CCEM.RF-S1.CL
(GTRF/02-03)
RF Power Measurements with 2.4 mm Connectors

Final Report

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1. Introduction

A comparison of RF power measurements at 8 frequencies was performed on two traveling standards at 9 national metrology laboratories. The motivation for the comparison was a desire to test measurements at the highest frequencies for which coaxial power calibration services are available. The 2.4 mm coaxial connectors on the standards have single mode operation up to 50 GHz. Although there have been two recent key comparisons for power measurements with coaxial connectors; CCEM.RF-K8.CL and CCEM.RF-K10.CL, there had not been a coaxial power comparison above 26 GHz. Therefore, a supplemental comparison with 2.4 mm connectors and a maximum frequency of 50 GHz was deemed an important test of existing standards.

The comparison was approved by the Working Group on Radio-Frequency Quantities (Groupe de Travail pour les Grandeurs aux Radiofrequences or GTRF) of the Consultative Committee for Electricity and Magnetism (Comite Consultatif d'Electricite et Magnetism or CCEM) in September 2002. Subsequently, BIPM guidelines were adopted stating that supplemental comparisons should be conducted by regional metrology organizations (RMO), and not by the CCEM. However, since the participants of this comparison come from a variety of regions, it was continued under the CCEM.

The participants represent the United States, the United Kingdom, the Netherlands, Switzerland, Canada, South Africa, Australia, Japan, and South Korea. The pilot laboratory was the National Institute of Standards and Technology (NIST) of the United States.

2. Participants and Schedule

The participants are indicated in Table 1 along with the dates when the standards were at their laboratory. All participants measured both standards. Three of the participants reported results from frequencies less than or equal to 40 GHz (6 of the 8 frequencies). All other participants measured all frequencies. In addition, 4 laboratories participated in an unofficial comparison at additional frequencies.

The participant list was modified after the comparison was approved to drop one laboratory that had initially expressed interest, but did not join. One other laboratory was added. Several participants were asked to move up their measurement periods as a result of these changes and all agreed. The schedule listed in the protocol in Appendix C reflects some, but not all of these changes. Contact information for several participants changed between the protocol and report stages. Table 1 shows the most recent information.

The comparison was performed in two loops with each participant given two months to complete their measurements and ship the standards to the next participant. An ATA Carnet was used for both loops. The customs documents were not processed properly on leaving the pilot laboratory's country at the start of the second loop. This resulted in a delay of about two months. The first participant in the loop (CSIR) performed their measurements very quickly which allowed the comparison to stay nearly on schedule.

No damage occurred to the traveling standards during the comparison. Two minor problems occurred with the auxiliary equipment that was circulated. A fuse blew out on the power meter when the switch for the line voltage was not set properly. One of the participants in the first loop noted that the 2.4 mm to Type N adapter used on the calibration output of the power meter had an off-center pin. A different adapter was used on the second loop.

3. Traveling Standards

The traveling standards consisted of two Agilent 8487A thermocouple power sensors. The device serial numbers are 3318A03629 and 3318A03815. They will be referred to as device 3629 and device 3815 respectively. A Hewlett Packard (now Agilent) 437B power meter was shipped with the traveling standards and all laboratories performed their measurements with this power meter. The operating frequency range of the sensors is 50 MHz to 50 GHz with a maximum power of 300 mW. They are controlled by the power meter which measures power relative to a reference power of 1 mW at 50 MHz. The sensors and power meter are shown in Figure 1.

National Metrology Institute	Acronym	Country	Contact	Date
National Institute of Standards and Technology	NIST 1	United States	Tom Crowley crowley@boulder.nist.gov	December 23, 2002 to January 15, 2003
National Physical Laboratory	NPL	United Kingdom	James Miall james.miall@npl.co.uk	February 3, 2003 to March 5, 2003
NMi Van Swinden Laboratorium	VSL	the Netherlands	Jan de Vreede jdevreede@nmi.nl	March 7, 2003 to April 29, 2003
Swiss Federal Office of Metrology and Accreditation	METAS	Switzerland	Juerg Furrer Juerg.Furrer@ metas.admin.ch	May 2, 2003 to June 19, 2003
National Research Council of Canada Institute for National Measurement Standards	INMS	Canada	Alain Michaud Alain.Michaud@ nrc-cnrc.gc.ca	June 26, 2003 to August 29, 2003
National Institute of Standards and Technology	NIST 2	United States		September 12, 2003 to November 13, 2003
CSIR-National Metrology Laboratory	CSIR	South Africa	Erik Dressler redressl@csir.co.za	January 15, 2004 to February 4, 2004
National Measurement Institute	NMIA	Australia	Tieren Zhang Tieren.Zhang@ measurement.gov.au	February 25, 2004 to April 2, 2004
National Metrology Institute of Japan	NMIJ	Japan	Kazuhiro Shimaoka kazuhiro-shimaoka@ aist.go.jp	April 9, 2004 to June 8, 2004
Korea Research Institute of Standards and Science	KRISS	South Korea	JeongHwan Kim kimjh@kriss.re.kr	June 14, 2004 to September 16, 2004
National Institute of Standards and Technology	NIST 3	United States		October 4, 2004 to November 23, 2004

Table 1. List of participants in CCEM.RF-S1.CL. The right hand column lists the dates on which the package initially arrived at the laboratory and its outgoing shipping date. The pilot laboratory is listed once for each measurement.

The calibration factor of the sensor relative to its 50 MHz value was measured by each laboratory. This quantity is expressed in equation (2) below. Calibration factor K is defined as the ratio of the power meter reading at a given frequency, P_{meter} to the incident RF power, P_{inc}, on the sensor

$$K(f) = \frac{P_{meter}(f)}{P_{inc}(f)}. \tag{1}$$

The value obtained for P_{meter} depends on the setting of the power meter electronics and is therefore arbitrary. The electronics are set using a calibration procedure in which a 50 MHz, 1 mW output signal from the power meter is used as a sensor input. The reported value for the comparison is the relative calibration factor,

$$K_{rel}(f) = \frac{K(f)}{K_{ref}} = \frac{P_{meter}(f)}{P_{inc}(f)} \frac{P_{inc,ref}}{P_{meter,ref}} \tag{2}$$

where the *ref* subscript indicates measurements made at the reference frequency of 50 MHz. Measurements were performed at the following frequencies: 2, 6, 18, 26.5, 33, 40, 45 and 50 GHz. Participants were instructed to use incident power levels of about 1 mW.

Figure 1. Power sensors and power meter used in the comparison. The upper right sensor is connected as for a reference calibration. The caliper opening in the foreground is 10 cm.

Participants were also instructed to:

1) make sure the power meter line voltage switches and fuse were set properly,

2) check the protrusion of the center conductor pin on both the power sensors and the laboratory test equipment before the measurements to prevent damage, and

3) attach the 2.4 mm connector with a torque wrench when connecting it to the measurement system. A torque of 0.90 N-m (8 in-lb) was recommended.

The traveling standards were characterized by the pilot laboratory in 100 MHz steps. The calibration factors and the reflection coefficient magnitudes are shown in Figure 2. The set of frequencies used in the comparison included points that were near dips in the calibration factor, but this does not appear to have produced any anomalous results.

4. Methods of Measurement

Figure 3 shows a generic drawing of a measurement setup typical of many participants. This type of measurement has been called a direct comparison system [1] or a power-splitter system. The combination of monitor and splitter/coupler is calibrated with the laboratory standard on port 2. The laboratory standard is then replaced with the traveling standard which is treated as an unknown device under test. Use of amplifiers depended on frequency and varied for different laboratories.

NIST used a resistive power splitter with no adapters for their measurements. NIST's standards were 2.4 mm thin film sensors calibrated in NIST's 2.4 mm microcalorimeter. Measurements were made at both output ports of the splitter and averaged.

METAS and CSIR also used resistive power splitters with no adapters. Their standards were Agilent 8487A sensors calibrated by NPL.

NMIA [2] used a resistive power splitter with adapters to two different laboratory standards. From 2 to 18 GHz, Type N thermistor sensors calibrated in NMIA's microcalorimeter were used while from 26.5 to 40 GHz, waveguide thermistor sensors calibrated at NIST were used.

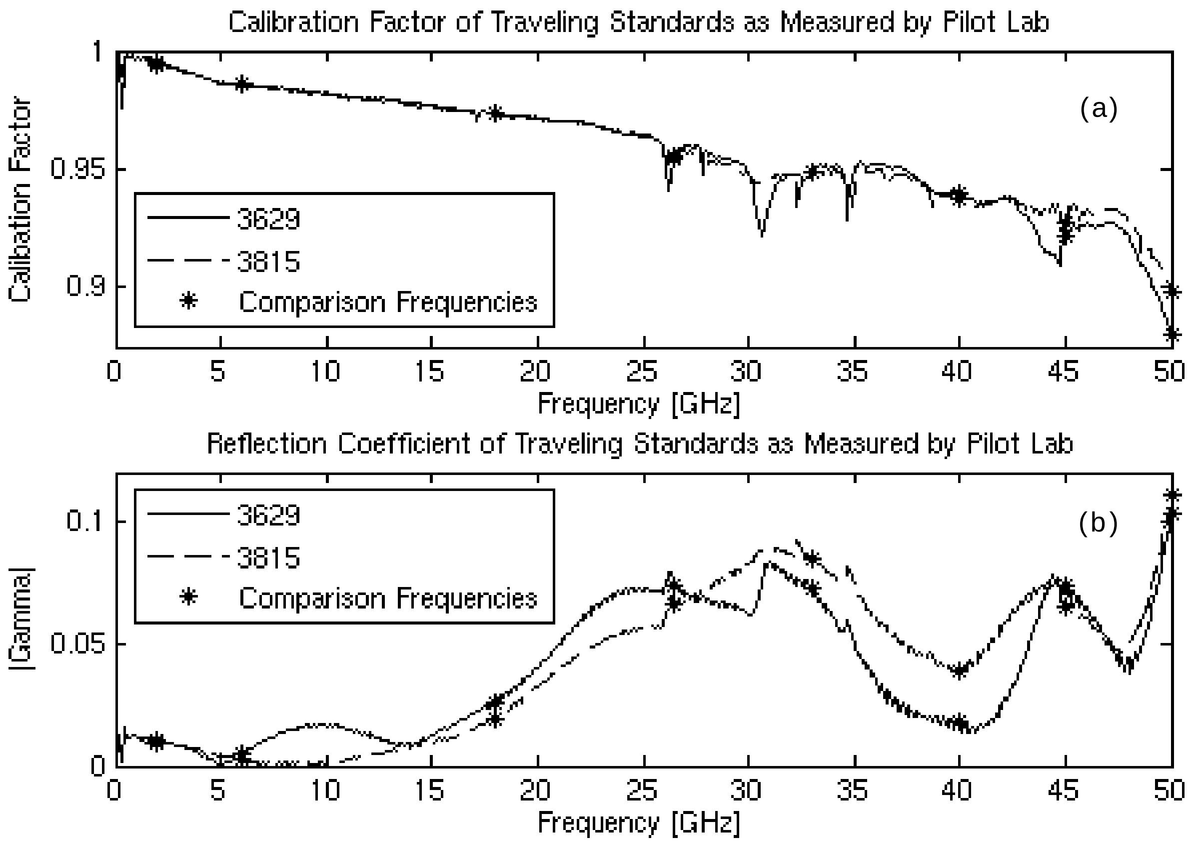

Figure 2 Average values of pilot lab measurements of the traveling standards. (a) calibration factor; (b) reflection coefficient magnitude. Comparison frequencies are highlighted using (*).

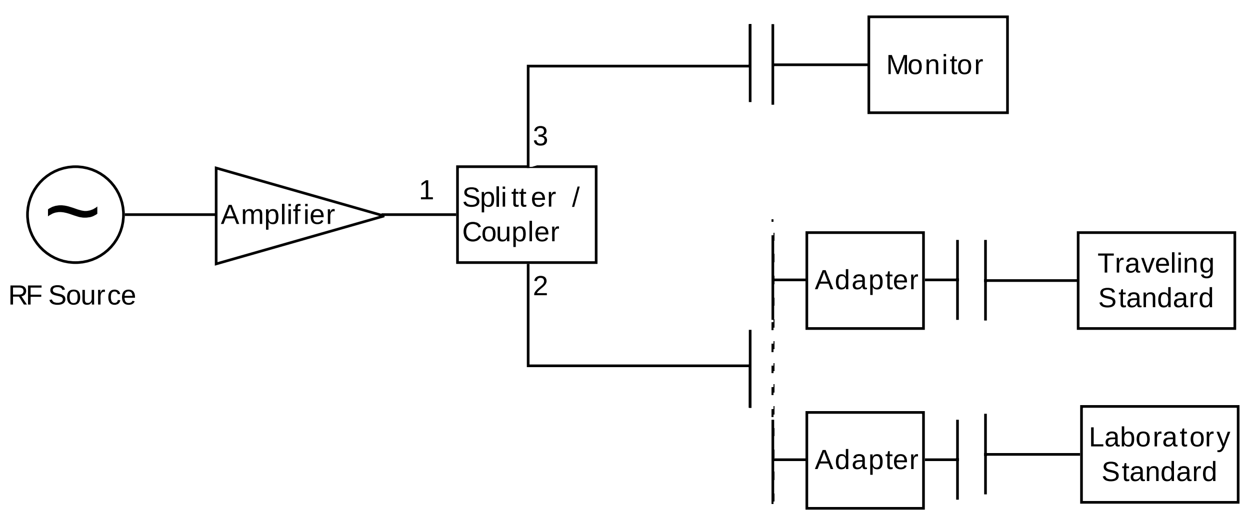

Figure 3 Generic drawing of a measurement setup common to many of the participants' measurements. Adapters and amplifiers were not used in all cases.

KRISS used a direct comparison system with 7 mm and waveguide laboratory standards. The laboratory standards were calibrated in microcalorimeters. Two standards were used at each frequency instead of one as shown in Figure 3. Adapters were placed on the traveling standards.

VSL made measurements with a resistive power splitter up to 40 GHz and a directional coupler above 40 GHz. No adapters were used. Their standard was calibrated by NPL.

NMIJ [3] used a dry type twin calorimeter for their measurements. A 2.92 mm coaxial power splitter divided the power between a monitor and one arm of the calorimeter. An adiabatic section (not shown in Figure 3) was between the power splitter and the measurement reference plane. An RF load and the traveling standard were then sequentially attached to the reference plane. An adapter was used between the traveling standards and the plane.

INMS explicitly treats the combination of coupler and monitor of Figure 3 as a transfer standard. The transfer standard is evaluated with a laboratory standard on port 2 of the coupler. At 2 and 6 GHz, hybrid couplers are used in the transfer standard and the laboratory standard is a 7 mm coaxial twin load calorimeter [4]. At the other frequencies, the transfer standards include waveguide directional couplers and the laboratory standards are waveguide thermistor mounts. The waveguide bands used were WR–62 (18 GHz), WR-42 (26.5 GHz), WR-28 (33 and 40 GHz), and WR-22 (45 and 50 GHz). The waveguide thermistor mounts were evaluated in a waveguide microcalorimeter [5]. Adapters were used with the traveling standard to match to port 2 of the transfer standard.

NPL used two separate methods. The first method was used at all frequencies and consisted of a resistive power splitter with a transfer standard calibrated against NPL's 2.4 mm dual dry load calorimeter. The second method is not illustrated by Figure 3. Waveguide multistate reflectometers with standards calibrated in NPL's waveguide microcalorimeters were used from 9 to 50 GHz. Calibrated adapters were used with the traveling standards. The calibration factor reported was the average of the two methods from 9 to 50 GHz.

5. Stability of the Traveling Standard

The transfer standards were measured at the pilot laboratory three times over the course of 23 months. At the frequencies used in this comparison, the maximum difference in calibration factor was 0.0078 at 45 GHz for device 3815. Only one other case had a difference greater than 0.004. Measurements made at additional frequencies also show that the vast majority of measurements differed by less than 0.004 and all changes were less than 0.01. The devices were assumed to be stable and no corrections were made for changes with time.

6. Measurement Results

The calibration factor, K_{rel}, and the standard uncertainties u_i, from all participants are shown in the Tables in Appendix A. Device 3629 is shown in Tables A.1 to A.3 while device 3815 is shown in Tables A.4 to A.6. Uncertainties are given as absolute values. Uncertainty budgets for the participants are shown in Appendix B.

The tables also show the reference value, $K_{reference}$, and its standard uncertainty at each frequency. $K_{reference}$ is the unweighted average of the independent laboratories' K_{rel} measurements. The pilot laboratory contribution to $K_{reference}$ was the average of its three measurements. Participants who traced their measurement to one of the other participants were excluded from this calculation. The original protocol stated that the reference would be the average of *all* measurements, but the method was changed so that the results would not be biased to a particular set of participants. The reason is that four of the participants trace at least some of their measurements through another participant and three of these trace back to the same laboratory. The average of all measurements was approximately 0.01 lower than $K_{reference}$ at 45 GHz and within 0.004 of $K_{reference}$ at all other frequencies. The standard uncertainty in $K_{reference}$ was calculated as:

$$u_{\langle K \rangle} = \frac{1}{N_{ind}} \sqrt{\sum_{1}^{N_{ind}} u_i^2} \qquad (3)$$

where the summation is over N_{ind} independent laboratories. The pilot laboratory's contribution to the sum was the average of its three u_i^2 values.

The tables show the difference,

$$D_i = K_{rel,i} - K_{reference} \qquad (4)$$

between each laboratory's measurement and $K_{reference}$. Figures 4 through 11 graphically display D_i and each participant's expanded (k=2) uncertainty error bars. D_i is less than $2u_i$ for every measurement indicating excellent agreement among the participants. Since this was a supplementary comparison, a degree of freedom analysis was not requested. Therefore, the confidence level cannot be calculated and in particular, it cannot be assumed that the error bars in the figures represent a 95% confidence limit.

The degrees of equivalence between each pair of labs was also calculated as

$$D_{ij} = K_{rel,i} - K_{rel,j} \qquad (5)$$

with an expanded uncertainty given by

$$U_{ij} = \sqrt{(2u_i)^2 + (2u_j)^2}\,. \qquad (6)$$

The maximum value of $|D_{ij}| / U_{ij}$ is less than 1.03 indicating good agreement between all participants. The full list of equivalences has not been included to save space.

7. Summary

The first comparison of power measurements above 26 GHz with coaxial connectors has been completed. All participants agree with the reference value within their expanded uncertainty indicating excellent agreement among the participants.

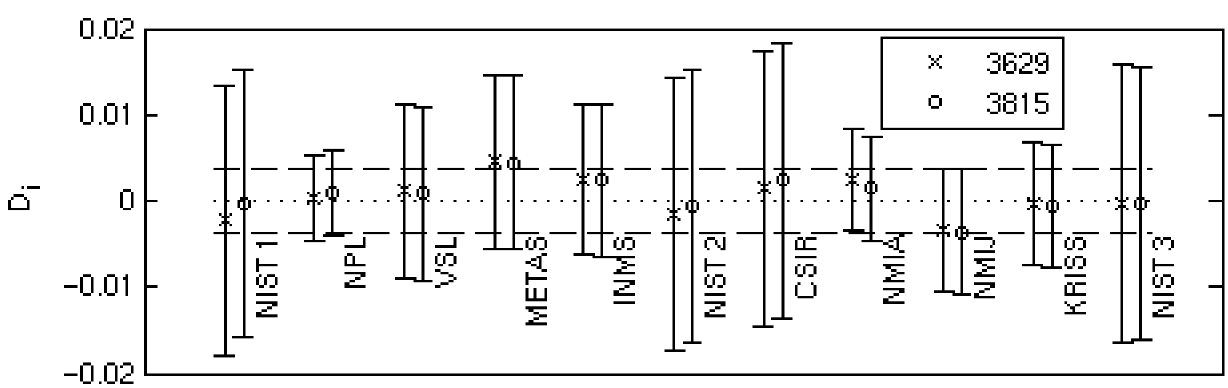

Figure 4 Difference between participant measurement and reference value at 2 GHz. Error bars indicate an expanded (k=2) uncertainty for the participant's measurement and dashed lined indicate the expanded (k=2) uncertainty of $K_{reference}$.

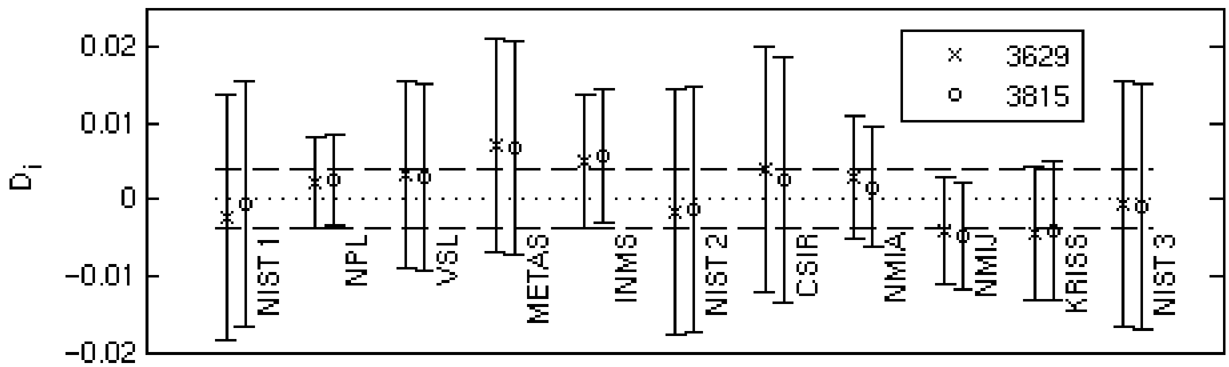

Figure 5 Difference between participant measurement and reference value at 6 GHz. Error bars indicate an expanded (k=2) uncertainty for the participant's measurement and dashed lined indicate the expanded (k=2) uncertainty of $K_{reference}$.

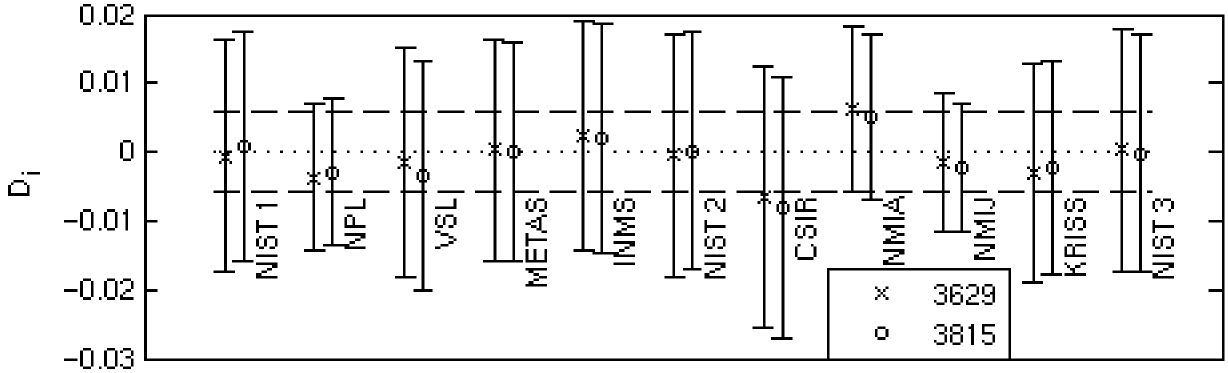

Figure 6 Difference between participant measurement and reference value at 18 GHz. Error bars indicate an expanded (k=2) uncertainty for the participant's measurement and dashed lined indicate the expanded (k=2) uncertainty of $K_{reference}$.

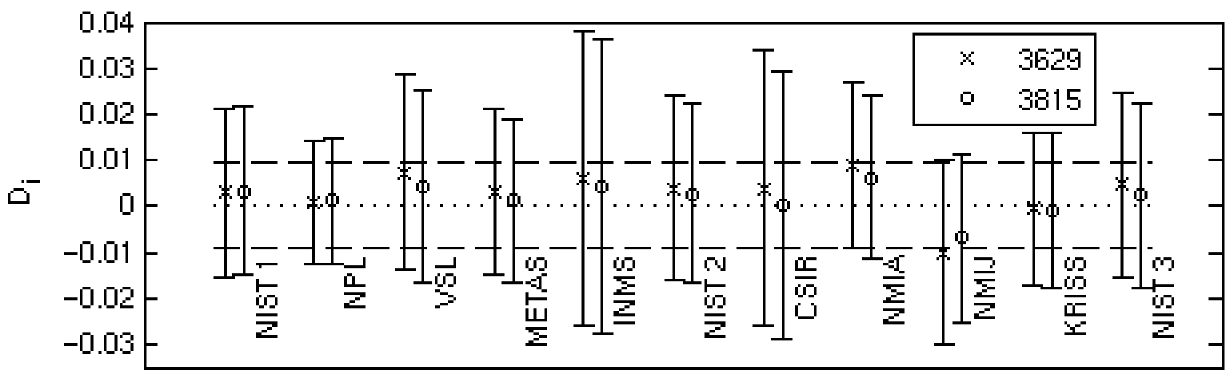

Figure 7 Difference between participant measurement and reference value at 26.5 GHz. Error bars indicate an expanded (k=2) uncertainty for the participant's measurement and dashed lined indicate the expanded (k=2) uncertainty of $K_{reference}$.

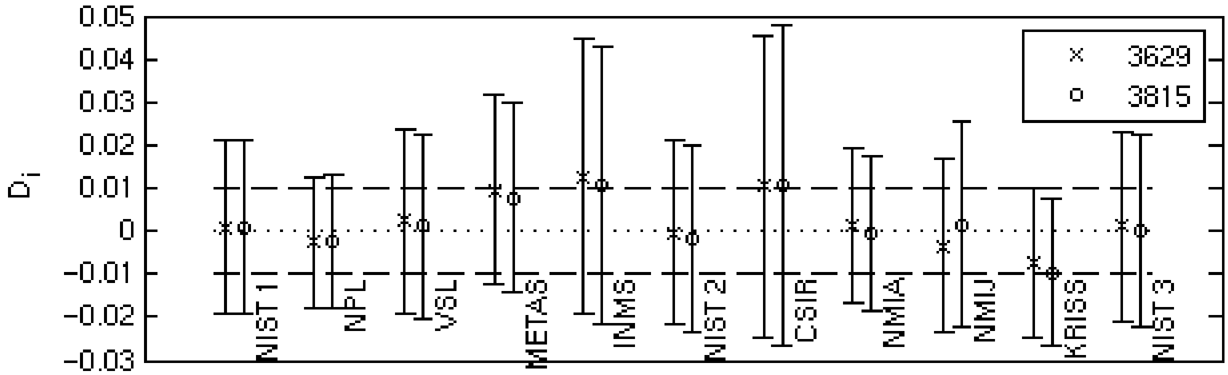

Figure 8 Difference between participant measurement and reference value at 33 GHz. Error bars indicate an expanded (k=2) uncertainty for the participant's measurement and dashed lined indicate the expanded (k=2) uncertainty of $K_{reference}$.

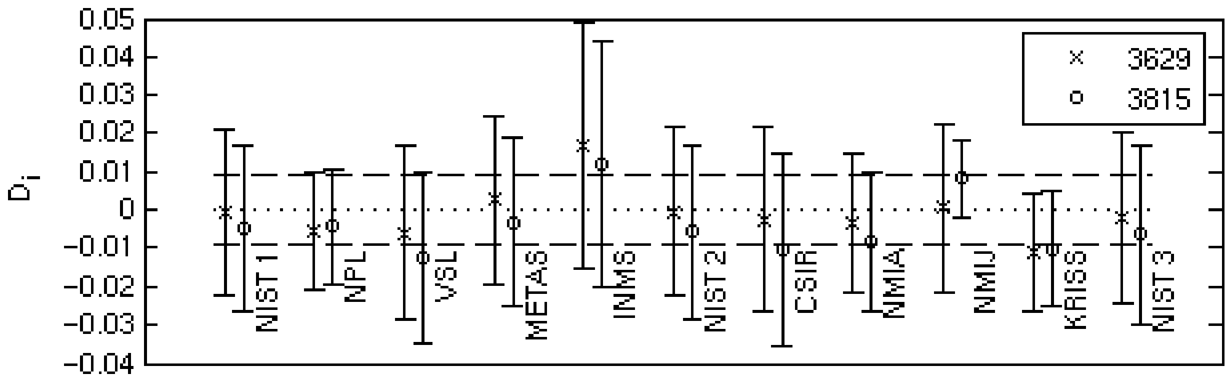

Figure 9 Difference between participant measurement and reference value at 40 GHz. Error bars indicate an expanded (k=2) uncertainty for the participant's measurement and dashed lined indicate the expanded (k=2) uncertainty of $K_{reference}$.

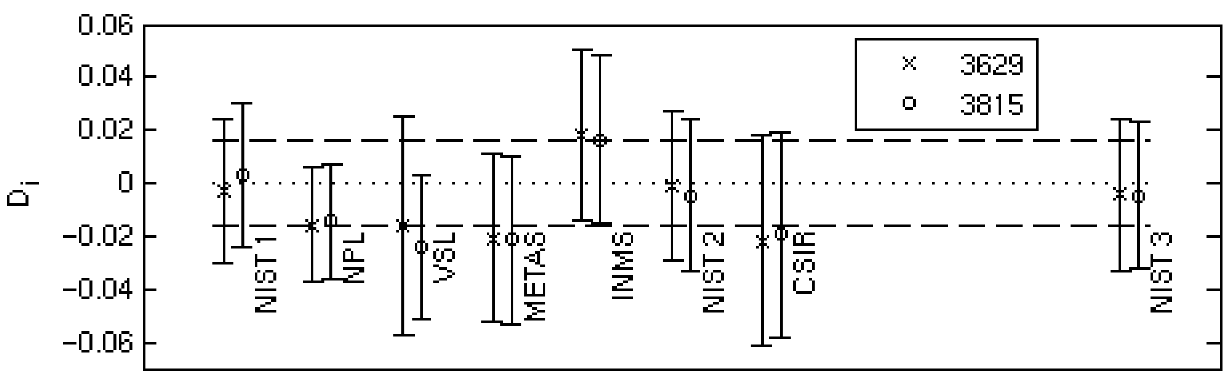

Figure 10 Difference between participant measurement and reference value at 45 GHz. Error bars indicate an expanded (k=2) uncertainty for the participant's measurement and dashed lined indicate the expanded (k=2) uncertainty of $K_{reference}$.

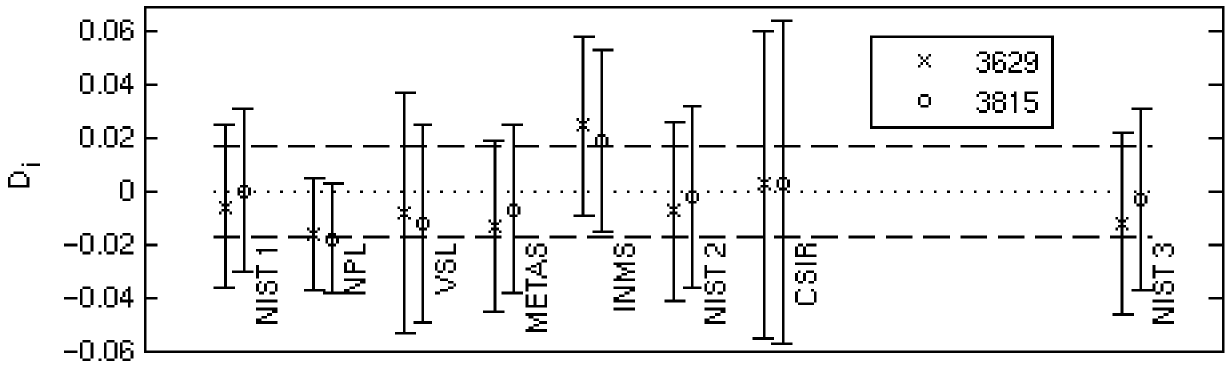

Figure 11 Difference between participant measurement and reference value at 50 GHz. Error bars indicate an expanded (*k*=2) uncertainty for the participant's measurement and dashed lined indicate the expanded (*k*=2) uncertainty of $K_{reference}$.

8. References

[1] John R. Juroshek, "NIST 0.05-50 GHz Direct-Comparison Power Calibration System", 2000 Conference on Precision Electromagnetic Measurements Digest, pp. 166-167, Sydney, Australia, 14-19 May 2000.

[2] Tieren Zhang, " A Novel Approach for Power Calibrations Using Power Splitters", 2004 Conference on Precision Electromagnetic Measurements Digest, pp. 111–112, London, England, 27 June -2 July 2004.

[3] Takemi Inoue and Kyouhei Yamamura, "A Broadband Power Meter Calibration System in the Frequency Range from 10 MHz to 40 GHz Using a Coaxial Calorimeter", IEEE Trans. on Instrum. Meas., Vol. 45, pp. 146-152, February, 1996.

[4] - A. Jurkus, "A Coaxial Calorimeter and Its Use as a Reference Standard in an Automated Microwave Power Standard", IEEE Trans. Instrum. Meas., vol IM-35, pp. 576-579, December 1986.

[5] - Richard F. Clark, "A Semiautomatic Calorimeter for Measurement of Effective Efficiency of Thermistor Mounts", IEEE Trans. Instrum. Meas. IM-23, pp. 403-408, December 1974.

Appendix A - Measurement Results

The tables below present the relative calibration factors K_{rel}, and standard (k=1) uncertainties u_i, reported by the participants. If the participants reported the uncertainty as a relative or percentage variation, it has been converted to an absolute value. Also shown is the difference D_i defined in equation (4), the reference value, $K_{reference}$, and its standard uncertainty.

Participant	2 GHz			6 GHz			18 GHz		
	Krel	*Di*	*ui*	*Krel*	*Di*	*ui*	*Krel*	*Di*	*ui*
NIST 1*	0.9932	-0.0023	0.0078	0.9846	-0.0025	0.0080	0.9731	-0.0006	0.0084
NPL*	0.9957	0.0002	0.0025	0.9892	0.0021	0.0030	0.9700	-0.0037	0.0053
VSL	0.9966	0.0011	0.0050	0.9904	0.0033	0.0061	0.9722	-0.0015	0.0083
METAS	1.0000	0.0045	0.0050	0.9940	0.0069	0.0070	0.9740	0.0003	0.0080
INMS*	0.9980	0.0025	0.0044	0.9920	0.0049	0.0044	0.9760	0.0023	0.0083
NIST 2*	0.9940	-0.0015	0.0079	0.9855	-0.0016	0.0080	0.9732	-0.0005	0.0088
CSIR	0.9970	0.0015	0.0080	0.9910	0.0039	0.0080	0.9670	-0.0067	0.0095
NMIA*	0.9980	0.0025	0.0030	0.9900	0.0029	0.0040	0.9800	0.0063	0.0060
NMIJ*	0.9920	-0.0035	0.0036	0.9831	-0.0040	0.0035	0.9721	-0.0016	0.0050
KRISS*	0.9951	-0.0004	0.0036	0.9827	-0.0044	0.0044	0.9706	-0.0031	0.0080
NIST 3*	0.9952	-0.0003	0.0080	0.9864	-0.0007	0.0080	0.9740	0.0003	0.0088
Kreference	0.9955		0.0018	0.9871		0.0020	0.9737		0.0029

Table A.1 Measurement results for device 3629 at 2, 6, and 18 GHz. Participants whose results were used to determine $K_{reference}$ are indicated by (*).

Participant	26.5 GHz			33 GHz			40 GHz		
	Krel	*Di*	*ui*	*Krel*	*Di*	*ui*	*Krel*	*Di*	*ui*
NIST 1*	0.9550	0.0029	0.0092	0.9494	0.0010	0.0100	0.9399	-0.0005	0.0107
NPL*	0.9530	0.0009	0.0067	0.9460	-0.0024	0.0076	0.9350	-0.0054	0.0076
VSL	0.9595	0.0074	0.0106	0.9508	0.0024	0.0107	0.9343	-0.0061	0.0113
METAS	0.9550	0.0029	0.0090	0.9580	0.0096	0.0110	0.9430	0.0026	0.0110
INMS*	0.9580	0.0059	0.0160	0.9610	0.0126	0.0160	0.9570	0.0166	0.0160
NIST 2*	0.9560	0.0039	0.0100	0.9482	-0.0002	0.0107	0.9401	-0.0003	0.0109
CSIR	0.9560	0.0039	0.0150	0.9590	0.0106	0.0175	0.9380	-0.0024	0.0120
NMIA	0.9610	0.0089	0.0089	0.9500	0.0016	0.0090	0.9370	-0.0034	0.0092
NMIJ*	0.9420	-0.0101	0.0100	0.9450	-0.0034	0.0100	0.9410	0.0006	0.0110
KRISS*	0.9516	-0.0005	0.0083	0.9412	-0.0072	0.0086	0.9295	-0.0109	0.0077
NIST 3*	0.9568	0.0047	0.0100	0.9495	0.0011	0.0109	0.9382	-0.0022	0.0112
Kreference	0.9521		0.0048	0.9484		0.0049	0.9404		0.0050

Table A.2 Measurement results for device 3629 at 26.5, 33, and 40 GHz. Participants whose results were used to determine $K_{reference}$ are indicated by (*).

Participant	45 GHz			50 GHz		
	Krel	*Di*	*ui*	*Krel*	*Di*	*ui*
NIST 1*	0.9220	-0.0027	0.0136	0.8824	-0.0058	0.0153
NPL*	0.9090	-0.0157	0.0108	0.8720	-0.0162	0.0104
VSL	0.9085	-0.0162	0.0205	0.8801	-0.0081	0.0225
METAS	0.9040	-0.0207	0.0160	0.8750	-0.0132	0.0160
INMS*	0.9430	0.0183	0.0160	0.9130	0.0248	0.0170
NIST 2*	0.9236	-0.0011	0.0143	0.8807	-0.0075	0.0169
CSIR	0.9030	-0.0217	0.0200	0.8910	0.0028	0.0290
NMIA						
NMIJ						
KRISS						
NIST 3*	0.9205	-0.0042	0.0143	0.8761	-0.0121	0.0169
Kreference	0.9247		0.0080	0.8882		0.0086

Table A.3 Measurement results for device 3629 at 45 and 50 GHz. Participants whose results were used to determine $K_{reference}$ are indicated by (*).

Participant	2 GHz			6 GHz			18 GHz		
	Krel	*Di*	*ui*	*Krel*	*Di*	*ui*	*Krel*	*Di*	*ui*
NIST 1*	0.9953	-0.0003	0.0078	0.9857	-0.0007	0.0080	0.9738	0.0009	0.0084
NPL*	0.9964	0.0008	0.0025	0.9889	0.0025	0.0030	0.9700	-0.0029	0.0053
VSL	0.9964	0.0008	0.0050	0.9893	0.0029	0.0061	0.9696	-0.0033	0.0083
METAS	1.0000	0.0044	0.0050	0.9930	0.0066	0.0070	0.9730	0.0001	0.0080
INMS*	0.9980	0.0024	0.0044	0.9920	0.0056	0.0044	0.9750	0.0021	0.0083
NIST 2*	0.9950	-0.0006	0.0079	0.9850	-0.0014	0.0080	0.9731	0.0002	0.0086
CSIR	0.9980	0.0024	0.0080	0.9890	0.0026	0.0080	0.9650	-0.0079	0.0095
NMIA*	0.9970	0.0014	0.0030	0.9880	0.0016	0.0040	0.9780	0.0051	0.0060
NMIJ*	0.9920	-0.0036	0.0036	0.9817	-0.0047	0.0035	0.9707	-0.0022	0.0047
KRISS*	0.9949	-0.0007	0.0036	0.9823	-0.0041	0.0045	0.9707	-0.0022	0.0078
NIST 3*	0.9952	-0.0004	0.0079	0.9854	-0.0010	0.0080	0.9727	-0.0002	0.0086
Kreference	0.9956		0.0018	0.9864		0.0020	0.9729		0.0028

Table A.4 Measurement results for device 3815 at 2, 6, and 18 GHz. Participants whose results were used to determine $K_{reference}$ are indicated by (*).

Participant	26.5 GHz			33 GHz			40 GHz		
	Krel	*Di*	*ui*	*Krel*	*Di*	*ui*	*Krel*	*Di*	*ui*
NIST 1*	0.9552	0.0033	0.0091	0.9494	0.0010	0.0100	0.9384	-0.0049	0.0107
NPL*	0.9530	0.0011	0.0067	0.9460	-0.0024	0.0076	0.9390	-0.0043	0.0076
VSL	0.9562	0.0043	0.0106	0.9495	0.0011	0.0106	0.9308	-0.0125	0.0112
METAS	0.9530	0.0011	0.0090	0.9560	0.0076	0.0110	0.9400	-0.0033	0.0110
INMS*	0.9560	0.0041	0.0160	0.9590	0.0106	0.0160	0.9550	0.0117	0.0160
NIST 2*	0.9547	0.0028	0.0098	0.9468	-0.0016	0.0109	0.9377	-0.0056	0.0113
CSIR	0.9520	0.0001	0.0145	0.9590	0.0106	0.0185	0.9330	-0.0103	0.0125
NMIA	0.9580	0.0061	0.0089	0.9480	-0.0004	0.0090	0.9350	-0.0083	0.0092
NMIJ*	0.9450	-0.0069	0.0091	0.9500	0.0016	0.0120	0.9516	0.0083	0.0050
KRISS*	0.9510	-0.0009	0.0085	0.9388	-0.0096	0.0086	0.9331	-0.0102	0.0075
NIST 3*	0.9542	0.0023	0.0100	0.9484	0.0000	0.0112	0.9369	-0.0064	0.0116
Kreference	0.9519		0.0047	0.9484		0.0051	0.9433		0.0046

Table A.5 Measurement results for device 3815 at 26.5, 33, and 40 GHz. Participants whose results were used to determine $K_{reference}$ are indicated by (*).

Participant	45 GHz			50 GHz		
	Krel	*Di*	*ui*	*Krel*	*Di*	*ui*
NIST 1*	0.9327	0.0032	0.0136	0.9002	0.0004	0.0154
NPL*	0.9150	-0.0145	0.0109	0.8820	-0.0178	0.0105
VSL	0.9051	-0.0244	0.0136	0.8880	-0.0118	0.0186
METAS	0.9080	-0.0215	0.0160	0.8930	-0.0068	0.0160
INMS*	0.9460	0.0165	0.0160	0.9190	0.0192	0.0170
NIST 2*	0.9250	-0.0045	0.0142	0.8979	-0.0019	0.0170
CSIR	0.9100	-0.0195	0.0195	0.9030	0.0032	0.0305
NMIA						
NMIJ						
KRISS						
NIST 3*	0.9249	-0.0046	0.0140	0.8968	-0.0030	0.0171
Kreference	0.9295		0.0080	0.8998		0.0086

Table A.6 Measurement results for device 3815 at 45 and 50 GHz. Participants whose results were used to determine $K_{reference}$ are indicated by (*).

Appendix B – Uncertainty Budgets

B.1 – Overview

Uncertainty Budgets for each of the participants are included in this appendix. The format is generally close to that submitted by the participant. If separate budgets were submitted for each frequency, only those for 2 and 40 GHz are enclosed. Similarly, if separate budgets were included for devices 3629 and 3815, then only 3629 is shown.

B.2 – NIST Uncertainty Budget

This budget is from the first set of measurements performed at NIST.

Source of Uncertainty	Type	Frequency [GHz]							
		2	6	18	26.5	33	40	45	50
Bolometric Standard	B	0.0034	0.0038	0.0046	0.0053	0.0063	0.0081	0.0100	0.0125
Mismatch	B	0.0001	0.0001	0.0007	0.0027	0.0033	0.0012	0.0061	0.0053
Power Meter	B	0.0069	0.0069	0.0069	0.0069	0.0069	0.0069	0.0069	0.0069
Electronics	A	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010
Repeatability	A	0.0006	0.0005	0.0003	0.0004	0.0002	0.0004	0.0008	0.0005
Combined (k=1)		0.0078	0.0080	0.0084	0.0092	0.0100	0.0107	0.0136	0.0153

Table B.2 NIST uncertainty budget for device 3629 at all frequencies.

B.3 – NPL Uncertainty Budget

Uncertainty budgets for both methods are enclosed. The standard uncertainty submitted for the comparison was the lower of the two methods.

Source of Uncertainty	Type	Standard uncertainty % for frequency GHz								
		2	6	12	18	26.5	33	40	45	50
Transfer Standard calibration	B	0.20	0.29	0.39	0.50	0.64	0.74	0.64	1.04	1.04
DUT ratio linearity	B	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Transfer Standard ratio linearity	B	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Mismatch at 50 MHz	B	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Mismatch at Calibration Frequency	B	0.01	0.02	0.05	0.07	0.10	0.20	0.10	0.50	0.50
Connector repeatability	A	0.02	0.02	0.02	0.02	0.05	0.05	0.05	0.10	0.10
Combined Standard Uncertainty		0.25	0.30	0.40	0.55	0.70	0.80	0.70	1.20	1.20

Table B.3.1 NPL uncertainty budget at all frequencies for method 1 based on a coaxial transfer standard.

Source of Uncertainty	Type	Standard uncertainty % for frequency GHz						
		12	18	26.5	33	40	45	50
Multistate Reflectometer	B	0.4	0.4	0.5	0.6	0.6	1.0	1.0
DC voltage measurements	B	0.05	0.05	0.05	0.05	0.05	0.05	0.05
50 MHz reference	B	0.15	0.15	.015	.015	.015	0.15	0.15
Adaptor Loss	B	0.5	0.5	0.5	0.5	0.5	0.6	0.6
Mismatch	B	0.05	0.05	0.1	0.1	0.1	0.1	0.1
Connector repeatability	A	0.05	0.05	0.05	0.07	0.07	0.1	0.1
Combined Standard Uncertainty		0.66	0.66	0.73	0.81	0.81	1.19	1.19

Table B.3.2 NPL uncertainty budget at all frequencies for method 2 based on a waveguide multistate reflectometer.

B.4 VSL Uncertainty Budget

The basic formula for obtaining the calibration factor K_x of the DUT is

$$K_x = (K_s + \delta K_s) * \frac{M_x}{M_s} * p * p_{C,r} * p_{C,C}$$

with K_s = calibration factor referred to 50 MHz of the standard

δK_s = change in calibration factor K_s due to drift

M_s = mismatch factor of the standard at the calibration frequency f_c

M_x = mismatch factor of the DUT at the calibration frequency f_c

p_{Cr} = correction of the observed ratio for non-linearity and limited resolution of the power ratio level at the reference frequency of 50 MHz

p_{Cc} = correction of the observed ratio for non-linearity and limited resolution of the power ratio level at the calibration frequency f_c

Quantity	Value	Stated uncertainty	Evaluation method	k=	Standard uncertainty	Sensitivity	Contr. To Unc.	Degrees of freedom
Ks	0.996	0.007	B	2	0.0035	1.0006	0.0035	100
dKs	0.0000	0.0020	B	1	0.0020	1.0006	0.0020	100
Ms	1.0000	0.0020	B	1	0.0020	0.9966	0.0020	100
Mx	1.0000	0.0020	B	1	0.0020	-0.9966	-0.0020	100
pcr	1.0000	0.0001	B	1	0.0001	0.9999	0.0001	100
pcc	1.0000	0.0001	B	1	0.0001	0.9999	0.0001	100
p	1.0006	0.0007	A	1	0.0007	0.9993	0.0007	5
Kx	**0.9966**					**k=1**	**0.0050**	**301**

Table B.4.1 VSL uncertainty budget at 2 GHz for device 3629

Quantity	Value	Stated uncertainty	Evaluation method	k=	Standard uncertainty	Sensitivity	Contr. To Unc.	Degrees of freedom
Ks	0.93	0.021	B	2	0.0105	1.0047	0.0105	100
dKs	0.0000	0.0020	B	1	0.0020	1.0047	0.0020	100
Ms	1.0018	0.0020	B	1	0.0020	0.9327	0.0019	100
Mx	1.0004	0.0020	B	1	0.0020	-0.9340	-0.0019	100
pcr	1.0000	0.0001	B	1	0.0001	0.9999	0.0001	100
pcc	1.0000	0.0001	B	1	0.0001	0.9999	0.0001	100
p	1.0032	0.0022	A	1	0.0022	0.9967	0.0022	5
Kx	**0.9343**					**k=1**	**0.0113**	**125**

Table B.4.2 VSL uncertainty budget at 40 GHz for device 3629

B.5 METAS Uncertainty Budget

Uncertainty Budget GT-RF-S1.CL	One Standard Deviation (k = 1)			**Frequency: 50 GHz**
Power Sensor 1 (Agilent 8487A thermocouple, sn 3318A03629, NIST 929823)				
Source of Uncertainty	Type	Probab.Distrib.	Sensit.Coeff.	Uncertainty contribution
Power Standard Calibration Factor (NPL, 1/2000)	B	normal	≈ 1	0.0150
Aging of Power Standard Calibration Factor	B	rectangular	≈ 1	0.0015
Powermeter Instrumentation, 50 MHz Calibration	B	rectangular	≈ 1	0.0017
Mismatch-Uncertainty	B	U-shaped	≈ 1	0.0018
Connector Repeatability Standard	A	normal	≈ 1	0.0029
Connector Repeatability DUT	A	normal	≈ 1	0.0020
	Combined Standard Uncertainty =			0.0157

Table B.5.1 METAS' detailed uncertainty budget for 50 GHz for device 3629.

Uncertainty Budget GT-RF-S1.CL	**Power Sensor 1 (8487A, sn 3318A03629, NIST 929823)**							
Frequency:	2	6	18	26.5	33	40	45	50
Source of Uncertainty	Unc. Contrib.	Unc. Contrib.	Unc. Contrib.	Unc. Contrib.	Unc. Contrib.	Unc. Contrib.	Unc. Contrib.	Unc. Contrib.
Power Standard Calibration Factor	0.0040	0.0060	0.0070	0.0075	0.0105	0.0105	0.0150	0.0150
Aging of Power Standard CalFac	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015
Powermeter Instrumentation, 50 MHz Calibration	0.0017	0.0017	0.0017	0.0017	0.0017	0.0017	0.0017	0.0017
Mismatch-Uncertainty	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018
Connector Repeatability Standard	0.0001	0.0001	0.0001	0.0001	0.0002	0.0003	0.0017	0.0029
Connector Repeatability DUT	0.0002	0.0002	0.0002	0.0001	0.0002	0.0004	0.0003	0.0020
Combined Standard Uncertainty (One Standard Deviation)	0.0050	0.0067	0.0076	0.0080	0.0109	0.0109	0.0154	0.0157

Table B.5.2 METAS uncertainty budget at 8 frequencies for device 3629

B.6 INMS Uncertainty Budget

	International Comparison GT-RF.S1.CL: NRC / INMS Measurement Report														
	Uncertainity Budget of the 2 GHz Measurement														
	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	Type	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	2000.0	2000.00	0.50	2.0	2.0	2000.00	4000000.00	8E+12	See note
4	RF-DC Current Distribution in Calorimeter	B		n	1	1	150.0	150.00	0.50	2.0	2.0	150.00	22500.00	3E+08	See note
5	Mismatch	B		n	1	1	500.0	500.0	0.25	30.0	30.0	500.00	250000	2E+09	See note
6	Attenuation of Adaptor	B		u	0.58	1	4000.0	2320.0	0.50	2.0	2.0	2320.00	5382400	1E+13	See note
7	Transfer Standard repeatability (stability)	B		n	1	1	1500.0	1500.0	0.25	3.0	3.0	1500.00	2250000.00	2E+12	See note
8	Transfer Standard / Calorimeter (disconnects)	A		n	1	1	500.0	500.0	NA	4	4.0	500.00	250000.00	2E+10	See note
9	Transfer Standard / Calorimeter (readings)	A		n	1	1	200.0	200.0	NA	4	4.0	200.00	40000.00	4E+08	See note
A	Transfer Standard / DUT (disconnects)	A		n	1	1	500.0	500.0	NA	3	3.0	500.00	250000.00	2E+10	See note
B	Transfer Standard / DUT (readings)	A		n	1	1	200.0	200.0	NA	3	3.0	200.00	40000.00	5E+08	See note
C	"Normalization"	B		n	1	1	2500.0	2500.0	0.20	12.5	12.5	2500.00	6250000.00	3E+12	See note
	column totals										ν_{eff}	U_c	19407700.00	3E+13	
	RSS Totals										13.7	4405.4			
	Thus a coverage factor of k=				2.16	is needed to obtain a 95% confidence									
	Thus the expanded uncertainty U_c=k*u_c is given by								U_c =	9517	with	13.7	degrees of freedom		
	and a coverage factor of k=					2.2	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 repeatability and the drift of the transfer standard over a medium period of time.
8	A series of five disconnects are done when the Calorimeter is applied on the Transfer standard
9	A set of 6 "OFF-ON-OFF" readings are done between the disconnects. This is the contribution to the total uncertainty
A	A series of 4 disconnects are done when the DUT is applied on the Transfer standard
B	A set of 16 "OFF-ON-OFF" readings are done between the disconnects. This is the contribution to the total uncertainty
C	This is the "normalization" factor in equation 2 of the protocol

Table B.6.1 INMS uncertainty Budget at 2 GHz.

International Comparison GT-RF.S1.CL: NRC / INMS Measurement Report

Uncertainity Budget of the 40 GHz Measurement

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	NORMALIZATION	B		n	1	1	2500.0	2500.00	0.20	12.5	12.5	2500.00	6250000.00	3E+12	See note
2	Calorimeter DC Power	B		u	0.58	1	20000.0	11600.00	0.50	2.0	2.0	11600.00	134560000.00	9E+15	See note
3	BLANK	B		n	1	1	0.0	0.00	0.50	2.0	2.0	0.00	0.00	0E+00	See note
4	BLANK	B		n	1	1	0.0	0.00	0.25	8.0	8.0	0.00	0.00	0E+00	See note
5	Mismatch	B	Refl	n	1	1	2000.0	2000.0	0.25	30.0	30.0	2000.00	4000000	5E+11	See note
6	Attenuation of Adaptor	B	Refl	n	1	1	10000.0	10000.0	0.25	8.0	8.0	10000.00	100000000	1E+15	See note
7	Transfer Standard repeatability (stability)	B		n	1	1	2000.0	2000.0	0.25	3.0	3.0	2000.00	4000000.00	5E+12	See note
8	Transfer Standard / Calorimeter (disconnects)	A		n	1	1	2000.0	2000.0	NA	4	4.0	2000.00	4000000.00	4E+12	See note
9	Transfer Standard / Calorimeter (readings)	A		n	1	1	200.0	200.0	NA	4	4.0	200.00	40000.00	4E+08	See note
A	Transfer Standard / DUT (disconnects)	A		n	1	1	1500.0	1500.0	NA	4	4.0	1500.00	2250000.00	1E+12	See note
B	Transfer Standard / DUT (readings)	A		n	1	1	200.0	200.0	NA	24	24.0	200.00	40000.00	7E+07	See note
	column totals										ν_{eff}	U_c	255140000.00	1E+16	
	RSS Totals										6.3	15973.1			

Thus a coverage factor of k= 2.45 is needed to obtain a 95% confidence

Thus the expanded uncertainity U_c=k*u_c is given by U_c = 39085 with 6.3 degrees of freedom

and a coverage factor of k= 2.4 which implies probability of 95% for the +/- U_c interval

#	Notes
1	This is the "normalization" factor in equation 2 of the protocol
2	Measurement of the DC power to the calorimeter including the shunt resistor and transfer standard and bias tee series resistor
3	
4	
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.
8	A series of five disconnects are done when the "Calorimeter mount" 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 6 disconnects are done when the DUT is applied on the Transfer standard
B	A set of 10 "OFF-ON-OFF" readings are done between the disconnects. This is the contribution to the total uncertainty

Table B.6.2 INMS uncertainty Budget at 40 GHz.

B.7 CSIR Uncertainty Budget

UNCERTAINTY BUDGET MATRIX (UBM)

Certificate No	
Procedure No	

References: ISO/TAG4 Guide to the Expression of Uncertainty in Measurement 1993 (BIPM, IEC, IFCC, ISO, IUPAC, IUPAP, OIML), EAL R2, NLA TG-3001

Description:	Power sensor (2,4 mm)	Type & Serial No	HP 8487A NIST 23	Range:	2 GHz	Metrologist: Erik

Formula:

Symbol	Source of Uncertainty	Relative Uncertainty Value U(Xi) +/-			Absolute Uncertainty Value U(Xi)	Probability Distribution (N, R, T, U)	Divisor factor	Sensitivity Coefficient C_i	Relative Uncertainty Contribution U_i (y) +/-		Absolute Uncertainty Contribution U_i (y)	Reliability (%)	1/v	Degrees of Freedom v	Remarks
	Standards and Reference Equipment (Uncorrelated)								%	+	Unit				
B1	Std. Sensor	0.9000	%	+		Normal k=2	2.00	1	0.4500	+	0.0	100	0.000	infinite	NPL cert. No. EG 04/01/061
B2	Drift since last cal	0.2000	%	+		Rectangular 3	1.73	1	0.1155	+	0.0	90	0.02	50	
B3	Power meter (RSS of two)	0.7000	%	+		Rectangular 3	1.73	1	0.4041	+	0.0	100	0.00	infinite	
				+		U-Shaped		1		+		90			TYPICAL CASE
B5	MISMATCH (REF) at 2 GHz	0.1000	%	+		U-Shaped	1.41	1	0.0707	+	0.0	90	0.02	50	TYPICAL CASE
B6	MISMATCH (MON) 50 MHz	0.1	%	+		U-Shaped	1.41	1	0.0707	+	0.0	90	0.02	50	
B7	MISMATCH (REF) 50 MHz	0.1	%	+		U-Shaped	1.41	1	0.1	+	0.0	90	0.02	50	
				+						+					
				+						+					
				+						+					
				+						+					
				+						+					
	Standards and Reference Equipment (Correlated)										*ONLY CHANGE CELLS IN BLUE*				
				+						+					
				+						+					
				+						+					
				+						+					
	Unit Under Test / Calibration (Uncorrelated)										*ONLY CHANGE CELLS IN BLUE*				
B3	Power meter (RSS of two)	0.7000	%	+		Rectangular 3	1.73	1	0.4041	+	0.0	100	0.00	infinite	
B4	MISMATCH (DUT) 2 GHz	0.1000	%	+		U-Shaped	1.41	1	0.0707	+	0.0	90	0.02	50	
B6	MISMATCH (DUT) 50 MHz	0.1	%	+		U-Shaped	1.41	1	0.1	+	0.0	90	0.02	50	
B6	MISMATCH (MON) 50 MHz	0.1	%	+		U-Shaped	1.41	1	0.1	+	0.0	90	0.02	50	
A1	Repeatability (Type "A" Calculation)	0.2000	%	+		Normal k=1	1.00	1	0.2000	+			0.5000	2	No of Readings 3
	Unit Under Test / Calibration (Correlated)										*ONLY CHANGE CELLS IN BLUE*				
				+						+					
				+						+					
				+						+					
	UNCERTAINTY BUDGET for (K=2)								%		Unit				
	Best Measurement Capability (Excluding UUT contribution)					Combined Uncertainty (Normal)			0.63	+	0.0	V_{eff}		30732	Checked and Approved By:
						Expanded Uncertainty			1.26	+	0.0	k =		2.00	
	Uncertainty of Measurement					Combined Uncertainty (Normal)			0.78	+	0.0	V_{eff}		465	
						Expanded Uncertainty			1.57	+	0.0	k =		2.00	

Table B.7.1 CSIR uncertainty budget for device 3629 at 2 GHz.

UNCERTAINTY BUDGET MATRIX (UBM)

Certificate No	
Procedure No	

References: ISO/TAG4 Guide to the Expression of Uncertainty in Measurement 1993 (BIPM, IEC, IFCC, ISO, IUPAC, IUPAP, OIML), EAL R2, NLA TG-3001

Description:	Power sensor (2,4 mm)	Type & Serial No	HP 8487A	Range:	40 GHz	Metrologist: Erik

Formula:

Symbol	Source of Uncertainty	Relative Uncertainty Value U(Xi) +/-		+	Absolute Uncertainty Value U(Xi)	Probability Distribution (N, R, T, U)	Divisor factor	Sensitivity Coefficient C_i	Relative Uncertainty Contribution U_i (y) +/-	+	Absolute Uncertainty Contribution U_i (y)	Reliability (%)	1/v	Degrees of Freedom v	Remarks
	Standards and Reference Equipment (Uncorrelated)								%	+	Unit				
B1	Std. Sensor	2.0000	%	+		Normal k=2	2.00	1	1.0000	+	0.0	100	0.000	infinite	NPL cert. No. EG.04/01/061
B2	Drift since last cal	0.2000	%	+		Rectangular 3	1.73	1	0.1155	+	0.0	90	0.02	50	
B3	Power meter (RSS of two)	0.7000	%	+		Rectangular 3	1.73	1	0.4041	+	0.0	100	0.00	infinite	
				+		U-Shaped		1		+		90			TYPICAL CASE
B5	MISMATCH (REF) at 40 GHz	0.5100	%	+		U-Shaped	1.41	1	0.3606	+	0.0	90	0.02	50	TYPICAL CASE
B6	MISMATCH (MON) 50 MHz	0.1	%	+		U-Shaped	1.41	1	0.0707	+	0.0	90	0.02	50	
B7	MISMATCH (REF) 50 MHz	0.1	%	+		U-Shaped	1.41	1	0.1	+	0.0	90	0.02	50	
				+						+					
				+						+					
				+						+					
				+						+					
				+						+					
	Standards and Reference Equipment (Correlated)								***ONLY CHANGE CELLS IN BLUE***						
				+						+					
				+						+					
				+						+					
				+						+					
	Unit Under Test / Calibration (Uncorrelated)								***ONLY CHANGE CELLS IN BLUE***						
B3	Power meter (RSS of two)	0.7000	%	+		Rectangular 3	1.73	1	0.4041	+	0.0	100	0.00	infinite	
B4	MISMATCH (DUT) 40 GHz	0.5800	%	+		U-Shaped	1.41	1	0.4101	+	0.0	90	0.02	50	
B6	MISMATCH (DUT) 50 MHz	0.1	%	+		U-Shaped	1.41	1	0.1	+	0.0	90	0.02	50	
B6	MISMATCH (MON) 50 MHz	0.1	%	+		U-Shaped	1.41	1	0.1	+	0.0	90	0.02	50	
A1	Repeatability (Type "A" Calculation)	0.2000	%	+		Normal k=1	1.00	1	0.2000	+			0.5000	2	No of Readings 3
	Unit Under Test / Calibration (Correlated)								***ONLY CHANGE CELLS IN BLUE***						
				+						+					
				+						+					
				+						+					
	UNCERTAINTY BUDGET for (K=2)								%		Unit				

Best Measurement Capability (<u>Excluding</u> UUT contribution)	Combined Uncertainty (Normal)	1.15	+	0.0	V_{eff}	5057	Checked and Approved By:
	Expanded Uncertainty	2.29	+	0.0	k =	2.00	
Uncertainty of Measurement	Combined Uncertainty (Normal)	1.30	+	0.0	V_{eff}	1687	
	Expanded Uncertainty	2.61	+	0.0	k =	2.00	

Table B.7.2 CSIR uncertainty budget for device 3629 at 40 GHz.

B.8 – NMIA Uncertainty Budget

In the uncertainty budget below:
uref is the uncertainty of the calibration factor of the reference thermistor mounts;
uadp is the uncertainty associated with the adaptor measurement;
upm is the uncertainty attributed to measuring the ratio of indicated powers;
uopt is the uncertainty attributed to measuring the output tracking of the splitter;
ueqMisMatch is the equivalent mismatch uncertainty;
ucon is the type A uncertainty associated with repeated measurements, including connector repeatability;
ucomb is the combined standard uncertainty and is the RSS value of all the above components (k=1).

Frequency (GHz)	u_{ref} Type B	u_{adp} Type A,B	u_{pm} Type A,B	u_{opt} Type A,B	$u_{eqMisMatch}$ Type B	u_{con} Type A	u_{comb}
2	0.0015	0.0022	0.0009	0.0006	0.00021	0.0008	0.0030
6	0.0020	0.0030	0.0009	0.0011	0.00024	0.0009	0.0040
18	0.0035	0.0040	0.0009	0.0024	0.00031	0.0010	0.0060
26.5	0.0056	0.0060	0.0012	0.0029	0.00041	0.0011	0.0089
33	0.0056	0.0062	0.0012	0.0030	0.00043	0.0012	0.0090
40	0.0056	0.0064	0.0012	0.0031	0.00045	0.0014	0.0092

Table B.8 NMIA uncertainty budget at all frequencies.

B.9 – NMIJ Uncertainty Budget

GT-RF.S1.CL	Type	SER No.
Power sensor	8487A	3318A03629
PC2.4(f) to PC2.9(m) adapter	11904S	5452
Power meter	437B	2949A02751
Type N(m) to PC2.4(f) adapter	-	NIST 002

Frequency (GHz)	2

Uncertainty of calibration factor with adapter $u_c(K_u)$

Standard uncertainty component	Estimate of the value of measurand	Unit	Source of uncertainty		Evaluation type of uncertainty	Distribution	Value of standard uncertainty $u(x_i)$	$c_i=df/dx_i$	$\|c_i\|*u(x_i)$
Power splitting ratio C_d	0.97449	none	Dispersion of measured C_d	0.00303	B	Standard	0.00303	-1.01419	0.00308
			Drift	0.00230	B	Uniform	0.00133	-1.01419	0.00135
Power meter reading Pu	1	mW	Resolution of reading	0.001	B	Uniform	0.00029	0.98832	0.00029
Monitor power meter reading Pmu	1	mW	Resolution of reading	0.001	B	Uniform	0.00029	-0.98832	0.00029
Mean calibration factor with PC2.4 to PC2.9 adapter	0.98832	mW	Dispersion of measured calibration factor	0.00107	A	t	0.00029	1.00000	0.00029
Multiple reflection of RF signal	1	none	Source reflection coefficients	0.05250	B	U	0.00087	0.98832	0.00086
			DUT reflection coefficients	0.01169	B	U			
								Quadratic sum of $\|c_i\|*u(x_i)$	0.00350

Uncertainty of relative calibration factor without adapter $u_c(K_{rel})$

Standard uncertainty component	Estimate of the value of measurand	Unit	Source of uncertainty		Evaluation type of uncertainty	Distribution	Value of standard uncertainty $u(x_i)$	$c_i=df/dx_i$	$\|c_i\|*u(x_i)$
Calibration factor of sensor with adapter	0.98832	none	Dispersion of measured K_u	0.0035	B	Standard	0.00350	1.00371	0.00352
Average reference calibration factor K_{ref}	0.99873	none	Dispersion of measured K_{ref}	0.00095	B	Standard	0.00095	-0.99324	0.00094
Adapter efficiency η_α	0.99757	none	Dispersion of measured η_α	0.00020	B	Standard	0.00020	-0.99440	0.00020
								Quadratic sum of $\|c_i\|*u(x_i)$	0.00364

Relative calibration factor K_{rel}	Combined uncertainty of relative calibration factor $u_c(K_{rel})$
0.9920	0.0036

Table B.9.1 NMIJ uncertainty budget for device 3629 at 2 GHz.

GT-RF.S1.CL	Type	SER No.
Power sensor	8487A	3318A03629
PC2.4(f) to PC2.9(m) adapter	11904S	5452
Power meter	437B	2949A02751
Type N(m) to PC2.4(f) adapter	-	NIST 002

Frequency (GHz)	40

Uncertainty of calibration factor with adapter $u_c(K_u)$

Standard uncertainty component	Estimate of the value of measurand	Unit	Source of uncertainty		Evaluation type of uncertainty	Distribution	Value of standard uncertainty $u(x_i)$	c_i=df/dx_i	$\|c_i\|*u(x_i)$
Power splitting ratio C_d	0.93753	none	Dispersion of measured C_d	0.00456	B	Standard	0.00456	-0.98797	0.00450
			Drift	0.00230	B	Uniform	0.00133	-0.98797	0.00131
Power meter reading Pu	1	mW	Resolution of reading	0.001	B	Uniform	0.00029	0.92626	0.00027
Monitor power meter reading Pmu	1	mW	Resolution of reading	0.001	B	Uniform	0.00029	-0.92626	0.00027
Mean calibration factor with PC2.4 to PC2.9 adapter	0.92626	mW	Dispersion of measured calibration factor	0.00131	A	t	0.00035	1.00000	0.00035
Multiple reflection of RF signal	1	none	Source reflection coefficients	0.13030	B	U	0.01038	0.92626	0.00962
			DUT reflection coefficients	0.05633	B	U			
								Quadratic sum of $\|c_i\|*u(x_i)$	0.01071

Uncertainty of relative calibration factor without adapter $u_c(K_{rel})$

Standard uncertainty component	Estimate of the value of measurand	Unit	Source of uncertainty		Evaluation type of uncertainty	Distribution	Value of standard uncertainty $u(x_i)$	c_i=df/dx_i	$\|c_i\|*u(x_i)$
Calibration factor of sensor with adapter	0.92626	none	Dispersion of measured K_u	0.0107	B	Standard	0.01071	1.01593	0.01088
Average reference calibration factor K_{ref}	0.99873	none	Dispersion of measured K_{ref}	0.00095	B	Standard	0.00095	-0.94221	0.00089
Adapter efficiency η_α	0.98557	none	Dispersion of measured η_α	0.00087	B	Standard	0.00087	-0.95480	0.00083
								Quadratic sum of $\|c_i\|*u(x_i)$	0.01095

Relative calibration factor K_{rel}	Combined uncertainty of relative calibration factor $u_c(K_{rel})$
0.9410	0.0109

Table B.9.2 NMIJ uncertainty budget for device 3629 at 40 GHz.

B.10 KRISS Uncertainty Budget

3318A03629
Frequency : 2 GHz

Sources of uncertainty	Type	Probability distribution	Standard uncertainty (ui)	Sensitivity factor (Ci)	ui X Ci
Calibration factor of the transfer standard 1	B	Normal	0.0009	0.9928	0.0009
Calibration factor of the transfer standard 2	B	Normal	0.0009	0.9926	0.0009
Power ratio of the transfer standard 1	B	Normal	0.0005	1.1689	0.0006
Power ratio of the transfer standard 2	B	Normal	0.0003	1.1707	0.0004
Power ratio of the traveling standard	B	Normal	0.0005	1.1611	0.0006
Mismatch between the transfer std. 1 and traveling std.	B	Normal	0.0004	0.9829	0.0004
Mismatch between the transfer std. 2 and traveling std.	B	Normal	0.0003	0.9835	0.0003
Measurement repeatability	A	Normal	0.0006	1.0000	0.0006
Adapter efficiency	B	Rectangular	0.0030	1.0000	0.0030
Combined uncertainty (1 standard deviation)					0.0036

Table B.10.1 KRISS uncertainty budget for device 3629 at 2 GHz.

3318A03629
Frequency : 40.0 GHz

Sources of uncertainty	Type	Probability distribution	Standard uncertainty (ui)	Sensitivity factor (Ci)	ui X Ci
Calibration factor of the transfer standard 1	B	Normal	0.0033	0.9629	0.0032
Calibration factor of the transfer standard 2	B	Normal	0.0029	0.9504	0.0028
Power ratio of the transfer standard 1	B	Normal	0.0003	0.8794	0.0003
Power ratio of the transfer standard 2	B	Normal	0.0004	0.8591	0.0003
Power ratio of the traveling standard	B	Normal	0.0007	0.8529	0.0006
Mismatch between the transfer std. 1 and traveling std.	B	Normal	0.0023	0.9033	0.0021
Mismatch between the transfer std. 2 and traveling std.	B	Normal	0.0033	0.9384	0.0031
Measurement repeatability	A	Normal	0.0010	1.0000	0.0010
Adapter efficiency	B	Rectangular	0.0050	1.0000	0.0050
Combined uncertainty (1 standard deviation)					0.0077

Table B.10.2 KRISS uncertainty budget for device 3629 at 40 GHz.

Protocol for CCEM.RF-S1.CL GTRF/02-03
RF Power Measurements with 2.4 mm Connectors

1. Traveling Standards

The traveling standards will consist of two Agilent 8487A thermocouple power sensors and a Hewlett Packard (now Agilent) 437B power meter. All laboratories should perform measurements with this power meter.

Specifications of the thermocouple power sensors are:

Operating frequency	50 MHz to 50 GHz
Maximum power	300 mW
Max SWR	1.5 (40-50 GHz)
Size (approx)	30 mm x 39 mm x 94 mm
Weight	140 g

Specifications for the 437B power meter are:

50 MHz Power reference	1.00 mW
Line Voltage	100,120, 220, 240 VAC (+5% to -10%)
Line Frequency	48 to 66 Hz (all voltages)
	360 to 440 Hz (100 or 120 VAC)
Remote Operation	HP-IB
Weight	2.6 kg
Size	88 mm (H) x 212 mm (W) x 273 mm (D)

Further details for the power sensors can be found at
http://cp.literature.agilent.com/litweb/pdf/5965-6382E.pdf
The power meter manual is at
http://cp.literature.agilent.com/litweb/pdf/00437-90047.pdf

2. Measurements to be Performed

The calibration factor of the sensor relative to its 50 MHz value will be measured by each laboratory. This quantity is expressed in equation (2) below. Calibration factor K is defined as the ratio of the power meter reading at a given frequency, P_{meter} to the incident RF power, P_{inc}, on the sensor

$$K(f) = \frac{P_{meter}(f)}{P_{inc}(f)}. \tag{1}$$

The value obtained for P_{meter} depends on the setting of the power meter electronics and is therefore arbitrary. The electronics are set using a calibration procedure in which a 50 MHz, 1 mW output signal from the power meter is used as a sensor input. At the pilot laboratory, the reference calibration factor is set to 100% which in turn sets the power meter electronics to yield $P_{meter,ref}$ = $P_{inc,ref}$ where the *ref* subscript indicates measurements made at the reference frequency of 50 MHz. Participating laboratories do not need to follow this same procedure. However, in order to compare results, all measurement values sent reported should be the relative calibration factor, K_{rel}:

$$K_{rel}(f) = \frac{K(f)}{K_{ref}} = \frac{P_{meter}(f)}{P_{inc}(f)} \frac{P_{inc,ref}}{P_{meter,ref}} \tag{2}$$

and the measurements at a given frequency need to be taken with the same power meter settings as the reference measurement. The measurement technique is left to the discretion of each participant, but it should match their normal calibration service method as much as possible.

The measurements will be will be performed at the following frequencies: 2, 6, 18, 26.5, 33, 40, 45 and 50 GHz. Since not all participants will be able to make measurements at all frequencies, all frequencies will be considered optional.

The 2.4 mm connector should be tightened with a torque wrench when connecting it to the measurement system. A torque of 0.90 N-m is typically used (8 in-lb). Incident power levels for the measurements should be about 1 mW.

3. Uncertainty

Participating laboratories should provide complete information about the principal components of the uncertainties and the total standard uncertainty for their measurement at each frequency. Uncertainties should be evaluated at one standard deviation and follow the principles in the Guide to the Expression of Uncertainty in Measurement. Degrees of freedom need not be evaluated.

For the pilot lab, a direct comparison system will be used with the principle components of the uncertainty as listed below. It is not expected that this will fit all laboratories since some laboratories will use calorimeter measurements and adapter corrections will be important for other labs. Thus, each lab should organize their uncertainty budget in a way that best matches their experiment.

Source of Uncertainty	**Type**
Power Meter Instrumentation and 50 MHz Reference Calibration	B
Direct Comparison Mismatch Correction	B
Microcalorimeter 2.4 mm Standard	B
Calibration of Direct Comparison	A
Connector Repeatability	A

Principle components of the uncertainty budget for the pilot laboratory.

4. Intercomparison pattern

Both power sensors and the power meter will be circulated together. Each participant will measure the devices and send them on to the next participant. Three sets of measurements will be made by the pilot lab to measure the stability of the traveling standards. The individual pilot lab measurements will be presented separately in a final report.

The expected time required for a participant to make their measurements and ship the traveling standards to the next participant is 2 months. The schedule for the measurements is given in the table below.

Institution	Country	Dates
NIST 1	United States	December, 2002
NPL	United Kingdom	January-February, 2003
NMi Van Swinden	Netherlands	March-April, 2003
metas	Switzerland	May-June, 2003
NRC	Canada	July-August, 2003
NIST 2	United States	September-December, 2003
CSIR-NML	South Africa	January-February, 2004
CSIRO-NML	Australia	March-April, 2004
AIST	Japan	May-June, 2004
KRISS	Korea	July-August, 2004
NIST 3	United States	September-October, 2004

In the event of failure of a thermocouple sensor or the power meter, the pilot lab should be contacted immediately. If one of the thermocouple sensors fail, the measurement loop will continue with the second standard only. If the power meter fails, then the measurements will continue, but each laboratory will have to use its own power meter. Power meters that are acceptable include Agilent E4418 or 43x series.

Each participant is responsible for arranging and paying for the transport (including where necessary customs clearance) and insurance of the devices from arrival in their laboratory until arrival in the subsequent laboratory. An ATA Carnet will be used for customs documentation.

5. Shipping

On arrival at each participating laboratory, the traveling standards and packaging will be inspected for damage during transit. The protrusion of the center conductor pin on both the power sensors and the laboratory test equipment should be checked before the measurements to prevent damage. The flat section of the center conductor pin must be recessed behind the outer conductor. The power meter line voltage switches and fuse must also be set properly by each participant. Upon shipping the devices to the next laboratory, participants should notify the pilot lab and the next laboratory of the shipment. Similarly upon arrival, the previous lab and the pilot lab should be informed.

6. Report on Progress and Results

The measurement results should be reported in English to the pilot laboratory within one month of completing the measurements. A summary of the measurements should be prepared as an ASCII text file and sent to the pilot lab via email. There should be a single table listing the calibration factor and combined standard uncertainty for each measurement frequency.

In addition, participants should submit their uncertainty budgets and a brief description (one or two paragraphs) of the apparatus and techniques used. These may be submitted either electronically or via mail. The description should be suitable for use in the final report. The names of all co-authors to the final report should be listed. The laboratory operating conditions (i.e. temperature, humidity), use of adapters to other connector sizes, and the traceability route for the measurements must also be described.

7. Intercomparison Report

A draft of the final report will be sent to all participating labs within two months of when the last measurement is made at the pilot laboratory. The report will include a summary of the measurement technique employed at each laboratory, along with the measured values and uncertainties. Results will be presented relative to a comparison value that is the unweighted mean of the measurements.

8. Pilot Laboratory Contact

The pilot laboratory contact is:

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9. List of Participating Laboratories and Contacts*

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KRISS	South Korea	JeongHwan Kim	kimjh@kriss.re.kr

*This is the participant list as it appeared in the original protocol. Table 1 of the main report has an updated list.