in 2000 a provisional Draft A report was discussed containing the results of Euromet project 393 (now the European loop of the CCEM key comparisons CCEM.RF-K8.CL). The results have been presented during CPEM2000 in Sydney, Australia, and have been published as well [1]. The main observations during this discussion were the apparently systematic deviation of the results of METAS from the other participants at higher frequencies. Also IEN expressed some worries about certain results. NPL has used a secondary standard that led to relative large uncertainties compared to other participants. All these points led to the suggestion of a follow-up to evaluate these points.

The Euromet experts proposed a new project aimed at repeating a comparison similar to Euromet project 393 with a limited number of participants (NPL, METAS, IEN and the pilot). NMi Van Swinden Laboratorium (NMi-VSL) agreed to act as pilot laboratory.

The proposal was distributed among the Euromet members under the code 633. Two other laboratories asked for participation to obtain a direct link for their new and/or extended facilities. Hence the Euromet Technical Chairman proposed to raise the level of the project to that of a Euromet key comparison. In 2001 the proposal was officially accepted as such. The pilot laboratory suggested to NRC, Canada, to join the project as the results of NRC in CCEM.RF-K8.CL gave some doubts about the consistency of the measurements. As there was a change in personnel shortly after the NRC participation as well, it would be advantageous if NRC would participate. Hence NRC decided to participate.

A new technical protocol was written, based upon the original guidelines of Euromet 393. After some minor changes the Euromet Technical Chairman agreed that the protocol was in line with the CIPM / Euromet guidelines for international comparisons. The project is put into the BIPM Database under the code EUROMET.EM.RF-K8.CL to indicate it is an official link (key comparison) to the relevant CCEM.RF key comparison.

2. Participants and schedule

The original time schedule for the first part of the project was proposed and finalised in July 2001. Near the end of the first part the time schedule for the second loop was proposed and finalised in December 2001 (see Appendix E2). The final scheme how the whole project is really implemented is given in Table 1.

Table 1. List of participants and measurement dates.

Acronym	National Metrology Institute	Country	Standard at the laboratory	Date of submission of report
NMi-VSL	NMi Van Swinden Laboratorium - Pilot	The Netherlands	August 2001	
NPL	National Physical Laboratory	United Kingdom	September 2001	November 2001
IENGF	Istituto Elettrotecnico Nazionale Galileo Ferraris	Italy	October 2001	February 2002
METAS	Swiss Office of Metrology	Switzerland	November 2001	December 2001
NMi-VSL	Pilot	The Netherlands	January 2002	
NRC	National Research Council	Canada	February 2002	March 2002
SMU	Slovak Institute of Metrology	Slovak Republic	April 2002	May 2002

Acronym	National Metrology Institute	Country	Standard at the laboratory	Date of submission of report
SP	SP Sveriges Provnings- och Forskninginstitut	Sweden	May 2002	December 2002
NMi-VSL	Pilot	The Netherlands	July 2002	

The measurements are considered to be of a routine nature: hence only two weeks of measurements and one or two weeks for transportation were allowed. The ATA carnet was used outside the European Union.

Concerning the time schedule of measurements a good performance is shown by almost all laboratories, despite the tight schedule of only three weeks per laboratory (including transport) within Europe (see original time schedule as given in Appendix E2). No significant problems arose with customs handling. In general, reports arrived very quickly after finishing the measurements, with one exception: the only laboratory that did not participate in the previous project (393). Apparently a learning process is necessary.

3. Transfer Standard and required measurements

Because the project is a follow-up of Euromet 393 it was decided to use a set of similar devices. Hence the following DUTs were used:

- Hewlett Packard model 8478B Opt.H48 (sn.2106 A 23878) with Type-N connector (the code TM4 is used in this report);
- Hewlett Packard model 8478B Opt.H49 (sn.3318 A 24991) with PC7 connector (the code TM5 is used in this report);
- Thermistor mount TM5 with an adapter PC7-Type-N: the adapter is part of a commercial VNA calibration kit (identifier c2-1) (the code TM6 is used in this report).

All devices are owned by NMi-VSL. To distinguish the present set from the one used in Euromet 393 (and GT-RF 98-1) a different code is used than was used in Euromet 393.
The DUT power detectors are thermistor mounts that must be used in connection with a thermistor bridge which keep the thermistor resistance to a fixed value of 200 Ω. Several commercial thermistor bridges are available to determine the DC substitution power P_{DC} when RF power is applied to the thermistor mount. The mount has an available compensation scheme that allows the detection of power, even when the ambient temperature is not constant. The two signals (V_{RF} and V_{comp}) from two separated bridges inside of commercial thermistor bridges may be detected separately to determine P_{DC} . It is also possible to use the recorder output, which is proportional to P_{DC} because of an internal electronic manipulation with the V_{RF} and V_{comp} signals.

The quantity under investigation in this comparison is the calibration factor K, which is defined by:

$K= P_{DC}/P_{inc}$ with:

P_{DC} - the DC substitution power determined by the thermistor bridge of the participant and
P_{inc} - the RF power incident to the thermistor mount (DUT) at the measurement frequency.

The participants were asked to submit measurement results on each thermistor mount at 8 frequencies (10 MHz, 50 MHz, 1 GHz, 4 GHz, 8 GHz, 12 GHz, 15 GHz and 18 GHz) concerning its calibration factor and also its reflection coefficient, both with an extended uncertainty (coverage factor k =1).
To substantiate the technical performance the technical protocol put emphasis on the uncertainty statements and the consistency of the measurement results. Hence, a detailed uncertainty budget,

containing sources and magnitudes, was requested, as well as the traceability of the standards, in order to take into account the possibility of correlation between the results.
In principle this information is easily available, as soon as a laboratory operates effectively according to a quality assurance system based upon standards like ISO 17025.

The quantity reflection is necessary for the uncertainty calculations. In this comparison it is not the quantity under investigation.

In the guidelines no requirements are given concerning the ambient conditions.

4. Behaviour of the transfer standard

As the DUTs are all provided by NMi-VSL and are part of its set of primary standards, the in-house stability is known. Based upon the experience obtained in Euromet 393 (CCEM.RF-K8.CL) and the small number of participants, no additional checks concerning stability for transport have been performed. Only one intermediate measurement was scheduled: NMi-VSL performed in total three measurements including those at the start and at the end of the comparison.

Before processing the data obtained in the comparison an investigation is done whether a significant drift in the DUTs has occurred, based upon the 3 results obtained at NMi-VSL (see Appendix A). Within the uncertainty no significant drift has occurred over a period of 12 months. Based upon this information it is decided that no correction for drift is necessary. However, the spread in the results in the three series of measurements at the pilot laboratory led to the decision by the pilot laboratory to use the average value from all three measurement series as the official entry to the comparison. In Appendix A the individual results are presented in graphs together with the official entry of the VSL-data (in tables).

5. Measurement methods

As indicated in the guidelines each laboratory should use the same measurement instrumentation as used for “high level” calibration for external customers. All systems are based on a (in)direct comparison between a (working) standard and the DUT.
The majority of the laboratories used a splitter system in which one of the arms is used to monitor the output power. On the other arm the standard and the DUT were attached and for each the response in relation to the monitor signal was measured.
For each laboratory the measurement procedure (including traceability) is briefly described here. Also information about the measurement of the reflection is given.

<u>NMi-VSL – pilot laboratory:</u>
A substitution system is used, where the signal comes from a stable signal generator, with a 10 dB attenuator to improve the VSWR of the output port. The standard and DUT are placed alternatively on the output port of the generator, and are of similar design (thermistor mounts). The response of the thermistor mounts is obtained using the recorder output of a self-balancing bridge, HP 432A. The recorder output has been characterised during normal maintenance using V_{RF} and V_{comp} readings.
Traceability is based on the primary VSL power facility (microcalorimeter): the working standard is calibrated in the microcalorimeter every half year.
The reflection coefficients are measured using Vector Network Analysers (HP 8753E with external test set and Wiltron 360A).

<u>NPL:</u>

The Travelling Standards were measured on two separate systems, one to obtain the Calibration Factor at a frequency of 50 MHz with respect to DC substituted power and the second to obtain the Calibration Factor at other frequencies with respect to 50 MHz.
At a frequency of 50 MHz the thermistor mounts were calibrated against the laboratory's 14mm Primary Standard Calorimeter using a transfer standard consisting of a power splitter, a thermistor mount and attenuators. At frequencies other than 50 MHz the thermistor mounts were calibrated against the laboratory’s 7mm (Type N) Primary Standard Calorimeter using a transfer standard consisting of a power splitter, a thermocouple power sensor and attenuator.
At 50 MHz the dc substitute power to the DUT thermistor was measured using the Vrf and Vcomp outputs of an HP432A power meter, at all other frequencies the recorder output was used to obtain the ratio with respect to the 50 MHz value. In both cases an attenuator is used to improve the VSWR of the splitter output port. The DUT and the calorimeter are attached alternatively to the measuring port with each time a different orientation for the DUT.
The reflection coefficients are measured using VNAs.

<u>IENGF</u>:
A power splitter system is used with the DUT and the standard each attached to an arm of the splitter HP 11667A. The splitter showed relative high effective source match even for power ratio measurements. During the measurements the positions of DUT and standard have been interchanged. The ratio between the responses of the power readings on both arms is obtained as measurement value.
The standard is a thermistor mount and traceable to the IEN primary power facility (a microcalorimeter).
The reflection coefficients are measured using Vector Network Analysers.

<u>METAS:</u>
A power splitter system is used with a Rohde und Schwarz NRV-Z51 power sensor permanently attached to one arm. The DUT and the standard are attached alternatively to the other arm of the splitter. An Arbiter 1096 type IV bridge and a HP 3458A DVM is used as power meter for the thermistor mounts. Two power splitters are used (one equipped with APC7 output connectors and one with type-N output connectors): The DUT TM4 and TM6 are measured on both systems using adapters if necessary.
The standards (different HP 8478B thermistor mounts) are traceable to NMi VSL and BNM-LCIE.
The reflection coefficients are measured using HP 8510C and 8753D VNAs.

<u>NRC:</u>
The transfer standards used were calibrated against the primary standard of NRC-INMS: a 7-mm twin-load calorimeter developed by A. Jurkus (NRC).
Three different measurement set-ups were used in this comparison.
<u>*At 4 GHz and above*</u>: The transfer standards consist of a 3 dB directional coupler (2 to 18 GHz band, 3 dB) attached to a thermistor mount (HP model 8478B) and a Tech USA (NBS type IV) bridge. The thermistor voltage is read using a precision voltmeter (Keithley model 196).
<u>*At 1 GHz*</u>: the system used is similar as before except that the transfer standard consists of a 3 dB hybrid coupler whose pass band is from 0.5 to 2 GHz.
<u>*At 10 and 50 MHz*</u>, the transfer standard consists of a symmetrical tee, which is reversed in order to cancel any asymmetry. The transfer standard is a thermistor mount (HP model 478A option H55).
The reflection coefficients are measured using VNAs, viz. a HP 8510C (1 GHz and above) and a HP 8751A (10 and 50 MHz).

<u>SMU:</u>
A power splitter system is used with female type-N adapter of the output arm to which alternatively the DUT and the standard are attached. The standard is a HP 8478B thermistor mount with type-N male connector. Its traceability is based upon an intercomparison with CMI (Czech Republic) and previous measurement data.

The reflection coefficients are measured using a VSWR-bridge (Wiltron).

SP:
A power splitter system is used with a Rohde und Schwarz NRV-Z51 power sensor permanently attached to one arm. The DUT and the standard are attached alternatively to the other arm of the splitter. The standard is another Rohde und Schwarz NRV-Z51 sensor, traceable to NPL, UK, for the calibrator factor relative to 50 MHz. The absolute power level is established at 1 kHz using voltage and resistance/impedance standards within SP. The signal from the DUT is obtained via the V_{RF} and V_{comp} outputs of a HP 432A power meter using two Agilent 34401A voltmeters.
The reflection coefficients are measured using an Agilent 8510C VNA. As this system cannot operate at 10 MHz, no measurements have been carried out at this frequency.

6. Technical protocol

In the protocol ("Technical Protocol for the comparison", see Appendix E1) participants were asked to present their measurement results in the format of the mean of the calibration factor and the magnitude of the reflection coefficient at the 8 frequencies, including a statement of uncertainty with a coverage factor of k = 1. In addition they were requested to give a detailed uncertainty budget that would allow the pilot laboratory to determine whether important contributions might have been overlooked and to allow for drafting a common agreed basis for uncertainty calculation in this field. Reference was made to the EA document on uncertainty (EA-04/02) [8] that gives guidance for providing such an uncertainty budget, and to the uncertainty budgets as given the Euromet project 393. Also the traceability for the standards used should be provided to ascertain that correlation between measurement results would not be overlooked. No common scheme to report the uncertainty budgets was given to the participants. In case that participants submitted a PDF-file, the pilot laboratory has asked for a conversion into a Word-format.
A torque wrench is provided by the pilot laboratory for use during the measurements.

7. Measurement results

7.1. General results

The participants were asked to submit measurement results on each thermistor mount at 8 frequencies (10 MHz, 50 MHz, 1 GHz, 4 GHz, 8 GHz, 12 GHz, 15 GHz and 18 GHz) concerning its calibration factor and also its reflection coefficient, both with an extended uncertainty (coverage factor k =1).
After receiving the measurement data (including uncertainty statement) the coordinator has compiled these results in an Excel spreadsheet for further analysis. Each laboratory has received the relevant part of this spreadsheet for checking the correctness of these data. In contrast to the technical protocol the pilot laboratory has used the expanded uncertainty (k=2) as an analysis tool throughout this document.

Figure 1 gives a first impression of the overall result of the comparison. The averages of the results (calibration factor and reflection coefficient) from all participants are given for each of the three DUTs, including the average of the stated uncertainties (k=2) as given by the participants.
In Figures 2.1 through 2.4 the results of the individual laboratories are given for the three DUTs with the actual measurement data. The uncertainty bars are the k=2 values based upon the information given by each of the laboratories.
Please, note that the vertical scale differs per frequency to accommodate for the variation in value of the calibration factor as function of frequency and in some cases for the size of the uncertainty bars.

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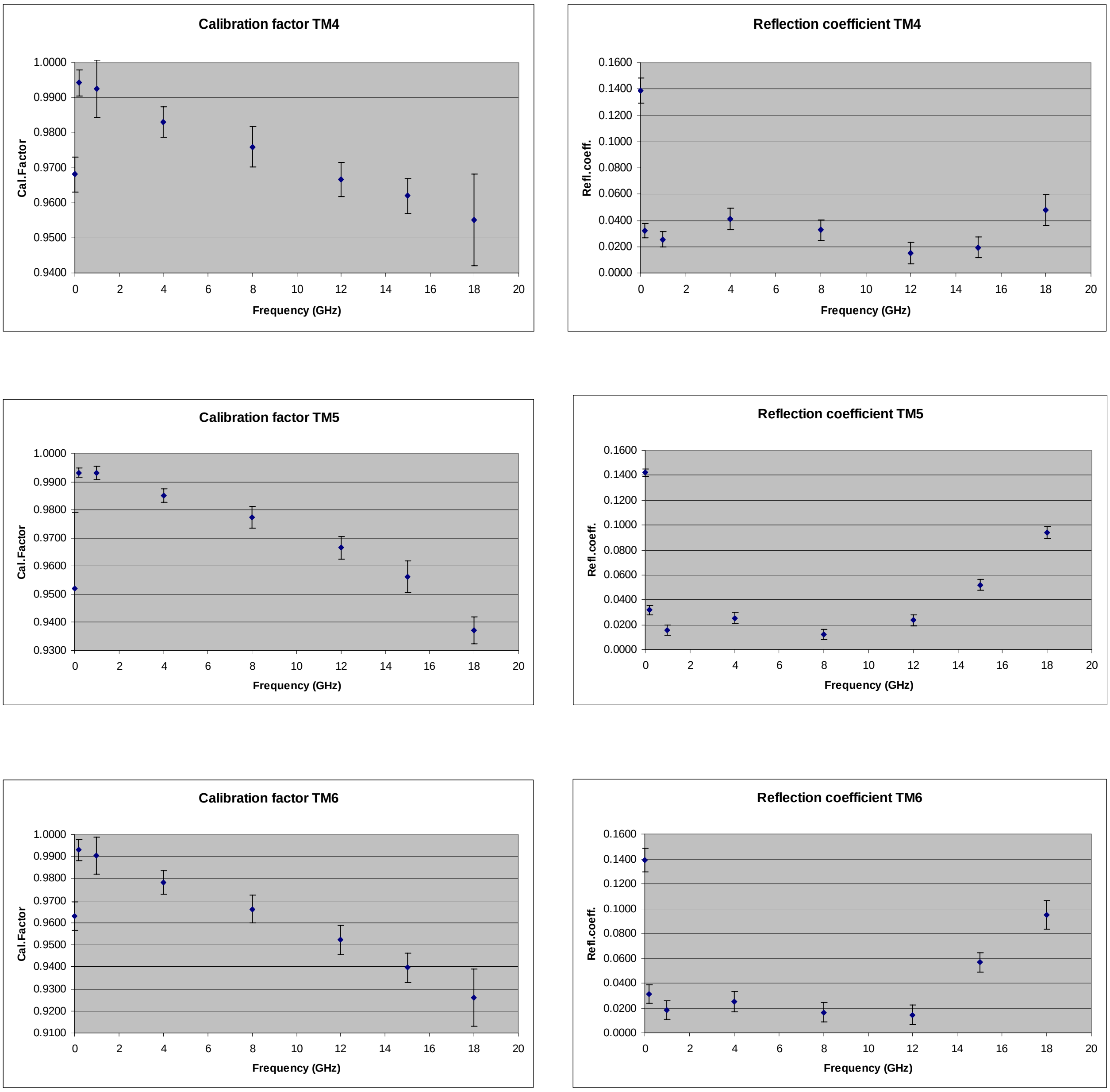
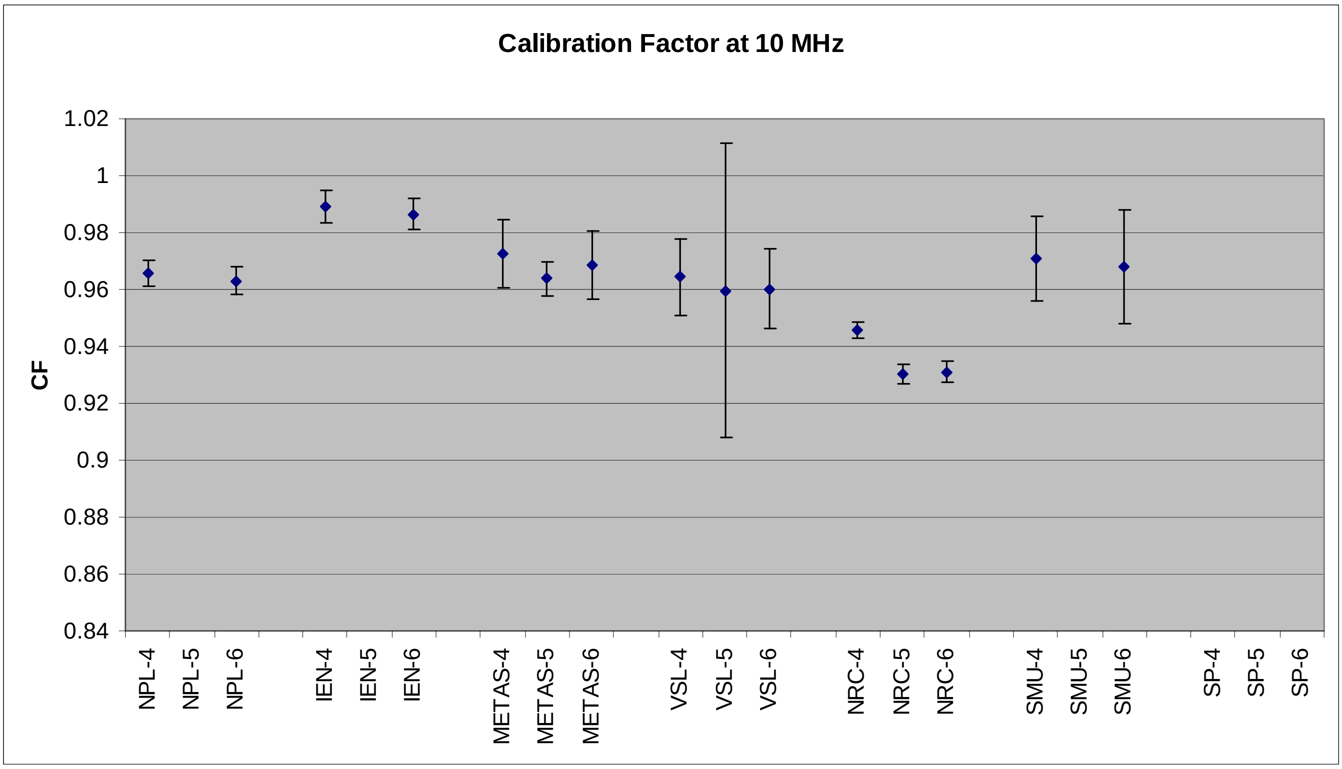


Figure 1: Global result obtained in the comparison for the three DUTs. The left column of the graphs presents the average calibration factor and the right column the average reflection coefficient. The uncertainty bars refer to the standard deviation (k=2) in the results of the participants.



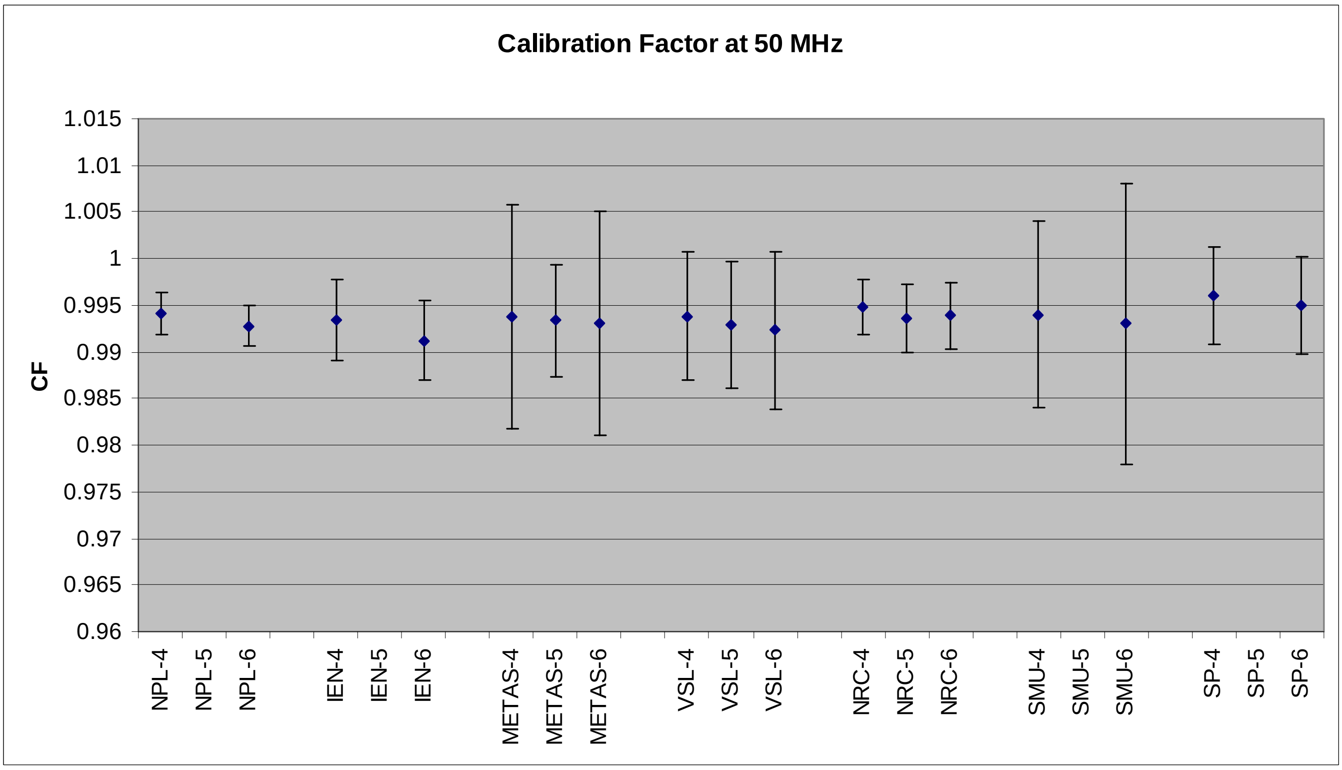
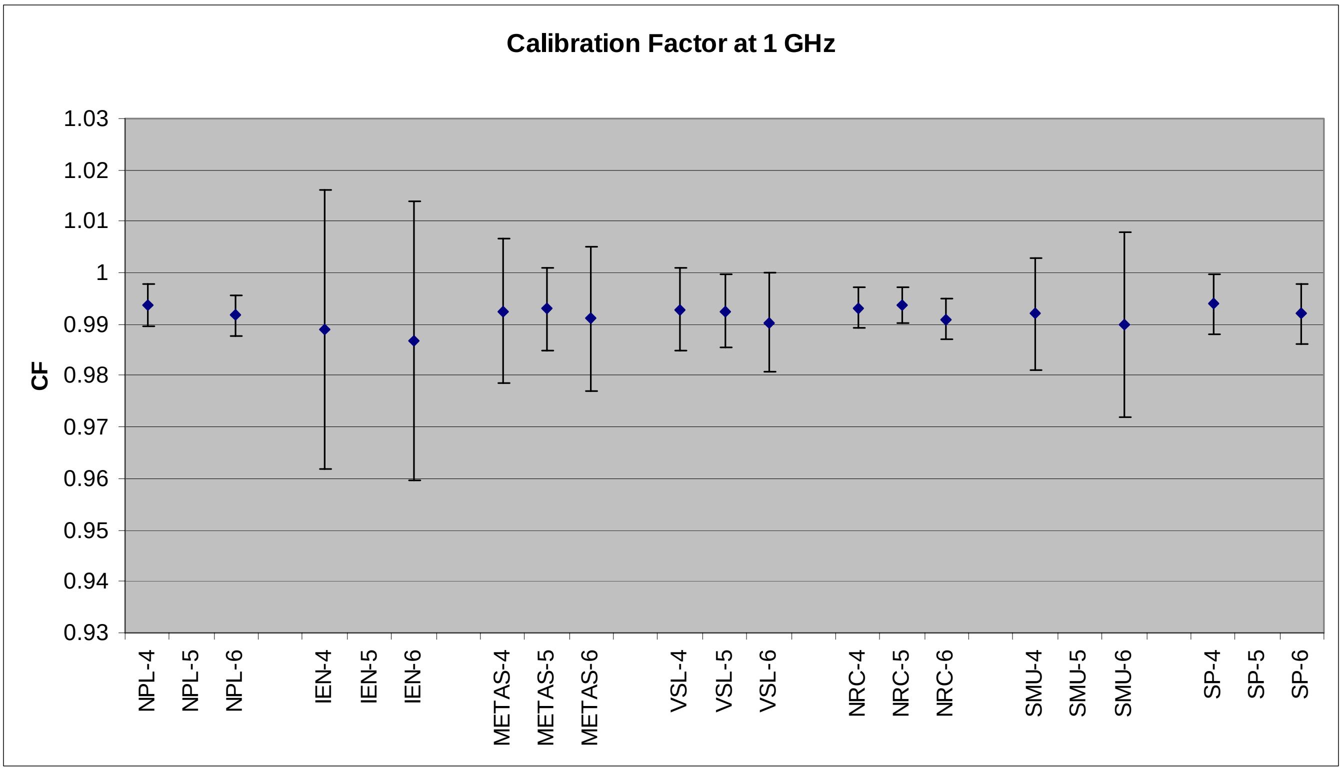


Figure 2.1: Measurements at 10 MHz (top) and 50 MHz (bottom). The error bars refer to the k=2 uncertainty as given by the participants. The number code refers to the identifier of the DUT.



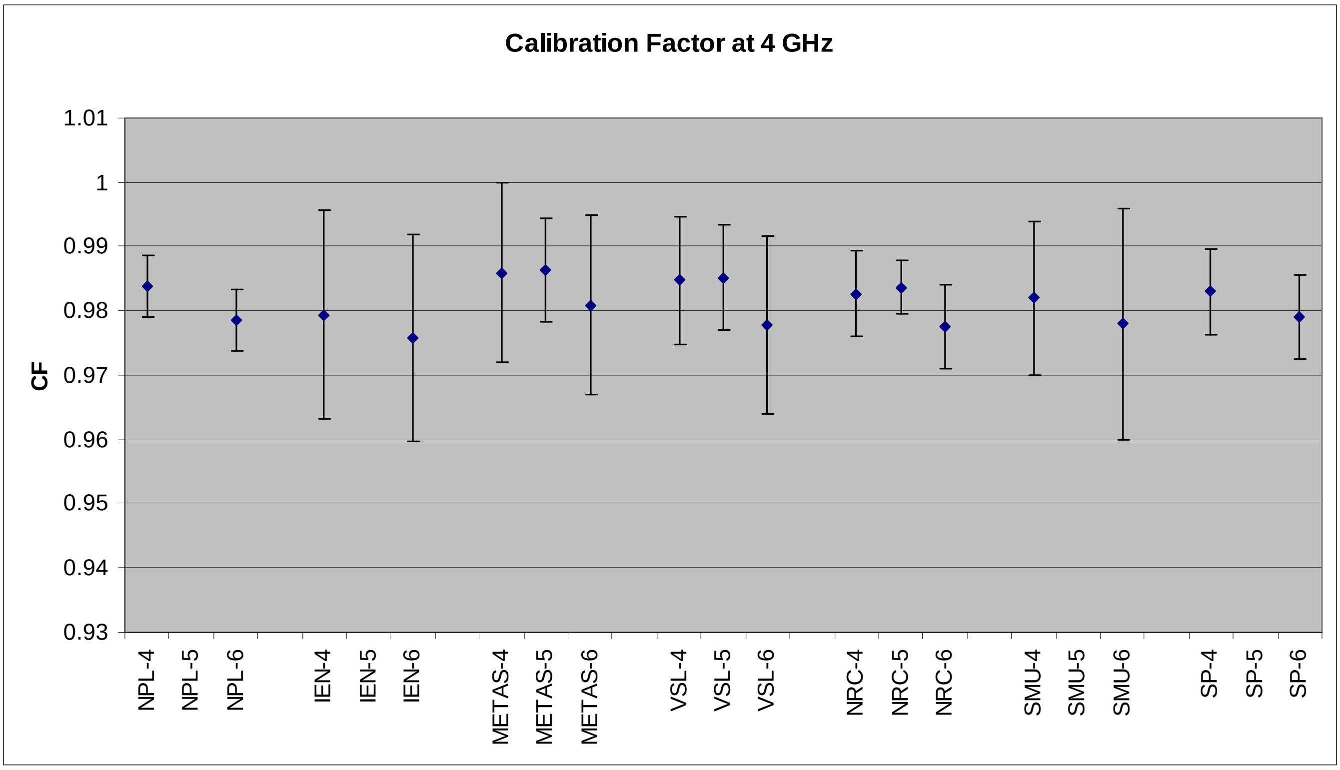
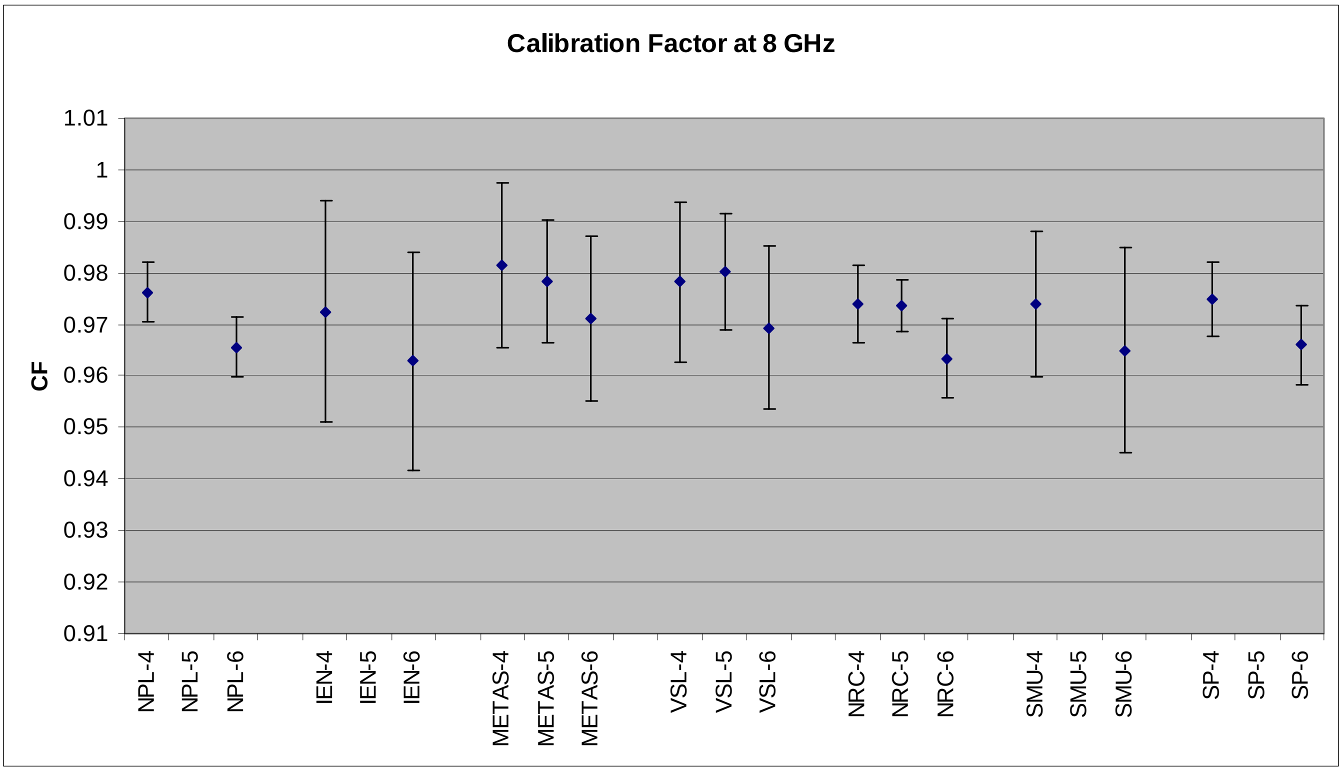


Figure 2.2: Measurements at 1 GHz (top) and 4 GHz (bottom). The error bars refer to the k=2 uncertainty as given by the participants. The number code refers to the identifier of the DUT.



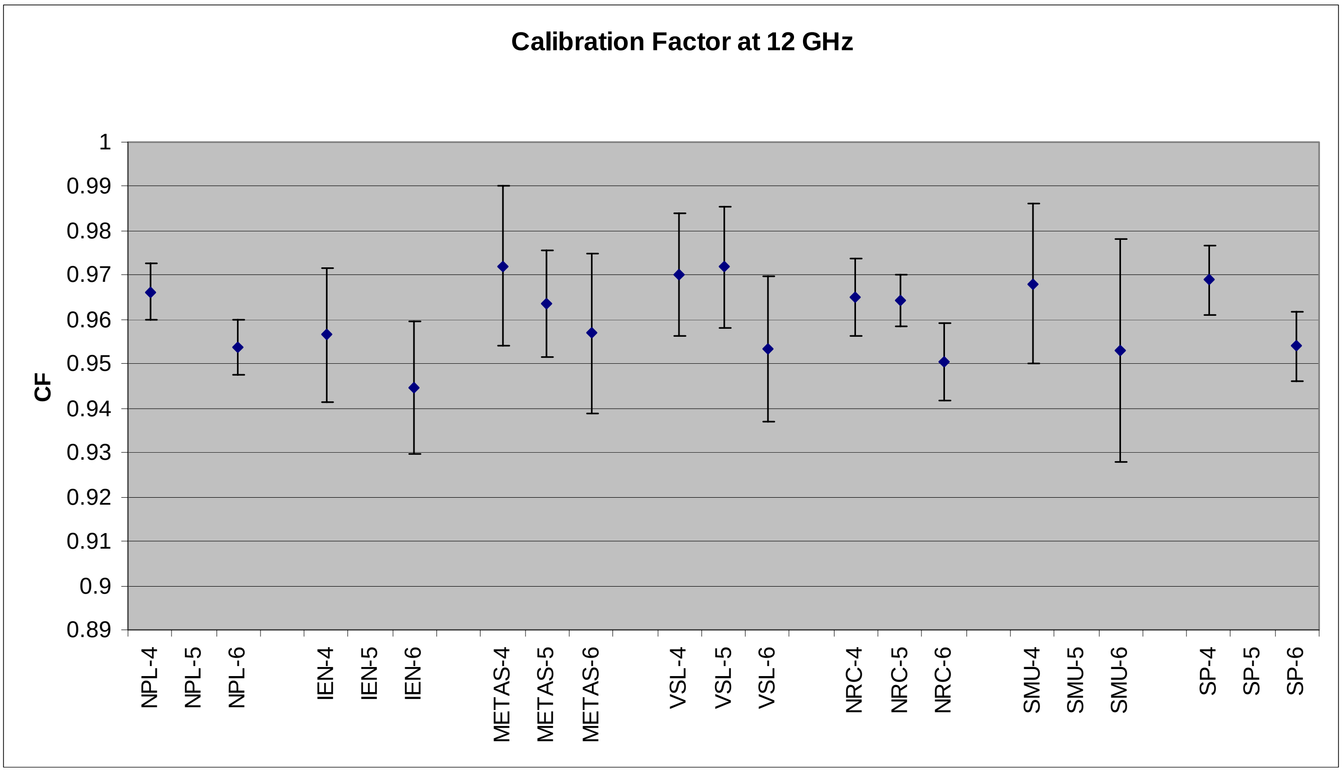
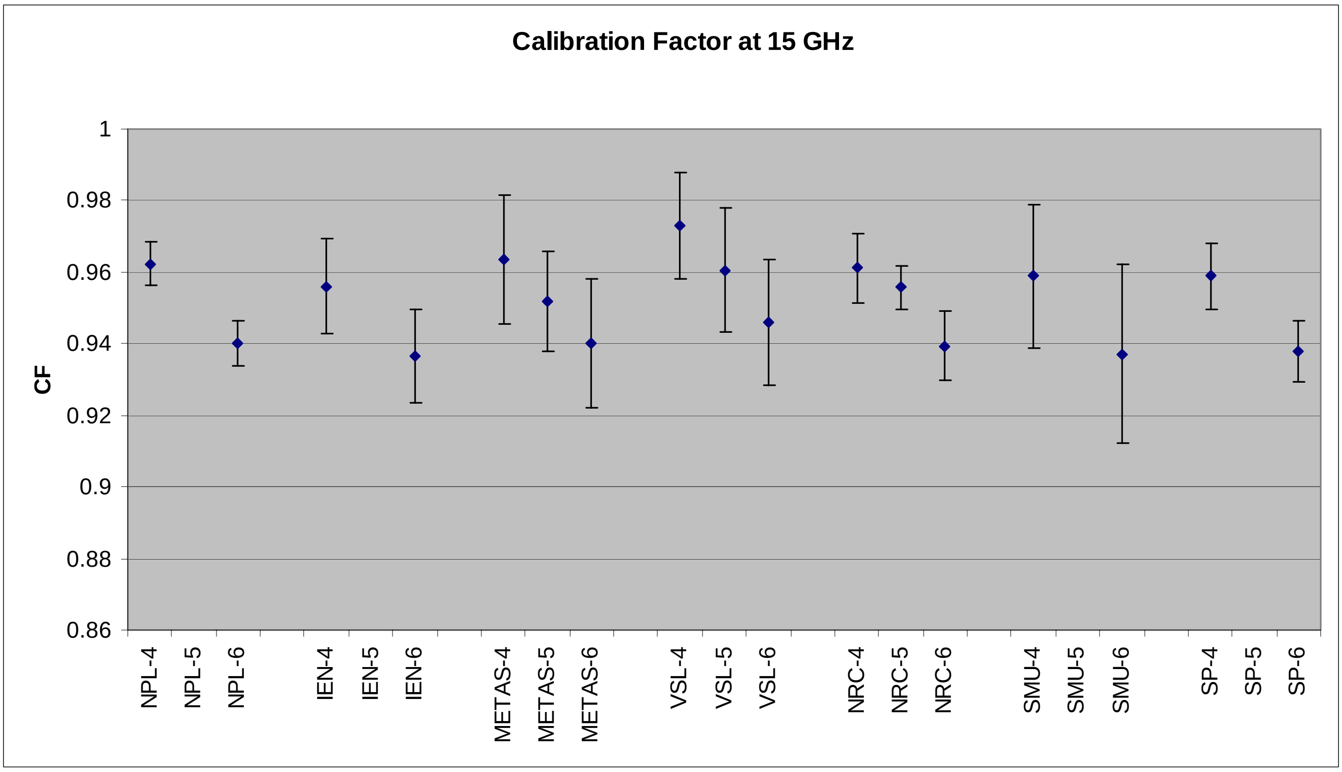


Figure 2.3: Measurements at 8 GHz (top) and 12 GHz (bottom). The error bars refer to the k=2 uncertainty as given by the participants. The number code refers to the identifier of the DUT.



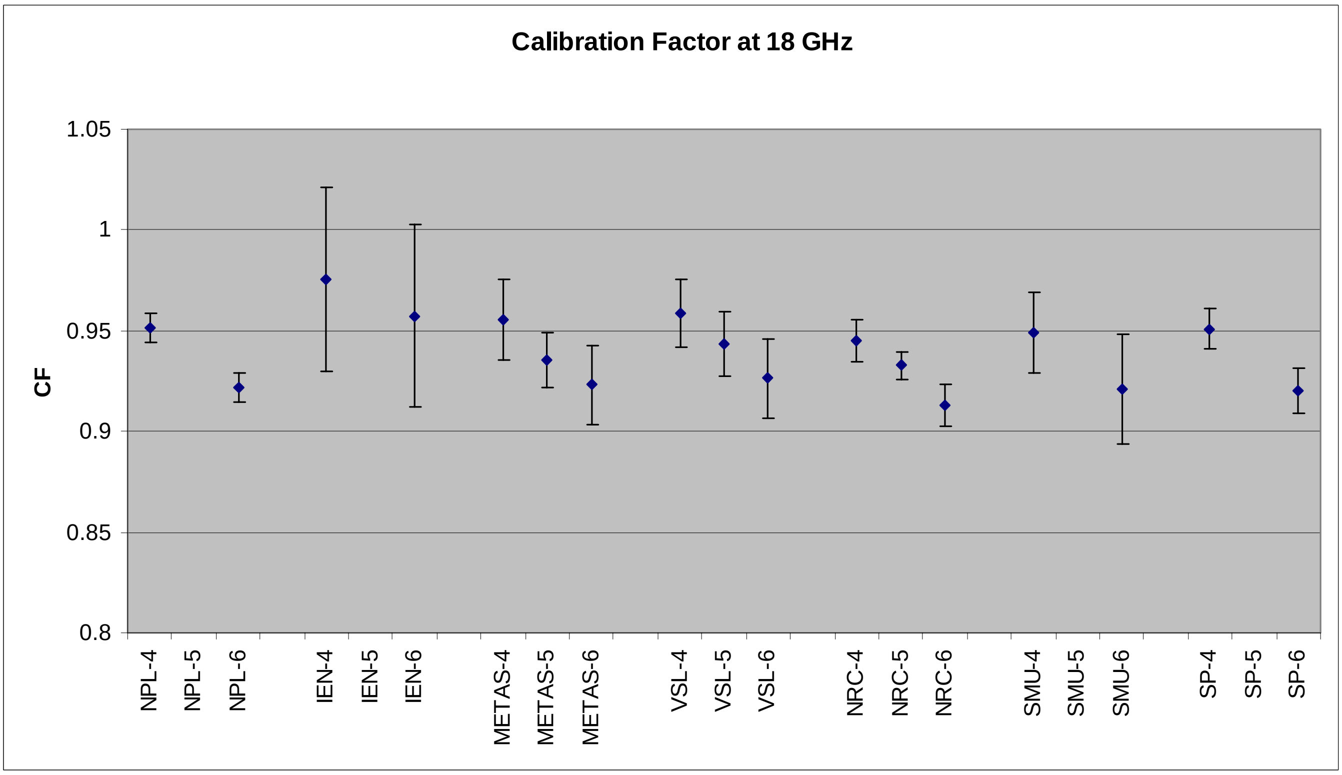


Figure 2.4: Measurements at 15 GHz (top) and 18 GHz (bottom). The error bars refer to the k=2 uncertainty as given by the participants. The number code refers to the identifier of the DUT.

7.2. Determining the Reference Value

To simplify the linking process between a regional key comparison (the present comparison) and the relevant CCEM key comparison the pilot laboratory would prefer to follow the same procedure as used in CCEM.RF-K8.CL: following the BIPM guidelines only the results from the members of the GT-RF that have an independent realisation of the quantity, are taken into account for the determination of the comparison reference value. This is done using the procedure given by J. Randa [5]: here the median and its associated MAD are used to determine whether results should be considered to be an outlier. These values are then excluded from the calculation of the comparison reference value. After the outliers have been found the unweighted mean is determined using the values from the remaining laboratories. The uncertainty in the results of each participant is determined using the laboratory's uncertainty combined with the uncertainty in the reference value, the method depending on whether the laboratory contributes to the reference value or not.

However, the Euromet project 633 is a regional comparison with a double purpose, first to contribute to solving problems as identified in the CCEM.RF-K8.CL and secondly to provide a link to SI for some laboratories. Hence, first one should look to this comparison as a stand-alone activity.
After this process we will look to the larger picture and see how a possible link to the CCEM.RF-K8.CL can be established.

7.2.1 Uncorrelated standards: The Euromet Reference Value (ERV)

As the project 633 is a regional comparison, it can be argued that the ERV should be based on the results of the participants in general, as long as there are no strict, preferably known, correlations. The ERV can be determined from the results of all participants, except SP (direct link to NPL), 6 in total.

Now, the Randa method is implemented using the following steps:
For each device the median is determined using all 6 laboratory results in the usual way, and afterwards the spread in the results, S(MAD), is determined using formula 1:

$$S(MAD) = 1.4826 * median_j \left\{ \left| Y_j - Y_{med} \right| \right\} \quad (1)$$

This quantity is more or less equivalent with the statistical spread for a gaussian distribution. Now a result is considered to be an outlier when it fulfils the requirement of formula 2:

$$\left| Y_i - Y_{med} \right| > 2.5 * S(MAD) \quad (2)$$

In Table 2 the result of this process is given.

The N results (N<=6) which are not outliers are used to determined the reference value, here called ERV, for an unweighted case:

$$ERV = \frac{1}{N} * \sum_{j=1}^{N} Y_j \quad (3)$$

and the associated uncertainty (formula 4):

$$u_{ERV}^2 = \frac{1}{N*(N-1)} * \sum_{j=1}^{N} \left(Y_j - ERV \right)^2 \quad (4)$$

The degrees of equivalence (DoE) or "deviation from the ERV" is defined as

$$\Delta_i = Y - ERV_i \qquad (5)$$

For each result the uncertainty calculation depends on the fact whether it contributed to the determination of the ERV: for an outlier formula 6 has to be used, otherwise formula 7:

$$U_{\Delta_i} = 2 * \sqrt{u_{Y_i}^2 + u_{ERV}^2} \qquad (6)$$

$$U_{\Delta_i} = 2 * \sqrt{u_{ERV}^2 + \left(1 - \frac{2}{N'}\right) u_{Y_i}^2} \qquad (7)$$

Table 2: List of laboratories without correlations to each other for the quantity power. “X” indicates outlier. “-“ indicates “No measurements”

Laboratory	Frequency																							
	10 MHz			50 MHz			1 GHz			4 GHz			8 GHz			12 GHz			15 GHz			18 GHz		
DUT (TM4, TM5 or TM6)	4	5	6	4	5	6	4	5	6	4	5	6	4	5	6	4	5	6	4	5	6	4	5	6
NPL		-			-			-			-			-			-			-			-	
IEN	X	-	X		-	X	X	-	X		-	X		-		X	-	X		-		X	-	X
METAS												X												
NMi-VSL																	X		X		X		X	
NRC	X	X	X	X							X													
SMU		-			-			-			-			-			-			-			-	

For convenience, the ERV is shifted to a value equal to zero: the actual value depends on the specific DUT, but it is not relevant for the quality of the measurement and it usually depends strongly on the measurement frequency.

In Tables 3.1 through 3.8 the final result from this process is given in values and in Figures 3.1 through 3.8 as graphs with uncertainty bars..

Table 3.1: Results at 10 MHz: deviation of calibration factor from the ERV for the three DUTs						
Laboratory	TM4		TM5		TM6	
	Value	Unc.	Value	Unc.	Value	Unc.
NPL	-0.0027	0.0052			-0.0019	0.0053
IEN	0.0208	0.0068			0.0214	0.0068
METAS	0.0041	0.0094	0.0033	0.0065	0.0038	0.0094
VSL	-0.0041	0.0102	-0.0033	0.0065	-0.0048	0.0107
NRC	-0.0226	0.0050	-0.0324	0.0075	-0.0340	0.0054
SMU	0.0026	0.0113			0.0030	0.0147
SP						

Table 3.2: Results at 50 MHz: deviation of calibration factor from the ERV for the three DUTs						
Laboratory	TM4		TM5		TM6	
	Value	Unc.	Value	Unc.	Value	Unc.
NPL	0.0003	0.0017			-0.0002	0.0018
IEN	-0.0004	0.0033			-0.0018	0.0043
METAS	-0.0001	0.0093	0.0001	0.0035	0.0001	0.0093
VSL	0.0000	0.0053	-0.0004	0.0039	-0.0007	0.0065
NRC	0.0010	0.0030	0.0003	0.0021	0.0009	0.0028
SMU	0.0002	0.0077			0.0000	0.0116
SP	0.0022	0.0052			0.0020	0.0052

Table 3.3: Results at 1 GHz: deviation of calibration factor from the ERV for the three DUTs						
Laboratory	TM4		TM5		TM6	
	Value	Unc.	Value	Unc.	Value	Unc.
NPL	0.0008	0.0032			0.0009	0.0032
IEN	-0.0039	0.0271			-0.0040	0.0270
METAS	-0.0003	0.0109	-0.0001	0.0047	0.0003	0.0109
VSL	0.0000	0.0062	-0.0005	0.0041	-0.0004	0.0076
NRC	0.0003	0.0032	0.0006	0.0021	0.0002	0.0032
SMU	-0.0009	0.0085			-0.0008	0.0140
SP	0.0011	0.0058			0.0012	0.0058

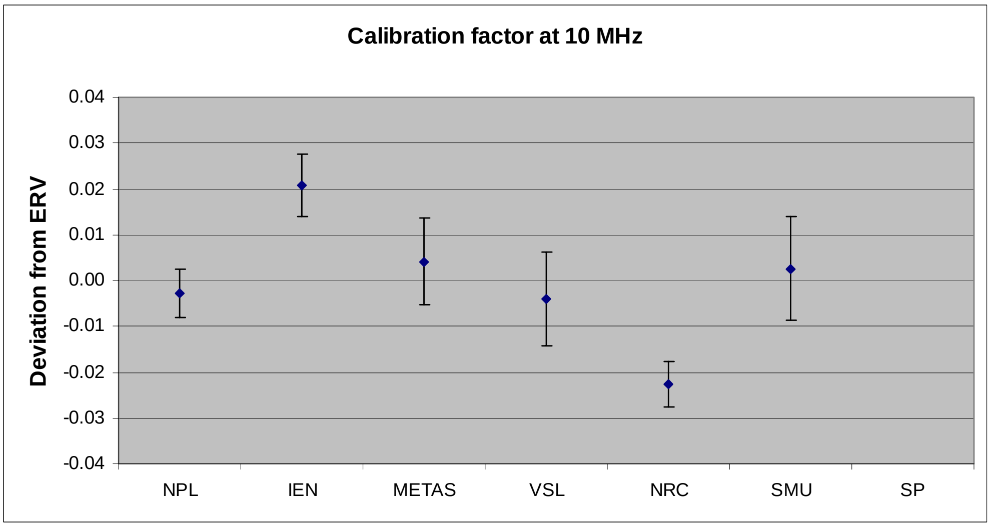
Table 3.4: Results at 4 GHz: deviation of calibration factor from the ERV for the three DUTs						
Laboratory	TM4		TM5		TM6	
	Value	Unc.	Value	Unc.	Value	Unc.
NPL	0.0007	0.0043			0.0005	0.0034
IEN	-0.0037	0.0134			-0.0022	0.0161
METAS	0.0028	0.0116	0.0013	0.0049	0.0029	0.0140
VSL	0.0017	0.0083	0.0001	0.0050	-0.0002	0.0097
NRC	-0.0004	0.0057	-0.0014	0.0029	-0.0004	0.0047
SMU	-0.0011	0.0100			0.0000	0.0127
SP	-0.0001	0.0069			0.0010	0.0066

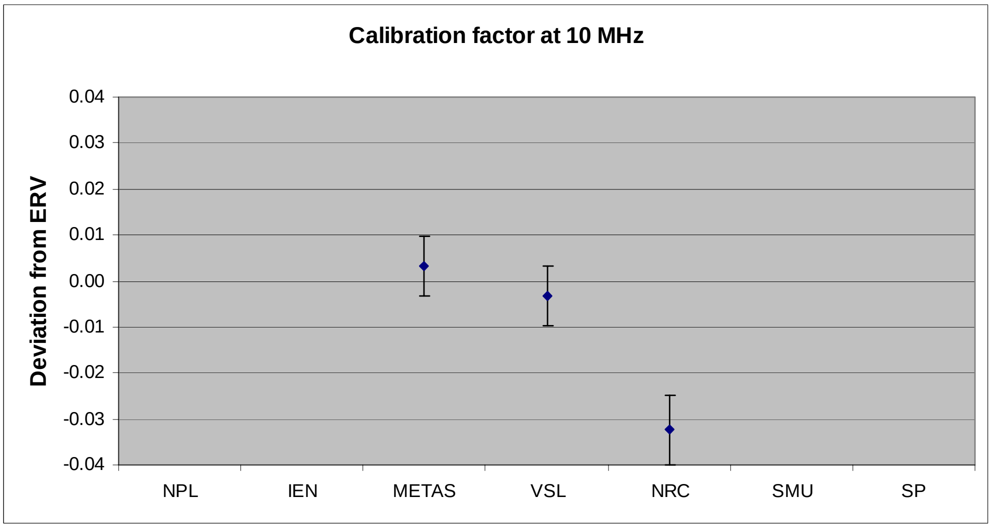
Table 3.5: Results at 8 GHz: deviation of calibration factor from the ERV for the three DUTs						
Laboratory	TM4		TM5		TM6	
	Value	Unc.	Value	Unc.	Value	Unc.
NPL	0.0002	0.0055			-0.0006	0.0054
IEN	-0.0036	0.0177			-0.0033	0.0175
METAS	0.0054	0.0133	0.0010	0.0080	0.0049	0.0133
VSL	0.0022	0.0130	0.0029	0.0077	0.0031	0.0133
NRC	-0.0022	0.0068	-0.0039	0.0050	-0.0028	0.0068
SMU	-0.0021	0.0118			-0.0012	0.0166
SP	-0.0011	0.0077			-0.0002	0.0081

Table 3.6: Results at 12 GHz: deviation of calibration factor from the ERV for the three DUTs						
Laboratory	TM4		TM5		TM6	
	Value	Unc.	Value	Unc.	Value	Unc.
NPL	-0.0020	0.0055			0.0002	0.0052
IEN	-0.0118	0.0154			-0.0088	0.0151
METAS	0.0038	0.0142	-0.0004	0.0008	0.0035	0.0141
VSL	0.0019	0.0111	0.0079	0.0137	-0.0001	0.0129
NRC	-0.0033	0.0073	0.0004	0.0008	-0.0030	0.0071
SMU	-0.0003	0.0142			-0.0004	0.0195
SP	-0.0003	0.0082			0.0006	0.0081

Table 3.7: Results at 15 GHz: deviation of calibration factor from the ERV for the three DUTs						
Laboratory	TM4		TM5		TM6	
	Value	Unc.	Value	Unc.	Value	Unc.
NPL	0.0020	0.0055			0.0015	0.0052
IEN	-0.0043	0.0107			-0.0021	0.0103
METAS	0.0030	0.0142	-0.0041	0.0095	0.0015	0.0140
VSL	0.0126	0.0151	0.0045	0.0111	0.0073	0.0178
NRC	0.0007	0.0079	-0.0004	0.0061	0.0008	0.0076
SMU	-0.0014	0.0157			-0.0016	0.0194
SP	-0.0014	0.0096			-0.0006	0.0087

Table 3.8: Results at 18 GHz: deviation of calibration factor from the ERV for the three DUTs						
Laboratory	TM4		TM5		TM6	
	Value	Unc.	Value	Unc.	Value	Unc.
NPL	-0.0004	0.0072			0.0009	0.0070
IEN	0.0236	0.0460			0.0364	0.0452
METAS	0.0031	0.0162	-0.0017	0.0103	0.0020	0.0161
VSL	0.0069	0.0139	0.0062	0.0112	0.0053	0.0157
NRC	-0.0068	0.0093	-0.0044	0.0075	-0.0081	0.0092
SMU	-0.0030	0.0162			0.0000	0.0214
SP	-0.0010	0.0112			-0.0010	0.0121





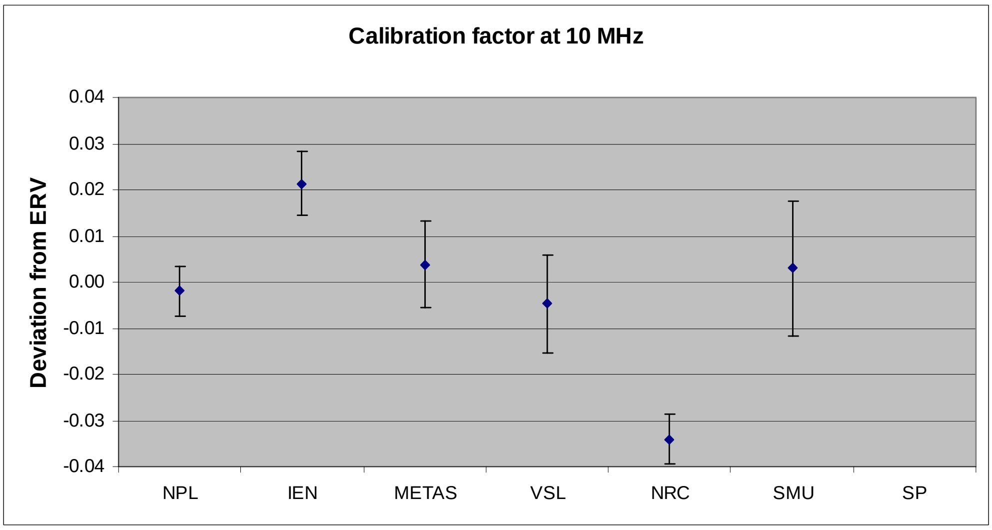


Figure 3.1: Final result of the measurements at 10 MHz for TM4 (top), TM5 (mid) and TM6 (bottom). The zero line is the reference value (ERV) as determined following the BIPM guidelines using the Randa method. The uncertainty (k=2) is calculated using the same method, taking into account whether a laboratory is contributing to ERV or not.

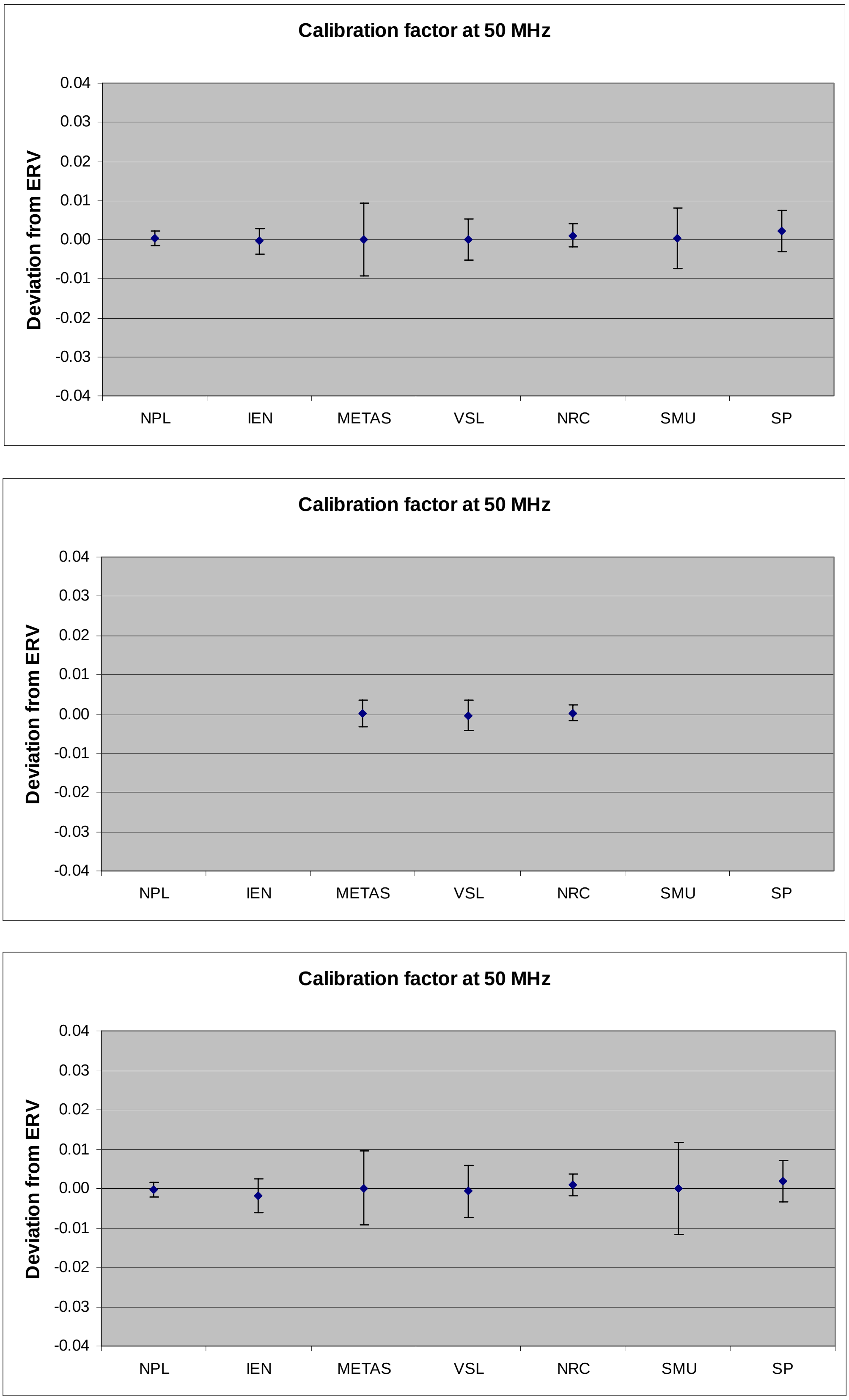
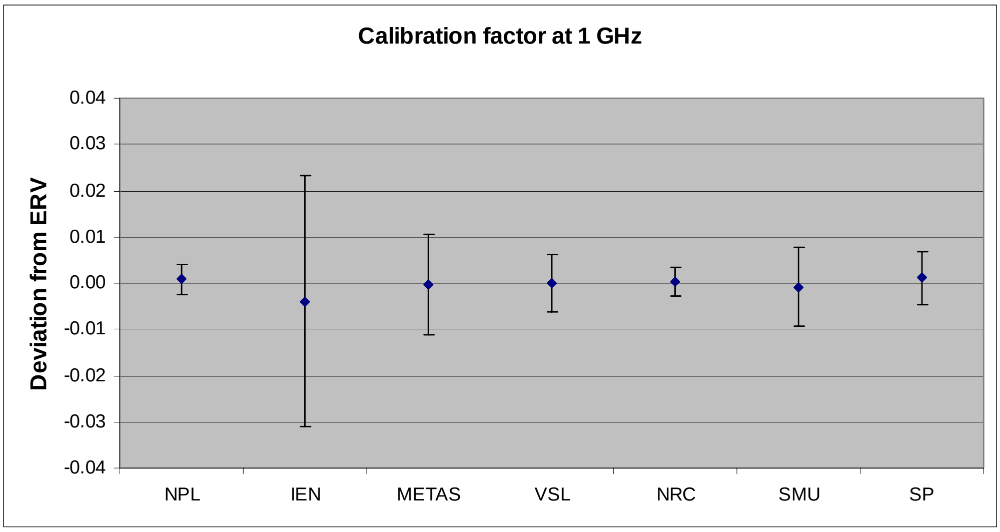
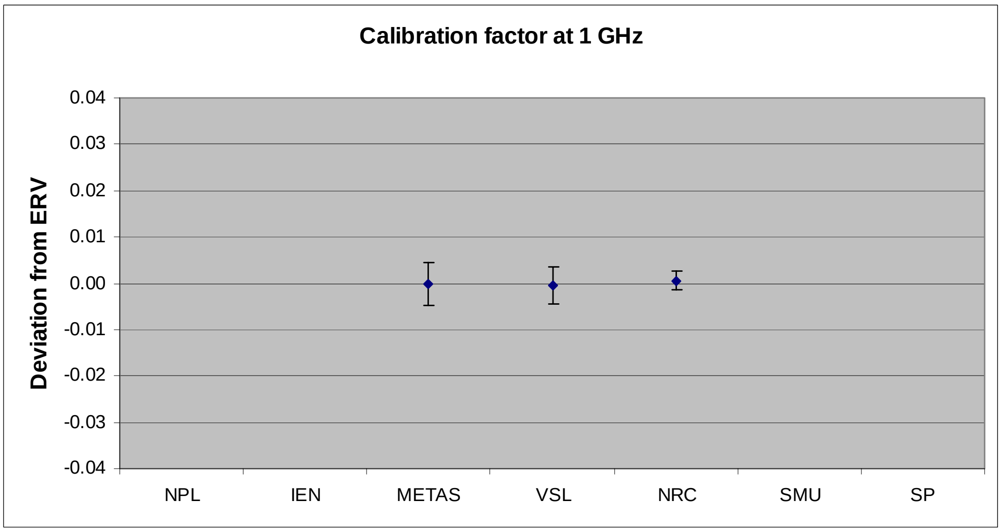


Figure 3.2: Final result of the measurements at 50 MHz for TM4 (top), TM5 (mid) and TM6 (bottom). The zero line is the reference value (ERV) as determined following the BIPM guidelines using the Randa method. The uncertainty (k=2) is calculated using the same method, taking into account whether a laboratory is contributing to ERV or not.





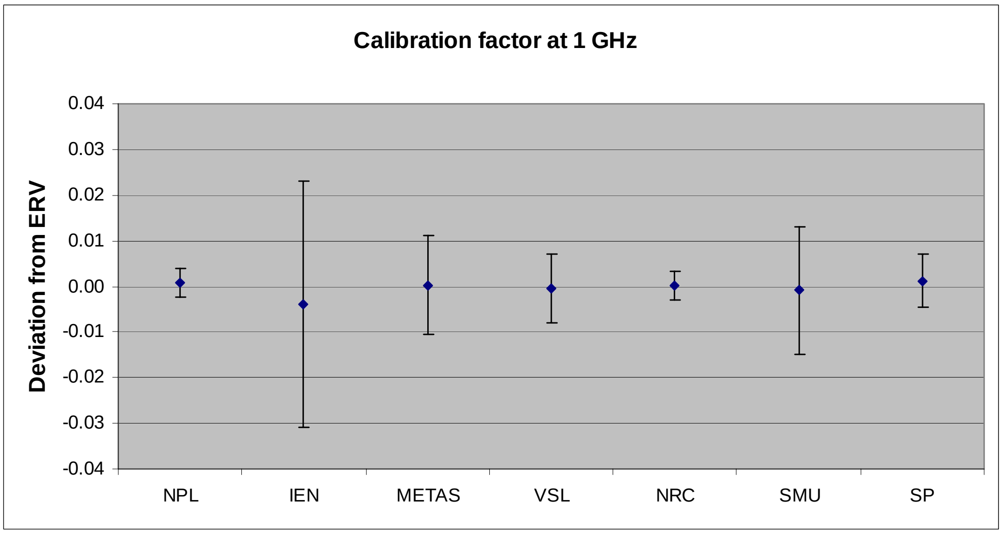
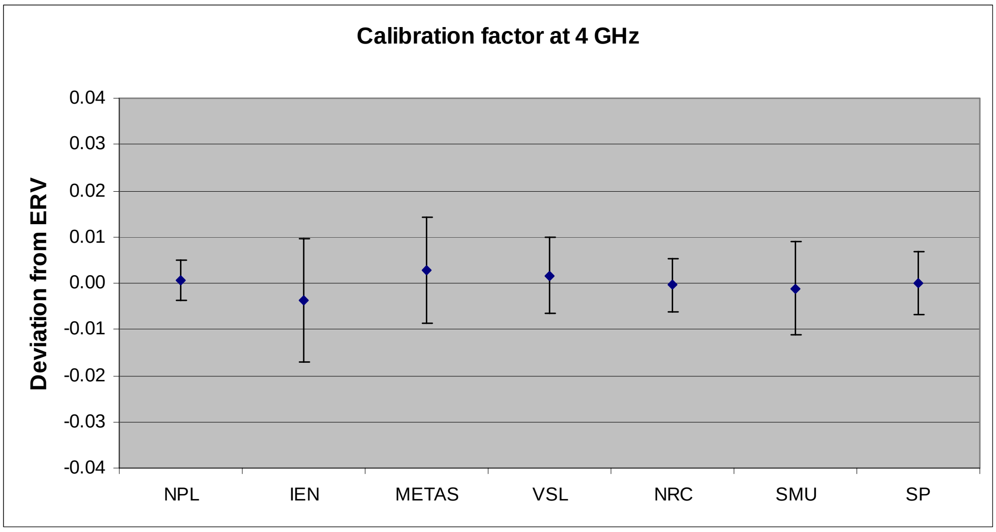
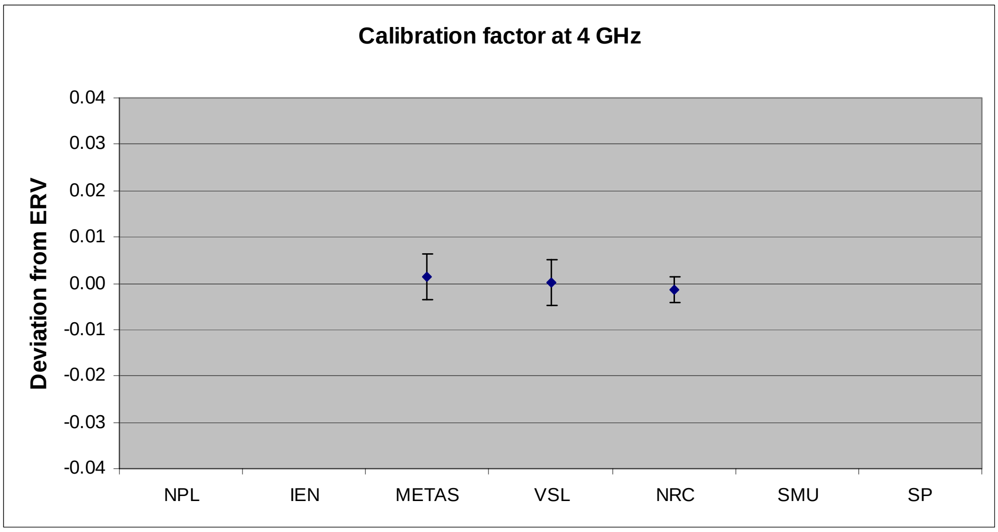


Figure 3.3: Final result of the measurements at 1 GHz for TM4 (top), TM5 (mid) and TM6 (bottom). The zero line is the reference value (ERV) as determined following the BIPM guidelines using the Randa method. The uncertainty (k=2) is calculated using the same method, taking into account whether a laboratory is contributing to ERV or not.





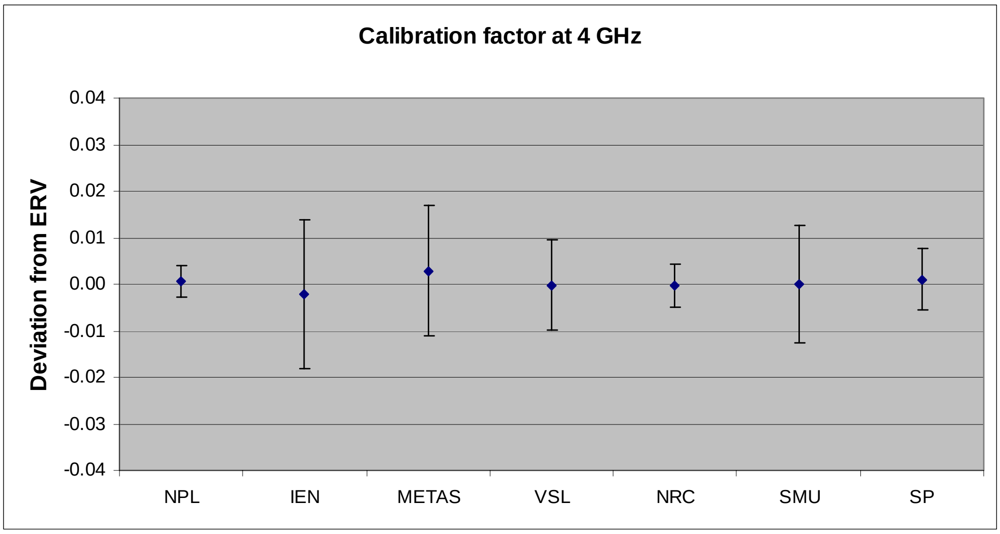
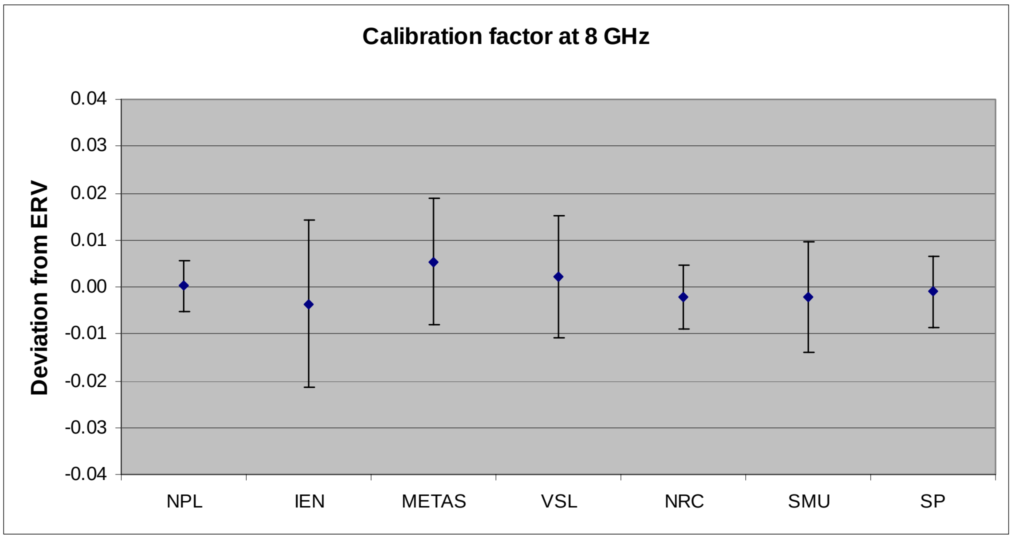
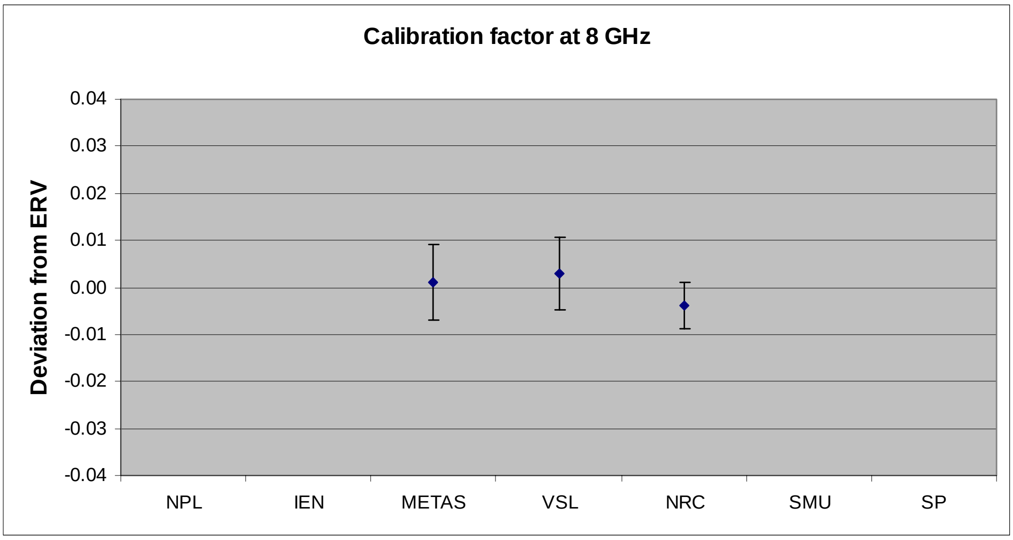


Figure 3.4: Final result of the measurements at 4 GHz for TM4 (top), TM5 (mid) and TM6 (bottom). The zero line is the reference value (ERV) as determined following the BIPM guidelines using the Randa method. The uncertainty (k=2) is calculated using the same method, taking into account whether a laboratory is contributing to ERV or not.





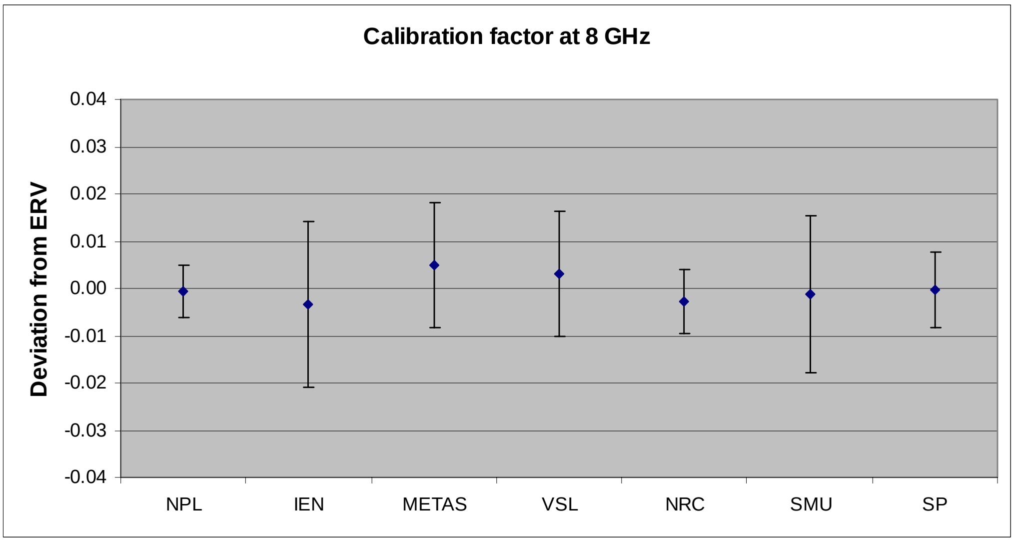


Figure 3.5: Final result of the measurements at 8 GHz for TM4 (top), TM5 (mid) and TM6 (bottom). The zero line is the reference value (ERV) as determined following the BIPM guidelines using the Randa method. The uncertainty (k=2) is calculated using the same method, taking into account whether a laboratory is contributing to ERV or not.

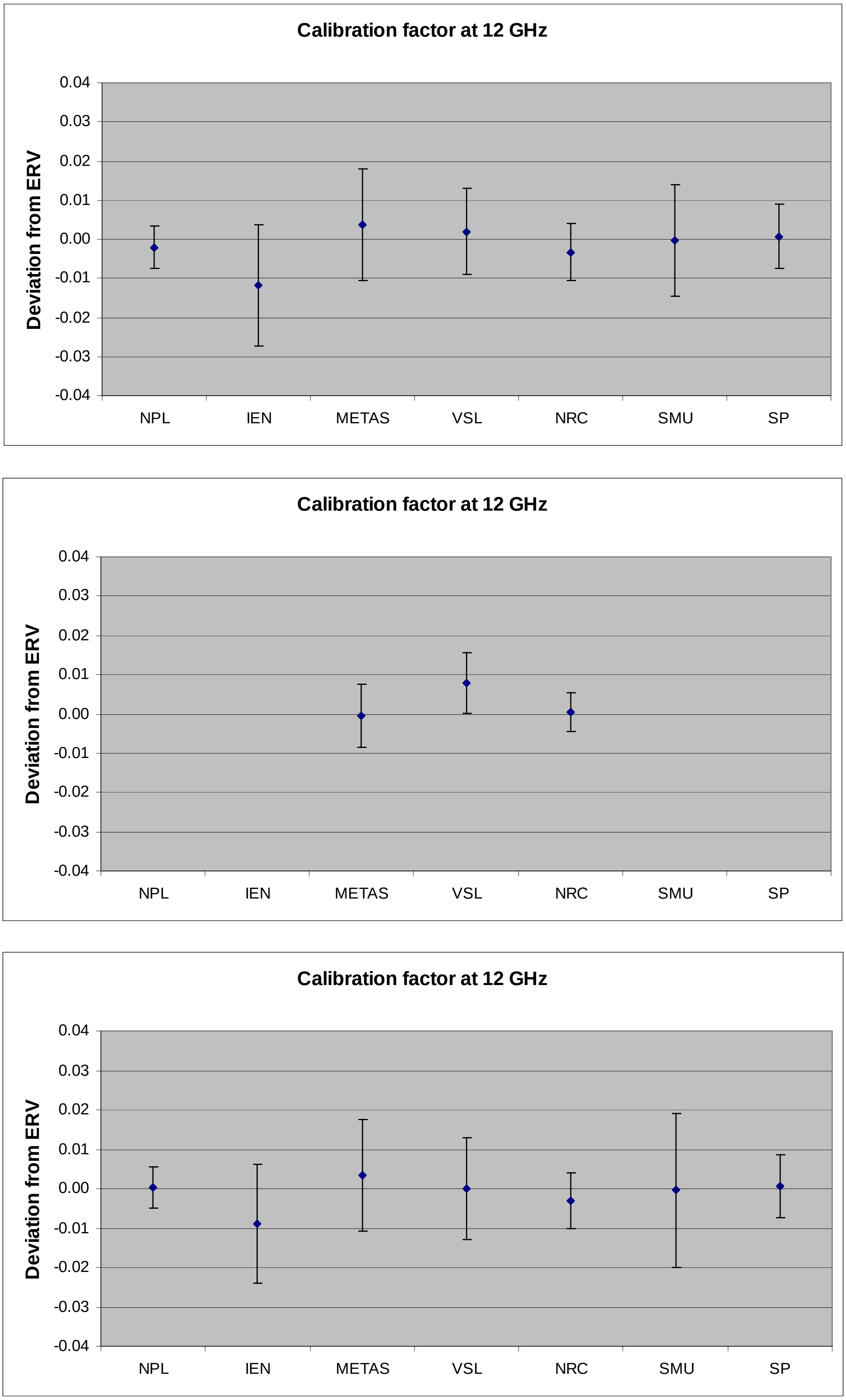
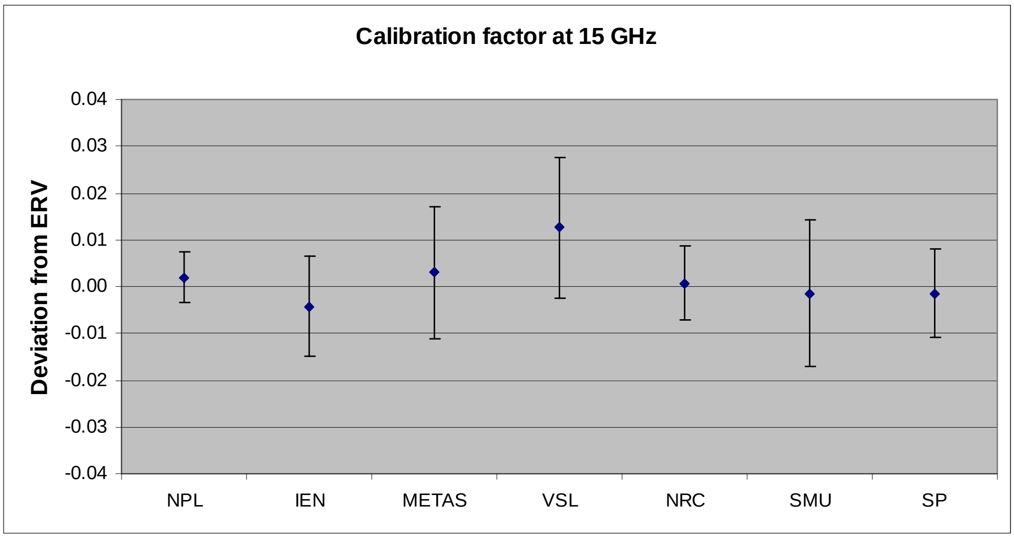
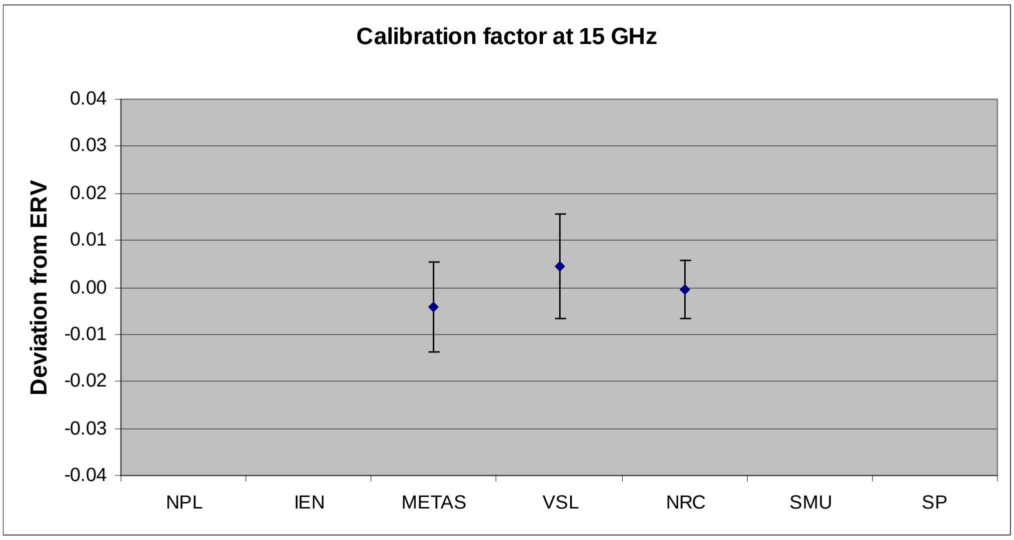


Figure 3.6: Final result of the measurements at 12 GHz for TM4 (top), TM5 (mid) and TM6 (bottom). The zero line is the reference value (ERV) as determined following the BIPM guidelines using the Randa method. The uncertainty (k=2) is calculated using the same method, taking into account whether a laboratory is contributing to ERV or not.





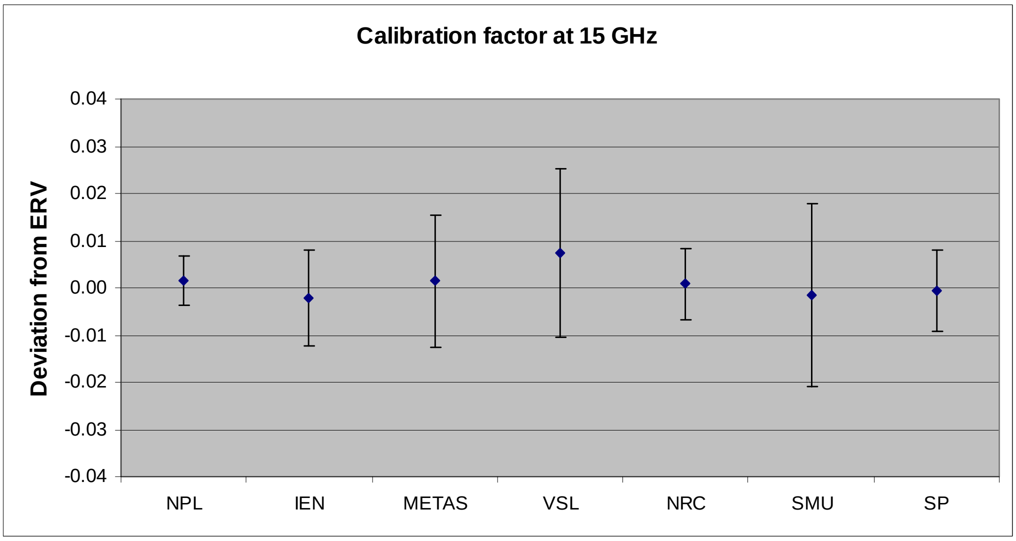
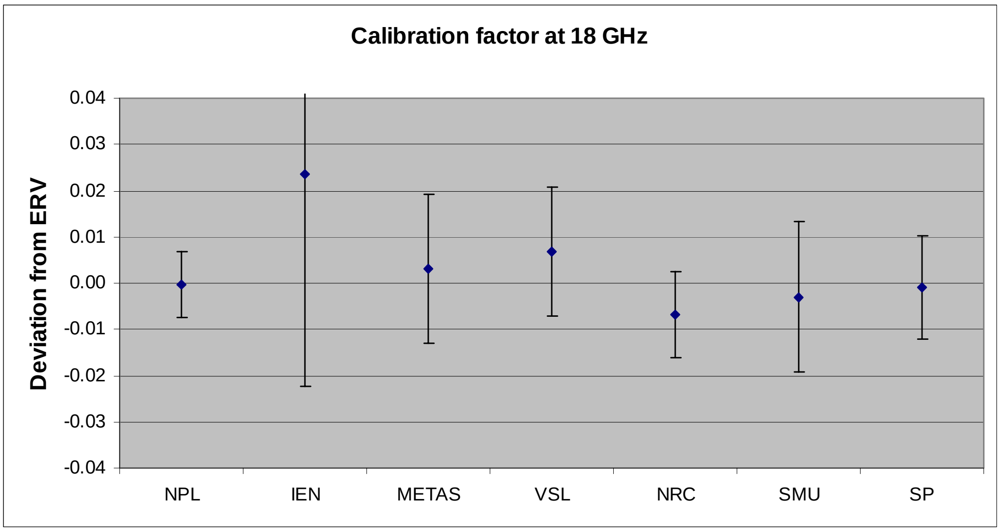
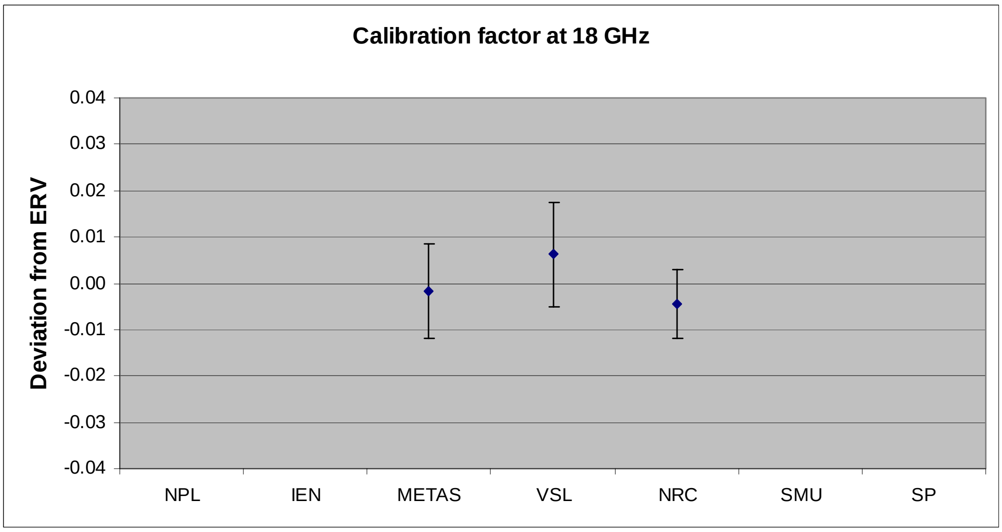


Figure 3.7: Final result of the measurements at 15 GHz for TM4 (top), TM5 (mid) and TM6 (bottom). The zero line is the reference value (ERV) as determined following the BIPM guidelines using the Randa method. The uncertainty (k=2) is calculated using the same method, taking into account whether a laboratory is contributing to ERV or not.





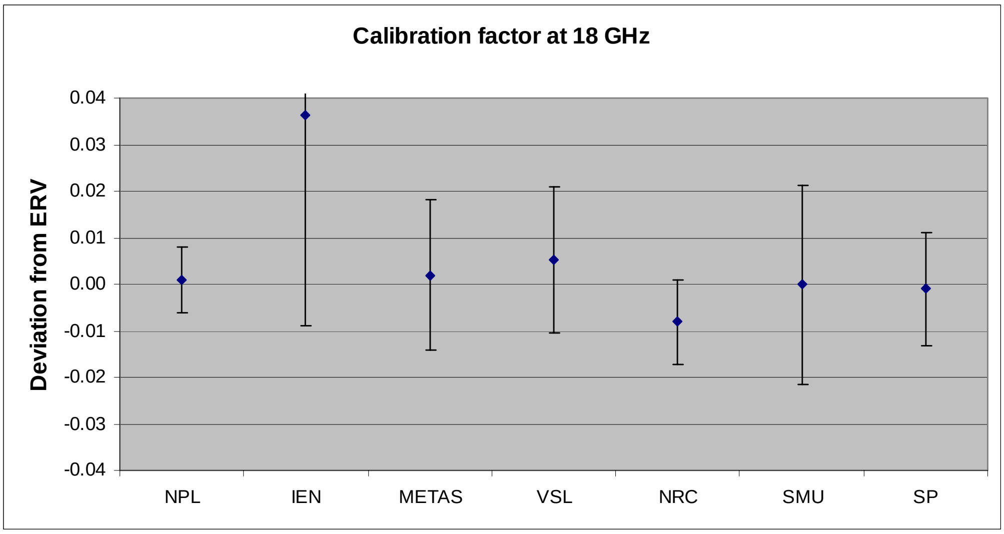


Figure 3.8: Final result of the measurements at 18 GHz for TM4 (top), TM5 (mid) and TM6 (bottom). The zero line is the reference value (ERV) as determined following the BIPM guidelines using the Randa method. The uncertainty (k=2) is calculated using the same method, taking into account whether a laboratory is contributing to ERV or not.

A visual inspection of the graphs indicates severe problems for NRC and IENGF at 10 MHz: large deviations (4% between the two results) that are significantly larger than the stated k=2 uncertainties. Furthermore IENGF presents large uncertainties (compared to the other participants) for 1 GHz and 18 GHz. In the latter case such a large uncertainty was “necessary” to get value in line with the others: IENGF may have problems as indicated in their system description.
Some strange results are obtained at 4 GHz and 18 GHz for TM5. In this case there is one outlier with only three participants. If two results are close together, the mathematics easily led to defining the third one as outlier. Then formula 7 leads to a small uncertainty in the result if the uncertainty of the laboratories is of the same order. At 4 GHz the outlier is NRC and at 18 GHz NMi-VSL.

The present choice for determining whether results should be included in the determination of the reference value, apparently has some drawbacks: at 10 MHz all results are included, but e.g. at 4 GHz some results are excluded, although there is no clear indication by just looking to Fig.3.4.

7.2.2. Linking to SI: the Comparison Reference Value (CRV) based upon independent realisations

As already mentioned above the KCRV of CCEM.RF-K8.CL is based upon contributions from GT-RF members with an independent realisation of the quantity power. In the present comparison only NPL, IEN, NMi-VSL and NRC have an independent realisation of this quantity (using microcalorimeters), and they are also member of the GT-RF. Only the latter two laboratories participated in the measurements on TM5, the thermistor mount with PC7-connector. Below a new reference value, now called CRV, is calculated using again the Randa method. In Table 4 the result from the outlier elimination process is given.
These CRV’s are the only values relevant for the linking between the RMO comparison and the CCEM.RF-K8.CL.

Table 4: List of laboratories, which have an independent realisation of the quantity power. “X” indicates outlier. “-“ indicates “No measurements”

Laboratory	Frequency																							
	10 MHz			50 MHz			1 GHz			4 GHz			8 GHz			12 GHz			15 GHz			18 GHz		
DUT (TM4, TM5 or TM6)	4	5	6	4	5	6	4	5	6	4	5	6	4	5	6	4	5	6	4	5	6	4	5	6
NPL		-			-			-			-			-			-			-			-	
IEN		-			-		X	-	X	X	-	X		-			-	X		-			-	X
NMi VSL																								
NRC																								

In tables 5.1 through 5.8 the CRV is presented in a similar way as for the ERV (deviation and uncertainty). Although the statistical basis is quite small, the results are a measure of a direct link to SI. Due to the small number of laboratories the uncertainty in the CRV is significantly larger than in the case of the ERV, especially for TM5.

Table 5.1: Results at 10 MHz: deviation of calibration factor from the CRV for the three DUTs						
Laboratory	TM4		TM5		TM6	
	Value	Unc.	Value	Unc.	Value	Unc.
NPL	-0.0006	0.0181			0.0029	0.0230
IEN	0.0229	0.0182			0.0262	0.0230
METAS	0.0062	0.0215	0.0211	0.0298	0.0086	0.0257
VSL	-0.0019	0.0201	0.0146	0.0292	0.0001	0.0248
NRC	-0.0205	0.0179	-0.0146	0.0292	-0.0292	0.0229
SMU	0.0047	0.0233			0.0078	0.0303
SP						

Table 5.2: Results at 50 MHz: deviation of calibration factor from the CRV for the three DUTs						
Laboratory	TM4		TM5		TM6	
	Value	Unc.	Value	Unc.	Value	Unc.
NPL	0.0001	0.0017			0.0002	0.0019
IEN	-0.0006	0.0031			-0.0014	0.0032
METAS	-0.0003	0.0120	0.0002	0.0060	0.0005	0.0121
VSL	-0.0002	0.0049	-0.0004	0.0007	-0.0002	0.0061
NRC	0.0008	0.0022	0.0004	0.0007	0.0013	0.0028
SMU	0.0000	0.0100			0.0004	0.0150
SP	0.0020	0.0052			0.0024	0.0053

Table 5.3: Results at 1 GHz: deviation of calibration factor from the CRV for the three DUTs						
Laboratory	TM4		TM5		TM6	
	Value	Unc.	Value	Unc.	Value	Unc.
NPL	0.0004	0.0024			0.0007	0.0024
IEN	-0.0043	0.0271			-0.0042	0.0270
METAS	-0.0007	0.0140	-0.0002	0.0081	0.0001	0.0140
VSL	-0.0004	0.0046	-0.0005	0.0011	-0.0006	0.0057
NRC	-0.0001	0.0024	0.0005	0.0011	0.0000	0.0024
SMU	-0.0013	0.0110			-0.0010	0.0180
SP	0.0007	0.0058			0.0010	0.0058

Table 5.4: Results at 4 GHz: deviation of calibration factor from the CRV for the three DUTs						
Laboratory	TM4		TM5		TM6	
	Value	Unc.	Value	Unc.	Value	Unc.
NPL	0.0000	0.0030			0.0005	0.0028
IEN	-0.0044	0.0162			-0.0022	0.0161
METAS	0.0021	0.0141	0.0020	0.0081	0.0029	0.0140
VSL	0.0010	0.0058	0.0007	0.0015	-0.0002	0.0080
NRC	-0.0011	0.0040	-0.0007	0.0015	-0.0004	0.0038
SMU	-0.0018	0.0121			0.0000	0.0180
SP	-0.0008	0.0067			0.0010	0.0066

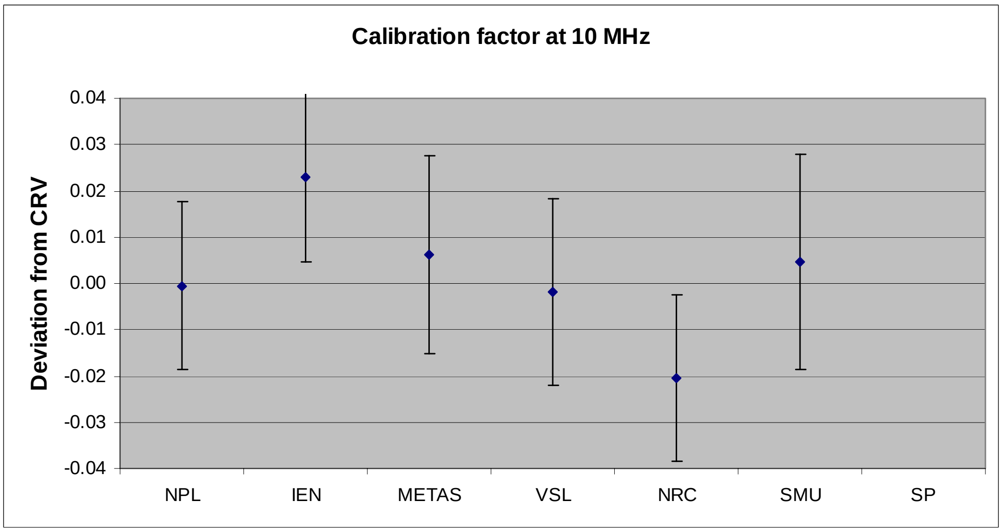
Table 5.5: Results at 8 GHz: deviation of calibration factor from the CRV for the three DUTs						
Laboratory	TM4		TM5		TM6	
	Value	Unc.	Value	Unc.	Value	Unc.
NPL	0.0011	0.0048			0.0003	0.0050
IEN	-0.0027	0.0153			-0.0024	0.0153
METAS	0.0063	0.0162	0.0015	0.0138	0.0058	0.0163
VSL	0.0030	0.0113	0.0034	0.0068	0.0040	0.0116
NRC	-0.0013	0.0059	-0.0034	0.0068	-0.0019	0.0061
SMU	-0.0012	0.0142			-0.0003	0.0202
SP	-0.0002	0.0076			0.0007	0.0081

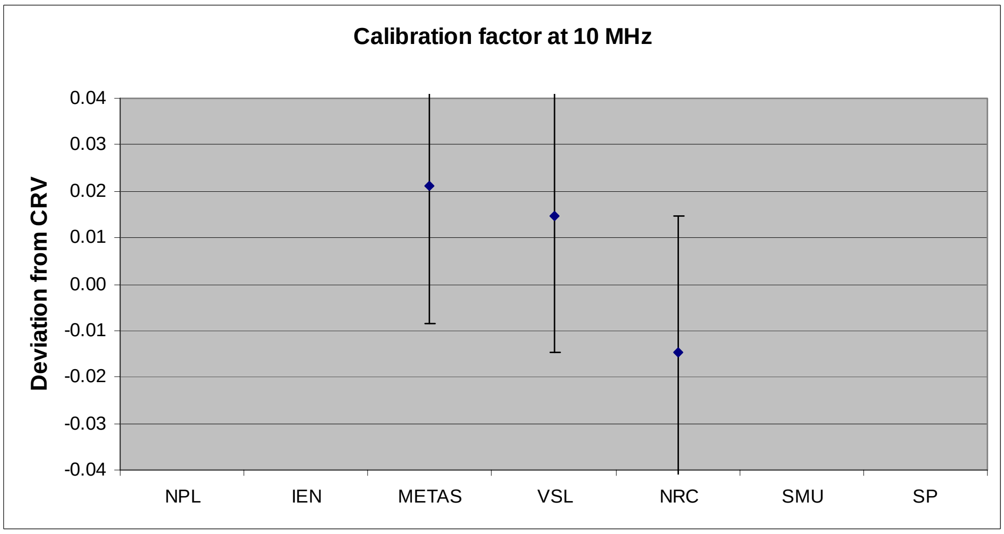
Table 5.6: Results at 12 GHz: deviation of calibration factor from the CRV for the three DUTs						
Laboratory	TM4		TM5		TM6	
	Value	Unc.	Value	Unc.	Value	Unc.
NPL	0.0018	0.0073			0.0012	0.0041
IEN	-0.0080	0.0122			-0.0078	0.0151
METAS	0.0076	0.0189	-0.0045	0.0141	0.0045	0.0181
VSL	0.0058	0.0114	0.0037	0.0075	0.0009	0.0097
NRC	0.0005	0.0085	-0.0037	0.0075	-0.0020	0.0055
SMU	0.0035	0.0189			0.0006	0.0251
SP	0.0045	0.0097			0.0016	0.0081

Table 5.7: Results at 15 GHz: deviation of calibration factor from the CRV for the three DUTs						
Laboratory	TM4		TM5		TM6	
	Value	Unc.	Value	Unc.	Value	Unc.
NPL	-0.0008	0.0084			-0.0004	0.0060
IEN	-0.0071	0.0119			-0.0040	0.0101
METAS	0.0002	0.0194	-0.0062	0.0148	-0.0004	0.0184
VSL	0.0099	0.0127	0.0025	0.0049	0.0055	0.0131
NRC	-0.0021	0.0098	-0.0025	0.0049	-0.0011	0.0079
SMU	-0.0042	0.0212			-0.0035	0.0253
SP	-0.0042	0.0116			-0.0025	0.0095

Table 5.8: Results at 18 GHz: deviation of calibration factor from the CRV for the three DUTs						
Laboratory	TM4		TM5		TM6	
	Value	Unc.	Value	Unc.	Value	Unc.
NPL	-0.0062	0.0140			0.0015	0.0089
IEN	0.0178	0.0349			0.0370	0.0457
METAS	-0.0027	0.0239	-0.0026	0.0176	0.0026	0.0215
VSL	0.0011	0.0177	0.0053	0.0106	0.0060	0.0137
NRC	-0.0126	0.0150	-0.0053	0.0106	-0.0075	0.0099
SMU	-0.0088	0.0239			0.0006	0.0281
SP	-0.0068	0.0166			-0.0004	0.0137

The results in graphical presentation are given in Fig.4.1 through 4.8:





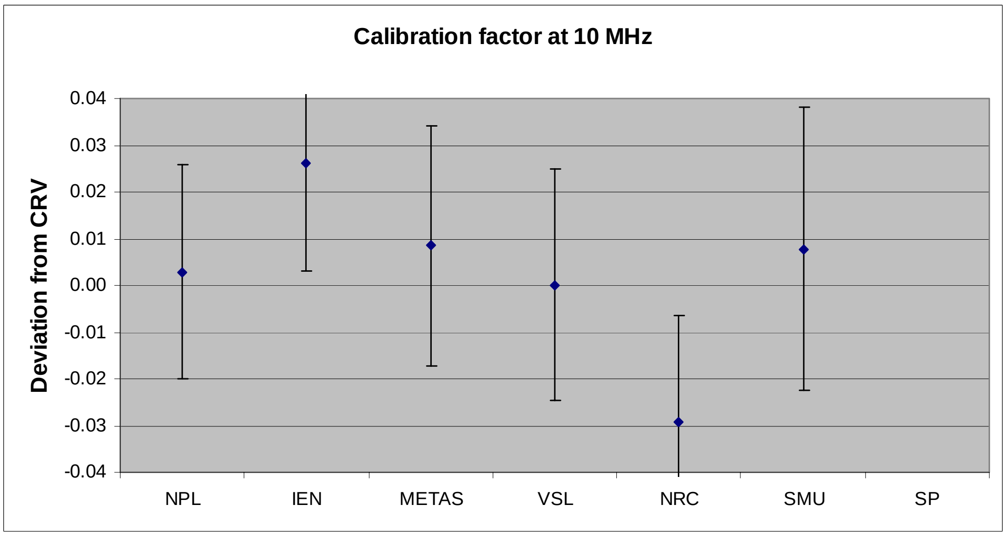
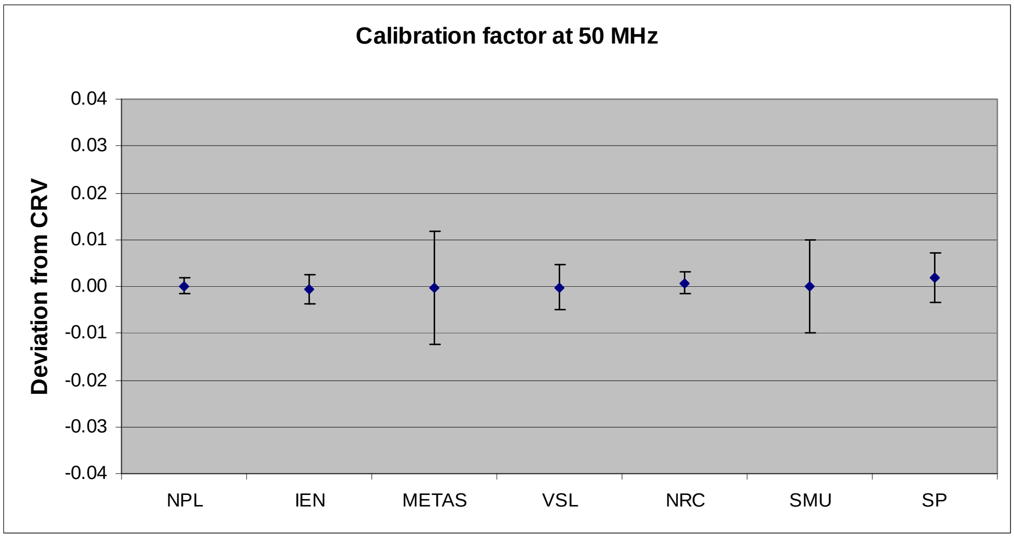
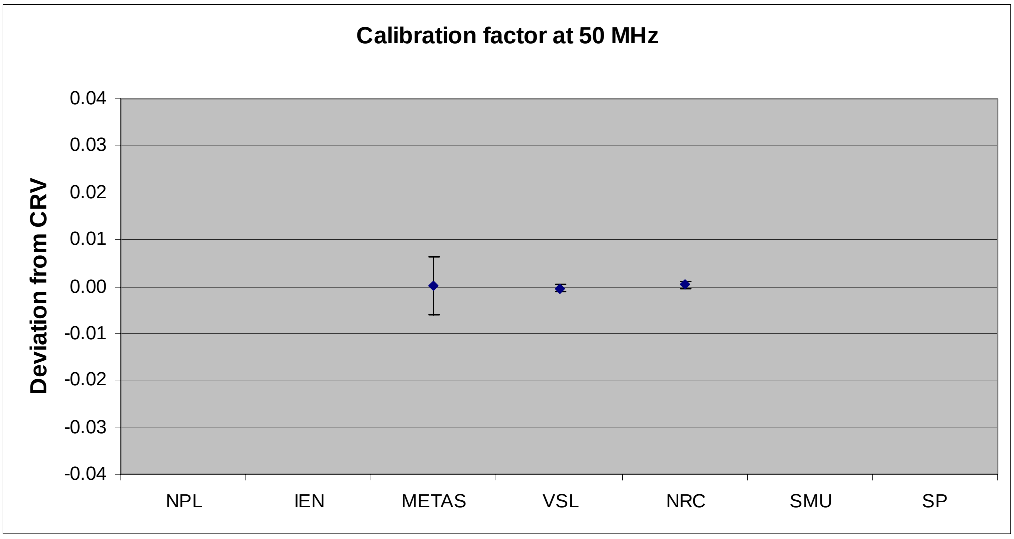


Figure 4.1: Final result of the measurements at 10 MHz for TM4 (top), TM5 (mid) and TM6 (bottom). The zero line is the reference value (CRV) as determined following the BIPM guidelines using the Randa method. The uncertainty (k=2) is calculated using the same method, taking into account whether a laboratory is contributing to CRV or not.





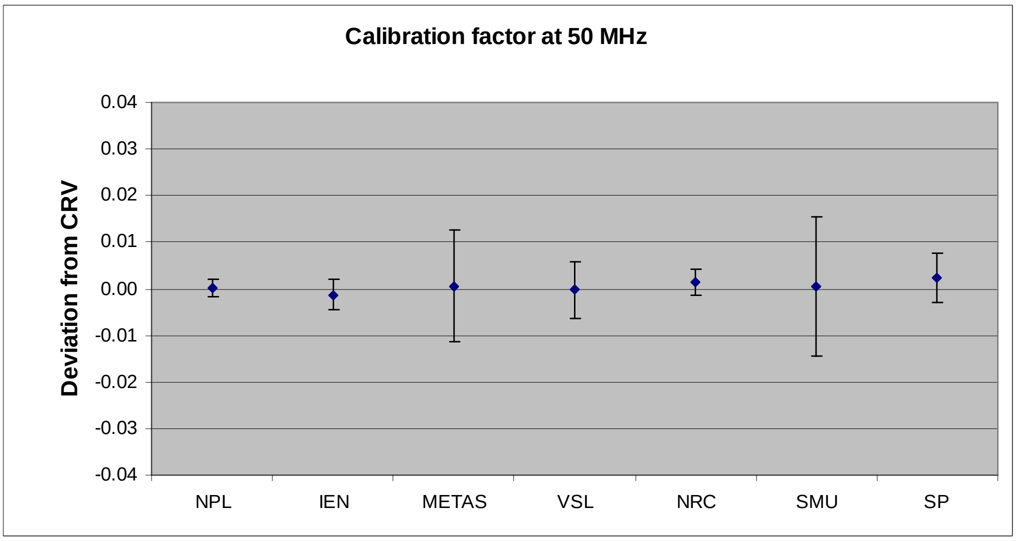
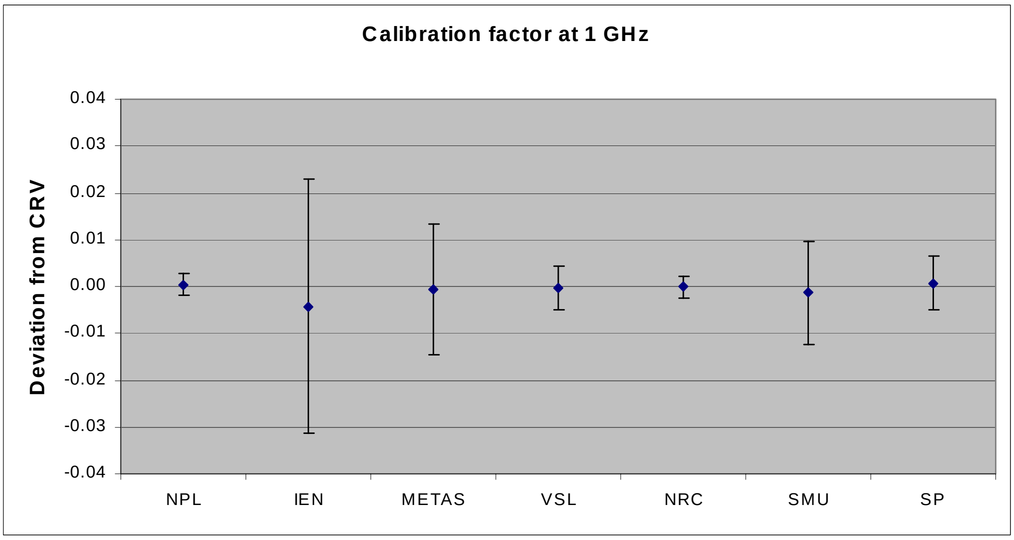
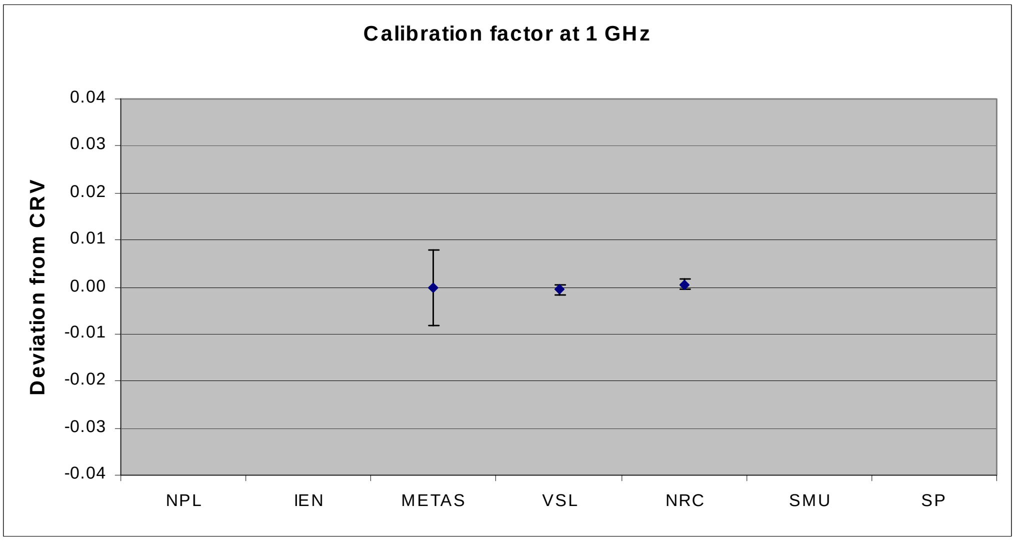


Figure 4.2: Final result of the measurements at 50 MHz for TM4 (top), TM5 (mid) and TM6 (bottom). The zero line is the reference value (CRV) as determined following the BIPM guidelines using the Randa method. The uncertainty (k=2) is calculated using the same method, taking into account whether a laboratory is contributing to CRV or not





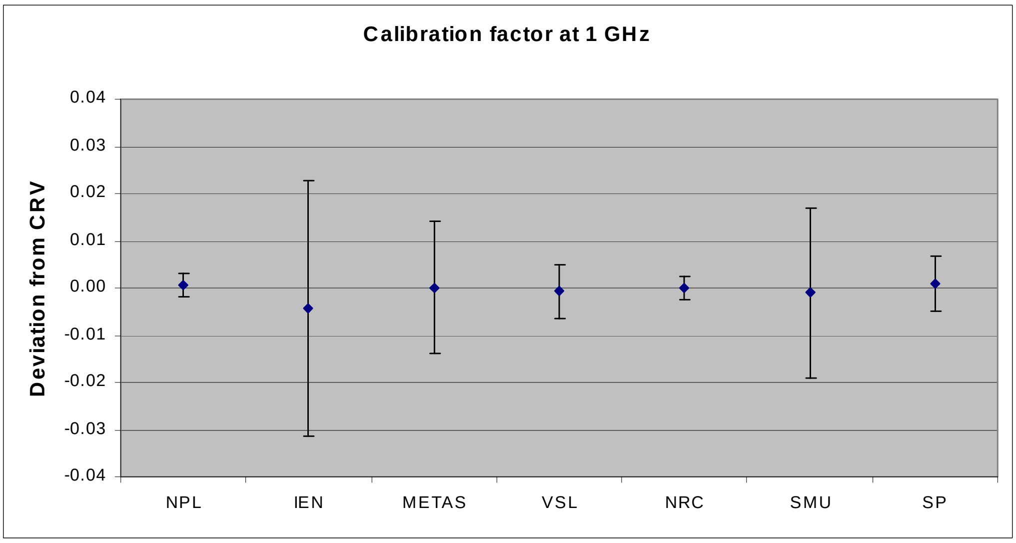


Figure 4.3: Final result of the measurements at 1 GHz for TM4 (top), TM5 (mid) and TM6 (bottom). The zero line is the reference value (CRV) as determined following the BIPM guidelines using the Randa method. The uncertainty (k=2) is calculated using the same method, taking into account whether a laboratory is contributing to CRV or not.

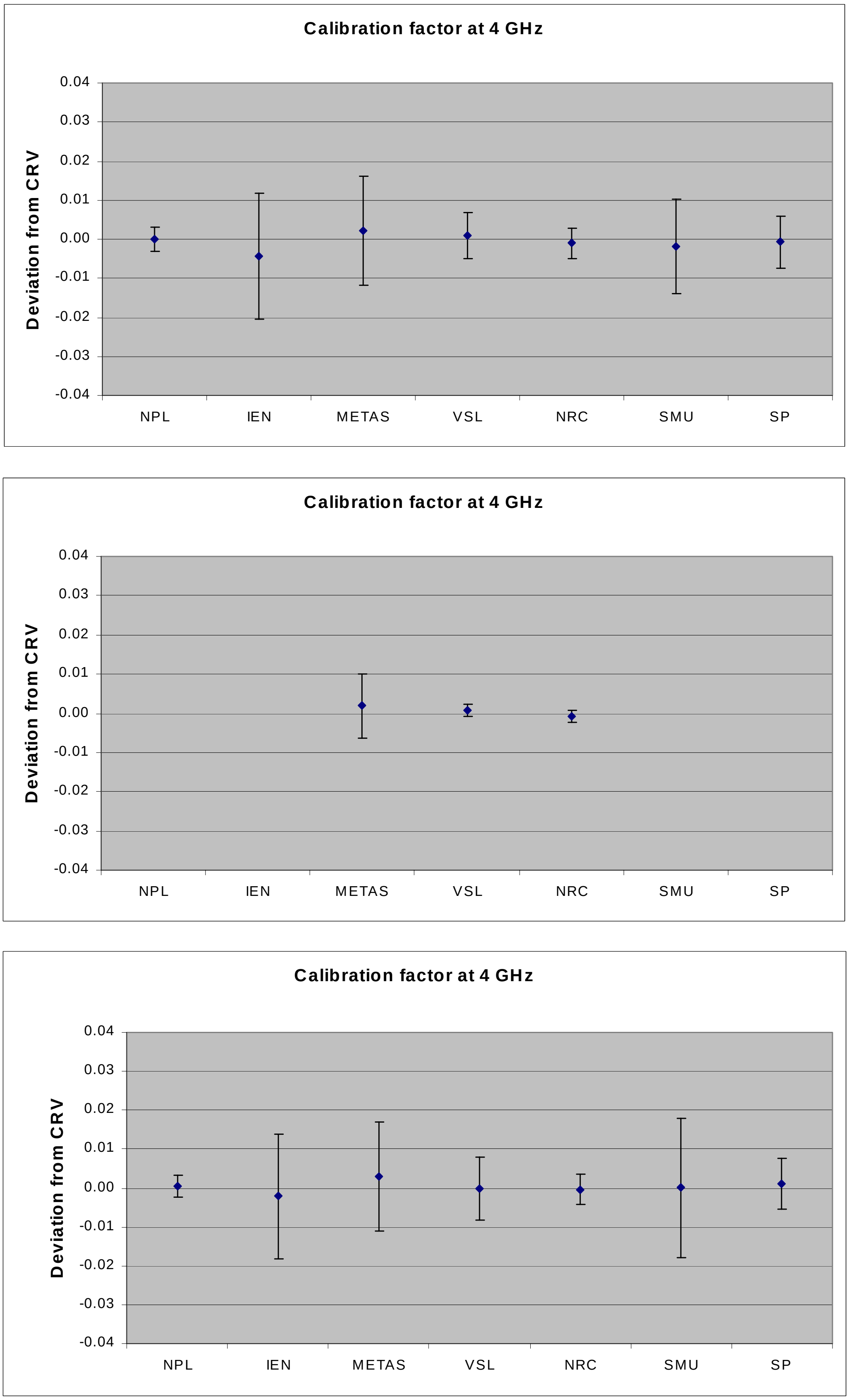
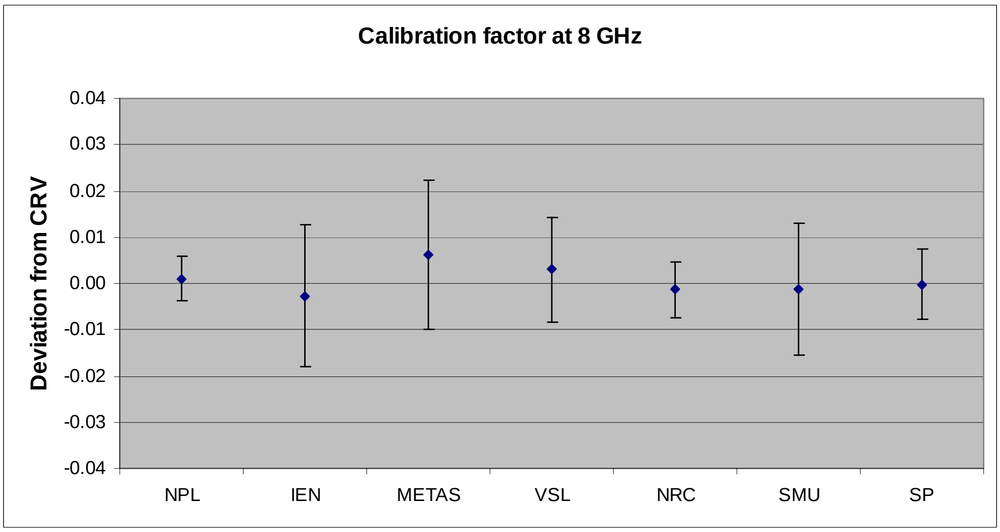
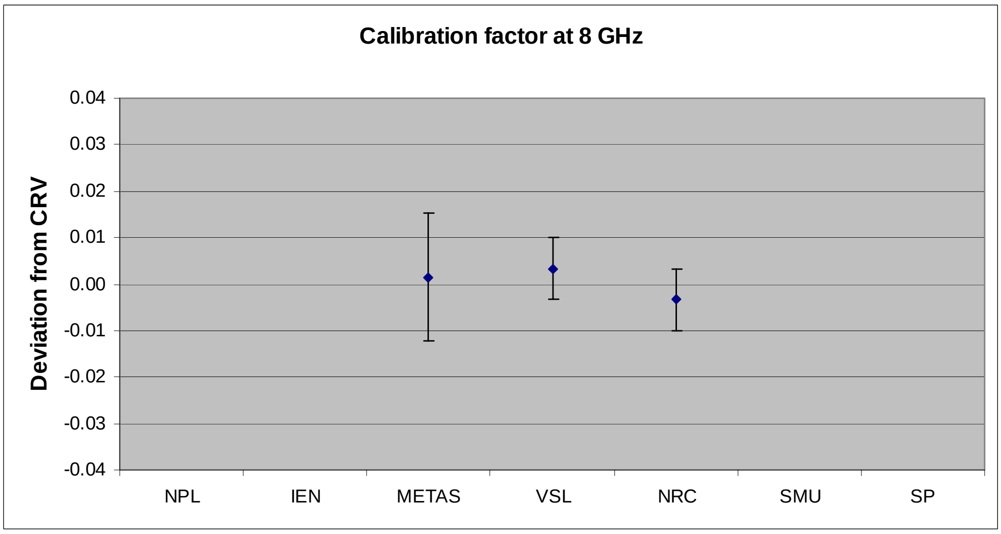


Figure 4.4: Final result of the measurements at 4 GHz for TM4 (top), TM5 (mid) and TM6 (bottom). The zero line is the reference value (CRV) as determined following the BIPM guidelines using the Randa method. The uncertainty (k=2) is calculated using the same method, taking into account whether a laboratory is contributing to CRV or not.





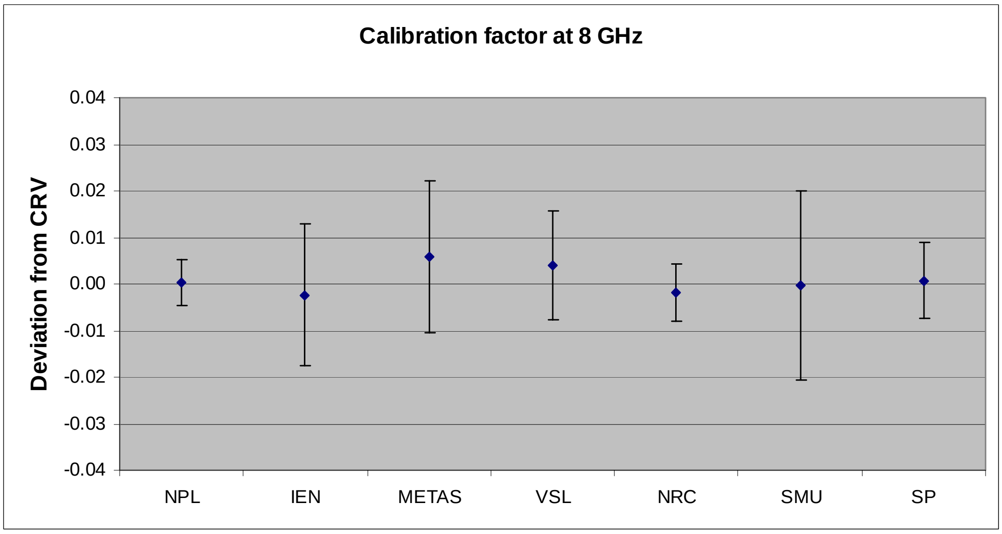
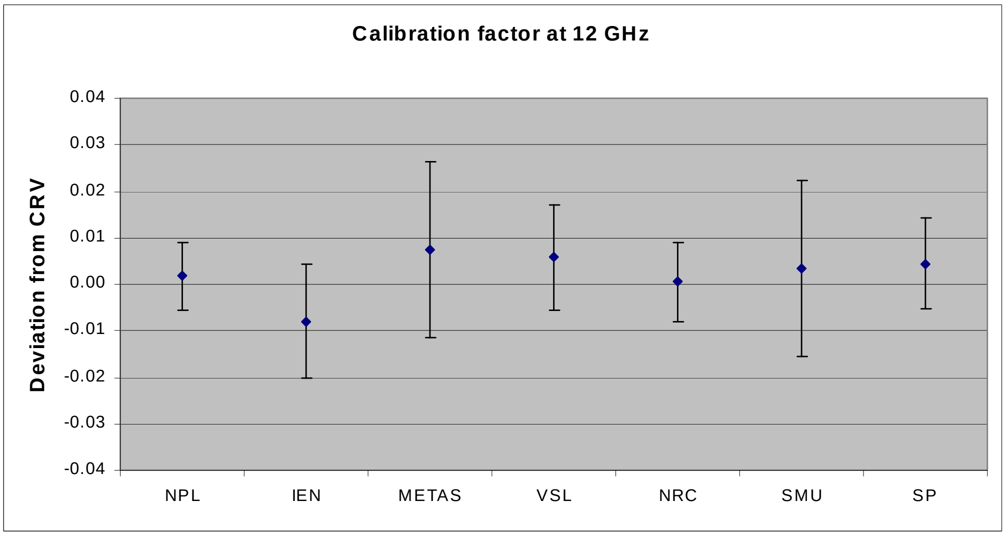
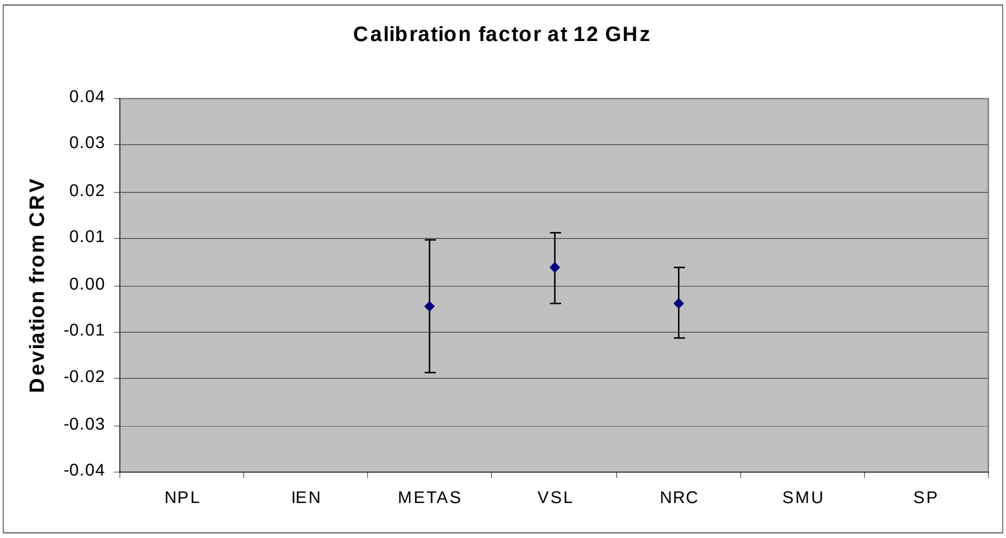


Figure 4.5: Final result of the measurements at 8 GHz for TM4 (top), TM5 (mid) and TM6 (bottom). The zero line is the reference value (CRV) as determined following the BIPM guidelines using the Randa method. The uncertainty (k=2) is calculated using the same method, taking into account whether a laboratory is contributing to CRV or not.





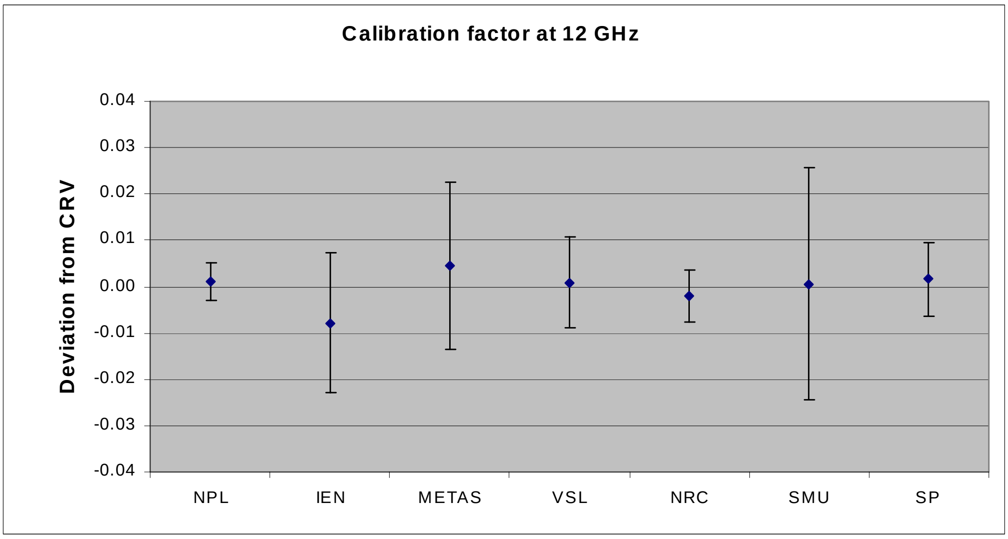


Figure 4.6: Final result of the measurements at 12 GHz for TM4 (top), TM5 (mid) and TM6 (bottom). The zero line is the reference value (CRV) as determined following the BIPM guidelines using the Randa method. The uncertainty (k=2) is calculated using the same method, taking into account whether a laboratory is contributing to CRV or not.

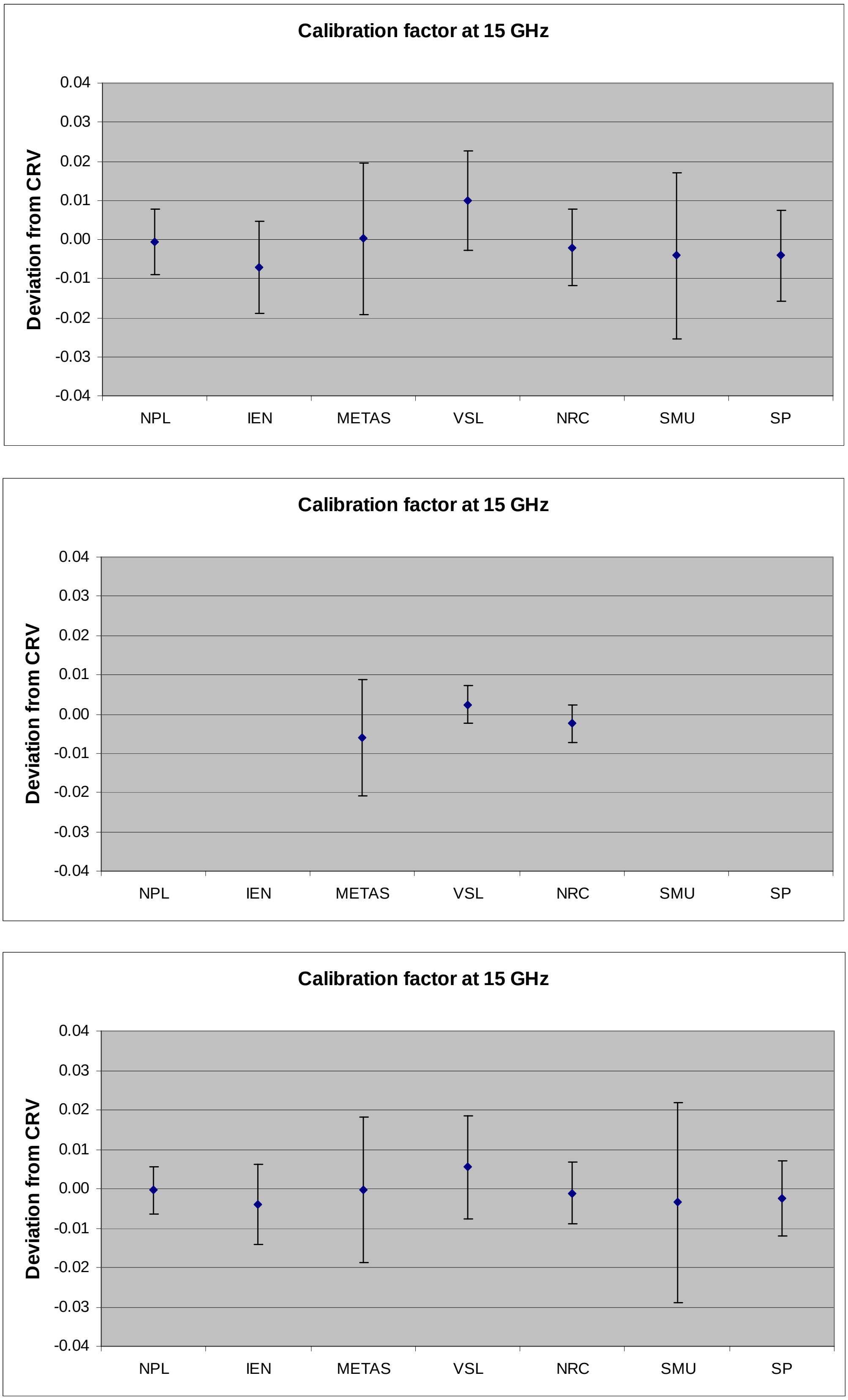


Figure 4.7: Final result of the measurements at 15 GHz for TM4 (top), TM5 (mid) and TM6 (bottom). The zero line is the reference value (CRV) as determined following the BIPM guidelines using the Randa method. The uncertainty (k=2) is calculated using the same method, taking into account whether a laboratory is contributing to CRV or not.

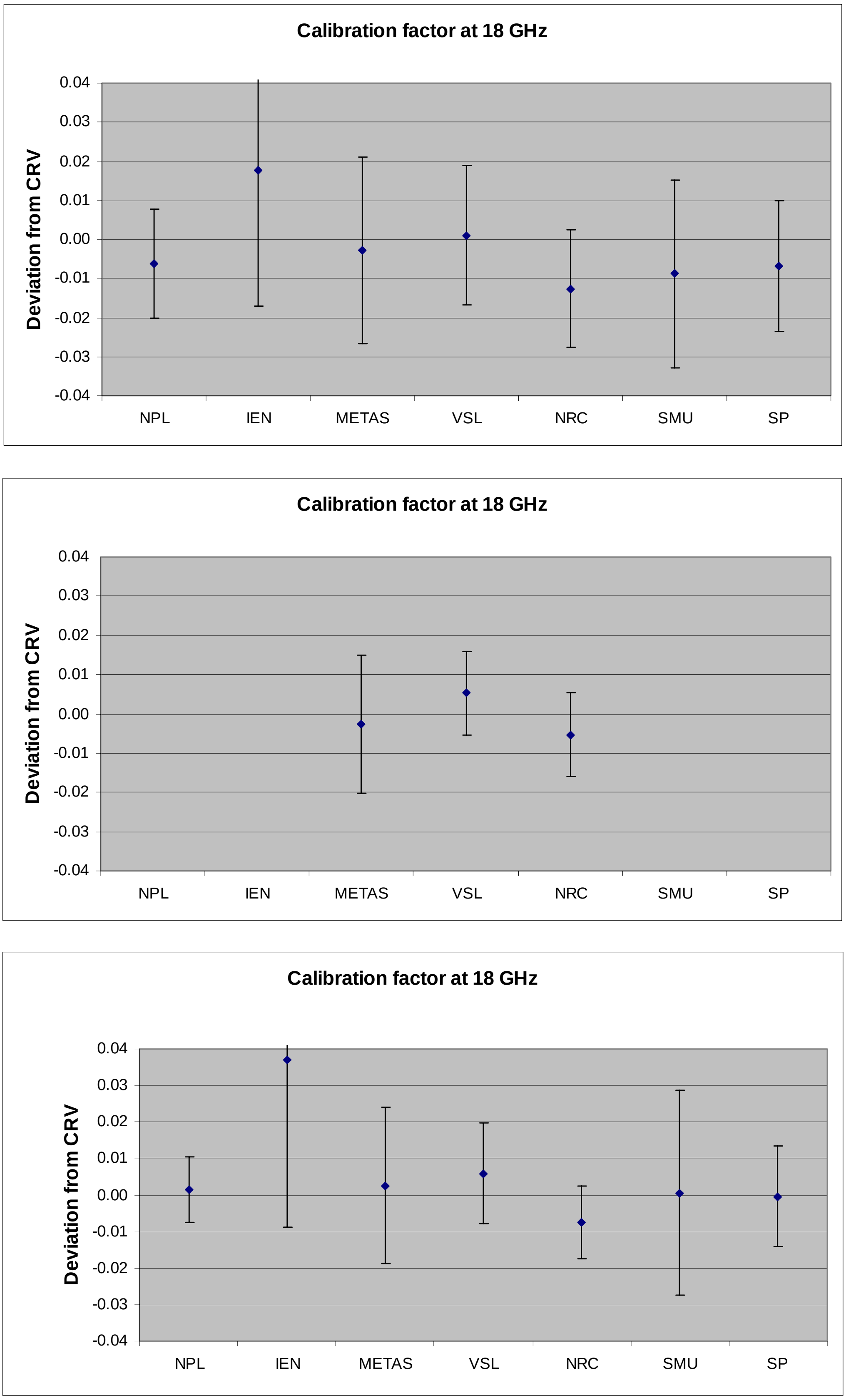


Figure 4.8: Final result of the measurements at 18 GHz for TM4 (top), TM5 (mid) and TM6 (bottom). The zero line is the reference value (CRV) as determined following the BIPM guidelines using the Randa method. The uncertainty (k=2) is calculated using the same method, taking into account whether a laboratory is contributing to CRV or not.

As mentioned before, in general the uncertainty bars are now larger than in the case of the ERV results. The effect of outliers combined with only two contributions to the CRV leads at a number of frequencies to strange results in the uncertainty for TM5.

Here again, but now more clearly, the present choice for determining whether results should be included in the determination of the reference value, has some drawbacks: at 10 MHz all results are included, but e.g. at 4 GHz some results are excluded, although there is no clear indication by just looking to Fig.3.4. Probably every statistical method dealing with small numbers of results might lead to strange results as in these cases it is very different to verify the underlying assumptions.

To stay more or less in line with the report on CCEM.RF-K8.CL the results of this comparison in terms of Calibration Factor (CF) are summarized in Table 6. CF is equal to the unmodified CRV,.i.e. before the shift to a value of 0.000. The uncertainty refers to the statistical uncertainty in the mean value.

Table 6: Calibration Factor of the DUTs			
DUT	TM4	TM5	TM6
Frequency			
10 MHz	0.9684 ± 0.0010	0.9628 ± 0.0016	0.9650 ± 0.0010
50 MHz	0.9938 ± 0.0001	0.9933 ± 0.0001	0.9930 ± 0.0001
1 GHz	0.9929 ± 0.0001	0.9931 ± 0.0002	0.9908 ± 0.0001
4 GHz	0.9831 ± 0.0005	0.9851 ± 0.0004	0.9780 ± 0.0001
8 GHz	0.9761 ± 0.0007	0.9774 ± 0.0010	0.9662 ± 0.0007
12 GHz	0.9683 ± 0.0006	0.9639 ± 0.0002	0.9534 ± 0.0005
15 GHz	0.9604 ± 0.0007	0.9561 ± 0.0012	0.9386 ± 0.0004
18 GHz	0.9520 ± 0.0012	0.9371 ± 0.0016	0.9210 ± 0.0011

7.2.3. Linking two comparisons

For linking two comparisons it is generally agreed that only the participants common to the two exercises should be considered. Here those laboratories are NMi-VSL, NPL, METAS, IEN, SMU and NRC. In this process again outliers should be considered as well as consistency of results and similarity (reproducibility) of the measurement set-up: how well are the results correlated for the two comparisons?

For this purpose a separate document is written: ref [10].

7.3. Uncertainty budgets

As usual in international comparisons the amount of information is quite dependent upon the specific laboratory. The detailed uncertainty budgets for two frequencies (10 MHz and 18 GHz) and one connector type (TM4) are presented in Appendix D. As far as possible an exact copy of the submitted uncertainty budget is given

On request of the coordinating laboratory SMU has submitted a more extensive uncertainty budget after distributing Draft A v1.0.

SP has found an error in its calculation of the calibration factor at 18 GHz for TM4 after distributing Draft A v1.0. A new report is submitted in which also the uncertainties for TM6 is slightly reduced.

In the budgets most laboratories indicate the following 4 main contributions:

- Uncertainty in reference standard
- Mismatch signal source - reference standard
- Mismatch signal source - DUT

- Reproducibility (spread in the measurement data)

Of course, variations are present in the budget, e.g. due to the specific measurement set-up.

7.4. Reflection coefficient

In the present framework the influence on the calibration factor due to discrepancies in reflection coefficients is rather small (of the order of 0.1%). In one particular case (NRC at 12 GHz) a significant deviation is reported. After the distribution of Draft A v1.0 the typing error in the report was discovered: in the uncertainty calculations the correct value was used.

More information about the reflection measurements is given in Appendix B.

7.5. Torque wrench

The protocol asked about the torque of the wrench. NMi-VSL measured the torque wrench before each dispatch of the package. All laboratories used the wrench provided, except for IEN (the standard did not allow the use of a wrench) and METAS. METAS used its own wrench, as it found a disfunctioning of the wrench: too high torque. This was confirmed by the pilot laboratory; itprovided another torque wrench for the second part of the comparison. METAS, NRC and SMU reported values of the breaking torque of the wrench used. NPL and VSL checked that the torque was within the specified limits.

8. Conclusions

The maximum stated uncertainty for the calibration factor ranges from 0.3 % at 50 MHz to more than 4.0 % at 18 GHz, independent of the type of connector on the DUT. Almost all results are consistent within the claimed uncertainty.

The uncertainty stated for the reflection coefficient was up to 0.03 in almost all cases. Most of the results are consistent within the claimed uncertainty.

Taking these facts into account, the results show a satisfactory agreement for both the calibration factor and the reflection coefficient. However, two participants got results at 10 MHz that significantly deviate from the others. SP did not measure at 10 MHz.

A statistically sound analysis is almost impossible with a limited number of participating laboratories, especially when additional restrictions (e.g. independent realisation of standards) are present. Maybe the concept of defining an official reference value should be avoided under circumstances where less than 4 laboratories may contribute to the reference value.

9. Proposal for Follow-up

NRC and IEN should investigate its system at 10 MHz as quickly as possible.

IEN should investigate its system at higher frequencies as well as it already has worries about the quality of the measurements.

9.1 Actions carried out after the Draft A report was published

NRC has decided to withdraw the measurement set-up used in this comparison, and to bring an older set-up back in operation.

IEN has checked carefully all components in its measurement set-up and replaced all devices that might be dubious.

10. References

[1] J.P.M. de Vreede et al., "International comparison for RF power in the frequency range up to 18 GHz", IEEE Trans. Instr. & Meas. Vol. 50 (2001) No 2, p. 409-413

[2] Guidelines for CIPM key comparisons (Appendix F of MRA), 1 March 1999, text available on the BIPM-website (www.bipm.fr)

[3] J. Achkar,"Calibration of thermistor mounts (Euromet project 341)", Metrologia 34, 1997, pp.443-444

[4] e.g., U. Stumper, "Power in coaxial lines at 12, 14 and 17 GHz (GT-RF 75-A11)", IEEE Trans. Instrum. Meas. I&M 43 (1995) pp.3-6

[5] J. Randa, "Proposal for KCRV & Degree of Equivalence for GTRF Key Comparisons", Document of the Working Group on radio frequency quantities of the CCEM, GT-RF/2000-12, September 2000.

[6] Mutual Recognition of National Measurement Standards and of Calibration and Measurement Certificates Issued by National Metrology Institutes, endorsed by the International Committee on Weight and Measures, text available on the BIPM web site (www.bipm.fr).

[7] "Guide to the Expression of Uncertainty in Measurement", ISO/TAG 4, published by ISO, 1993, corrected and reprinted 1995.

[8] "Expression of the Uncertainty in Measurement in Calibration" document EA-04/02, December 1999, available on the EA-website (www.european-accreditation.org)

[9] Jan P.M. de Vreede, Final Report: "CCEM.RF-K8.CL COMPARISON - CALIBRATION FACTOR OF THERMISTOR MOUNTS May 2005"

[10] Jan P.M. de Vreede, "Report Link Euromet-CCEM.RF-K8.CL ", September 2006

APPENDIX A

Measurements of the pilot laboratory

No specific measurements were planned to check the stability of the DUTs during the original set-up of the Euromet 633 comparison. Due to the extension of this project with three participants, one intermediate check was added, which led to a total of three measurements at the pilot laboratory.
In this Appendix the details concerning the results of these measurements are described.

Each time the DUTs are measured several times against some of the working standards. In figures A1 and A2 the results per frequency are given for each device in terms of one result per measuring period. As the reflection coefficient is needed only as support for the uncertainty calculation, the reflection coefficient has not been measured always.

A least square fit is made to all series of measurements. Although no clear drift as function of time is found in the measurements, the measurement results show a relative large spread compared to those in CCEM.RF-K8.CL. Hence, the pilot laboratory decided to use the average result from its measurements as entry in the comparison instead of one particular measurement result.
It should be noted that METAS replaced the collet on the TM5 before returning it to NMi-VSL. The reason was that the reproducibility was quite poor compared to similar devices owned by METAS.

The measurement dates are as follows (in general the measurements cover a period of less than one month): - 15 September 2001; - 15 January 2002; - 15 July 2002.

The maximum statistical variation (k=2) is 1.6% at 18 GHz for TM5. Most others are about 1.0%.

Table A1: The official entries of the pilot laboratory concerning the calibration factors and reflection coefficients measured on the three DUTs.

DUT	TM4		TM5		TM6	
Freq (GHz)	Cal.factor	Uncert. k=2)	Cal.factor	Uncert. (k=2)	Cal.factor	Uncert. (k=2)
0.01	0.9643	0.0133	0.9596	0.0517 -> 0.0100	0.1399	0.0103
0.05	0.9938	0.0069	0.9929	0.0067	0.0316	0.0101
1	0.9929	0.0080	0.9926	0.0071	0.0156	0.0102
4	0.9848	0.0099	0.9852	0.0082	0.0262	0.0102
8	0.9783	0.0155	0.9803	0.0113	0.0127	0.0102
12	0.9703	0.0139	0.9718	0.0136	0.0212	0.0114
15	0.9730	0.0148	0.9606	0.0172	0.0536	0.0110
18	0.9589	0.0169	0.9433	0.0158	0.0939	0.0116

DUT	TM4		TM5		TM6	
Freq (GHz)	Reflection coefficient	Uncert. (k=2)	Reflection coefficient	Uncert. (k=2)	Reflection coefficient	Uncert. (k=2)
0.01	0.1398	0.0105	0.1399	0.0103	0.1397	0.0105
0.05	0.0323	0.0102	0.0316	0.0101	0.0312	0.0101
1	0.0252	0.0101	0.0156	0.0102	0.0181	0.0103
4	0.0419	0.0101	0.0262	0.0102	0.0327	0.0107
8	0.0305	0.0101	0.0127	0.0102	0.0109	0.0108
12	0.0195	0.0102	0.0212	0.0114	0.0200	0.0123
15	0.0214	0.0103	0.0536	0.0110	0.0534	0.0107
18	0.0535	0.0105	0.0939	0.0116	0.0991	0.0122

For TM5, the DUT with a PC7 connector, the measurements were carried out in a set-up against a similar transfer standard. This means that the uncertainty is quite large at 10 MHz as it is based upon a sensor with frequency range (0.01 – 18) GHz. In the previous comparison the uncertainty of the measurements at 10 MHz were reduced by additional measurements, using an adapter PC7-N, against a thermistor mount with Type-N connector and optimised for frequencies below 1 GHz. Those results led to the conclusion that the uncertainty could be reduced to 1.0%. To be in line with the previous comparison this smaller uncertainty will be used in the main text.

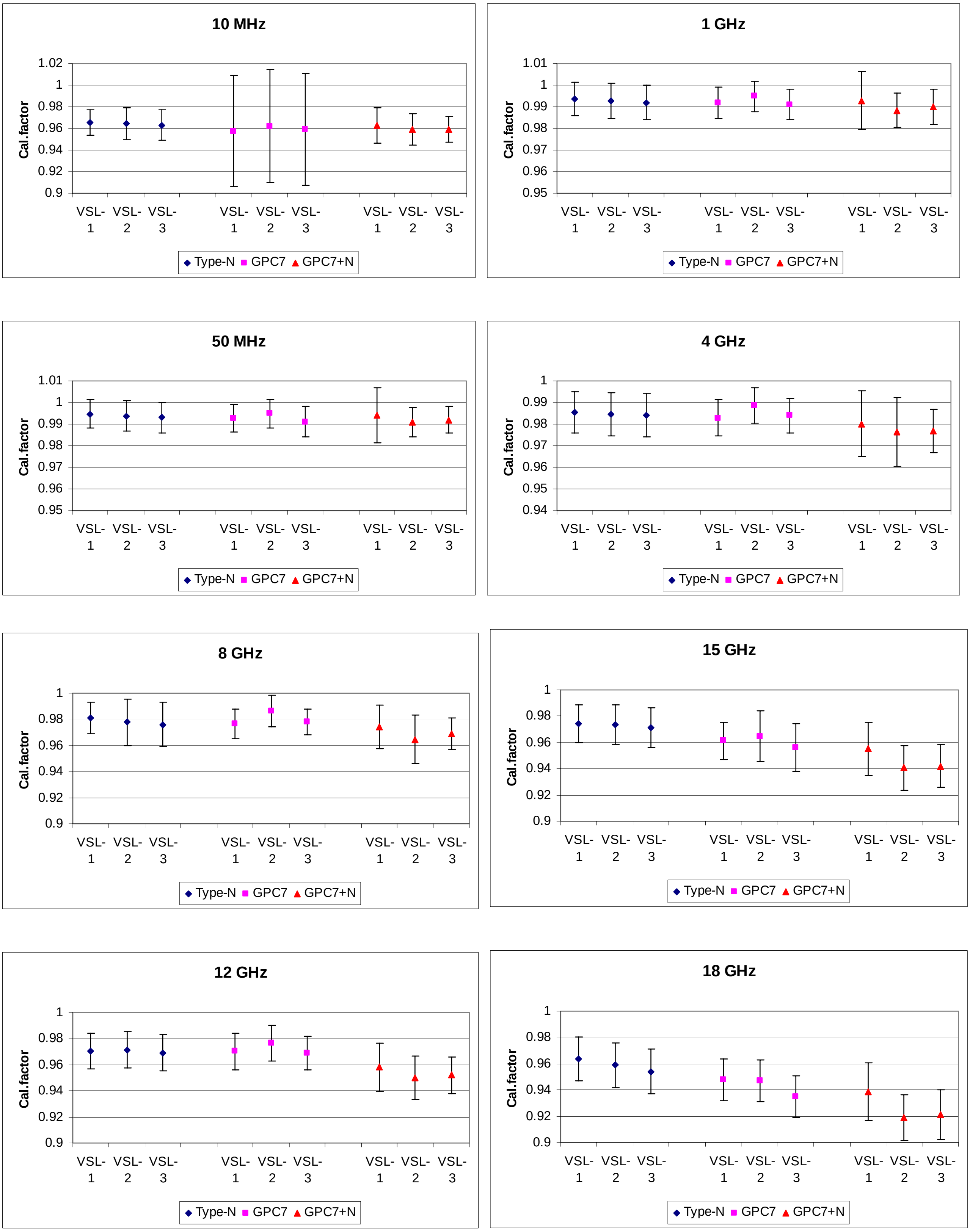


Figure A1: Overview of the individual results on the calibration factor obtained by NMi-VSL during the intercomparison. The results are grouped for each DUT. The number in the code refers to the measurement period.

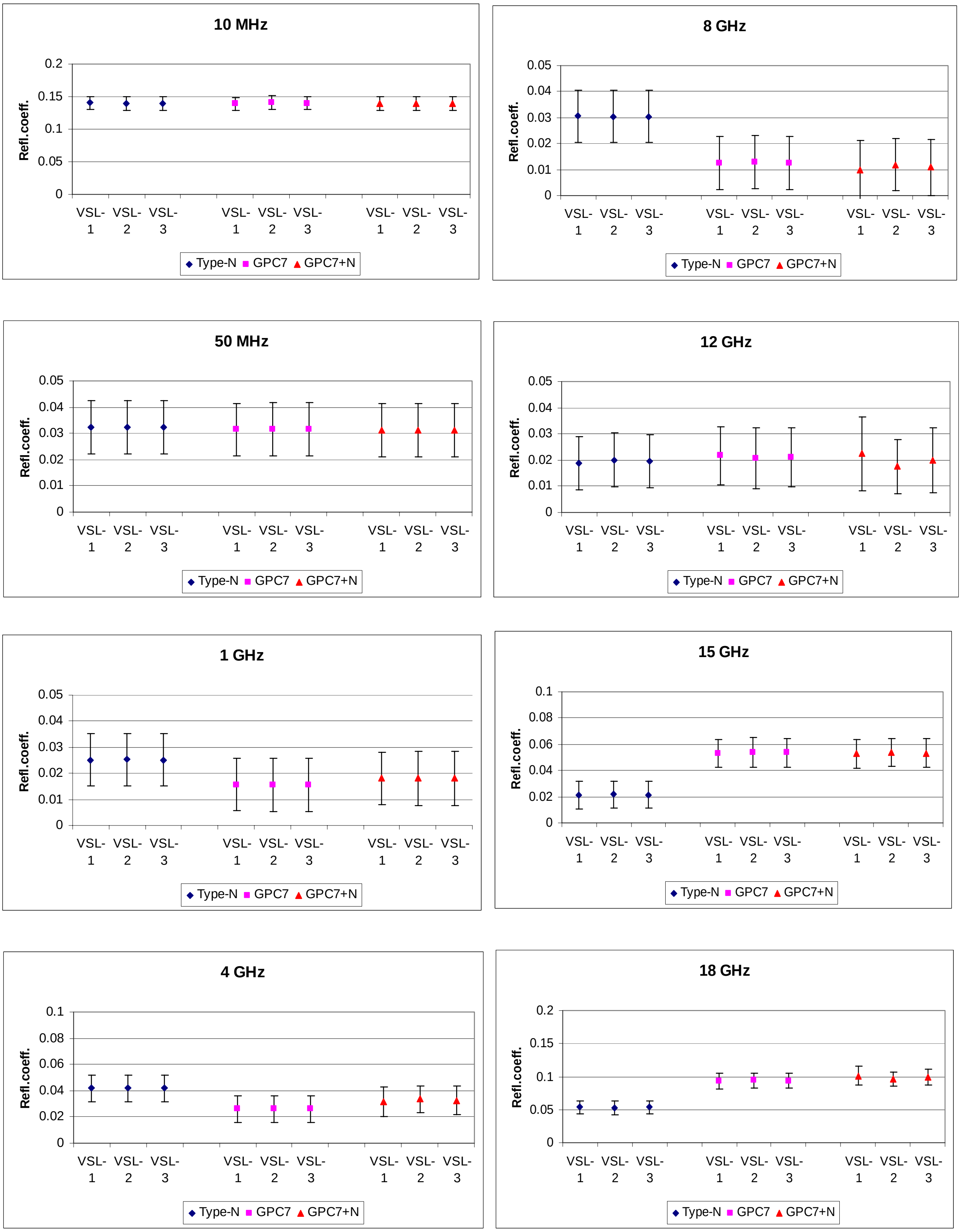
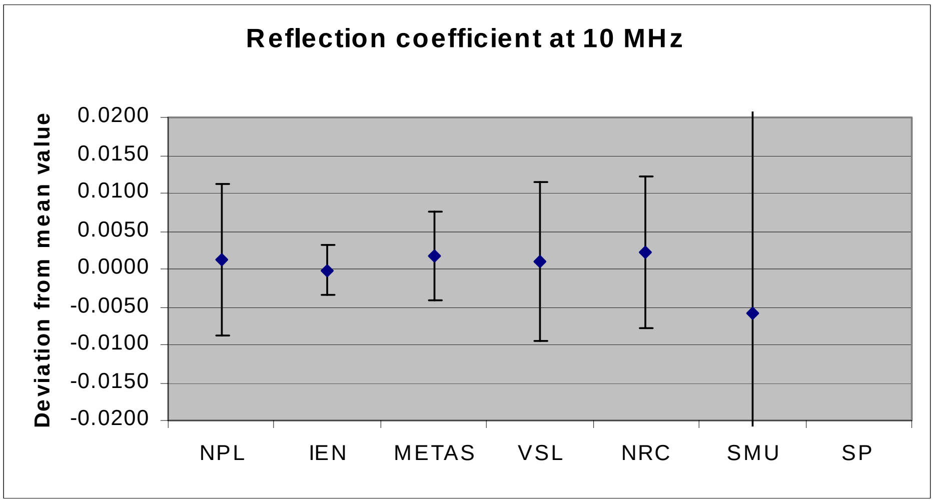
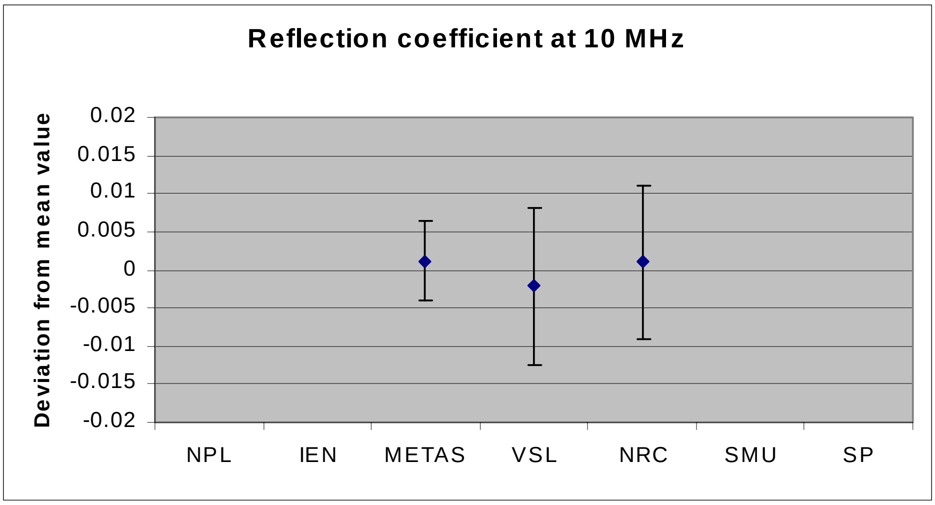


Figure A.2: Overview of the individual results of the reflection coefficient obtained by NMi-VSL during the intercomparison. The results are grouped for each DUT. The number in the code refers to the measurement period.

APPENDIX B
Reflection measurements





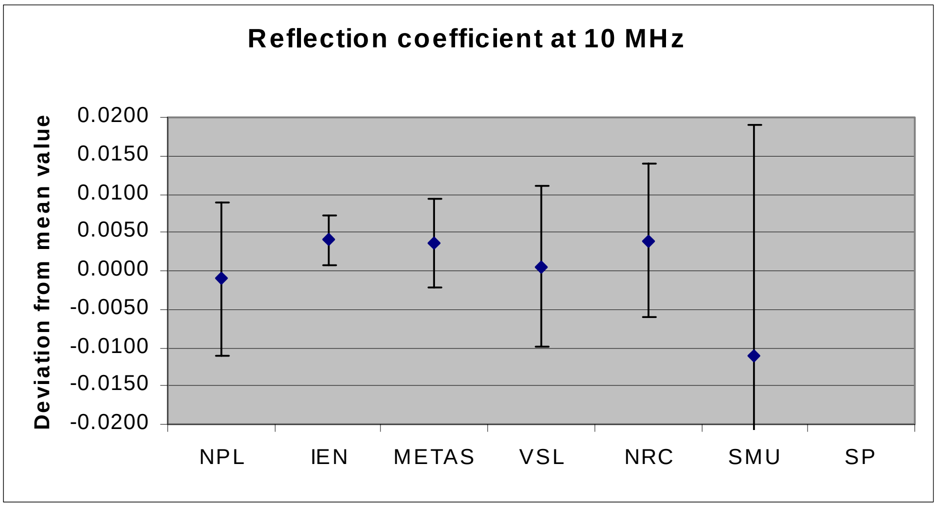
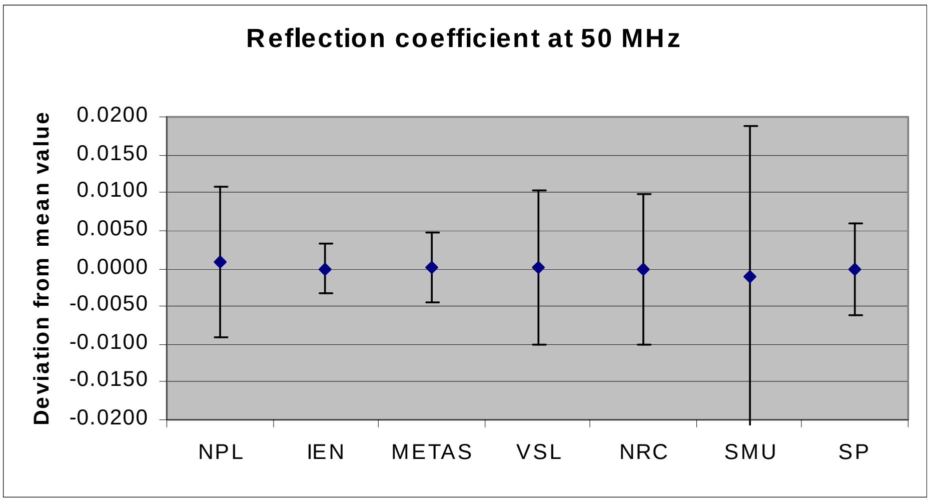
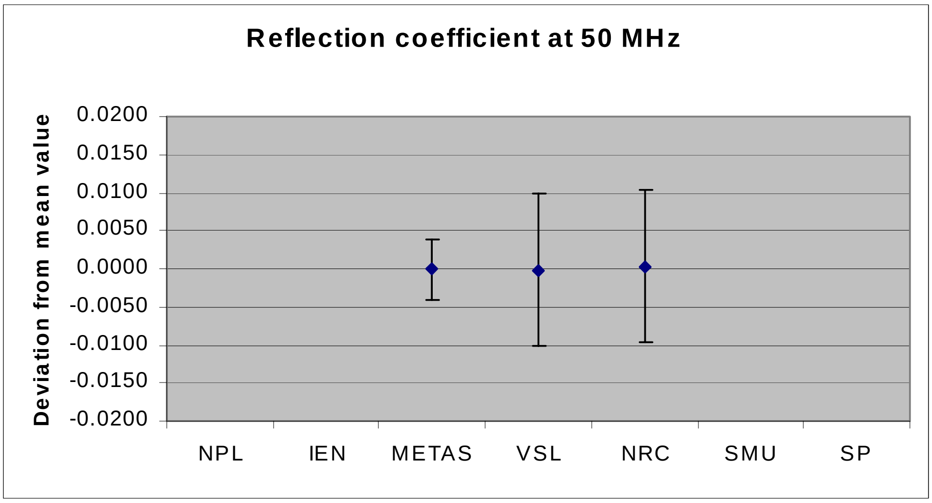


Figure B1: Reflection coefficient measured at 10 MHz: Deviation from the mean measured value (from all laboratories). From top to bottom: TM 4, TM5 and TM6.





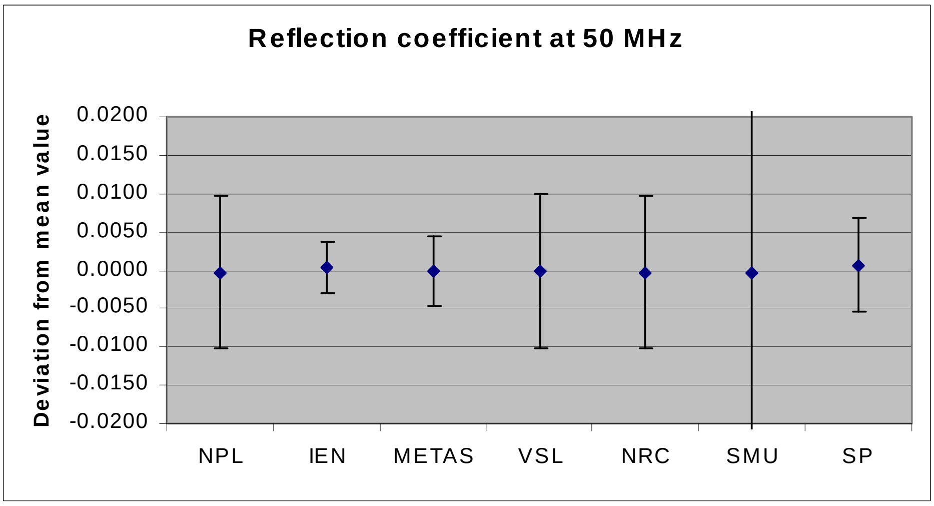
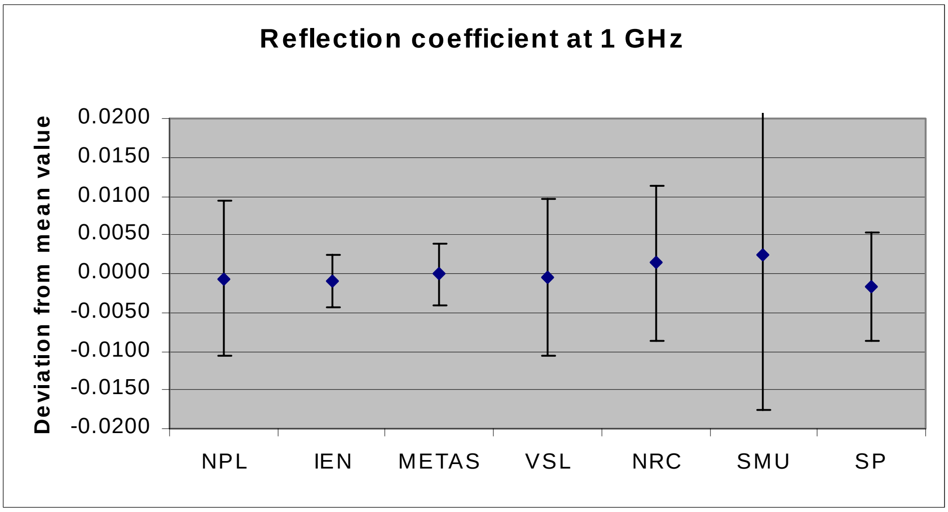
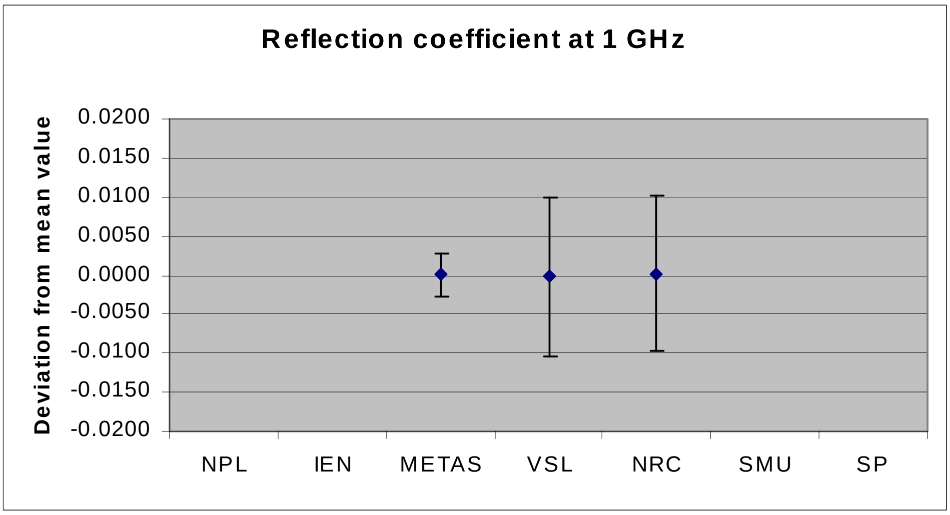


Figure B2: Reflection coefficient measured at 50 MHz: Deviation from the mean measured value (from all laboratories). From top to bottom: TM 4, TM5 and TM6





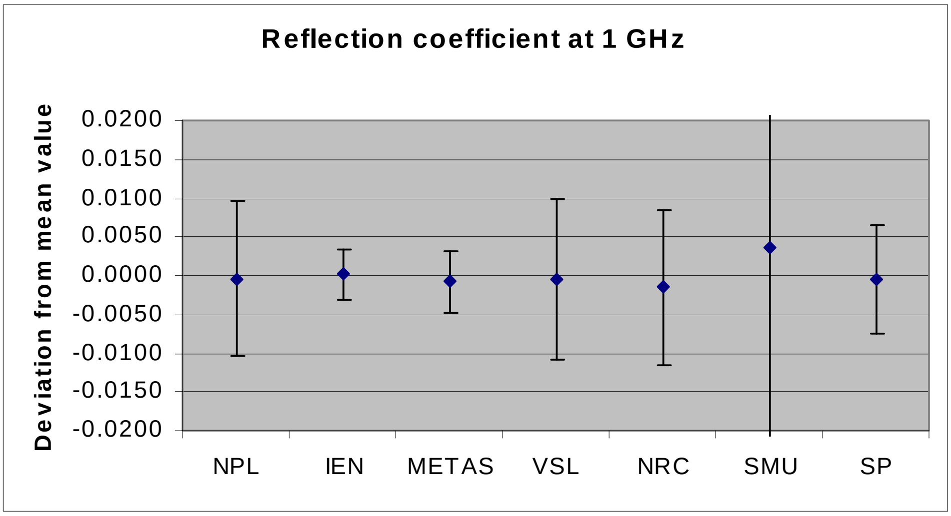
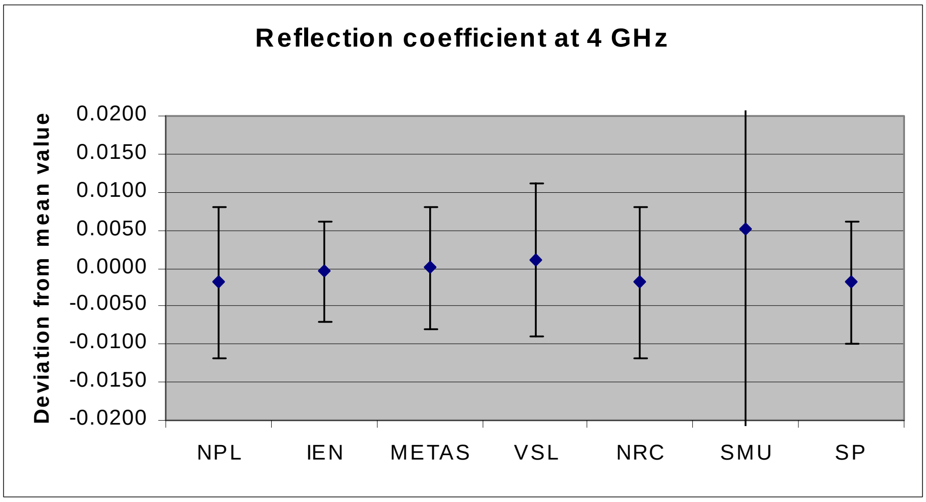
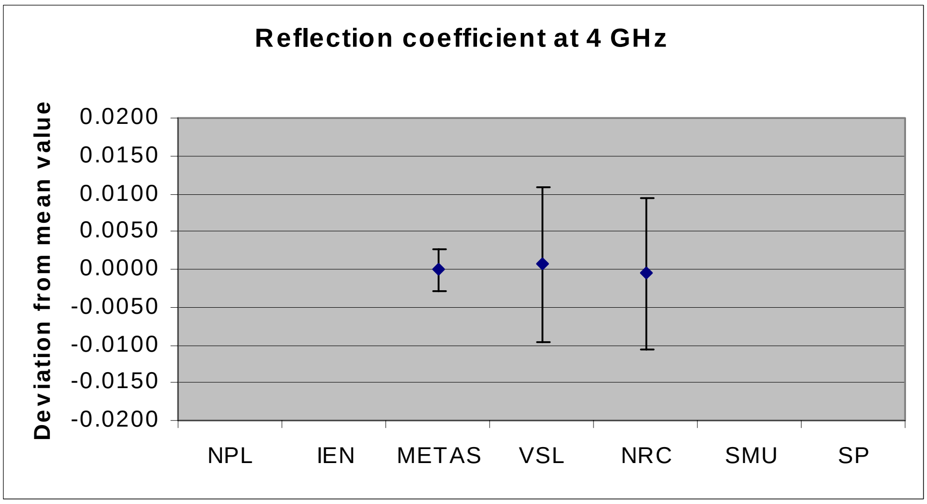


Figure B3: Reflection coefficient measured at 1 GHz: Deviation from the mean measured value (from all laboratories). From top to bottom: TM 4, TM5 and TM6





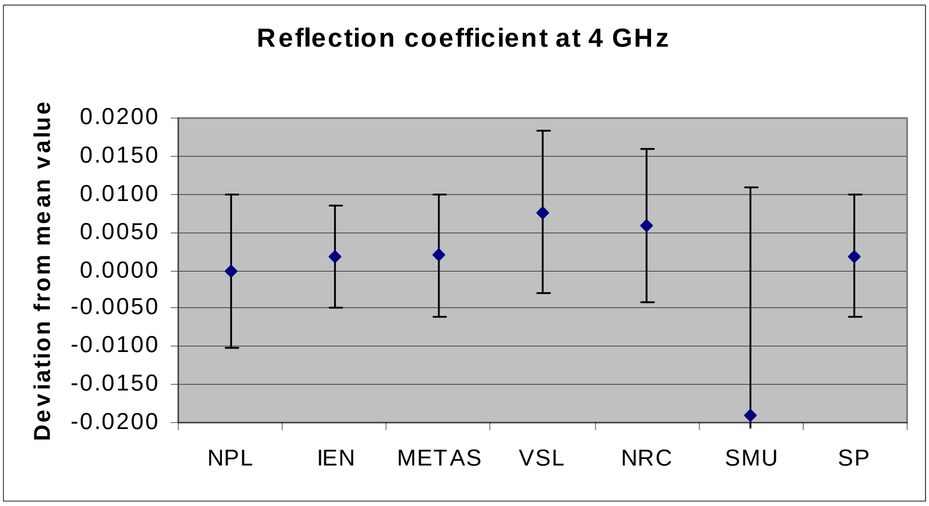
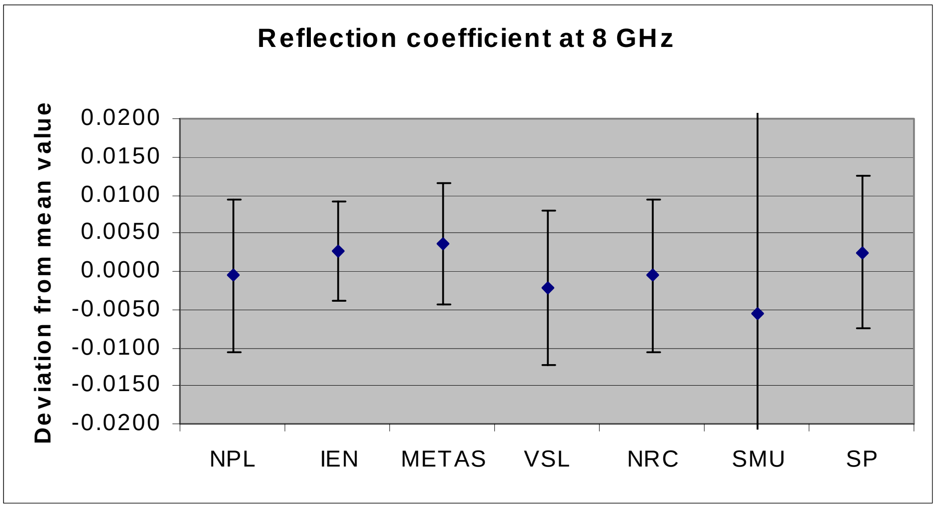
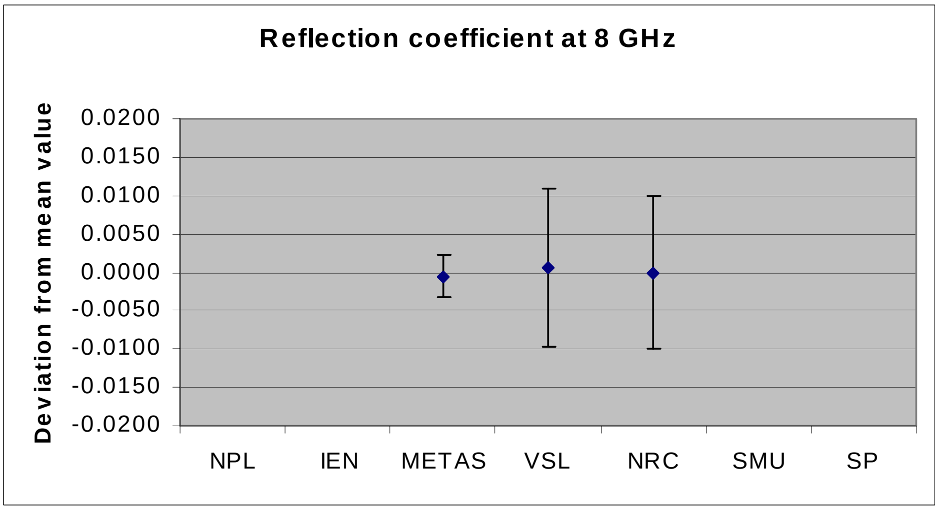


Figure B4: Reflection coefficient measured at 4 GHz: Deviation from the mean measured value (from all laboratories). From top to bottom: TM 4, TM5 and TM6.





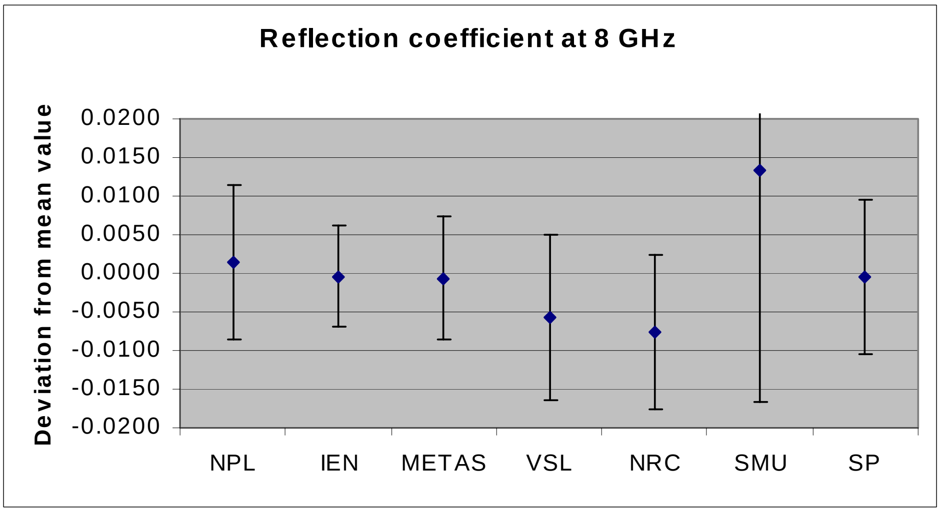
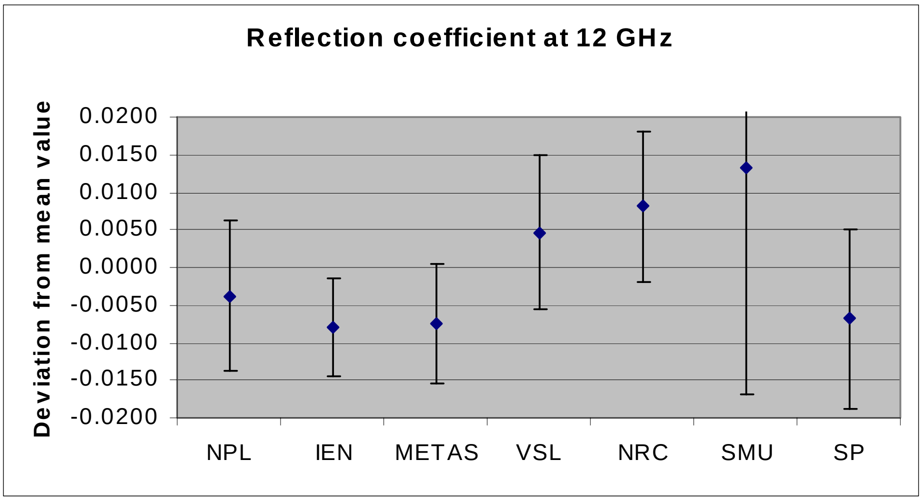
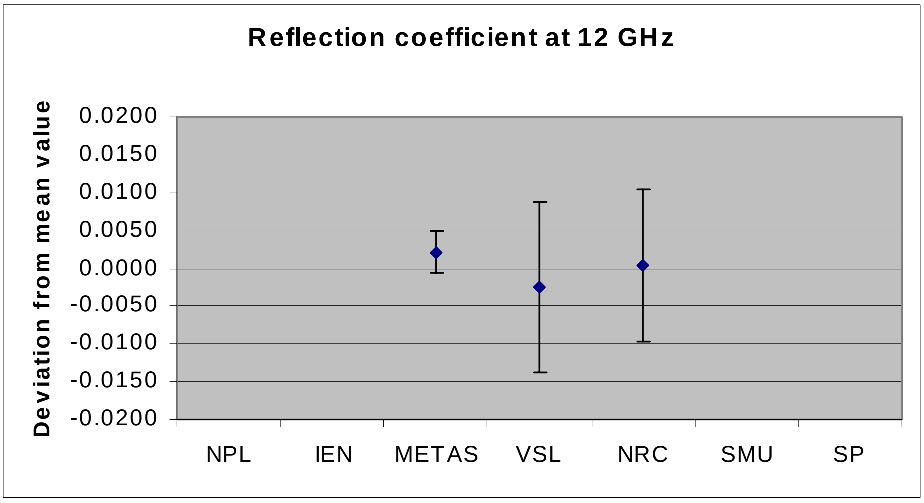


Figure B5: Reflection coefficient measured at 8 GHz: Deviation from the mean measured value (from all laboratories). From top to bottom: TM 4, TM5 and TM6





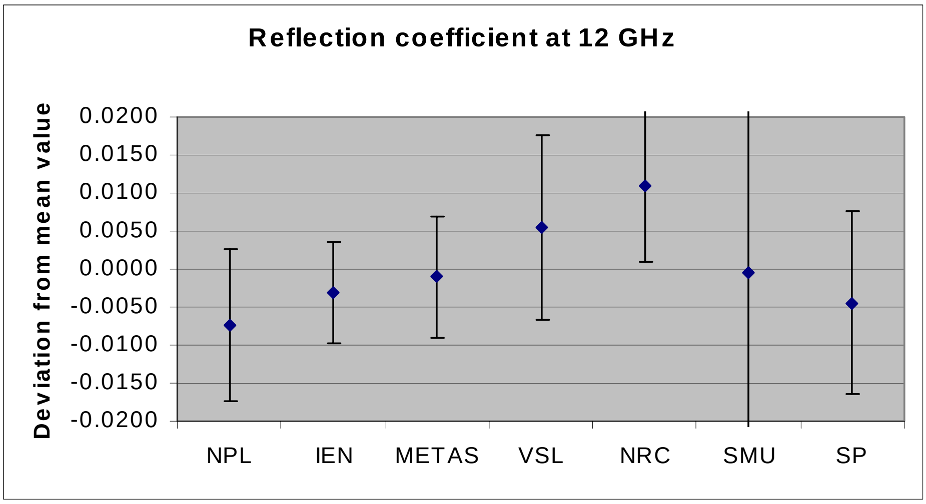
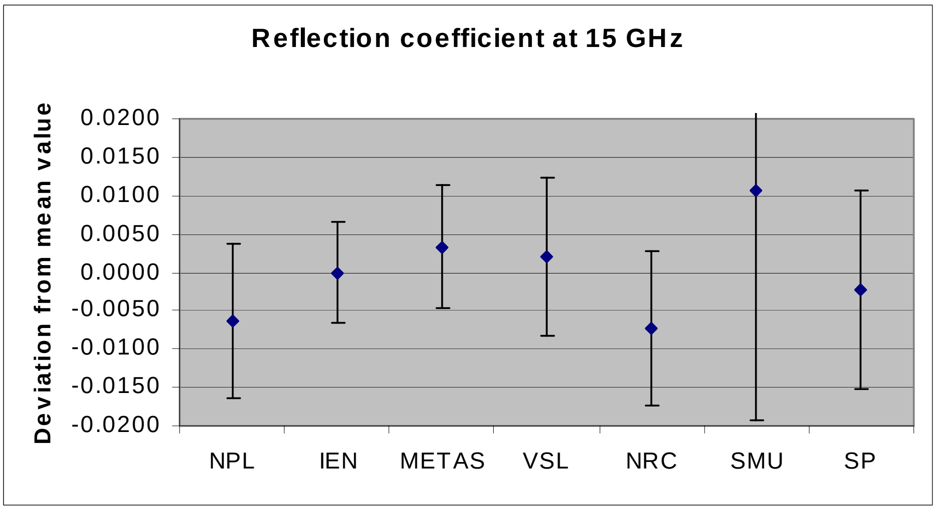
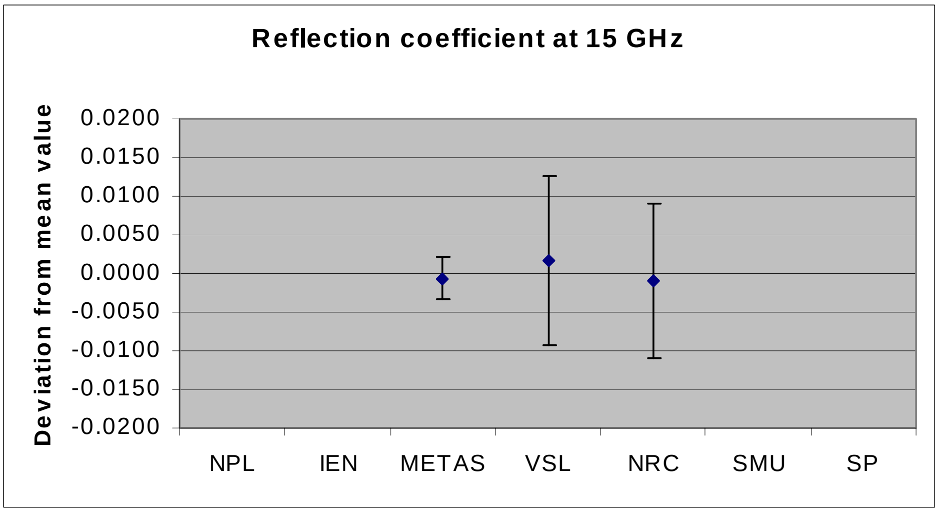


Figure B6: Reflection coefficient measured at 12 GHz: Deviation from the mean measured value (from all laboratories). From top to bottom: TM 4, TM5 and TM6.





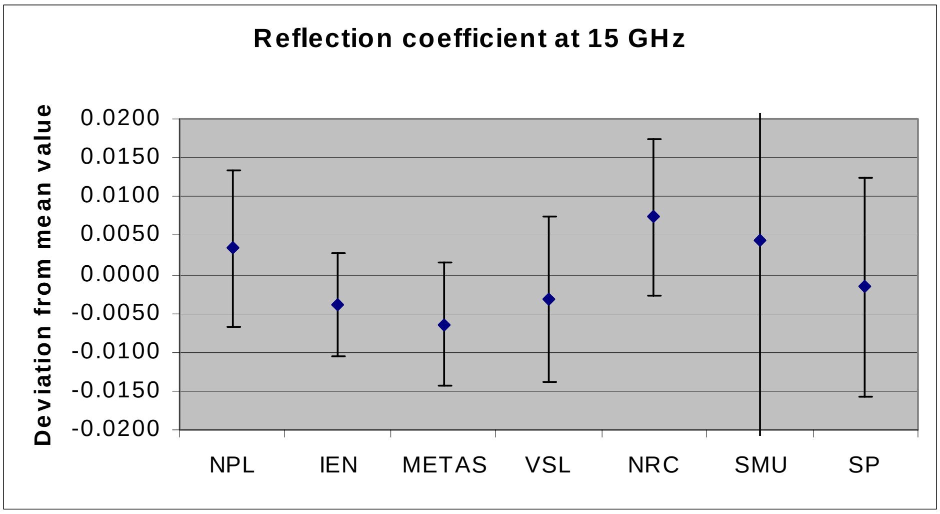
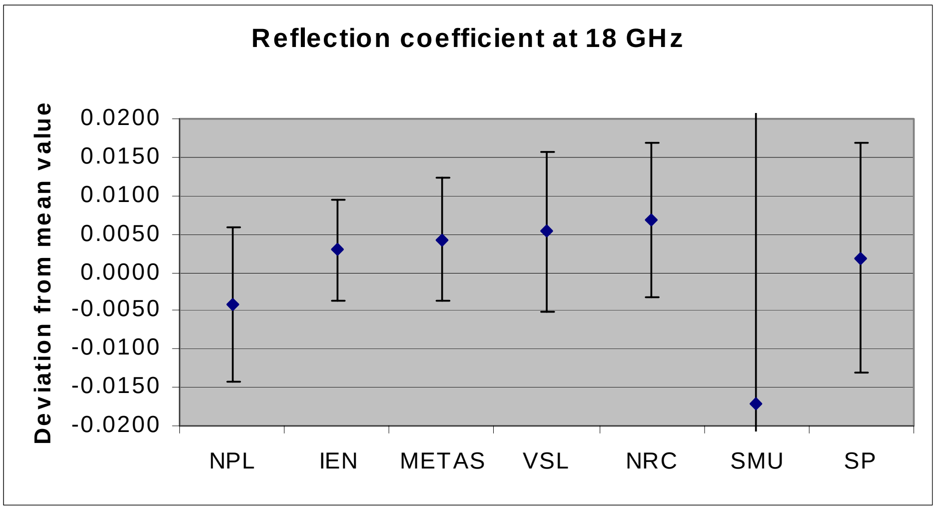
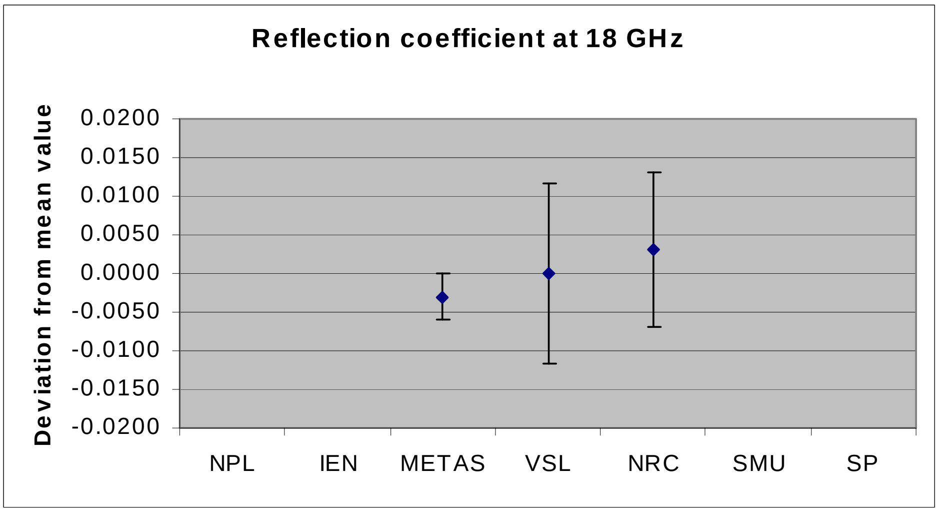


Figure B7: Reflection coefficient measured at 15 GHz: Deviation from the mean measured value (from all laboratories). From top to bottom: TM 4, TM5 and TM6.





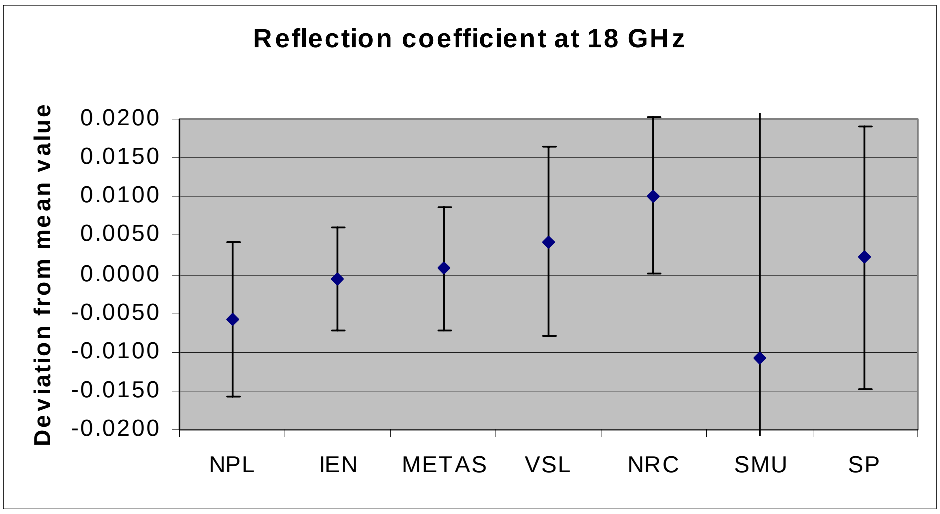


Figure B8: Reflection coefficient measured at 18 GHz: Deviation from the mean measured value (from all laboratories). From top to bottom: TM 4, TM5 and TM6.

APPENDIX C

Degrees of equivalence for calibration factor at 10 MHz and at 18 GHz

Regional Key comparison: Euromet.EM.RF-K8.1.CL

Measurand: calibration factor in coaxial 7 mm transmission line Nominal value: 1.00
Pilot laboratory: NMi-VSL
Travelling standards: three thermistor mounts identified as TM4, TM5 and TM6; TM4 and TM6 have a male type N 50 ohm connector and TM5 has a GPC7-connector (for more details, see the Final Report)

For the degrees of equivalence only the results at 10 MHz and 18 GHz are given. For the results at the other 6 frequencies see the Final Report on the comparison.
As the actual calibration factors of the DUTs are not relevant for the quality of the measurement results, for each DUT the results are given as the difference between the laboratory result and the relevant ERV (the reference value for this regional key comparison). The nominal value of the calibration factor for each DUT is therefore zero for each frequency.
D_i = the difference from the ERV (the unweighted mean of selected laboratories) for laboratory i
U_i = the uncertainty of $D_{,i}$ taken into account the uncertainty of the ERV.

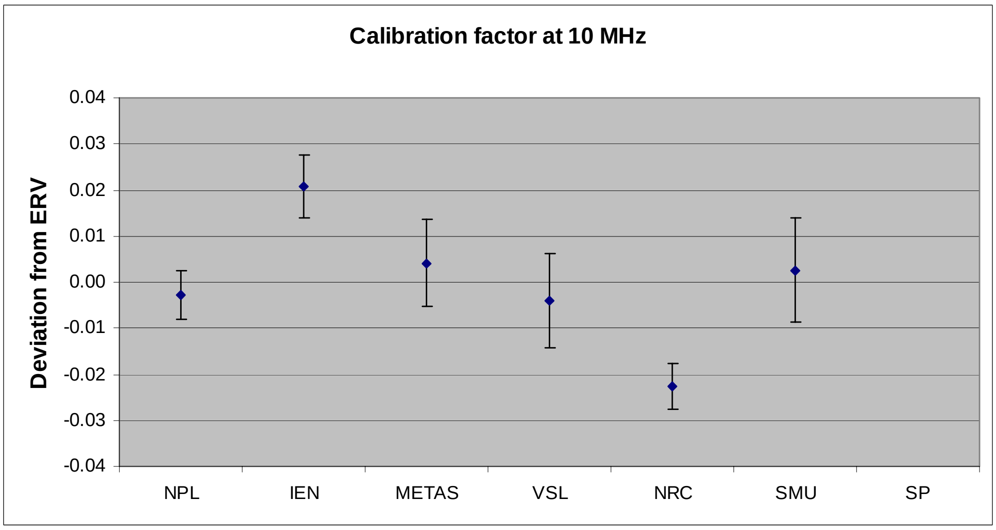
Measurement frequency: 10 MHz

Laboratory	TM4		TM5		TM6	
	D_i	U_i	D_i	U_i	D_i	U_i
NPL	-0.0027	0.0052	N/A	N/A	-0.0019	0.0053
IEN	0.0208	0.0068	N/A	N/A	0.0214	0.0068
METAS	0.0041	0.0094	0.0033	0.0065	0.0038	0.0094
VSL	-0.0041	0.0102	-0.0033	0.0065	-0.0048	0.0107
NRC	-0.0226	0.0050	-0.0324	0.0075	-0.0340	0.0054
SMU	0.0026	0.0113	N/A	N/A	0.0030	0.0147
SP	--	--	N/A	N/A	--	--

Measurement frequency: 18 GHz

Laboratory	TM4		TM5		TM6	
	D_i	U_i	D_i	D_i	U_i	D_i
NPL	-0.0004	0.0072	N/A	N/A	0.0009	0.0070
IEN	0.0236	0.0460	N/A	N/A	0.0364	0.0452
METAS	0.0031	0.0162	-0.0017	0.0103	0.0020	0.0161
VSL	0.0069	0.0139	0.0062	0.0112	0.0053	0.0157
NRC	-0.0068	0.0093	-0.0044	0.0075	-0.0081	0.0092
SMU	-0.0030	0.0162	N/A	N/A	0.0000	0.0214
SP	-0.0010	0.0112	N/A	N/A	-0.0010	0.0121

Laboratories in green have not participated in the definition of the ERV
-- indicates no measurements on the specified device at this frequency.
N/A = no measurement on this device


Calibration factor at 10 MHz
Deviation from ERV
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0.03
0.02
0.01
0.00
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-0.02
-0.03
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IEN
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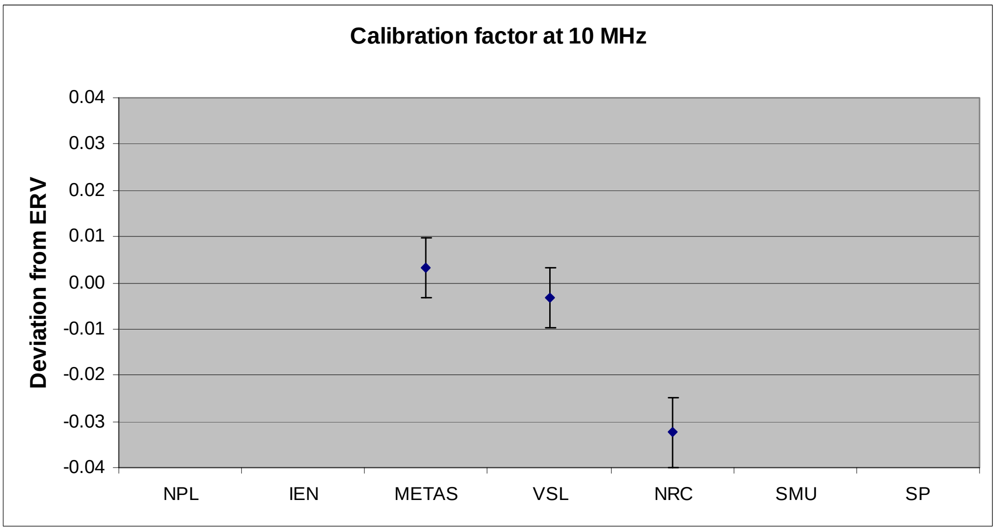
VSL
NRC
SMU
SP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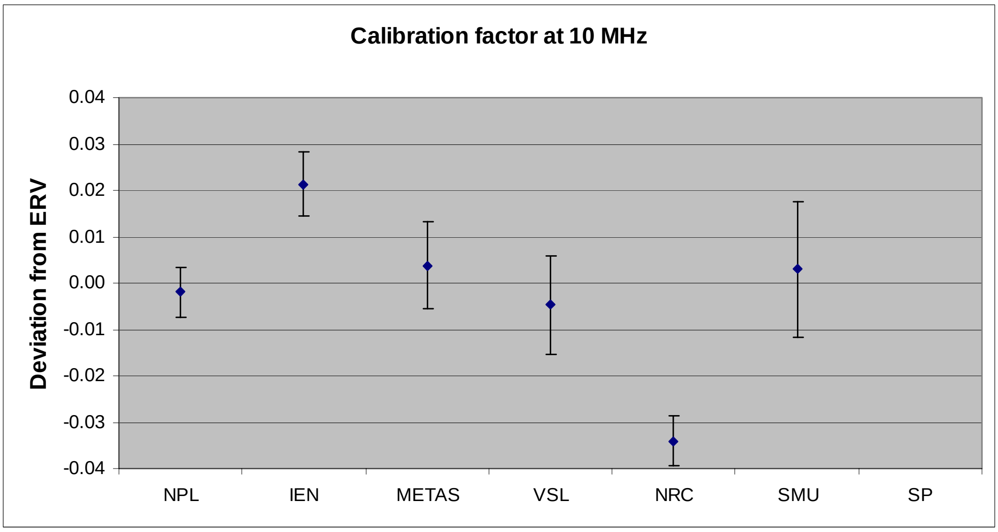
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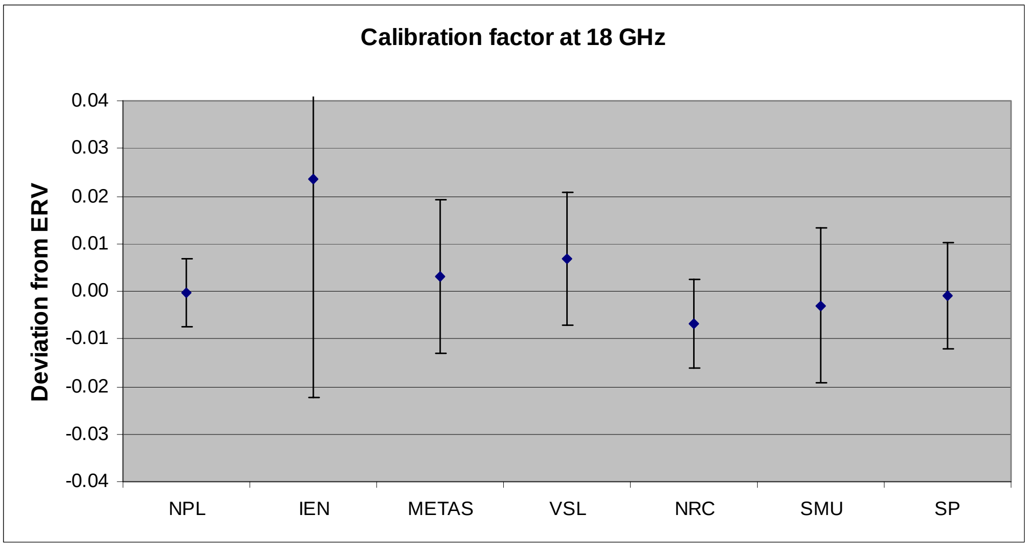
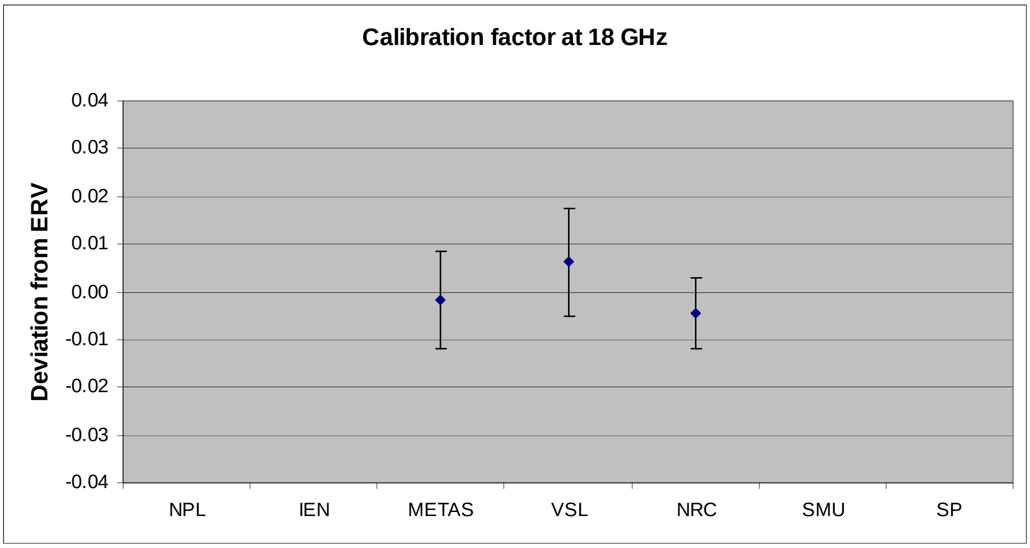
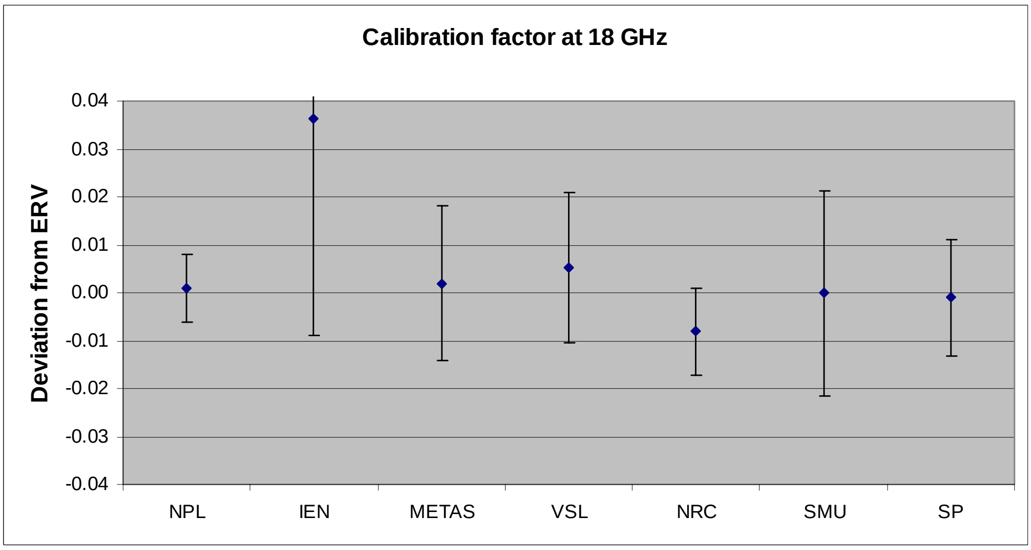
IEN
METAS
VSL
NRC
SMU
SP


Calibration factor at 18 GHz
Deviation from ERV
0.04
0.03
0.02
0.01
0.00
-0.01
-0.02
-0.03
-0.04
NPL
IEN
METAS
VSL
NRC
SMU
SP


Calibration factor at 18 GHz
Deviation from ERV
0.04
0.03
0.02
0.01
0.00
-0.01
-0.02
-0.03
-0.04
NPL
IEN
METAS
VSL
NRC
SMU
SP


Calibration factor at 18 GHz
Deviation from ERV
0.04
0.03
0.02
0.01
0.00
-0.01
-0.02
-0.03
-0.04
NPL
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SMU
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Appendix D
Participant uncertainty budget for thermistor mount TM4
Frequencies 10 MHz and 18 GHz

Pilot laboratory: NMi-VSL

Note: this is the same information as given in CCEM.RF-K8.CL
They refer to an individual measurement and not to the average of a series of measurements. The data are indicative for the frequency range and the type of DUT

Frequncy 10 MHz

REF: VSL-H48.4 Type-N connector
Data from: [HF\Beheer97\Sensor2]H48_4

VSWR source: Users_HF\Euromet\periode4\onz_p4

DUT Users_HF\euromet\periode4\vna
Data from 1998

		Value	Uncertainty	Distribution	factor	St.dev	sens.factor	Contr.to Unc	Square
Ks	Calibration factor REF at 10 MHz	0.9619	0.0034	Normal	1	0.0034	1.004124	0.003414	1.17E-05
dKd	uncertainty due drift	0	0.001	rectangular	1.732051	0.000577	1.004124	0.00058	3.36E-07
Msr	mismatch REF 50 MHz	1	0.0004	U	1.414214	0.000283	0.965867	0.000273	7.46E-08
Msc	mismatch REF 10 MHz	1	0.002	U	1.414214	0.001414	0.965867	0.001366	1.87E-06
Mxr	mismatch DUT 50 MHz	1	0.0005	U	1.414214	0.000354	0.965867	0.000341	1.17E-07
Mxc	mismatch DUT 10 MHz	1	0.0021	U	1.414214	0.001485	0.965867	0.001434	2.06E-06
pcr	nonlinearity etc at 50 MHz	1	0.0012	normal	2	0.0006	0.965867	0.00058	3.36E-07
pcc	nonlinearity etc at 10 MHz	1	0.0012	normal	2	0.0006	0.965867	0.00058	3.36E-07
p	ratio in response tov 50 MHz	0.9983	0.0004	normal	1	0.0004	0.967512	0.000387	1.5E-07
Kx=		0.960		0.004114	(k=1)			0.004114	1.69E-05
				0.008	(k=2)				

Frequency 18 GHz

REF: VSL-H48.4 Type-N connector
Data from: [HF\Beheer97\Sensor2]H48_4

VSWR source: Users_HF\Euromet\periode4\onz_p4

DUT Users_HF\euromet\periode4\vna
Data from 1998

		Value	Uncertainty	Distribution	factor	St.dev	sens.factor	Contr.to Unc	Square
Ks	Kalibratiefactor REF at 18 GHz	0.9363	0.0082	normal	1	0.0082	1.031578	0.008459	7.16E-05
dKd	uncertainty due drift	0	0.001	rechthoek	1.732051	0.000577	1.031578	0.000596	3.55E-07
Msr	mismatch REF 50 MHz	1	0.0004	U	1.414214	0.000283	0.965867	0.000273	7.46E-08
Msc	mismatch REF 18 GHz	1	0.0051	U	1.414214	0.003606	0.965867	0.003483	1.21E-05
Mxr	mismatch DUT 50 MHz	1	0.0005	U	1.414214	0.000354	0.965867	0.000341	1.17E-07
Mxc	mismatch DUT 18 GHz	1	0.0025	U	1.414214	0.001768	0.965867	0.001707	2.92E-06
pcr	nonlinearity etc at 50 MHz	1	0.0012	normaal	2	0.0006	0.965867	0.00058	3.36E-07
pcc	nonlinearity etc at 18 GHz	1	0.0012	normaal	2	0.0006	0.965867	0.00058	3.36E-07
p	ratio in response tov 50 MHz	0.9973	0.0067	normaal	1	0.0067	0.968482	0.006489	4.21E-05
Kx=		0.934		0.011398	(k=1)			0.011398	0.00013
				0.023	(k=2)				

NPL

Uncertainty Budgets

Table 3 Uncertainties for the calibration of the 14mm Transfer Standard against the calorimeter

Source of Uncertainty	Probability. Distribution	Standard Uncertainty %
Calorimeter Eff at 50 MHz	Normal	0.075
DC Power to Calorimeter	Normal	0.01
DC Power to Transfer Standard	Normal	0.01
Drift in Transfer Standard per year	Rectangular	0.05
Mismatch for Cal at 50 MHz	Normal	0.02
Random (a)	Normal	0.03
Combined Standard Uncertainty	Normal	0.10

Table 4 Uncertainties for the calibration of the DUT against the Transfer Standard

Source of Uncertainty	Probability Distribution	Standard Uncertainty %
Transfer Standard Calibration Const.	Normal	0.10
DC Power to Transfer Standard	Normal	0.01
DC Power to DUT	Normal	0.01
Mismatch for DUT at 50 MHz	Normal	0.02
Random (a)	Normal	0.02
Random (b)	Normal	0.02
Combined Standard Uncertainty	Normal	0.11

Table 5 Uncertainty Bubget for the Calibration of the 7mm Transfer Standard against the Calorimeter

Source of Uncertainty	Probability	Standard Uncertainty % for the Frequency (GHz)						
	Distribution	0.01	1	4	8	12	15	18
Calorimeter Eff at 50 MHz	Normal	0.050	0.050	0.050	0.050	0.050	0.05	0.050
Calorimeter Eff at rf	Normal	0.050	0.100	0.150	0.200	0.225	0.25	0.250
Transfer Standard Ratio Linearity	Rectangular	0.029	0.029	0.029	0.029	0.029	0.029	0.029
Calorimeter Output Ratio Linearity	Rectangular	0.012	0.012	0.012	0.012	0.012	0.023	0.023
Drift in Transfer Standard per year	Rectangular	0.058	0.087	0.115	0.115	0.115	0.115	0.115
Mismatch for Cal at 50 MHz	Normal	0.010	0.010	0.010	0.010	0.010	0.01	0.010
Mismatch for Cal at rf	Normal	0.004	0.005	0.014	0.018	0.027	0.022	0.032
Random (a)	Normal	0.050	0.050	0.050	0.050	0.050	0.05	0.050
Random (b)	Normal	0.020	0.050	0.050	0.080	0.100	0.12	0.150
Combined Standard Uncertainty	Normal	0.11	0.16	0.21	0.26	0.29	0.29	0.33

Table 6 Uncertainty Budget for the Calibration of the Travelling Standard 23878 against the 7mm Transfer Standard

Source of Uncertainty	Probability	Standard Uncertainty % for the Frequency (GHz)						
	Distribution	0.01	1	4	8	12	15	18
DUT Calibration Factor at 50 MHz	Normal	0.11	0.11	0.11	0.11	0.11	0.11	0.11
Transfer Standard Calibration Const.	Normal	0.11	0.16	0.21	0.26	0.29	0.29	0.33
DUT Ratio Linearity	Rectangular	0.029	0.029	0.029	0.029	0.029	0.029	0.029
Transfer Standard Ratio Linearity	Rectangular	0.029	0.029	0.029	0.029	0.029	0.029	0.029
Mismatch at 50 MHz	Normal	0.01	0.01	0.01	0.01	0.01	0.01	0.02
Mismatch at Cal. Frequency	Normal	0.18	0.04	0.040	0.04	0.02	0.02	0.045
Random	Normal	0.01	0.01	0.02	0.02	0.01	0.02	0.03
Combined Standard Uncertainty	Normal	0.24	0.20	0.24	0.29	0.31	0.31	0.35

Table 7 Uncertainty Budget for the Calibration of the Travelling Standard 24991 with APC-7 to N adaptor against the 7mm Transfer Standard

Source of Uncertainty	Probability	Standard Uncertainty % for the Frequency (GHz)						
	Distribution	0.01	1	4	8	12	15	18
DUT Calibration Factor at 50 MHz	Normal	0.11	0.11	0.11	0.11	0.11	0.11	0.11
Transfer Standard Calibration Const.	Normal	0.11	0.16	0.21	0.26	0.29	0.29	0.33
DUT Ratio Linearity	Rectangular	0.029	0.029	0.029	0.029	0.029	0.029	0.029
Transfer Standard Ratio Linearity	Rectangular	0.029	0.029	0.029	0.029	0.029	0.029	0.029
Mismatch at 50 MHz	Normal	0.01	0.01	0.01	0.01	0.01	0.01	0.02
Mismatch at Cal. Frequency	Normal	0.18	0.02	0.040	0.023	0.014	0.057	0.046
Random	Normal	0.01	0.01	0.01	0.03	0.02	0.01	0.02
Combined Standard Uncertainty	Normal	0.24	0.20	0.24	0.29	0.31	0.32	0.35

Example Uncertainty Calculation

The following example of the uncertainty calculations relates to the calibration of the type N Thermistor Mount at a frequency of 8 GHz on the 7mm system. The budget for the calibration of the transfer standard against the calorimeter and for the calibration of the Thermistor Mount at a frequency of 50 MHz are of similar form and composition.

DUT Calibration Factor at 50 MHz: The calibration factor of the thermistor mount was measured using the 14mm coaxial system as 0.9941 with an uncertainty of 0.11% for $k = 1$ with a normal probability distribution.

Transfer Standard Calibration Constant: The calibration constant of the transfer standard was measured using the 7mm calorimeter as 0.98392 with an uncertainty of calibration factor of the thermistor mount was measured using the 14mm coaxial system as 0.9941 with an uncertainty of 0.26% for $k = 1$ with a normal probability distribution

Transfer Standard Ratio Linearity: The measured transfer standard ratios are given in table 8. The uncertainty in the measurement of this ratio due to linearity and discrimination is estimated to be 0.029% for $k = 1$ with a rectangular probability distribution.

DUT Ratio Linearity: The measured transfer standard ratios are given in table 8. The uncertainty in the measurement of this ratio due to linearity and discrimination is estimated to be 0.029% for $k = 1$ with a rectangular probability distribution.

Mismatch between the DUT and the Transfer Standard at 50 MHz: The mismatch factor M is obtained from the measurements of the complex reflection coefficients for calorimeter and the effective source match using a Vector Network Analyser. The uncertainty in the mismatch factor can be calculated from the equation for M by applying the uncertainties in the measurements of both real and imaginary components of the VNA measurements. However, because all the measured values were obtained using the same VNA and the same calibration standards there is a possibility of correlation between the errors in these measurements. The degree of correlation is not known and it has proved impossible to derive an expression that allows this to be evaluated. A compromise solution was used to obtain the mismatch uncertainty that involved calculating the standard deviation in the mismatch factor from a large sample (10000) of randomly generated errors based on a rectangular distribution for each of the four contributing errors. A correlation coefficient of 0.5 was used to generate the random errors for both magnitude and phase. A correlation of 0.5 was used because the measurement uncertainty for the VNA comprises approximately equal contributions from systematic errors that are to some extent correlated and random errors (mostly connector variations) that are not correlated The VNA uncertainties used to obtain the uncertainty in M were ±0.005 for both real and imaginary components in the measurement of the DUT and ±0.03 (k = 1) for the measurement of the effective source match. Whilst the individual contribution are considered to have rectangular distributions the combination of all four contributions is assumed to have a normal distribution with k=1.

At 50 MHz the value of the reflection coefficients were as follows:

DUT	0.033<-97.2°
Effective Source Match	0.016< 177.3°

These reflection coefficients gave a value for the mismatch factor of 1.0002 with an uncertainty of ±0.038% for k =1 with a normal probability distribution.

Mismatch between the DUT and the Transfer Standard at 8 GHz: Details as above

At 8 GHz the value of the reflection coefficients were as follows:

DUT	0.031<-170.4°
Effective Source Match	0.028< 126.0°

These reflection coefficients gave a value for the mismatch factor of 1.0012 with an uncertainty of ±0.036% for k =1 with a normal probability distribution.

Random : This is the variation in the measurement of the Calibration Factor of the DUT. This factor has an expectation of 1.00 with an uncertainty, calculated from the standard deviation of the mean of 7 measurements, of 0.036%
Correlation: Apart for the correlation mentioned above in the measurement of voltage reflection coefficients, none of the input quantities are considered to be correlated to any significant extent.

Measurements: 7 separate measurements are made which involve disconnection and reconnection of the DUT and on the power transfer system. The observed power ratio readings used to calculate the calibration factor of the unknown mount , CF_u, were as follows:

Table 8 Measurement results

No:	R_{DUT50}	R_{DUTrf}	$R = R_{DUTrf}/R_{DUT50}$
1	0.26776	0.26788	1.00045
2	0.26687	0.26653	0.99873
3	0.26688	0.26667	0.99921
4	0.26660	0.26623	0.99861
5	0.26695	0.26666	0.99891
6	0.26646	0.26635	0.99959
7	0.26664	0.26641	0.99914
Mean	**0.26688**	**0.26668**	**0.99923**

arithmetic mean: $\overline{R} = 0.99923$

experimental standard deviation $s(R) = 0.06\%$

standard uncertainty: $u(R) = s(\overline{R}) = \frac{0.06}{\sqrt{7}} = 0.02\%$

Table 9 Uncertainty budget for 8 GHz:

Quantity X_i	Estimate x_i	standard uncertainty $u(x_i)$%	Probability Distribution	sensitivity coefficient c_i	Uncertainty Contribution $u_i(y)$%
CF_{DUT50}	0.9941	0.11	Normal	1.0	0.11
R_{DURrf}	0.26668	0.029	Rectangular	1.0	0.029
R_{DUT50}	0.26688	0.029	Rectangular	1.0	0.029
MF_{DUT50}	1.0002	0.01	Normal	1.0	0.01
MF_{DUTrf}	1.0012	0.036	Normal	1.0	0.036
CC_{TSrf}	0.98392	0.26	Normal	1.0	0.26
R	0.99923	0.02	Normal	1.0	0.02
CF_{DUTrf}	0.9763				0.29

Expanded uncertainty:

$$U = ku(CF_{DUTrf}) = 2 \times 0.29\% \approx 0.58\%$$

Reported result:

The calibration factor of the power sensor at 8 GHz is 0.9763 % ±0.6 %

The reported expanded uncertainty of measurement is stated as the standard uncertainty of measurement multiplied by the coverage factor 2, which for a normal distribution corresponds to a coverage probability of approximately 95%.

IEN

Data Analysis and Accuracy Assessment.

No filtering process has been applied to the original measured power ratios *p*. Concerning the accuracy assessment, the procedure suggested in EA-4/02 Document have been used. The scheme of the uncertainty budget is reported in the Table I below for the power sensor H48.2 at the frequency of 18GHz .

Quantity	estimate	standard uncertainty	Probability distribution	sensitivity coefficient	uncertainty contribution
X_i	x_i	$u(x_i)$		c_i	$u_i(y)$
K_S	0.9448	0.0028	normal	1.0326	0.0029
M_S	1	0.0196	U-shaped	-0.9756	-0.0191
M_X	1	0.0123	U-shaped	0.9756	0.0120
$p=P_U/P_S$	1.0326	0.0032	normal	0.9948	0.0030
$y=K_U$	0.9756			K=1	0.0230

Table I: Uncertainty budged for the travelling standard H48.2 at the frequency of 18GHz .

Error propagation has been calculated on the basis of the formula:

$$K_U = K_S \frac{P_U}{P_S} p \qquad (1)$$

in which the quantities K_S, P_S, P_U are assumed having a gaussian distribution, while M_S, M_U having a U-shaped probability distribution.

The uncertainty related to Calibration Factor K_S of the IENGF standard is basically the uncertainty claimed by IENGF for its primary power standard in the frequency range 10 MHz-18 GHz.

The uncertainty related to the mismatch factors M_S and M_U, whose values are assumed equal 1, has been calculated by means the formula

$$u(M_x) = \frac{2|\Gamma_{eq}||\Gamma_x|}{\sqrt{2}} \quad ; x=S, U \qquad (2)$$

using the reflection coefficients of equivalent generator (power splitter output ports), of the standard and unknown $\Gamma_{eq}, \Gamma_S, \Gamma_U$.

It must be pointed out, the uncertainties related to K_S, M_S, M_U are type B terms only. At the quantity *p* instead, both a type A and a type B uncertainty term is associated.

Indeed, the power levels P_S , P_U are quantities measured by means of the dc-substitution method through the following formula:

$$P = R_T \left(\frac{V_{1dc}}{2R}\right)^2 - R_T \left(\frac{V_{2dc}}{2R}\right)^2 \qquad (3)$$

where R_T is the dynamic resistance of the thermistor, while $\frac{V_{1dc}}{2R}$ and $\frac{V_{2dc}}{2R}$ are the dc-bias supplied by the self-balancing bridge to the thermistor mount without and with HF-power respectively. All the quantities involved in formula (3) are known or measured with great accuracy, therefore their contribution to the type B uncertainty is very small and could be neglected. In other words, the quantity *p* could be considered affected by an uncertainty term of type A only, that is the standard deviation resulting from the measurements. Anyway, the supplied Official Data has been calculated including all the uncertainty terms.

Error budget does not include the direct contribution of the power splitter asymmetry on *p*. This error term is considered negligible and compensated by the sensor exchange on the output ports.

Official IEN Data

The final results coming from IEN are reported in the following Tables 1,2.

Results of EUROMET 633: Table 1				
Laboratory: IENGF(Italy)			Power Sensor H48.2	
Frequency (GHz)	Cal. Factor Ku	Uncertainty U(Ku) (k=2)	Refl. Coeff. |Γ|	Uncertainty U(|Γ|) (k=2)
0.01	0.9892	0.0055	0.1387	0.0033
0.05	0.9934	0.0043	0.0321	0.0033
1	0.9890	0.0271	0.0246	0.0033
4	0.9794	0.0162	0.0404	0.0066
8	0.9725	0.0214	0.0352	0.0066
12	0.9565	0.0152	0.0069	0.0066
15	0.9561	0.0134	0.0193	0.0066
18	0.9756	0.0458	0.0511	0.0066

Results of EUROMET 633: Table 2				
Laboratory: IENGF(Italy)			Power Sensor H49.3	
Frequency (GHz)	Cal. Factor Ku	Uncertainty U(Ku) (k=2)	Refl. Coeff. |Γ|	Uncertainty U(|Γ|) (k=2)
0.01	0.9864	0.0055	0.1431	0.0033
0.05	0.9912	0.0043	0.0317	0.0033
1	0.9868	0.0270	0.0186	0.0033
4	0.9758	0.0161	0.0269	0.0066
8	0.9629	0.0212	0.0162	0.0066
12	0.9446	0.0150	0.0114	0.0066
15	0.9365	0.0131	0.0528	0.0066
18	0.9574	0.0450	0.0943	0.0066

Table 1-2: Calibration Factors, Reflection Coefficients and relevant Uncertainties of the travelling standards

METAS

Uncertainty budget for Device TM4 at 10 MHz:

Uncertainty Cal.Factor K_e Thermistor hp8478B, sn2103A23878, N, Euromet 633, DUT # 1								
Frequency : 10 MHz								
Quantity	Standard Uncertainty $u(x_i)$ (dB)	Standard Uncertainty $u(x_i)$ (linear)	Probability Distribution (Form) (factor)	Probability Distribution di (used value)	Sensitivity Coefficient ci	Uncertainty Contribution	Uncertainty Contributon squared	Degree of freedom ν_i
Ke uncertainty	-	0.00200	U (0.707)	1	1	0.00200	4.000E-06	
δ Ke uncertainty (drift, aging)	-	0.00050	Rect (0.577)	1	1	0.00050	2.500E-07	
Mismatch-Error (Split to DUT)	-	0.00029	U (0.707)	0.707	1	0.00020	4.096E-08	
Mismatch-Error (Split to REF)	-	0.00029	U (0.707)	0.707	1	0.00020	4.165E-08	
Mismatch-Error (Split to Adapter)	-	0.00000	U (0.707)	0.707	1	0.00000	1.999E-12	
Mismatch-Error (Adapter to REF)	-	0.00029	U (0.707)	0.707	1	0.00020	4.165E-08	
Adapter S21 uncertainty (REF-side)	0.0221	0.00510	normal (0.5)	1	1	0.00510	2.603E-05	
Stability betw. Diff. Meas. Rows		0.00200	U (0.707)	1	1	0.00200	4.000E-06	
Meas_Val Power Ratio DUT / MON		0.00075	normal (0.5)	1	1	0.00075	5.625E-07	7
Meas_Val Power Ratio REF / MON		0.00075	normal (0.5)	1	1	0.00075	5.625E-07	7
Comb stand. uncert. $u_c(y)$						**$u_c(y)$ =**	**0.00596**	
Overal eff. degree of freedom						**ν_{eff} =**		13961
Coverage Factor k_p						**$k_p = t_p(\nu)$ =**		**2**
Expanded Uncertainty U_p						**U_{p} =**	**0.0119**	

Uncertainty budget for Device TM4 at 18 GHz:

Uncertainty Cal.Factor K_e Thermistor hp8478B, sn2103A23878, N, Euromet 633, DUT # 1								
Frequency : 18000 MHz								
Quantity	Standard Uncertainty $u(x_i)$ (dB)	Standard Uncertainty $u(x_i)$ (linear)	Probability Distribution (Form) (factor)	Probability Distribution di (used value)	Sensitivity Coefficient ci	Uncertainty Contribution	Uncertainty Contributon squared	Degree of freedom ν_i
Ke uncertainty	-	0.00600	U (0.707)	1	1	0.00600	3.600E-05	
δ Ke uncertainty (drift, aging)	-	0.00050	Rect (0.577)	1	1	0.00050	2.500E-07	
Mismatch-Error (Split to DUT)	-	0.00400	U (0.707)	0.707	1	0.00283	8.001E-06	
Mismatch-Error (Split to REF)	-	0.00198	U (0.707)	0.707	1	0.00140	1.967E-06	
Mismatch-Error (Split to Adapter)	-	0.00110	U (0.707)	0.707	1	0.00078	6.048E-07	
Mismatch-Error (Adapter to REF)	-	0.00225	U (0.707)	0.707	1	0.00159	2.540E-06	
Adapter S21 uncertainty (REF-side)	0.0236	0.00545	normal (0.5)	1	1	0.00545	2.969E-05	
Stability betw. Diff. Meas. Rows		0.00200	U (0.707)	1	1	0.00200	4.000E-06	
Meas_Val Power Ratio DUT / MON		0.00075	normal (0.5)	1	1	0.00075	5.625E-07	7
Meas_Val Power Ratio REF / MON		0.00075	normal (0.5)	1	1	0.00075	5.625E-07	7
Comb stand. uncert. $u_c(y)$						**$u_c(y)$ =**	**0.00917**	
Overal eff. degree of freedom						**ν_{eff} =**		78382
Coverage Factor k_p						**$k_p = t_p(\nu)$ =**		**2**
Expanded Uncertainty U_p						**U_{p} =**	**0.0183**	

NRC

International Comparison EUROMET 633: NRC / INMS Measurement Report
Uncertainity Budget Excel Spreadsheet of the 18 GHz Measurement
N(m) type Input Thermistor Mount
Note: All values expressed in 1e-6

	Component Data in units of the uncertainity component parameter										Measurand Components				
			x			c_i	$U(x_i)$	$u(x_i)$	$\Delta u/u$	ν	ν_{eff}	$u(y)$			
#	Component	Typ	Name	Dist	std_Fac	Sen	Unc	Std Unc	du/u	DF	eff DF	Std Unc	StdUnc^2	ui^4 /vi	
1	Calorimeter resistance	B		u	0.58	1	1000.0	580	0.50	2.0	2.0	580.00	336400.00	6E+10	See note
2	Calorimeter DC Power	B		u	0.58	1	1000.0	580.00	0.50	2.0	2.0	580.00	336400.00	6E+10	See note
3	Att. of Calorimeter input Lines	B		n	1	1	3000.0	3000.00	0.50	2.0	2.0	3000.00	9000000.00	4E+13	See note
4	RF-DC Current Distribution in Calorimeter	B		n	1	1	200.0	200.00	0.25	8.0	8.0	200.00	40000.00	2E+08	See note
5	Mismatch	B	Refl	n	1	1	25.0	25.0	0.25	8.0	8.0	25.00	625	5E+04	See note
6	Attenuation of Adaptor	B	Refl	n	1	1	3000.0	3000.0	0.25	8.0	8.0	3000.00	9000000	1E+13	See note
7	Transfer Standard repeatability (stability)	B	K2	n	1	1	1000.0	1000.0	0.25	8.0	8.0	1000.00	1000000.00	1E+11	See note
8	Transfer Standard / Calorimeter (disconnects)	A	K2	n	1	1	250.0	250.0	NA	4	4.0	250.00	62500.00	1E+09	See note
9	Transfer Standard / Calorimeter (readings)	A	K2	n	1	1	160.0	160.0	NA	4	4.0	160.00	25600.00	2E+08	See note
A	Transfer Standard / DUT (disconnects)	A		n	1	1	2600.0	2600.0	NA	4	4.0	2600.00	6760000.00	1E+13	See note
B	Transfer Standard / DUT (readings)	A		n	1	1	300.0	300.0	NA	3	3.0	300.00	90000.00	3E+09	See note
	column totals										ν_{eff}	U_c	26651525.00	6E+13	
	RSS Totals										11.4	5162.5			
	Thus a coverage factor of k=				2.20	is needed to obtain a 95% confidence									

Thus the expanded uncertainity U_c=k*u_c is given by U_c = 11362.6 with 11.4 degrees of freedom

and a coverage factor of k= ## which implies probability of 95% for the +/- U_c interval

#	Notes
1	Measurement of the DC input resistance of the calorimeter including the resistance of the connector
2	Measurement of the DC power to the calorimeter including the shunt resistor and transfer standard and bias tee series resistor
3	Attenuation of Calorimeter Input Lines at the frequency of measurement
4	RF-DC current distribution inside the calorimeter. At the measurement frequency vs at DC.
5	Based on the uncertainty on the Reflection Coefficients and source impedance.
6	Based on the uncertainty on the transmission of the adapter.
7	The repeatibility and the drift of the transfer standard over a medium period of time (Typical).
8	A series of five disconnects are done when the Calorimeter is applied on the Transfer standard
9	A set of 5 "OFF-ON-OFF" readings are done between the disconnects. This is the contribution to the total uncertainty
A	A series of five disconnects are done when the DUT is applied on the Transfer standard
B	A set of 4 "OFF-ON-OFF" readings are done between the disconnects. This is the contribution to the total uncertainty

SMU

Uncertainty budget for Thermistor mount sn. 2106A23878

Frequency : 10 MHz

	Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Sensitivity coefficient c_i	Uncertainty contribution $u_i(y)$
Stand.Cal. Factor	K_S	0.9735	0.0040	normal	1	0.002
Leveling, etc.	U_{lev}	1.000	0.0010	rectangular	1	0.0006
Stand. Mismatch	M_S	1.000	0.0075	U-shaped	1	0.0053
DUT Mismatch	M_M	1.000	0.0075	U-shaped	1	0.0053
Type A			0.0002	normal	1	0.0001
K_{DUT}		0.971				0.0156

Frequency : 18 GHz

	Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Sensitivity coefficient c_i	Uncertainty contribution $u_i(y)$
Stand.Cal. Factor	K_S	0.938	0.009	normal	1	0.0045
Leveling, etc.	U_{lev}	1.000	0.002	rectangular	1	0.00115
Stand. Mismatch	M_S	1.000	0.009	U-shaped	1	0.00636
DUT Mismatch	M_M	1.000	0.009	U-shaped	1	0.00636
Type A			0.0003	normal	1	0.00015
K_{DUT}		0.949				0.0203

SP

We use relative standard uncertainties. Therefore all sensitivity coefficients are unity and can be left out.

Source of relative uncertainty contribution	**Probability distribution**	**Relative standard uncertainty [%] for the frequency [GHz]**						
		0.05	1	4	8	12	15	18
Random errors at the calibration frequency	Normal	0.014	0.011	0.014	0.017	0.015	0.017	0.023
Calibration factor of the standard sensor	Normal	0.150	0.200	0.250	0.300	0.300	0.350	0.350
Drift in the standard sensor per year	Uniform	0.058	0.061	0.071	0.083	0.096	0.106	0.115
Mismatch at the calibration frequency	Normal	0.013	0.016	0.038	0.078	0.092	0.179	0.291
DC substituted power of the DUT	Normal	0.019	0.019	0.019	0.019	0.020	0.019	0.021
Read out of the monitor sensor when the DUT is connected	Uniform	0.063	0.063	0.063	0.063	0.063	0.063	0.063
Read out of the standard sensor	Uniform	0.063	0.063	0.063	0.063	0.063	0.063	0.063
Read out of the monitor sensor when the standard sensor is connected	Uniform	0.063	0.063	0.063	0.063	0.063	0.063	0.063
Random errors at the absolute calibration frequency	Normal	0.007	0.007	0.007	0.007	0.007	0.007	0.007
Calibration factor of the standard sensor at the absolute calibration frequency	Normal	0.150	0.150	0.150	0.150	0.150	0.150	0.150
Drift in the standard sensor at the absolute calibration frequency per year	Uniform	0.058	0.058	0.058	0.058	0.058	0.058	0.058
Read out of the standard sensor during absolute calibration	Uniform	0.063	0.063	0.063	0.063	0.063	0.063	0.063
Voltage measurement during absolute calibration	Normal	0.018	0.018	0.018	0.018	0.018	0.018	0.018
Mismatch at the absolute calibration frequency	Normal	0.010	0.010	0.010	0.010	0.010	0.010	0.010
Combined relative standard uncertainty	Normal	0.262	0.294	0.334	0.382	0.388	0.457	0.513

Table 1 Uncertainty budget for the sensor ID H48.2

Source of relative uncertainty contribution	**Prob-ability distri-bution**	**Relative standard uncertainty [%] for the frequency [GHz]**						
		0.05	1	4	8	12	15	18
Random errors at the calibration frequency	Normal	0.009	0.010	0.013	0.017	0.023	0.031	0.068
Calibration factor of the standard sensor	Normal	0.150	0.200	0.250	0.300	0.300	0.350	0.350
Drift in the standard sensor per year	Uniform	0.058	0.061	0.071	0.083	0.096	0.106	0.115
Mismatch at the calibration frequency	Normal	0.013	0.008	0.035	0.065	0.089	0.081	0.362
DC substituted power of the DUT	Normal	0.018	0.018	0.018	0.019	0.019	0.019	0.020
Read out of the monitor sensor when the DUT is connected	Uniform	0.063	0.063	0.063	0.063	0.063	0.063	0.063
Read out of the standard sensor	Uniform	0.063	0.063	0.063	0.063	0.063	0.063	0.063
Read out of the monitor sensor when the standard sensor is connected	Uniform	0.063	0.063	0.063	0.063	0.063	0.063	0.063
Random errors at the absolute calibration frequency	Normal	0.004	0.004	0.004	0.004	0.004	0.004	0.004
Calibration factor of the standard sensor at the absolute calibration frequency	Normal	0.150	0.150	0.150	0.150	0.150	0.150	0.150
Drift in the standard sensor at the absolute calibration frequency per year	Uniform	0.058	0.058	0.058	0.058	0.058	0.058	0.058
Read out of the standard sensor during absolute calibration	Uniform	0.063	0.063	0.063	0.063	0.063	0.063	0.063
Voltage measurement during absolute calibration	Normal	0.018	0.018	0.018	0.018	0.018	0.018	0.018
Mismatch at the absolute calibration frequency	Normal	0.010	0.010	0.010	0.010	0.010	0.010	0.010
Combined relative standard uncertainty	Normal	0.261	0.294	0.333	0.379	0.387	0.428	0.560

Table 2 Uncertainty budget for sensor ID H49.3 with adapter APC7 to type-N

APPENDIX E

Comparison protocol and schedule

E1) Technical Protocol

E2) Original Schedule

E3) Contact Persons

E1) Technical Protocol

Technical Protocol for Euromet project 633

Scope:
This project is a follow-up of Euromet project 393. In Euromet project 393 some problems were encountered and it was not immediately clear why these arose. Hence it was suggested to repeat the exercise with a small group of participants. In essence the same procedure will be followed as in Euromet 393 and its international extension CCEM.RF-K8.CL. In this way a firm link may be obtained with the two other comparisons.

Measuring quantity:
Power sensors are usually calibrated in terms of calibration factor. In most cases a reference frequency of 50 MHz is used to obtain the frequency dependence of a power sensor.
Thermistor mounts are considered to be the most fundamental power measuring device for traceability to the fundamental SI units. Therefore they are used as primary standards in most of the national standards laboratories. Also high level calibration laboratories use these devices as their highest internal standard.
The purpose of the exercise is to determine the level of consistency of calibration results as given by different national standards laboratories.
The main measuring quantity therefore is the calibration factor as determined at a number of prescribed frequencies, together with the appropiate uncertainty statement. Also the value of the reflection coefficient has to be determined, as it is, at least, necessary for the uncertainty calculation.

Travelling standards
A set of two thermistor mounts is used, one with an APC7 connector and the other with a type-N male connector. In case no facilities and/or traceability for APC7 connectors are available, an APC7-N adapter should be used to 'convert' the device under test. For this purpose such an adapter and an suitable torque wrench is supplied as well.
This means that effectively a set of three different sensors is sent for measurements:

1: travelling standard
- Hewlett Packard
- model 8478b Option H48
- sn. 2106 A 23878
- connector: Type-N male
- Ident: H48.2

2: travelling standard
- Hewlett Packard
- model 8478b
- sn. 3318 A 24991
- connector: APC7
- Ident: H49.3

3: : travelling standard
- Identical with travelling standard 2
- But including adapter c2-2
- Hence effective connector: Type-N male

Measurement procedure
As already indicated, the normal laboratory procedure for high level calibration of power sensors should be used. Hence, no attempt should be made to improve facilities just for this comparison.
Usually customers expect to be served within a couple of weeks. This is also the main reason for allowing a relative short turn-around time for the measurements.
The two (preferably three) travelling standards are to be calibrated, in the appropiate connector type. The measurement frequencies (in GHz) are: 0.010, 0.050, 1.00, 4.00, 8.00, 12.00, 15.00 and 18.00.
If it is possible, please determine the breaking torque of the wrench and report it as well.

Submission of results
Each laboratory is expected to submit its report to the coordinator within **6 weeks** after the end of its measuring period.
Anyway, the pilot laboratory needs sufficient information to make a first evaluation of the results before a general discussion can take place on the draft report as prepared by the pilot laboratory.

A breakdown of the uncertainty budget is an essential part of evaluating measurement results. According to the CIPM guidelines the ISO Guide on the Calculation of Uncertainties in Measurements (GUM) should be followed. A practical implementation of this document within the European Accreditation bodies is the EA-04/02 (1999) document. (this document is available on the EA website: www.european-accreditation.org).
The report should also contain at least a short description of the measurement set-up, preferably with some schematic drawing, the relevant statistical information on the individual measurement results and traceability chain.
An example of presenting a summary of the basic results is given in the table below.

Results of Euromet project 633				
Laboratory:				
Frequency [GHz]	Calibration factor	Uncertainty (k=1)	Reflection coefficient	Uncertainty in refl. coefficient (k=1)
0.01				
0.05				
1.00				
4.00				
8.00				
12.00				
15.00				
18.00				

Contributions to the uncertainty
In Euromet project 393 the following contributions were considered mainly to be responsible for the uncertainty in the determination of the calibration factor:
- reflection coefficient of the source
- reflection coefficient of the internal working standard
- reflection coefficient of the travelling standard
- uncertainty in the calibration factor of the internal working standard.

The term “internal working standard” is used here to describe the power sensor used directly in calibrating the travelling standards.
The BIPM Guideline, which is also used for Euromet comparisons with minor changes, requests an uncertainty evaluation at the level of one standard uncertainty, giving also the number of degrees of freedom.

Discussion of results
It is expected that an open discussion will take place as quickly as possible after distributing a draft report containing a compilation of the results and a first attempt of interpretation.
Afterwards the final result can be published in Metrologia (in short form) and preferably as a full paper in the open literature as well.

Problems during the exercise:

If technical and/or other problems arise, it is of the utmost importance to contact immediately the coordinator to discuss the matter and to inform the laboratory next in line about this fact. If the problem can not be solved within the allowed time frame, it will be necessary to adapt the schedule by shifting a few laboratories to a latter time slot.
It is assumed that the participating laboratory takes care of insurance of the package during the stay at the laboratory and the transportation to the next participant.

Transport and customs
The travelling standards can be sent using regular package mail. The devices (2 thermistors mounts) and the accessories (an adapter APC7-N(male) and a torque wrench) are stored in a plastic container, which is provided by the coordinator. Additional packaging as protection is suggested.
Inside the European Union no customs papers are necessary, but a pro-forma invoice is provided in case of questioning. For all participants outside the Union, an ATA-carnet will be provided, if applicable.

Circulation time schedule
The circulation schedule is agreed upon between the original participants.
Updates of the schedule will be sent when and where necessary. A turn-around time between laboratories of 3 weeks is used. It is the responsibility of each participating laboratory to inform the next participant in advance to arrange the transportation of the standards, and to inform the coordinator about the date of transportation.

The time schedule is as follows:

Institute	Measuring Period	Contact person
NPL	September 2001	Geoff Orford
IEN	October 2001	Luciano Brunetti
METAS	November 2001	Juerg Furrer
NMi VSL	December 2001	Jan de Vreede
NRC	January / February 2002	Alain Michaud
SMU	February / March 2002	Ivan Petras
SP	March / April 2002	Klas Yhland
NMi VSL	April / May 2002	Jan de Vreede

Coordinator
The pilot laboratory for this comparison is NMi Van Swinden Laboratorium (VSL). The coordinator for this comparison is:
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NMi Van Swinden Laboratorium
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P.O. Box 654
2600 AR Delft
The Netherlands

Telephone: +31 - 15 269 1500
Fax: +31 - 15 261 2971
E-mail: JdeVreede@nmi.nl

E2) Original Schedule

Period	Laboratory	Country
	Pilot The Netherlands	
September 2001	**NPL**	**UK**
October	**IENGF**	**Italy**
November	**METAS**	**Switzerland**
December 2001	**Pilot The Netherlands**	
January / February 2002	**NRC**	**Canada**
February / March	**SMU**	**Slovak Republic**
March / April	**SP**	**Sweden**
May 2002	**Pilot The Netherlands**	

E3) Contact Persons

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