CIPM MRA
Comparison reports

APMP.EM.RF-K8.CL

Power in 50 ohm coaxial lines

KEY COMPARISON

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Final report
APMP.EM.RF-K8.CL. comparison
Calibration factor of power meters

Kazuhiro Shimaoka[1)], Tieren Zhang[2)], Liu Xinmeng[3)], Yuan Wenze[3)], Hau Wah Lai[4)], C.M.Tsui[4)], Saood Ahmad[5)], Jeong Hwan Kim[6)], Jae-Yong Kwon[6)], Jeong Il Park[6)], Arshad bin Selamat[7)], Blair Hall[8)], Yueyan Shan[9)], Yusong Meng[9)], Erik Dressler[10)], Mariesa Nel[10)], Linoh Magagula[10)], Sarinya Pasakawee[11)], Vitawat Sittakul [11)], Chairat Wichainmongkonkun[11)]

[1)] National Metrology Institute of Japan (NMIJ), AIST, Japan,
[2)] National Measurement Institute (NMIA), Australia,
[3)] National Institute of Metrology (NIM), People's Republic of China,
[4)] Standards and Calibration Laboratory (SCL), Hong Kong, China
[5)] National Physical Laboratory (NPL), Republic of India,
[6)] Korea Research Institute of Standards and Science (KRISS), Republic of Korea,
[7)] National Metrology Laboratory (NML), Malaysia,
[8)] Measurement Standards Laboratory of New Zealand (MSL), New Zealand,
[9)] National Metrology Centre (NMC), A*STAR , Republic of Singapore,
[10)] National Metrology Institute of South Africa (NMISA), Republic of South Africa,
[11)] National Institute of Metrology (NIMT), Kingdom of Thailand

February 19, 2026

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1. Introduction

An international key comparison (KC), CCEM.RF-K8, was conducted between August 1999 and December 2000, for which the final report was published in May 2005 [1]. The calibration factors of three thermistor mounts were reported from 17 national metrology institutes (NMIs) at eight frequencies in the range of 10 MHz to 18 GHz. The results showed good agreement among most of the participants. The International Committee on Weights and Measures (CIPM) Mutual Recognition Agreement (MRA) [2] requires that Regional Metrology Organization (RMO) KCs be linked to the corresponding CIPM KCs by means of joint participants.

Before the seventh meeting of the Technical Committee on Electricity and Magnetism (TCEM) Asia Pacific Metrology Program (APMP) [3] in October 2004, the Chair expressed his opinion, which was that APMP KC planning should be given higher priority. Thus, a questionnaire was distributed to investigate the available resources for KCs. The National Metrology Institute of Japan (NMIJ) indicated the possibility of a contribution to radio frequency (RF) power measurement. After the investigation, the Chair proposed an RF-power (10 MHz to 18 GHz) comparison, numbered APMP.EM.RF-K8, as a possible APMP KC in TCEM APMP. This proposal was approved at the meeting.

The coordinator planned the comparison to start during 2006 [4]; however, the start was postponed until 2007. This delay was mainly due to the time required to investigate the KC rules [5-11], the method of calculating the KC reference value (KCRV) [12-19], and the means of linking the RMO results to the KC results [20-25].

Although the comparison almost started in early 2008, it was found that traveling standards were not permitted to be exported to one participating country for political reasons. As it was difficult to prepare a new traveling standard, this problem was reported at the 11th APMP TCEM meeting. It was agreed that the comparison should proceed with the other participants.

Additionally, a problem regarding the linking method between APMP KC and CIPM KC remained. During the investigation by the pilot laboratory into many linking reports on other RMO comparisons, it was recognized that a special linking method should be prepared for APMP.EM.RF-K8.CL. The pilot laboratory developed a new linking method with the assistance of the Applied Statistics Division of NMIJ in 2009. The members of the organization group (NMIJ, Korea Research Institute of Standards and Science [KRISS], National Metrology Centre [NMC], and National Measurement Institute of Australia [NMIA]) discussed this linking method at the Conference on Precision Electromagnetic Measurements 2010 held in South Korea. However, the members could not reach an agreement regarding the adoption of the method. As the coordinator reasoned that all possible efforts had been made, he decided to suspend this problem temporarily and restarted the preparation of traveling standards.

However, the Higashi-Nihon Great Earthquake in 2011 forced the pilot laboratory to suspend the preparations for six months.

Eleven NMIs from the APMP finally participated in this comparison. The comparison started in July 2012 and was completed in June 2014. During the comparison, the Measurement Standards Laboratory of New Zealand (MSLNZ) reported that a torque wrench sent with the traveling standards showed over-torque and returned it to the pilot laboratory. The pilot laboratory replaced it with a new torque wrench, because an oil shortage was observed.

KRISS and NMIA requested a re-submission of their measurement results. As the requests were made before the publication of Draft A, the pilot laboratory accepted the re-submission according to international comparison rules.

Additionally, a few laboratories erroneously reported relative values although the technical protocol required absolute values. They also re-submitted their results.

The technical protocol was prepared according to the Guidelines for CIPM Key Comparisons [5, 6].

2. Participants and schedule

Eleven countries participated in the international comparison, as listed in Table 2.1. This comparison was divided into two stages. Six and five countries participated in each half. The pilot laboratory conducted an initial measurement before the first stage, an intermediate measurement between the two stages, and a final measurement after completion of the second stage. The complete schedule is summarized in Table 2.2.

Table 2.1 List of participants

Country/Institute	Primary contact person	Address	E-mail
Australia, National Measurement Institute (NMIA) [1), 2)]	Tieren Zhang	36 Bradfield Road West Lindfield NSW 2070, Australia	tieren.zhang@ measurement.gov.au
People's Republic of China, National Institute of Metrology (NIM) [1)]	Yuan Wenze	No. 18, Bei San Huan Dong Lu, Beijing, China	yuanwz@nim.ac.cn
Hong Kong, China, Standards and Calibration Laboratory (SCL)	Hau Wah Lai	4/F, North Tower, Tseung Kwan O Government Offices, 30 Tong Yin Street, Tseung Kwan O, Sai Kung, New Territories, Hong Kong, China	terry.lai@itc.gov.hk
Republic of India, National Physical Laboratory (NPL)	Saood Ahmad	Dr. K S Krishnan Road, New Delhi - 110012, India	ahmads@nplindia.org
Japan, National Metrology Institute of Japan (NMIJ) [1), 3)]	Kazuhiro Shimaoka	3-1 Central, 1-1-1 Umezono, Tsukuba, Ibaraki, 305-8563, Japan	kazuhiro-shimaoka @aist.go.jp
Republic of Korea, Korea Research Institute of Standards and Science (KRISS) [1), 2)]	Jae-Yong Kwon	267 Gajeong-ro, Yuseong-gu, Daejeon 34113, Republic of Korea	jykwon@kriss.re.kr

Malaysia, National Metrology Laboratory (NML)	Arshad bin Selamat	Lot PT 4803, Bandar Baru, Salak Tinggi, 43900 Sepang, Selangor Darul Ehsan, Malaysia	arshads@sirim.my
New Zealand, Measurement Standards Laboratory of New Zealand (MSLNZ)	Blair Hall	69 Gracefield Road, PO Box 31-310, Lower Hutt 5040, New Zealand	Blair.Hall@ measurement.govt.nz
Republic of Singapore, National Metrology Centre (NMC)[1), 2)]	Yusong Meng	8 CleanTech Loop, #01-20, Singapore 637145	meng_yusong@ a-star.edu.sg
Republic of South Africa, National Metrology Institute of South Africa (NMISA)	Linoh Magagula	Building 5, CSIR Campus, Meiring Naudé Road, Brummeria, Pretoria, 0001, South Africa	LMagagula@ nmisa.org
Kingdom of Thailand, National Institute of Metrology (NIMT)	Sarinya Pasakawee	3/4-5 Moo 3, Klong 5, Klong Luang, Pathumthani 12120, Thailand	sarinya@nimt.or.th

[1)] Linking laboratories

[2)] Supporting group members

[3)] Pilot laboratory

Table 2.2 Circulation time schedule

Institution ID	Institution	Country	Start date	Time for measurement and transport (weeks)
0	NMIJ	Japan	15 June 2012	6
1	SCL	Hong Kong, China	1 August 2012	6
2	NMIA	Australia	15 September 2012	6
3	MSLNZ	New Zealand	1 November 2012	6
4	NML	Malaysia	15 December 2012	6

5	NMISA	South Africa	1 February 2013	6
0	NMIJ	Japan	15 March 2013	6
6	NMC	Singapore	1 June 2013	6
7	NPL	India	15 July 2013	6
8	KRISS	Republic of Korea	28 October 2013	14
9	NIM	People's Republic of China	20 January 2014	11
10	NIMT	Kingdom of Thailand	22 April 2014	12
0	NMIJ	Japan	17 June 2014	7

3. Traveling standards and measurands

The traveling standards were two Agilent 8481A thermocouple power sensors with an Agilent E4419B power meter. The detailed specifications of these devices are shown in the technical protocol (see Appendix B). The traveling standards are listed in Table 3.1.

Table 3.1 List of traveling standards

Identifier	Model	Serial number
Sensor No. 1	Agilent Technologies 8481A	US41031012
Sensor No. 2	Agilent Technologies 8481A	US41031013
Power meter No. 1	Agilent Technologies E4419B	MY45100436

The calibration factor was measured at specified frequencies f. The calibration factor $K(f)$ of a set consisting of a power meter and a sensor is defined as the indication on the power meter $P_{\mathrm{m}}(f)$ divided by the incident power supplied to the power sensor, $P_{\mathrm{in}}(f)$.

$$K(f) = \frac{P_m(f)}{P_{in}(f)} \tag{3.1}$$

Each laboratory also reported the associated combined standard uncertainties $u_{\mathrm{c}}(K)$ and their coverage factors k, where the expanded uncertainties $U = ku_{\mathrm{c}}(K)$ define intervals having a level of confidence of approximately 95 percent.

It was necessary to calibrate the gain of the power meter to the thermocouple power sensor using a 50 MHz, 1 mW reference power source before each use [28]. Each of the laboratories was required to use the same calibrator built inside the traveling standard (E4419B). The power level of the reference power source could have changed slightly during transport. This stability was monitored by the pilot laboratory.

The measurements were performed at 10 MHz, 50 MHz, 1 GHz, 4 GHz, 8 GHz, 12 GHz, 15 GHz, and 18 GHz as per CCEM.RF-K8. The incident power $P_{\mathrm{in}}(f)$ was nominally 1 mW. However, it was not problematic if the incident power level slightly differed from 1 mW, because of the excellent detector linearity around 1 mW. Therefore, any difference could be easily characterized as a very small uncertainty component. The measurement technique was left to the discretion of the participants, although it was required to be the same as the method used in the ordinary calibration service.

The reflection coefficients of the traveling standards were reported. The report was not requisite and does not constitute the KC. Both vector (complex) and scalar reflection coefficients were acceptable. Their uncertainties were required to be reported as intervals having levels of confidence of approximately 95 percent. Their traceability sources were required to be reported. If the reported values lacked uncertainties and/or traceability, they were not included in the final report.

4. Behavior of the traveling standards

The behavior of the traveling standards during the comparison was confirmed by four monitoring indices. These indices were the following measurement results obtained by the pilot laboratory: calibration factors, pin depths, reflection coefficients of the power sensors, and output power of 1 mW built-in power reference of the power meter.

4.1 Calibration factors reported by the pilot laboratory

Table 4.1 Calibration factors reported by the pilot laboratory

(a) Sensor No. 1

Measurement frequency	15 June 2012	15 March 2013	17 June 2014	Standard deviation
10 MHz	0.9924	0.9925	0.9914	0.0006
50 MHz	0.9946	0.9943	0.9946	0.0002
1 GHz	0.9793	0.9788	0.9788	0.0003
4 GHz	0.9683	0.9675	0.9671	0.0006
8 GHz	0.9528	0.9509	0.9512	0.0010
12 GHz	0.9296	0.9292	0.9289	0.0004
15 GHz	0.9155	0.9153	0.9149	0.0003
18 GHz	0.9117	0.9094	0.9093	0.0014

(b) Sensor No. 2

Measurement frequency	15 June 2012	15 March 2013	17 June 2014	Standard deviation
10 MHz	0.9904	0.9912	0.9906	0.0004
50 MHz	0.9942	0.9939	0.9945	0.0003
1 GHz	0.9795	0.9789	0.9794	0.0003
4 GHz	0.9678	0.9669	0.9670	0.0005
8 GHz	0.9510	0.9487	0.9498	0.0011
12 GHz	0.9292	0.9279	0.9279	0.0008
15 GHz	0.9135	0.9131	0.9121	0.0007
18 GHz	0.9117	0.9096	0.9101	0.0011

The standard deviations of the calibration factors reported by the pilot laboratory for each frequency at the starting time point, intermediate time point, and ending time point were less than 2/3 of the standard uncertainty of the pilot laboratory.

4. 2 50 MHz, 1 mW built-in power reference output

The stability of the 50 MHz, 1 mW built-in power reference output was monitored using a thermistor mount.

Table 4.2 Ratios of the calibration factors of the traveling standards to that of a thermistor mount.

Sensor No.	18 July 2012	15 May 2013	19 June 2014	Standard deviation
1	0.9946	0.9944	0.9952	0.0004
2	0.9941	0.9940	0.9950	0.0006

The output of the 50 MHz, 1 mW built-in power reference varied by less than 0.1 percent. This stability was confirmed by the standard deviations of the ratios of the calibration factors of the sensors to that of the thermistor mount. The thermistor mount was carefully kept in a calibration room of the pilot laboratory during the comparison.

4.3 Pin depth

Table 4.3 Pin depth ($\times 10^{-4}$ inch (μm))

Sensor No.	18 July 2012	15 May 2013	19 June 2014
1	-16.3 (-41.4)	-16.3 (-41.4)	-16.2 (-41.1)
2	-12.3 (-31.2)	-12.2 (-31.0)	-12.2 (-31.0)

The pin depths of the sensors were stable to within 0.1 $\times 10^{-4}$ inch.

4.4 Reflection coefficient of the power sensors

Table 4.4 Reflection coefficient of the power sensors

(a) Sensor No. 1

Measurement frequency	19 May 2012		26 April 2013		9 June 2014	
	Real	Imaginary	Real	Imaginary	Real	Imaginary
10 MHz	0.0056	-0.0630	0.0054	-0.0629	0.0056	-0.0628
50 MHz	-0.0028	-0.0133	-0.0031	-0.0136	-0.0030	-0.0133
1 GHz	0.0081	-0.0018	0.0080	-0.0016	0.0081	-0.0013
4 GHz	0.0110	0.0103	0.0111	0.0107	0.0106	0.0109
8 GHz	-0.0133	-0.0096	-0.0133	-0.0108	-0.0142	-0.0104
12 GHz	-0.0278	0.0142	-0.0286	0.0146	-0.0296	0.0133
15 GHz	-0.0101	0.0263	-0.0102	0.0280	-0.0102	0.0290

18 GHz	-0.0484	0.0571	-0.0492	0.0559	-0.0491	0.0586

(b) Sensor No. 2

Measurement frequency	19 May 2012		26 April 2013		9 June 2014	
	Real	Imaginary	Real	Imaginary	Real	Imaginary
10 MHz	0.0068	-0.0647	0.0066	-0.0645	0.0068	-0.0646
50 MHz	-0.0018	-0.0137	-0.0018	-0.0139	-0.0016	-0.0137
1 GHz	0.0080	-0.0031	0.0080	-0.0031	0.0077	-0.0031
4 GHz	0.0121	0.0052	0.0121	0.0054	0.0115	0.0052
8 GHz	-0.0145	-0.0066	-0.0146	-0.0068	-0.0149	-0.0065
12 GHz	-0.0205	0.0084	-0.0211	0.0094	-0.0212	0.0070
15 GHz	-0.0047	0.0184	-0.0033	0.0172	-0.0038	0.0183
18 GHz	-0.0396	0.0474	-0.0394	0.0477	-0.0395	0.0479

The real and imaginary parts of the reflection coefficients of the sensors typically varied by less than ±0.001. The maximum change was 0.0027.

5. Measurement methods

This section contains excerpts from the reports provided by the participants.

5.1 Australia, National Measurement Institute (NMIA) [34]

A type-N power calibration splitter system was used in this comparison. A reference thermistor mount was connected to one of the output ports of the splitter, and the device under test (DUT) was connected to the other output port. The calibration factor of the DUT was derived using the method of [35]. The reference thermistor mount was operated with a pair of NMIA dual precision self-balancing bridges. The power meter readings of the DUT were taken from the IEEE Bus of the power meter.

Two reference thermistor mounts were used for the measurements, and the reported calibration factors were obtained by averaging the values derived from these two references. The reference thermistor mounts were calibrated using an NMIA microcalorimeter.

The measurements of the reflection coefficients for both the reference thermistor mounts and DUT were performed using an Agilent E8364B vector network analyzer (VNA), which is traceable to the NMIA coaxial airline impedance standards.

5.2 People's Republic of China, National Institute of Metrology (NIM) [36]

The measurement method was a comparison method. The calibration method has not been modified since CCEM.RF-K8.CL. A microcalorimeter developed by NIM was used to calibrate a thermistor power sensor, which was used as a reference standard to calibrate a transfer standard. The calibrated transfer standard was used to measure the traveling standards. The measurement of the reflection coefficients of the traveling standards is traceable to National Scattering Parameter Standard at NIM.

5.3 Hong Kong, China, Standards and Calibration Laboratory (SCL) [37]

The absolute calibration factor of the unit under test (UUT) was calibrated by using a laboratory HP 8478B thermistor mount power sensor that was connected to a laboratory HP 432B power meter. A sinusoidal signal with a power level of approximately 6 dBm was applied to the input port of the laboratory two-resistor power splitter such that there was a nominal 1 mW (0 dBm) power level at the output ports of the power splitter. The UUT was connected to one output port of the power splitter, while the laboratory power sensor was connected to another port of the power splitter. The power readings of the UUT and laboratory power meter were recorded. After half of the four measurements were performed, the two power sensors were swapped. The power measurements were metrologically traceable to the laboratory microcalorimeter system. The microcalorimeter was used to calibrate the effective efficiency of the laboratory thermistor mount power sensor.

5.4 Republic of India, National Physical Laboratory (NPL) [38]

A resistive power splitter system was used with an R&S NRV-Z51 power sensor permanently attached to one arm. The device under calibration (DUC) and standard were attached alternately to the other arm of the splitter. The reference standard is traceable to the NPL-India Primary Standard (coaxial microcalorimeter system). The measurements were repeated eight times.

The reflection coefficients of the DUC were measured using Agilent E8257D and Anritsu 37247B VNAs. The reflection coefficient measurement using VNA is traceable to the dimensional metrology and DC resistance standard at NPL India through transfer standards (coaxial airlines and calibration kit components).

5.5 Japan, National Metrology Institute of Japan (NMIJ) [39]

The power measurement principle was based on an isothermally controlled twin-type dry calorimetric measurement. The calorimeter included two circuits that were designed to be electrically and thermally equivalent, so as to cancel out any thermal influence caused by room temperature changes. Power measurement was performed only for one circuit.

The power source consisted of a power splitter, monitoring power meter, and wideband synthesized power source. The RF signal from the synthesized power source was divided into two at the power splitter. The monitoring power meter was connected to one output port of the power splitter to monitor the input power. The RF signal from the other output port of the power splitter was fed to a test port. The output power from the test port was calorimetrically measured, and the ratio of the output power to the monitored (indicated) power was recorded. Before DUT calibration, it was necessary to evaluate this ratio (called a power splitting ratio) at the required calibration frequencies.

DUT calibration was performed after removing the RF load, sensing and cooling device, thermal reference block, and thermal jackets. A DUT was connected to the test port, and the calibration factor of the DUT was evaluated based on the value indicated by the DUT and the monitoring power meter. If the connector type was different from PC 7, it was necessary to use a suitable conversion adapter.

The digital voltmeter and programmable current source were calibrated using a digital multimeter calibrated by an MRA-accredited laboratory. For the current calibration, a standard resister was also used.

The RF loads installed in the 7 mm coaxial calorimeters require DC resistance (50 Ω) calibration. A VNA was used for the reflection coefficient measurement of customer DUTs. Traceability to the SI for PC 7 and type-N connectors was ensured using PC 7 and type-N wideband loads traceable to NMIJ.

5.6 Republic of Korea, Korea Research Institute of Standards and Science (KRISS) [40]

The traveling standards were calibrated by direct comparison with the coaxial transfer standards. The effective efficiencies of the transfer standards were calibrated using the new type-N microcalorimeter at KRISS.

The reflection coefficients of the traveling standards were measured with a VNA calibrated using the SOSL (Short/Open/Sliding load) technique and a type-N calibration kit traceable to the impedance standards of KRISS.

5.7 Malaysia, National Metrology Laboratory (NML) [41]

The RF power generated by a signal generator was delivered to a resistive power splitter before being delivered to the two measurement arms of the splitter. The nominal power of each arm was 1 mW. One arm of the splitter was connected to the reference sensor (mount), while the other arm was connected to the unknown sensor (DUT). The NML-SIRIM standard thermistors used are directly traceable to KRISS. The reflection coefficient measurements for both the reference mount and DUT sensor were performed using 8510C and 8753D VNAs.

5.8 New Zealand, Measurement Standards Laboratory of New Zealand (MSLNZ) [42]

An Agilent 8478B thermistor mount was used as a transfer standard to calibrate the two Agilent 8481A power sensors in conjunction with the Agilent E4419B power meter supplied in this comparison.

A resistive power splitter delivered power from a signal generator to a pair of output ports. A second Agilent 8478B thermistor mount power sensor was connected to one of these output ports (the reference port) and used to normalize the readings of power sensors connected to the other port (the measurement port). The power ratio (the measurement port power level divided by the reference port power level) was recorded at each frequency.

Traceability to the SI was achieved via standards calibrated at two NMIs: the National Physical Laboratory (UK), for the calibration factor of the MSLNZ thermistor mount, and METAS (Switzerland), for measurements of the voltage reflection coefficients (VRCs) of type-N open, short, and load standards used to adjust the VNAs.

The resistance measurements of a precision resistor inside the Larsen Bridges are traceable to the MSLNZ realization of the ohm. The microwave signal generator and VNAs were synchronized to a 10 MHz reference from the MSLNZ frequency standards.

5.9 Singapore, National Metrology Centre (NMC) [43]

The measurement method used in APMP.EM.RF-K8.CL is different from that of CCEM.RF-K8.CL and can be described as follows.

The calibration factors of the two power sensors (traveling standards) were measured using the direct comparison measurement technique, in which the effective efficiency of a reference power standard is transferred to an unknown (uncalibrated) power sensor (DUT).

The method is based on alternate connections between a reference standard and unknown (uncalibrated) power sensor (DUT) to one of the output ports of a passive power splitter. The other output port of the power splitter is used to correct the power variation during the measurement. An RF source is connected to the input port of the power splitter.

The calibration factors of the traveling standards from 10 MHz to 18 GHz are traceable to two reference power standards. The reference power standard for 10 MHz is a temperature-stabilized thermistor mount and is traceable to the single junction thermal converter voltage standards maintained at NMC (Singapore). The reference power standard for 50 MHz to 18 GHz is also a thermistor mount and is traceable to the type-N calorimeter maintained at NMC (Singapore).

The reflection coefficients of the traveling standards were measured using two VNAs, which are traceable through impedance standards to NMC (Singapore) and NPL (UK).

All of the other working standards are traceable to the national reference standards maintained at NMC (Singapore).

5.10 Republic of South Africa, National Metrology Institute of South Africa (NMISA) [44]

The calibration factor of the DUT was determined by employing a calibrated transfer standard consisting of a two-resistor power splitter, model HP11677A (Weinschel model 1870A at 10 MHz only) and a HP series 8000 monitor power sensor, which was connected to port 3 of the splitter. During calibration, the DUT was connected to port 2 of the power splitter.

The system calibration factors were determined by connecting the national RF power standard to port 2 of the power splitter. The power standard is a dry twin-load calorimeter with type-N input connectors. It measures RF power by using RF-DC substitution techniques. The accuracy of the power standard is traceable to the national measurement standards of DC voltage, resistance and 50 Ω RF attenuation and impedance.

The VRC magnitudes of the DUT sensors were determined by direct measurement against two VNAs: an HP8753D and a PNA. Both VNAs were calibrated with relevant calibration kits before measurement, the HP8753D with an HP85032B kit and the PNA with an HP85054B kit. The accuracies of both VNAs are traceable to the two national measurement standards: the 50 Ω RF attenuation, which is a waveguide below-cutoff piston attenuator, and the national measurement standard for RF impedance, which is a coaxial 50 Ω airline for the relevant transmission line size.

5.11 Kingdom of Thailand, National Institute of Metrology (NIMT) [45]

The power sensors were calibrated by comparing their output settings with the measured values obtained from standards maintained by the NIMT RF and Microwave Laboratory.

The stated measurement uncertainties are the expanded measurement uncertainties obtained from the combined standard measurement uncertainties multiplied by the coverage factor $k = 2$. They were determined in accordance with JCGM 100: 2008 "Evaluation of measurement data - Guide to the expression of uncertainty in measurement." The values of the measurand lie within the assigned range of values with a probability of approximately 95 %.

The measurements were performed at an ambient temperature of (23.0 ± 2.0) °C and a relative humidity of (50 ± 15) %.

6. Technical protocol

The technical protocol [46] was prepared according to the Guidelines for CIPM Key Comparisons [5, 6] and is provided in Appendix D.

7. Measurement analysis

7.1 Report from the pilot laboratory

Although the pilot laboratory performed a total of three measurements, the first measurement was submitted as the official entry. The second and third measurements were used to monitor behavior of the transfer standards (see 4.1.)

7.2 Determining the KCRV

The APMP reference value ($APMP\ RV$) was determined from the weighted mean of the results reported by Consultative Committee for Electricity and Magnetism (CCEM) member laboratories [46]. On the basis of the method proposed by Cox [18, 19], *the weighted mean was calculated from the largest consistent subset. The largest consistent subset included the reported data obtained after the removal of outliers*. To evaluate the weighted mean, standard uncertainty, and degrees of equivalences (*DoE*s), Procedure A described in [18] was used, while the values that contributed to the calculations were determined using the procedure described in [19]. The details of the procedure are available in the references. The procedure in [19] revealed that it was necessary to eliminate only two of the reported values from the *APMP RV* calculations as outliers, which justifies adoption of the weighted mean. Two values by NMIA (Sensor 2,1 GHz, 4 GHz) significantly increased the chi-squared value and thus had to be eliminated from the *APMP RV* calculations.

$$APMP\ RV = \frac{\sum_i \frac{m(L_i)}{u^2(m(L_i))}}{\sum_i \frac{1}{u^2(m(L_i))}} \tag{7.2.1}$$

Here, $m(L_i)$ is the value reported by laboratory L_i and $u(m(L_i))$ is the combined standard uncertainty of $m(L_i)$. The subscript i represents the institution ID listed in Table 2.2. The combined standard uncertainty of *APMP RV* is given by

$$u(APMP\ RV) = \frac{1}{\sqrt{\sum_i \frac{1}{u^2(m(L_i))}}}. \tag{7.2.2}$$

The *DoE* between $m(L_i)$ and *APMP RV* is given by the pair $[d_i, U(d_i)]_{APMP}$.

$$DoE(m(L_i), APMP\ RV) = [d_i, U(d_i)]_{APMP} \tag{7.2.3}$$

$$d_i = m(L_i) - APMP\ RV \tag{7.2.4}$$

$$U(d_i) = 2u(d_i) \tag{7.2.5}$$

and

$$u(d_i) = \sqrt{u^2(m(L_i)) - u^2(APMP\ RV)} \tag{7.2.6}$$

or

$$u(d_i) = \sqrt{u^2(m(L_i)) + u^2(APMP\ RV)} \tag{7.2.7}$$

Equation (7.2.6) was applied to the reported value $m(L_i)$ that contributed to the *APMP RV* calculations, while (7.2.7) was applied to the reported values $m(L_i)$ that did not contribute to the *APMP RV* calculations.

The *DoE* between $m(L_i)$ and $m(L_{i'})$ is given by the pair $[d_{i,i'}, U(d_{i,i'})]$.

$$DoE\left(m(L_i), m(L_{i'})\right) = \left[d_{i,i'}, U\left(d_{i,i'}\right)\right] \quad (7.2.8)$$

$$d_{i,i'} = m(L_i) - m(L_{i'}) \quad (7.2.9)$$

$$u\left(d_{i,i'}\right) = \sqrt{u^2\left(m(L_i)\right) + u^2\left(m(L_{i'})\right)} \quad (7.2.10)$$

$$U\left(d_{i,i'}\right) = 2u\left(d_{i,i'}\right) \quad (7.2.11)$$

The *DoE* between $m(L_i)$ and *APMP RV* was calculated for all of the measurement frequencies and each traveling standard, and the results are presented in the following tables and graphs.

8. APMP RV and *DoE*

The *APMP RV* and u(*APMP RV*) are given in Table 8.1 and 8.2.

Table 8.1 *APMP RV* (Sensor No. 1)

Frequency	*APMP RV*	u(*APMP RV*) (k = 1)
10 MHz	0.9938	0.0011
50 MHz	0.9942	0.0007
1 GHz	0.9784	0.0009
4 GHz	0.9677	0.0009
8 GHz	0.9527	0.0011
12 GHz	0.9294	0.0011
15 GHz	0.9148	0.0011
18 GHz	0.9128	0.0017

Table 8.2 *APMP RV* (Sensor No. 2)

Frequency	*APMP RV*	*u*(*APMP RV*) (*k* = 1)
10 MHz	0.9926	0.0011
50 MHz	0.9937	0.0007
1 GHz	0.9783	0.0009
4 GHz	0.9668	0.0009
8 GHz	0.9511	0.0011
12 GHz	0.9291	0.0011
15 GHz	0.9132	0.0011
18 GHz	0.9128	0.0015

The *DoE* between $m(L_i)$ and $APMP\ RV$ is presented in the following tables and graphs.

Table 8.3 *DoE* between $m(L_i)$ and *APMP RV* (10 MHz)

Institution ID i	Institution	*DoE* Sensor No. 1		*DoE* Sensor No. 2	
		$d_{i,\ APMP\ RV}$	$U(d_{i,\ APMP\ RV})$ $(k = 2)$	$d_{i,\ APMP\ RV}$	$U(d_{i,\ APMP\ RV})$ $(k = 2)$
0	NMIJ	-0.0014	0.0035	-0.0022	0.0036
1	SCL	-0.0028	0.0142	-0.0036	0.0122
2	NMIA	-0.0012	0.0044	-0.0007	0.0045
3	MSLNZ				
4	NML	-0.0266	0.0317	-0.0272	0.0317
5	NMISA	-0.0008	0.0157	-0.0036	0.0157
6	NMC	-0.0005	0.0124	-0.0008	0.0124
7	NPL	-0.0023	0.0083	-0.0007	0.0081
8	KRISS	0.0033	0.0029	0.0027	0.0026
9	NIM	-0.0079	0.0096	-0.0056	0.0096
10	NIMT	-0.0048	0.0132	-0.0056	0.0132

Fig. 8.1 *DoE* between $m(L_i)$ and *APMP RV* (10 MHz, Sensor No. 1)

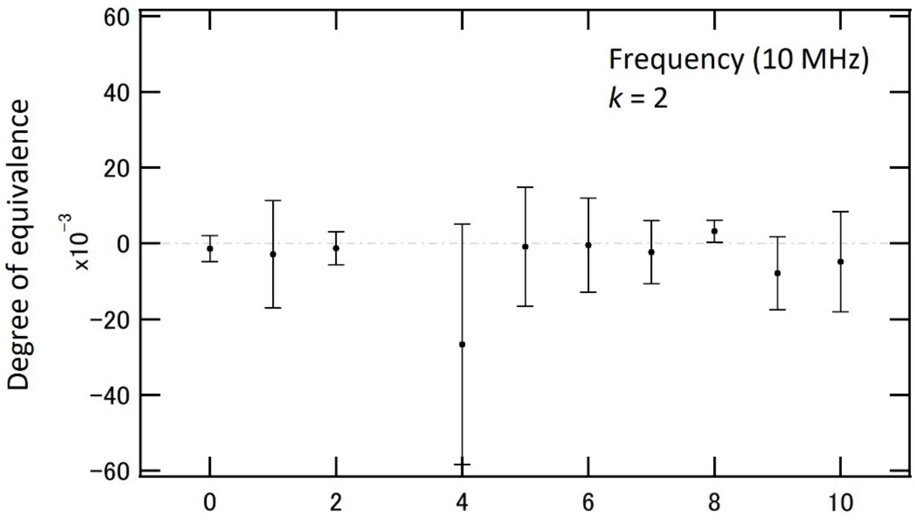


Fig. 8.2 *DoE* between $m(L_i)$ and *APMP RV* (10 MHz, Sensor No. 2)

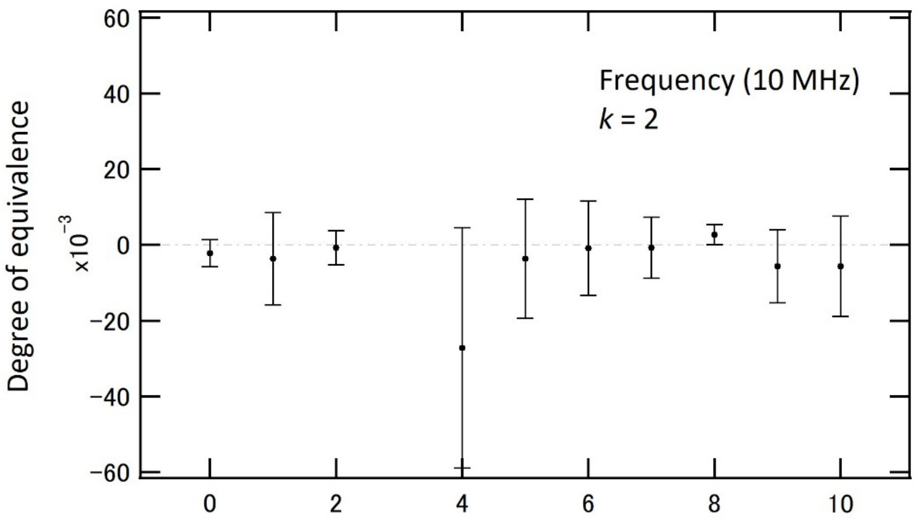


Table 8.4 *DoE* between $m(L_i)$ and *APMP RV* (50 MHz)

Institution ID i	Institution	*DoE* Sensor No. 1		*DoE* Sensor No. 2	
		$d_{i, APMP RV}$	$U(d_{i, APMP RV})$ $(k = 2)$	$d_{i, APMP RV}$	$U(d_{i, APMP RV})$ $(k = 2)$
0	NMIJ	0.0005	0.0027	0.0004	0.0027
1	SCL	-0.0002	0.0062	0.0003	0.0062
2	NMIA	0.0008	0.0047	0.0013	0.0051
3	MSLNZ	0.0007	0.0023	0.0009	0.0023
4	NML	-0.0016	0.0314	-0.0008	0.0314
5	NMISA	0.0028	0.0159	0.0023	0.0159
6	NMC	-0.0025	0.0037	-0.0027	0.0037
7	NPL	0.0067	0.0060	0.0075	0.0060
8	KRISS	-0.0023	0.0031	-0.0025	0.0029
9	NIM	-0.0026	0.0097	0.0000	0.0095
10	NIMT	0.0018	0.0121	0.0013	0.0121

Fig. 8.3 *DoE* between $m(L_i)$ and *APMP RV* (50 MHz, Sensor No. 1)

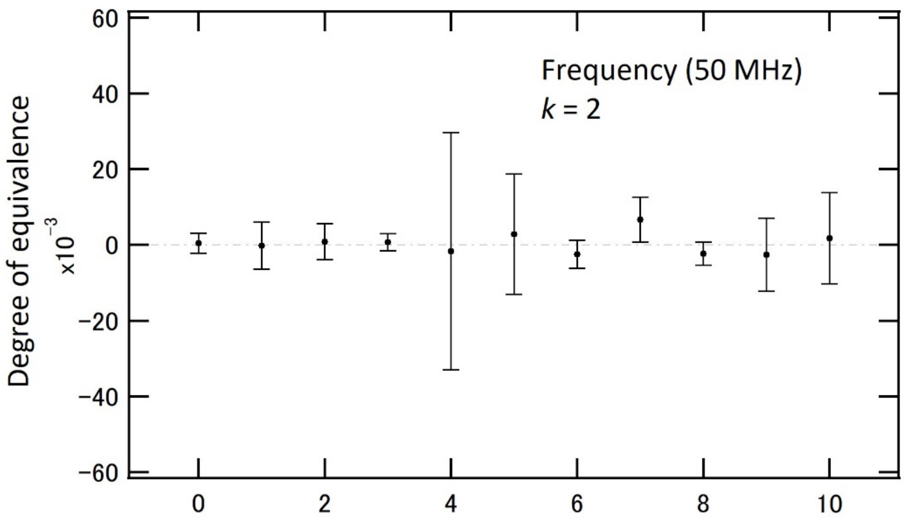


Fig. 8.4 *DoE* between $m(L_i)$ and *APMP RV* (50 MHz, Sensor No. 2)

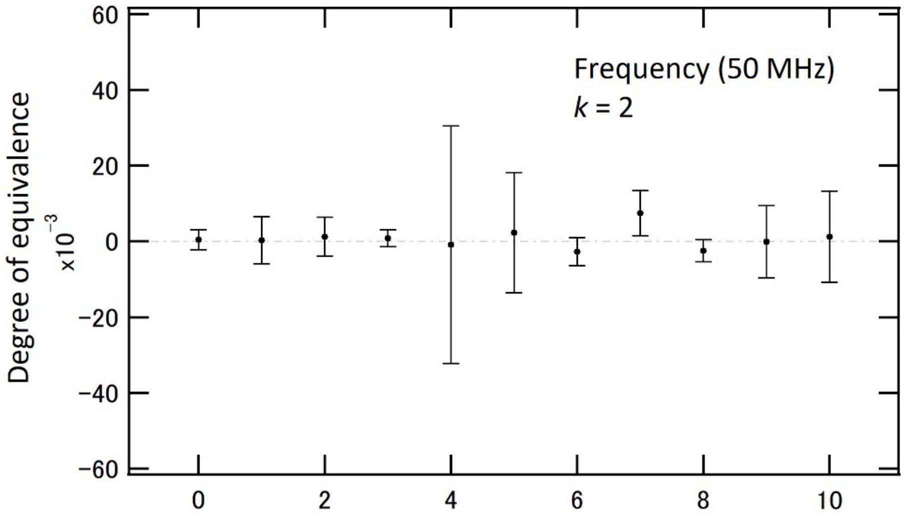


Table 8.5 *DoE* between $m(L_i)$ and *APMP RV* (1 GHz)

Institution ID i	Institution	*DoE* Sensor No. 1		*DoE* Sensor No. 2	
		$d_{i, APMP\ RV}$	$U(d_{i, APMP\ RV})$ $(k = 2)$	$d_{i, APMP\ RV}$	$U(d_{i, APMP\ RV})$ $(k = 2)$
0	NMIJ	0.0008	0.0025	0.0012	0.0024
1	SCL	-0.0014	0.0082	-0.0013	0.0063
2	NMIA	0.0028	0.0046	0.0069	0.0053
3	MSLNZ	0.0005	0.0043	0.0009	0.0041
4	NML	0.0020	0.0358	0.0031	0.0358
5	NMISA	0.0056	0.0157	0.0037	0.0156
6	NMC	-0.0032	0.0034	-0.0031	0.0033
7	NPL	0.0090	0.0074	0.0093	0.0074
8	KRISS	-0.0034	0.0045	-0.0032	0.0044
9	NIM	-0.0032	0.0094	-0.0010	0.0088
10	NIMT	0.0036	0.0131	0.0037	0.0131

Fig. 8.5 *DoE* between $m(L_i)$ and *APMP RV* (1 GHz, Sensor No. 1)

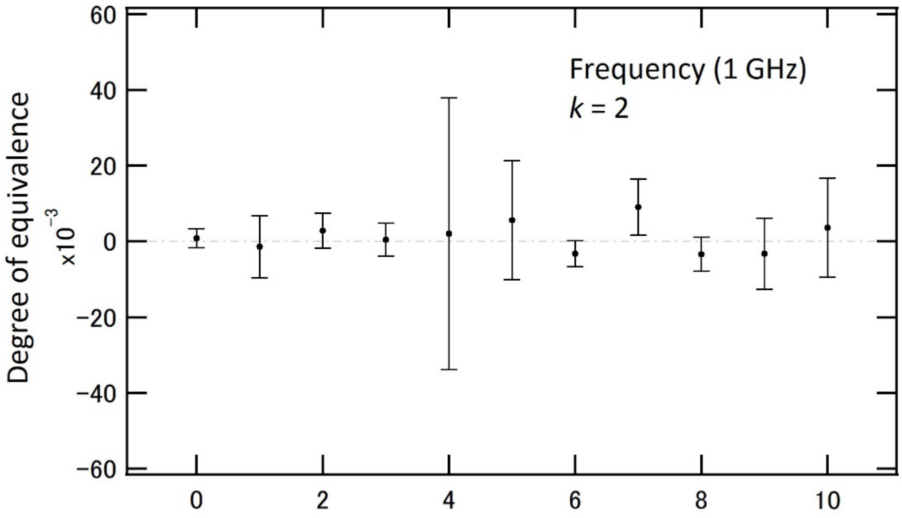


Fig. 8.6 *DoE* between $m(L_i)$ and *APMP RV* (1 GHz, Sensor No. 2)

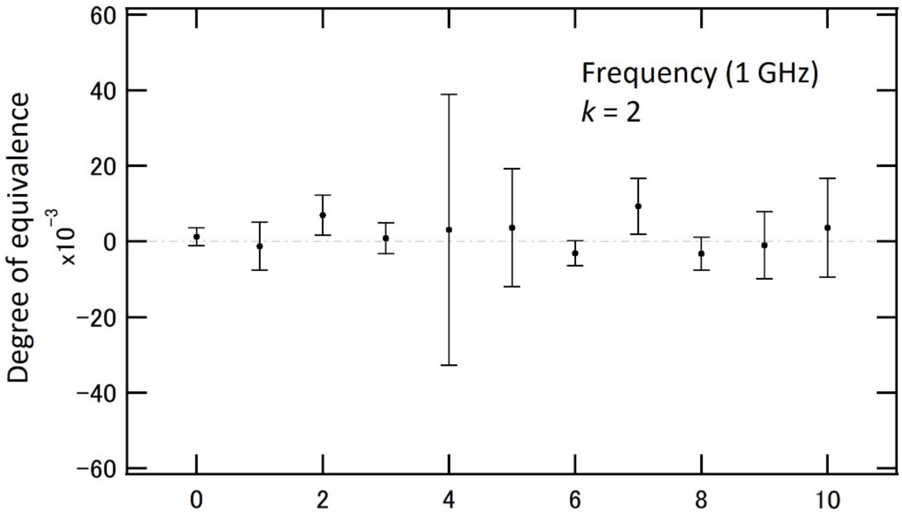


Table 8.6 *DoE* between $m(L_i)$ and *APMP RV* (4 GHz)

Institution ID i	Institution	*DoE* Sensor No. 1		*DoE* Sensor No. 2	
		$d_{i, APMP\ RV}$	$U(d_{i, APMP\ RV})$ ($k = 2$)	$d_{i, APMP\ RV}$	$U(d_{i, APMP\ RV})$ ($k = 2$)
0	NMIJ	0.0006	0.0025	0.0010	0.0024
1	SCL	-0.0017	0.0102	-0.0018	0.0102
2	NMIA	0.0045	0.0050	0.0091	0.0057
3	MSLNZ	0.0000	0.0044	0.0006	0.0043
4	NML	0.0004	0.0356	0.0026	0.0358
5	NMISA	-0.0047	0.0192	-0.0018	0.0192
6	NMC	-0.0031	0.0038	-0.0036	0.0038
7	NPL	0.0028	0.0090	0.0046	0.0092
8	KRISS	-0.0008	0.0040	0.0003	0.0040
9	NIM	-0.0022	0.0105	0.0006	0.0096
10	NIMT	0.0043	0.0141	0.0042	0.0141

Fig. 8.7 *DoE* between $m(L_i)$ and *APMP RV* (4 GHz, Sensor No. 1)

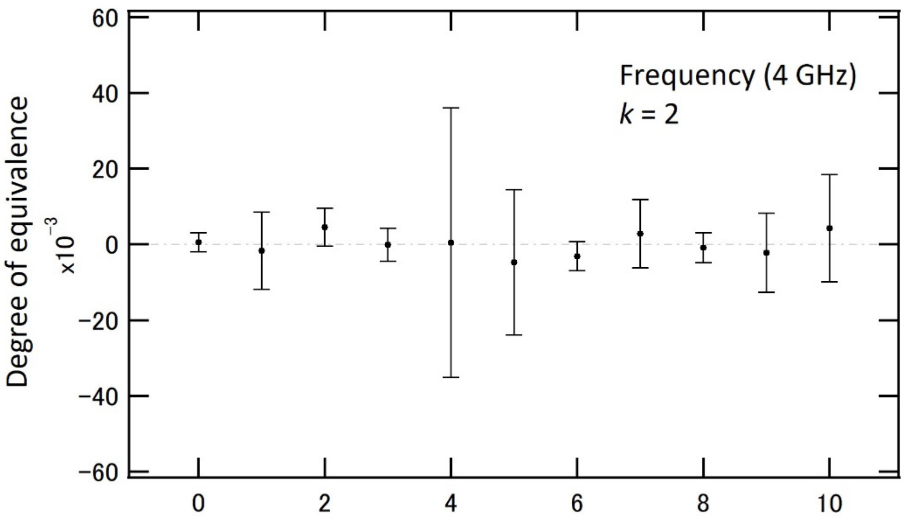


Fig. 8.8 *DoE* between $m(L_i)$ and *APMP RV* (4 GHz, Sensor No. 2)

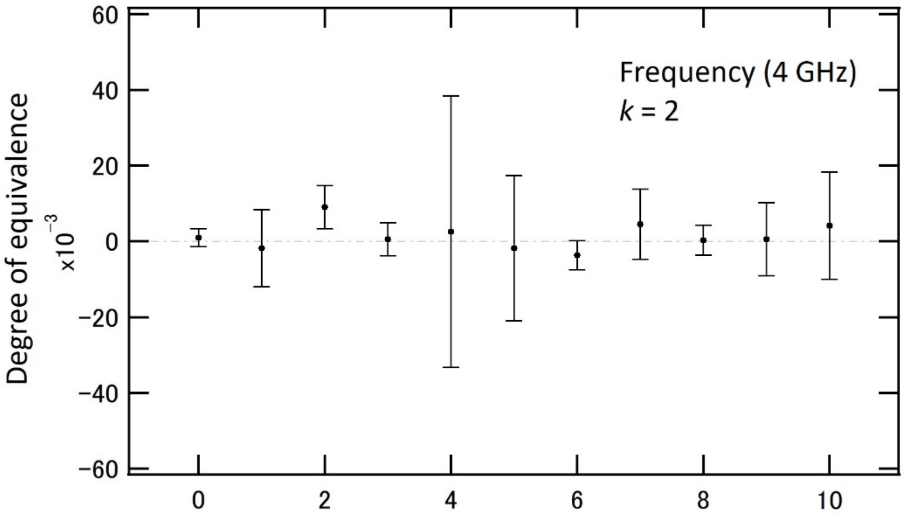


Table 8.7 *DoE* between $m(L_i)$ and *APMP RV* (8 GHz)

Institution ID i	Institution	*DoE* Sensor No. 1		*DoE* Sensor No. 2	
		$d_{i, APMP\,RV}$	$U(d_{i, APMP\,RV})$ ($k = 2$)	$d_{i, APMP\,RV}$	$U(d_{i, APMP\,RV})$ ($k = 2$)
0	NMIJ	0.0000	0.0024	-0.0002	0.0024
1	SCL	-0.0087	0.0161	-0.0091	0.0142
2	NMIA	0.0029	0.0063	0.0073	0.0067
3	MSLNZ	-0.0023	0.0072	-0.0018	0.0072
4	NML	-0.0004	0.0363	0.0078	0.0365
5	NMISA	0.0033	0.0209	0.0069	0.0210
6	NMC	-0.0008	0.0049	-0.0047	0.0049
7	NPL	0.0005	0.0132	0.0035	0.0134
8	KRISS	-0.0012	0.0056	0.0000	0.0056
9	NIM	0.0042	0.0124	0.0029	0.0102
10	NIMT	0.0103	0.0191	0.0099	0.0191

Fig. 8.9 *DoE* between $m(L_i)$ and *APMP RV* (8 GHz, Sensor No. 1)

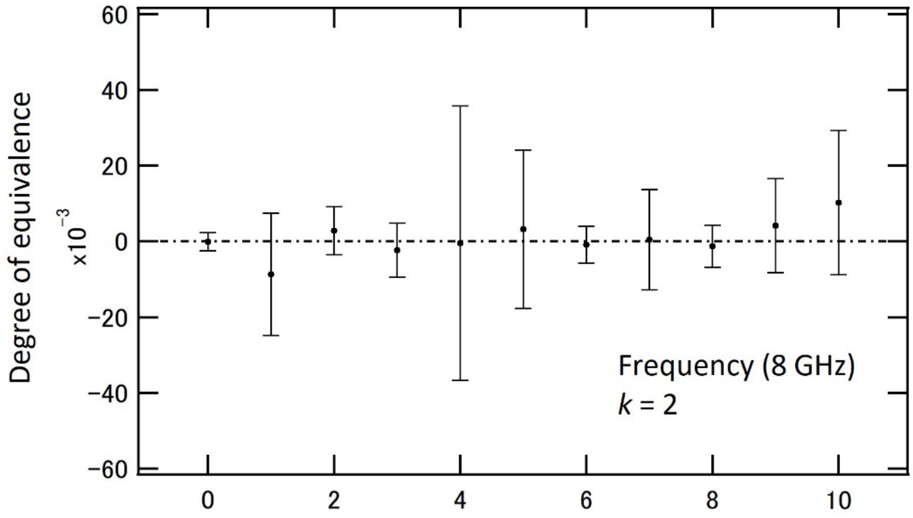


Fig. 8.10 *DoE* between $m(L_i)$ and *APMP RV* (8 GHz, Sensor No. 2)

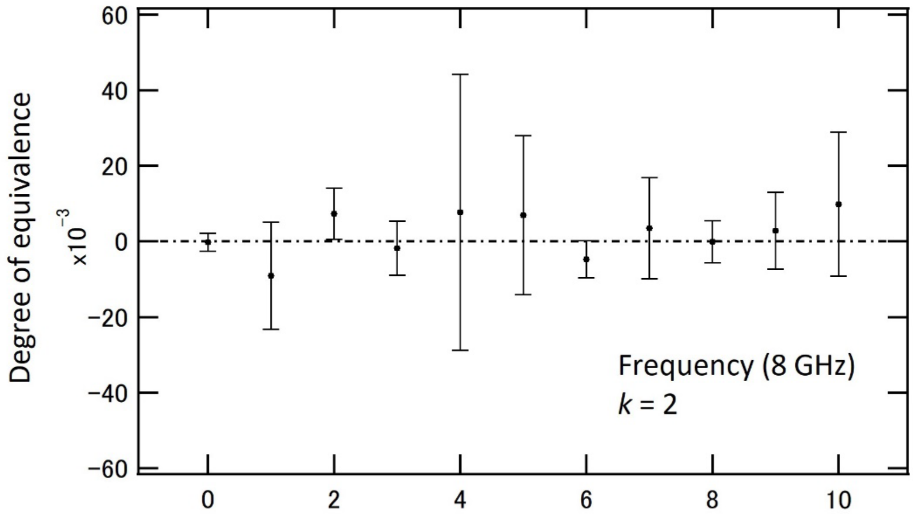


Table 8.8 *DoE* between $m(L_i)$ and *APMP RV* (12 GHz)

Institution ID i	Institution	*DoE* Sensor No. 1		*DoE* Sensor No. 2	
		$d_{i, APMP\ RV}$	$U(d_{i, APMP\ RV})$ $(k = 2)$	$d_{i, APMP\ RV}$	$U(d_{i, APMP\ RV})$ $(k = 2)$
0	NMIJ	0.0002	0.0028	0.0001	0.0025
1	SCL	0.0026	0.0122	0.0029	0.0122
2	NMIA	0.0027	0.0069	0.0064	0.0070
3	MSLNZ	-0.0013	0.0072	-0.0014	0.0074
4	NML	0.0087	0.0423	0.0111	0.0421
5	NMISA	-0.0044	0.0258	-0.0031	0.0258
6	NMC	-0.0002	0.0047	-0.0023	0.0047
7	NPL	0.0046	0.0175	0.0096	0.0167
8	KRISS	-0.0007	0.0045	-0.0005	0.0045
9	NIM	-0.0038	0.0126	-0.0024	0.0104
10	NIMT	0.0046	0.0201	0.0049	0.0201

Fig. 8.11 *DoE* between $m(L_i)$and *APMP RV* (12 GHz, Sensor No. 1)

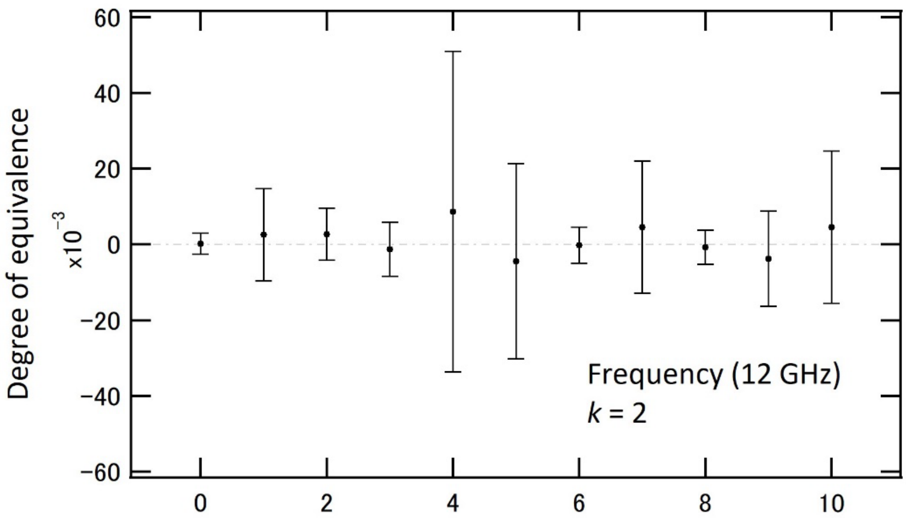


Fig. 8.12 *DoE* between $m(L_i)$ and *APMP RV* (12 GHz, Sensor No. 2)

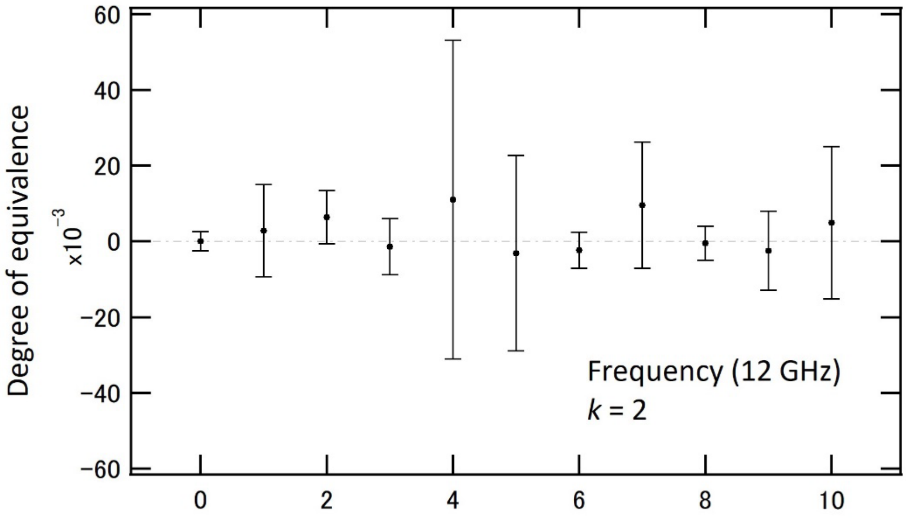


Table 8.9 *DoE* between $m(L_i)$ and *APMP RV* (15 GHz)

Institution ID i	Institution	*DoE* Sensor No. 1		*DoE* Sensor No. 2	
		$d_{i,\,APMP\,RV}$	$U(d_{i,\,APMP\,RV})$ ($k = 2$)	$d_{i,\,APMP\,RV}$	$U(d_{i,\,APMP\,RV})$ ($k = 2$)
0	NMIJ	0.0007	0.0025	0.0003	0.0023
1	SCL	0.0022	0.0181	0.0028	0.0161
2	NMIA	0.0025	0.0077	0.0071	0.0077
3	MSLNZ	-0.0025	0.0069	-0.0027	0.0071
4	NML	0.0027	0.0429	0.0084	0.0423
5	NMISA	-0.0138	0.0305	-0.0102	0.0306
6	NMC	0.0001	0.0051	-0.0022	0.0049
7	NPL	0.0029	0.0183	0.0078	0.0177
8	KRISS	-0.0007	0.0055	0.0004	0.0054
9	NIM	-0.0083	0.0152	-0.0076	0.0124
10	NIMT	0.0042	0.0152	0.0048	0.0142

Fig. 8.13 *DoE* between $m(L_i)$ and *APMP RV* (15 GHz, Sensor No. 1)

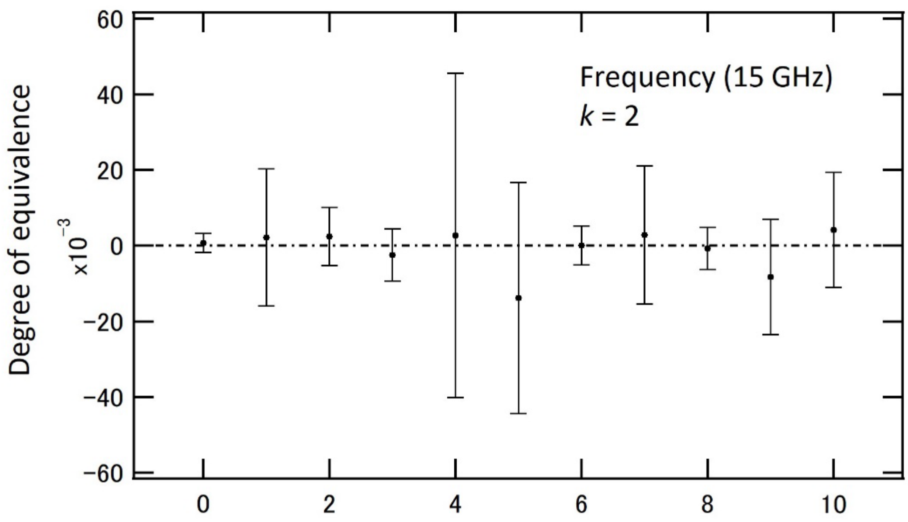


Fig. 8.14 *DoE* between $m(L_i)$ and *APMP RV* (15 GHz, Sensor No. 2)

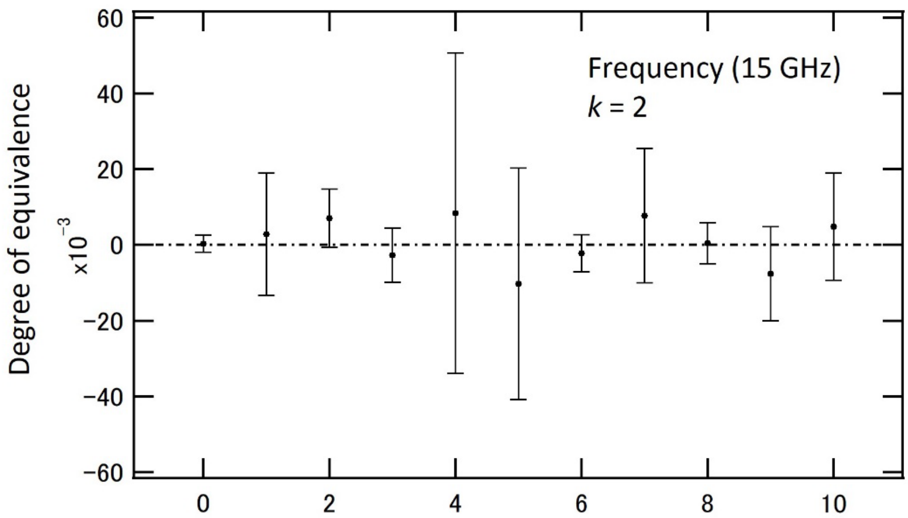


Table 8.10 *DoE* between $m(L_i)$ and *APMP RV* 18 GHz

Institution ID i	Institution	*DoE* Sensor No. 1		*DoE* Sensor No. 2	
		$d_{i, APMP\ RV}$	$U(d_{i, APMP\ RV})$ ($k = 2$)	$d_{i, APMP\ RV}$	$U(d_{i, APMP\ RV})$ ($k = 2$)
0	NMIJ	-0.0010	0.0035	-0.0010	0.0028
1	SCL	0.0152	0.0302	0.0152	0.0282
2	NMIA	0.0059	0.0084	0.0103	0.0083
3	MSLNZ	0.0009	0.0110	0.0006	0.0112
4	NML	-0.0293	0.0545	-0.0199	0.0533
5	NMISA	-0.0028	0.0436	0.0022	0.0420
6	NMC	-0.0001	0.0086	-0.0035	0.0081
7	NPL	-0.0035	0.0250	-0.0007	0.0228
8	KRISS	0.0041	0.0107	0.0031	0.0100
9	NIM	-0.0153	0.0152	-0.0120	0.0139
10	NIMT	0.0052	0.0242	0.0062	0.0242

Fig. 8.15 *DoE* between $m(L_i)$ and *APMP RV* (18 GHz, Sensor No. 1)

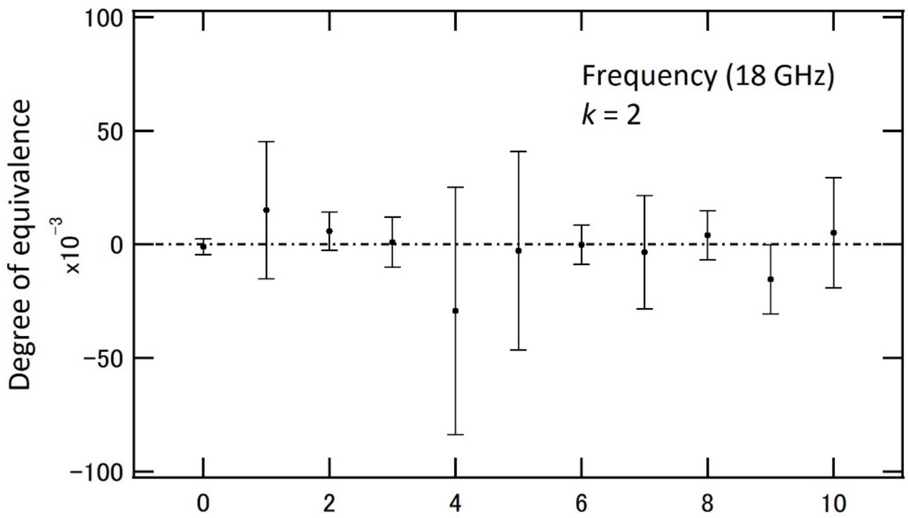
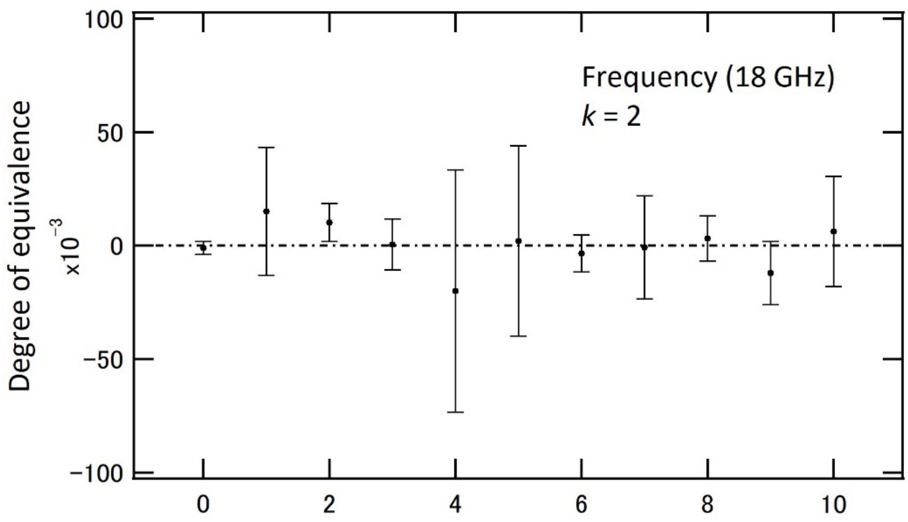


Fig. 8.16 *DoE* between $m(L_i)$ and *APMP RV* (18 GHz, Sensor No. 2)



9. Linking to CCEM KC and *DoE*

9.1 Analysis

APMP.EM.RF-K8.CL was analyzed and linked to the corresponding CCEM KC (CCEM.RF-K8.CL) using the method presented in [47][48]. In this method, it is assumed that a value $m_j(L_i)$ assigned to a traveling standard T_j by a participating institute L_i can be modelled using the sum of the bias $\Delta(L_i)$ of the i th institute, unknown calibration factor m_j of T_j, and random errors or disturbances $e_{j,i}$. Then, an approximation of the best linear unbiased estimator (BLUE) of the bias, $\hat{\Delta}(L_i)$, can be calculated by generalized least-squares (GLS) estimation. The *DoE* between $m(L_i)$ and the *CCEM KCRV* is given as a pair of $\hat{\Delta}(L_i)$ and its uncertainty $U(\hat{\Delta}(L_i))$. The details of the procedure are available in the references. A brief description of the analysis is provided below.

The equation describing the measurement in the two comparisons can be written as

$$m_j(L_i) - APMP\ RV_j = \Delta(L_i) - \left(APMP\ RV_j - m_j\right) + e_{j,i} \quad (9.1.1)$$

$$m_c(L_i) - CCEM\ KCRV = \Delta(L_i) - (CCEM\ KCRV - m_c) + e_{c,i} \quad (9.1.2)$$

where $APMP\ RV_j$ is the *APMP RV* of T_j (j = 1, 2), $m_c(L_i)$ is the linking value assigned to a traveling standard $TM1$ (see below) in the CCEM.RF-K8.CL by a linking institute L_i, m_c is the unknown calibration factor of $TM1$, and $e_{c,i}$ represents all of the random errors or disturbances.

Three traveling standards $TM1$, $TM2$, and $TM3$, were used in the CCEM.RF-K8.CL and the five linking institutes NMIJ, NMIA, NMC, KRISS, and NIM, assigned values to the traveling standards. However, the $TM1$ values were only used as $m_c(L_i)$, because all of the linking institutes performed comparisons for $TM1$, while only two institutes performed comparisons for $TM2$ and $TM3$ differed from T_j in the connector type.

The simultaneous equations (9.1.1) and (9.1.2) can be expressed as

$$\boldsymbol{y} = \boldsymbol{X}\boldsymbol{\beta} + \boldsymbol{e} \quad , \tag{9.1.3}$$

where

$$\boldsymbol{y} = (m_1(L_0), \ldots, m_1(L_{10}), m_2(L_0), \ldots, m_2(L_{10}), m_c(L_0), m_c(L_2), \ldots, m_c(L_9), 0)^{\mathrm{T}} \tag{9.1.4}$$

is a column vector of $m_j(L_i)$ and $m_c(L_i)$ and superscript T denotes transposition. The last component of $\boldsymbol{y}$ is the value of the constraint $CCEM\ KCRV - m_c$. $\boldsymbol{X}$ is a design matrix [47] and $\boldsymbol{\beta}$ is a column vector of unknowns. $\boldsymbol{\beta}$ can be expressed as

$$\boldsymbol{\beta} = (\Delta(L_0), \ldots, \Delta(L_{10}), APMP\ RV_1 - m_1, APMP\ RV_2 - m_2, CCEM\ KCRV - m_c)^{\mathrm{T}} \quad . \tag{9.1.5}$$

$\boldsymbol{e}$ is a column vector of the random errors or disturbances.

$$\boldsymbol{e} = \left(e_{1,0}, \ldots, e_{1,10}, e_{2,0}, \ldots, e_{2,10}, e_{c,0}, e_{c,2}, \ldots, e_{c,9}, e_{const}\right)^{\mathrm{T}} \tag{9.1.6}$$

$\boldsymbol{e}_{\mathrm{const}}$ is the random error or disturbance of the constraint $CCEM\ KCRV - m_c$.

Here, the expected value of $E[e_m]$ is 0, and $E[e_m e_n] = \Phi_{mn}$ where e_m represents the m-th component of $\boldsymbol{e}$. Φ_{mn} is the element in the m-th row and n-th column of the covariance matrix $\boldsymbol{\Phi}$. The number of degrees of freedom ν is a positive integer given by the subtraction of the component number of $\boldsymbol{\beta}$ from $\boldsymbol{y}$.

An approximation to the BULE of $\boldsymbol{\beta}$ is given by the results vector $\widehat{\boldsymbol{\beta}}$:

$$\widehat{\boldsymbol{\beta}} = \widehat{\boldsymbol{C}}\boldsymbol{X}^{\mathrm{T}}\widehat{\boldsymbol{\Phi}}^{-1}\boldsymbol{y} \tag{9.1.7}$$

with uncertainty matrix

$$\widehat{\boldsymbol{C}} = \left(\boldsymbol{X}^{\mathbf{T}}\widehat{\boldsymbol{\Phi}}^{-1}\boldsymbol{X}\right)^{-1} \tag{9.1.8}$$

.

Here, $\widehat{\boldsymbol{\Phi}}$ is an input covariance matrix. The diagonal elements $\widehat{\Phi}_{mm}$ of $\widehat{\boldsymbol{\Phi}}$ are the squared standard uncertainties of the m th component of $\boldsymbol{y}$. The off-diagonal elements $\widehat{\Phi}_{mn}$ = $\widehat{\Phi}_{nm}$ are the covariances of the m-th and n-th component of $\boldsymbol{y}$, which are assumed to be the squared standard uncertainties arising from the direct use of a common reference standard. Correlations between T_1 and T_2 were only considered as the covariance (see 9.2). The diagonal element $\hat{C}_{mm}$ of $\hat{\mathbf{C}}$ is the estimated variance of the m-th component of $\widehat{\boldsymbol{\beta}}$. Then, $U(\hat{\Delta}(L_i))$ is given by $k\sqrt{\hat{C}_{ii}}$ where k is the coverage factor. k was taken to be 2 in this analysis.

The estimated residual sum of squares χ^2 can be used as a measure of the goodness-of-fit of the model.

$$\chi^2 = \left(\boldsymbol{y} - \boldsymbol{X}\widehat{\boldsymbol{\beta}}\right)^{\mathrm{T}}\widehat{\Phi}^{-1}\left(\boldsymbol{y} - \boldsymbol{X}\widehat{\boldsymbol{\beta}}\right) \tag{9.1.9}$$

If (9.1.3) holds and $\boldsymbol{e}$ is drawn from a multivariate normal distribution with Φ, χ^2 will be drawn from a chi-squared distribution with ν degrees of freedom. ν is 13 for 10 MHz and 14 for other frequencies. The *DoE* between the $m(L_i)$ and *CCEM KCRV* given as a set of $\hat{\Delta}(L_i)$ and $U(\hat{\Delta}(L_i))$ is regarded as consistent if

$$\chi^2 \le \chi^2_{\nu,\alpha}, \tag{9.1.10}$$

where $\chi^2_{\nu,\alpha}$ denotes the 100α percentage point of the chi-squared distribution with ν degrees of freedom. α was taken as 0.05 in this analysis.

9.2 Estimation of residual sum of squares χ^2

Table 9.1 Estimation of residual sum of squares χ^2

Frequency (GHz)	Degrees of freedom ν	χ^2
0.01	13	2.826
0.05	14	5.483
1	14	16.028
4	14	12.302
8	14	9.268
12	14	9.721
15	14	14.602
18	14	18.901

Simultaneously with the calculation of $\hat{\boldsymbol{\beta}}$ and $\hat{\mathbf{C}}$, a chi-squared test was performed as a consistency check. The χ^2 values obtained from the test are listed in Table 9.1. The fact that each χ^2 is smaller than $\chi^2_{13,0.05}$ = 22.362 for 10 MHz or $\chi^2_{14,0.05}$ = 23.685 for other frequencies clearly shows the appropriateness of the measurement model. Note that off-diagonal elements $\hat{\Phi}_{mn}$ related to *TM1* were taken to be 0. In fact, we evaluated another case assuming that the off-diagonal elements related to *TM1* had the same value as the covariance, which represents the correlation between T_1 and T_2. However, the evaluation showed that χ^2 was significantly increased and was larger than $\chi^2_{14,0.05}$ for a few measurement frequencies, demonstrating that (9.1.3) no longer holds. We suspect that the overestimation of the off-diagonal elements related to *TM1* caused the increase in χ^2 because the linking laboratories regularly perform independent calibration of the reference standards and the use of the independently calibrated reference standard decreases the measurement correlations over time. Therefore, only the correlation between T_1 and T_2 was considered in this analysis.

9.3 Linking results

The *DoE* between $m(L_i)$ and *CCEM KCRV* is presented in the following tables.

Table 9.2 *DoE* between $m(L_i)$ and *CCEM KCRV* (10 MHz)

Institution ID i	Institution	*DoE*	
		$\hat{\Delta}(L_i)$	$U(\hat{\Delta}(L_i))$ (k = 2)
0	NMIJ	0.0012	0.0059
1	SCL	0.0004	0.0108
2	NMIA	0.0024	0.0055
3	MSLNZ		
4	NML	-0.0233	0.0232
5	NMISA	0.0014	0.0146
6	NMC	0.0029	0.0103
7	NPL	0.0021	0.0084
8	KRISS	0.0071	0.0052
9	NIM	-0.0017	0.0079
10	NIMT	-0.0016	0.0124

Fig. 9.1 *DoE* between $m(L_i)$ and *CCEM KCRV* (10 MHz)

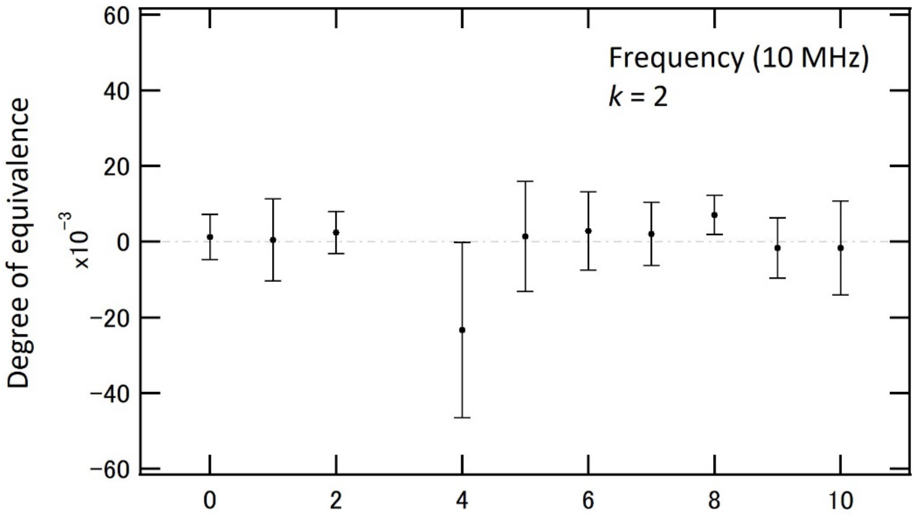


Table 9.3 *DoE* between $m(L_i)$ and *CCEM KCRV* (50 MHz)

Institution ID i	Institution	*DoE*	
		$\hat{\Delta}(L_i)$	$U(\hat{\Delta}(L_i))$ (k = 2)
0	NMIJ	0.0029	0.0036
1	SCL	0.0028	0.0056
2	NMIA	0.0015	0.0029
3	MSLNZ	0.0036	0.0037
4	NML	0.0016	0.0226
5	NMISA	0.0053	0.0139
6	NMC	0.0013	0.0036
7	NPL	0.0099	0.0056
8	KRISS	0.0008	0.0020
9	NIM	0.0020	0.0051
10	NIMT	0.0043	0.0109

Fig. 9.2 *DoE* between $m(L_i)$ and *CCEM KCRV* (50 MHz)

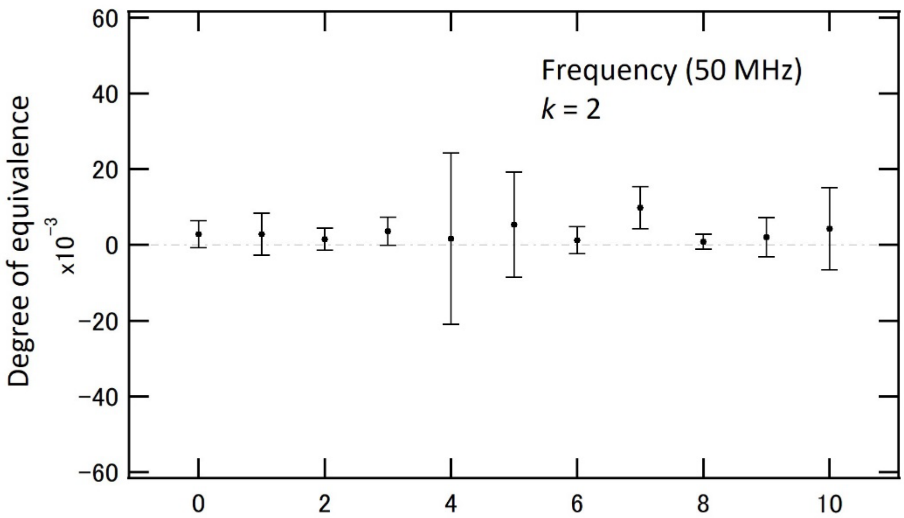


Table 9.4 *DoE* between $m(L_i)$ and *CCEM KCRV* (1 GHz)

Institution ID i	Institution	*DoE*	
		$\hat{\Delta}(L_i)$	$U(\hat{\Delta}(L_i))$ ($k = 2$)
0	NMIJ	0.0031	0.0038
1	SCL	0.0009	0.0062
2	NMIA	0.0032	0.0032
3	MSLNZ	0.0030	0.0054
4	NML	0.0049	0.0264
5	NMISA	0.0070	0.0138
6	NMC	0.0011	0.0035
7	NPL	0.0115	0.0073
8	KRISS	0.0006	0.0023
9	NIM	-0.0010	0.0048
10	NIMT	0.0060	0.0119

Fig. 9.3 *DoE* between $m(L_i)$ and *CCEM KCRV* (1 GHz)

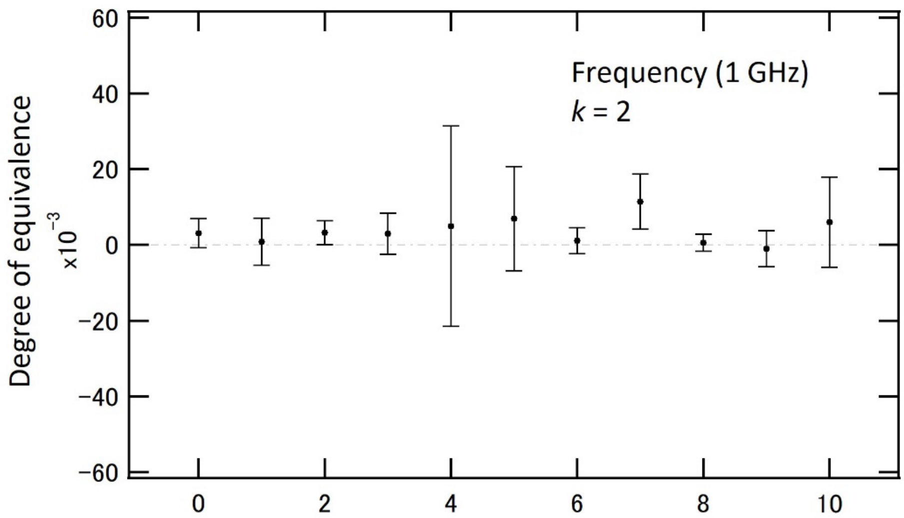


Table 9.5 *DoE* between $m(L_i)$ and *CCEM KCRV* (4 GHz)

Institution ID i	Institution	*DoE* Sensor	
		$\hat{\Delta}(L_i)$	$U(\hat{\Delta}(L_i))$ (k = 2)
0	NMIJ	0.0006	0.0046
1	SCL	-0.0016	0.0097
2	NMIA	0.0035	0.0041
3	MSLNZ	0.0004	0.0060
4	NML	0.0016	0.0264
5	NMISA	-0.0031	0.0175
6	NMC	-0.0017	0.0046
7	NPL	0.0038	0.0086
8	KRISS	0.0004	0.0041
9	NIM	0.0016	0.0059
10	NIMT	0.0044	0.0130

Fig. 9.4 *DoE* between $m(L_i)$ and *CCEM KCRV* (4 GHz)

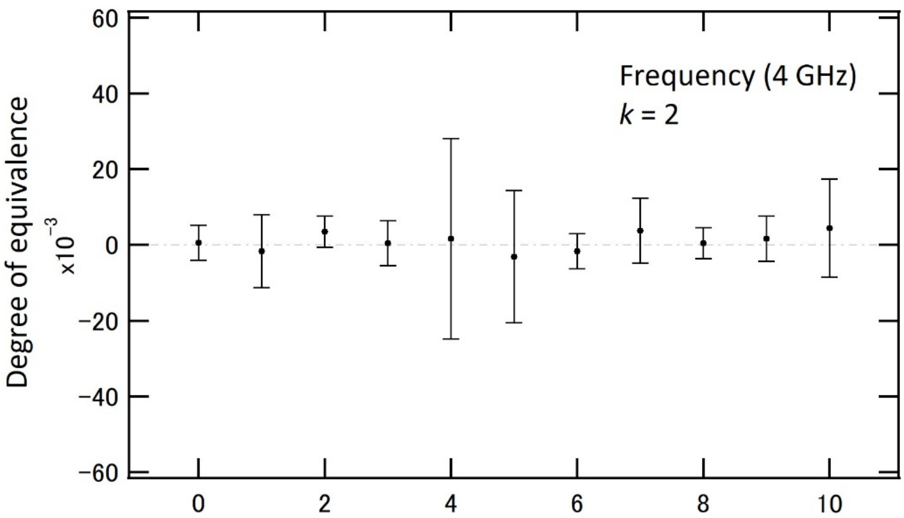


Table 9.6 *DoE* between $m(L_i)$ and *CCEM KCRV* (8 GHz)

Institution ID i	Institution	*DoE*	
		$\hat{\Delta}(L_i)$	$U(\hat{\Delta}(L_i))$ ($k = 2$)
0	NMIJ	-0.0015	0.0065
1	SCL	-0.0103	0.0148
2	NMIA	0.0018	0.0066
3	MSLNZ	-0.0034	0.0091
4	NML	0.0024	0.0272
5	NMISA	0.0038	0.0206
6	NMC	-0.0022	0.0068
7	NPL	0.0007	0.0123
8	KRISS	-0.0029	0.0067
9	NIM	0.0033	0.0080
10	NIMT	0.0088	0.0186

Fig. 9.5 *DoE* between $m(L_i)$ and *CCEM KCRV* (8 GHz)

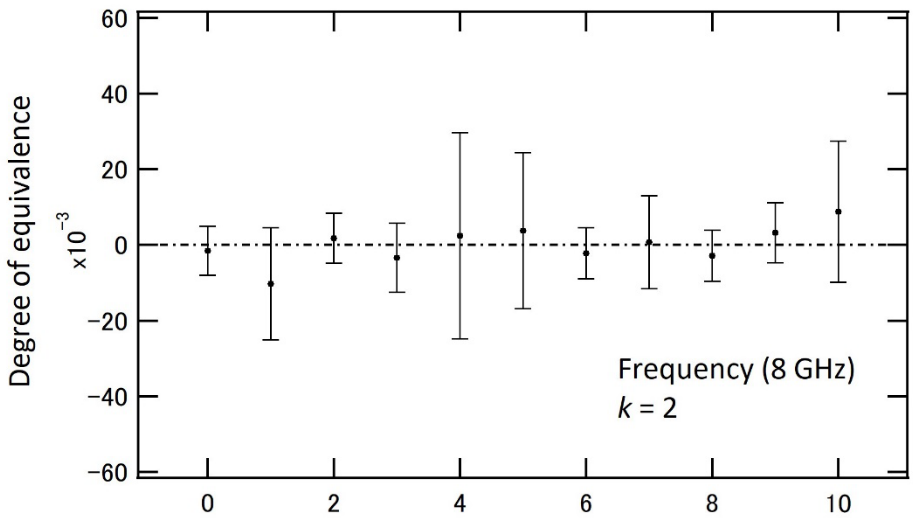


Table 9.7 *DoE* between $m(L_i)$ and *CCEM KCRV* (12 GHz)

Institution ID i	Institution	*DoE*	
		$\hat{\Delta}(L_i)$	$U(\hat{\Delta}(L_i))$ ($k = 2$)
0	NMIJ	0.0024	0.0054
1	SCL	0.0060	0.0107
2	NMIA	0.0044	0.0058
3	MSLNZ	0.0029	0.0087
4	NML	0.0177	0.0317
5	NMISA	0.0065	0.0242
6	NMC	0.0028	0.0053
7	NPL	0.0109	0.0141
8	KRISS	0.0026	0.0055
9	NIM	0.0041	0.0063
10	NIMT	0.0090	0.0183

Fig. 9.6 *DoE* between $m(L_i)$ and *CCEM KCRV* (12 GHz)

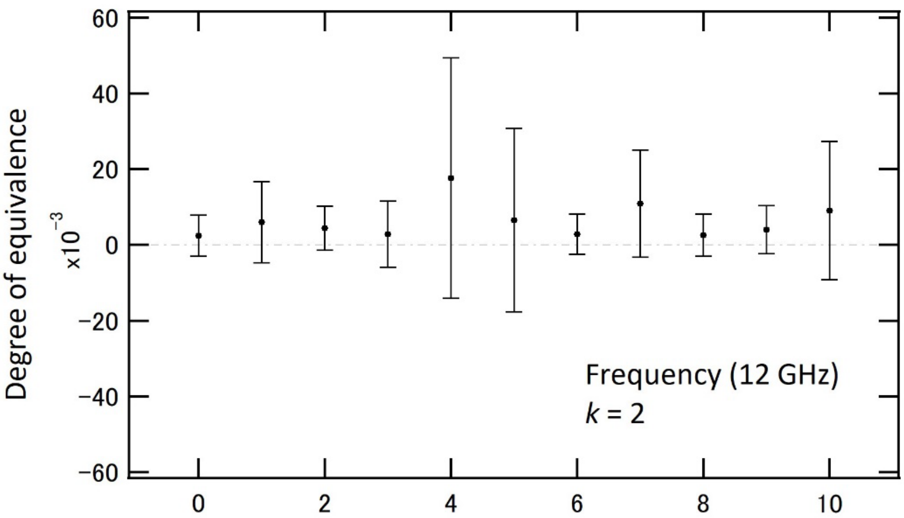


Table 9.8 *DoE* between $m(L_i)$ and *CCEM KCRV* (15 GHz)

Institution ID i	Institution	*DoE*	
		$\hat{\Delta}(L_i)$	$U(\hat{\Delta}(L_i))$ (k = 2)
0	NMIJ	-0.0010	0.0068
1	SCL	0.0013	0.0149
2	NMIA	-0.0023	0.0076
3	MSLNZ	-0.0039	0.0095
4	NML	0.0043	0.0322
5	NMISA	-0.0133	0.0300
6	NMC	-0.0010	0.0069
7	NPL	0.0042	0.0153
8	KRISS	-0.0014	0.0071
9	NIM	0.0004	0.0078
10	NIMT	0.0033	0.0141

Fig. 9.7 *DoE* between $m(L_i)$ and *CCEM KCRV* (15 GHz)

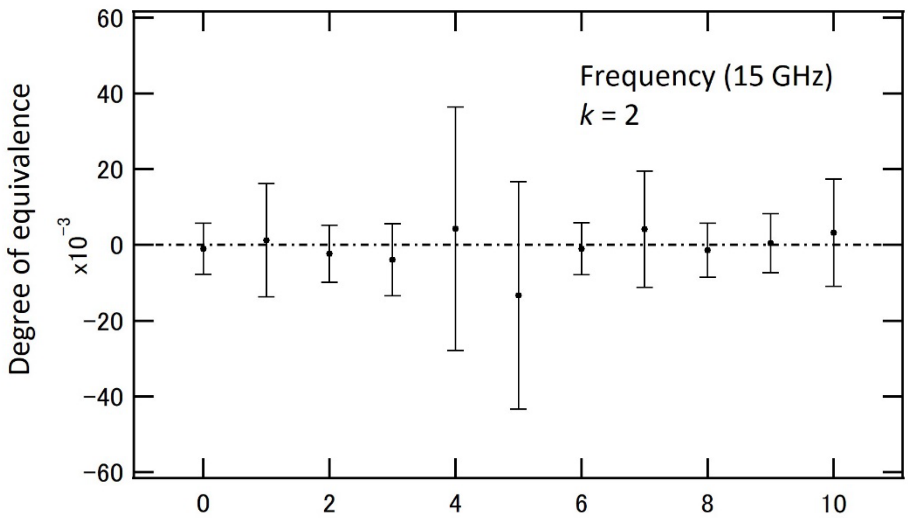
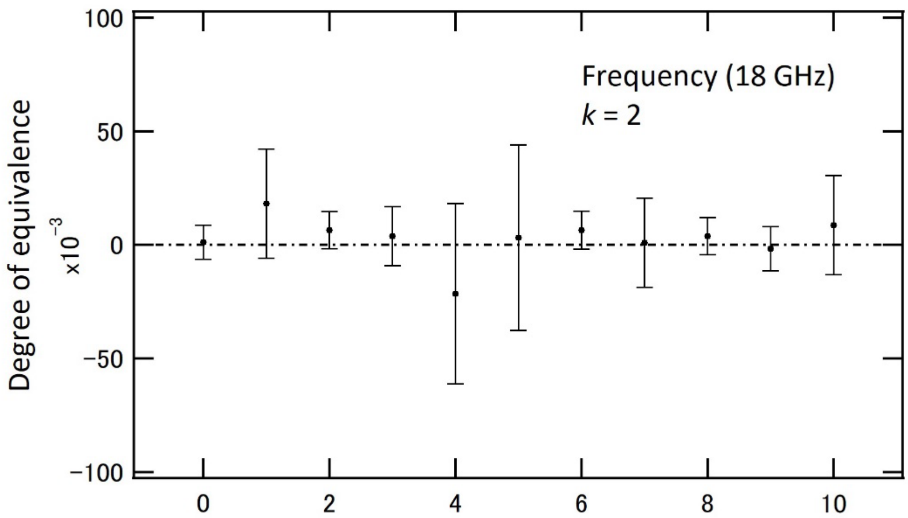


Table 9.9 *DoE* between $m(L_i)$ and *CCEM KCRV* (18 GHz)

Institution ID i	Institution	*DoE*	
		$\hat{\Delta}(L_i)$	$U(\hat{\Delta}(L_i))$ (k = 2)
0	NMIJ	0.0013	0.0075
1	SCL	0.0182	0.0240
2	NMIA	0.0066	0.0082
3	MSLNZ	0.0038	0.0129
4	NML	-0.0214	0.0397
5	NMISA	0.0031	0.0408
6	NMC	0.0066	0.0083
7	NPL	0.0011	0.0196
8	KRISS	0.0039	0.0082
9	NIM	-0.0016	0.0098
10	NIMT	0.0088	0.0218

Fig. 9.8 *DoE* between $m(L_i)$ and *CCEM KCRV* (18 GHz)



10. Conclusions

The calibration factors of the pilot laboratory were reported at the starting time point, intermediate time point, and ending time point. Their changes were significantly smaller than the dispersion of the calibration factors reported by all of the participants, which proves that the traveling standards had sufficient stability.

The dispersion of the calibration factors and reported uncertainties were of the same order of magnitude and no over dispersion was observed.

Only two outliers were found among the total of 174 reported calibration factors, which justifies adoption of the weighted mean as the *APMP RV* calculation method.

The comparison results were analyzed and linked to the KC CCEM.RF-K8.CL using GLS estimation. The simultaneously performed chi-squared test confirmed the appropriateness of the linking model.

These facts strongly support that this comparison was successfully performed and that the *DoE* between the calibration factors of the participants, *APMP RV* and *CCEM KCRV* can be reliably used to establish the calibration measurement capability of each participating institution.

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Appendix

Appendix A Reflection measurements

Appendix B Technical protocol

Appendix C Measurement reports

Appendix A Reflection measurements

NIMT did not report the uncertainty or traceability source; therefore, their data are not plotted in the following graphs. The institution ID numbers are the same as those given in the first columns of Table 8.3–8.10.

Fig. A.1 Reflection coefficient (10 MHz, Sensor No.1)

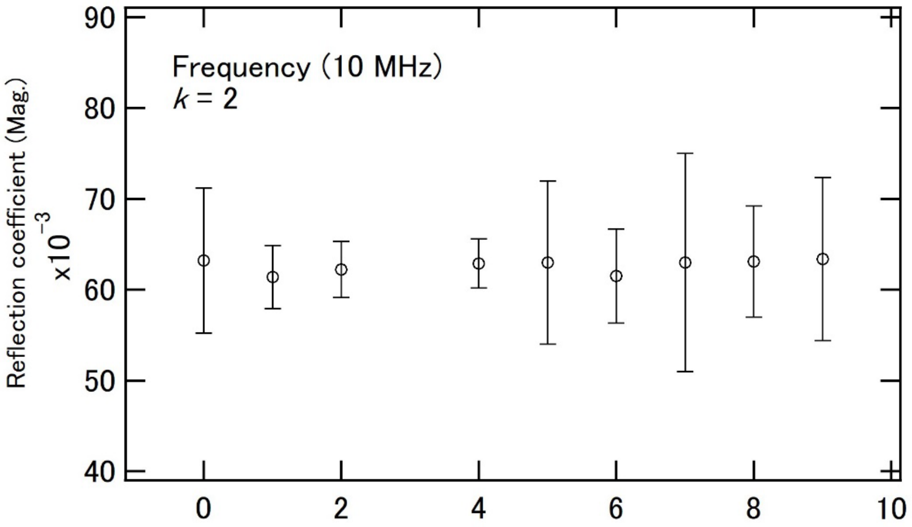


Fig. A.2 Reflection coefficient (10 MHz, Sensor No.2)

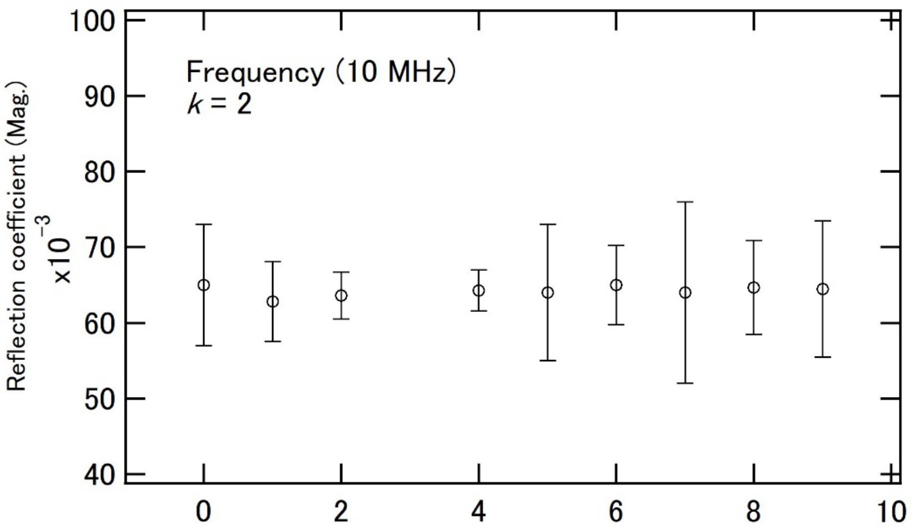


Fig. A.3 Reflection coefficient (50 MHz, Sensor No.1)

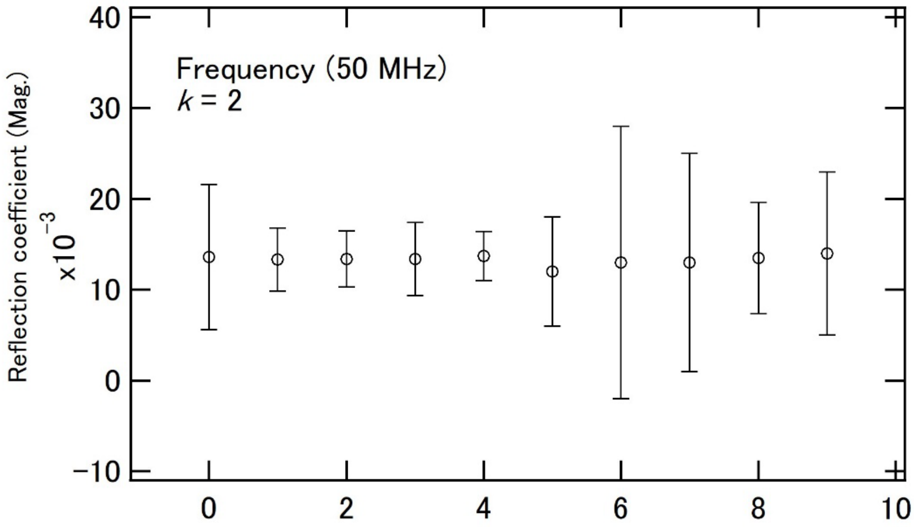


Fig. A.4 Reflection coefficient (50 MHz, Sensor No.2)

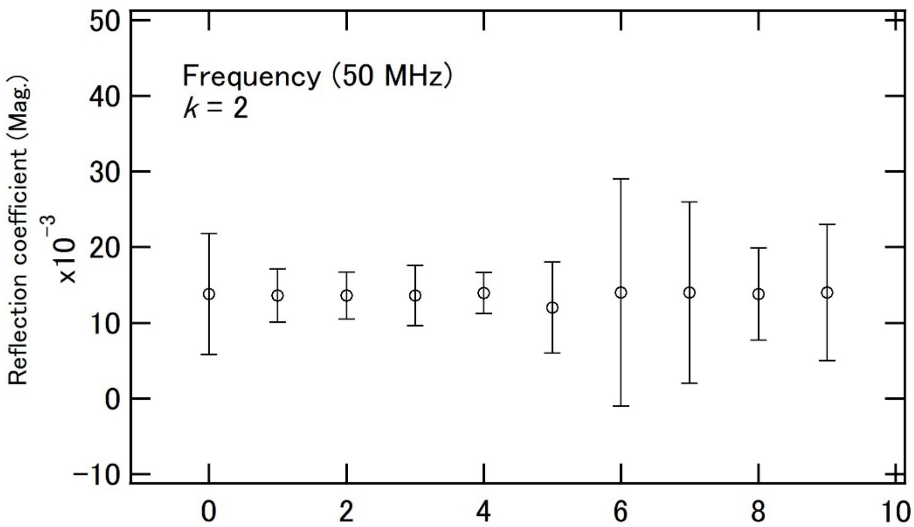


Fig. A.5 Reflection coefficient (1 GHz, Sensor No.1)

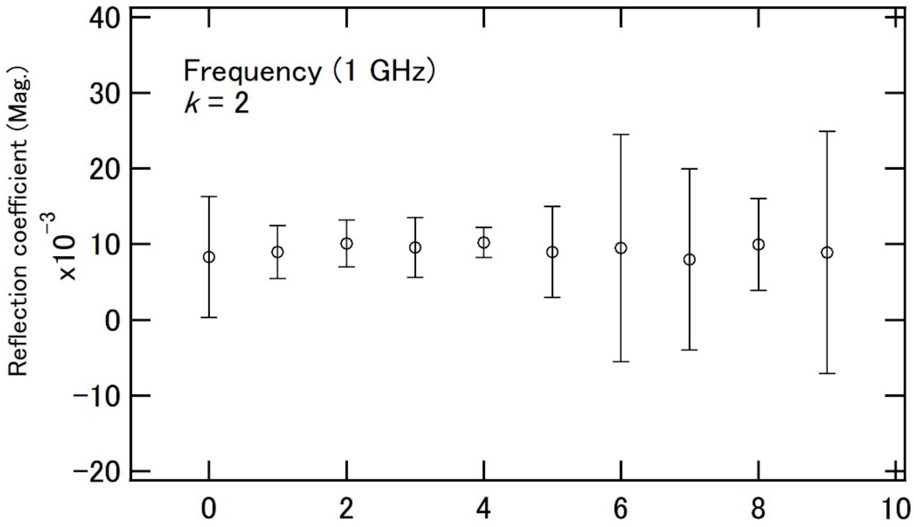


Fig. A.6 Reflection coefficient (1 GHz, Sensor No.2)

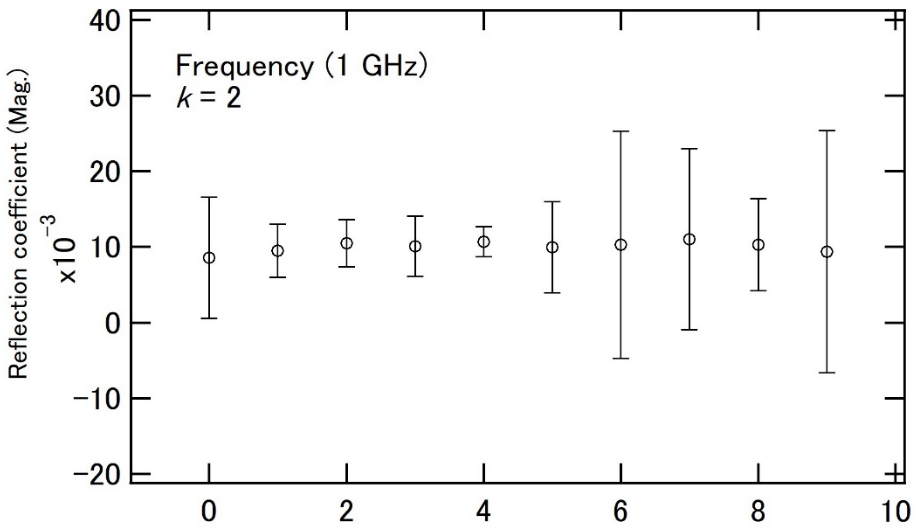


Fig. A.7 Reflection coefficient (4 GHz, Sensor No.1)

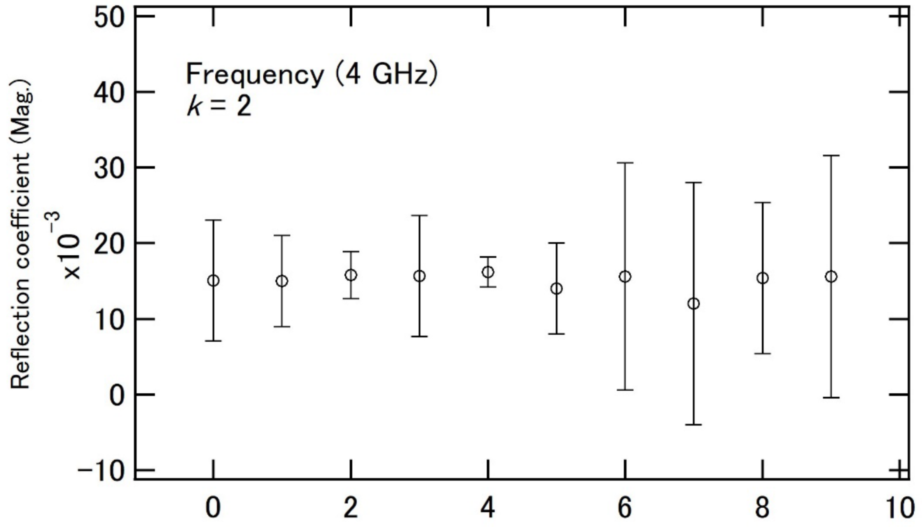


Fig. A.8 Reflection coefficient (4 GHz, Sensor No.2)

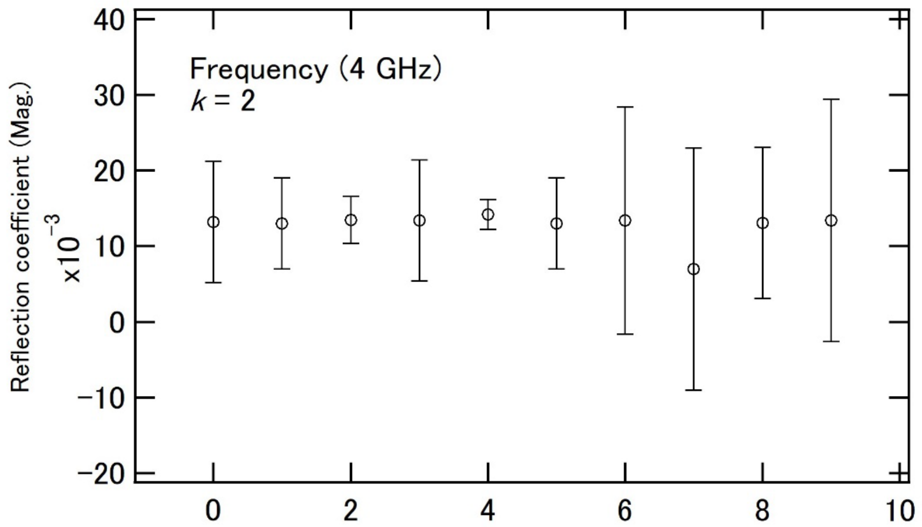


Fig. A.9 Reflection coefficient (8 GHz, Sensor No.1)

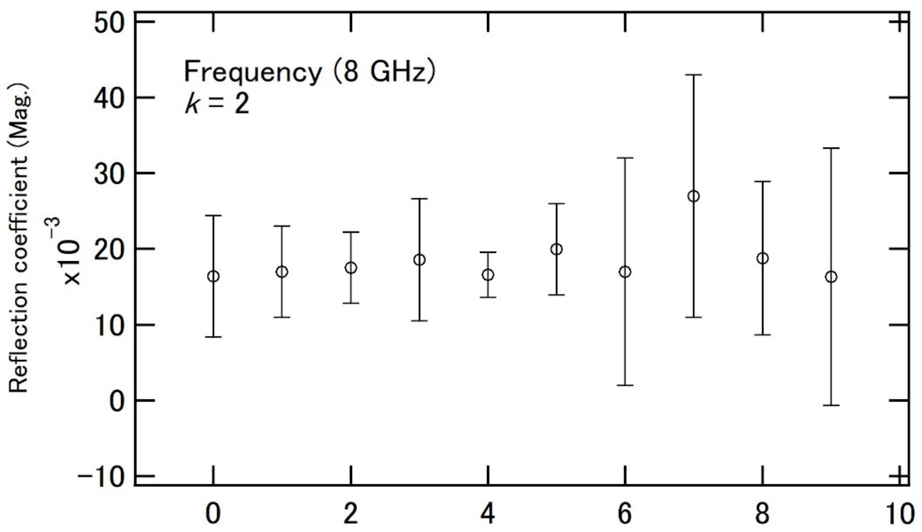


Fig. A.10 Reflection coefficient (8 GHz, Sensor No.2)

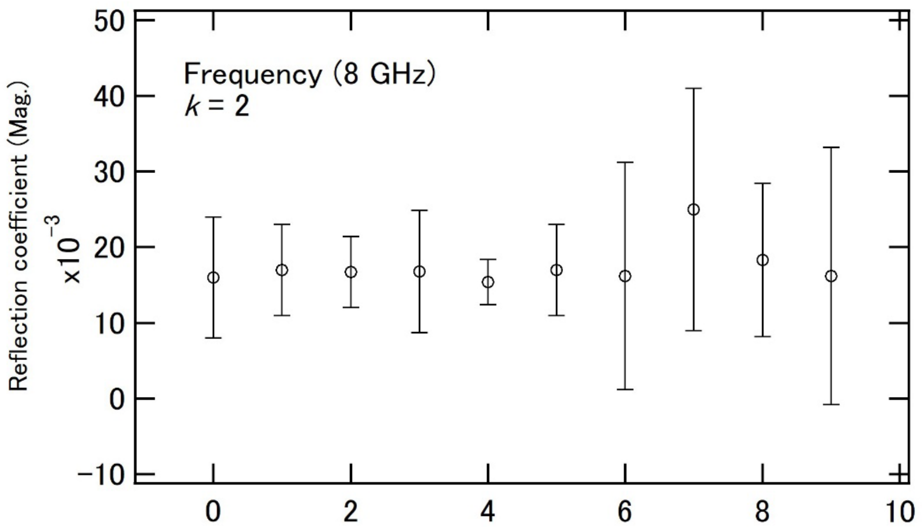


Fig. A.11 Reflection coefficient (12 GHz, Sensor No.1)

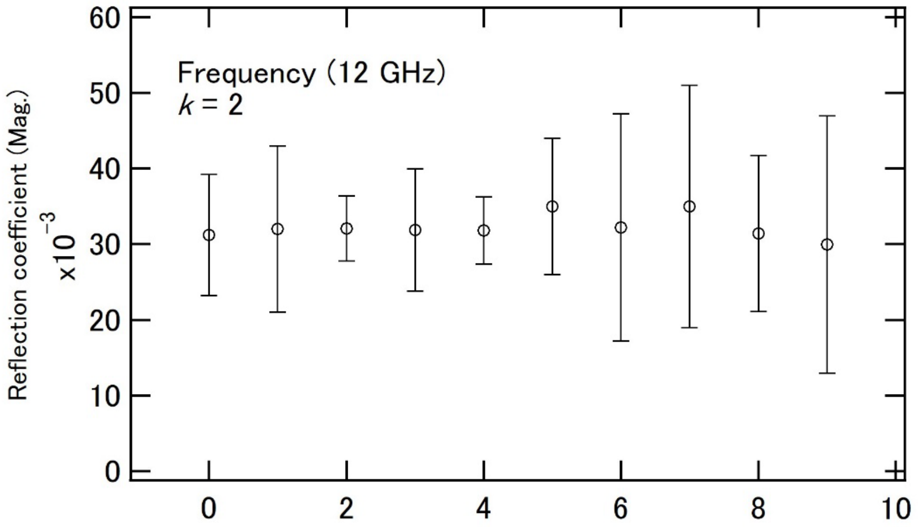


Fig. A.12 Reflection coefficient (12 GHz, Sensor No.2)

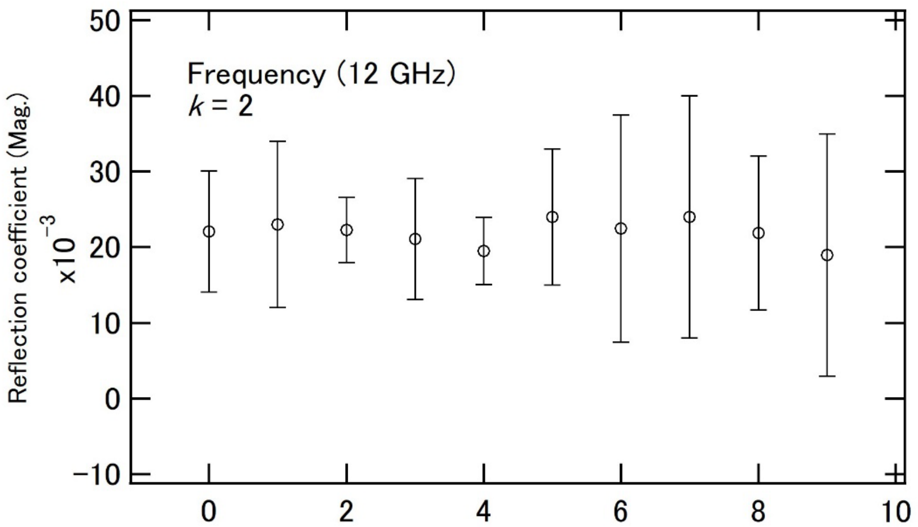


Fig. A.13 Reflection coefficient (15 GHz, Sensor No.1)

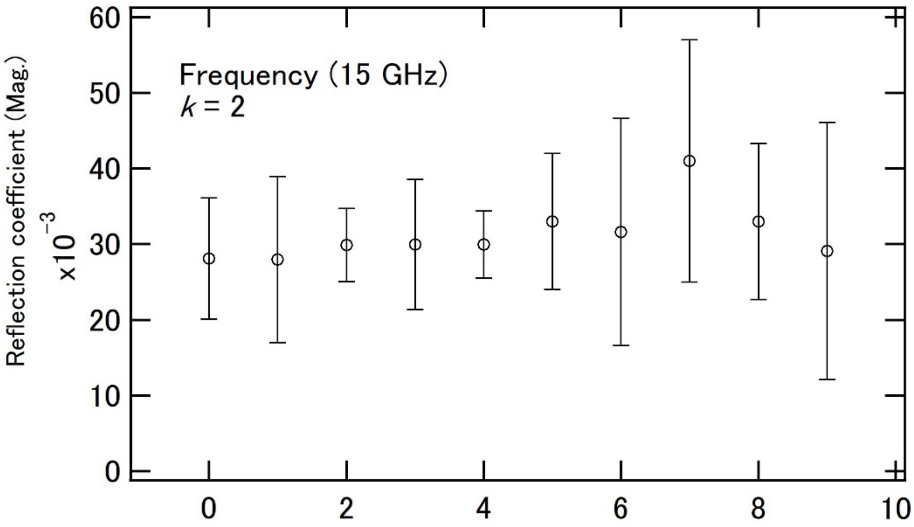


Fig. A.14 Reflection coefficient (15 GHz, Sensor No.2)

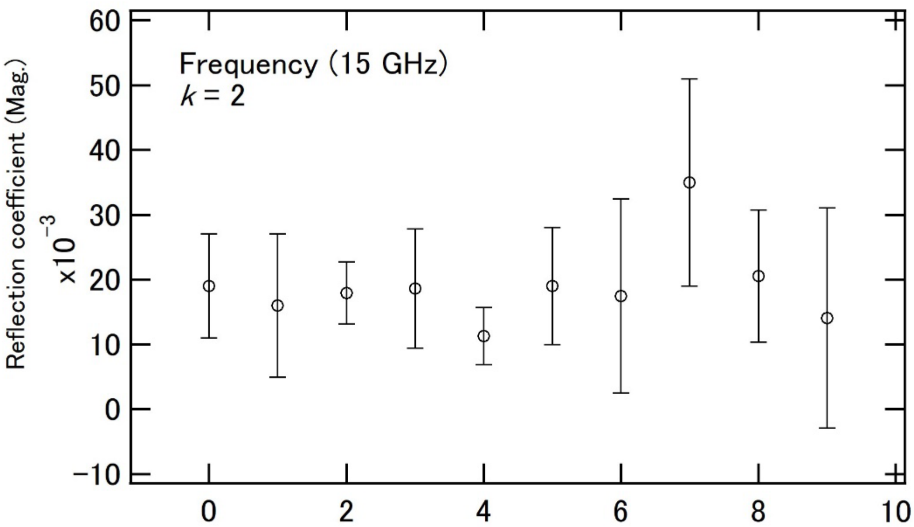


Fig. A.15 Reflection coefficient (18 GHz, Sensor No.1)

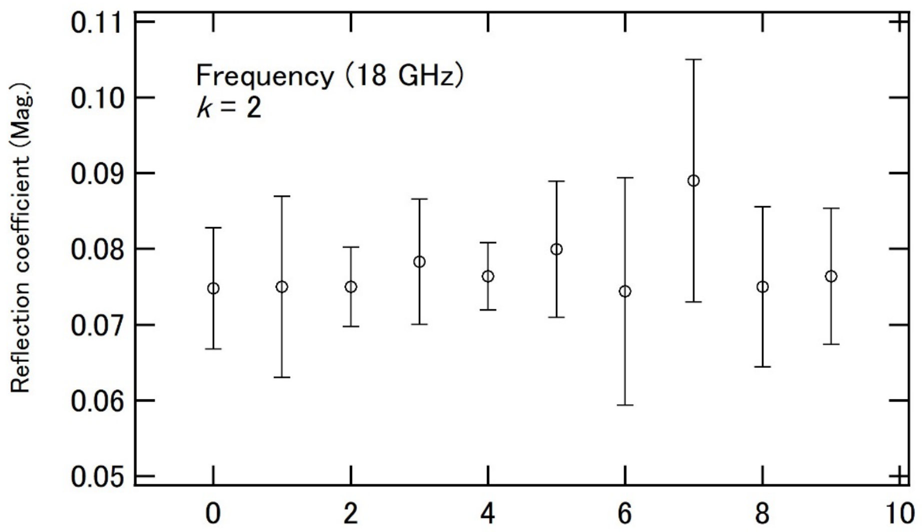
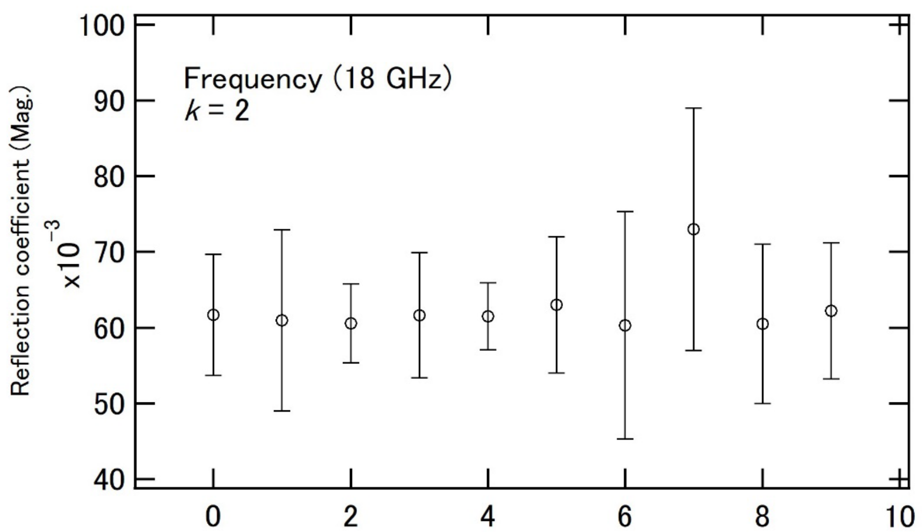


Fig. A.16 Reflection coefficient (18 GHz, Sensor No.2)



Appendix B Technical protocol

Final(ver. 6.3.2)

APMP KEY COMPARISON APMP.EM.RF-K8.CL

“Power in 50 Ω coaxial line, frequency: 10 MHz to 18 GHz”

Technical protocol

Contents

1. Introduction

An international key comparison (KC), CCEM.RF-K8, was carried out between August 1999 and December 2000. The final report [1] was published in May 2005. The calibration factors of three thermistor mounts were reported from 17 national metrology institutes (NMI) at eight frequencies ranging from 10 MHz to 18 GHz. The results showed good agreement among most of the participants. The CIPM MRA [2] requires that Regional Metrology Organization (RMO) KCs be linked to the corresponding CIPM KCs by means of joint participants. Five NMIs from the Asia Pacific Metrology Program (APMP) are planning to participate in this comparison.

Before the seventh meeting of the Technical Committee on Electricity and Magnetism Asia Pacific Metrology Program (TCEM APMP) [3] in October 2004, the Chair expressed his opinion that the planning of APMP KCs should be given higher priority. Following this opinion, a questionnaire was sent out to investigate the available resources for KCs. The National Metrology Institute of Japan (NMIJ) indicated the possibility of a contribution to radio frequency (RF) power measurement. After the investigation, the Chair proposed an RF-power (10 MHz to 18 GHz) comparison, which was numbered APMP.EM.RF-K8, as a possible APMP KC in TCEM APMP. This proposal was approved in the meeting.

The coordinator planned the start of the comparison to be during 2006 [4]. However, the start was postponed to 2007. This was mainly because of the time needed for investigating the KC rules [5-11], the method of calculating the key comparison reference value (KCRV) [12-19], and the means of linking the RMO result to KC results [20-25].

Although the comparison almost started in early 2008, it was found that traveling standards are not allowed for export to one participating country for political reasons. As it was difficult to prepare a new traveling standard, this problem was reported in the 11th APMP TCEM Meeting. It was agreed that the comparison should proceed with other participants at the meeting.

Additionally, a problem regarding the linking method between APMP KC and CIPM KC remained. As the pilot laboratory investigated many linking reports on other RMO comparisons, it was found that a special linking method should have been designed for APMP.EM.RF-K8.CL. The pilot laboratory developed a new linking method with the assistance of the Applied Statistics Division of NMIJ in 2009. This linking method was discussed between the members of the organization group at Conference on Precision Electromagnetic Measurements 2010 held in South Korea. However, the members could not reach on agreement about the adoption of the method. As the coordinator reasoned all possible efforts had been made, he decided to suspend this problem temporally, and restarted the preparation of traveling standards.

Because of the Higashi-Nihon Great Earthquake, the pilot laboratory had to suspend the preparation for six month.

This technical protocol was prepared according to the Guidelines for CIPM Key Comparisons [5, 6].

2. Traveling standards

2.1 General requirements

In international comparisons of RF power, thermal sensors have been used as traveling standards [1, 26, 27]. These sensors transform incident RF power into heat in the RF load installed in the sensors. Then, the temperature change of the RF load is transformed into DC power or DC voltage. The DC power or DC voltage directly reflects the averaged incident RF power. The reflection coefficients of the sensors should be as small as possible to minimize source mismatch error.

There are two representative thermal sensors: thermistor sensors and thermocouple sensors. Thermistor sensors are a type of bolometer, in which the RF power absorbed in the thermistor changes its resistance. A control circuit then decreases the initially fed DC power into the thermistor so that its resistance is constant regardless of incident RF power. Consequently, the decreased DC power directly represents the incident RF power. Thermocouple sensors are based on the Seebeck effect, which is related to the heat of absorbed RF power. The absorbed RF power increases the temperature of the thermocouple installed in the sensor; then, the voltage generated by the Seebeck effect is measured. Thermistor sensors were used in the CCEM key comparison CCEM.RF-K8.CL [1], while thermocouple sensors were used in EUROMET.EM.RF-K10.CL [26] and CCEM.RF-S1.CL [27].

In this comparison, APMP.EM.RF-K8.CL, two thermocouple sensors with an RF power meter are used for the following reasons:

(1) The thermocouple sensor is most often used for transferring the calibration factor of RF power, whereas the thermistor sensor has a relatively limited use.
(2) A universal design is adopted for the power source of modern RF power meters for thermocouple sensors. This makes it possible to avoid the problem of the different power voltages among countries. On the other hand, the power meter for the thermistor sensor has only a localized power source.
(3) Generally, thermocouple sensors have smaller reflection coefficients than thermistor sensors. This reduces the uncertainty associated with source mismatch error.

Note that because the output is given as a DC voltage proportional to the incident RF power, at least one reference incident RF power is required to adjust the indication of the power meter; in most cases, this reference power source is provided as a built-in power source of corresponding power meters. The results of measurements thus depend on the stability of this reference incident RF power. This stability will be monitored by the calibration laboratory. Should a significant drift be observed, the organization group (see chapter 3) will discuss the necessity of correction.

2.2 Description of standards

The traveling standards consist of two Agilent 8481A thermocouple power sensors and an E4419B power meter.

Specifications of the 8481A thermocouple power sensors:

Operating frequency	10 MHz to 18 GHz
Maximum power	300 mW (average)
Connector type	Type-N male
Maximum SWR	1.40 (10 MHz to 30 MHz)
	1.18 (30 MHz to 50 MHz)
	1.10 (50 MHz to 2 GHz)
	1.18 (2 GHz to 12.4 GHz)
	1.28 (12.4 GHz to 18 GHz)
Dimensions	38 mm wide, 30 mm high, 150 mm long
Weight	0.2 kg

Specifications of the E4419B power meter:

50 MHz power reference	1.00 mW
Line power	85 to 264 VAC, automatic selection
Line frequency	50 to 440 Hz
Interface	HP-IB, IEEE RS-232, and RS-442
Dimensions	212.6 mm wide, 88.5 mm high, 348.3 mm long
Weight	4.1 kg

Fig. 1 Agilent Technologies E4419B power meter and 8481A power sensor

Further information can be found on the Agilent Technologies website.

Table 2.1 List of traveling standards

Identifier	Model name and number	Serial number
Sensor No. 1	8481A	US41031012
Sensor No. 2	8481A	US41031013
Power meter No. 1	E4419B	MY45100436

2.3 Quantities to be measured

The calibration factor at specified frequencies f is measured. The calibration factor $K(f)$ of a set comprising a power meter and a sensor is defined as the indication on the power meter $P_{\mathrm{m}}(f)$ divided by the incident power to the power sensor, $P_{\mathrm{in}}(f)$.

$$K(f) = \frac{P_m(f)}{P_{in}(f)} \quad (2.3.1)$$

Each laboratory also reports associated combined standard uncertainties $u_c(K)$ and their coverage factors k, where expanded uncertainties $U = ku_c(K)$ define intervals having a level of confidence of 95 %.

The gain of the power meter must be calibrated to a thermocouple power sensor using a 50 MHz 1 mW reference power source before its use [28]. **Each of the laboratories is required to use the same calibrator built inside a traveling standard (E4419B).** The power level of the reference power source may change slightly during transport. This stability will be monitored by the pilot laboratory. Should a significant drift be observed, the organization group will discuss the necessity of correction.

The measurements will be performed at 10 MHz, 50 MHz, 1 GHz, 4 GHz, 8 GHz, 12 GHz, 15 GHz, and 18 GHz. These are the same as the frequencies used in CCEM.RF-K8. The incident power $P_{in}(f)$ is 1 mW. This incident power level can be slightly different from 1 mW because the detector's linearity at approximately 1 mW is excellent. Therefore, the difference can be easily characterized as a very small uncertainty component. The measurement technique is left to the discretion of the participant. However, it should be the same as the method used in the ordinary calibration service.

The type-N connector should be tightened using a torque of 1.36 Nm (12 in-lb). The protrusion of the center conductor pin and the laboratory test port must be checked to prevent damage to the traveling standards [29]. **The traveling standards should not be connected to the test port of a calibration system without measuring the pin depths of both the traveling standards and the test port.** The pin depths should be checked to determine whether they are within their specifications; if not, the pilot laboratory should be immediately contacted.

2.4 Additional measurements

The reflection coefficients of the traveling standards can be reported. *This report is not requisite and does not constitute a key comparison.* Both vector (complex) and scalar reflection coefficients are acceptable. Their uncertainties must be reported as an interval having a level of confidence of approximately 95 %. Their traceability sources must be reported. If the reported values lack uncertainties and/or traceability, it is not reflected in the final report.

2.5 Method of computation of KCRV

The key comparison reference value (KCRV) will be determined from the weighted mean of the results reported from member laboratories of CCEM. On the basis of the method proposed by Cox [18, 19], the weighted mean is calculated from the largest consistent subset. To evaluate the weighted mean, standard uncertainty, and degree of equivalences, *procedure A* shown in ref. 18 is used, while the values contributing to the calculation are determined by the procedure described in ref. 19. The detailed procedure is available in the references.

3. Organization

Three participants who declared their interest in participation from July to August 2006 were invited to assist the pilot laboratory as members of the supporting group [5]. Dr. Kim (Korea), Dr. Shan (Singapore), and Mr. Zhang (Australia) agreed to this arrangement in August 2006. The pilot laboratory and supporting group will be called "the organization group" hereafter. The APMP TCEM chair, who serves as an observer, is informed of the progress of this comparison.

3.1 Coordinator and members of support group

The address of the coordinator is as follows.

Dr. Kazuhiro Shimaoka
Senior Research Scientist
National Institute of Advanced Industrial Science and Technology (AIST)
National Metrology Institute of Japan (NMIJ)
Electromagnetic Waves Division, Radio-Frequency Section
Central 3, 1-1-1 Umezono, Tsukuba, Ibaraki 305-8563, Japan
TEL: +81-29-861-6828, FAX: +81-29-861-4289
E-mail: kazuhiro-shimaoka@aist.go.jp

The addresses of the members of the support group are as follows.

Dr. Jeong-Hwan Kim
Principal Researcher
Division of Physical Metrology
Electromagnetic Metrology Group
KRISS
Korea Research Institute of Standards and Science
P.O. Box 102, Yusong, Taejon 305-600, Korea
TEL: +82-42-868-5170
FAX:+82-42-868-5018
E-mail: kimjh@kriss.re.kr

Dr. Yueyan Shan
Senior Metrologist
Electromagnetic Metrology Department
National Metrology Centre
Agency for Science, Technology and Research
1 Science Park Drive, 118221, Singapore
TEL: (65) 6279 1929
FAX: (65) 6279 1992
E-mail: shan_yueyan@nmc.a-star.edu.sg

Dr. Tieren Zhang
Research Scientist
Radio Frequency & Microwave Metrology
National Measurement Institute, Australia
Bradfield Rd, West Lindfield, NSW 2070, Australia
TEL: +61-2-8467-3560
FAX: +61-2-8447-3610
E-mail: tieren.zhang@measurement.gov.au

3.2 Participants

A list of all participants is given in Table 1.

Table 1 List of participants (provisional)

Country/Institute	Name	Address	E-mail
The commonwealth of Australia, *National Measurement Institute (NMIA)	Tieren Zhang	Bradfield Rd, West Lindfield, NSW 2070, Australia	tieren.zhang@ measurement.gov.au
The People's Republic of China, *National Institute of Metrology (NIM)	Liu Xinmeng	No. 18, Bei San Huan DongLu, Beijing, China	liuxm@nim.ac.cn
Hong Kong, China Standards and Calibration Laboratory (SCL)	C.M.Tsui	36th Floor, Immigration Tower, 7 Gloucester Road, Wan Chai, Hong Kong, China	cmtsui@itc.gov.hk
The Republic of India, National Physical Laboratory (NPL)	Saood Ahmad	Dr. K S Krishnan Road, New Delhi - 110012, INDIA	ahmads@nplindia.org
Japan, *National Metrology Institute of Japan (NMIJ)	Kazuhiro Shimaoka	3-1 Central, 1-1-1 Umezono, Tsukuba, Ibaraki, 305-8563, Japan	kazuhiro-shimaoka @aist.go.jp
The Republic of Korea, *Korea Research Institute of Standards and Science (KRISS)	Jeong-Hwan Kim	P.O. Box 102, Yusong, Taejon 305-600, Korea	kimjh@kriss.re.kr
Malaysia, National Metrology Laboratory (NML)	Arshad bin Selamat	Lot PT 4803, Bandar Baru, Salak Tinggi, 43900 Sepang, Selangor Darul Ehsan, Malaysia	arshads@sirim.my

New Zealand, Measurement Standards Laboratory of New Zealand (MSL)	Blair Hall	69 Gracefield Road, PO Box 31-310, Lower Hutt 5040, New Zealand	B.Hall@irl.cri.nz
Singapore, *National Metrology Centre (NMC)	Yueyan Shan	1 Science Park Drive, 118221, Singapore	shan_yueyan@nmc.a-star.edu.sg
The Republic of South Africa, National Metrology Institute of South Africa (NMISA)	Erik Dressler Mariesa Nel	Building 5, CSIR Campus, Meiring Naudé Road, Brummeria, Pretoria, 0001, South Africa	redressler@nmisa.org
The Kingdom of Thailand, National Institute of Metrology (NIMT)	Chairat Wichainmongkonkun	3/4-5 Moo 3, Klong 5, Klong Luang, Pathumthani 12120, Thailand	chairat@nimt.or.th

* Linking laboratories

3.3 Time schedule

Each of the laboratories is entitled to spend 4 weeks of measurement, and 2 weeks of transport. The final schedule will be decided after conducting an inquiry and reaching on agreement. As this comparison continues over a period of 18 months, the pilot laboratory measures the intermediate value to ensure the stability of the traveling standards.

In the case of delay, the participant immediately informs the pilot laboratory and the pilot laboratory adjusts the time schedule.

Table 2 Proposed circulation time schedule (Provisional)

Institution	Country	Start date	Time for measurement and transport (weeks)
*NMIJ	Japan	15 June 2012	6
SCL	Hong Kong, China	1 August 2012	6
*NMIA	Australia	15 September 2012	6
MSLNZ	New Zealand	1 November 2012	6
NML	Malaysia	15 December 2012	6
NMISA	South Africa	1 February 2013	6
*NMIJ	Japan	15 March 2013	6
*NMC	Singapore	1 May 2013	6
NPL	India	15 June 2013	6
*KRISS	The Republic of Korea	1 August 2013	6
*NIM	The People's Republic of China	15 September 2013	6
NIMT	The Kingdom of Thailand	1 November 2013	6
*NMIJ	Japan	15 December 2013	6

* Linking laboratories

3.4 Transport

An ATA carnet will be used for exporting and importing the traveling standard. The carnet should be properly handled and safely kept by all participants. Its loss will result in a serious unavoidable delay. The laboratory in each country is responsible for all necessary procedures for safe transport in the country. **If the person in charge is inexperienced with the handling of the ATA carnet, delegate the shipment task to a professional agency.**

Each of the laboratories is required to inform the shipment of the traveling standard to the next laboratory and the pilot laboratory before shipment. The laboratory that receives the traveling standard informs the previous laboratory of the receipt and sends a brief report on the status of the traveling standard to the pilot laboratory. (Use the confirmation notes in Annexes 5 and 6.) If any problem arises during transport, the laboratory should immediately report it to the pilot laboratory. If a problem arises in customs formalities, the laboratory of the country is responsible for any necessary action.

A carrying case designed by NMIJ for E4419B and 8481A will be used for transport. It is 223 mm wide, 415 mm high, and 554 mm long. Hand-carrying is not necessary. **If not hand-carrying, commissioning a professional transport agency is highly recommended**. The pilot laboratory has used this case for several international shipments and has experienced no trouble up to the present. ESD connector caps and bags, which will be prepared by the pilot laboratory, must be used before packing the traveling standards. **Should a deficiency be found, the participants must provide a replacement.** This is very important to prevent connector trouble. Do not dispatch the traveling standard without the ESD bags or ESD connector caps.

3.5 Unpacking, handling, packing

The following items will be included in the carrying case.

(1)	Agilent E4419B power meter (with three connector caps)	x 1
(2)	Agilent 8481A power sensor (with two connector caps)	x 2
(3)	Sensor cable (with two connector caps)	x 1
(4)	ESD bags	x 3
(5)	Torque wrench (1.36 Nm)	x 1
(6)	Connector gage (Type N (f))	x 1
(7)	Gage master (Type N (m))	x 1
(8)	Copy of this protocol	x 1
(9)	Manuals for E4419B and 8481A	x 1
(10)	Spare fuses for E4419B	x 2

Note that no power cable is attached because of the difference in sockets among countries. Each laboratory must prepare a power cable suitable for E4419B. The selection of the voltage range of its power source is automatic.

3.5.1 Precalibration inspection

(a) After receipt of the carrying case, confirm that all items are present. Then, inspect them for any damage or dirt. Should any problems be found, contact the pilot laboratory.

(b) When the ambient temperatures inside and outside the room differ, leave the carrying case in the calibration room for a sufficient amount of time before opening it.

(c) The traveling standards are susceptible to static electricity. The participants are required to prepare an antistatic measuring environment.

(d) Measure the pin depth of the two 8481A sensors [29], then record the values in the space on the confirmation note of receipt (Annex 5).

(e) Connect one of the 8481A sensors to the E4419B power meter (Channel A) using a sensor cable, then preset the power meter. Run the self-test program of the E4419B power meter, and verify its normal operation. Check the normal operation of the built-in reference power source. As the reference calibration factors of the traveling standards are 100 %, the E4419B power meter must indicate 1.000 mW for the reference output. Repeat the same operation for the other sensor.

(f) Fill out the confirmation note of receipt (Annex 5), and send it to the previous laboratory and the pilot laboratory by e-mail or FAX.

(g) Start the measurement of the NMI.

3.5.2 Inspection for shipment

After the completion of the measurement, first, **the laboratory informs the time schedule of shipment to the pilot laboratory and the next laboratory**. The use of the template shown in Annex 6 will greatly reduce the labour of reporting the status of the traveling standard. Confirm whether the next laboratory is ready to receive the traveling standard. Then, pack all the items into the carrying case and send the set to the next laboratory. The shipment should be prepared beforehand.

The following is the dispatch procedure.

(a) Measure the pin depth of the two 8481A sensors, then record the values in the space on the confirmation note of dispatch (Annex 6).

(b) Connect one of the 8481A sensors to the E4419B power meter using a sensor cable, then preset the power meter. Run the self-test program of the E4419B power meter, and verify its normal operation. Check the normal operation of the built-in reference power source. As the reference calibration factors of the traveling standards are 100 %, the E4419B power meter must indicate 1.000 mW for the reference output. Repeat the same operation for the other sensor.

(c) Before dispatching the traveling standard, confirm that the items are complete. Then, inspect them for any damage or dirt. Should any problems be found, contact the pilot laboratory.

(d) Fill out the confirmation note of dispatch (Annex 6), and send it to the next laboratory and the pilot laboratory by e-mail or FAX.

(f) Dispatch the traveling standard.

3.6 Failure of traveling standard

If one power sensor fails, the comparison will continue using only the remaining sensor. If the power meter should fail, the pilot laboratory will send another power meter. The effect of the built-in reference power source in determining KCRV will be taken into consideration.

3.7 Financial aspects, insurance

Each laboratory must cover the cost of transport to the next laboratory. The cost should include insurance. The total cost of the traveling standards, including the carrying case, is approximately 1,300,000 Japanese yen. In addition, the participants must cover the costs of measurements, mechanical and electrical problems, and customs duties in their country.

The general cost of the organization and preparation of the comparison is covered by the pilot laboratory. The pilot laboratory has no insurance for any problems occurring during transport.

4. Measurement instructions

4.1 Tests before measurements

A visual inspection must be conducted when a connection is made. If the connectors of the traveling standards show deep scratches or dents, stop the measurements and report the condition to the pilot laboratory. The pin depth must be measured using a connector gage before and after the measurements. The values should be between 0.2070+0.0005 and 0.2070+0.0027 inches. The measured pin depth must be reported using the confirmation notes (Annexes 5 and 6, see sections 3.5.1 and 3.5.2). The detailed procedures of connector care and pin depth measurement are given in, for example, ref. 29.

The electrical check must be conducted as follows.

(a) Preset the power meter.

(b) Run the "Instrument Self-Test" of the power meter and confirm that all messages are "Passed".

(c) After zeroing and calibration with the built-in 50 MHz reference output, confirm that the indication is 1.000 mW when the reference output power is on. Should an error message appear, report it to the pilot laboratory.

4.2 Measurement performance

(a) Power level

The incident power input to the power sensor must be approximately 1 mW. As the linearity of the traveling standard is good at this power level, a 10 % deviation from 1 mW is acceptable.

(b) Connection

The result should include the type-A uncertainty of connection reproducibility. The number of independent measurements with disconnection and reconnection is decided by each participant. A 1.36 Nm (12 in-lb) torque wrench must be used.

4.3 Measurement methods

The two general measurement methods are as follows.

1. Calorimetry
This is practically the only method that independently realizes values traceable to SI units. In most cases, the effective efficiency of a bolometric device is calorimetrically determined and transferred to the traveling standard. The effective efficiency can be easily converted to a calibration factor using the reflection coefficients of the bolometric device and traveling standard. In some cases, the effective efficiency of the traveling standard is directly evaluated.

2. Comparison method
In this method, the traveling standard is compared with a primary standard, which is traceable to SI units. It has been established that the comparison method using a power splitter and a reference power meter has high accuracy [30]. The correction of source mismatch error is effective in reducing the measurement uncertainty.

The participants are required to submit a brief report on their method in addition to the results of the comparison (see Annex 4).

5. Uncertainty of measurement

All participants must report the measurement results, uncertainties, and complete uncertainty budgets (see Annex 3). The uncertainty budgets must be provided for all reported frequencies. The combined standard uncertainties $u_c(K)$ and their coverage factors k, where expanded uncertainties $U = ku_c(K)$ define intervals having a level of confidence of 95 %, must be evaluated according to the ISO Guide to the Expression of Uncertainty in Measurement (GUM) [31].

5.1 Main uncertainty components, including sources and typical values

In section 5.2, lists of the principal uncertainty components are provided. It is impossible to describe all possible components. Therefore, only the components related to the methods described in section 4.3 are listed.

5.2 Scheme for reporting uncertainty budget

1. Example: Calorimetry

Measurement method: The method shown here is described in ref. 32. In this calorimeter, a parameter called the power-splitting ratio C_d is evaluated instead of the effective efficiency. C_d is defined as

$$\begin{aligned} C_d &= \frac{P_{rf}}{P_{ms}} \\ &= \frac{1}{P_{ms}} \cdot \frac{k}{1-|\Gamma_\ell|^2}\left(1-\frac{q\alpha}{1-\alpha}\right)\left(P_{h1}-P_{h2}\right). \end{aligned} \qquad (5.2.1)$$

The following parameters contribute to the uncertainty of measurement.

P_{rf}	-Incident power to RF load of calorimeter
P_{ms}	-Observed value of monitor power meter when RF power is input to RF load of calorimeter
k	-Substitution coefficient of RF and DC power
Γ_ℓ	-Reflection coefficient of RF load of calorimeter
q	-Ratio of heat per second conducted to RF load of calorimeter to the RF power consumed in adiabatic line
α	- $1-|S_{21}|^2$, where S_{21} is the scattering parameter of the adiabatic line
P_{h1}-P_{h2}	- Substituted DC power

After evaluating C_d, the calibration factor of the traveling standard is measured.

$$K_{\mathrm{DUT}}(f) = \frac{P_{\mathrm{DUT}}(f)}{P_{m\_\mathrm{DUT}} \cdot (C_d + \delta C_d)} \cdot M \qquad (5.2.2)$$

The following parameters contribute to the uncertainty of measurement.

C_d	- Power-splitting ratio of calorimeter
δC_d	- Drift of power-splitting ratio C_d of calorimeter
$P_{\mathrm{DUT}}(f)$	- Observed value of power indication of traveling standard

$P_{m\_DUT}(f)$ - Observed value of power indication of monitor power meter when RF power is input to traveling standard

M - Source mismatch factor

K - Repeatability associated with multiple measurements

Table 5.1 Example of uncertainty budget of $K_{DUT}(f)$ for calorimeter

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution/ method of evaluation (A, B)	Sensitivity coef-ficient $c_i = \frac{\partial K_{DUT}(f)}{\partial x_i}$	Uncertainty contribution $\lvert c_i \rvert u(x_i) = u_i(K_{DUT}(f))$	Degrees of free-dom ν_i
C_d			B/ normal			
δC_d			B/ normal			
$P_{DUT}(f)$			B/ uniform			
$P_{m\_DUT}(f)$			B/ uniform			
M			B/ U			
K			A/ t	1		
				Combined standard uncertainty $u_c(K_{DUT})$	Coverage factor k, level of con-fidence 95%	Effective degrees of free-dom ν_{eff}
			$K_{DUT}(f)$			

From ref. 31, the combined standard uncertainty $u_c[K_{DUT}(f)]$ is given by

$$u_c^2[K_{DUT}(f)] = \sum_i u_i^2[K_{DUT}(f)] = \sum_i \left[\frac{\partial K_{DUT}(f)}{\partial x_i}\right]^2 \cdot u^2(x_i). \qquad (5.2.3)$$

The distribution of the variable

$$\frac{\overline{K}_{DUT}(f) - E[K_{DUT}(f)]}{u_c[K_{DUT}(f)]} \qquad (5.2.4)$$

may be approximated by a t-distribution with an effective degrees of freedom ν_{eff}, where $\overline{K}_{DUT}(f)$ and $E[K_{DUT}(f)]$ are the arithmetic mean of N times observations and the expected value of $K_{DUT}(f)$, respectively. ν_{eff} is given by

$$\nu_{eff} = \frac{u_c^4[K_{DUT}(f)]}{\sum_i u_i^4[K_{DUT}(f)]}. \qquad (5.2.5)$$

2. Example: Comparison method

Measuring method: A broadband power splitter is sometimes used [33]. A signal generator supplies RF power to the power splitter. A power sensor monitoring the power level is connected to an output port of the power splitter. Another output port is used as a test port. Firstly, a standard power meter is connected to the test port, and is fed RF power at the level of calibration. To avoid an increase in uncertainty, the ratio of the power indication of the standard power meter $P_{\mathrm{STD}}(f)$ to the power indication of the monitor power meter $P_{\mathrm{m\_STD}}(f)$ is recorded. Secondly, the traveling standard is connected to the test port. The ratio of the power indication of the traveling standard power meter $P_{\mathrm{DUT}}(f)$ to the power indication of the monitor power meter $P_{\mathrm{m\_DUT}}(f)$ is similarly recorded. Finally, the calibration factor of the traveling standard $K_{\mathrm{DUT}}(f)$ is given by the following formula.

$$K_{DUT}(f) = [K_{STD}(f) + \delta K_{STD}(f)] \cdot \frac{\dfrac{P_{DUT}(f)}{P_{m\_DUT}}}{\dfrac{P_{STD}(f)}{P_{m\_STD}}} \cdot M \cdot L \qquad (5.2.6)$$

$K_{DUT}(f)$	- Calibration factor of traveling standard
$K_{STD}(f)$	- Calibration factor of standard power meter
$\delta K_{STD}(f)$	- Drift of calibration factor of standard power meter
$P_{\mathrm{STD}}(f)$	- Observed value of power indication of standard power meter
$P_{\mathrm{m\_STD}}(f)$	- Observed value of power indication of monitor power meter for standard power meter
$P_{\mathrm{DUT}}(f)$	- Observed value of power indication of traveling standard
$P_{\mathrm{m\_DUT}}(f)$	- Observed value of power indication of monitor power meter for

	traveling standard
M	- Source mismatch factor
L	- Correction of observed ratio for nonlinearity
K	- Repeatability associated with multiple measurements

Table 5.2 Example of uncertainty budget of $K_{\mathrm{DUT}}(f)$ for comparison method

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution/ method of evaluation (A, B)	Sensitivity coef-ficient $c_i = \frac{\partial K_{DUT}(f)}{\partial x_i}$	Uncertainty contribution $\lvert c_i \rvert u(x_i) = u_i(K_{\mathrm{DUT}}(f))$	Degrees of free-dom ν_i
$K_{\mathrm{STD}}(f)$			B/ normal			
$\delta K_{\mathrm{STD}}(f)$			B/ normal			
$P_{\mathrm{STD}}(f)$			B/ uniform			
$P_{m\_\mathrm{STD}}(f)$			B/ uniform			
$P_{\mathrm{DUT}}(f)$			B/ uniform			
$P_{m\_\mathrm{DUT}}(f)$			B/ uniform			
M			B/ U			
L			B/ normal			
K			A/ t	1		
				Combined standard uncertainty $u_c(K_{\mathrm{DUT}})$	Coverage factor k, level of con-fidence 95%	Effective degrees of free-dom ν_{eff}
			$K_{\mathrm{DUT}}(f)$			

The combined standard uncertainty $u_c(K_{\mathrm{DUT}})$ and the effective degrees of freedom ν_{eff} are similarly given by (5.2.3) and (5.2.5), respectively.

6. Measurement report

The measurement results, a brief explanation of the measurement method and setup, and a detailed uncertainty budget must be reported (see Annexes 3 and 4). Because the reported budget sheets for a few frequencies are attached to the final comparison report, they must be sufficiently clear to calculate the reported uncertainty.

All participants should send the report within six weeks after the measurement [6]. When any of the results deviate from the provisional KCRV, the coordinator will report the fact only to the corresponding participants [5]. Neither the amount of deviation nor the sign will be shown. The participants have two choices. Firstly, if after a careful check no numerical mistake is found, the reported value stands. Secondly, the participants can withdraw their result. Once all participants have been informed of the results, individual values and uncertainties may be changed or removed, or the complete comparison abandoned, but only with the agreement of all participants.

7. Report of comparison

The first version, draft A, will be prepared by the organization group within three months after the completion of the circulation. Draft A, which includes provisional KCRV, degrees of equivalence, and the difference in national standards, will be sent to all participants for comment. This version of the comparison report is confidential to the participants. The comments must be returned to the pilot laboratory within one month. If any comments are received by the organization group, they are circulated to all participants, and the discussion will continue until a consensus is reached. After agreement on the result described in Draft A by all participants, Draft B will be prepared. Draft B is not confidential, and it will become the final report after approval by the APMP TCEM and CCEM.

7.1 Reference value

APMP reference value (*APMP RV*) will be determined from the weighted mean of the results reported by member laboratories of CCEM. On the basis of the method proposed by Cox [18, 19], ***the weighted mean is calculated from the largest consistent subset.*** **The largest consistent subset includes the reported data obtained after the removal of outliers.** To evaluate the weighted mean, standard uncertainty, and degree of equivalences, *procedure A* shown in ref. 18 is used, while the values that contribute to the calculation are determined by the procedure described in ref. 19. Details of the procedure are available in the references.

$$APMP\ RV = \frac{\sum_j \frac{m_j}{u^2\left(m_j\right)}}{\sum_j \frac{1}{u^2\left(m_j\right)}} \tag{7.1.1}$$

m_j is a value reported by a laboratory j, and $u(m_j)$ is the combined standard uncertainty of m_j. The combined standard uncertainty of *APMP RV* is given by

$$u\left(APMP\ RV\right) = \frac{1}{\sqrt{\sum_j \frac{1}{u^2\left(m_j\right)}}}. \tag{7.1.2}$$

Degree of equivalence (*DoE*) between m_j and *APMP RV* is given as the pair of $[d_j,\ U(d_j)]_{APMP}$.

$$DoE(j, APMP\ RV) = \left[d_j, U\left(d_j\right)\right]_{APMP} \tag{7.1.3}$$

$$d_j = m_j - APMP\ RV \tag{7.1.4}$$

$$U\left(d_j\right) = 2u\left(d_j\right) \tag{7.1.5}$$

and

$$u\left(d_j\right) = \sqrt{u^2\left(m_j\right) - u^2\left(APMP\ RV\right)} \tag{7.1.6}$$

or

$$u\left(d_j\right) = \sqrt{u^2\left(m_j\right) + u^2\left(APMP\ RV\right)} \tag{7.1.7}$$

(7.1.6) is applied to a reported value m_j that contributes to the calculation of *APMP RV*, while (7.1.7) is applied to a reported value m_j that are treated as an outlier.

DoE between m_j and $m_{j'}$ is given as the pair of $[d_{j,j'},\ U(d_{j,j'})]$.

$$DoE(j, j') = \left[d_{j,j'}, U\left(d_{j,j'}\right)\right] \tag{7.1.8}$$

$$d_{j,j'} = m_j - m_{j'} \tag{7.1.9}$$

$$u\left(d_{j,j'}\right) = \sqrt{u^2\left(m_j\right) + u^2\left(m_{j'}\right)} \tag{7.1.10}$$

$$U\left(d_{j,j'}\right) = 2u\left(d_{j,j'}\right) \tag{7.1.11}$$

These degrees of equivalence are calculated for all measuring frequencies and each traveling standard.

7.2 Linking APMP.EM.RF-K8.CL and CIPM.EM.RF-K8.CL

Although a few linking methods were considered, the organization group have not reached on agreement about them. As the comparison should start as soon as possible, the coordinator decided to discuss this problem during the comparison.

* The final linking method will be published in a linking report.

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Annexes

A1. List of participants

Country/Institute	Name	Address	E-mail
The commonwealth of Australia, *National Measurement Institute (NMIA)	Tieren Zhang	Bradfield Rd, West Lindfield, NSW 2070, Australia	tieren.zhang@ measurement.gov.au
The People's Republic of China, *National Institute of Metrology (NIM)	Liu Xinmeng	No. 18, Bei San Huan DongLu, Beijing, China	liuxm@nim.ac.cn
Hong Kong, China Standards and Calibration Laboratory (SCL)	C.M.Tsui	36th Floor, Immigration Tower, 7 Gloucester Road, Wan Chai, Hong Kong, China	cmtsui@itc.gov.hk
The Republic of India, National Physical Laboratory (NPL)	Saood Ahmad	Dr. K.S. Krishnan Road, New Delhi-110012, India	ahmads@nplindia.org
Japan, *National Metrology Institute of Japan (NMIJ)	Kazuhiro Shimaoka	3-1 Central, 1-1-1 Umezono, Tsukuba, Ibaraki, 305-8563, Japan	kazuhiro-shimaoka @aist.go.jp
The Republic of Korea, *Korea Research Institute of Standards and Science (KRISS)	Jeong-Hwan Kim	P.O. Box 102, Yusong, Taejon 305-600, Korea	kimjh@kriss.re.kr
Malaysia, National Metrology Laboratory (NML)	Arshad bin Selamat	Lot PT 4803, Bandar Baru, Salak Tinggi, 43900 Sepang, Selangor Darul Ehsan, Malaysia	arshads@sirim.my

New Zealand, Measurement Standards Laboratory of New Zealand (MSL)	Blair Hall	69 Gracefield Road, PO Box 31-310, Lower Hutt 5040, New Zealand	B.Hall@irl.cri.nz
Singapore, *National Metrology Centre (NMC)	Yueyan Shan	1 Science Park Drive, 118221, Singapore	shan_yueyan@nmc.a-star.edu.sg
The Republic of South Africa, National Metrology Institute of South Africa (NMISA)	Erik Dressler Mariesa Nel	Building 5, CSIR Campus, Meiring Naudé Road, Brummeria, Pretoria, 0001, South Africa	redressler@nmisa.org
The Kingdom of Thailand, National Institute of Metrology (NIMT)	Chairat Wichainmongkonkun	3/4-5 Moo 3, Klong 5, Klong Luang, Pathumthani 12120, Thailand	chairat@nimt.or.th

* Linking laboratories

A2. Schedule of measurements

Institution	Country	Start date	Time for measurement and transport (weeks)
*NMIJ	Japan	15 June 2012	6
SCL	Hong Kong, China	1 August 2012	6
*NMIA	Australia	15 September 2012	6
MSLNZ	New Zealand	1 November 2012	6
NML	Malaysia	15 December 2012	6
NMISA	South Africa	1 February 2013	6
*NMIJ	Japan	15 March 2013	6
*NMC	Singapore	1 May 2013	6
NPL	India	15 June 2013	6
*KRISS	The Republic of Korea	1 August 2013	6
*NIM	The People's Republic of China	15 September 2013	6
NIMT	The Kingdom of Thailand	1 November 2013	6
*NMIJ	Japan	15 December 2013	6

* Linking laboratories

A3. Typical scheme for uncertainty budget

A3.1 Example of uncertainty budget of $K_{\mathrm{DUT}}(f)$ for calorimeter

The quantity $K_{\mathrm{DUT}}(f)$ is estimated as follows.

$$K_{\mathrm{DUT}}(f) = \frac{P_{\mathrm{DUT}}(f)}{P_{m\_\mathrm{DUT}} \cdot (C_d + \delta C_d)} \cdot M$$

C_d	- Power-splitting ratio of calorimeter
δC_d	- Drift of power-splitting ratio C_d of calorimeter
$P_{\mathrm{DUT}}(f)$	- Observed value of power indication of traveling standard
$P_{m\_\mathrm{DUT}}(f)$	- Observed value of power indication of monitor power meter when RF power is input to traveling standard
M	- Source mismatch factor
K	- Repeatability associated with multiple measurements

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_\mathrm{i})$	Probability distribution/ method of evaluation (A, B)	Sensitivity coef-ficient $c_i = \frac{\partial K_{DUT}(f)}{\partial x_i}$	Uncertainty contribution $\lvert c_\mathrm{i} \rvert \mathrm{u}(x_\mathrm{i}) = u_\mathrm{i}(K_{\mathrm{DUT}}(f))$	Degrees of free-dom ν_i
C_d			B/ normal			
δC_d			B/ normal			
$P_{\mathrm{DUT}}(f)$			B/ uniform			
$P_{m\_\mathrm{DUT}}(f)$			B/ uniform			
M			B/ U			
K			A/ t			
				Combined standard uncertainty $u_\mathrm{c}(K_{\mathrm{DUT}})$	Coverage factor k, level of con-fidence 95%	Effective degrees of free-dom ν_{eff}
			$K_{\mathrm{DUT}}(f)$			

A3.2 Example of uncertainty budget of $K_{\mathrm{DUT}}(f)$ for comparison method

The quantity $K_{\mathrm{DUT}}(f)$ is estimated as follows.

$$K_{DUT}(f) = [K_{STD}(f) + \delta K_{STD}(f)] \cdot \frac{\dfrac{P_{DUT}(f)}{P_{m\_DUT}}}{\dfrac{P_{STD}(f)}{P_{m\_STD}}} \cdot M \cdot L$$

$K_{DUT}(f)$	- Calibration factor of traveling standard
$K_{STD}(f)$	- Calibration factor of standard power meter
$\delta K_{STD}(f)$	- Drift of calibration factor of standard power meter
$P_{\mathrm{STD}}(f)$	- Observed value of power indication of standard power meter
$P_{\mathrm{m\_STD}}(f)$	- Observed value of power indication of monitor power meter for standard power meter
$P_{\mathrm{DUT}}(f)$	- Observed value of power indication of traveling standard
$P_{\mathrm{m\_DUT}}(f)$	- Observed value of power indication of monitor power meter for traveling standard
M	- Source mismatch factor
L	- Correction of observed ratio for nonlinearity
K	- Repeatability associated with multiple measurements

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution/ method of evaluation (A, B)	Sensitivity coef-ficient $c_i = \dfrac{\partial K_{DUT}(f)}{\partial x_i}$	Uncertainty contribution $\lvert c_i \rvert u(x_i) = u_i(K_{\mathrm{DUT}}(f))$	Degrees of free-dom ν_i
$K_{\mathrm{STD}}(f)$			B/ normal			
$\delta K_{\mathrm{STD}}(f)$			B/ normal			
$P_{\mathrm{STD}}(f)$			B/ uniform			
$P_{m\_\mathrm{STD}}(f)$			B/ uniform			
$P_{\mathrm{DUT}}(f)$			B/ uniform			
$P_{m\_\mathrm{DUT}}(f)$			B/ uniform			
M			B/ U			
L			B/ normal			

K			A/ t	1		
				Combined standard uncertainty $u_c(K_{DUT})$	Coverage factor k, level of confidence 95%	Effective degrees of freedom ν_{eff}
			$K_{DUT}(f)$			

A4. Form of measurement report

The participants must report the following information with detailed uncertainty budgets (A3). **This report must be submitted within six weeks after the measurement.** The data should be provided in an electronic file (.doc). For editorial reasons, PDF files are discouraged.

(1) Organization, country, contact person, and address

(2) Measurement methods

Type of standard: If not an independent standard, report the source of its traceability.
If a non-type-N test port is used, report the method of correction (e.g., adaptor efficiency)
Number of repeated measurements
Report the type of mismatch consideration (e.g., correction by complex Γ)
If possible, report the reflection coefficients Γ of the traveling standards (with standard uncertainties and coverage factors of 95 % confidence level.)
The linking laboratory must report if the calibration method has been modified or completely supplanted after CCEM.RF-K8.CL (this will be reflected in the linking report.)

(3) Measuring system

Give a brief description of the measuring system used for the comparison. Attach a schematic diagram if possible.

(4) List of results

No. 1

Frequency [GHz]	Calibration factor K	Combined standard uncertainty $u_c(K)$ ($k = 1$)	Coverage factor k corresponding to a level of confidence of 95 %
0.01			
0.05			

1			
4			
8			
12			
15			
18			

No. 2

Frequency [GHz]	Calibration factor K	Combined standard uncertainty $u_c(K)$ ($k = 1$)	Coverage factor k corresponding to a level of confidence of 95 %
0.01			
0.05			
1			
4			
8			
12			
15			
18			

(4) Measurement conditions

Ambient temperature in °C and humidity in %.

(5) Additional measurement

Reflection coefficients of the traveling standards

Although these items need not be reported, in the case that they are reported, uncertainties and the traceability source must be reported.

The measurement of reflection coefficients of the traveling standards is traceable to

____.

No.1

Frequency [GHz]	Real component [Lin.]	Imaginary component [Lin.]	Uncertainty of magnitude [Lin.]
0.01			
0.05			
1			
4			
8			
12			
15			
18			

No.2

Frequency [GHz]	Real component [Lin.]	Imaginary component [Lin.]	Uncertainty of magnitude [Lin.]
0.01			
0.05			
1			
4			
8			
12			
15			
18			

* If the measurement is reported as scalar values, please modify the tables.

A5. Confirmation note of receipt

Subject: Receipt of the traveling standards: APMP.EM.RF-K8.CL

To: (previous laboratory),

Cc: Dr. Kazuhiro Shimaoka
National Institute of Metrology Japan,
Central 3, Umezono, Tsukuba, Ibaraki, 305-8563, Japan
kazuhiro-shimaoka@aist.go.jp
FAX No.: +81 29 861 6828

From: (laboratory that received the traveling standards)

Date:

We confirm having received the traveling standards for APMP.EM.RF-K8.CL key comparison. After the precalibration inspection described in 3.5.1 in the technical protocol,

(Please write "x" inside the parentheses of the relevant comment.)

( ) No damage has been noted upon visual inspection, and the items operated normally in all checking procedures. The pin depths were

No. 1 ____________ x10^{-4} inch

No. 2 ____________ x10^{-4} inch.

( ) We report the following damage (or deficiency).

A6. Confirmation note of dispatch

Subject: Shipment of the traveling standards: APMP.EM.RF-K8.CL

To: (next laboratory),
Cc: Dr. Kazuhiro Shimaoka
National Institute of Metrology Japan,
Central 3, Umezono, Tsukuba, Ibaraki, 305-8563, Japan
kazuhiro-shimaoka@aist.go.jp
FAX No.: +81 29 861 6828

From: (laboratory that dispatched the traveling standards)

Date:

We confirm having dispatched the traveling standards for APMP.EM.RF-K8.CL key comparison. After the inspection of the shipment described in 3.5.2 in the technical protocol,

(Please write "x" inside the parentheses of the relevant comment.)
(   ) No damage has been noted upon visual inspection, and the items operated normally in all checking procedures. The pin depths were

No. 1 ____________ $x10^{-4}$ inch
No. 2 ____________ $x10^{-4}$ inch.

(   ) We report the following damage (or deficiency).

(   ) We have used a spare fuse for E4419B. The number of spare fuses is now _____ .

(   ) We dispatched the items directly from our laboratory.

(   ) We consigned the transport of the traveling standards to a professional agency.
Name and contact address of the agency:

Appendix C Measurement reports

(1) National Metrology Institute of Japan (NMIJ), Japan
(2) Standards and Calibration Laboratory (SCL), Hong Kong, China
(3) National Measurement Institute (NMIA), Australia
(4) Measurement Standards Laboratory of New Zealand (MSL), New Zealand
(5) National Metrology Laboratory (NML), Malaysia
(6) National Metrology Institute of South Africa (NMISA), Republic of South Africa
(7) National Metrology Centre (NMC), Republic of Singapore
(8) National Physical Laboratory (NPL), Republic of India
(9) Korea Research Institute of Standards and Science (KRISS), Republic of Korea
(10) National Institute of Metrology (NIM), People’s Republic of China
(11) National Institute of Metrology (NIMT), Kingdom of Thailand

APMP Key Comparison APMP.EM.RF-K8.CL
“Power in 50 Ω coaxial line, frequency 10 MHz to 18 GHz”
Measurement report

(1) Organization, country, contact person, and address

National Metrology Institute of Japan (NMIJ), Japan
Kazuhiro Shimaoka
3-1 Central, 1-1-1 Umezono, Tsukuba, Ibaraki, 305-8563, Japan
kazuhiro-shimaoka@aist.go.jp

(2) Measurement methods

Direct comparison with the alternate connections method was used. The ratio of indicated power by device-under-test (DUT) and the simultaneous monitoring power at all calibrating frequencies was measured, then the calibration factor of the DUT was calculated using the power splitting ratio C_d evaluated beforehand.

(3) Measuring system

A schematic diagram of a 7-mm coaxial calorimeter (calibration mode) is shown in Fig. 1. The principle of power measurement is based on an isothermally controlled twin-type dry calorimetric measurement. This calorimeter involves two circuits that are designed to be electrically and thermally equivalent so as to cancel out thermal influence caused by ambient temperature change. Power measurement is done only for one circuit.

The power source has a leveling loop that consists of a power splitter, a monitoring power meter, and a wideband synthesized power source. The radio frequency (RF) signal from the synthesized power source is divided into two at the power splitter. The monitoring power meter is connected to one output port of the power splitter, to monitor input power. The RF signal from the other output port of the power splitter is fed to a test port. The output power from the test port is calorimetrically measured, and the ratio of the output power to monitored (indicated) power is recorded. Before device under test (DUT) calibration, this ratio (called a power splitting ratio) must be evaluated at the frequencies required for the calibration.

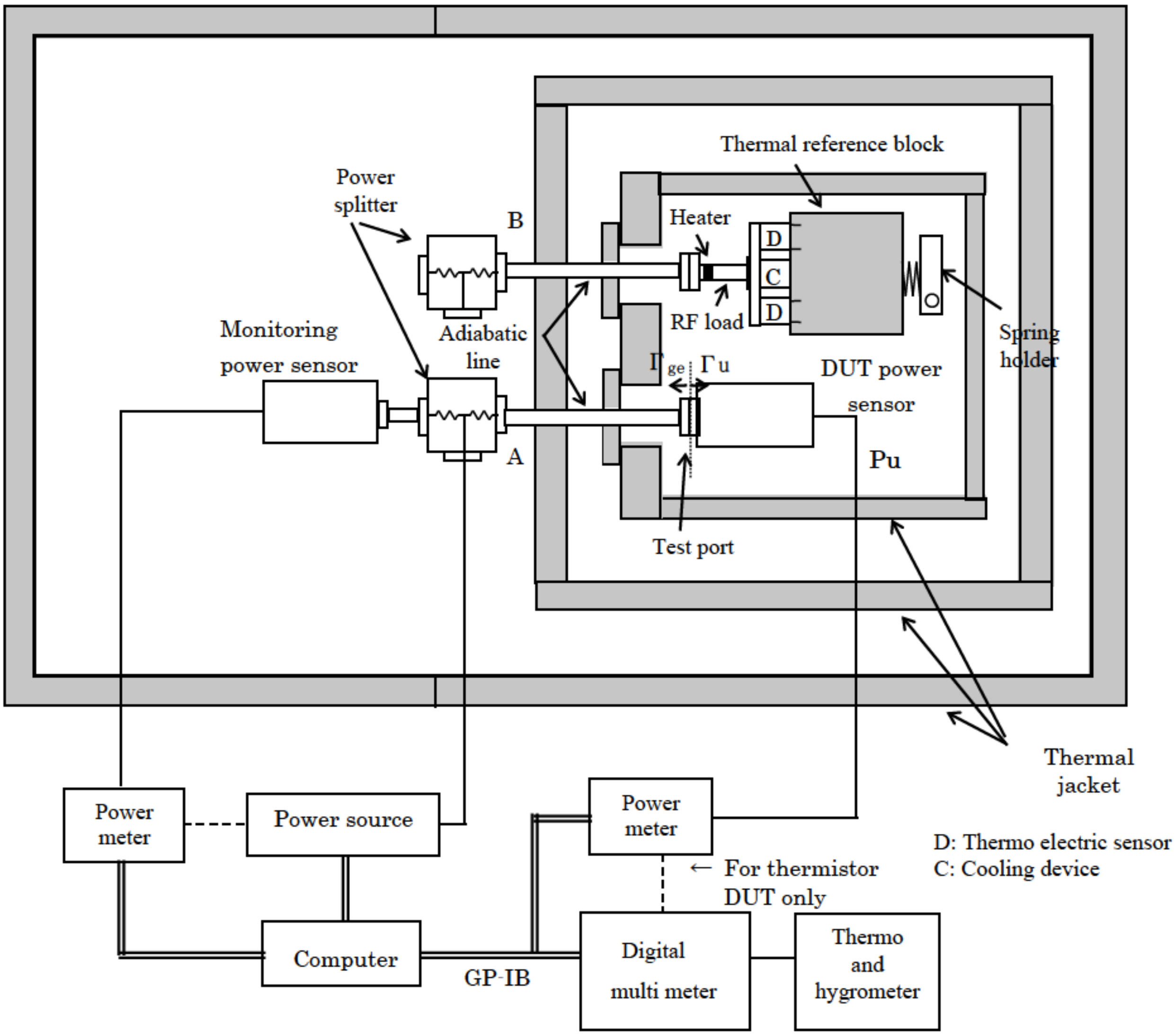

Fig. 1 7 mm coaxial calorimeter, comparison calibration mode

DUT calibration is carried out after removing the RF load, the sense and cooling device, thermal reference block, and thermal jackets. A DUT is connected to the test port, and the calibration factor of the DUT is evaluated from the indicated value of the DUT and the monitoring power meter. If the connector type is different from PC 7 a suitable conversion adopter must be used.
The calibration factor of DUT is obtained as follows.

$$K = \frac{P_u M_u}{C_d P_{mu} \eta_l \eta_a} \qquad (1)$$

Here, P_u is the indicated power by the DUT power meter. M_u is a correction coefficient. The correction corresponding to $M_s = |1- \Gamma_g \Gamma_s|^2$, which is included in C_d, is also done.

C_d is the ratio of calorimetrically determined power P_{rf} and simultaneously indicated monitoring power P_{ms}, which is called the power splitting ratio.

P_{mu} is the indicated power by the monitoring power meter during DUT calibration.

η_ℓ is the efficiency of the extension airline.
η_α is the efficiency of the conversion adaptor.

$M_u = |1 - \Gamma_g \Gamma_u|^2$ is the coefficient corresponding to DUT source mismatch.

Γ_g is the source reflection coefficient.
Γ_u is the source reflection coefficient.

The power splitting ratio C_d is evaluated from calorimetric measurements at corresponding frequencies.

The modeling formula is derived using the ISO guide "Guide to the expression of uncertainty in measurement (GUM)." Each uncertainty factor is theoretically and experimentally estimated, and standard uncertainty is calculated.

The combined standard uncertainty of the calibration factor K is derived from (1) and expressed by

$$u_c^2(K) = \left(\frac{\partial f}{\partial C_d}\right)^2 u^2(C_d) + \left(\frac{\partial f}{\partial P_u}\right)^2 u^2(P_u) + \left(\frac{\partial f}{\partial P_{mu}}\right)^2 u^2(P_{mu}) + \left(\frac{\partial f}{\partial \eta_l}\right)^2 u^2(\eta_l)$$
$$+ \left(\frac{\partial f}{\partial \eta_a}\right)^2 u^2(\eta_a) + \left(\frac{\partial f}{\partial M_u}\right)^2 u^2(M_u) + s^2(K) \qquad (2)$$

$$K = f(C_d, P_u, P_{mu}, \eta_\ell, \eta_\alpha, M_u)$$

M_u is a coefficient corresponding to DUT source mismatch.
$s(K)$ is an experimental standard deviation of the mean.

Among these parameters, C_d, η_ℓ and η_α are dependent on frequency.
The sensitivity coefficients are as follows.

$$\frac{\partial f}{\partial P_u} = \frac{K}{P_u} \quad (3) \qquad \frac{\partial f}{\partial C_d} = -\frac{K}{C_d} \quad (4) \qquad \frac{\partial f}{\partial P_{mu}} = -\frac{K}{P_{mu}} \quad (5)$$

$$\frac{\partial f}{\partial \eta_l} = -\frac{K}{P_l} \quad (6) \qquad \frac{\partial f}{\partial \eta_a} = -\frac{K}{\eta_a} \quad (7) \qquad \frac{\partial f}{\partial M_u} = \frac{K}{M_u} \quad (8)$$

Each uncertainty factor in the modeling formula is estimated as follows.

$u(C_d)$: Standard uncertainty of the power splitting ratio
Estimated from its definition in the previous section.

$u(P_u)$: Standard uncertainty of the measurement by the DUT
This is of the resolution of DUT defined by the smallest possible indicated increment.

$u(P_{mu})$: Standard uncertainty of the measurement by the monitoring power meter.
This is of the resolution of the monitoring power meter defined by the smallest possible indicated increment.

$u(\eta_\ell)$: Standard uncertainty of the efficiency of extension line
This is the uncertainty of the efficiency of extension line used for large DUTs. If the extension line is not used, this uncertainty is zero.

$u(\eta_\alpha)$: Standard uncertainty of the efficiency of the conversion adaptor

The test port of this calorimeter is a PC 7 connector. For calibration of a DUT with different connecter type, such as a type N connector, a conversion adaptor is required. If the conversion adaptor is not required, the adaptor efficiency is one and its uncertainty is zero.

$u(M_u)$: Standard uncertainty corresponding to source mismatch error
The uncertainty $u(M_u)$ of $M_u = |1-\Gamma_g\Gamma_u|^2$ is evaluated as a part of the uncertainty $u(M)$ of $M = |1-\Gamma_g\Gamma_u|^2/|1-\Gamma_g\Gamma_s|^2$. M is treated as a correction factor of K and is defined by

$$u^2(M) = 4\cdot\left[u^2(|\Gamma_g|)\cdot|\Gamma_S-\Gamma_D|^2+|\Gamma_g|^2\cdot\left\{u^2(|\Gamma_S|)+u^2(|\Gamma_D|)\right\}\right]$$

As the uncertainty $u(M)$ is added when the combined uncertainty K is calculated, the uncertainty $u(M_s)$ of $M_s = |1-\Gamma_g\Gamma_s|^2$ is treated as 0 in the uncertainty budget of power splitting ratio C_d.

$s(K)$: Standard uncertainty corresponding to statistic deviation of measurement

This statistic deviation of measurement is expressed by the experimental standard deviation of the mean.

After evaluation of each uncertainty factor, the uncertainty of the DUT calibration factor is calculated using Formula (2). The uncertainty budgets of the calibration factor of a power meter with Type N connector in 10 MHz, 50 MHz, 1 GHz, 5 GHz, 8 GHz, 10 GHz, 15 GHz and 18 GHz are shown in Table 4.1 to 4.8.

The calculation of these budgets is automatically performed by a spread-sheet, then an uncertainty budget is prepared and filed in the “Calibration record file”. The result of evaluation for all frequencies is filed in the “Calibration record file” as “Results of uncertainty evaluation”.

(4) List of results

Table 1. Calibration factor (Sensor No. 1)

Frequency [GHz]	Calibration factor K	Combined standard uncertainty $u_c(K)$ (k = 1)	Coverage factor k corresponding to a level of confidence of 95 %
0.01	0.9924	0.0021	2
0.05	0.9946	0.0015	2
1	0.9793	0.0015	2
4	0.9683	0.0015	2
8	0.9528	0.0016	2
12	0.9296	0.0018	2
15	0.9155	0.0017	2
18	0.9117	0.0024	2

Table 2. Calibration factor (Sensor No. 2)

Frequency [GHz]	Calibration factor K	Combined standard uncertainty $u_c(K)$ (k = 1)	Coverage factor k corresponding to a level of confidence of 95 %
0.01	0.9904	0.0021	2
0.05	0.9942	0.0015	2
1	0.9795	0.0015	2

4	0.9678	0.0015	2
8	0.9510	0.0016	2
12	0.9292	0.0016	2
15	0.9135	0.0016	2
18	0.9117	0.0020	2

(4) Measurement conditions

Ambient temperature 23 ± 1 °C and humidity 50 ± 20 %.

(5) Additional measurement

Reflection coefficients of the traveling standards

The measurement of reflection coefficients of the traveling standards is traceable to

NMIJ .

Table 3. Reflection coefficient (Sensor No.1)

Frequency [GHz]	Real component [Lin.]	Imaginary component [Lin.]	Uncertainty of magnitude [Lin.] (k = 2)
0.01	0.0056	-0.0630	0.0080
0.05	-0.0028	-0.0133	0.0080
1	0.0081	-0.0018	0.0080
4	0.0110	0.0103	0.0080
8	-0.0133	-0.0096	0.0080
12	-0.0278	0.0142	0.0080
15	-0.0101	0.0263	0.0080
18	-0.0484	0.0571	0.0080

Table 4. Reflection coefficient (Sensor No.2)

Frequency [GHz]	Real component	Imaginary component	Uncertainty of magnitude [Lin.]

	[Lin.]	[Lin.]	(k = 2)
0.01	0.0068	-0.0647	0.0080
0.05	-0.0018	-0.0137	0.0080
1	0.0080	-0.0031	0.0080
4	0.0121	0.0052	0.0080
8	-0.0145	-0.0066	0.0080
12	-0.0205	0.0084	0.0080
15	-0.0047	0.0184	0.0080
18	-0.0396	0.0474	0.0080

Uncertainty budgets (NMIJ)

Sensor No.1 (0.01 GHz)

Uncertainty of calibration factor(1mW,		0.01	GHz)								
Date : 2012/07/18											
Model:	8481A, E4419B										
Serial number :	US41031012, MY45100436										
Product : Power Meter											
Manufacturer :											
Quantity	Input estimate Xi	Unit	Uncertainty factor		Type	Distribution	Sensitivity coefficiect Ci	Standard uncertainty u(Xi)	|Ci|u(Xi) =ui(Ku)	Degrees of freedom	ui^4(Ku)/νi
Power splitting ratio (Cd)	1.0105	1	u(Cd) (1σ)	0.00117	B	Normal	-0.9819	0.00117	1.15E-03	9	1.96E-13
			Long term drift (±δXi)	0.00160	B	Uniform	-0.9819	0.00092	9.07E-04	***	0
DUT power (Pu)	1	mW	Resolution (±δXi)	0.00010	B	Uniform	0.9922	2.9E-05	2.86E-05	***	0
Monitoring power(Pmu)	1	mW	Resolution (±δXi)	0.00010	B	Uniform	-0.9922	2.9E-05	2.86E-05	***	0
Efficiency of adaptor (η_a)	1.000	1	Adaptor correction	0.000445	B	Normal	-0.9924	0.00045	4.42E-04	***	0
Average of Ku	0.9922	1	Dispersion of Ku (σn-1)	0.00047	A	t	1	9.5E-05	9.50E-05	24	3.39003E-18
Vector correction coefficient			Source mismatch (Γg, Γs, Γu)	0.001	B	Normal	0.9922	0.00139	1.37E-03	50	7.14379E-14
				0.00139							
Output	Input estimate	Unit									
Calibration factor of DUT Ku (Before ADP correction)	0.9922	1	Level of confidence	95%					Combined standard uncertainty	Effective degrees of freedom νeff	Total ui^4(Ku)/νi
			Coverage factor	1.9960					0.0021	67	2.67E-13
Calibration factor of DUT Ku (After ADP correction)	0.9924		Used coverage factor: k =	2							
			Expanded uncertainty U(Ku)=k*uc(Ku)	0.0041	0.42%						

Uncertainty budgets (NMIJ)

Sensor No.1 (0.05 GHz)

Uncertainty of calibration factor(1mW,		0.05	GHz)								
Date : 2012/07/18											
Model:	8481A, E4419B										
Serial number :	US41031012, MY45100436										
Product : Power Meter											
Manufacturer :											
Quantity	Input estimate Xi	Unit	Uncertainty factor		Type	Distribution	Sensitivity coefficiect Ci	Standard uncertainty u(Xi)	|Ci|u(Xi) =ui(Ku)	Degrees of freedom	ui^4(Ku)/νi
Power splitting ratio (Cd)	1.0053	1	u(Cd) (1σ)	0.00117	B	Normal	-0.9888	0.00117	1.15E-03	9	1.96E-13
			Long term drift (±δXi)	0.00160	B	Uniform	-0.9888	0.00092	9.13E-04	***	0
DUT power (Pu)	1	mW	Resolution (±δXi)	0.00010	B	Uniform	0.9940	2.9E-05	2.87E-05	***	0
Monitoring power(Pmu)	1	mW	Resolution (±δXi)	0.00010	B	Uniform	-0.9940	2.9E-05	2.87E-05	***	0
Efficiency of adaptor (η_a)	0.999	1	Adaptor correction	0.00016	B	Normal	-0.9946	0.00016	1.59E-04	***	0
Average of Ku	0.9940	1	Dispersion of Ku (σn-1)	0.00045	A	t	1	9E-05	9.02E-05	24	2.75387E-18
Vector correction coefficient			Source mismatch (Γg, Γs, Γu)	0.003	B	Normal	0.9940	0.00029	2.93E-04	50	1.46785E-16
				0.00029							
Output	Input estimate	Unit									
Calibration factor of DUT Ku (Before ADP correction)	0.9940	1	Level of confidence	95%					Combined standard uncertainty	Effective degrees of freedom νeff	Total ui^4(Ku)/νi
			Coverage factor	2.0555					0.0015	26	1.96E-13
Calibration factor of DUT Ku (After ADP correction)	0.9946		Used coverage factor: k =	2							
			Expanded uncertainty U(Ku)=k*uc(Ku)	0.0030	0.30%						

Uncertainty budgets (NMIJ)
Sensor No.1 (1 GHz)

Uncertainty of calibration factor(1mW,		1	GHz)								
Date : 2012/07/18											
Model:	8481A, E4419B										
Serial number :	US41031012, MY45100436										
Product : Power Meter											
Manufacturer :											
Quantity	Input estimate Xi	Unit	Uncertainty factor		Type	Distribution	Sensitivity coefficiect Ci	Standard uncertainty u(Xi)	|Ci|u(Xi) =ui(Ku)	Degrees of freedom	ui^4(Ku)/νi
Power splitting ratio (Cd)	1.0156	1	u(Cd) (1σ)	0.00118	B	Normal	-0.9605	0.00118	1.14E-03	9	1.85E-13
			Long term drift (±δXi)	0.00160	B	Uniform	-0.9605	0.00092	8.87E-04	***	0
DUT power (Pu)	1	mW	Resolution (±δXi)	0.00010	B	Uniform	0.9755	2.9E-05	2.82E-05	***	0
Monitoring power(Pmu)	1	mW	Resolution (±δXi)	0.00010	B	Uniform	-0.9755	2.9E-05	2.82E-05	***	0
Efficiency of adaptor (η_a)	0.996	1	Adaptor correction	0.000371	B	Normal	-0.9793	0.00037	3.63E-04	***	0
Average of Ku	0.9755	1	Dispersion of Ku (σn-1)	0.00032	A	t	1	6.5E-05	6.46E-05	24	7.26586E-19
Vector correction coefficient			Source mismatch (Γg, Γs, Γu)	0.008	B	Normal	0.9755	0.00027	2.60E-04	50	9.19438E-17
				0.00027							
Output	Input estimate	Unit									
Calibration factor of DUT Ku (Before ADP correction)	0.9755	1	Level of confidence	95%					Combined standard uncertainty	Effective degrees of freedom ν eff	Total ui^4(Ku)/νi
			Coverage factor	2.0484					0.0015	28	1.85E-13
Calibration factor of DUT Ku (After ADP correction)	0.9793		Used coverage factor: k =	2							
			Expanded uncertainty U(Ku)=k*uc(Ku)	0.0030	0.31%						

Uncertainty budgets (NMIJ)

Sensor No.1 (4 GHz)

Uncertainty of calibration factor (1mW,		4	GHz)								
Date : 2012/07/18											
Model:	8481A, E4419B										
Serial number :	US41031012, MY45100436										
Product : Power Meter											
Manufacturer :											
Quantity	Input estimate Xi	Unit	Uncertainty factor		Type	Distribution	Sensitivity coefficiect Ci	Standard uncertainty u(Xi)	|Ci|u(Xi) =ui(Ku)	Degrees of freedom	ui^4(Ku)/νi
Power splitting ratio (Cd)	1.0193	1	u(Cd) (1σ)	0.00121	B	Normal	-0.9425	0.00121	1.14E-03	10	1.67E-13
			Long term drift (±δXi)	0.00160	B	Uniform	-0.9425	0.00092	8.71E-04	***	0
DUT power (Pu)	1	mW	Resolution (±δXi)	0.00010	B	Uniform	0.9606	2.9E-05	2.77E-05	***	0
Monitoring power (Pmu)	1	mW	Resolution (±δXi)	0.00010	B	Uniform	-0.9606	2.9E-05	2.77E-05	***	0
Efficiency of adaptor (η_a)	0.992	1	Adaptor correction	0.000325	B	Normal	-0.9683	0.00033	3.15E-04	***	0
Average of Ku	0.9606	1	Dispersion of Ku (σn-1)	0.00011	A	t	1	2.3E-05	2.30E-05	24	1.1603E-20
Vector correction coefficient			Source mismatch (Γg, Γs, Γu)	0.013	B	Normal	0.9606	0.00051	4.91E-04	50	1.16568E-15
				0.00051							
Output	Input estimate	Unit									
Calibration factor of DUT Ku (Before ADP correction)	0.9606	1	Level of confidence	95%					Combined standard uncertainty	Effective degrees of freedom νeff	Total ui^4(Ku)/νi
			Coverage factor	2.0322					0.0015	34	1.68E-13
Calibration factor of DUT Ku (After ADP correction)	0.9683		Used coverage factor: k =	2							
			Expanded uncertainty U(Ku)=k*uc(Ku)	0.0031	0.32%						

Uncertainty budgets (NMIJ)

Sensor No.1 (8 GHz)

Uncertainty of calibration factor (1mW, 8 GHz)

Date : 2012/07/18

Model: 8481A, E4419B

Serial number : US41031012, MY45100436

Product : Power Meter

Manufacturer :

Quantity	Input estimate Xi	Unit	Uncertainty factor		Type	Distribution	Sensitivity coefficiect Ci	Standard uncertainty u(Xi)	|Ci|u(Xi) =ui(Ku)	Degrees of freedom	ui^4(Ku)/νi
Power splitting ratio (Cd)	1.0296	1	u(Cd) (1σ)	0.00125	B	Normal	-0.9137	0.00125	1.14E-03	11	1.54E-13
			Long term drift (±δXi)	0.00160	B	Uniform	-0.9137	0.00092	8.44E-04	***	0
DUT power (Pu)	1	mW	Resolution (±δXi)	0.00010	B	Uniform	0.9408	2.9E-05	2.72E-05	***	0
Monitoring power (Pmu)	1	mW	Resolution (±δXi)	0.00010	B	Uniform	-0.9408	2.9E-05	2.72E-05	***	0
Efficiency of adaptor (η_a)	0.987	1	Adaptor correction	0.000567	B	Normal	-0.9528	0.00057	5.40E-04	***	0
Average of Ku	0.9408	1	Dispersion of Ku (σn-1)	0.00211	A	t	1	0.00042	4.23E-04	24	1.32977E-15
Vector correction coefficient			Source mismatch (Γg, Γs, Γu)	0.016	B	Normal	0.9408	0.00042	3.95E-04	50	4.85069E-16
				0.00042							
Output	Input estimate	Unit									
Calibration factor of DUT Ku (Before ADP correction)	0.9408	1	Level of confidence	95%					Combined standard uncertainty	Effective degrees of freedom νeff	Total ui^4(Ku)/νi
			Coverage factor	2.0154					0.0016	44	1.56E-13
Calibration factor of DUT Ku (After ADP correction)	0.9528		Used coverage factor: k =	2							
			Expanded uncertainty U(Ku)=k*uc(Ku)	0.0033	0.35%						

Uncertainty budgets (NMIJ)

Sensor No.1 (12 GHz)

Uncertainty of calibration factor (1mW, 12 GHz)

Date : 2012/07/18

Model: 8481A, E4419B

Serial number : US41031012, MY45100436

Product : Power Meter

Manufacturer :

Quantity	Input estimate Xi	Unit	Uncertainty factor		Type	Distribution	Sensitivity coefficiect Ci	Standard uncertainty u(Xi)	|Ci|u(Xi) =ui(Ku)	Degrees of freedom	ui^4(Ku)/νi
Power splitting ratio (Cd)	1.0403	1	u(Cd) (1σ)	0.00133	B	Normal	-0.8798	0.00133	1.17E-03	13	1.43E-13
			Long term drift (±δXi)	0.00160	B	Uniform	-0.8798	0.00092	8.13E-04	***	0
DUT power (Pu)	1	mW	Resolution (±δXi)	0.00010	B	Uniform	0.9153	2.9E-05	2.64E-05	***	0
Monitoring power (Pmu)	1	mW	Resolution (±δXi)	0.00010	B	Uniform	-0.9153	2.9E-05	2.64E-05	***	0
Efficiency of adaptor (η_a)	0.985	1	Adaptor correction	0.000539	B	Normal	-0.9296	0.00054	5.01E-04	***	0
Average of Ku	0.9153	1	Dispersion of Ku (σn-1)	0.00059	A	t	1	0.00012	1.18E-04	24	8.0971E-18
Vector correction coefficient			Source mismatch (Γg, Γs, Γu)	0.010	B	Normal	0.9153	0.00099	9.09E-04	50	1.36734E-14
				0.00099							
Output	Input estimate	Unit									
Calibration factor of DUT Ku (Before ADP correction)	0.9153	1	Level of confidence	95%					Combined standard uncertainty	Effective degrees of freedom νeff	Total ui^4(Ku)/νi
			Coverage factor	1.9996					0.0018	61	1.57E-13
Calibration factor of DUT Ku (After ADP correction)	0.9296		Used coverage factor: k =	2							
			Expanded uncertainty U(Ku)=k*uc(Ku)	0.0035	0.39%						

Uncertainty budgets (NMIJ)

Sensor No.1 (15 GHz)

Uncertainty of calibration factor (1mW,		15	GHz)								
Date : 2012/07/18											
Model:	8481A, E4419B										
Serial number :	US41031012, MY45100436										
Product : Power Meter											
Manufacturer :											
Quantity	Input estimate Xi	Unit	Uncertainty factor		Type	Distribution	Sensitivity coefficiect Ci	Standard uncertainty u(Xi)	|Ci|u(Xi) =ui(Ku)	Degrees of freedom	ui^4(Ku)/νi
Power splitting ratio (Cd)	1.0423	1	u(Cd) (1σ)	0.00139	B	Normal	-0.8631	0.00139	1.20E-03	15	1.38E-13
			Long term drift (±δXi)	0.00160	B	Uniform	-0.8631	0.00092	7.97E-04	***	0
DUT power (Pu)	1	mW	Resolution (±δXi)	0.00010	B	Uniform	0.8995	2.9E-05	2.60E-05	***	0
Monitoring power (Pmu)	1	mW	Resolution (±δXi)	0.00010	B	Uniform	-0.8995	2.9E-05	2.60E-05	***	0
Efficiency of adaptor (η_a)	0.983	1	Adaptor correction	0.0005	B	Normal	-0.9155	0.0005	4.58E-04	***	0
Average of Ku	0.8995	1	Dispersion of Ku (σn-1)	0.00115	A	t	1	0.00023	2.31E-04	24	1.17743E-16
Vector correction coefficient			Source mismatch (Γg, Γs, Γu)	0.030	B	Normal	0.8995	0.00078	7.05E-04	50	4.94609E-15
				0.00078							
Output	Input estimate	Unit									
Calibration factor of DUT Ku (Before ADP correction)	0.8995	1	Level of confidence	95%					Combined standard uncertainty	Effective degrees of freedom νeff	Total ui^4(Ku)/νi
			Coverage factor	2.0032					0.0017	56	1.43E-13
Calibration factor of DUT Ku (After ADP correction)	0.9155		Used coverage factor: k =	2							
			Expanded uncertainty U(Ku)=k*uc(Ku)	0.0034	0.37%						

Uncertainty budgets (NMIJ)

Sensor No.1 (18 GHz)

Uncertainty of calibration factor (1mW,		18	GHz)								
Date : 2012/07/18											
Model:	8481A, E4419B										
Serial number :	US41031012, MY45100436										
Product : Power Meter											
Manufacturer :											

Quantity	Input estimate Xi	Unit	Uncertainty factor		Type	Distribution	Sensitivity coefficiect Ci	Standard uncertainty u(Xi)	|Ci|u(Xi) =ui(Ku)	Degrees of freedom	ui^4(Ku)/νi
Power splitting ratio (Cd)	1.0477	1	u(Cd) (1σ)	0.00140	B	Normal	-0.8541	0.0014	1.19E-03	16	1.27E-13
			Long term drift (±δXi)	0.00160	B	Uniform	-0.8541	0.00092	7.89E-04	***	0
DUT power (Pu)	1	mW	Resolution (±δXi)	0.00010	B	Uniform	0.8949	2.9E-05	2.58E-05	***	0
Monitoring power (Pmu)	1	mW	Resolution (±δXi)	0.00010	B	Uniform	-0.8949	2.9E-05	2.58E-05	***	0
Efficiency of adaptor (ηa)	0.982	1	Adaptor correction	0.000823	B	Normal	-0.9117	0.00082	7.50E-04	***	0
Average of Ku	0.8949	1	Dispersion of Ku (σn-1)	0.00067	A	t	1	0.00013	1.34E-04	24	1.34789E-17
Vector correction coefficient			Source mismatch (Γg, Γs, Γu)	0.035	B	Normal	0.8949	0.00198	1.78E-03	50	1.98892E-13
				0.00198							

Output	Input estimate	Unit									
Calibration factor of DUT Ku (Before ADP correction)	0.8949	1	Level of confidence	95%					Combined standard uncertainty	Effective degrees of freedom νeff	Total ui^4(Ku)/νi
			Coverage factor	1.9835					0.0024	102	3.26E-13
Calibration factor of DUT Ku (After ADP correction)	0.9117		Used coverage factor: k =	2							
			Expanded uncertainty U(Ku)=k*uc(Ku)	0.0048	0.54%						

Uncertainty budgets (NMIJ)

Sensor No. 2 (0.01 GHz)

Uncertainty of calibration factor(1mW,		0.01	GHz)								
Date : 2012/07/18											
Model:	8481A, E4419B										
Serial number :	US41031013, MY45100436										
Product : Power Meter											
Manufacturer :											
Quantity	Input estimate Xi	Unit	Uncertainty factor		Type	Distribution	Sensitivity coefficiect Ci	Standard uncertainty u(Xi)	|Ci|u(Xi) =ui(Ku)	Degrees of freedom	ui^4(Ku)/νi
Power splitting ratio (Cd)	1.0105	1	u(Cd) (1σ)	0.00117	B	Normal	-0.9800	0.00117	1.15E-03	9	1.95E-13
			Long term drift (±δXi)	0.00160	B	Uniform	-0.9800	0.00092	9.05E-04	***	0
DUT power (Pu)	1	mW	Resolution (±δXi)	0.00010	B	Uniform	0.9903	2.9E-05	2.86E-05	***	0
Monitoring power(Pmu)	1	mW	Resolution (±δXi)	0.00010	B	Uniform	-0.9903	2.9E-05	2.86E-05	***	0
Efficiency of adaptor (η_a)	1.000	1	Adaptor correction	0.000451	B	Normal	-0.9904	0.00045	4.47E-04	***	0
Average of Ku	0.9903	1	Dispersion of Ku (σn-1)	0.00015	A	t	1	3.1E-05	3.05E-05	24	3.61079E-20
Vector correction coefficient			Source mismatch (Γg, Γs, Γu)	0.001	B	Normal	0.9903	0.00142	1.41E-03	50	7.8732E-14
				0.00142							
Output	Input estimate	Unit									
Calibration factor of DUT Ku (Before adaptor correction)	0.9903	1	Level of confidence	95%					Combined standard uncertainty	Effective degrees of freedom νeff	Total ui^4(Ku)/νi
			Coverage factor	1.9955					0.0021	68	2.73E-13
Calibration factor of DUT Ku (After adaptor correction)	0.9904		Used coverage factor: k =	2							
			Expanded uncertainty U(Ku)=k*uc(Ku)	0.0042	0.42%						

Uncertainty budgets (NMIJ)
Sensor No. 2 (0.05 GHz)

Uncertainty of calibration factor(1mW,	0.05	GHz)
Date : 2012/07/18		
Model:	8481A, E4419B	
Serial number :	US41031013, MY45100436	
Product : Power Meter		
Manufacturer :		

Quantity	Input estimate Xi	Unit	Uncertainty factor		Type	Distribution	Sensitivity coefficiect Ci	Standard uncertainty u(Xi)	|Ci|u(Xi) =ui(Ku)	Degrees of freedom	ui^4(Ku)/νi
Power splitting ratio (Cd)	1.0053	1	u(Cd) (1σ)	0.00117	B	Normal	-0.9883	0.00117	1.15E-03	9	1.96E-13
			Long term drift (±δXi)	0.00160	B	Uniform	-0.9883	0.00092	9.13E-04	***	0
DUT power (Pu)	1	mW	Resolution (±δXi)	0.00010	B	Uniform	0.9936	2.9E-05	2.87E-05	***	0
Monitoring power(Pmu)	1	mW	Resolution (±δXi)	0.00010	B	Uniform	-0.9936	2.9E-05	2.87E-05	***	0
Efficiency of adaptor (η_a)	0.999	1	Adaptor correction	0.00016	B	Normal	-0.9942	0.00016	1.59E-04	***	0
Average of Ku	0.9936	1	Dispersion of Ku (σn-1)	0.00020	A	t	1	4E-05	4.01E-05	24	1.07759E-19
Vector correction coefficient			Source mismatch (Γg, Γs, Γu)	0.003	B	Normal	0.9936	0.0003	2.98E-04	50	1.58226E-16
				0.00030							

Output	Input estimate	Unit									
Calibration factor of DUT Ku (Before adaptor correction)	0.9936	1	Level of confidence	95%					Combined standard uncertainty	Effective degrees of freedom νeff	Total ui^4(Ku)/νi
			Coverage factor	2.0555					0.0015	26	1.96E-13
Calibration factor of DUT Ku (After adaptor correction)	0.9942		Used coverage factor: k =	2							
			Expanded uncertainty U(Ku)=k*uc(Ku)	0.0030	0.30%						

Uncertainty budgets (NMIJ)
Sensor No. 2 (1 GHz)

Uncertainty of calibration factor (1mW,		1	GHz)								
Date : 2012/07/18											
Model:	8481A, E4419B										
Serial number :	US41031013, MY45100436										
Product : Power Meter											
Manufacturer :											

Quantity	Input estimate Xi	Unit	Uncertainty factor		Type	Distribution	Sensitivity coefficiect Ci	Standard uncertainty u(Xi)	|Ci|u(Xi) =ui(Ku)	Degrees of freedom	ui^4(Ku)/νi
Power splitting ratio (Cd)	1.0156	1	u(Cd) (1σ)	0.00118	B	Normal	-0.9608	0.00118	1.14E-03	9	1.85E-13
			Long term drift (±δXi)	0.00160	B	Uniform	-0.9608	0.00092	8.88E-04	***	0
DUT power (Pu)	1	mW	Resolution (±δXi)	0.00010	B	Uniform	0.9758	2.9E-05	2.82E-05	***	0
Monitoring power (Pmu)	1	mW	Resolution (±δXi)	0.00010	B	Uniform	-0.9758	2.9E-05	2.82E-05	***	0
Efficiency of adaptor (η_a)	0.996	1	Adaptor correction	0.000371	B	Normal	-0.9795	0.00037	3.63E-04	***	0
Average of Ku	0.9758	1	Dispersion of Ku (σn-1)	0.00016	A	t	1	3.2E-05	3.25E-05	24	4.62756E-20
Vector correction coefficient			Source mismatch (Γg, Γs, Γu)	0.008	B	Normal	0.9758	0.00028	2.74E-04	50	1.12166E-16
				0.00028							

Output	Input estimate	Unit									
Calibration factor of DUT Ku (Before adaptor correction)	0.9758	1	Level of confidence	95%					Combined standard uncertainty	Effective degrees of freedom ν eff	Total ui^4(Ku)/νi
			Coverage factor	2.0484					0.0015	28	1.85E-13
Calibration factor of DUT Ku (After adaptor correction)	0.9795		Used coverage factor: k =	2							
			Expanded uncertainty U(Ku)=k*uc(Ku)	0.0030	0.31%						

Uncertainty budgets (NMIJ)
Sensor No. 2 (4 GHz)

Uncertainty of calibration factor(1mW,		4	GHz)								
Date : 2012/07/18											
Model:	8481A, E4419B										
Serial number :	US41031013, MY45100436										
Product : Power Meter											
Manufacturer :											

Quantity	Input estimate Xi	Unit	Uncertainty factor		Type	Distribution	Sensitivity coefficiect Ci	Standard uncertainty u(Xi)	|Ci|u(Xi) =ui(Ku)	Degrees of freedom	ui^4(Ku)/νi
Power splitting ratio (Cd)	1.0193	1	u(Cd) (1σ)	0.00121	B	Normal	-0.9420	0.00121	1.14E-03	10	1.67E-13
			Long term drift (±δXi)	0.00160	B	Uniform	-0.9420	0.00092	8.70E-04	***	0
DUT power (Pu)	1	mW	Resolution (±δXi)	0.00010	B	Uniform	0.9601	2.9E-05	2.77E-05	***	0
Monitoring power(Pmu)	1	mW	Resolution (±δXi)	0.00010	B	Uniform	-0.9601	2.9E-05	2.77E-05	***	0
Efficiency of adaptor (ηa)	0.992	1	Adaptor correction	0.000317	B	Normal	-0.9678	0.00032	3.07E-04	***	0
Average of Ku	0.9601	1	Dispersion of Ku (σn-1)	0.00030	A	t	1	6.1E-05	6.09E-05	24	5.74722E-19
Vector correction coefficient			Source mismatch (Γg, Γs, Γu)	0.013	B	Normal	0.9601	0.00048	4.57E-04	50	8.71058E-16
				0.00048							

Output	Input estimate	Unit									
Calibration factor of DUT Ku (Before adaptor correction)	0.9601	1	Level of confidence	95%					Combined standard uncertainty	Effective degrees of freedom νeff	Total ui^4(Ku)/νi
			Coverage factor	2.0345					0.0015	33	1.67E-13
Calibration factor of DUT Ku (After adaptor correction)	0.9678		Used coverage factor: k =	2							
			Expanded uncertainty U(Ku)=k*uc(Ku)	0.0031	0.32%						

Uncertainty budgets (NMIJ)
Sensor No. 2 (8 GHz)

Uncertainty of calibration factor(1mW,		8	GHz)							
Date : 2012/07/18										
Model:	8481A, E4419B									
Serial number :	US41031013, MY45100436									
Product : Power Meter										
Manufacturer :										

Quantity	Input estimate Xi	Unit	Uncertainty factor		Type	Distribution	Sensitivity coefficiect Ci	Standard uncertainty u(Xi)	|Ci|u(Xi) =ui(Ku)	Degrees of freedom	ui^4(Ku)/νi
Power splitting ratio (Cd)	1.0296	1	u(Cd) (1σ)	0.00125	B	Normal	−0.9121	0.00125	1.14E−03	11	1.53E−13
			Long term drift (±δXi)	0.00160	B	Uniform	−0.9121	0.00092	8.43E−04	***	0
DUT power (Pu)	1	mW	Resolution (±δXi)	0.00010	B	Uniform	0.9391	2.9E−05	2.71E−05	***	0
Monitoring power(Pmu)	1	mW	Resolution (±δXi)	0.00010	B	Uniform	−0.9391	2.9E−05	2.71E−05	***	0
Efficiency of adaptor (η_a)	0.988	1	Adaptor correction	0.000526	B	Normal	−0.9510	0.00053	5.00E−04	***	0
Average of Ku	0.9391	1	Dispersion of Ku (σn−1)	0.00251	A	t	1	0.0005	5.03E−04	24	2.66377E−15
Vector correction coefficient			Source mismatch (Γg, Γs, Γu)	0.016	B	Normal	0.9391	0.00039	3.69E−04	50	3.69664E−16
				0.00039							

Output	Input estimate	Unit									
Calibration factor of DUT Ku (Before adaptor correction)	0.9391	1	Level of confidence	95%					Combined standard uncertainty	Effective degrees of freedom νeff	Total ui^4(Ku)/νi
			Coverage factor	2.0154					0.0016	44	1.56E−13
Calibration factor of DUT Ku (After adaptor correction)	0.9510		Used coverage factor: k =	2							
			Expanded uncertainty U(Ku)=k*uc(Ku)	0.0033	0.35%						

Uncertainty budgets (NMIJ)
Sensor No. 2 (12 GHz)

Uncertainty of calibration factor(1mW,		12	GHz)								
Date : 2012/07/18											
Model:	8481A, E4419B										
Serial number :	US41031013, MY45100436										
Product : Power Meter											
Manufacturer :											

Quantity	Input estimate Xi	Unit	Uncertainty factor		Type	Distribution	Sensitivity coefficiect Ci	Standard uncertainty u(Xi)	|Ci|u(Xi) =ui(Ku)	Degrees of freedom	ui^4(Ku)/νi
Power splitting ratio (Cd)	1.0403	1	u(Cd) (1σ)	0.00133	B	Normal	-0.8794	0.00133	1.17E-03	13	1.43E-13
			Long term drift (±δXi)	0.00160	B	Uniform	-0.8794	0.00092	8.12E-04	***	0
DUT power (Pu)	1	mW	Resolution (±δXi)	0.00010	B	Uniform	0.9148	2.9E-05	2.64E-05	***	0
Monitoring power(Pmu)	1	mW	Resolution (±δXi)	0.00010	B	Uniform	-0.9148	2.9E-05	2.64E-05	***	0
Efficiency of adaptor (η_a)	0.985	1	Adaptor correction	0.000481	B	Normal	-0.9292	0.00048	4.47E-04	***	0
Average of Ku	0.9148	1	Dispersion of Ku (σn-1)	0.00085	A	t	1	0.00017	1.69E-04	24	3.40158E-17
Vector correction coefficient			Source mismatch (Γg, Γs, Γu)	0.010	B	Normal	0.9148	0.00072	6.58E-04	50	3.74256E-15
				0.00072							
Output	Input estimate	Unit									
Calibration factor of DUT Ku (Before adaptor correction)	0.9148	1	Level of confidence	95%					Combined standard uncertainty	Effective degrees of freedom νeff	Total ui^4(Ku)/νi
			Coverage factor	2.0096					0.0016	49	1.47E-13
Calibration factor of DUT Ku (After adaptor correction)	0.9292		Used coverage factor: k =	2							
			Expanded uncertainty U(Ku)=k*uc(Ku)	0.0033	0.36%						

Uncertainty budgets (NMIJ)
Sensor No. 2 (15 GHz)

Uncertainty of calibration factor(1mW,		15	GHz)								
Date : 2012/07/18											
Model:	8481A, E4419B										
Serial number :	US41031013, MY45100436										
Product : Power Meter											
Manufacturer :											
Quantity	Input estimate Xi	Unit	Uncertainty factor		Type	Distribution	Sensitivity coefficiect Ci	Standard uncertainty u(Xi)	|Ci|u(Xi) =ui(Ku)	Degrees of freedom	ui^4(Ku)/νi
Power splitting ratio (Cd)	1.0423	1	u(Cd) (1σ)	0.00139	B	Normal	-0.8612	0.00139	1.20E-03	15	1.37E-13
			Long term drift (±δXi)	0.00160	B	Uniform	-0.8612	0.00092	7.96E-04	***	0
DUT power (Pu)	1	mW	Resolution (±δXi)	0.00010	B	Uniform	0.8976	2.9E-05	2.59E-05	***	0
Monitoring power(Pmu)	1	mW	Resolution (±δXi)	0.00010	B	Uniform	-0.8976	2.9E-05	2.59E-05	***	0
Efficiency of adaptor (η_a)	0.983	1	Adaptor correction	0.000437	B	Normal	-0.9135	0.00044	3.99E-04	***	0
Average of Ku	0.8976	1	Dispersion of Ku (σn-1)	0.00193	A	t	1	0.00039	3.86E-04	24	9.22999E-16
Vector correction coefficient			Source mismatch (Γg, Γs, Γu)	0.030	B	Normal	0.8976	0.00038	3.45E-04	50	2.84697E-16
				0.00038							
Output	Input estimate	Unit									
Calibration factor of DUT Ku (Before adaptor correction)	0.8976	1	Level of confidence	95%					Combined standard uncertainty	Effective degrees of freedom νeff	Total ui^4(Ku)/νi
			Coverage factor	2.0141					0.0016	45	1.38E-13
Calibration factor of DUT Ku (After adaptor correction)	0.9135		Used coverage factor: k =	2							
			Expanded uncertainty U(Ku)=k*uc(Ku)	0.0032	0.35%						

Uncertainty budgets (NMIJ)
Sensor No. 2 (18 GHz)

Uncertainty of calibration factor(1mW, 18 GHz)
Date : 2012/07/18
Model: 8481A, E4419B
Serial number : US41031013, MY45100436
Product : Power Meter
Manufacturer :

Quantity	Input estimate Xi	Unit	Uncertainty factor		Type	Distribution	Sensitivity coefficiect Ci	Standard uncertainty u(Xi)	|Ci|u(Xi) =ui(Ku)	Degrees of freedom	ui^4(Ku)/ν i
Power splitting ratio (Cd)	1.0477	1	u(Cd) (1σ)	0.00140	B	Normal	-0.8536	0.0014	1.19E-03	16	1.26E-13
			Long term drift (±δXi)	0.00160	B	Uniform	-0.8536	0.00092	7.89E-04	***	0
DUT power (Pu)	1	mW	Resolution (±δXi)	0.00010	B	Uniform	0.8943	2.9E-05	2.58E-05	***	0
Monitoring power(Pmu)	1	mW	Resolution (±δXi)	0.00010	B	Uniform	-0.8943	2.9E-05	2.58E-05	***	0
Efficiency of adaptor (η_a)	0.981	1	Adaptor correction	0.000728	B	Normal	-0.9117	0.00073	6.64E-04	***	0
Average of Ku	0.8943	1	Dispersion of Ku (σn-1)	0.00044	A	t	1	8.9E-05	8.88E-05	24	2.59637E-18
Vector correction coefficient			Source mismatch (Γg, Γs, Γu)	0.035	B	Normal	0.8943	0.00144	1.29E-03	50	5.56814E-14
				0.00144							
Output	Input estimate	Unit									
Calibration factor of DUT Ku (Before adaptor correction)	0.8943	1	Level of confidence	95%					Combined standard uncertainty	Effective degrees of freedom ν eff	Total ui^4(Ku)/ν i
			Coverage factor	1.9853					0.0020	95	1.82E-13
Calibration factor of DUT Ku (After adaptor correction)	0.9117		Used coverage factor: k =	2							
			Expanded uncertainty U(Ku)=k*uc(Ku)	0.0041	0.46%						

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Certificate of Calibration 校正證書

Certificate No. 證書編號	**RF120172**

Customer / 客戶	**Asia Pacific Metrology Programme**
Equipment / 儀器	
Description / 名稱	**Power Meter with Two Power Sensors**
Make / 製造商	**Agilent Technologies**
Model / 型號	**E4419B (power meter) and 8481A (power sensor)**
Serial No. / 序號	**MY45100436 (power meter), US41031012 (power sensor) and US41031013 (power sensor)**
Date of Receipt / 收件日期	**31 July 2012**
Test Environment / 測試環境	
Temperature / 溫度	**(23 ± 1) °C**
Relative Humidity / 相對濕度	**(45 ± 8) %**
Air Pressure / 氣壓	**(98.2 - 99.0) kPa**
Date of Test / 測試日期	**1 to 9 August 2012**

Test Specifications / 測試規格

To measure the calibration factor and the voltage reflection coefficient magnitude of two power sensors.

Test Results / 測試結果

Test results are presented in the subsequent pages.

Approved Signatory 批簽 **Yan Yui Kuen** **Date:** 日期 **17 September 2012**

The results shown in this certificate are metrologically traceable to the International System of Units (S.I.) or recognised measurement standards.
本證書所載結果可溯源至國際單位制或公認的計量標準。

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Main Laboratory : 36/F, Immigration Tower, 7 Gloucester Road, Wan Chai, Hong Kong. Tel : 2829 4830
Branch Laboratory : G04, Public Works Central Laboratory Building, 2B Cheung Yip Street, Kowloon Bay, Kowloon. Tel : 2798 7347
總所：香港灣仔告士打道 7 號入境事務大樓 36 樓 電話：2829 4830
分所：九龍九龍灣祥業街 2 號 B 工務中央試驗所大樓地下 04 室 電話：2798 7347

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1. The unit-under-test (UUT) was allowed to stabilise in the laboratory environment at an ambient temperature of 23 °C for over twelve hours. It was switched on for more than one hour before the commencement of the tests. The power supply to the power meter was 230 V, 50 Hz.

2. Before subsequent measurements, the pin depth of UUT was measured with the supplied connector gage. The measured values were within 0.2075 and 0.2097 inches.

3. Prior to measurement of absolute calibration factor, zeroing and self calibration of the UUT were performed.

4. The absolute calibration factor of the UUT was calibrated by using a laboratory HP 8478B thermistor mount power sensor which was connected with laboratory HP 432B power meter. A sinusoidal signal of approximately 6 dBm power level was applied to the input port of laboratory two-resistor power splitter such that there is a nominal 1 mW (0 dBm) power level at the output ports of the power splitter. The UUT was connected to one output port of the power splitter while the laboratory power sensor was connected to another port of the power splitter. Power readings of the UUT and the laboratory power meter were recorded. After half of the four measurements were performed, the two power sensors were swapped. The schematic diagram is shown in Figure 1.

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5. Calibration factor K of UUT power sensor is defined as the ratio of the power meter reading of UUT, P_{mf}, to the incident power to the laboratory power sensor, P_{if}, with the uncertainty introduced by the power mismatch factors, M_{mf} and M_{mrf} respectively.

$K = P_{mf}M_{mf}/P_{if}$
$P_{if} = P_{mrf}\,M_{mrf}/K_{rf}$

Taking into account the linearity factor, then
$K = \eta_{rf}(1\text{-}\Gamma_{rf}^{2})P_{mf}M_{mf}L/(P_{mrf}M_{mrf}) = \eta_{rf}(1\text{-}\Gamma_{rf}^{2})P_{rf}M_{mf}L/M_{mrf}$

where,
K_{rf} = calibration factor of laboratory power sensor at frequency f = $\eta_{rf}(1\text{-}\Gamma_{rf}^{2})$
η_{rf} = effective efficiency of laboratory power sensor at frequency f
Γ_{rf} = voltage reflection coefficient (magnitude) of laboratory power sensor at frequency f
P_{mf} = power reading of UUT power meter at frequency f
M_{mf} = power mismatch factor for the mismatch between UUT power sensor and the power splitter at frequency f
P_{mrf} = power reading of laboratory power meter at frequency f
M_{mrf} = power mismatch factor for the mismatch between laboratory power sensor and the power splitter at frequency f
P_{rf} = P_{mf} divided by P_{mrf} at frequency f
L = linearity of laboratory power sensor at test level

6. Power measurement is metrologically traceable to the laboratory microcalorimeter system. The microcalorimeter is used to calibrate the effective efficiency of the laboratory thermistor mount power sensor. Test results of the absolute calibration factor of UUT are presented in Tables 1 and 2.

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7. The measurement uncertainty budgets of the calibration factor of the two power sensors are shown in Appendices 1 and 2.

8. The magnitude (scalar) of the voltage reflection coefficient (VRC) of the UUT was measured by a laboratory automatic network analyzer. The VRC measurement is metrologically traceable to the laboratory beadless airline. The VRC of the airline is calculated from the dimensions of the airline which were measured by our dimension laboratory and traceable to SCL's length standards. Test results of the VRC of the UUT are presented in Tables 3 and 4.

9. The measurement uncertainty evaluation has been carried out in accordance with principles in the Evaluation of Measurement Data – Guide to the Expression of Uncertainty in Measurement, JCGM 100:2008. The expanded measurement uncertainty U, with its coverage factor k, corresponds to a 95 % probability that the value of the measurand Y lies within the interval y-U to y+U. The combined standard measurement uncertainty u_c can be calculated as $u_c = U/k$ and its degrees of freedom ν_{eff} is given by the t-distribution with the respective k value.

10. The values given in this Certificate of Calibration only relate to the values measured at the time of the test and any measurement uncertainties quoted will not include allowances for the equipment long term drift, variations with environmental changes, vibration and shock during transportation, or the capability of any other laboratory to repeat the measurement.

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Table 1
Test Results of Calibration Factor Measurement

Power Sensor Serial No.: US41031012

Test Frequency (GHz)	Measured Calibration Factor K		
	Value y	Combined Standard Measurement Uncertainty $u_c(K)$	Coverage Factor k corresponding to a level of confidence of 95 %
0.01	0.991	0.007	2.0
0.05	0.994	0.003	2.2
1	0.977	0.004	2.2
4	0.966	0.005	2.1
8	0.944	0.008	2.1
12	0.932	0.006	2.0
15	0.917	0.009	2.0
18	0.928	0.015	2.0

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Table 2
Test Results of Calibration Factor Measurement

Power Sensor Serial No.: US41031013

Test Frequency (GHz)	Measured Calibration Factor K		
	Value y	Combined Standard Measurement Uncertainty $u_c(K)$	Coverage Factor k corresponding to a level of confidence of 95 %
0.01	0.989	0.006	2.0
0.05	0.994	0.003	2.1
1	0.977	0.003	2.1
4	0.965	0.005	2.1
8	0.942	0.007	2.1
12	0.932	0.006	2.0
15	0.916	0.008	2.0
18	0.928	0.014	2.0

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Table 3
Test Results of VRC Magnitude

Power Sensor Serial No.: US41031012

Test Frequency (GHz)	Measured VRC Magnitude		
	Value y	Combined Standard Measurement Uncertainty u_c	Coverage Factor k corresponding to a level of confidence of 95 %
0.01	0.061 4	0.005 3	2.0
0.05	0.013 3	0.003 5	2.0
1	0.009 0	0.003 5	2.0
4	0.015	0.006	2.0
8	0.017	0.006	2.0
12	0.032	0.011	2.0
15	0.028	0.011	2.0
18	0.075	0.012	2.0

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Table 4
Test Results of VRC Magnitude

Power Sensor Serial No.: US41031013

Test Frequency (GHz)	Measured VRC Magnitude		
	Value y	Combined Standard Measurement Uncertainty u_c	Coverage Factor k corresponding to a level of confidence of 95 %
0.01	0.062 8	0.005 3	2.0
0.05	0.013 6	0.003 5	2.0
1	0.009 5	0.003 5	2.0
4	0.013	0.006	2.0
8	0.017	0.006	2.0
12	0.023	0.011	2.0
15	0.016	0.011	2.0
18	0.061	0.012	2.0

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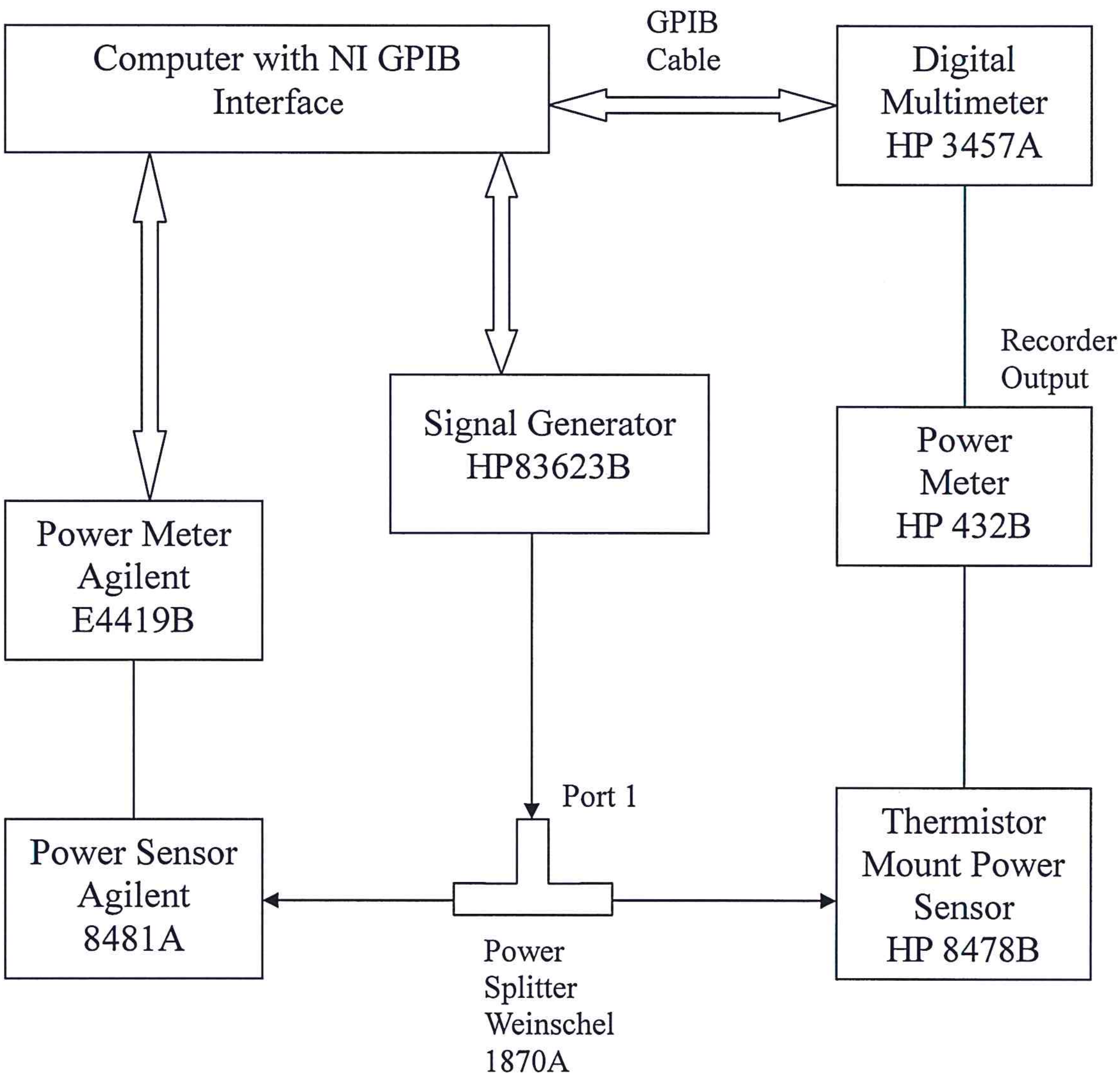

Figure 1 – Measurement Set Up Diagram

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Appendix 1

Measurement Uncertainty Budget of Calibration Factor of Power Sensor
(serial number of power sensor: US41031012)

Test Frequency (GHz)	Quantity X_i	Estimate x_i	Standard Measurement Uncertainty $u(x_i)$	Probability Distribution/Method of Evaluation (A or B)	Sensitivity Coefficient c_i	Uncertainty Contribution $\|c_i\|*u(x_i)$	Degrees of Freedom v_i
0.01	η_{rf}	0.98090	0.00180	B/Normal	1.00981	0.00182	15
	Γ_{rf}	0.14500	0.00381	B/Normal	-0.29342	0.00112	50
	P_{rf}	1.03150	0.00203	A/t	0.96028	0.00195	3
	M_{mf}	1.00000	0.00208	B/U	0.99053	0.00206	1E+99
	M_{mrf}	1.00000	0.00493	B/U	-0.99053	0.00488	1E+99
	L	1.00000	0.00029	B/R	0.99053	0.00029	1E+99
					Combined Standard Measurement Uncertainty $u_c(K)$	Coverage Factor, Level of Confidence 95 % k	Effective Degrees of Freedom v_{eff}
					0.00604	1.970	239.1

Test Frequency (GHz)	Quantity X_i	Estimate x_i	Standard Measurement Uncertainty $u(x_i)$	Probability Distribution/Method of Evaluation (A or B)	Sensitivity Coefficient c_i	Uncertainty Contribution $\|c_i\|*u(x_i)$	Degrees of Freedom v_i
0.050	η_{rf}	0.99160	0.00170	B/Normal	1.00222	0.00170	16
	Γ_{rf}	0.03400	0.00321	B/Normal	-0.06766	0.00022	50
	P_{rf}	1.00338	0.00196	A/t	0.99045	0.00194	3
	M_{mf}	1.00000	0.00045	B/U	0.99380	0.00045	1E+99
	M_{mrf}	1.00000	0.00117	B/U	-0.99380	0.00117	1E+99
	L	1.00000	0.00029	B/R	0.99380	0.00029	1E+99
					Combined Standard Measurement Uncertainty $u_c(K)$	Coverage Factor, Level of Confidence 95 % k	Effective Degrees of Freedom v_{eff}
					0.00289	2.156	13.3

Calibrated by : H.W. Li

Checked by : C.K. Ko

Date : 10 September 2012

Date : 10 September 2012

Certificate of Calibration (Continuation Page)
校正證書（續頁）

Certificate No. RF120172
證書編號

Appendix 1

Measurement Uncertainty Budget of Calibration Factor of Power Sensor
(serial number of power sensor: US41031012)

Test Frequency (GHz)	Quantity X_i	Estimate x_i	Standard Measurement Uncertainty $u(x_i)$	Probability Distribution/Method of Evaluation (A or B)	Sensitivity Coefficient c_i	Uncertainty Contribution $\|c_i\|*u(x_i)$	Degrees of Freedom ν_i
1.00	η_{rf}	0.98830	0.00200	B/Normal	0.98865	0.00198	15
	Γ_{rf}	0.02000	0.00336	B/Normal	-0.03910	0.00013	50
	P_{rf}	0.98905	0.00221	A/t	0.98790	0.00218	3
	M_{mf}	1.00000	0.00031	B/U	0.97709	0.00030	1E+99
	M_{mrf}	1.00000	0.00072	B/U	-0.97709	0.00070	1E+99
	L	1.00000	0.00029	B/R	0.97709	0.00028	1E+99
					Combined Standard Measurement Uncertainty $u_c(K)$	Coverage Factor, Level of Confidence 95 % k	Effective Degrees of Freedom ν_{eff}
					0.00306	2.222	10.2

Test Frequency (GHz)	Quantity X_i	Estimate x_i	Standard Measurement Uncertainty $u(x_i)$	Probability Distribution/Method of Evaluation (A or B)	Sensitivity Coefficient c_i	Uncertainty Contribution $\|c_i\|*u(x_i)$	Degrees of Freedom ν_i
4.00	η_{rf}	0.97660	0.00380	B/Normal	0.98877	0.00376	12
	Γ_{rf}	0.03100	0.00520	B/Normal	-0.05993	0.00031	50
	P_{rf}	0.98973	0.00280	A/t	0.97566	0.00273	3
	M_{mf}	1.00000	0.00074	B/U	0.96564	0.00072	1E+99
	M_{mrf}	1.00000	0.00157	B/U	-0.96564	0.00152	1E+99
	L	1.00000	0.00029	B/R	0.96564	0.00028	1E+99
					Combined Standard Measurement Uncertainty $u_c(K)$	Coverage Factor, Level of Confidence 95 % k	Effective Degrees of Freedom ν_{eff}
					0.00495	2.108	17.2

Calibrated by : H.W. Li

Date : 10 September 2012

Checked by : C.K. Ko

Date : 10 September 2012

Certificate of Calibration (Continuation Page)
校正證書（續頁）

Appendix 1

Measurement Uncertainty Budget of Calibration Factor of Power Sensor
(serial number of power sensor: US41031012)

Test Frequency (GHz)	Quantity X_i	Estimate x_i	Standard Measurement Uncertainty $u(x_i)$	Probability Distribution/Method of Evaluation (A or B)	Sensitivity Coefficient c_i	Uncertainty Contribution $\|c_i\|*u(x_i)$	Degrees of Freedom v_i
8.00	η_{rf}	0.95770	0.00620	B/Normal	0.98552	0.00611	9
	Γ_{rf}	0.02900	0.00519	B/Normal	-0.05479	0.00028	50
	P_{rf}	0.98635	0.00327	A/t	0.95689	0.00313	3
	M_{mf}	1.00000	0.00116	B/U	0.94383	0.00110	1E+99
	M_{mrf}	1.00000	0.00209	B/U	-0.94383	0.00197	1E+99
	L	1.00000	0.00029	B/R	0.94383	0.00027	1E+99
					Combined Standard Measurement Uncertainty $u_c(K)$	Coverage Factor, Level of Confidence 95 % k	Effective Degrees of Freedom v_{eff}
					0.00724	2.136	14.7

Test Frequency (GHz)	Quantity X_i	Estimate x_i	Standard Measurement Uncertainty $u(x_i)$	Probability Distribution/Method of Evaluation (A or B)	Sensitivity Coefficient c_i	Uncertainty Contribution $\|c_i\|*u(x_i)$	Degrees of Freedom v_i
12.00	η_{rf}	0.96170	0.00310	B/Normal	0.96923	0.00300	12
	Γ_{rf}	0.02200	0.01005	B/Normal	-0.04103	0.00041	50
	P_{rf}	0.96970	0.00319	A/t	0.96123	0.00307	3
	M_{mf}	1.00000	0.00313	B/U	0.93211	0.00292	1E+99
	M_{mrf}	1.00000	0.00295	B/U	-0.93211	0.00275	1E+99
	L	1.00000	0.00029	B/R	0.93211	0.00027	1E+99
					Combined Standard Measurement Uncertainty $u_c(K)$	Coverage Factor, Level of Confidence 95 % k	Effective Degrees of Freedom v_{eff}
					0.00589	2.034	33.3

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Date : 10 September 2012 Date : 10 September 2012

Certificate of Calibration (Continuation Page)
校正證書（續頁）

Certificate No. RF120172 證書編號

Appendix 1

Measurement Uncertainty Budget of Calibration Factor of Power Sensor
(serial number of power sensor: US41031012)

Test Frequency (GHz)	Quantity X_i	Estimate x_i	Standard Measurement Uncertainty $u(x_i)$	Probability Distribution/Method of Evaluation (A or B)	Sensitivity Coefficient c_i	Uncertainty Contribution $\|c_i\|*u(x_i)$	Degrees of Freedom v_i
15.00	η_{rf}	0.95360	0.00460	B/Normal	0.96177	0.00442	9
	Γ_{rf}	0.06300	0.01000	B/Normal	-0.11602	0.00116	50
	P_{rf}	0.96560	0.00186	A/t	0.94982	0.00177	3
	M_{mf}	1.00000	0.00275	B/U	0.91714	0.00252	1E+99
	M_{mrf}	1.00000	0.00654	B/U	-0.91714	0.00600	1E+99
	L	1.00000	0.00029	B/R	0.91714	0.00026	1E+99
					Combined Standard Measurement Uncertainty $u_c(K)$	Coverage Factor, Level of Confidence 95 % k	Effective Degrees of Freedom v_{eff}
					0.00815	1.985	96.5

Test Frequency (GHz)	Quantity X_i	Estimate x_i	Standard Measurement Uncertainty $u(x_i)$	Probability Distribution/Method of Evaluation (A or B)	Sensitivity Coefficient c_i	Uncertainty Contribution $\|c_i\|*u(x_i)$	Degrees of Freedom v_i
18.00	η_{rf}	0.95140	0.00740	B/Normal	0.97497	0.00721	21
	Γ_{rf}	0.10600	0.01008	B/Normal	-0.19888	0.00200	50
	P_{rf}	0.98605	0.00050	A/t	0.94071	0.00047	3
	M_{mf}	1.00000	0.00747	B/U	0.92759	0.00693	1E+99
	M_{mrf}	1.00000	0.01068	B/U	-0.92759	0.00991	1E+99
	L	1.00000	0.00029	B/R	0.92759	0.00027	1E+99
					Combined Standard Measurement Uncertainty $u_c(K)$	Coverage Factor, Level of Confidence 95 % k	Effective Degrees of Freedom v_{eff}
					0.01423	1.968	317.3

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Date : 10 September 2012

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Date : 10 September 2012

Certificate of Calibration (Continuation Page)
校正證書（續頁）

Appendix 2

Measurement Uncertainty Budget of Calibration Factor of Power Sensor
(serial number of power sensor: US41031013)

Test Frequency (GHz)	Quantity X_i	Estimate x_i	Standard Measurement Uncertainty $u(x_i)$	Probability Distribution/Method of Evaluation (A or B)	Sensitivity Coefficient c_i	Uncertainty Contribution $\|c_i\|*u(x_i)$	Degrees of Freedom v_i
0.01	η_{rf}	0.98090	0.00180	B/Normal	1.00837	0.00182	15
	Γ_{rf}	0.14500	0.00381	B/Normal	-0.29300	0.00112	50
	P_{rf}	1.03003	0.00156	A/t	0.96028	0.00149	3
	M_{mf}	1.00000	0.00213	B/U	0.98911	0.00211	1E+99
	M_{mrf}	1.00000	0.00493	B/U	-0.98911	0.00487	1E+99
	L	1.00000	0.00029	B/R	0.98911	0.00029	1E+99
					Combined Standard Measurement Uncertainty $u_c(K)$	Coverage Factor, Level of Confidence 95 % k	Effective Degrees of Freedom v_{eff}
					0.00592	1.965	509.3

Test Frequency (GHz)	Quantity X_i	Estimate x_i	Standard Measurement Uncertainty $u(x_i)$	Probability Distribution/Method of Evaluation (A or B)	Sensitivity Coefficient c_i	Uncertainty Contribution $\|c_i\|*u(x_i)$	Degrees of Freedom v_i
0.05	η_{rf}	0.99160	0.00170	B/Normal	1.00192	0.00170	16
	Γ_{rf}	0.03400	0.00321	B/Normal	-0.06764	0.00022	50
	P_{rf}	1.00308	0.00150	A/t	0.99045	0.00148	3
	M_{mf}	1.00000	0.00046	B/U	0.99350	0.00046	1E+99
	M_{mrf}	1.00000	0.00117	B/U	-0.99350	0.00117	1E+99
	L	1.00000	0.00029	B/R	0.99350	0.00029	1E+99
					Combined Standard Measurement Uncertainty $u_c(K)$	Coverage Factor, Level of Confidence 95 % k	Effective Degrees of Freedom v_{eff}
					0.00261	2.076	21.6

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Certificate of Calibration (Continuation Page)
校正證書（續頁）

Certificate No. RF120172
證書編號

Appendix 2

Measurement Uncertainty Budget of Calibration Factor of Power Sensor
(serial number of power sensor: US41031013)

Test Frequency (GHz)	Quantity X_i	Estimate x_i	Standard Measurement Uncertainty $u(x_i)$	Probability Distribution/Method of Evaluation (A or B)	Sensitivity Coefficient c_i	Uncertainty Contribution $\|c_i\|*u(x_i)$	Degrees of Freedom v_i
1.00	η_{rf}	0.98830	0.00200	B/Normal	0.98903	0.00198	15
	Γ_{rf}	0.02000	0.00336	B/Normal	-0.03911	0.00013	50
	P_{rf}	0.98943	0.00167	A/t	0.98790	0.00165	3
	M_{mf}	1.00000	0.00032	B/U	0.97746	0.00032	1E+99
	M_{mrf}	1.00000	0.00072	B/U	-0.97746	0.00070	1E+99
	L	1.00000	0.00029	B/R	0.97746	0.00028	1E+99
					Combined Standard Measurement Uncertainty $u_c(K)$	Coverage Factor, Level of Confidence 95 % k	Effective Degrees of Freedom v_{eff}
					0.00271	2.127	15.4

Test Frequency (GHz)	Quantity X_i	Estimate x_i	Standard Measurement Uncertainty $u(x_i)$	Probability Distribution/Method of Evaluation (A or B)	Sensitivity Coefficient c_i	Uncertainty Contribution $\|c_i\|*u(x_i)$	Degrees of Freedom v_i
4.00	η_{rf}	0.97660	0.00380	B/Normal	0.98790	0.00375	12
	Γ_{rf}	0.03100	0.00520	B/Normal	-0.05987	0.00031	50
	P_{rf}	0.98885	0.00208	A/t	0.97566	0.00203	3
	M_{mf}	1.00000	0.00065	B/U	0.96478	0.00063	1E+99
	M_{mrf}	1.00000	0.00157	B/U	-0.96478	0.00152	1E+99
	L	1.00000	0.00029	B/R	0.96478	0.00028	1E+99
					Combined Standard Measurement Uncertainty $u_c(K)$	Coverage Factor, Level of Confidence 95 % k	Effective Degrees of Freedom v_{eff}
					0.00459	2.086	20.0

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Appendix 2

Measurement Uncertainty Budget of Calibration Factor of Power Sensor
(serial number of power sensor: US41031013)

Test Frequency (GHz)	Quantity X_i	Estimate x_i	Standard Measurement Uncertainty $u(x_i)$	Probability Distribution/Method of Evaluation (A or B)	Sensitivity Coefficient c_i	Uncertainty Contribution $\|c_i\|*u(x_i)$	Degrees of Freedom v_i
8.00	η_{rf}	0.95770	0.00620	B/Normal	0.98325	0.00610	9
	Γ_{rf}	0.02900	0.00519	B/Normal	-0.05466	0.00028	50
	P_{rf}	0.98408	0.00239	A/t	0.95689	0.00229	3
	M_{mf}	1.00000	0.00113	B/U	0.94166	0.00107	1E+99
	M_{mrf}	1.00000	0.00209	B/U	-0.94166	0.00197	1E+99
	L	1.00000	0.00029	B/R	0.94166	0.00027	1E+99
					Combined Standard Measurement Uncertainty $u_c(K)$	Coverage Factor, Level of Confidence 95 % k	Effective Degrees of Freedom v_{eff}
					0.00690	2.146	13.9

Test Frequency (GHz)	Quantity X_i	Estimate x_i	Standard Measurement Uncertainty $u(x_i)$	Probability Distribution/Method of Evaluation (A or B)	Sensitivity Coefficient c_i	Uncertainty Contribution $\|c_i\|*u(x_i)$	Degrees of Freedom v_i
12.00	η_{rf}	0.96170	0.00310	B/Normal	0.96951	0.00301	12
	Γ_{rf}	0.02200	0.01005	B/Normal	-0.04104	0.00041	50
	P_{rf}	0.96998	0.00242	A/t	0.96123	0.00232	3
	M_{mf}	1.00000	0.00224	B/U	0.93237	0.00209	1E+99
	M_{mrf}	1.00000	0.00295	B/U	-0.93237	0.00275	1E+99
	L	1.00000	0.00029	B/R	0.93237	0.00027	1E+99
					Combined Standard Measurement Uncertainty $u_c(K)$	Coverage Factor, Level of Confidence 95 % k	Effective Degrees of Freedom v_{eff}
					0.00516	2.017	42.8

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Date : 10 September 2012

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Certificate No. **RF120172**
證書編號

Appendix 2

Measurement Uncertainty Budget of Calibration Factor of Power Sensor
(serial number of power sensor: US41031013)

Test Frequency (GHz)	Quantity X_i	Estimate x_i	Standard Measurement Uncertainty $u(x_i)$	Probability Distribution/Method of Evaluation (A or B)	Sensitivity Coefficient c_i	Uncertainty Contribution $\|c_i\|*u(x_i)$	Degrees of Freedom ν_i
15.00	η_{rf}	0.95360	0.00460	B/Normal	0.96017	0.00442	9
	Γ_{rf}	0.06300	0.01000	B/Normal	-0.11583	0.00116	50
	P_{rf}	0.96400	0.00129	A/t	0.94982	0.00123	3
	M_{mf}	1.00000	0.00161	B/U	0.91562	0.00148	1E+99
	M_{mrf}	1.00000	0.00654	B/U	-0.91562	0.00599	1E+99
	L	1.00000	0.00029	B/R	0.91562	0.00026	1E+99
					Combined Standard Measurement Uncertainty $u_c(K)$	Coverage Factor, Level of Confidence 95 % k	Effective Degrees of Freedom ν_{eff}
					0.00778	1.988	85.0

Test Frequency (GHz)	Quantity X_i	Estimate x_i	Standard Measurement Uncertainty $u(x_i)$	Probability Distribution/Method of Evaluation (A or B)	Sensitivity Coefficient c_i	Uncertainty Contribution $\|c_i\|*u(x_i)$	Degrees of Freedom ν_i
18.00	η_{rf}	0.95140	0.00740	B/Normal	0.97574	0.00722	21
	Γ_{rf}	0.10600	0.01008	B/Normal	-0.19904	0.00201	50
	P_{rf}	0.98683	0.00013	A/t	0.94071	0.00012	3
	M_{mf}	1.00000	0.00608	B/U	0.92832	0.00564	1E+99
	M_{mrf}	1.00000	0.01068	B/U	-0.92832	0.00992	1E+99
	L	1.00000	0.00029	B/R	0.92832	0.00027	1E+99
					Combined Standard Measurement Uncertainty $u_c(K)$	Coverage Factor, Level of Confidence 95 % k	Effective Degrees of Freedom ν_{eff}
					0.01365	1.969	267.8

- END -

Calibrated by : H.W. Li

Checked by : C.K. Ko

Date : 10 September 2012

Date : 10 September 2012

MEASUREMENT REPORT ON

APMP Key Comparison APMP.EM.RF-K8.CL

Power Meter and Power Sensor

Agilent Models: E4419B and 8481A

Serial Numbers: MY45100436 and US41031012

Replacement for Report RN12688A dated 22 July 2016

Telephone +61 2 8467 3560
Facsimile +61 2 8467 3610
For further information please contact: Dr T. Zhang Email: tieren.zhang@measurement.gov..au

Ref: RN122688B *File: CB/12/1304* *Checked:* *Date: 15 August 2016*

For:	National Institute of Advanced Industrial Science and Technology (AIST) National Metrology Institute of Japan (NMIJ) Electromagnetic Waves Division, Radio-Frequency Section Central 3, 1-1-1 Umezono Tsukuba Ibaraki 305-8563 Japan
Manufacturer:	
Power Meter:	Agilent
Power Sensor:	Agilent
Model:	
Power Meter:	E4419B
Power Sensor:	8481A
Serial Number:	
Power Meter:	MY45100436
Power Sensor:	US41031012
Connector:	Type N male
Date of tests:	2 October to 18 October 2012
Measurement Procedures:	RFM-POW-02-v2 RFM-Proc-Soft-0009-2 RFM-Proc-Soft-9101-7
Ambient Temperature:	22.7 °C ± 1.0 °C

Description of Measurement Method and Traceability

The Type-N power calibration splitter system was used in this comparison. A reference thermistor mount was connected to one of the output ports of the splitter and the device under test (DUT) was connected to the other output port. The calibration factor of the DUT is derived using the method of [1]. The reference thermistor mount was operated with a pair of NMIA Dual Precision self balancing bridges. The power meter readings of DUT were taken from the IEEE Bus of the power meter.

Two reference thermistor mounts were used for the measurements and the reported calibration factors are the averaged values derived from these two references. The reference thermistor mounts were calibrated using NMIA Microcalorimeter.

The measurements of the reflection coefficients for both reference thermistor mounts and DUT were performed using Agilent E8364B vector network analyzer, which is traceable to NMIA's standard airlines.

Reference Output Power Measurement of the Power Meter

With the reference port of the power meter terminated by a load whose reflection coefficient magnitude was less than 0.01 the reference power output was:

Reference power: 1.005 mW
Uncertainty: ±0.003 mW (Note 2)

Power Meter Configuration

The power meter was set to *PRESET/DEFAULT*. Prior to each measurement, the power meter was zeroed and then was calibrated by connecting the power sensor to the power meter's reference output port.

The frequency correction was turned off for all measurements.

Calibration Factor Measurement

The calibration factors were measured at a nominal power level of 1 mW. The measured calibration factors of the power sensor are given in Table 1:

TABLE 1

Frequency (MHz)	Calibration Factor (Note 1)	Uncertainty (Note 2)
10	0.9926	± 0.0049
50	0.9950	± 0.0049
1000	0.9812	± 0.0049
4000	0.9722	± 0.0053
8000	0.9556	± 0.0067
12000	0.9321	± 0.0072
15000	0.9173	± 0.0080
18000	0.9187	± 0.0090

Uncertainty Budget for Calibration Factor *K*

Uncertainty budget for calibration factor measurements is shown in Table 2:

TABLE 2

Frequency (MHz)	u_{ref} (Type B)	u_{pm} (Type A,B)	u_{opt} (Type A,B)	$u_{eqMisMatch}$ (Type A,B)	u_{con} (Type A)	u_{P50} (Type B)	u_{comb}	U (K) (Note 2)
10	0.0015	0.0006	0.0008	0.0002	0.0004	0.0015	0.0024	0.0049
50	0.0015	0.0006	0.0008	0.0002	0.0004	0.0015	0.0024	0.0049
1000	0.0015	0.0007	0.0008	0.0003	0.0004	0.0015	0.0024	0.0049
4000	0.0017	0.0007	0.0010	0.0004	0.0004	0.0015	0.0026	0.0053
8000	0.0023	0.0008	0.0012	0.0004	0.0011	0.0015	0.0033	0.0067
12000	0.0028	0.0008	0.0013	0.0004	0.0004	0.0015	0.0036	0.0072
15000	0.0032	0.0009	0.0013	0.0005	0.0008	0.0015	0.0040	0.0080
18000	0.0035	0.0009	0.0017	0.0005	0.0012	0.0015	0.0045	0.0090

u_{ref} is the uncertainty of the calibration factor of the reference thermistor mounts;

u_{pm} is the uncertainty attributed to measuring the ratio of indicated powers;

u_{opt} is the uncertainty attributed to measuring the output tracking of the power splitter;

$u_{eqMisMatch}$ is the equivalent mismatch uncertainty;

u_{con} is the type A uncertainty associated with repeated measurements, including connector repeatability;

u_{P50} is a type B uncertainty associated with the power meter's 50 MHz reference output power measurement;

u_{comb} is the combined standard uncertainty and is the RSS value of all the above components, where sensitivity coefficient for each component is taken as 1;

$U(K)$ is the expanded uncertainty with the coverage factor k=2.0.

Reflection Coefficient Measurement

The measured reflection coefficients at a nominal power level of 1 mW are given in Table 3:

TABLE 3

FREQUENCY (MHZ)	REFLECTION COEFFICIENT		
	Real	Imaginary	Uncertainty (Note 2)
10	0.0072	-0.0618	± 0.0031
50	-0.0012	-0.0133	± 0.0031
1000	0.0097	-0.0029	± 0.0031
4000	0.0113	0.0111	± 0.0031
8000	-0.0141	-0.0103	± 0.0047
12000	-0.0284	0.0150	± 0.0043
15000	-0.0089	0.0285	± 0.0048
18000	-0.0471	0.0584	± 0.0052

Note 1: The calibration factor is defined as the ratio of the power presented on the IEEE bus output of the power meter, to the incident RF power, when the reference output power of the power meter at 50 MHz was used as absolute power reference.

Note 2: The uncertainty stated in this Report has been calculated in accordance with the principles in *JCGM 100:2008 – Evaluation of measurement data - Guide to the expression of uncertainty in measurement*, and gives an interval estimated to have a level of confidence of 95%. The coverage factor is 2.0.

The uncertainty applies at the time of measurement only and takes no account of any drift or other effects that may apply afterwards. When estimating the uncertainty at any later time, other relevant information should also be considered, including, where possible, the history of the performance of the instrument and the manufacturer's specifications.

Dr T Zhang
For Dr P T H Fisk
Chief Metrologist

References:

[1] T. Zhang, "A Novel Approach For Power Calibrations Using Power Splitters", Conference Digest of the 24th Conference on Precision Electromagnetic Measurements (CPEM2004), London, UK, 27 June to 2 July 2004.

MEASUREMENT REPORT ON

APMP Key Comparison APMP.EM.RF-K8.CL

Power Meter and Power Sensor

Agilent Models: E4419B and 8481A

Serial Numbers: MY45100436 and US41031013

Replacement for Report RN122689A dated 22 July 2016

For further information please contact: Dr T. Zhang

Telephone +61 2 8467 3560
Facsimile +61 2 8467 3610
Email: tieren.zhang@measurement.gov..au

Ref: RN122689B File: CB/12/1305 Checked: Date: 15 August 2016

For:	National Institute of Advanced Industrial Science and Technology (AIST) National Metrology Institute of Japan (NMIJ) Electromagnetic Waves Division, Radio-Frequency Section Central 3, 1-1-1 Umezono Tsukuba Ibaraki 305-8563 Japan
Manufacturer:	
Power Meter:	Agilent
Power Sensor:	Agilent
Model:	
Power Meter:	E4419B
Power Sensor:	8481A
Serial Number:	
Power Meter:	MY45100436
Power Sensor:	US41031013
Connector:	Type N male
Date of tests:	2 October to 18 October 2012
Measurement Procedures:	RFM-POW-02-v2 RFM-Proc-Soft-0009-2 RFM-Proc-Soft-9101-7
Ambient Temperature:	22.7 °C ± 1.0 °C

Description of Measurement Method

The Type-N power calibration splitter system was used in this comparison. A reference thermistor mount was connected to one of the output ports of the splitter and the device under test (DUT) was connected to the other output port. The calibration factor of the DUT is derived using the method of [1]. The reference thermistor mount was operated with a pair of NMIA Dual Precision self balancing bridges. The power meter readings of DUT were taken from the IEEE Bus of the power meter.

Two reference thermistor mounts were used for the measurements and the reported calibration factors are the averaged values derived from these two references. The reference thermistor mounts were calibrated using NMIA Microcalorimeter.

The measurements of reflection coefficients for both reference thermistor mounts and DUT were performed using Agilent E8364B vector network analyser, which is traceable to NMIA's standard airlines.

Reference Output Power Measurement of the Power Meter

With the reference port of the power meter terminated by a load whose reflection coefficient magnitude was less than 0.01 the reference power output was:

Reference power: 1.005 mW
Uncertainty: ±0.003 mW (Note 2)

Power Meter Configuration

The power meter was set to *PRESET/DEFAULT*. Prior to each measurement, the power meter was zeroed and then was calibrated by connecting the power sensor to the power meter's reference output port.

The frequency correction was turned off for all measurements.

Calibration Factor Measurement

The calibration factors were measured at a nominal power level of 1 mW. The measured calibration factors of the power sensor are given in Table 1:

TABLE 1

Frequency (MHz)	Calibration Factor (Note 1)	Uncertainty (Note 2)
10	0.9919	± 0.0050
50	0.9950	± 0.0053
1000	0.9852	± 0.0050
4000	0.9759	± 0.0054
8000	0.9584	± 0.0070
12000	0.9355	± 0.0073
15000	0.9203	± 0.0080
18000	0.9231	± 0.0088

<u>Uncertainty Budget for Calibration Factor *K*</u>

Uncertainty budget for calibration factor measurements is shown in Table 2:

TABLE 2

Frequency (MHz)	u_{ref} (Type B)	u_{pm} (Type A,B)	u_{opt} (Type A,B)	$u_{eqMisMatch}$ (Type A,B)	u_{con} (Type A)	u_{P50} (Type B)	u_{comb}	$U(K)$ (Note 2)
10	0.0015	0.0006	0.0008	0.0002	0.0008	0.0015	0.0025	0.0050
50	0.0015	0.0006	0.0008	0.0002	0.0011	0.0015	0.0026	0.0053
1000	0.0015	0.0007	0.0008	0.0003	0.0006	0.0015	0.0025	0.0050
4000	0.0017	0.0007	0.0010	0.0004	0.0007	0.0015	0.0027	0.0054
8000	0.0023	0.0008	0.0012	0.0004	0.0015	0.0015	0.0035	0.0070
12000	0.0028	0.0008	0.0013	0.0004	0.0007	0.0015	0.0036	0.0073
15000	0.0032	0.0009	0.0013	0.0005	0.0007	0.0015	0.0040	0.0080
18000	0.0035	0.0009	0.0017	0.0005	0.0008	0.0015	0.0044	0.0088

u_{ref} is the uncertainty of the calibration factor of the reference thermistor mounts;

u_{pm} is the uncertainty attributed to measuring the ratio of indicated powers;

u_{opt} is the uncertainty attributed to measuring the output tracking of the power splitter;

$u_{eqMisMatch}$ is the equivalent mismatch uncertainty;

u_{con} is the type A uncertainty associated with repeated measurements, including connector repeatability;

u_{P50} is a type B uncertainty associated with the power meter's 50 MHz reference output power measurement;

u_{comb} is the combined standard uncertainty and is the RSS value of all the above components, where sensitivity coefficient for each component is taken as 1;

$U(K)$ is the expanded uncertainty with the coverage factor k=2.0.

Reflection Coefficient Measurement

The measured reflection coefficients at a nominal power level of 1 mW are given in Table 3:

TABLE 3

FREQUENCY (MHZ)	REFLECTION COEFFICIENT		
	Real	Imaginary	Uncertainty (Note 2)
10	0.0080	-0.0631	± 0.0031
50	0.0000	-0.0136	± 0.0031
1000	0.0095	-0.0045	± 0.0031
4000	0.0123	0.0056	± 0.0031
8000	-0.0154	-0.0064	± 0.0047
12000	-0.0202	0.0095	± 0.0043
15000	-0.0036	0.0175	± 0.0048
18000	-0.0377	0.0474	± 0.0052

Note 1: The calibration factor is defined as the ratio of the power presented on the IEEE bus output of the power meter, to the incident RF power, when the reference output power of the power meter at 50 MHz was used as absolute power reference.

Note 2: The uncertainty stated in this Report has been calculated in accordance with the principles in *JCGM 100:2008 – Evaluation of measurement data - Guide to the expression of uncertainty in measurement*, and gives an interval estimated to have a level of confidence of 95%. The coverage factor is 2.0.

The uncertainty applies at the time of measurement only and takes no account of any drift or other effects that may apply afterwards. When estimating the uncertainty at any later time, other relevant information should also be considered, including, where possible, the history of the performance of the instrument and the manufacturer's specifications.

Dr T Zhang
For Dr P T H Fisk
Chief Metrologist

References:

[1] T. Zhang, "A Novel Approach For Power Calibrations Using Power Splitters", Conference Digest of the 24th Conference on Precision Electromagnetic Measurements (CPEM2004), London, UK, 27 June to 2 July 2004.

APMP Key Comparison APMP.EM.RF-K8.CL

"Power in 50 Ω coaxial line, frequency 10 MHz to 18 GHz"

Report from the Measurement Standards Laboratory of New Zealand

Measurement Method

Measurements were made at a nominal power of 1 mW and at the frequencies: 50 MHz, 1000 MHz, 4000 MHz, 8000 MHz, 12000 MHz, 15000 MHz and 18000 MHz (no measurement is reported at 10 MHz). The laboratory temperature was maintained at 23 $\pm$1°C.

An Agilent 8478B thermistor mount was used as a transfer standard for calibrating the two Agilent 8481A power sensors in conjunction with the Agilent E4419B power meter supplied in this comparison.

A resistive power splitter delivered power from a signal generator to a pair of output ports. A second Agilent 8478B thermistor mount power sensor was connected to one of these output ports (the reference port) and used to normalise the readings of power sensors connected to the other port (the measurement port). The power ratio (the measurement port power level divided by the reference port power level) was recorded at each frequency.

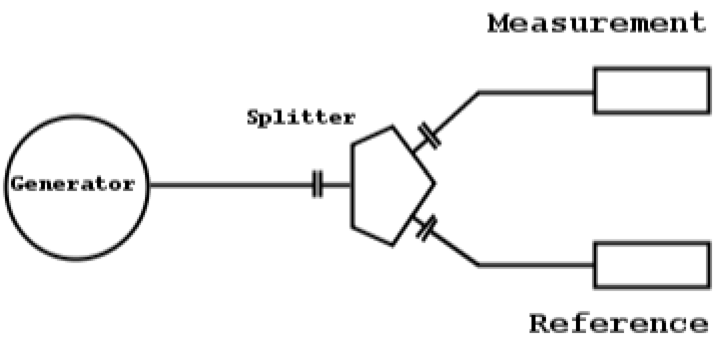

Figure 1: Measurement setup showing sensors connected to the reference and measurement ports.

The sensor being measured (the MSL standard or one of the 8481A sensors) was re-connected several times, changing the orientation of the sensor to the measurement port each time. Connections were tightened with a 1.36 Nm torque wrench. Before each connection of the 8481A sensors, the E4419B meter was adjusted by connecting the sensor to the nominal 1 mW 50 MHz power reference and running the instrument's internal calibration routine.

The two 8481A sensors, when paired with the E4419B meter, are treated as distinct 'units under test' (UUT) in this comparison.

The measurement equation used to transfer a value of calibration factor from MSL's standard thermistor mount to a UUT is

$$K_\mathrm{u} = K_\mathrm{c}\,\frac{R_\mathrm{u}}{R_\mathrm{c}}\frac{M_\mathrm{u}}{M_\mathrm{c}},$$

where the subscript 'u' refers to the UUT being calibrated and 'c' refers to the standard thermistor mount. The symbol *K* stands for calibration factor, *R* for power ratio and *M* for mismatch.

The mismatch factor

$$M = \left|1 - \Gamma_\mathrm{s}\Gamma_x\right|^2$$

where Γ_s is the complex-valued voltage reflection coefficient (VRC) of the splitter measurement port and Γ_x stands for the complex VRC of the sensor connected to the measurement port.

Measurements of Γ_x were made with a vector network analyser (VNA), adjusted using a set of calibrated open, short and load standards. The sensor being measured (the MSL standard thermistor or one of the 8481A sensors) was re-connected several times, changing the orientation of the sensor to the VNA port each time. Connections were tightened with a 1.36 Nm torque wrench.

Measurements of Γ_s for the splitter were made by using the direct method of Juroshek [1], which determines Γ_s by a procedure similar to one-port VNA calibration. The same set of open, short and load VNA standards were used in this procedure.

Equipment

The main pieces of MSL equipment used were: an Agilent E8363B and an Agilent 8753ES (VNAs), an Agilent 85054B calibration kit, an Agilent 83640L microwave generator, an Agilent 3458A digital multimeter, an Agilent 11667A power splitter and a pair of Larsen (NBS Type-IV) self-balancing RF bridges built at MSL [2].

The Agilent E4419B power meter was supplied in the comparison.

Traceability

Traceability to the SI is achieved via standards calibrated at two national metrology institutes: the National Physical Laboratory (UK), for values of the calibration factor of the MSL thermistor mount, and METAS (Switzerland), for measurements of the VRCs of type-N open, short and load standards used to adjust the VNAs.

Resistance measurements of a precision resistor inside the Larsen Bridges are traceable to the MSL realisation of the ohm. The microwave signal generator and the VNAs were synchronised to a 10 MHz reference from MSL Frequency standards.

Results

Results for the calibration factor of each UUT and the voltage reflection coefficient for sensors 1 and 2 are reported in Tables 1, 2, 3 and 4 below. Expanded uncertainties at a level of confidence of approximately 95% are reported. These were obtained by multiplying the standard uncertainty by a coverage factor $k = 2$.

The correlation coefficient between the real and imaginary components of the VRCs were also calculated and found to be small in most cases.

Calibration factor

UUT 1 (sensor US41031012)

f (MHz)	K	$U(K)$
50	0.9949	0.0027
1000	0.9789	0.0046
4000	0.9677	0.0047
8000	0.9504	0.0075
12000	0.9281	0.0075
15000	0.9123	0.0073
18000	0.9137	0.0115

Table 1: Measured values of calibration factor for UUT 1. The column on the right reports expanded uncertainties.

UUT 2 (sensor US41031013)

f (MHz)	K	$U(K)$
50	0.9946	0.0027
1000	0.9792	0.0045
4000	0.9674	0.0047
8000	0.9493	0.0075
12000	0.9277	0.0077
15000	0.9105	0.0074
18000	0.9134	0.0116

Table 2: Measured values of calibration factor for UUT 2. The column on the right reports expanded uncertainties.

Voltage reflection coefficient

Sensor 1 (US41031012)

f (MHz)	Γ_{re}	$U(\Gamma_{re})$	Γ_{im}	$U(\Gamma_{im})$
50	-0.0017	0.0040	-0.0133	0.0040
1000	0.0090	0.0040	-0.0032	0.0040
4000	0.0106	0.0080	0.0116	0.0080
8000	-0.0154	0.0081	-0.0104	0.0081
12000	-0.0295	0.0081	0.0122	0.0081
15000	-0.0067	0.0082	0.0292	0.0086
18000	-0.0515	0.0082	0.0590	0.0084

Table 3: Measured values of the real and imaginary components of the voltage reflection coefficient of sensor 1. Expanded uncertainties are reported in the column next to each measured component.

The correlation coefficient between measured values of Γ_{re} and Γ_{im} was generally less than 0.01, except at 8000 MHz, where it was -0.012, and at 15000 MHz, where it was -0.033.

Sensor 2 (US41031013)

f (MHz)	Γ_{re}	$U(\Gamma_{\mathrm{re}})$	Γ_{im}	$U(\Gamma_{\mathrm{im}})$
50	-0.0006	0.0040	-0.0136	0.0040
1000	0.0090	0.0040	-0.0046	0.0040
4000	0.0122	0.0080	0.0055	0.0080
8000	-0.0152	0.0081	-0.0071	0.0082
12000	-0.0196	0.0080	0.0077	0.0080
15000	-0.0021	0.0085	0.0185	0.0092
18000	-0.0418	0.0082	0.0452	0.0083

Table 4: Measured values of the real and imaginary components of the voltage reflection coefficient of sensor 2. Expanded uncertainties are reported in the column next to each measured component.

The correlation coefficient between measured values of Γ_{re} and Γ_{im} was generally less than 0.01, except at 8000 MHz, where it was -0.025, and at 15000 MHz, where it was -0.119.

Uncertainty

Details about the uncertainty of the calibration factor measurements at each frequency and for each UUT are reported in this section.

Two different views of the measurement uncertainty are given. One view considers the uncertainty contributions in terms of the main measurement equation for calibration factor. The other reports the largest contributions to the uncertainty from direct inputs to the measurement model.

Main measurement equation uncertainty budget

The first table in the subsections below reports the components of uncertainty in the calibration factor due to the measured values of quantities in the equation

$$K_\mathrm{u} = K_\mathrm{c} \frac{R_\mathrm{u}}{R_\mathrm{c}} \frac{M_\mathrm{u}}{M_\mathrm{c}},$$

The GUM notation is used in the column labels: X_i stands for an influence quantity, x_i for an estimate of that quantity, $u_i(y)$ for the standard uncertainty of that estimate, c_i for the partial derivative of the measurement equation with respect to the influence quantity and $u_i(y)$ for the component of standard uncertainty in the result due to uncertainty of the estimate.

The values reported in the tables are intermediate results obtained during the calculation of calibration factor. In some cases the estimates obtained are not independent so we also report the correlation coefficients between estimates.

The combined standard uncertainty can be calculated from the information in these tables and the usual GUM formula for uncertainty propagation (eq-16 [3])

$$u_c^2(y) = \sum_{i=1}^{N} c_i^2 u^2(x_i) + 2 \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} c_i c_j u(x_i) u(x_j) r(x_i, x_j)$$

Values of the effective degrees of freedom associated with the calibration factor uncertainty have been calculated and were generally large.

General comments

The uncertainty budget for the calibration factor measurement is dominated by uncertainty in the estimates of the calibration factor of the MSL transfer standard.

Briefly, the biggest influences on intermediate quantities in the main calibration equation are as follows

- Standard sensor calibration factor ($\boldsymbol{K}_\mathbf{c}$)

  The calibration factor of the MSL thermistor mount used as a transfer standard was measured at NPL. The uncertainty in the reported value is dominant and some allowance for drift since calibration has also been included.

- Ratio of power readings for unknown sensor ($\boldsymbol{R}_\mathbf{u}$)

The type-A reproducibility of results when a thermal sensor is re-connected a number of times is the dominant influence.

- Ratio of power readings for standard sensor ($\boldsymbol{R}_c$)

  The type-A reproducibility of results when the thermistor mount sensor is re-connected several times is the dominant influence. Uncertainties associated with the thermal stability of the Larsen Bridges and with the type-A stability of repeated power readings are lesser influences of comparable magnitude.

  The small value of correlation coefficient between measurements of $\boldsymbol{R}_\mathrm{u}$ and $\boldsymbol{R}_\mathrm{c}$ is due to the common influence of the power meter instrumentation connected to the reference port of the splitter. Power readings made at this port are used to calculate both $\boldsymbol{R}_\mathrm{u}$ and $\boldsymbol{R}_c$, so the instrumentation errors affect both measurements.

- Mismatch factors for unknown sensor measurements ($\boldsymbol{M}_\mathrm{u}$ and $\boldsymbol{M}_c$)

  Uncertainty in the calibrated values of the open, short and load standards, used to adjust the VNAs, dominate the uncertainty budget of the mismatch terms. Uncertainty associated with imperfect connectors (non-zero reflection coefficients at the connection) is a lesser influence, comparable in magnitude to the reproducibility of VRC observations.

  The strong correlation between measurements of $\boldsymbol{M}_\mathrm{u}$ and $\boldsymbol{M}_\mathrm{c}$ is due to the common influence of the VRC values of the open, short and load standards. These standards were used to adjust the VNAs, before measuring sensor VRCs, as well as in the Juroshek procedure used to measure the splitter source match.

Main influence quantities

The quantities in the calibration equation, which are reported in the first table of each subsection below, are generally influenced by direct inputs to the measurement model. A large number of influence quantities (approximately 500) were included in the model used to calculate the uncertainty of results.

Although it is impractical to prepare an uncertainty budget that includes every influence, it is insightful to report the most significant contributions to the combined uncertainty. For this reason, a second table is included in each subsection below. This reports the 10 largest $|\boldsymbol{u}_i(\boldsymbol{y})|$ values, for X_i that are direct inputs to the measurement model. The associated quantity estimates x_i were not correlated, so the combined standard uncertainty can be calculated (approximately) as

$$u_c^2(y) \approx \sum_{i=1}^{10} u_i^2(y)$$

The additional quantity symbols are summarised in the following table. Note that some symbols can appear in more than once in an uncertainty budget (e.g., $\boldsymbol{E}_c^\mathrm{A}$ and $\boldsymbol{E}_{11}^\mathrm{conn}$) because they are associated with different independent errors that arise during repeat measurements.

X_i	Quantity
K_{cal}	MSL Standard calibration factor
$E_{K_{cal:drift}}$	Drift in MSL standard calibration factor
Γ_{imag}^{short}	Imaginary component of offset-short standard
Γ_{imag}^{open}	Imaginary component of offset-open standard
Γ_{imag}^{load}	Imaginary component of load standard
Γ_{real}^{short}	Real component of offset-short standard
Γ_{real}^{open}	Real component of offset-open standard
Γ_{real}^{load}	Real component of load standard
E_{R_u}	Type-A estimate of repeatability in power ratio for UUT
E_{R_c}	Type-A estimate of repeatability in power ratio standard sensor
E_{temp}^{Larsen}	Thermal error associated with Larsen bridge
E_{11}^{conn}	Imperfect connection error (VNA)
E_u^A	Type-A estimate of error in UUT readings
E_c^A	Type-A estimate of error in standard sensor readings
$E_{\Gamma\cdot real}^A$	Type-A estimate of error in standard sensor Γ readings

Table 5: Additional influence quantity symbols

Uncertainty data for UUT 1 (sensor US41031012)

50 MHz – UUT1

X_i	x_i	$u(x_i)$	c_i	$u_i(y)$	$r(x_i, K_c)$	$r(x_i, R_u)$	$r(x_i, R_c)$	$r(x_i, M_u)$	$r(x_i, M_c)$
K_c	0.99870	0.001345	0.996148	0.001339	1.000	0.000	0.000	0.000	0.000
R_u	0.99670	0.000263	0.998148	0.000262	0.000	1.000	0.044	0.000	0.000
R_c	1.00056	0.000072	-0.994295	-0.000071	0.000	0.044	1.000	0.000	0.000
M_u	0.99997	0.000099	0.994884	0.000099	0.000	0.000	0.000	1.000	0.997
M_c	0.99996	0.000105	-0.994892	-0.000104	0.000	0.000	0.000	0.997	1.000

X_i	$\lvert u_i(y) \rvert$
K_{cal}	0.00124
$E_{K_{cal: drift}}$	0.00050
E_{R_u}	0.00026
E_{R_c}	0.00006
E_{temp}^{Larsen}	0.00002
E_{temp}^{Larsen}	0.00002
E_c^A	0.00001
E_u^A	0.00001
E_c^A	0.00001
E_u^A	0.00001

1000 MHz – sensor 1

X_i	x_i	$u(x_i)$	c_i	$u_i(y)$	$r(x_i, K_c)$	$r(x_i, R_u)$	$r(x_i, R_c)$	$r(x_i, M_u)$	$r(x_i, M_c)$
K_c	0.99180	0.00229	0.98698	0.00226	1.000	0.000	0.000	0.000	0.000
R_u	0.98881	0.00025	0.98996	0.00025	0.000	1.000	0.063	0.000	0.000
R_c	1.00210	0.00005	-0.97683	-0.00005	0.000	0.063	1.000	0.000	0.000
M_u	1.00008	0.00006	0.97880	0.00006	0.000	0.000	0.000	1.000	-0.869
M_c	0.99983	0.00016	-0.97905	-0.00015	0.000	0.000	0.000	-0.869	1.000

X_i	$\lvert u_i(y) \rvert$
K_{cal}	0.00220
$E_{K_{cal:drift}}$	0.00049
E_{R_u}	0.00025
Γ_{imag}^{short}	0.00012
Γ_{imag}^{open}	0.00011
Γ_{imag}^{load}	0.00010
Γ_{real}^{load}	0.00004
Γ_{real}^{open}	0.00003
Γ_{real}^{short}	0.00003
E_{R_c}	0.00003

4000 MHz – UUT 1

X_i	x_i	$u(x_i)$	c_i	$u_i(y)$	$r(x_i, K_c)$	$r(x_i, R_u)$	$r(x_i, R_c)$	$r(x_i, M_u)$	$r(x_i, M_c)$
K_c	0.98090	0.00226	0.98655	0.00223	1.000	0.000	0.000	0.000	0.000
R_u	0.99585	0.00027	0.97174	0.00027	0.000	1.000	0.050	0.000	0.000
R_c	1.00788	0.00006	-0.96014	-0.00006	0.000	0.050	1.000	0.000	0.000
M_u	0.99945	0.00025	0.96824	0.00024	0.000	0.000	0.000	1.000	-0.739
M_c	1.00099	0.00058	-0.96675	-0.00056	0.000	0.000	0.000	-0.739	1.000

X_i	$\lvert u_i(y) \rvert$
K_{cal}	0.00218
$E_{K_{\text{cal : drift}}}$	0.00048
$\Gamma_{\text{real}}^{\text{open}}$	0.00042
$\Gamma_{\text{real}}^{\text{short}}$	0.00042
$\Gamma_{\text{real}}^{\text{load}}$	0.00034
E_{R_u}	0.00026
$\Gamma_{\text{imag}}^{\text{short}}$	0.00023
$\Gamma_{\text{imag}}^{\text{open}}$	0.00022
$\Gamma_{\text{imag}}^{\text{load}}$	0.00021
E_{11}^{conn}	0.00008

8000 MHz – UUT 1

X_i	x_i	$u(x_i)$	c_i	$u_i(y)$	$r(x_i, K_c)$	$r(x_i, R_u)$	$r(x_i, R_c)$	$r(x_i, M_u)$	$r(x_i, M_c)$
K_c	0.96410	0.00298	0.98574	0.00294	1.000	0.000	0.000	0.000	0.000
R_u	0.98550	0.00208	0.96434	0.00201	0.000	1.000	0.003	0.000	0.000
R_c	1.00519	0.00014	-0.94544	-0.00013	0.000	0.003	1.000	0.000	0.000
M_u	1.00202	0.00063	0.94844	0.00060	0.000	0.000	0.000	1.000	0.166
M_c	0.99659	0.00124	-0.95360	-0.00119	0.000	0.000	0.000	0.166	1.000

X_i	$\lvert u_i(y) \rvert$
K_{cal}	0.00290
E_{R_u}	0.00201
Γ_{real}^{short}	0.00050
Γ_{imag}^{open}	0.00050
Γ_{imag}^{short}	0.00049
Γ_{real}^{open}	0.00049
$E_{K_{cal:drift}}$	0.00048
Γ_{imag}^{load}	0.00045
Γ_{real}^{load}	0.00040
E_{R_c}	0.00013

12000 MHz – UUT 1

X_i	x_i	$u(x_i)$	c_i	$u_i(y)$	$r(x_i, K_c)$	$r(x_i, R_u)$	$r(x_i, R_c)$	$r(x_i, M_u)$	$r(x_i, M_c)$
K_c	0.95270	0.00356	0.97420	0.00347	1.000	0.000	0.000	0.000	0.000
R_u	0.97167	0.00026	0.95518	0.00025	0.000	1.000	0.011	0.000	0.000
R_c	1.00527	0.00028	-0.92326	-0.00026	0.000	0.011	1.000	0.000	0.000
M_u	0.99973	0.00087	0.92838	0.00080	0.000	0.000	0.000	1.000	0.720
M_c	0.99190	0.00205	-0.93570	-0.00192	0.000	0.000	0.000	0.720	1.000

X_i	$\|u_i(y)\|$
K_{cal}	0.00343
Γ_{imag}^{open}	0.00076
Γ_{imag}^{short}	0.00073
Γ_{real}^{open}	0.00054
Γ_{real}^{short}	0.00053
$E_{K_{cal:drift}}$	0.00046
Γ_{imag}^{load}	0.00045
Γ_{real}^{load}	0.00028
E_{R_c}	0.00026
E_{R_u}	0.00025

15000 MHz – UUT 1

X_i	x_i	$u(x_i)$	c_i	$u_i(y)$	$r(x_i, K_c)$	$r(x_i, R_u)$	$r(x_i, R_c)$	$r(x_i, M_u)$	$r(x_i, M_c)$
K_c	0.95030	0.00341	0.95997	0.00327	1.000	0.000	0.000	0.000	0.000
R_u	0.96706	0.00097	0.94334	0.00092	0.000	1.000	0.004	0.000	0.000
R_c	1.00764	0.00020	-0.90534	-0.00018	0.000	0.004	1.000	0.000	0.000
M_u	1.00100	0.00071	0.91135	0.00065	0.000	0.000	0.000	1.000	-0.657
M_c	1.00074	0.00095	-0.91158	-0.00087	0.000	0.000	0.000	-0.657	1.000

X_i	$\lvert u_i(y) \rvert$
K_{cal}	0.00324
E_{R_u}	0.00092
Γ_{real}^{open}	0.00068
Γ_{imag}^{short}	0.00064
Γ_{imag}^{open}	0.00063
Γ_{real}^{short}	0.00062
$E_{K_{cal:drift}}$	0.00046
Γ_{imag}^{load}	0.00039
Γ_{real}^{load}	0.00034
E_{11}^{conn}	0.00019

18000 MHz – UUT 1

X_i	x_i	$u(x_i)$	c_i	$u_i(y)$	$r(x_i, K_c)$	$r(x_i, R_u)$	$r(x_i, R_c)$	$r(x_i, M_u)$	$r(x_i, M_c)$
K_c	0.91320	0.00495	1.00058	0.00496	1.000	0.000	0.000	0.000	0.000
R_u	0.99374	0.00038	0.91948	0.00035	0.000	1.000	0.003	0.000	0.000
R_c	0.98300	0.00079	-0.92953	-0.00073	0.000	0.003	1.000	0.000	0.000
M_u	1.01680	0.00217	0.89863	0.00195	0.000	0.000	0.000	1.000	0.672
M_c	1.02732	0.00411	-0.88943	-0.00366	0.000	0.000	0.000	0.672	1.000

X_i	$\lvert u_i(y) \rvert$
K_{cal}	0.00493
Γ_{imag}^{short}	0.00181
Γ_{imag}^{open}	0.00164
Γ_{imag}^{load}	0.00105
E_{R_c}	0.00073
$E_{K_{cal:drift}}$	0.00046
E_{11}^{conn}	0.00042
E_{R_u}	0.00035
Γ_{real}^{short}	0.00034
E_{11}^{conn}	0.00024

Uncertainty data for UUT 2 (sensor US41031013)

50 MHz – UUT 2

X_i	x_i	$u(x_i)$	c_i	$u_i(y)$	$r(x_i, K_c)$	$r(x_i, R_u)$	$r(x_i, R_c)$	$r(x_i, M_u)$	$r(x_i, M_c)$
K_c	0.9987	0.0013	0.9959	0.0013	1.000	0.000	0.000	0.000	0.000
R_u	0.9964	0.0001	0.9981	0.0001	0.000	1.000	0.209	0.000	0.000
R_c	1.0006	0.0001	-0.9940	-0.0001	0.000	0.209	1.000	0.000	0.000
M_u	1.0000	0.0001	0.9946	0.0001	0.000	0.000	0.000	1.000	1.000
M_c	1.0000	0.0001	-0.9946	-0.0001	0.000	0.000	0.000	1.000	1.000

X_i	$\|u_i(y)\|$
K_{cal}	0.00124
$E_{K_{cal:drift}}$	0.00050
E_{R_c}	0.00006
E_{R_u}	0.00004
E_{temp}^{Larsen}	0.00002
E_{temp}^{Larsen}	0.00002
E_c^A	0.00001
E_u^A	0.00001
E_c^A	0.00001
E_u^A	0.00001

1000 MHz – UUT 2

X_i	x_i	$u(x_i)$	c_i	$u_i(y)$	$r(x_i, K_c)$	$r(x_i, R_u)$	$r(x_i, R_c)$	$r(x_i, M_u)$	$r(x_i, M_c)$
K_c	0.9918	0.0023	0.9873	0.0023	1.000	0.000	0.000	0.000	0.000
R_u	0.9891	0.0001	0.9900	0.0001	0.000	1.000	0.131	0.000	0.000
R_c	1.0021	0.0001	-0.9772	-0.0001	0.000	0.131	1.000	0.000	0.000
M_u	1.0001	0.0001	0.9791	0.0001	0.000	0.000	0.000	1.000	-0.865
M_c	0.9998	0.0002	-0.9794	-0.0002	0.000	0.000	0.000	-0.865	1.000

X_i	$\lvert u_i(y) \rvert$
K_{cal}	0.00220
$E_{K_{cal:drift}}$	0.00049
Γ_{imag}^{short}	0.00012
E_{R_u}	0.00012
Γ_{imag}^{open}	0.00011
Γ_{imag}^{load}	0.00010
Γ_{real}^{load}	0.00004
Γ_{real}^{open}	0.00004
Γ_{real}^{short}	0.00004
E_{R_c}	0.00003

4000 MHz – UUT 2

X_i	x_i	$u(x_i)$	c_i	$u_i(y)$	$r(x_i, K_c)$	$r(x_i, R_u)$	$r(x_i, R_c)$	$r(x_i, M_u)$	$r(x_i, M_c)$
K_c	0.9809	0.0023	0.9862	0.0022	1.000	0.000	0.000	0.000	0.000
R_u	0.9954	0.0001	0.9719	0.0001	0.000	1.000	0.106	0.000	0.000
R_c	1.0079	0.0001	-0.9598	-0.0001	0.000	0.106	1.000	0.000	0.000
M_u	0.9996	0.0003	0.9677	0.0002	0.000	0.000	0.000	1.000	-0.680
M_c	1.0010	0.0006	-0.9664	-0.0006	0.000	0.000	0.000	-0.680	1.000

X_i	$\lvert u_i(y) \rvert$
K_{cal}	0.00218
$E_{K_{cal:drift}}$	0.00048
Γ_{real}^{open}	0.00044
Γ_{real}^{short}	0.00043
Γ_{real}^{load}	0.00035
Γ_{imag}^{short}	0.00018
Γ_{imag}^{open}	0.00017
Γ_{imag}^{load}	0.00016
E_{R_u}	0.00012
E_{11}^{conn}	0.00008

8000 MHz – UUT 2

X_i	x_i	$u(x_i)$	c_i	$u_i(y)$	$r(x_i, K_c)$	$r(x_i, R_u)$	$r(x_i, R_c)$	$r(x_i, M_u)$	$r(x_i, M_c)$
K_c	0.9641	0.0030	0.9846	0.0029	1.000	0.000	0.000	0.000	0.000
R_u	0.9847	0.0021	0.9640	0.0020	0.000	1.000	0.003	0.000	0.000
R_c	1.0052	0.0001	-0.9444	-0.0001	0.000	0.003	1.000	0.000	0.000
M_u	1.0016	0.0006	0.9478	0.0006	0.000	0.000	0.000	1.000	0.207
M_c	0.9965	0.0012	-0.9526	-0.0012	0.000	0.000	0.000	0.207	1.000

X_i	$\lvert u_i(y) \rvert$
K_{cal}	0.00290
E_{R_u}	0.00203
Γ_{real}^{short}	0.00049
Γ_{imag}^{open}	0.00048
Γ_{real}^{open}	0.00048
$E_{K_{cal:drift}}$	0.00047
Γ_{imag}^{short}	0.00047
Γ_{imag}^{load}	0.00043
Γ_{real}^{load}	0.00039
E_{R_c}	0.00013

12000 MHz – UUT 2

X_i	x_i	$u(x_i)$	c_i	$u_i(y)$	$r(x_i, K_c)$	$r(x_i, R_u)$	$r(x_i, R_c)$	$r(x_i, M_u)$	$r(x_i, M_c)$
K_c	0.9527	0.0036	0.9738	0.0035	1.000	0.000	0.000	0.000	0.000
R_u	0.9709	0.0004	0.9555	0.0004	0.000	1.000	0.007	0.000	0.000
R_c	1.0053	0.0003	-0.9228	-0.0003	0.000	0.007	1.000	0.000	0.000
M_u	0.9999	0.0007	0.9278	0.0006	0.000	0.000	0.000	1.000	0.553
M_c	0.9917	0.0021	-0.9354	-0.0019	0.000	0.000	0.000	0.553	1.000

X_i	$\lvert u_i(y) \rvert$
K_{cal}	0.00343
Γ_{imag}^{open}	0.00082
Γ_{imag}^{short}	0.00078
Γ_{real}^{open}	0.00067
Γ_{real}^{short}	0.00066
Γ_{imag}^{load}	0.00049
$E_{K_{cal:drift}}$	0.00046
E_{R_u}	0.00040
Γ_{real}^{load}	0.00035
E_{R_c}	0.00026

15000 MHz – UUT 2

X_i	x_i	$u(x_i)$	c_i	$u_i(y)$	$r(x_i, K_c)$	$r(x_i, R_u)$	$r(x_i, R_c)$	$r(x_i, M_u)$	$r(x_i, M_c)$
K_c	0.9503	0.0034	0.9582	0.0033	1.000	0.000	0.000	0.000	0.000
R_u	0.9652	0.0014	0.9434	0.0014	0.000	1.000	0.003	0.000	0.000
R_c	1.0076	0.0002	-0.9036	-0.0002	0.000	0.003	1.000	0.000	0.000
M_u	1.0008	0.0005	0.9098	0.0005	0.000	0.000	0.000	1.000	-0.461
M_c	1.0005	0.0009	-0.9101	-0.0008	0.000	0.000	0.000	-0.461	1.000

X_i	$\|u_i(y)\|$
K_{cal}	0.00323
E_{R_u}	0.00135
Γ_{real}^{open}	0.00055
Γ_{imag}^{short}	0.00051
Γ_{real}^{short}	0.00051
Γ_{imag}^{open}	0.00050
$E_{K_{cal:drift}}$	0.00046
Γ_{imag}^{load}	0.00031
Γ_{real}^{load}	0.00028
E_{R_c}	0.00018

18000 MHz – UUT 2

X_i	x_i	$u(x_i)$	c_i	$u_i(y)$	$r(x_i, K_c)$	$r(x_i, R_u)$	$r(x_i, R_c)$	$r(x_i, M_u)$	$r(x_i, M_c)$
K_c	0.9132	0.0050	1.0003	0.0050	1.000	0.000	0.000	0.000	0.000
R_u	0.9964	0.0005	0.9167	0.0004	0.000	1.000	0.002	0.000	0.000
R_c	0.9830	0.0008	-0.9292	-0.0007	0.000	0.002	1.000	0.000	0.000
M_u	1.0132	0.0018	0.9015	0.0016	0.000	0.000	0.000	1.000	0.613
M_c	1.0268	0.0040	-0.8896	-0.0036	0.000	0.000	0.000	0.613	1.000

X_i	$\|u_i(y)\|$
K_{cal}	0.00493
Γ_{imag}^{short}	0.00189
Γ_{imag}^{open}	0.00169
Γ_{imag}^{load}	0.00110
E_{R_c}	0.00073
$E_{K_{cal:drift}}$	0.00046
E_{11}^{conn}	0.00044
E_{R_u}	0.00041
E_{11}^{conn}	0.00033
$E_{\Gamma\cdot real}^{A}$	0.00025

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Measurement Report (APMP.EM.RF-K8.CL)

1) Organization : NATIONAL METROLOGY LABORATORY, SIRIM Berhad (NML-SIRIM)

Country : MALAYSIA

Contact Person: Arshad Selamat

Address : Lot PT 4803, Bandar Baru Salak Tinggi, 43900 Sepang, Selangor Darul Ehsan.

2) Measurement methods

NML-SIRIM measurement setup

RF power generated by a signal generator is delivered to a resistive power splitter before been delivered to the splitter’s two measurement arms. Nominal power for each arm is 1 mW. One arm of the splitter is connected to the reference sensor (mount) while the other arm is connected to the unknown sensor (DUT). The NML-SIRIM standard thermistors used are directly traceable to KRISS. Measurement of the reflection coefficient for both the reference mount and DUT sensor have been performed using 8510C and 8753D vector network analyzer.

NML-SIRIM uncertainty budget

The following equation is used to transfer the calibration factor value of calibrated mount to the un-calibrated sensor.

$$K_D = (K_S + \delta K_S).\left(\frac{(S_{21})^2}{(S_{31})^2}\right).\left(\frac{P_{DUT} + P_{D\_r}}{P_{STD} + P_{S\_r} + P_{S\_co}}\right).\left(\frac{(1-|\Gamma_{g3}||\Gamma_D|)^2}{(1-|\Gamma_{g2}||\Gamma_S|)^2}\right)$$

K_D - Calibration factor of the traveling standard

K_S - Calibration factor of the reference standard

δK_S - Reference standard calibration factor drift

P_{DUT} - Traveling power meter power indication observed value

P_{STD} - Reference power meter power indication observed value

$\left(\frac{(S_{21})^2}{(S_{31})^2}\right)$- Power splitter ratio

$\left(\frac{(1-|\Gamma_{g3}||\Gamma_D|)^2}{(1-|\Gamma_{g2}||\Gamma_S|)^2}\right)$ - mismatch correction factor

P_{S_r} - Reference standard meter resolution

P_{S_co} - Reference standard meter zero carry over

P_{D_r} - DUT meter resolution

Sensor 1

Table 1: Example of the uncertainty budget at 15 GHz frequency.

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$ (± %)	Probability distribution/method of evaluation (A,B)	Sensitivity Coefficient $c_i = \frac{\delta K_D(f)}{\delta x_i}$	Uncertainty contribution $\|c_i\|u(x_i)$	Degrees of freedom v_i
K_S	0.9594	0.75	B/Normal	0.970623	0.727967	∞
δK_S	-	0.04	B/Rectangular	0.970623	0.038825	∞
P_{S_r}	0.00001	0.0003	B/Rectangular	-0.924581	-0.000277	∞
P_{S_co}	0.005	0.289	B/Rectangular	-0.924581	-0.266926	∞
P_{D_r}	0.00001	0.0003	B/Rectangular	0.956223	0.000287	∞
S_{21}	0.49692	0.12	B/Normal	3.740503	0.448860	∞
S_{31}	0.49757	0.12	B/Normal	-3.729921	-0.447591	∞
M_{S_sx}	1	0.30290	B/U-shaped	0.999945	0.302883	∞
M_{D_sx}	1	0.21040	B/U-shaped	0.999973	-0.210394	∞
P_{STD}	1.00530	0.01620	A/t-distribution	-0.924581	-0.014978	9
P_{DUT}	0.966861	0.03340	A/t-distribution	0.956223	0.031938	9
				Combined Standard Uncertainty $u_c(K_D)$ (± %)	Coverage factor k, level of confidence 95%	Effective degree of freedom V_{eff}
K_D	0.9175			2.14	2	1019

Sensor 1

Table 2: Example of the uncertainty budget for reflection coefficient at 15 GHz frequency

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution/method of evaluation (A,B)	Sensitivity Coefficient $c_i = \frac{\delta \Gamma_D(f)}{\delta x_i}$	Uncertainty contribution $\|c_i\|u(x_i)$	Degrees of freedom v_i
Γ_D	0.029976	0.0000130	A/t-distribution	1	0.00001300	9
VNA_r	0.000001	0.0000003	B/Rectangular	1	0.00000030	∞
VNA_u	0.1	0.0022000	B/Normal	1	0.00220000	∞
				Combined Standard Uncertainty $u_c(\Gamma_D)$	Coverage factor k, level of confidence 95%	Effective degree of freedom V_{eff}
			Γ_D	0.0044	2	7382274128

Sensor 2

Table 3: Example of the uncertainty budget at 15 GHz frequency.

Quantity X_i	Estimate x_i (± %)	Standard uncertainty $u(x_i)$ (%)	Probability distribution/method of evaluation (A,B)	Sensitivity Coefficient $c_i = \frac{\delta K_D(f)}{\delta x_i}$	Uncertainty contribution $\|c_i\|u(x_i)$	Degrees of freedom v_i
K_S	0.9594	0.75	B/Normal	0.978045	0.733534	∞
δK_S	-	0.04	B/Rectangular	0.978045	0.039122	∞
P_{S_r}	0.00001	0.00030	B/Rectangular	-0.931678	-0.000280	∞
P_{S_co}	0.005	0.28870	B/Rectangular	-0.931768	-0.268975	∞
P_{D_r}	0.00001	0.0003	B/Rectangular	0.955049	0.000287	∞
S_{21}	0.49692	0.12	B/Normal	3.769104	0.452292	∞
S_{31}	0.49757	0.12	B/Normal	-3.755546	-0.450666	∞
M_{S_sx}	1	0.30290	B/U-shaped	0.999943	0.302883	∞
M_{D_sx}	1	0.07960	B/U-shaped	0.999996	0.079600	∞
P_{STD}	1.00842	0.00450	A/t-distribution	-0.931678	-0.004193	9
P_{DUT}	0.97248	0.01010	A/t-distribution	0.955049	0.009646	9
				Combined Standard Uncertainty $u_c(K_{DUT})$ (± %)	Coverage factor *k*, level of confidence 95%	Effective degree of freedom V_{eff}
K_D	0.9216			2.11	2	1195

Sensor 2

Table 4: Example of the uncertainty budget for reflection coefficient at 15 GHz frequency.

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution/method of evaluation (A,B)	Sensitivity Coefficient $c_i = \frac{\delta \Gamma_D(f)}{\delta x_i}$	Uncertainty contribution $\|c_i\|u(x_i)$	Degrees of freedom v_i
Γ_D	0.011332	0.0000232	A/t-distribution	1	0.0000232	9
VNA_r	0.000001	0.0000003	B/Rectangular	1	0.0000003	∞
VNA_u	0.1	0.0022000	B/Normal	1	0.0022000	∞
				Combined Standard Uncertainty $u_c(\Gamma_D)$	Coverage factor *k*, level of confidence 95%	Effective degree of freedom V_{eff}
			Γ_D	0.0044	2	722472929

K_S - Calibration factor of the reference standard

The reference standard has been sent to KRISS Korea for its annual calibration. The uncertainty of ±1.5% (at 15 GHz) has been reported with confidence level of 95%.

δK_S - Reference standard calibration factor drift

The long term stability of the standard mount is estimated from the last five calibrations. A rectangular distribution is assumed and the value is divided by √3 to be ±0.04%.

P_{DUT} - Traveling power meter power indication observed value

Ten repeatability measurements have been employed in the measurement. Uncertainty of the mean is calculated using the standard statistical analysis as shown below.

Run	Power (mW)
1	0.9651
2	0.9662
3	0.9660
4	0.9658
5	0.9667
6	0.9673
7	0.9674
8	0.9679
9	0.9682
10	0.9679
Average	0.9669
Std dev	1.06E-03

The standard uncertainty of the mean is calculated by dividing the standard deviation with the square root of the number of repeatability (i.e. √10) = 0.033%.

P_{STD} **- Reference power meter power indication observed value**

Ten repeatability measurements have been employed in the measurement. Uncertainty of the mean is calculated using the standard statistical analysis as shown below.

Run	Power (mW)
1	1.0044
2	1.0047
3	1.0052
4	1.0048
5	1.0057
6	1.0056
7	1.0057
8	1.0059
9	1.0057
10	1.0054
Average	1.0053
Std dev	5.11E-04

The standard uncertainty of the mean is calculated by dividing the standard deviation with the square root of the number of repeatability (i.e. √10) = 0.016%.

Mismatch

Mismatch uncertainty is estimated using ± $200\,|\Gamma_G||\Gamma_L|$equation where $|\Gamma_G|$ and $|\Gamma_L|$ are the generator and load reflection coefficients respectively.

M_{S_sx}- Mismatch uncertainty at 15 GHz between generator (i.e. ($|\Gamma_G|= 0.040$))and reference mount (i.e. ($|\Gamma_L|=0.053$)).

M_{D_sx}– Mismatch uncertainty at 15 GHz between generator (i.e. ($|\Gamma_G|= 0.050$)) and DUT sensor (i.e. ($|\Gamma_L|=0.030$)).

The final standard uncertainty is calculated by: $\pm (200\,|\Gamma_G||\Gamma_L|) / \sqrt{2}$

$\left(\frac{(S_{21})^2}{(S_{31})^2}\right)$**- Power splitter ratio**

The uncertainty of the power splitter for both ports configuration is ±0.12%.

P_{S_r} **- Reference standard meter resolution**

The resolution of the standard power meter is 0.00001 based on the digital multimeter resolution. The uncertainty based on the digital multimeter meter resolution is ±0.0003%.

P_{S_co} **- Reference standard meter zero carry over**

The zero carry over uncertainty of the power meter is ± 0.5%.

P_{D_r} **- DUT meter resolution**

The resolution of the standard power meter is 0.00001 based on the digital multimeter resolution.The uncertainty based on the digital multimeter meter resolution is ±0.0003%.

3) Measuring system

The RF Power measurement system in NML-SIRIM uses the direct dc substitution method. Figure 1 shows the schematic diagram of the system.

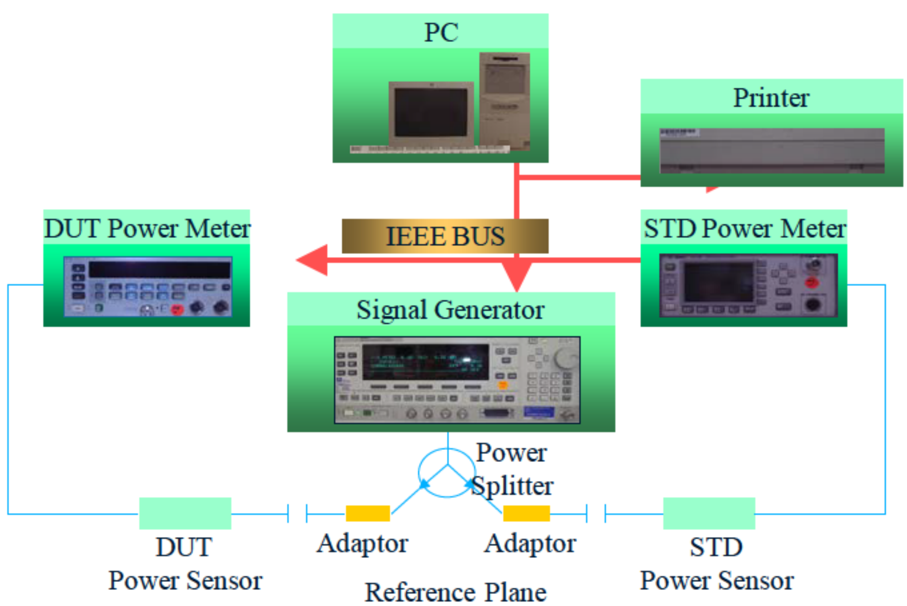

Figure 1

4) List of results

Sensor 1

Frequency (GHz)	Calibration factor *K*	Combined Standard uncertainty *uc(K)* *(k=1)*	Coverage factor *k* corresponding to the level of confidence of 95%
0.01	96.72%	1.58%	2
0.05	99.26%	1.57%	2
1	98.04%	1.79%	2
4	96.81%	1.78%	2
8	95.23%	1.81%	2
12	93.81%	2.11%	2
15	91.75%	2.14%	2
18	88.35%	2.72%	2

Sensor 2

Frequency (GHz)	Calibration factor *K*	Combined Standard uncertainty *uc(K)* *(k=1)*	Coverage factor *k* corresponding to the level of confidence of 95%
0.01	96.54%	1.58%	2
0.05	99.29%	1.57%	2
1	98.14%	1.79%	2
4	96.94%	1.79%	2
8	95.89%	1.82%	2
12	94.02%	2.10%	2
15	92.16%	2.11%	2
18	89.29%	2.66%	2

5) Measurement conditions

Ambient temperature : 21 °C ± 3 °C

Humidity : 60 % ± 5 %

6) Additional measurement

Reflection Coefficients of the traveling standards

Sensor 1

Frequency (GHz)	Magnitude	Phase	Uncertainty of magnitude
0.01	0.06289	-83.68	0.0027
0.05	0.01367	-84.90	0.0027
1	0.01023	-21.55	0.0020
4	0.01616	45.40	0.0020
8	0.01664	-42.58	0.0030
12	0.03183	23.51	0.0044
15	0.02998	68.65	0.0044
18	0.07644	48.03	0.0044

Sensor 2

Frequency (GHz)	Magnitude	Phase	Uncertainty of magnitude
0.01	0.06434	-82.77	0.0027
0.05	0.01398	-89.55	0.0027
1	0.01072	-29.93	0.0020
4	0.01421	25.86	0.0020
8	0.01540	-21.99	0.0030
12	0.01954	15.34	0.0044
15	0.01133	74.96	0.0044
18	0.06152	46.50	0.0044

Appendix

Sensor 1

Table 2**:** Uncertainty budget at 10 MHz frequency.

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$ (± %)	Probability distribution/method of evaluation (A,B)	Sensitivity Coefficient $c_i = \frac{\delta K_D(f)}{\delta x_i}$	Uncertainty contribution $\lvert c_i \rvert u(x_i)$	Degrees of freedom v_i
K_S	0.9385	0.25	B/Normal	1.059754	0.264938	∞
δK_S	-	0.15	B/Rectangular	1.059754	0.158963	∞
P_{S_r}	0.00001	0.00030	B/Rectangular	-0.989876	-0.000297	∞
P_{S_co}	0.005	0.28870	B/Rectangular	-0.989876	-0.285777	∞
P_{D_r}	0.00001	0.00040	B/Rectangular	0.942003	0.000377	∞
S_{21}	0.49934	0.12000	B/Normal	3.983606	0.478033	∞
S_{31}	0.49933	0.12000	B/Normal	-3.908774	-0.469053	∞
M_{S_sx}	1	0.014500	B/U-shaped	1.000000	0.014500	∞
M_{D_sx}	1	0.00540	B/U-shaped	1.000000	0.005400	∞
P_{STD}	1.00178	0.020100	A/t-distribution	-0.989876	-0.019897	9
P_{DUT}	1.054554	0.02670	A/t-distribution	0.942003	0.025151	9
				Combined Standard Uncertainty $u_c(K_D)$ (± %)	Coverage factor k, level of confidence 95%	Effective degree of freedom V_{eff}
K_D	0.9672			1.58	2	5286298

Table 2**:** Uncertainty budget for reflection coefficient at 10 MHz frequency

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution/method of evaluation (A,B)	Sensitivity Coefficient $c_i = \frac{\delta \Gamma_D(f)}{\delta x_i}$	Uncertainty contribution $\lvert c_i \rvert u(x_i)$	Degrees of freedom v_i
Γ_D	0.062895	0.000001	A/t-distribution	1	0.00000134	9
VNA_r	0.000001	0.0000003	B/Rectangular	1	0.00000030	∞
VNA_u	0.1	0.001350	B/Normal	1	0.00135000	∞
				Combined Standard Uncertainty $u_c(\Gamma_D)$	Coverage factor k, level of confidence 95%	Effective degree of freedom V_{eff}
			Γ_D	0.0027	2	9210465377492

Table 3**:** Uncertainty budget at 50 MHz frequency.

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$ (± %)	Probability distribution/method of evaluation (A,B)	Sensitivity Coefficient $c_i = \frac{\delta K_D(f)}{\delta x_i}$	Uncertainty contribution $\lvert c_i \rvert u(x_i)$	Degrees of freedom v_i
K_S	0.9928	0.25	B/Normal	1.013713	0.253428	∞
δK_S	-	0.02	B/Rectangular	1.013713	0.020274	∞
P_{S_r}	0.00001	0.00030	B/Rectangular	-1.001439	-0.000300	∞
P_{S_co}	0.005	0.28870	B/Rectangular	-1.001439	-0.289116	∞
P_{D_r}	0.00001	0.00030	B/Rectangular	0.990251	0.000297	∞
S_{21}	0.49866	0.12000	B/Normal	4.036497	0.484380	∞
S_{31}	0.49865	0.12000	B/Normal	-4.031997	-0.483840	∞
M_{S_sx}	1	0.00350	B/U-shaped	1.000000	0.003500	∞
M_{D_sx}	1	0.00120	B/U-shaped	1.000000	0.001200	∞
P_{STD}	1.00774	0.01180	A/t-distribution	-1.001439	-0.011817	9
P_{DUT}	1.008621	0.01510	A/t-distribution	0.990251	0.014953	9
				Combined Standard Uncertainty $u_c(K_D)$ (± %)	Coverage factor k, level of confidence 95%	Effective degree of freedom V_{eff}
K_D	0.9926			1.57	2	43918646

Table 4**:** Uncertainty budget for reflection coefficient at 50 MHz frequency

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution/method of evaluation (A,B)	Sensitivity Coefficient $c_i = \frac{\delta \Gamma_D(f)}{\delta x_i}$	Uncertainty contribution $\lvert c_i \rvert u(x_i)$	Degrees of freedom v_i
Γ_D	0.013669	0.000001	A/t-distribution	1	0.00000141	9
VNA_r	0.000001	0.0000003	B/Rectangular	1	0.00000030	∞
VNA_u	0.1	0.001350	B/Normal	1	0.00135000	∞
				Combined Standard Uncertainty $u_c(\Gamma_D)$	Coverage factor k, level of confidence 95%	Effective degree of freedom V_{eff}
			Γ_D	0.0027	2	7475263715347

Table 5: Uncertainty budget at 1 GHz frequency.

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$ (± %)	Probability distribution/method of evaluation (A,B)	Sensitivity Coefficient $c_i = \frac{\delta K_D(f)}{\delta x_i}$	Uncertainty contribution $\lvert c_i \rvert u(x_i)$	Degrees of freedom v_i
K_S	0.9944	0.5	B/Normal	0.997655	0.498828	∞
δK_S	-	0.09	B/Rectangular	0.997655	0.089789	∞
P_{S_r}	0.00001	0.00030	B/Rectangular	-0.987083	-0.000296	∞
P_{S_co}	0.005	0.28870	B/Rectangular	-0.987083	-0.284971	∞
P_{D_r}	0.00001	0.00030	B/Rectangular	0.992587	0.000298	∞
S_{21}	0.49509	0.12000	B/Normal	4.007654	0.480919	∞
S_{31}	0.49496	0.12000	B/Normal	-4.008161	-0.480979	∞
M_{S_sx}	1	0.004700	B/U-shaped	1.000000	0.004700	∞
M_{D_sx}	1	0.00170	B/U-shaped	1.000000	0.001700	∞
P_{STD}	1.00749	0.012400	A/t-distribution	-0.987083	-0.012240	9
P_{DUT}	0.992064	0.01050	A/t-distribution	0.992587	0.010422	9
				Combined Standard Uncertainty $u_c(K_D)$ (± %)	Coverage factor k, level of confidence 95%	Effective degree of freedom V_{eff}
K_D	0.9804			1.79	2	147597980

Table 6: Uncertainty budget for reflection coefficient at 1 GHz frequency

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution/method of evaluation (A,B)	Sensitivity Coefficient $c_i = \frac{\delta \Gamma_D(f)}{\delta x_i}$	Uncertainty contribution $\lvert c_i \rvert u(x_i)$	Degrees of freedom v_i
Γ_D	0.010227	0.000019	A/t-distribution	1	0.00001914	9
VNA_r	0.000001	0.0000003	B/Rectangular	1	0.00000030	∞
VNA_u	0.1	0.001000	B/Normal	1	0.00100000	∞
				Combined Standard Uncertainty $u_c(\Gamma_D)$	Coverage factor k, level of confidence 95%	Effective degree of freedom V_{eff}
			Γ_D	0.0020	2	67046957

Table 7**:** Uncertainty budget at 4 GHz frequency.

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$ (± %)	Probability distribution/method of evaluation (A,B)	Sensitivity Coefficient $c_i = \frac{\delta K_D(f)}{\delta x_i}$	Uncertainty contribution $\lvert c_i \rvert u(x_i)$	Degrees of freedom v_i
K_S	0.9849	0.5	B/Normal	0.989576	0.494788	∞
δK_S	-	0.05	B/Rectangular	0.989576	0.049479	∞
P_{S_r}	0.00001	0.00030	B/Rectangular	-0.969712	-0.000291	∞
P_{S_co}	0.005	0.28870	B/Rectangular	-0.969712	-0.279956	∞
P_{D_r}	0.00001	0.00030	B/Rectangular	0.986310	0.000296	∞
S_{21}	0.48625	0.12000	B/Normal	4.008803	0.481056	∞
S_{31}	0.48692	0.12000	B/Normal	-3.999763	-0.479972	∞
M_{S_sx}	1	0.013900	B/U-shaped	1.000000	0.013900	∞
M_{D_sx}	1	0.00320	B/U-shaped	1.000000	0.003200	∞
P_{STD}	1.00103	0.007800	A/t-distribution	-0.969712	-0.007564	9
P_{DUT}	0.987154	0.02040	A/t-distribution	0.986310	0.020121	9
				Combined Standard Uncertainty $u_c(K_D)$ (± %)	Coverage factor k, level of confidence 95%	Effective degree of freedom V_{eff}
K_D	0.9681			1.78	2	22980628

Table 8**:** Uncertainty budget for reflection coefficient at 4 GHz frequency

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution/method of evaluation (A,B)	Sensitivity Coefficient $c_i = \frac{\delta \Gamma_D(f)}{\delta x_i}$	Uncertainty contribution $\lvert c_i \rvert u(x_i)$	Degrees of freedom v_i
Γ_D	0.016165	0.000017	A/t-distribution	1	0.00001683	9
$VNA_{\_r}$	0.000001	0.0000003	B/Rectangular	1	0.00000030	∞
$VNA_{\_u}$	0.1	0.001000	B/Normal	1	0.00100000	∞
				Combined Standard Uncertainty $u_c(\Gamma_D)$	Coverage factor k, level of confidence 95%	Effective degree of freedom V_{eff}
			Γ_D	0.0020	2	112248976

Table 9: Uncertainty budget at 8 GHz frequency.

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$ (± %)	Probability distribution/method of evaluation (A,B)	Sensitivity Coefficient $c_i = \frac{\delta K_D(f)}{\delta x_i}$	Uncertainty contribution $\lvert c_i \rvert u(x_i)$	Degrees of freedom v_i
K_S	0.9772	0.5	B/Normal	0.985389	0.492694	∞
δK_S	-	0.15	B/Rectangular	0.985389	0.147808	∞
P_{S_r}	0.00001	0.00030	B/Rectangular	-0.958043	-0.000287	∞
P_{S_co}	0.005	0.28870	B/Rectangular	-0.958043	-0.276587	∞
P_{D_r}	0.00001	0.00030	B/Rectangular	0.972992	0.000292	∞
S_{21}	0.47895	0.12000	B/Normal	4.020997	0.482520	∞
S_{31}	0.48001	0.12000	B/Normal	-4.007269	-0.480872	∞
M_{S_sx}	1	0.106000	B/U-shaped	0.999992	0.105999	∞
M_{D_sx}	1	0.03280	B/U-shaped	0.999999	0.032800	∞
P_{STD}	1.00609	0.004300	A/t-distribution	-0.958043	-0.004120	9
P_{DUT}	0.983718	0.01800	A/t-distribution	0.972992	0.017514	9
				Combined Standard Uncertainty $u_c(K_D)$ (± %)	Coverage factor k, level of confidence 95%	Effective degree of freedom V_{eff}
K_D	0.9523			1.81	2	36367

Table 12: Uncertainty budget for reflection coefficient at 8 GHz frequency

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution/method of evaluation (A,B)	Sensitivity Coefficient $c_i = \frac{\delta \Gamma_D(f)}{\delta x_i}$	Uncertainty contribution $\lvert c_i \rvert u(x_i)$	Degrees of freedom v_i
Γ_D	0.016638	0.000009	A/t-distribution	1	0.00000866	9
$VNA_{\_r}$	0.000001	0.0000003	B/Rectangular	1	0.00000030	∞
$VNA_{\_u}$	0.1	0.001500	B/Normal	1	0.00150000	∞
				Combined Standard Uncertainty $u_c(\Gamma_D)$	Coverage factor k, level of confidence 95%	Effective degree of freedom V_{eff}
			Γ_D	0.0030	2	8101365517

Table 33: Uncertainty budget at 12 GHz frequency.

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$ (± %)	Probability distribution/method of evaluation (A,B)	Sensitivity Coefficient $c_i = \frac{\delta K_D(f)}{\delta x_i}$	Uncertainty contribution $\|c_i\|u(x_i)$	Degrees of freedom v_i
K_S	0.9675	0.75	B/Normal	0.979880	0.734910	∞
δK_S	-	0.06	B/Rectangular	0.979880	0.058793	∞
P_{S_r}	0.00001	0.00030	B/Rectangular	-0.943191	-0.000283	∞
P_{S_co}	0.005	0.28870	B/Rectangular	-0.943191	-0.272299	∞
P_{D_r}	0.00001	0.00030	B/Rectangular	0.966914	0.000290	∞
S_{21}	0.49192	0.12000	B/Normal	3.854419	0.462530	∞
S_{31}	0.49232	0.12000	B/Normal	-3.850544	-0.462065	∞
M_{S_sx}	1	0.210000	B/U-shaped	0.999971	0.209994	∞
M_{D_sx}	1	0.16390	B/U-shaped	0.999983	0.163897	∞
P_{STD}	1.00482	0.006700	A/t-distribution	-0.943191	-0.006319	9
P_{DUT}	0.975824	0.01760	A/t-distribution	0.966914	0.017018	9
				Combined Standard Uncertainty $u_c(K_D)$ (± %)	Coverage factor k, level of confidence 95%	Effective degree of freedom V_{eff}
K_D	0.9381			2.11	2	3539

Table 14: Uncertainty budget for reflection coefficient at 12 GHz frequency

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution/method of evaluation (A,B)	Sensitivity Coefficient $c_i = \frac{\delta \Gamma_D(f)}{\delta x_i}$	Uncertainty contribution $\|c_i\|u(x_i)$	Degrees of freedom v_i
Γ_D	0.031835	0.000016	A/t-distribution	1	0.00001631	9
$VNA_{\_r}$	0.000001	0.0000003	B/Rectangular	1	0.00000030	∞
$VNA_{\_u}$	0.1	0.002200	B/Normal	1	0.00220000	∞
				Combined Standard Uncertainty $u_c(\Gamma_D)$	Coverage factor k, level of confidence 95%	Effective degree of freedom V_{eff}
			Γ_D	0.0044	2	2979892181

Table 45**:** Uncertainty budget at 18 GHz frequency.

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$ (± %)	Probability distribution/method of evaluation (A,B)	Sensitivity Coefficient $c_i = \frac{\delta K_D(f)}{\delta x_i}$	Uncertainty contribution $\lvert c_i \rvert u(x_i)$	Degrees of freedom v_i
K_S	0.9357	0.75	B/Normal	0.954122	0.715592	∞
δK_S	-	0.52	B/Rectangular	0.954122	0.496143	∞
P_{S_r}	0.00001	0.00030	B/Rectangular	-0.888103	-0.000266	∞
P_{S_co}	0.005	0.28870	B/Rectangular	-0.888103	-0.256395	∞
P_{D_r}	0.00001	0.00030	B/Rectangular	0.932129	0.000280	∞
S_{21}	0.47024	0.12000	B/Normal	3.797098	0.455652	∞
S_{31}	0.47104	0.12000	B/Normal	-3.812331	-0.457480	∞
M_{S_sx}	1	0.527700	B/U-shaped	0.999856	0.527624	∞
M_{D_sx}	1	0.57840	B/U-shaped	0.999827	0.578300	∞
P_{STD}	1.00507	0.030100	A/t-distribution	-0.888103	-0.026732	9
P_{DUT}	0.953052	0.04300	A/t-distribution	0.932129	0.040082	9
				Combined Standard Uncertainty $u_c(K_D)$ (± %)	Coverage factor k, level of confidence 95%	Effective degree of freedom V_{eff}
K_D	0.8835			2.72	2	140

Table 16**:** Uncertainty budget for reflection coefficient at 18 GHz frequency

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution/method of evaluation (A,B)	Sensitivity Coefficient $c_i = \frac{\delta \Gamma_D(f)}{\delta x_i}$	Uncertainty contribution $\lvert c_i \rvert u(x_i)$	Degrees of freedom v_i
Γ_D	0.076442	0.000051	A/t-distribution	1	0.00005082	9
VNA_r	0.000001	0.0000003	B/Rectangular	1	0.00000030	∞
VNA_u	0.1	0.002200	B/Normal	1	0.00220000	∞
				Combined Standard Uncertainty $u_c(\Gamma_D)$	Coverage factor k, level of confidence 95%	Effective degree of freedom V_{eff}
			Γ_D	0.0044	2	31630534

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Table 57**:** Uncertainty budget at 10 MHz frequency.

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$ (± %)	Probability distribution/method of evaluation (A,B)	Sensitivity Coefficient $c_i = \frac{\delta K_D(f)}{\delta x_i}$	Uncertainty contribution $\lvert c_i \rvert u(x_i)$	Degrees of freedom v_i
K_S	0.9385	0.25	B/Normal	1.057358	0.264339	∞
δK_S	-	0.15	B/Rectangular	1.057358	0.158604	∞
P_{S_r}	0.00001	0.00030	B/Rectangular	-0.987627	-0.000296	∞
P_{S_co}	0.005	0.28870	B/Rectangular	-0.987627	-0.285128	∞
P_{D_r}	0.00001	0.00040	B/Rectangular	0.942319	0.000377	∞
S_{21}	0.49934	0.12000	B/Normal	3.974599	0.476952	∞
S_{31}	0.49933	0.12000	B/Normal	-3.900657	-0.468079	∞
M_{S_sx}	1	0.01450	B/U-shaped	1.000000	0.014500	∞
M_{D_sx}	1	0.00550	B/U-shaped	1.000000	0.005500	∞
P_{STD}	1.00144	0.01360	A/t-distribution	-0.987627	-0.013432	9
P_{DUT}	1.05216	0.01090	A/t-distribution	0.942319	0.010271	9
				Combined Standard Uncertainty $u_c(K_D)$ (± %)	Coverage factor k, level of confidence 95%	Effective degree of freedom V_{eff}
K_D	0.9654			1.58	2	33671951

Table 18**:** Uncertainty budget for reflection coefficient at 10 MHz frequency

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution/method of evaluation (A,B)	Sensitivity Coefficient $c_i = \frac{\delta \Gamma_D(f)}{\delta x_i}$	Uncertainty contribution $\lvert c_i \rvert u(x_i)$	Degrees of freedom v_i
Γ_D	0.064342	0.0000013	A/t-distribution	1	0.0000013	9
$VNA_{\_r}$	0.000001	0.0000003	B/Rectangular	1	0.0000003	∞
$VNA_{\_u}$	0.1	0.00135	B/Normal	1	0.00135	∞
				Combined Standard Uncertainty $u_c(\Gamma_D)$	Coverage factor k, level of confidence 95%	Effective degree of freedom V_{eff}
			Γ_D	0.0027	2	11870303647944

Table 69**:** Uncertainty budget at 50 MHz frequency.

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$ (± %)	Probability distribution/method of evaluation (A,B)	Sensitivity Coefficient $c_i = \frac{\delta K_D(f)}{\delta x_i}$	Uncertainty contribution $\lvert c_i \rvert u(x_i)$	Degrees of freedom v_i
K_S	0.9928	0.25	B/Normal	1.013405	0.253351	∞
δK_S	-	0.02	B/Rectangular	1.013405	0.020268	∞
P_{S_r}	0.00001	0.00030	B/Rectangular	-1.001134	-0.000300	∞
P_{S_co}	0.005	0.28870	B/Rectangular	-1.001134	-0.289027	∞
P_{D_r}	0.00001	0.00030	B/Rectangular	0.990798	0.000297	∞
S_{21}	0.49866	0.12000	B/Normal	4.035273	0.484233	∞
S_{31}	0.49865	0.12000	B/Normal	-4.030809	-0.483697	∞
M_{S_sx}	1	0.00350	B/U-shaped	1.000000	0.003500	∞
M_{D_sx}	1	0.00120	B/U-shaped	1.000000	0.001200	∞
P_{STD}	1.00718	0.01690	A/t-distribution	-1.001134	-0.016919	9
P_{DUT}	1.008314	0.01830	A/t-distribution	0.990798	0.018132	9
				Combined Standard Uncertainty $u_c(K_D)$ (± %)	Coverage factor k, level of confidence 95%	Effective degree of freedom V_{eff}
K_D	0.9929			1.57	2	16088457

Table 20**:** Uncertainty budget for reflection coefficient at 50 MHz frequency

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution/method of evaluation (A,B)	Sensitivity Coefficient $c_i = \frac{\delta \Gamma_D(f)}{\delta x_i}$	Uncertainty contribution $\lvert c_i \rvert u(x_i)$	Degrees of freedom v_i
Γ_D	0.013981	0.0000008	A/t-distribution	1	0.0000008	9
VNA_r	0.000001	0.0000003	B/Rectangular	1	0.0000003	∞
VNA_u	0.1	0.00135	B/Normal	1	0.00135	∞
				Combined Standard Uncertainty $u_c(\Gamma_D)$	Coverage factor k, level of confidence 95%	Effective degree of freedom V_{eff}
			Γ_D	0.0027	2	92772512640300

Table 27**:** Uncertainty budget at 1 GHz frequency.

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$ (± %)	Probability distribution/method of evaluation (A,B)	Sensitivity Coefficient $c_i = \frac{\delta K_D(f)}{\delta x_i}$	Uncertainty contribution $\lvert c_i \rvert u(x_i)$	Degrees of freedom v_i
K_S	0.9944	0.5	B/Normal	0.998033	0.499016	∞
δK_S	-	0.09	B/Rectangular	0.998033	0.089823	∞
P_{S_r}	0.00001	0.00030	B/Rectangular	-0.987459	-0.000296	∞
P_{S_co}	0.005	0.28870	B/Rectangular	-0.987459	-0.285079	∞
P_{D_r}	0.00001	0.00030	B/Rectangular	0.993230	0.000298	∞
S_{21}	0.49509	0.12000	B/Normal	4.009172	0.481101	∞
S_{31}	0.49496	0.12000	B/Normal	-4.009721	-0.481167	∞
M_{S_sx}	1	0.00470	B/U-shaped	1.000000	0.004700	∞
M_{D_sx}	1	0.00180	B/U-shaped	1.000000	0.001800	∞
P_{STD}	1.00683	0.01110	A/t-distribution	-0.987459	-0.010961	9
P_{DUT}	0.992443	0.01410	A/t-distribution	0.993230	0.014005	9
				Combined Standard Uncertainty $u_c(K_D)$ (± %)	Coverage factor k, level of confidence 95%	Effective degree of freedom V_{eff}
K_D	0.9814			1.79	2	96252527

Table 22**:** Uncertainty budget for reflection coefficient at 1 GHz frequency

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution/method of evaluation (A,B)	Sensitivity Coefficient $c_i = \frac{\delta \Gamma_D(f)}{\delta x_i}$	Uncertainty contribution $\lvert c_i \rvert u(x_i)$	Degrees of freedom v_i
Γ_D	0.010717	0.0000153	A/t-distribution	1	0.0000153	9
VNA_r	0.000001	0.0000003	B/Rectangular	1	0.0000003	∞
VNA_u	0.1	0.001	B/Normal	1	0.001	∞
				Combined Standard Uncertainty $u_c(\Gamma_D)$	Coverage factor k, level of confidence 95%	Effective degree of freedom V_{eff}
			Γ_D	0.0020	2	163827560

Table 23**:** Uncertainty budget at 4 GHz frequency.

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$ (± %)	Probability distribution/method of evaluation (A,B)	Sensitivity Coefficient $c_i = \frac{\delta K_D(f)}{\delta x_i}$	Uncertainty contribution $\lvert c_i \rvert u(x_i)$	Degrees of freedom v_i
K_S	0.9849	0.5	B/Normal	0.997428	0.498714	∞
δK_S	-	0.05	B/Rectangular	0.997428	0.049871	∞
P_{S_r}	0.00001	0.00030	B/Rectangular	-0.977445	-0.000293	∞
P_{S_co}	0.005	0.28870	B/Rectangular	-0.977445	-0.282188	∞
P_{D_r}	0.00001	0.00030	B/Rectangular	0.979823	0.000294	∞
S_{21}	0.48625	0.12000	B/Normal	4.040610	0.484873	∞
S_{31}	0.48692	0.12000	B/Normal	-4.031260	-0.483751	∞
M_{S_sx}	1	0.01390	B/U-shaped	1.000000	0.013900	∞
M_{D_sx}	1	0.00290	B/U-shaped	1.000000	0.002900	∞
P_{STD}	1.00769	0.00770	A/t-distribution	-0.977445	-0.007526	9
P_{DUT}	0.995021	0.00710	A/t-distribution	0.979823	0.006957	9
				Combined Standard Uncertainty $u_c(K_D)$ (± %)	Coverage factor *k*, level of confidence 95%	Effective degree of freedom V_{eff}
K_D	0.9694			1.79	2	103426891

Table 24**:** Uncertainty budget for reflection coefficient at 4 GHz frequency

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution/method of evaluation (A,B)	Sensitivity Coefficient $c_i = \frac{\delta \Gamma_D(f)}{\delta x_i}$	Uncertainty contribution $\lvert c_i \rvert u(x_i)$	Degrees of freedom v_i
Γ_D	0.014214	0.0000144	A/t-distribution	1	0.0000144	9
VNA_r	0.000001	0.0000003	B/Rectangular	1	0.0000003	∞
VNA_u	0.1	0.001	B/Normal	1	0.001	∞
				Combined Standard Uncertainty $u_c(\Gamma_D)$	Coverage factor *k*, level of confidence 95%	Effective degree of freedom V_{eff}
			Γ_D	0.0020	2	206831233

Table 25: Uncertainty budget at 8 GHz frequency.

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$ (± %)	Probability distribution/method of evaluation (A,B)	Sensitivity Coefficient $c_i = \frac{\delta K_D(f)}{\delta x_i}$	Uncertainty contribution $\lvert c_i\rvert u(x_i)$	Degrees of freedom v_i
K_S	0.9772	0.5	B/Normal	0.992291	0.496145	∞
δK_S	-	0.15	B/Rectangular	0.992291	0.148844	∞
P_{S_r}	0.00001	0.00030	B/Rectangular	-0.964787	-0.000289	∞
P_{S_co}	0.005	0.28870	B/Rectangular	-0.964787	-0.278534	∞
P_{D_r}	0.00001	0.00030	B/Rectangular	0.972927	0.000292	∞
S_{21}	0.47895	0.12000	B/Normal	4.049160	0.485899	∞
S_{31}	0.48001	0.12000	B/Normal	-4.035177	-0.484221	∞
M_{S_sx}	1	0.10600	B/U-shaped	0.999992	0.105999	∞
M_{D_sx}	1	0.03030	B/U-shaped	0.999999	0.030300	∞
P_{STD}	1.00619	0.00640	A/t-distribution	-0.964787	-0.006175	9
P_{DUT}	0.990609	0.01190	A/t-distribution	0.972927	0.011578	9
				Combined Standard Uncertainty $u_c(K_D)$ (± %)	Coverage factor k, level of confidence 95%	Effective degree of freedom V_{eff}
K_D	0.9589			1.82	2	37324

Table 26: Uncertainty budget for reflection coefficient at 8 GHz frequency

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution/method of evaluation (A,B)	Sensitivity Coefficient $c_i = \frac{\delta \Gamma_D(f)}{\delta x_i}$	Uncertainty contribution $\lvert c_i\rvert u(x_i)$	Degrees of freedom v_i
Γ_D	0.015401	0.0000139	A/t-distribution	1	0.0000139	9
$VNA_{\_r}$	0.000001	0.0000003	B/Rectangular	1	0.0000003	∞
$VNA_{\_u}$	0.1	0.0015	B/Normal	1	0.0015	∞
				Combined Standard Uncertainty $u_c(\Gamma_D)$	Coverage factor k, level of confidence 95%	Effective degree of freedom V_{eff}
			Γ_D	0.0030	2	1216040505

Table 27**:** Uncertainty budget at 12 GHz frequency.

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$ (± %)	Probability distribution/method of evaluation (A,B)	Sensitivity Coefficient $c_i = \frac{\delta K_D(f)}{\delta x_i}$	Uncertainty contribution $\|c_i\|u(x_i)$	Degrees of freedom v_i
K_S	0.9675	0.75	B/Normal	0.982491	0.736868	∞
δK_S	-	0.06	B/Rectangular	0.982491	0.058949	∞
P_{S_r}	0.00001	0.00030	B/Rectangular	-0.945713	-0.000284	∞
P_{S_co}	0.005	0.28870	B/Rectangular	-0.945713	-0.273027	∞
P_{D_r}	0.00001	0.00030	B/Rectangular	0.967363	0.000290	∞
S_{21}	0.49192	0.12000	B/Normal	3.864691	0.463763	∞
S_{31}	0.49232	0.12000	B/Normal	-3.858366	-0.463004	∞
M_{S_sx}	1	0.21000	B/U-shaped	0.999971	0.209994	∞
M_{D_sx}	1	0.10060	B/U-shaped	0.999993	0.100599	∞
P_{STD}	1.00526	0.00620	A/t-distribution	-0.945713	-0.005863	9
P_{DUT}	0.977557	0.00590	A/t-distribution	0.967363	0.005707	9
				Combined Standard Uncertainty $u_c(K_D)$ (± %)	Coverage factor k, level of confidence 95%	Effective degree of freedom V_{eff}
K_D	0.9402			2.10	2	4508

Table 28**:** Uncertainty budget for reflection coefficient at 12 GHz frequency

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution/method of evaluation (A,B)	Sensitivity Coefficient $c_i = \frac{\delta \Gamma_D(f)}{\delta x_i}$	Uncertainty contribution $\|c_i\|u(x_i)$	Degrees of freedom v_i
Γ_D	0.019536	0.0000214	A/t-distribution	1	0.0000214	9
$VNA_{\_r}$	0.000001	0.0000003	B/Rectangular	1	0.0000003	∞
$VNA_{\_u}$	0.1	0.0022	B/Normal	1	0.0022	∞
				Combined Standard Uncertainty $u_c(\Gamma_D)$	Coverage factor k, level of confidence 95%	Effective degree of freedom V_{eff}
			Γ_D	0.0044	2	1010975697

Table 29: Uncertainty budget at 18 GHz frequency.

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$ (± %)	Probability distribution/method of evaluation (A,B)	Sensitivity Coefficient $c_i = \frac{\delta K_D(f)}{\delta x_i}$	Uncertainty contribution $\lvert c_i \rvert u(x_i)$	Degrees of freedom v_i
K_S	0.9357	0.75	B/Normal	0.965638	0.724228	∞
δK_S	-	0.52	B/Rectangular	0.965638	0.502132	∞
P_{S_r}	0.00001	0.00030	B/Rectangular	-0.898871	-0.000270	∞
P_{S_co}	0.005	0.28870	B/Rectangular	-0.898871	-0.259504	∞
P_{D_r}	0.00001	0.00030	B/Rectangular	0.932331	0.000280	∞
S_{21}	0.47024	0.12000	B/Normal	3.842926	0.461151	∞
S_{31}	0.47104	0.12000	B/Normal	-3.850371	-0.462045	∞
M_{S_sx}	1	0.52770	B/U-shaped	0.999849	0.527620	∞
M_{D_sx}	1	0.46550	B/U-shaped	0.999883	0.465446	∞
P_{STD}	1.00647	0.00470	A/t-distribution	-0.898871	-0.004225	9
P_{DUT}	0.963063	0.00970	A/t-distribution	0.932331	0.009044	9
				Combined Standard Uncertainty $u_c(K_D)$ (± %)	Coverage factor *k*, level of confidence 95%	Effective degree of freedom V_{eff}
K_D	0.8929			2.66	2	192

Table 30: Uncertainty budget for reflection coefficient at 18 GHz frequency

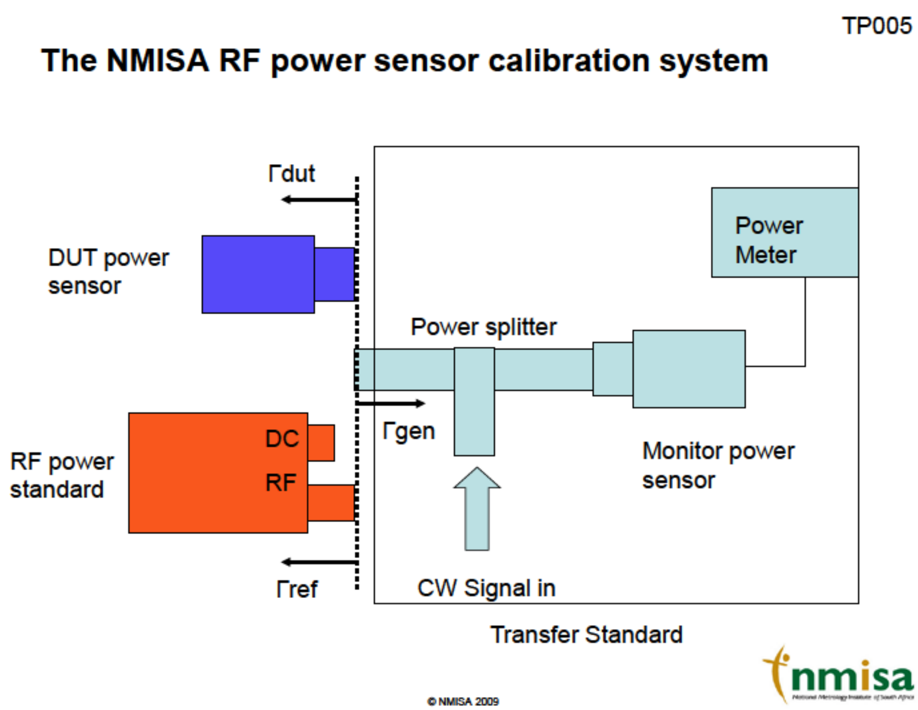
Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution/method of evaluation (A,B)	Sensitivity Coefficient $c_i = \frac{\delta \Gamma_D(f)}{\delta x_i}$	Uncertainty contribution $\lvert c_i \rvert u(x_i)$	Degrees of freedom v_i
Γ_D	0.061523	0.0000518	A/t-distribution	1	0.0000518	9
VNA_r	0.000001	0.0000003	B/Rectangular	1	0.0000003	∞
VNA_u	0.1	0.0022	B/Normal	1	0.0022	∞
				Combined Standard Uncertainty $u_c(\Gamma_D)$	Coverage factor *k*, level of confidence 95%	Effective degree of freedom V_{eff}
			Γ_D	0.0044	2	29399961

APMP.EM.RF-K8.CL **revised** Measurement Report:

National Metrology Institute of South Africa (NMISA)
South Africa
Erik Dressler (Performed the measurements - Retired in March 2015)
Linoh Magagula
lmagagula@nmisa.org

Measurement method

The calibration factor of the device under test (DUT) was determined by employing a calibrated transfer standard consisting of a two-resistor power splitter, model HP11677A (Weinschel model 1870A at 10 MHz only) and a HP series 8000 monitor power sensor which was connected to port 3 of the splitter. During calibration the DUT was connected to port 2 of the power splitter. An illustration of the measuring set-up is shown below.



The calibration factor of the DUT was determined by using the following formula:

Kb(DUT) = Ksys * P(DUT)/P(Monitor)

where P(DUT) and P(Monitor) are the power readings of the DUT power meter and the monitor power meter respectively.

The calibration factor results as listed in the two tables below were **not** normalised.

The system calibration factors (Ksys) of the transfer standard are determined periodically according to the maintenance schedule of the national RF power standard measurement system. The calibration data were last updated in 2012 but are also verified from time to time against power sensors with calibration data from overseas. The system calibration factors are determined by connecting the national RF power standard to port 2 of the power splitter. The power standard is a dry twin-load calorimeter with type N input connectors. It measures RF power by using RF-DC substitution techniques. The accuracy of the power standard is traceable to the national measurement standards of DC voltage, resistance and 50 Ω RF attenuation and impedance. The main uncertainty contributions of the determination of Ksys are due to the RF power standard (DC and RF correction factors) and the mismatch at port 2 of the transfer device.

The uncertainty budgets for the measurement of K(DUT) are contained in two EXCEL-files attached to this report. It should be noted that for the mismatch uncertainty term the RSS value of the measured DUT voltage reflection coefficient (VRC) and its uncertainty and the measured magnitude of effective source VRC of the power splitter were used. No mismatch correction techniques were employed.

Voltage reflection coefficient (VRC) magnitude of the DUT sensors was determined by direct measurement against two vector network analysers, an HP8753D and a PNA. Both VNAs were calibrated with relevant calibration kits before the measurements, the HP8753D with an HP85032B kit and the PNA with an HP85054B kit. The accuracies of both VNAs were traceable to the national measurement standards of 50 Ω RF attenuation, a WBCO piston attenuator, and the national measurement standard for RF impedance, a coaxial 50 Ω airline for the relevant transmission line size.

List of Results:

DUT No. 1 (N47021)

Frequency (GHz)	Calibration Factor K	Combined standard uncertainty u_c(K) (k=1)	Coverage factor k for confidence level of 95 %
0,01	0,993	0,8	2
0,05	0,997	0,8	2
1	0,984	0,8	2
4	0,963	1,0	2
8	0,956	1,1	2
12	0,925	1,4	2
15	0,901	1,7	2
18	0,910	2,4	2

DUT No. 2 (N47022)

Frequency (GHz)	Calibration Factor K	Combined standard uncertainty $u_c(K)$ (k=1)	Coverage factor k for confidence level of 95 %
0,01	0,989	0,8	2
0,05	0,996	0,8	2
1	0,982	0,8	2
4	0,965	1,0	2
8	0,958	1,1	2
12	0,926	1,4	2
15	0,903	1,7	2
18	0,915	2,3	2

DUT No. 1 (N47021)

Frequency (GHz)	VRC (magnitude)	Combined standard uncertainty $u_c(K)$ (k=1)	Coverage factor k for confidence level of 95 %
0,01	0,063	0,0045	2
0,05	0,012	0,003	2
1	0,009	0,003	2
4	0,014	0,003	2
8	0,020	0,003	2
12	0,035	0,0045	2
15	0,033	0,0045	2
18	0,080	0,0045	2

DUT No. 2 (N47022)

Frequency (GHz)	VRC (magnitude)	Combined standard uncertainty $u_c(K)$ (k=1)	Coverage factor k for confidence level of 95 %
0,01	0,064	0,0045	2
0,05	0,012	0,003	2
1	0,010	0,003	2
4	0,013	0,003	2
8	0,017	0,003	2
12	0,024	0,0045	2
15	0,019	0,0045	2
18	0,063	0,0045	2

Measurement conditions:

Ambient temperature: +23 °C ± 2 °C
Humidity (rH): 50 % ± 15 %

8 September 2016

Sensor No.1 (10 MHz)

UNCERTAINTY BUDGET for (K=2)

UBM or Certificate Number

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	Calibration of	Type:	HP 8481A (47021)	Range:	10 MHz	Metrologist
	power sensors (50 Ohm)		Power splitter: Weinschel (RF257)			E Dressler

Symbol	Source of Uncertainty	Relative Value U(Xi) +/-	Unit		Absolute Value U(Xi) +/-	Unit	Probability Distribution (N, R, T, U)	Divisor Factor	Sensitivity Coefficient Ci	Relative Uncertainty Contribution Unit	Absolute Uncertainty Contribution Ui (y) Unit	Reliability %	Degrees of Freedom vi	Remarks	
Std	Calibration of Ksys	1.10E+00	%	+			N	2.00	1	5.50E-01		100	infinite		
	Drift since last cal	3.00E-01	%	+			R	1.73	1	1.73E-01		90	50.00		
	Pwr. meter instrumentation	7.00E-01	%	+			R	1.73	1	4.04E-01		80	12.50		
	Mismatch			+			U	1.41	1						
	Std at 50 MHz		%	+			U	1.41	1						
	DUT at 50 MHz	2.00E-01	%	+			U	1.41	1	1.41E-01		90	50.00	200*.03*.03	
	Std worst over range		%	+			U	1.41	1					Included in Ksys	
	DUT at freq.	1.40E-01	%	+			U	1.41	1	9.90E-02		100	infinite	200*0.01*0.07	0.14
	drift of mon. sensor	3.00E-01	%	+			R	1.73	1	1.73E-01		90	50.00		
	drift of 50 MHz source	2.00E-01	%	+			R	1.73	1	1.15E-01		80	12.50		
				+											
				+											
				+											
UUT	Repeatability (Type "A")	2.00E-01	%	+			Normal	1.00	1	2.00E-01			2	Number of Readings	3
				+											
				+											
				+											
				+											
				+											
				+											
				+											
				+											
				+											

Combined Uncertainty	**BMC (k=1)**	+	#####	**Total**	**Normal**	0.78	+	#VALUE!	**Veff**	94.10	Checked and Approved By
Expanded Uncertainty	95.45% (k=2)	+	#####		**Normal (k=2)**	**1.58**	+	#VALUE!	St'd (t)	2.03	Signature

Sensor No.1 (50 MHz)

UNCERTAINTY BUDGET for (K=2)

UBM or Certificate Number

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	Calibration of	Type:	HP 8481A (47021)	Range:	50 MHz	Metrologist
	power sensors (50 Ohm)		Power splitter: HP11667A (RF057)			E Dressler

Symbol	Source of Uncertainty	Relative Value U(Xi) +/-	Unit		Absolute Value U(Xi) +/-	Unit	Probability Distribution (N, R, T, U)	Divisor Factor	Sensitivity Coefficient Ci	Relative Uncertainty Contribution Unit	Ui (y)	Absolute Unit	Reliability %	Degrees of Freedom vi	Remarks	
Std	Calibration of Ksys	1.10E+00	%	+			N	2.00	1	5.50E-01			100	infinite		
	Drift since last cal	3.00E-01	%	+			R	1.73	1	1.73E-01			90	50.00		
	Pwr. meter instrumentation	7.00E-01	%	+			R	1.73	1	4.04E-01			80	12.50		
	Mismatch			+			U	1.41	1							
	Std at 50 MHz		%	+			U	1.41	1							
	DUT at 50 MHz	2.00E-01	%	+			U	1.41	1	1.41E-01			90	50.00	200*.03*.03	
	Std worst over range		%	+			U	1.41	1							
	DUT at freq.	5.00E-02	%	+			U	1.41	1	3.54E-02			100	infinite	200*0.01*0.025	0.05
	drift of mon. sensor	3.00E-01	%	+			R	1.73	1	1.73E-01			90	50.00		
	drift of 50 MHz source	2.00E-01	%	+			R	1.73	1	1.15E-01			80	12.50		
				+												
				+												
				+												
UUT	Repeatability (Type "A")	2.00E-01	%	+			Normal	1.00	1	2.00E-01				2	Number of Readings	3
				+												
				+												
				+												
				+												
				+												
				+												
				+												
				+												
				+												

Combined Uncertainty	**BMC (k=1)**	**+**	**Total**	**Normal**	0.77	+	**Veff**	115.73	Checked and Approved By
Expanded Uncertainty	95.45% (k=2)	+		**Normal (k=2)**	**1.55**	+	St'd (t)	2.00	Signature

Sensor No.1 (1 GHz)

UNCERTAINTY BUDGET for (K=2)

UBM or Certificate Number

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	**Calibration of**	**Type:**	HP 8481A (47021)	**Range:**	1 GHz	**Metrologist**
	power sensors (50 Ohm)		Power splitter: HP11667A (RF057)			E Dressler

Symbol	Source of Uncertainty	Relative Value U(Xi) +/-	Unit		Absolute Value U(Xi) +/-	Unit	Probability Distribution (N, R, T, U)	Divisor Factor	Sensitivity Coefficient Ci	Relative Uncertainty Contribution Ui (y) Unit	Absolute Uncertainty Contribution Ui (y) Unit	Reliability %	Degrees of Freedom vi	Remarks	
Std	Calibration of Ksys	1.10E+00	%	+			N	2.00	1	5.50E-01		100	infinite		
	Drift since last cal	3.00E-01	%	+			R	1.73	1	1.73E-01		90	50.00		
	Pwr. meter instrumentation	7.00E-01	%	+			R	1.73	1	4.04E-01		80	12.50		
	Mismatch			+			U	1.41	1						
	Std at 50 MHz		%	+			U	1.41	1						
	DUT at 50 MHz	2.00E-01	%	+			U	1.41	1	1.41E-01		90	50.00	200*.03*.03	
	Std worst over range		%	+			U	1.41	1						
	DUT at freq.	4.00E-02	%	+			U	1.41	1	2.83E-02		100	infinite	200*0.01*0.02	0.04
	drift of mon. sensor	3.00E-01	%	+			R	1.73	1	1.73E-01		90	50.00		
	drift of 50 MHz source	2.00E-01	%	+			R	1.73	1	1.15E-01		80	12.50		
				+											
				+											
				+											
UUT	Repeatability (Type "A")	2.00E-01	%	+			Normal	1.00	1	2.00E-01			2	Number of Readings	**3**
				+											
				+											
				+											
				+											
				+											
				+											
				+											
				+											
				+											

Combined Uncertainty	**BMC (k=1)**	**+**	**Total**	**Normal**	0.77	+	**Veff**	115.55	Checked and Approved By
Expanded Uncertainty	95.45% (k=2)	+		**Normal (k=2)**	**1.55**	+	St'd (t)	2.00	Signature

Sensor No.1 (4 GHz)

UNCERTAINTY BUDGET for (K=2)

UBM or Certificate Number

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	**Calibration of**	**Type:**	HP 8481A (47021)	**Range:**	4 GHz	**Metrologist**
	power sensors (50 Ohm)		Power splitter: HP11667A (RF057)			E Dressler

Symbol	Source of Uncertainty	Relative Value U(Xi) +/-	Unit		Absolute Value U(Xi) +/-	Unit	Probability Distribution (N, R, T, U)	Divisor Factor	Sensitivity Coefficient Ci	Relative Uncertainty Contribution Unit	Ui (y)	Absolute Unit	Reliability %	Degrees of Freedom vi	Remarks	
Std	Calibration of Ksys	1.50E+00	%	+			N	2.00	1	7.50E-01			100	infinite	RF power standard	
	Drift since last cal	3.00E-01	%	+			R	1.73	1	1.73E-01			90	50.00		
	Pwr. meter instrumentation	7.00E-01	%	+			R	1.73	1	4.04E-01			80	12.50		
	Mismatch			+			U	1.41	1							
	Std at 50 MHz		%	+			U	1.41	1							
	DUT at 50 MHz	2.00E-01	%	+			U	1.41	1	1.41E-01			90	50.00	200*.03*.03	
	Std worst over range		%	+			U	1.41	1							
	DUT at freq.	8.00E-02	%	+			U	1.41	1	5.66E-02			100	infinite	200*0.02*0.02	
	drift of mon. sensor	3.00E-01	%	+			R	1.73	1	1.73E-01			90	50.00		
	drift of 50 MHz source	2.00E-01	%	+			R	1.73	1	1.15E-01			80	12.50		
				+												
				+												
				+												
UUT	Repeatability (Type "A")	2.00E-01	%	+			Normal	1.00	1	2.00E-01				2	Number of Readings	**3**
				+												
				+												
				+												
				+												
				+												
				+												
				+												
				+												
				+												

Combined Uncertainty	**BMC (k=1)**	**+**	**Total**	**Normal**	0.93	+	**Veff**	242.04	Checked and Approved By
Expanded Uncertainty	95.45% (k=2)	+		**Normal (k=2)**	**1.86**	+	St'd (t)	2.00	Signature

Sensor No.1 (8 GHz)

UNCERTAINTY BUDGET for (K=2)

UBM or Certificate Number

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	**Calibration of** power sensors (50 Ohm)	**Type:** HP 8481A (47021) Power splitter: HP11667A (RF057)	**Range:** 8 GHz	**Metrologist** E Dressler

Symbol	Source of Uncertainty	Relative Value U(Xi) +/-	Unit		Absolute Value U(Xi) +/-	Unit	Probability Distribution (N, R, T, U)	Divisor Factor	Sensitivity Coefficient Ci	Relative Uncertainty Contribution Ui (y) Unit	Absolute Uncertainty Contribution Ui (y) Unit	Reliability %	Degrees of Freedom vi	Remarks	
Std	Calibration of Ksys	1.90E+00	%	+			N	2.00	1	9.50E-01		100	infinite	RF power standard	
	Drift since last cal	3.00E-01	%	+			R	1.73	1	1.73E-01		90	50.00		
	Pwr. meter instrumentation	7.00E-01	%	+			R	1.73	1	4.04E-01		80	12.50		
	Mismatch			+			U	1.41	1						
	Std at 50 MHz		%	+			U	1.41	1						
	DUT at 50 MHz	2.00E-01	%	+			U	1.41	1	1.41E-01		90	50.00	200*.03*.03	
	Std worst over range		%	+			U	1.41	1						
	DUT at freq.	2.85E-01	%	+			U	1.41	1	2.02E-01		100	infinite	200*0.057*0.025	0.285
	drift of mon. sensor	3.00E-01	%	+			R	1.73	1	1.73E-01		90	50.00		
	drift of 50 MHz source	2.00E-01	%	+			R	1.73	1	1.15E-01		80	12.50		
				+											
				+											
				+											
UUT	Repeatability (Type "A")	2.00E-01	%	+			Normal	1.00	1	2.00E-01			2	Number of Readings	**3**
				+											
				+											
				+											
				+											
				+											
				+											
				+											
				+											
				+											

Combined Uncertainty	**BMC (k=1)**	**+**	**Total**	**Normal**	1.11	+	**Veff**	>500	Checked and Approved By
Expanded Uncertainty	95.45% (k=2)	+		**Normal (k=2)**	**2.23**	+	St'd (t)	2.00	Signature

Sensor No.1 (12 GHz)

UNCERTAINTY BUDGET for (K=2)

UBM or Certificate Number

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	Calibration of	Type:	HP 8481A (47021)	Range:	12 GHz	Metrologist
	power sensors (50 Ohm)		Power splitter: HP11667A (RF057)			E Dressler

Symbol	Source of Uncertainty	Relative Value U(Xi) +/-	Unit		Absolute Value U(Xi) +/-	Unit	Probability Distribution (N, R, T, U)	Divisor Factor	Sensitivity Coefficient Ci	Relative Uncertainty Contribution Unit	Absolute Uncertainty Contribution Ui (y) Unit	Reliability %	Degrees of Freedom vi	Remarks		
Std	Calibration of Ksys	2.30E+00	%	+			N	2.00	1	1.15E+00		100	infinite	RF power standard		
	Drift since last cal	5.00E-01	%	+			R	1.73	1	2.89E-01		90	50.00			
	Pwr. meter instrumentation	7.00E-01	%	+			R	1.73	1	4.04E-01		80	12.50			
	Mismatch			+			U	1.41	1							
	Std at 50 MHz		%	+			U	1.41	1							
	DUT at 50 MHz	2.00E-01	%	+			U	1.41	1	1.41E-01		90	50.00	200*.03*.03		
	Std worst over range		%	+			U	1.41	1							
	DUT at freq.	4.07E-01	%	+			U	1.41	1	2.88E-01		100	infinite	200*0.055*0.037		0.407
	drift of mon. sensor	3.00E-01	%	+			R	1.73	1	1.73E-01		90	50.00			
	drift of 50 MHz source	2.00E-01	%	+			R	1.73	1	1.15E-01		80	12.50			
				+												
				+												
				+												
UUT	Repeatability (Type "A")	3.00E-01	%	+			Normal	1.00	1	3.00E-01			2	Number of Readings	3	
				+												
				+												
				+												
				+												
				+												
				+												
				+												
				+												
				+												

Combined Uncertainty	BMC (k=1)	+	Total	Normal	1.34	+	Veff	>500	Checked and Approved By	
Expanded Uncertainty	95.45% (k=2)	+		Normal (k=2)	2.69	+	St'd (t)	2.00	Signature	

Sensor No.1 (15 GHz)

UNCERTAINTY BUDGET for (K=2)

UBM or Certificate Number

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	Calibration of	Type:	HP 8481A (47021)	Range:	15 GHz	Metrologist
	power sensors (50 Ohm)		Power splitter: HP11667A (RF057)			E Dressler

Symbol	Source of Uncertainty	Relative Value U(Xi) +/-	Unit		Absolute Value U(Xi) +/-	Unit	Probability Distribution (N, R, T, U)	Divisor Factor	Sensitivity Coefficient Ci	Relative Uncertainty Contribution Unit	Absolute Ui (y) Unit	Reliability %	Degrees of Freedom vi	Remarks	
Std	Calibration of Ksys	3.10E+00	%	+			N	2.00	1	1.55E+00		100	infinite	RF power standard	
	Drift since last cal	5.00E-01	%	+			R	1.73	1	2.89E-01		90	50.00		
	Pwr. meter instrumentation	7.00E-01	%	+			R	1.73	1	4.04E-01		80	12.50		
	Mismatch			+			U	1.41	1						
	Std at 50 MHz		%	+			U	1.41	1						
	DUT at 50 MHz	2.00E-01	%	+			U	1.41	1	1.41E-01		90	50.00	200*.03*.03	
	Std worst over range		%	+			U	1.41	1						
	DUT at freq.	3.85E-01	%	+			U	1.41	1	2.72E-01		100	infinite	200*0.052*0.037	0.3848
	drift of mon. sensor	3.00E-01	%	+			R	1.73	1	1.73E-01		90	50.00		
	drift of 50 MHz source	2.00E-01	%	+			R	1.73	1	1.15E-01		80	12.50		
				+											
				+											
				+											
UUT	Repeatability (Type "A")	3.00E-01	%	+			Normal	1.00	1	3.00E-01			2	Number of Readings	3
				+											
				+											
				+											
				+											
				+											
				+											
				+											
				+											
				+											

Combined Uncertainty	**BMC (k=1)**	+	**Total**	**Normal**	1.70	+	**Veff**	>500	Checked and Approved By
Expanded Uncertainty	95.45% (k=2)	+		**Normal (k=2)**	**3.39**	+	St'd (t)	2.00	Signature

Sensor No.1 (18 GHz)

BUDGET for (K=2)

UBM or Certificate Number

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	**Calibration of**	**Type:**	HP 8481A (47021)	**Range:**	18 GHz	**Metrologist**
	power sensors (50 Ohm)		Power splitter: HP11667A (RF057)			E Dressler

Symbol	Source of Uncertainty	Relative Value U(Xi) +/-	Unit		Absolute Value U(Xi) +/-	Unit	Probability Distribution (N, R, T, U)	Divisor Factor	Sensitivity Coefficient Ci	Uncertainty Contribution Ui (y) Relative Unit	Uncertainty Contribution Ui (y) Absolute Unit	Reliability %	Degrees of Freedom vi	Remarks		
Std	Calibration of Ksys	4.10E+00	%	+			N	2.00	1	2.05E+00		100	infinite	RF power standard		
	Drift since last cal	5.00E-01	%	+			R	1.73	1	2.89E-01		90	50.00			
	Pwr. meter instrumentation	7.00E-01	%	+			R	1.73	1	4.04E-01		80	12.50			
	Mismatch			+			U	1.41	1							
	Std at 50 MHz		%	+			U	1.41	1							
	DUT at 50 MHz	2.00E-01	%	+			U	1.41	1	1.41E-01		90	50.00	200*.03*.03		
	Std worst over range		%	+			U	1.41	1							
	DUT at freq.	1.65E+00	%	+			U	1.41	1	1.16E+00		100	infinite	200*0.098*0.084		1.6464
	drift of mon. sensor	3.00E-01	%	+			R	1.73	1	1.73E-01		90	50.00			
	drift of 50 MHz source	2.00E-01	%	+			R	1.73	1	1.15E-01		80	12.50			
				+												
				+												
				+												
UUT	Repeatability (Type "A")	3.00E-01	%	+			Normal	1.00	1	3.00E-01			2	Number of Readings	**3**	
				+												
				+												
				+												
				+												
				+												
				+												
				+												
				+												
				+												

Combined Uncertainty	**BMC (k=1)**	**+**	**Total**	**Normal**	2.44	+	**Veff**	>500	Checked and Approved By	
Expanded Uncertainty	95.45% (k=2)	+		**Normal (k=2)**	**4.88**	+	St'd (t)	2.00	Signature	

Sensor No.2 (10 MHz)

UNCERTAINTY BUDGET for (K=2)

UBM or Certificate Number

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	Calibration of	Type:	HP 8481A (47022)	Range:	10 MHz	Metrologist
	power sensors (50 Ohm)		Power splitter: Weinschel (RF257)			E Dressler

Symbol	Source of Uncertainty	Relative Value U(Xi) +/-	Unit		Absolute Value U(Xi) +/-	Unit	Probability Distribution (N, R, T, U)	Divisor Factor	Sensitivity Coefficient Ci	Relative Uncertainty Contribution Ui (y) Unit		Absolute Uncertainty Contribution Ui (y) Unit	Reliability %	Degrees of Freedom vi	Remarks		
Std	Calibration of Ksys	1.10E+00	%	+			N	2.00	1	5.50E-01			100	infinite			
	Drift since last cal	3.00E-01	%	+			R	1.73	1	1.73E-01			90	50.00			
	Pwr. meter instrumentation	7.00E-01	%	+			R	1.73	1	4.04E-01			80	12.50			
	Mismatch			+			U	1.41	1								
	Std at 50 MHz		%	+			U	1.41	1								
	DUT at 50 MHz	2.00E-01	%	+			U	1.41	1	1.41E-01			90	50.00	200*.03*.03		
	Std worst over range		%	+			U	1.41	1						Included in Ksys		
	DUT at freq.	1.40E-01	%	+			U	1.41	1	9.90E-02			100	infinite	200*0.01*0.07		0.14
	drift of mon. sensor	3.00E-01	%	+			R	1.73	1	1.73E-01			90	50.00			
	drift of 50 MHz source	2.00E-01	%	+			R	1.73	1	1.15E-01			80	12.50			
				+													
				+													
				+													
UUT	Repeatability (Type "A")	2.00E-01	%	+			Normal	1.00	1	2.00E-01				2	Number of Readings	3	
				+													
				+													
				+													
				+													
				+													
				+													
				+													
				+													
				+													

	Uncertainty	BMC				Total	Distribution	Relative		Absolute			
	Combined Uncertainty	BMC (k=1)	+	#####		Total	Normal	0.78	+	#VALUE!	Veff	94.10	Checked and Approved By
	Expanded Uncertainty	95.45% (k=2)	+	#####			Normal (k=2)	**1.58**	+	#VALUE!	St'd (t)	2.03	Signature

Sensor No.2 (50 MHz)

UNCERTAINTY BUDGET for (K=2)

UBM or Certificate Number

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

Calibration of	**Type:**	HP 8481A (47022)	**Range:**	50 MHz	**Metrologist**
power sensors (50 Ohm)		Power splitter: HP11667A (RF057)			E Dressler

Source of Uncertainty	Relative Value U(Xi) +/-	Unit		Absolute Value U(Xi) +/-	Unit	Probability Distribution (N, R, T, U)	Divisor Factor	Sensitivity Coefficient Ci	Relative Uncertainty Contribution Unit	Ui (y)	Absolute Uncertainty Contribution Unit	Reliability %	Degrees of Freedom vi	Remarks	
Calibration of Ksys	1.10E+00	%	+			N	2.00	1	5.50E-01			100	infinite		
Drift since last cal	3.00E-01	%	+			R	1.73	1	1.73E-01			90	50.00		
Pwr. meter instrumentation	7.00E-01	%	+			R	1.73	1	4.04E-01			80	12.50		
Mismatch			+			U	1.41	1							
Std at 50 MHz		%	+			U	1.41	1							
DUT at 50 MHz	2.00E-01	%	+			U	1.41	1	1.41E-01			90	50.00	200*.03*.03	
Std worst over range		%	+			U	1.41	1							
DUT at freq.	5.00E-02	%	+			U	1.41	1	3.54E-02			100	infinite	200*0.01*0.025	0.05
drift of mon. sensor	3.00E-01	%	+			R	1.73	1	1.73E-01			90	50.00		
drift of 50 MHz source	2.00E-01	%	+			R	1.73	1	1.15E-01			80	12.50		
			+												
			+												
			+												
Repeatability (Type "A")	2.00E-01	%	+			Normal	1.00	1	2.00E-01				2	Number of Readings	3
			+												
			+												
			+												
			+												
			+												
			+												
			+												
			+												
			+												

Combined Uncertainty	**BMC (k=1)**	**+**	**Total**	**Normal**	0.77	+	**Veff**	115.73	Checked and Approved By
Expanded Uncertainty	95.45% (k=2)	+		**Normal (k=2)**	**1.55**	+	St'd (t)	2.00	Signature

Sensor No.2 (1 GHz)

UNCERTAINTY BUDGET for (K=2) — UBM or Certificate Number

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	Calibration of	Type:	HP 8481A (47022)	Range:	1 GHz	Metrologist
	power sensors (50 Ohm)		Power splitter: HP11667A (RF057)			E Dressler

Symbol	Source of Uncertainty	Relative Value U(Xi) +/-	Unit		Absolute Value U(Xi) +/-	Unit	Probability Distribution (N, R, T, U)	Divisor Factor	Sensitivity Coefficient Ci	Relative Uncertainty Contribution Unit	Ui (y)	Absolute Uncertainty Contribution Unit	Reliability %	Degrees of Freedom vi	Remarks	
Std	Calibration of Ksys	1.10E+00	%	+			N	2.00	1	5.50E-01			100	infinite		
	Drift since last cal	3.00E-01	%	+			R	1.73	1	1.73E-01			90	50.00		
	Pwr. meter instrumentation	7.00E-01	%	+			R	1.73	1	4.04E-01			80	12.50		
	Mismatch			+			U	1.41	1							
	Std at 50 MHz		%	+			U	1.41	1							
	DUT at 50 MHz	2.00E-01	%	+			U	1.41	1	1.41E-01			90	50.00	200*.03*.03	
	Std worst over range		%	+			U	1.41	1							
	DUT at freq.	4.00E-02	%	+			U	1.41	1	2.83E-02			100	infinite	200*0.01*0.02	0.04
	drift of mon. sensor	3.00E-01	%	+			R	1.73	1	1.73E-01			90	50.00		
	drift of 50 MHz source	2.00E-01	%	+			R	1.73	1	1.15E-01			80	12.50		
				+												
				+												
				+												
UUT	Repeatability (Type "A")	2.00E-01	%	+			Normal	1.00	1	2.00E-01				2	Number of Readings	3
				+												
				+												
				+												
				+												
				+												
				+												
				+												
				+												
				+												

Combined Uncertainty	BMC (k=1)	+	Total	Normal	0.77	+	Veff	115.55	Checked and Approved By
Expanded Uncertainty	95.45% (k=2)	+		Normal (k=2)	**1.55**	+	St'd (t)	2.00	Signature

Sensor No.2 (4 GHz)

UNCERTAINTY BUDGET for (K=2)

UBM or Certificate Number

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	Calibration of	Type:	HP 8481A (47022)	Range:	4 GHz	Metrologist
	power sensors (50 Ohm)		Power splitter: HP11667A (RF057)			E Dressler

Symbol	Source of Uncertainty	Relative Value U(Xi) +/-	Unit		Absolute Value U(Xi) +/-	Unit	Probability Distribution (N, R, T, U)	Divisor Factor	Sensitivity Coefficient Ci	Relative Uncertainty Contribution Unit	Absolute Ui (y) Unit	Reliability %	Degrees of Freedom vi	Remarks		
Std	Calibration of Ksys	1.50E+00	%	+			N	2.00	1	7.50E-01		100	infinite	RF power standard		
	Drift since last cal	3.00E-01	%	+			R	1.73	1	1.73E-01		90	50.00			
	Pwr. meter instrumentation	7.00E-01	%	+			R	1.73	1	4.04E-01		80	12.50			
	Mismatch			+			U	1.41	1							
	Std at 50 MHz		%	+			U	1.41	1							
	DUT at 50 MHz	2.00E-01	%	+			U	1.41	1	1.41E-01		90	50.00	200*.03*.03		
	Std worst over range		%	+			U	1.41	1							
	DUT at freq.	8.00E-02	%	+			U	1.41	1	5.66E-02		100	infinite	200*0.02*0.02		0.08
	drift of mon. sensor	3.00E-01	%	+			R	1.73	1	1.73E-01		90	50.00			
	drift of 50 MHz source	2.00E-01	%	+			R	1.73	1	1.15E-01		80	12.50			
				+												
				+												
				+												
UUT	Repeatability (Type "A")	2.00E-01	%	+			Normal	1.00	1	2.00E-01			2	Number of Readings	3	
				+												
				+												
				+												
				+												
				+												
				+												
				+												
				+												
				+												

Combined Uncertainty	**BMC (k=1)**	**+**	**Total**	**Normal**	0.93	+	**Veff**	242.04	Checked and Approved By
Expanded Uncertainty	95.45% (k=2)	+		**Normal (k=2)**	**1.86**	+	St'd (t)	2.00	Signature

Sensor No.2 (8 GHz)

UNCERTAINTY BUDGET for (K=2)

UBM or Certificate Number

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	Calibration of	Type:	HP 8481A (47022)	Range:	8 GHz	Metrologist
	power sensors (50 Ohm)		Power splitter: HP11667A (RF057)			E Dressler

Symbol	Source of Uncertainty	Relative Value U(Xi) +/-	Unit		Absolute Value U(Xi) +/-	Unit	Probability Distribution (N, R, T, U)	Divisor Factor	Sensitivity Coefficient Ci	Relative Uncertainty Contribution Unit	Absolute Uncertainty Contribution Ui (y) Unit	Reliability %	Degrees of Freedom vi	Remarks		
Std	Calibration of Ksys	1.90E+00	%	+			N	2.00	1	9.50E-01		100	infinite	RF power standard		
	Drift since last cal	3.00E-01	%	+			R	1.73	1	1.73E-01		90	50.00			
	Pwr. meter instrumentation	7.00E-01	%	+			R	1.73	1	4.04E-01		80	12.50			
	Mismatch			+			U	1.41	1							
	Std at 50 MHz		%	+			U	1.41	1							
	DUT at 50 MHz	2.00E-01	%	+			U	1.41	1	1.41E-01		90	50.00	200*.03*.03		
	Std worst over range		%	+			U	1.41	1							
	DUT at freq.	2.85E-01	%	+			U	1.41	1	2.02E-01		100	infinite	200*0.057*0.025		0.285
	drift of mon. sensor	3.00E-01	%	+			R	1.73	1	1.73E-01		90	50.00			
	drift of 50 MHz source	2.00E-01	%	+			R	1.73	1	1.15E-01		80	12.50			
				+												
				+												
				+												
UUT	Repeatability (Type "A")	2.00E-01	%	+			Normal	1.00	1	2.00E-01			2	Number of Readings	3	
				+												
				+												
				+												
				+												
				+												
				+												
				+												
				+												
				+												

Combined Uncertainty	BMC (k=1)	+	Total	Normal	1.11 +	Veff	>500	Checked and Approved By
Expanded Uncertainty	95.45% (k=2)	+		Normal (k=2)	**2.23** +	St'd (t)	2.00	Signature

Sensor No.2 (12 GHz)

UNCERTAINTY BUDGET for (K=2)

UBM or Certificate Number

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	Calibration of	Type:	HP 8481A (47022)	Range:	12 GHz	Metrologist
	power sensors (50 Ohm)		Power splitter: HP11667A (RF057)			E Dressler

Symbol	Source of Uncertainty	Relative Value U(Xi) +/-	Unit		Absolute Value U(Xi) +/-	Unit	Probability Distribution (N, R, T, U)	Divisor Factor	Sensitivity Coefficient Ci	Relative Uncertainty Contribution Ui (y) Unit	Absolute Uncertainty Contribution Unit	Reliability %	Degrees of Freedom vi	Remarks		
Std	Calibration of Ksys	2.30E+00	%	+			N	2.00	1	1.15E+00		100	infinite	RF power standard		
	Drift since last cal	5.00E-01	%	+			R	1.73	1	2.89E-01		90	50.00			
	Pwr. meter instrumentation	7.00E-01	%	+			R	1.73	1	4.04E-01		80	12.50			
	Mismatch			+			U	1.41	1							
	Std at 50 MHz		%	+			U	1.41	1							
	DUT at 50 MHz	2.00E-01	%	+			U	1.41	1	1.41E-01		90	50.00	200*.03*.03		
	Std worst over range		%	+			U	1.41	1							
	DUT at freq.	2.86E-01	%	+			U	1.41	1	2.02E-01		100	infinite	200*0.055*0.026		0.286
	drift of mon. sensor	3.00E-01	%	+			R	1.73	1	1.73E-01		90	50.00			
	drift of 50 MHz source	2.00E-01	%	+			R	1.73	1	1.15E-01		80	12.50			
				+												
				+												
				+												
UUT	Repeatability (Type "A")	3.00E-01	%	+			Normal	1.00	1	3.00E-01			2	Number of Readings	3	
				+												
				+												
				+												
				+												
				+												
				+												
				+												
				+												
				+												

Combined Uncertainty	**BMC (k=1)**	**+**	**Total**	**Normal**	1.33	+	**Veff**	482.39	Checked and Approved By
Expanded Uncertainty	95.45% (k=2)	+		**Normal (k=2)**	**2.66**	+	St'd (t)	2.00	Signature

Sensor No.2 (15 GHz)

UNCERTAINTY BUDGET for (K=2)

UBM or Certificate Number

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	Calibration of	Type:	HP 8481A (47022)	Range:	15 GHz	Metrologist
	power sensors (50 Ohm)		Power splitter: HP11667A (RF057)			E Dressler

Symbol	Source of Uncertainty	Relative Value U(Xi) +/-	Unit		Absolute Value U(Xi) +/-	Unit	Probability Distribution (N, R, T, U)	Divisor Factor	Sensitivity Coefficient Ci	Relative Uncertainty Contribution Unit	Ui (y)	Absolute Uncertainty Contribution Unit	Reliability %	Degrees of Freedom vi	Remarks	
Std	Calibration of Ksys	3.10E+00	%	+			N	2.00	1	1.55E+00			100	infinite	RF power standard	
	Drift since last cal	5.00E-01	%	+			R	1.73	1	2.89E-01			90	50.00		
	Pwr. meter instrumentation	7.00E-01	%	+			R	1.73	1	4.04E-01			80	12.50		
	Mismatch			+			U	1.41	1							
	Std at 50 MHz		%	+			U	1.41	1							
	DUT at 50 MHz	2.00E-01	%	+			U	1.41	1	1.41E-01			90	50.00	200*.03*.03	
	Std worst over range		%	+			U	1.41	1							
	DUT at freq.	2.39E-01	%	+			U	1.41	1	1.69E-01			100	infinite	200*0.05*0.023	0.2392
	drift of mon. sensor	3.00E-01	%	+			R	1.73	1	1.73E-01			90	50.00		
	drift of 50 MHz source	2.00E-01	%	+			R	1.73	1	1.15E-01			80	12.50		
				+												
				+												
				+												
UUT	Repeatability (Type "A")	3.00E-01	%	+			Normal	1.00	1	3.00E-01				2	Number of Readings	3
				+												
				+												
				+												
				+												
				+												
				+												
				+												
				+												
				+												

Combined Uncertainty	BMC (k=1)	+	Total	Normal	1.68	+	Veff	>500	Checked and Approved By
Expanded Uncertainty	95.45% (k=2)	+		Normal (k=2)	**3.37**	+	St'd (t)	2.00	Signature

Sensor No.2 (18 GHz)

UNCERTAINTY BUDGET for (K=2)

UBM or Certificate Number

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	**Calibration of** power sensors (50 Ohm)	**Type:** HP 8481A (47022) Power splitter: HP11667A (RF057)	**Range:** 18 GHz
Metrologist	E Dressler		

Symbol	Source of Uncertainty	Relative Value U(Xi) +/-	Unit		Absolute Value U(Xi) +/-	Unit	Probability Distribution (N, R, T, U)	Divisor Factor	Sensitivity Coefficient Ci	Relative Uncertainty Contribution Unit	Ui (y)	Absolute Uncertainty Contribution Unit	Reliability %	Degrees of Freedom vi	Remarks	
Std	Calibration of Ksys	4.10E+00	%	+			N	2.00	1	2.05E+00			100	infinite	RF power standard	
	Drift since last cal	5.00E-01	%	+			R	1.73	1	2.89E-01			90	50.00		
	Pwr. meter instrumentation	7.00E-01	%	+			R	1.73	1	4.04E-01			80	12.50		
	Mismatch			+			U	1.41	1							
	Std at 50 MHz		%	+			U	1.41	1							
	DUT at 50 MHz	2.00E-01	%	+			U	1.41	1	1.41E-01			90	50.00	200*.03*.03	
	Std worst over range		%	+			U	1.41	1							
	DUT at freq.	1.25E+00	%	+			U	1.41	1	8.87E-01			100	infinite	200*0.098*0.064	1.2544
	drift of mon. sensor	3.00E-01	%	+			R	1.73	1	1.73E-01			90	50.00		
	drift of 50 MHz source	2.00E-01	%	+			R	1.73	1	1.15E-01			80	12.50		
				+												
				+												
				+												
UUT	Repeatability (Type "A")	3.00E-01	%	+			Normal	1.00	1	3.00E-01				2	Number of Readings	3
				+												
				+												
				+												
				+												
				+												
				+												
				+												
				+												
				+												

Combined Uncertainty	**BMC (k=1)**	+	**Total**	**Normal**	2.32	+	**Veff**	>500	Checked and Approved By
Expanded Uncertainty	95.45% (k=2)	+		**Normal (k=2)**	**4.64**	+	St'd (t)	2.00	Signature

Subject	:	APMP KEY COMPARISON APMP.EM.RF-K8.CL Power in 50Ω coaxial line, frequency: 10 MHz to 18 GHz	

Country : Singapore
Organisation : National Metrology Centre (NMC), A*STAR
Contact person : Dr SHAN Yueyan
Address : 1 Science Park Drive
Singapore 118221
Email : shan_yueyan@nmc.a-star.edu.sg

Traveling Standards : Agilent 8481A Thermocouple Power Sensor (serial no.: US41031012)
Agilent 8481A Thermocouple Power Sensor (serial no.: US41031013)
E4419B Power Meter (serial no.: MY45100436)

Date Measured : 18 to 28 Jun 2013

Ambient Conditions

Temperature : $(23 \pm 2)\ ^{o}C$
Relative Humidity : (55 ± 10) % relative humidity

This comparison was carried out at the National Metrology Centre (A*STAR) under the ambient conditions stated above. The calibration factors of the power sensors together with the power meter were measured at 10 MHz, 50 MHz, 1 GHz, 4 GHz, 8 GHz, 12 GHz, 15 GHz and 18 GHz at 1 milliwatt. The reflection coefficients of the power sensors were also measured.

A direct comparison system was used to measure the calibration factors of the power sensors. Before measurement, the power sensor together with the power meter was zeroed. The gain of the traveling power meter was calibrated to the traveling power sensor using the 50 MHz 1mW reference power source of the traveling power meter.

A short description of the measurement set up is described on pages 2 to 4. The results of measurement and their estimated uncertainties for Agilent 8481A power sensor (serial nos.: US41031012 and serial no.: US41031013) are tabulated on pages 4 to 16.

Neo Hoon (Ms)
Calibration Officer

Dr Shan Yueyan
Approving Officer
National Metrology Centre

Measurement Method

The measurement method used in APMP.EM.RF-K8.CL is different from that of CCEM.RF-K8.CL.

The method used for the APMP.EM.RF-K8.CL is described as follows:

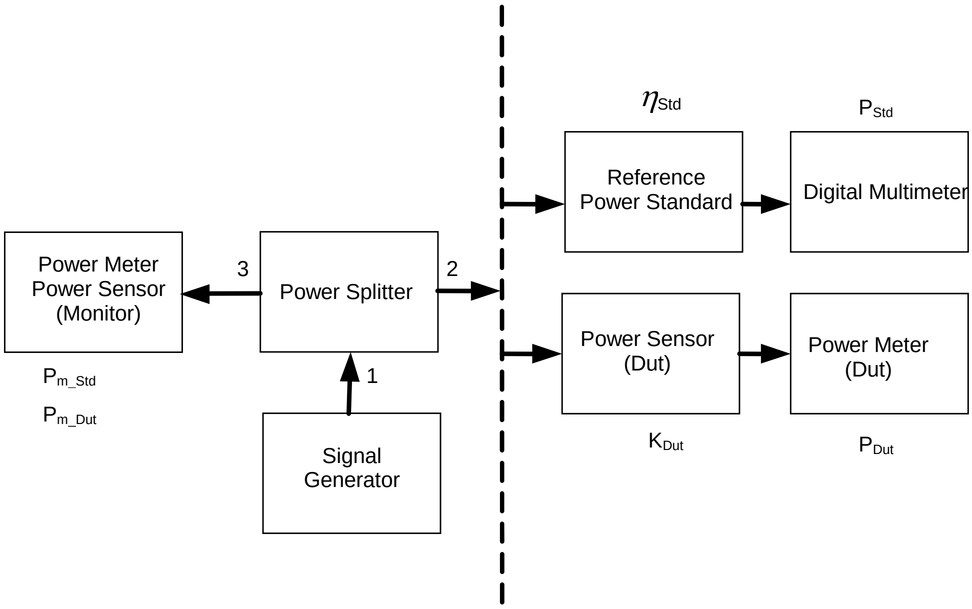
The calibration factors of the two power sensors (traveling standards) were measured using the direct comparison measurement technique, which transfers the effective efficiency of a reference power standard to an unknown (uncalibrated) power sensor (DUT).

The method is based on alternate connections between a reference standard and unknown (uncalibrated) power sensor (DUT) to one of the output ports of a passive power splitter. The other output port of the power splitter is used for correcting the power variation during the measurement. A rf source is connected to the input port of the power splitter.

To reduce mismatch error, the complex reflection coefficients of the reference power standard, unknown (uncalibrated) power sensor (DUT) and power splitter were considered when computing the calibration factors of the two power sensors (travelling standards).

The direct comparison system comprises two reference thermistor mounts, a Type IV power meter, a digital multimeter, a signal generator, a power splitter Type N and a monitoring power meter and power sensor.

Two vector network analysers were used to measure the reflection coefficients of the reference standards, traveling standards and the equivalent reflection coefficient of the power splitter.



Direct Comparison System Setup

Calibration Officer

Measurement Traceability

The calibration factors of the traveling standards from 10 MHz to 18 GHz are traceable to two reference power standards. The reference power standard for 10 MHz is a temperature stabilized thermistor mount and is traceable to the Single Junction Thermal Converter voltage standards maintained in NMC (Singapore). The reference power standard for 50 MHz to 18 GHz is also a thermistor mount and is traceable to the Type N Calorimeter maintained in NMC (Singapore).

The reflection coefficients of the traveling standards are measured using two vector network analysers, which are traceable through impedance standards to NMC (Singapore) and NPL (UK).

All other working standards are traceable to the national reference standards maintained at the NMC (Singapore).

The serial numbers for the reference and working standards are as follows:

1. Reference thermistor mounts (serial nos.: 2858, cn36)
2. Type IV power meter (serial no.: 089)
3. Digital multimeter (serial no.: 4225004)
4. Signal generator (serial no.: 100503)
5. Power splitter Type N (serial no.:2654)
6. Monitoring power meter / power sensor (serial nos.:MY50000319 / MY41097736)
7. Vector network analysers (serial nos.: MY49101580, US43140732)

Mathematical Model

The mathematical model for the calibration factor of the power sensor (DUT) is as follows:

$$K_{Dut} = \eta_{Std} \times \frac{P_{Dut}}{P_{Std}} \frac{P_{m\_Std}}{P_{m\_Dut}} \times \frac{(1-|\Gamma_{Std}|^2)\times|1-\Gamma_{Dut}\Gamma_{EG}|^2}{|1-\Gamma_{Std}\Gamma_{EG}|^2}$$

where K_{Dut} is the calibration factor of the traveling standard (Dut)

η_{Std} is the effective efficiency of the reference standard
P_{Dut} is the power indication of the traveling standard
P_{Std} is the DC substitution power of the reference standard
P_{m_Std} is the power indication of monitor power meter for reference standard
P_{m_Dut} is the power indication of monitor power meter for traveling standard
Γ_{Std} is the complex reflection coefficient of the reference standard
Γ_{Dut} is the complex reflection coefficient of the traveling standard
Γ_{EG} is the complex equivalent source reflection coefficient of power splitter that is connected to reference standard and traveling standard

Uncertainty Analysis

In the mathematical model, the reflection coefficient is a complex term. The measurement uncertainty is estimated according to the "Guide to the expression of Uncertainty in Measurement" (GUM). The sensitivity coefficients for each of the contribution sources are the partial derivatives with respect to each variable in the equation.

The combined uncertainty of K_{DUT} can be expressed as

$$u_c^{\,2}(K_{Dut}) = \sum_{n=1}^{M} c_n^2 u_n^2$$

where

$u_c\,(K_{Dut})$ is the combined uncertainty
K_{Dut} is the calibration factor of the traveling standard
c_n is the sensitivity coefficient of the nth uncertainty source.
u_n is the standard uncertainty of the nth uncertainty source.
M is the total uncertainty number of the uncertainty sources.

The expanded uncertainty U can be expressed as

$$U = k\,u_c(K_{Dut})$$

where

U is the expanded uncertainty
k is the coverage factor
$u_c\,(K_{Dut})$ is the combined uncertainty

Results of Measurement

In the tables, each calibration factor is the mean of six measurement runs. Before each run, the power sensor was disconnected from and reconnected to the measurement port.

The expanded measurement uncertainties were evaluated with a coverage factor k=2, which defines an interval estimated to have a level of confidence of approximately 95%.

Calibration Factor

Table 1: Traveling Standard Agilent 8481A Power Sensor (serial no.: US41031012)

Frequency (GHz)	Calibration Factor, K	Combined Uncertainty, u_c(K), (k=1)	Coverage factor, k Confidence Level 95%
0.01	0.9933	0.0063	2
0.05	0.9917	0.0020	2
1	0.9752	0.0019	2
4	0.9646	0.0021	2
8	0.9519	0.0027	2
12	0.9292	0.0026	2
15	0.9149	0.0028	2
18	0.9127	0.0046	2

Table 2: Traveling Standard Agilent 8481A Power Sensor (serial no.: US41031013)

Frequency (GHz)	Calibration Factor, K	Combined Uncertainty, u_c(K), (k=1)	Coverage factor, k Confidence Level 95%
0.01	0.9918	0.0063	2

Calibration Officer

0.05	0.9910	0.0020	2
1	0.9752	0.0019	2
4	0.9632	0.0021	2
8	0.9464	0.0027	2
12	0.9268	0.0026	2
15	0.9110	0.0027	2
18	0.9093	0.0043	2

Reflection Coefficient

Table 3: Traveling Standard Agilent 8481A Power Sensor (serial no.: US41031012)

Frequency (GHz)	Reflection Coefficient (Real)	Reflection Coefficient (Imaginary)	Expanded Uncertainty Magnitude (Lin)
0.01	0.0075	-0.0610	0.0052
0.05	-0.001	-0.013	0.015
1	0.009	-0.003	0.015
4	0.011	0.011	0.015
8	-0.013	-0.011	0.015
12	-0.029	0.014	0.015
15	-0.010	0.030	0.015
18	-0.049	0.056	0.015

Table 4: Traveling Standard Agilent 8481A Power Sensor (serial no.: US41031013)

Frequency (GHz)	Reflection Coefficient (Real)	Reflection Coefficient (Imaginary)	Expanded Uncertainty Magnitude (Lin)
0.01	0.0083	-0.0645	0.0052
0.05	0.001	-0.014	0.015
1	0.009	-0.005	0.015
4	0.012	0.006	0.015
8	-0.015	-0.006	0.015
12	-0.021	0.008	0.015
15	-0.004	0.017	0.015
18	-0.039	0.046	0.015

Calibration Officer

Uncertainty Budget of K_{Dut}

Table 5: Traveling Standard : Agilent 8481A Power Sensor (serial no.: US41031012) Frequency : 10 MHz

$u(x_i)$	Quantity X_i	Estimate x_i (units)	Standard Uncertainty $u(x_i)$ (units)	Prob Distri (A,B)	Sensitivity Coefficient, c_i (units)	Uncertainty Contribution $c_i*u(x_i)$	DOF
u(1)	η_S	1.001315 (-)	0.006063 (-)	Normal (B)	9.92E-01 (-)	0.00601	∞
u(2)	P_{Std}	0.00102 (watt)	4.09E-07 (watt)	Normal (B)	-9.74E+02 ($watt^{-1}$)	-0.0004	∞
u(3)	P_{Dut}	0.001011 (watt)	1.46E-06 (watt)	Normal (B)	9.82E+02 ($watt^{-1}$)	0.00143	∞
u(4)	P_{m_Std}	0.001 (watt)	1E-07 (watt)	Normal (B)	9.94E+02 ($watt^{-1}$)	9.9E-05	∞
u(5)	P_{m_Dut}	0.000999 (watt)	1E-07 (watt)	Normal (B)	-9.95E+02 ($watt^{-1}$)	-9.9E-05	∞
u(6)	Γ_{Std}(mag)	0.000445 (-)	0.0026 (-)	Normal (B)	-6.35E-03 (-)	-1.6E-05	∞
u(7)	Γ_{Std}(phase)	-0.10737 (rad)	1.570883 (rad)	Normal (B)	-4.61E-07 (rad^{-1})	-7.2E-07	∞
u(8)	Γ_{Dut}(mag)	0.0614 (-)	0.0026 (-)	Normal (B)	2.35E-04 (-)	6.1E-07	∞
u(9)	Γ_{Dut}(phase)	-1.44902 (rad)	0.042761 (rad)	Normal (B)	3.42E-04 (rad^{-1})	1.5E-05	∞
u(10)	Γ_{EG}(mag)	0.002803 (-)	0.009706 (-)	Normal (B)	4.27E-03 (-)	4.1E-05	∞
u(11)	Γ_{EG}(phase)	3.061779 (rad)	1.570797 (rad)	Normal (B)	3.41E-04 (rad^{-1})	0.00054	∞
u(12)	Repeatability	0.00007 (-)	3.06E-05 (-)	Normal (A)	1 (-)	3.1E-05	5
$u_c(K_{Dut})$	**Combined standard uncertainty**					**Eff DOF**	
	@ 10 MHz			Normal	0.00622	8.6E+09	
$U(K_{Dut})$	**Expanded uncertainty, k=2, 95% confidence level**					**Eff DOF**	
	@ 10 MHz			Normal	0.0125	8.6E+09	
K_{Dut}	**@ 10 MHz = 0.9933**						

Table 6: Traveling Standard : Agilent 8481A Power Sensor (serial no.: US41031012) Frequency : 50 MHz

$u(x_i)$	Quantity X_i	Estimate x_i (units)	Standard Uncertainty $u(x_i)$ (units)	Prob Distri (A,B)	Sensitivity Coefficient, c_i (units)	Uncertainty Contribution $c_i*u(x_i)$	DOF
u(1)	η_S	0.989575 (-)	0.001137 (-)	Normal (B)	1.00E+00 (-)	0.00114	∞
u(2)	P_{Std}	0.000997 (watt)	3.67E-07 (watt)	Normal (B)	-9.95E+02 ($watt^{-1}$)	-0.00036	∞
u(3)	P_{Dut}	0.001001 (watt)	1.44E-06 (watt)	Normal (B)	9.91E+02 ($watt^{-1}$)	0.00143	∞
u(4)	P_{m_Std}	0.000998 (watt)	1E-07 (watt)	Normal (B)	9.94E+02 ($watt^{-1}$)	9.9E-05	∞
u(5)	P_{m_Dut}	0.000997 (watt)	1E-07 (watt)	Normal (B)	-9.95E+02 ($watt^{-1}$)	-9.9E-05	∞
u(6)	Γ_{Std}(mag)	0.040249 (-)	0.0075 (-)	Normal (B)	-7.89E-02 (-)	-0.00059	∞
u(7)	Γ_{Std}(phase)	-1.48234 (rad)	0.141373 (rad)	Normal (B)	-8.69E-05 (rad^{-1})	-1.2E-05	∞

u(8)	Γ_{Dut}(mag)	0.013264 (-)	0.0075 (-)	Normal (B)	-1.46E-03 (-)	-1.1E-05	∞
u(9)	Γ_{Dut}(phase)	-1.64266 (rad)	0.596903 (rad)	Normal (B)	2.59E-05 (rad^{-1})	1.5E-05	∞
u(10)	Γ_{EG}(mag)	0.001227 (-)	0.009706 (-)	Normal (B)	2.12E-02 (-)	0.00021	∞
u(11)	Γ_{EG}(phase)	2.572069 (rad)	1.571406 (rad)	Normal (B)	-6.10E-05 (rad^{-1})	-9.6E-05	∞
u(12)	Repeatability	0.00019 (-)	7.86E-05 (-)	Normal (A)	1 (-)	7.9E-05	5
$u_c(K_{Dut})$	**Combined standard uncertainty**					**Eff DOF**	
	@ 50 MHz			Normal	0.00198	2.0E+06	
$U(K_{Dut})$	**Expanded uncertainty, k=2, 95% confidence level**					**Eff DOF**	
	@ 50 MHz			Normal	0.0040	2.0E+06	
K_{Dut}	**@ 50 MHz = 0.9917**						

Table 7: Traveling Standard : Agilent 8481A Power Sensor (serial no.: US41031012)
Frequency : 1 GHz

$u(x_i)$	Quantity X_i	Estimate x_i (units)	Standard Uncertainty $u(x_i)$ (units)	Prob Distri (A,B)	Sensitivity Coefficient, c_i (units)	Uncertainty Contribution $c_i*u(x_i)$	DOF
u(1)	η_S	0.987328 (-)	0.001134 (-)	Normal (B)	9.88E-01 (-)	0.00112	∞
u(2)	P_{Std}	0.000998 (watt)	3.67E-07 (watt)	Normal (B)	-9.77E+02 ($watt^{-1}$)	-0.00036	∞
u(3)	P_{Dut}	0.000987 (watt)	1.42E-06 (watt)	Normal (B)	9.88E+02 ($watt^{-1}$)	0.00141	∞
u(4)	P_{m_Std}	0.000999 (watt)	1E-07 (watt)	Normal (B)	9.77E+02 ($watt^{-1}$)	9.8E-05	∞
u(5)	P_{m_Dut}	0.001 (watt)	1E-07 (watt)	Normal (B)	-9.76E+02 ($watt^{-1}$)	-9.8E-05	∞
u(6)	Γ_{Std}(mag)	0.008329 (-)	0.0075 (-)	Normal (B)	-2.38E-02 (-)	-0.00018	∞
u(7)	Γ_{Std}(phase)	-2.95803 (rad)	0.779312 (rad)	Normal (B)	1.00E-04 (rad^{-1})	7.8E-05	∞
u(8)	Γ_{Dut}(mag)	0.009798 (-)	0.0075 (-)	Normal (B)	-1.25E-02 (-)	-9.4E-05	∞
u(9)	Γ_{Dut}(phase)	-0.33489 (rad)	0.67457 (rad)	Normal (B)	6.55E-05 (rad^{-1})	4.4E-05	∞
u(10)	Γ_{EG}(mag)	0.007266 (-)	0.009511 (-)	Normal (B)	-2.55E-02 (-)	-0.00024	∞
u(11)	Γ_{EG}(phase)	0.826312 (rad)	1.312948 (rad)	Normal (B)	1.65E-04 (rad^{-1})	0.00022	∞
u(12)	Repeatability	0.00027 (-)	0.000112 (-)	Normal (A)	1 (-)	0.00011	5
$u_c(K_{Dut})$	**Combined standard uncertainty**					**Eff DOF**	
	@ 1 GHz			Normal	0.00188	4.1E+05	
$U(K_{Dut})$	**Expanded uncertainty, k=2, 95% confidence level**					**Eff DOF**	
	@ 1 GHz			Normal	0.0038	4.1E+05	
K_{Dut}	**@ 1 GHz = 0.9752**						

Table 8: Traveling Standard : Agilent 8481A Power Sensor (serial no.: US41031012) Frequency : 4 GHz

$u(x_j)$	Quantity X_i	Estimate x_i (units)	Standard Uncertainty $u(x_i)$ (units)	Prob Distri (A,B)	Sensitivity Coefficient, c_i (units)	Uncertainty Contribution $c_i*u(x_j)$	DOF
u(1)	η_S	0.981255 (-)	0.001252 (-)	Normal (B)	9.83E-01 (-)	0.00123	∞
u(2)	P_{Std}	0.000992 (watt)	3.67E-07 (watt)	Normal (B)	-9.72E+02 ($watt^{-1}$)	-0.00036	∞
u(3)	P_{Dut}	0.000975 (watt)	1.41E-06 (watt)	Normal (B)	9.89E+02 ($watt^{-1}$)	0.00139	∞
u(4)	P_{m_Std}	0.000999 (watt)	1E-07 (watt)	Normal (B)	9.65E+02 ($watt^{-1}$)	9.7E-05	∞
u(5)	P_{m_Dut}	0.000997 (watt)	1E-07 (watt)	Normal (B)	-9.67E+02 ($watt^{-1}$)	-9.7E-05	∞
u(6)	Γ_{Std}(mag)	0.028393 (-)	0.0075 (-)	Normal (B)	-7.69E-02 (-)	-0.00058	∞
u(7)	Γ_{Std}(phase)	-0.649 (rad)	0.286304 (rad)	Normal (B)	-7.71E-05 (rad^{-1})	-2.2E-05	∞
u(8)	Γ_{Dut}(mag)	0.015493 (-)	0.0075 (-)	Normal (B)	5.34E-03 (-)	4E-05	∞
u(9)	Γ_{Dut}(phase)	0.80208 (rad)	0.597775 (rad)	Normal (B)	-3.35E-04 (rad^{-1})	-0.0002	∞
u(10)	Γ_{EG}(mag)	0.011534 (-)	0.011321 (-)	Normal (B)	-4.72E-02 (-)	-0.00053	∞
u(11)	Γ_{EG}(phase)	-2.6151 (rad)	0.987273 (rad)	Normal (B)	-4.12E-04 (rad^{-1})	-0.00041	∞
u(12)	Repeatability	0.000263 (-)	0.000107 (-)	Normal (A)	1 (-)	0.00011	5
$u_c(K_{Dut})$	**Combined standard uncertainty**					**Eff DOF**	
	@ 4 GHz			Normal	0.00211	7.4E+05	
$U(K_{Dut})$	**Expanded uncertainty, k=2, 95% confidence level**					**Eff DOF**	
	@ 4 GHz			Normal	0.0043	7.4E+05	
K_{Dut}	**@ 4 GHz = 0.9646**						

Table 9: Traveling Standard : Agilent 8481A Power Sensor (serial no.: US41031012) Frequency : 8 GHz

$u(x_j)$	Quantity X_i	Estimate x_i (units)	Standard Uncertainty $u(x_i)$ (units)	Prob Distri (A,B)	Sensitivity Coefficient, c_i (units)	Uncertainty Contribution $c_i*u(x_j)$	DOF
u(1)	η_S	0.971407 (-)	0.001454 (-)	Normal (B)	9.77E-01 (-)	0.00142	∞
u(2)	P_{Std}	0.000979 (watt)	3.67E-07 (watt)	Normal (B)	-9.69E+02 ($watt^{-1}$)	-0.00036	∞
u(3)	P_{Dut}	0.000958 (watt)	1.38E-06 (watt)	Normal (B)	9.90E+02 ($watt^{-1}$)	0.00137	∞
u(4)	P_{m_Std}	0.000999 (watt)	1E-07 (watt)	Normal (B)	9.50E+02 ($watt^{-1}$)	9.5E-05	∞
u(5)	P_{m_Dut}	0.000998 (watt)	1E-07 (watt)	Normal (B)	-9.51E+02 ($watt^{-1}$)	-9.5E-05	∞
u(6)	Γ_{Std}(mag)	0.051637 (-)	0.0075 (-)	Normal (B)	-1.04E-01 (-)	-0.00078	∞
u(7)	Γ_{Std}(phase)	0.708996 (rad)	0.115403 (rad)	Normal (B)	-2.07E-03 (rad^{-1})	-0.00024	∞
u(8)	Γ_{Dut}(mag)	0.016814 (-)	0.0075 (-)	Normal (B)	-4.64E-03 (-)	-3.5E-05	∞

u(9)	Γ_{Dut}(phase)	-2.46395 (rad)	0.597775 (rad)	Normal (B)	-6.77E-04 (rad^{-1})	-0.0004	∞
u(10)	Γ_{EG}(mag)	0.021344 (-)	0.011588 (-)	Normal (B)	-1.81E-02 (-)	-0.00021	∞
u(11)	Γ_{EG}(phase)	1.008322 (rad)	0.543724 (rad)	Normal (B)	-2.75E-03 (rad^{-1})	-0.00149	∞
u(12)	Repeatability	0.00034 (-)	0.000137 (-)	Normal (A)	1 (-)	0.00014	5
$u_c(K_{Dut})$	**Combined standard uncertainty**					**Eff DOF**	
	@ 8 GHz			Normal	0.00268	7.3E+05	
$U(K_{Dut})$	**Expanded uncertainty, k=2, 95% confidence level**					**Eff DOF**	
	@ 8 GHz			Normal	0.0054	7.3E+05	
K_{Dut}	**@ 8 GHz = 0.9519**						

Table 10: Traveling Standard : Agilent 8481A Power Sensor (serial no.: US41031012)
Frequency : 12 GHz

$u(x_i)$	Quantity X_i	Estimate x_i (units)	Standard Uncertainty $u(x_i)$ (units)	Prob Distri (A,B)	Sensitivity Coefficient, c_i (units)	Uncertainty Contribution $c_i*u(x_i)$	DOF
u(1)	η_S	0.960728 (-)	0.001702 (-)	Normal (B)	9.67E-01 (-)	0.00165	∞
u(2)	P_{Std}	0.000967 (watt)	3.67E-07 (watt)	Normal (B)	-9.61E+02 (watt^{-1})	-0.00035	∞
u(3)	P_{Dut}	0.00094 (watt)	1.36E-06 (watt)	Normal (B)	9.89E+02 (watt^{-1})	0.00134	∞
u(4)	P_{m_Std}	0.000998 (watt)	1E-07 (watt)	Normal (B)	9.31E+02 (watt^{-1})	9.3E-05	∞
u(5)	P_{m_Dut}	0.000998 (watt)	1E-07 (watt)	Normal (B)	-9.31E+02 (watt^{-1})	-9.3E-05	∞
u(6)	Γ_{Std}(mag)	0.057515 (-)	0.0075 (-)	Normal (B)	-1.50E-01 (-)	-0.00113	∞
u(7)	Γ_{Std}(phase)	2.615503 (rad)	0.117217 (rad)	Normal (B)	2.73E-03 (rad^{-1})	0.00032	∞
u(8)	Γ_{Dut}(mag)	0.031655 (-)	0.0075 (-)	Normal (B)	3.85E-02 (-)	0.00029	∞
u(9)	Γ_{Dut}(phase)	2.700215 (rad)	0.191114 (rad)	Normal (B)	-1.61E-03 (rad^{-1})	-0.00031	∞
u(10)	Γ_{EG}(mag)	0.034406 (-)	0.011613 (-)	Normal (B)	-3.59E-02 (-)	-0.00042	∞
u(11)	Γ_{EG}(phase)	1.365957 (rad)	0.327897 (rad)	Normal (B)	1.12E-03 (rad^{-1})	0.00037	∞
u(12)	Repeatability	0.00013 (-)	5.42E-05 (-)	Normal (A)	1 (-)	5.4E-05	5
$u_c(K_{Dut})$	**Combined standard uncertainty**					**Eff DOF**	
	@ 12 GHz			Normal	0.00255	2.5E+07	
$U(K_{Dut})$	**Expanded uncertainty, k=2, 95% confidence level**					**Eff DOF**	
	@ 12 GHz			Normal	0.0052	2.5E+07	
K_{Dut}	**@ 12 GHz = 0.9292**						

Table 11: Traveling Standard : Agilent 8481A Power Sensor (serial no.: US41031012) Frequency : 15 GHz

$u(x_i)$	Quantity X_i	Estimate x_i (units)	Standard Uncertainty $u(x_i)$ (units)	Prob Distri (A,B)	Sensitivity Coefficient, c_i (units)	Uncertainty Contribution $c_i*u(x_i)$	DOF
u(1)	η_S	0.955557 (-)	0.001917 (-)	Normal (B)	9.57E-01 (-)	0.00184	∞
u(2)	P_{Std}	0.000956 (watt)	3.67E-07 (watt)	Normal (B)	-9.57E+02 ($watt^{-1}$)	-0.00035	∞
u(3)	P_{Dut}	0.00092 (watt)	1.33E-06 (watt)	Normal (B)	9.94E+02 ($watt^{-1}$)	0.00132	∞
u(4)	P_{m_Std}	0.000999 (watt)	1E-07 (watt)	Normal (B)	9.16E+02 ($watt^{-1}$)	9.2E-05	∞
u(5)	P_{m_Dut}	0.001 (watt)	1E-07 (watt)	Normal (B)	-9.15E+02 ($watt^{-1}$)	-9.2E-05	∞
u(6)	Γ_{Std}(mag)	0.027266 (-)	0.0076 (-)	Normal (B)	-1.04E-01 (-)	-0.00078	∞
u(7)	Γ_{Std}(phase)	-1.1232 (rad)	0.290407 (rad)	Normal (B)	-1.51E-04 (rad^{-1})	-4.4E-05	∞
u(8)	Γ_{Dut}(mag)	0.031283 (-)	0.0075 (-)	Normal (B)	-5.24E-02 (-)	-0.00039	∞
u(9)	Γ_{Dut}(phase)	1.88481 (rad)	0.191114 (rad)	Normal (B)	-3.97E-04 (rad^{-1})	-7.6E-05	∞
u(10)	Γ_{EG}(mag)	0.029458 (-)	0.011494 (-)	Normal (B)	-1.05E-01 (-)	-0.00121	∞
u(11)	Γ_{EG}(phase)	-2.12176 (rad)	0.382938 (rad)	Normal (B)	-5.48E-04 (rad^{-1})	-0.00021	∞
u(12)	Repeatability	0.00007 (-)	2.67E-05 (-)	Normal (A)	1 (-)	2.7E-05	5
$u_c(K_{Dut})$	**Combined standard uncertainty**					**Eff DOF**	
	@ 15 GHz			Normal	0.00275	5.6E+08	
$U(K_{Dut})$	**Expanded uncertainty, k=2, 95% confidence level**					**Eff DOF**	
	@ 15 GHz			Normal	0.0055	5.6E+08	
K_{Dut}	**@ 15 GHz = 0.9149**						

Table 12: Traveling Standard : Agilent 8481A Power Sensor (serial no.: US41031012) Frequency : 18 GHz

$u(x_i)$	Quantity X_i	Estimate x_i (units)	Standard Uncertainty $u(x_i)$ (units)	Prob Distri (A,B)	Sensitivity Coefficient, c_i (units)	Uncertainty Contribution $c_i*u(x_i)$	DOF
u(1)	η_S	0.947953 (-)	0.002219 (-)	Normal (B)	9.63E-01 (-)	0.00214	∞
u(2)	P_{Std}	0.000952 (watt)	3.67E-07 (watt)	Normal (B)	-9.58E+02 ($watt^{-1}$)	-0.00035	∞
u(3)	P_{Dut}	0.000916 (watt)	1.32E-06 (watt)	Normal (B)	9.96E+02 ($watt^{-1}$)	0.00132	∞
u(4)	P_{m_Std}	0.000998 (watt)	1E-07 (watt)	Normal (B)	9.15E+02 ($watt^{-1}$)	9.1E-05	∞
u(5)	P_{m_Dut}	0.000999 (watt)	1E-07 (watt)	Normal (B)	-9.14E+02 ($watt^{-1}$)	-9.1E-05	∞
u(6)	Γ_{Std}(mag)	0.070546 (-)	0.0076 (-)	Normal (B)	-7.32E-02 (-)	-0.00056	∞
u(7)	Γ_{Std}(phase)	-0.67873 (rad)	0.088629 (rad)	Normal (B)	1.01E-02 (rad^{-1})	0.0009	∞
u(8)	Γ_{Dut}(mag)	0.074181 (-)	0.0075 (-)	Normal (B)	3.15E-02 (-)	0.00024	∞

u(9)	Γ_{Dut}(phase)	2.284033 (rad)	0.086394 (rad)	Normal (B)	1.11E-02 (rad^{-1})	0.00096	∞
u(10)	Γ_{EG}(mag)	0.084203 (-)	0.012491 (-)	Normal (B)	7.49E-02 (-)	0.00094	∞
u(11)	Γ_{EG}(phase)	-0.51275 (rad)	0.156245 (rad)	Normal (B)	2.13E-02 (rad^{-1})	0.00332	∞
u(12)	Repeatability	0.00034 (-)	1.40E-04 (-)	Normal (A)	1 (-)	0.00014	5
$u_c(K_{Dut})$	**Combined standard uncertainty**					**Eff DOF**	
	@ 18 GHz			Normal	0.00452	5.4E+06	
$U(K_{Dut})$	**Expanded uncertainty, k=2, 95% confidence level**					**Eff DOF**	
	@ 18 GHz			Normal	0.0091	5.4E+06	
K_{Dut}	**@ 18 GHz = 0.9127**						

Table 13: Traveling Standard : Agilent 8481A Power Sensor (serial no.: US41031013)
Frequency : 10 MHz

$u(x_i)$	Quantity X_i	Estimate x_i (units)	Standard Uncertainty $u(x_i)$ (units)	Prob Distri (A,B)	Sensitivity Coefficient, c_i (units)	Uncertainty Contribution $c_i*u(x_i)$	DOF
u(1)	η_S	1.001315 (-)	0.006063 (-)	Normal (B)	0.990233 (-)	0.006004	∞
u(2)	P_{Std}	0.00102 (watt)	4.09E-07 (watt)	Normal (B)	-971.911 ($watt^{-1}$)	-0.0004	∞
u(3)	P_{Dut}	0.001009 (watt)	1.46E-06 (watt)	Normal (B)	982.6917 ($watt^{-1}$)	0.001431	∞
u(4)	P_{m_Std}	0.001 (watt)	1E-07 (watt)	Normal (B)	992.032 ($watt^{-1}$)	9.92E-05	∞
u(5)	P_{m_Dut}	0.000998 (watt)	1E-07 (watt)	Normal (B)	-993.224 ($watt^{-1}$)	-9.9E-05	∞
u(6)	Γ_{Std}(mag)	0.000445 (-)	0.00255 (-)	Normal (B)	-0.00634 (-)	-1.6E-05	∞
u(7)	Γ_{Std}(phase)	-0.10737 (rad)	1.570883 (rad)	Normal (B)	-4.6E-07 (rad^{-1})	-7.2E-07	∞
u(8)	Γ_{Dut}(mag)	0.065055 (-)	0.0026 (-)	Normal (B)	0.000271 (-)	7.05E-07	∞
u(9)	Γ_{Dut}(phase)	-1.44234 (rad)	0.042761 (rad)	Normal (B)	0.000361 (rad^{-1})	1.54E-05	∞
u(10)	Γ_{EG}(mag)	0.002803 (-)	0.009706 (-)	Normal (B)	0.005429 (-)	5.27E-05	∞
u(11)	Γ_{EG}(phase)	3.061779 (rad)	1.570797 (rad)	Normal (B)	0.000361 (rad^{-1})	0.000567	∞
u(12)	Repeatability	0.000288 (-)	0.000118 (-)	Normal (A)	1 (-)	0.000118	5
$u_c(K_{Dut})$	**Combined standard uncertainty**					**Eff DOF**	
	@ 10 MHz			Normal	0.006214	3.9E+07	
$U(K_{Dut})$	**Expanded uncertainty, k=2, 95% confidence level**					**Eff DOF**	
	@ 10 MHz			Normal	0.0125	3.9E+07	
K_{Dut}	**@ 10 MHz = 0.9918**						

Table 14: Traveling Standard : Agilent 8481A Power Sensor (serial no.: US41031013) Frequency : 50 MHz

$u(x_i)$	Quantity X_i	Estimate x_i (units)	Standard Uncertainty $u(x_i)$ (units)	Prob Distri (A,B)	Sensitivity Coefficient, c_i (units)	Uncertainty Contribution $c_i*u(x_i)$	DOF
u(1)	η_S	0.989575 (-)	0.001137 (-)	Normal (B)	1.001289 (-)	0.001138	∞
u(2)	P_{Std}	0.000997 (watt)	3.67E-07 (watt)	Normal (B)	-993.613 ($watt^{-1}$)	-0.00036	∞
u(3)	P_{Dut}	0.001001 (watt)	1.44E-06 (watt)	Normal (B)	989.861 ($watt^{-1}$)	0.00143	∞
u(4)	P_{m_Std}	0.000999 (watt)	1E-07 (watt)	Normal (B)	993.1351 ($watt^{-1}$)	9.93E-05	∞
u(5)	P_{m_Dut}	0.000997 (watt)	1E-07 (watt)	Normal (B)	-992.24 ($watt^{-1}$)	-9.9E-05	∞
u(6)	Γ_{Std}(mag)	0.040249 (-)	0.0075 (-)	Normal (B)	-0.07877 (-)	-0.00059	∞
u(7)	Γ_{Std}(phase)	-1.48234 (rad)	0.141373 (rad)	Normal (B)	-8.7E-05 (rad^{-1})	-1.2E-05	∞
u(8)	Γ_{Dut}(mag)	0.013697 (-)	0.0075 (-)	Normal (B)	-0.00128 (-)	-9.6E-06	∞
u(9)	Γ_{Dut}(phase)	-1.55493 (rad)	0.596903 (rad)	Normal (B)	2.83E-05 (rad^{-1})	1.69E-05	∞
u(10)	Γ_{EG}(mag)	0.001227 (-)	0.009706 (-)	Normal (B)	0.022633 (-)	0.00022	∞
u(11)	Γ_{EG}(phase)	2.572069 (rad)	1.571406 (rad)	Normal (B)	-5.8E-05 (rad^{-1})	-9.2E-05	∞
u(12)	Repeatability	0.000166 (-)	6.78E-05 (-)	Normal (A)	1 (-)	6.78E-05	5
$u_c(K_{Dut})$	**Combined standard uncertainty**					**Eff DOF**	
	@ 50 MHz			Normal	0.001976	3.6E+06	
$U(K_{Dut})$	**Expanded uncertainty, k=2, 95% confidence level**					**Eff DOF**	
	@ 50 MHz			Normal	0.0040	3.6E+06	
K_{Dut}	**@ 50 MHz = 0.9910**						

Table 15: Traveling Standard : Agilent 8481A Power Sensor (serial no.: US41031013) Frequency : 1 GHz

$u(x_i)$	Quantity X_i	Estimate x_i (units)	Standard Uncertainty $u(x_i)$ (units)	Prob Distri (A,B)	Sensitivity Coefficient, c_i (units)	Uncertainty Contribution $c_i*u(x_i)$	DOF
u(1)	η_S	0.987328 (-)	0.001134 (-)	Normal (B)	0.987718 (-)	0.00112	∞
u(2)	P_{Std}	0.000998 (watt)	3.67E-07 (watt)	Normal (B)	-977.181 ($watt^{-1}$)	-0.00036	∞
u(3)	P_{Dut}	0.000987 (watt)	1.42E-06 (watt)	Normal (B)	990.0524 ($watt^{-1}$)	0.001408	∞
u(4)	P_{m_Std}	0.000999 (watt)	1E-07 (watt)	Normal (B)	976.471 ($watt^{-1}$)	9.76E-05	∞
u(5)	P_{m_Dut}	0.000998 (watt)	1E-07 (watt)	Normal (B)	-977.45 ($watt^{-1}$)	-9.8E-05	∞
u(6)	Γ_{Std}(mag)	0.008329 (-)	0.0075 (-)	Normal (B)	-0.02379 (-)	-0.00018	∞
u(7)	Γ_{Std}(phase)	-2.95803 (rad)	0.779312 (rad)	Normal (B)	9.99E-05 (rad^{-1})	7.79E-05	∞
u(8)	Γ_{Dut}(mag)	0.010332 (-)	0.0075 (-)	Normal (B)	-0.0133 (-)	-1E-04	∞

u(9)	Γ_{Dut}(phase)	-0.47246 (rad)	0.596903 (rad)	Normal (B)	5.07E-05 (rad^{-1})	3.03E-05	∞
u(10)	Γ_{EG}(mag)	0.007266 (-)	0.009511 (-)	Normal (B)	-0.02755 (-)	-0.00026	∞
u(11)	Γ_{EG}(phase)	0.826312 (rad)	1.312948 (rad)	Normal (B)	0.000151 (rad^{-1})	0.000198	∞
u(12)	Repeatability	0.00022 (-)	8.99E-05 (-)	Normal (A)	1 (-)	8.99E-05	5
$u_c(K_{Dut})$	**Combined standard uncertainty**					**Eff DOF**	
	@ 1 GHz			Normal	0.001884	9.6E+05	
$U(K_{Dut})$	**Expanded uncertainty, k=2, 95% confidence level**					**Eff DOF**	
	@ 1 GHz			Normal	0.0038	9.6E+05	
K_{Dut}	**@ 1 GHz = 0.9752**						

Table 16: Traveling Standard : Agilent 8481A Power Sensor (serial no.: US41031013) Frequency : 4 GHz

$u(x_i)$	Quantity X_i	Estimate x_i (units)	Standard Uncertainty $u(x_i)$ (units)	Prob Distri (A,B)	Sensitivity Coefficient, c_i (units)	Uncertainty Contribution c_i*$u(x_i)$	DOF
u(1)	η_S	0.981255 (-)	0.001252 (-)	Normal (B)	0.981123 (-)	0.001228	∞
u(2)	P_{Std}	0.000992 (watt)	3.67E-07 (watt)	Normal (B)	-970.212 (watt^{-1})	-0.00036	∞
u(3)	P_{Dut}	0.000975 (watt)	1.41E-06 (watt)	Normal (B)	987.1134 (watt^{-1})	0.00139	∞
u(4)	P_{m_Std}	0.000999 (watt)	1E-07 (watt)	Normal (B)	963.5025 (watt^{-1})	9.64E-05	∞
u(5)	P_{m_Dut}	0.001 (watt)	1E-07 (watt)	Normal (B)	-963.021 (watt^{-1})	-9.6E-05	∞
u(6)	Γ_{Std}(mag)	0.028393 (-)	0.0075 (-)	Normal (B)	-0.07675 (-)	-0.00058	∞
u(7)	Γ_{Std}(phase)	-0.649 (rad)	0.286304 (rad)	Normal (B)	-7.7E-05 (rad^{-1})	-2.2E-05	∞
u(8)	Γ_{Dut}(mag)	0.013221 (-)	0.0075 (-)	Normal (B)	0.012337 (-)	9.25E-05	∞
u(9)	Γ_{Dut}(phase)	0.455372 (rad)	0.597775 (rad)	Normal (B)	-0.00024 (rad^{-1})	-0.00015	∞
u(10)	Γ_{EG}(mag)	0.011534 (-)	0.011321 (-)	Normal (B)	-0.0401 (-)	-0.00045	∞
u(11)	Γ_{EG}(phase)	-2.6151 (rad)	0.987273 (rad)	Normal (B)	-0.00032 (rad^{-1})	-0.00032	∞
u(12)	Repeatability	0.000303 (-)	0.000123 (-)	Normal (A)	1 (-)	0.000123	5
$u_c(K_{Dut})$	**Combined standard uncertainty**					**Eff DOF**	
	@ 4 GHz			Normal	0.002066	3.9E+05	
$U(K_{Dut})$	**Expanded uncertainty, k=2, 95% confidence level**					**Eff DOF**	
	@ 4 GHz			Normal	0.0042	3.9E+05	
K_{Dut}	**@ 4 GHz = 0.9632**						

Table 17: Traveling Standard : Agilent 8481A Power Sensor (serial no.: US41031013) Frequency : 8 GHz

$u(x_i)$	Quantity X_i	Estimate x_i (units)	Standard Uncertainty $u(x_i)$ (units)	Prob Distri (A,B)	Sensitivity Coefficient, c_i (units)	Uncertainty Contribution $c_i*u(x_i)$	DOF
u(1)	η_S	0.971407 (-)	0.001454 (-)	Normal (B)	0.970446 (-)	0.001411	∞
u(2)	P_{Std}	0.000979 (watt)	3.67E-07 (watt)	Normal (B)	-962.877 ($watt^{-1}$)	-0.00035	∞
u(3)	P_{Dut}	0.000952 (watt)	1.37E-06 (watt)	Normal (B)	990.2286 ($watt^{-1}$)	0.001361	∞
u(4)	P_{m_Std}	0.000999 (watt)	1E-07 (watt)	Normal (B)	943.5468 ($watt^{-1}$)	9.44E-05	∞
u(5)	P_{m_Dut}	0.000998 (watt)	1E-07 (watt)	Normal (B)	-944.398 ($watt^{-1}$)	-9.4E-05	∞
u(6)	Γ_{Std}(mag)	0.051637 (-)	0.0075 (-)	Normal (B)	-0.10353 (-)	-0.00078	∞
u(7)	Γ_{Std}(phase)	0.708996 (rad)	0.115403 (rad)	Normal (B)	-0.00206 (rad^{-1})	-0.00024	∞
u(8)	Γ_{Dut}(mag)	0.016018 (-)	0.0075 (-)	Normal (B)	0.006045 (-)	4.53E-05	∞
u(9)	Γ_{Dut}(phase)	-2.72957 (rad)	0.597775 (rad)	Normal (B)	-0.00064 (rad^{-1})	-0.00038	∞
u(10)	Γ_{EG}(mag)	0.021344 (-)	0.011588 (-)	Normal (B)	-0.00978 (-)	-0.00011	∞
u(11)	Γ_{EG}(phase)	1.008322 (rad)	0.543724 (rad)	Normal (B)	-0.00269 (rad^{-1})	-0.00146	∞
u(12)	Repeatability	0.000232 (-)	9.45E-05 (-)	Normal (A)	1 (-)	9.45E-05	5
$u_c(K_{Dut})$	**Combined standard uncertainty**					**Eff DOF**	
	@ 8 GHz			Normal	0.002638	3.0E+06	
$U(K_{Dut})$	**Expanded uncertainty, k=2, 95% confidence level**					**Eff DOF**	
	@ 8 GHz			Normal	0.0053	3.0E+06	
K_{Dut}	**@ 8GHz = 0.9464**						

Table 18: Traveling Standard : Agilent 8481A Power Sensor (serial no.: US41031013) Frequency : 12 GHz

$u(x_i)$	Quantity X_i	Estimate x_i (units)	Standard Uncertainty $u(x_i)$ (units)	Prob Distri (A,B)	Sensitivity Coefficient, c_i (units)	Uncertainty Contribution $c_i*u(x_i)$	DOF
u(1)	η_S	0.960728 (-)	0.001702 (-)	Normal (B)	0.964646 (-)	0.001642	∞
u(2)	P_{Std}	0.000967 (watt)	3.67E-07 (watt)	Normal (B)	-958.08 ($watt^{-1}$)	-0.00035	∞
u(3)	P_{Dut}	0.000938 (watt)	1.35E-06 (watt)	Normal (B)	988.0195 ($watt^{-1}$)	0.001338	∞
u(4)	P_{m_Std}	0.000998 (watt)	1E-07 (watt)	Normal (B)	928.8988 ($watt^{-1}$)	9.29E-05	∞
u(5)	P_{m_Dut}	0.000998 (watt)	1E-07 (watt)	Normal (B)	-928.806 ($watt^{-1}$)	-9.3E-05	∞
u(6)	Γ_{Std}(mag)	0.057515 (-)	0.007536 (-)	Normal (B)	-0.14954 (-)	-0.00113	∞
u(7)	Γ_{Std}(phase)	2.615503 (rad)	0.117217 (rad)	Normal (B)	0.002724 (rad^{-1})	0.000319	∞
u(8)	Γ_{Dut}(mag)	0.02219 (-)	0.0075 (-)	Normal (B)	0.034786 (-)	0.000261	∞

u(9)	Γ_{Dut}(phase)	2.769856 (rad)	0.287107 (rad)	Normal (B)	-0.00119 (rad^{-1})	-0.00034	∞
u(10)	Γ_{EG}(mag)	0.034406 (-)	0.011613 (-)	Normal (B)	-0.04875 (-)	-0.00057	∞
u(11)	Γ_{EG}(phase)	1.365957 (rad)	0.327897 (rad)	Normal (B)	0.001538 (rad^{-1})	0.000504	∞
u(12)	Repeatability	0.000158 (-)	6.44E-05 (-)	Normal (A)	1 (-)	6.44E-05	5
$u_c(K_{Dut})$	**Combined standard uncertainty**					**Eff DOF**	
	@ 12 GHz			Normal	0.0026	1.3E+07	
$U(K_{Dut})$	**Expanded uncertainty, k=2, 95% confidence level**					**Eff DOF**	
	@ 12 GHz			Normal	0.0052	1.3E+07	
K_{Dut}	**@ 12 GHz = 0.9268**						

Table 19: Traveling Standard : Agilent 8481A Power Sensor (serial no.: US41031013)
Frequency : 15 GHz

$u(x_i)$	Quantity X_i	Estimate x_i (units)	Standard Uncertainty $u(x_i)$ (units)	Prob Distri (A,B)	Sensitivity Coefficient, c_i (units)	Uncertainty Contribution $c_i*u(x_i)$	DOF
u(1)	η_S	0.955557 (-)	0.001917 (-)	Normal (B)	0.953219 (-)	0.001828	∞
u(2)	P_{Std}	0.000956 (watt)	3.67E-07 (watt)	Normal (B)	-952.445 ($watt^{-1}$)	-0.00035	∞
u(3)	P_{Dut}	0.000915 (watt)	1.32E-06 (watt)	Normal (B)	995.7959 ($watt^{-1}$)	0.001315	∞
u(4)	P_{m_Std}	0.000999 (watt)	1E-07 (watt)	Normal (B)	911.9489 ($watt^{-1}$)	9.12E-05	∞
u(5)	P_{m_Dut}	0.000999 (watt)	1E-07 (watt)	Normal (B)	-911.858 ($watt^{-1}$)	-9.1E-05	∞
u(6)	Γ_{Std}(mag)	0.027266 (-)	0.00755 (-)	Normal (B)	-0.10304 (-)	-0.00078	∞
u(7)	Γ_{Std}(phase)	-1.1232 (rad)	0.290407 (rad)	Normal (B)	-0.00015 (rad^{-1})	-4.4E-05	∞
u(8)	Γ_{Dut}(mag)	0.017334 (-)	0.0075 (-)	Normal (B)	-0.05045 (-)	-0.00038	∞
u(9)	Γ_{Dut}(phase)	1.772632 (rad)	0.597775 (rad)	Normal (B)	-0.00032 (rad^{-1})	-0.00019	∞
u(10)	Γ_{EG}(mag)	0.029458 (-)	0.011494 (-)	Normal (B)	-0.07905 (-)	-0.00091	∞
u(11)	Γ_{EG}(phase)	-2.12176 (rad)	0.382938 (rad)	Normal (B)	-0.00047 (rad^{-1})	-0.00018	∞
u(12)	Repeatability	0.000147 (-)	6E-05 (-)	Normal (A)	1 (-)	6E-05	5
$u_c(K_{Dut})$	**Combined standard uncertainty**					**Eff DOF**	
	@ 15 GHz			Normal	0.002618	1.8E+07	
$U(K_{Dut})$	**Expanded uncertainty, k=2, 95% confidence level**					**Eff DOF**	
	@ 15 GHz			Normal	0.0053	1.8E+07	
K_{Dut}	**@ 15 GHz = 0.9110**						

Table 20: Traveling Standard : Agilent 8481A Power Sensor (serial no.: US41031013) Frequency : 18 GHz

$u(x_i)$	Quantity X_i	Estimate x_i (units)	Standard Uncertainty $u(x_i)$ (units)	Prob Distri (A,B)	Sensitivity Coefficient, c_i (units)	Uncertainty Contribution $c_i*u(x_i)$	DOF
u(1)	η_S	0.947953 (-)	0.002219 (-)	Normal (B)	0.959164 (-)	0.002128	∞
u(2)	P_{Std}	0.000952 (watt)	3.67E-07 (watt)	Normal (B)	-954.609 ($watt^{-1}$)	-0.00035	∞
u(3)	P_{Dut}	0.000913 (watt)	1.32E-06 (watt)	Normal (B)	996.2115 ($watt^{-1}$)	0.001312	∞
u(4)	P_{m_Std}	0.000998 (watt)	1E-07 (watt)	Normal (B)	911.0644 ($watt^{-1}$)	9.11E-05	∞
u(5)	P_{m_Dut}	0.000998 (watt)	1E-07 (watt)	Normal (B)	-910.791 ($watt^{-1}$)	-9.1E-05	∞
u(6)	Γ_{Std}(mag)	0.070546 (-)	0.007606 (-)	Normal (B)	-0.07289 (-)	-0.00055	∞
u(7)	Γ_{Std}(phase)	-0.67873 (rad)	0.088629 (rad)	Normal (B)	0.010078 (rad^{-1})	0.000893	∞
u(8)	Γ_{Dut}(mag)	0.059866 (-)	0.0075 (-)	Normal (B)	0.028916 (-)	0.000217	∞
u(9)	Γ_{Dut}(phase)	2.268756 (rad)	0.116937 (rad)	Normal (B)	0.008993 (rad^{-1})	0.001052	∞
u(10)	Γ_{EG}(mag)	0.084203 (-)	0.012491 (-)	Normal (B)	0.067504 (-)	0.000843	∞
u(11)	Γ_{EG}(phase)	-0.51275 (rad)	0.156245 (rad)	Normal (B)	0.019071 (rad^{-1})	0.00298	∞
u(12)	Repeatability	0.000336 (-)	0.000137 (-)	Normal (A)	1 (-)	0.000137	5
$u_c(K_{Dut})$	**Combined standard uncertainty**					**Eff DOF**	
	@ 18 GHz			Normal	0.004273	4.7E+06	
$U(K_{Dut})$	**Expanded uncertainty, k=2, 95% confidence level**					**Eff DOF**	
	@ 18 GHz			Normal	0.0086	4.7E+06	
K_{Dut}	**@ 18 GHz = 0.9093**						

-------------------- End of Report --------------------

Calibration Officer

Measurement Report (APMP.EM.RF-K8.CL)

1. **National Physical Laboratory, INDIA.**

   Saood Ahmad

   Senior scientist,

   Microwave Standards, ALSIM,

   Dr. K.S Krishnan Road,

   National Physical Laboratory,

   New Delhi-110012, INDIA.

2. **Measurement Methods**

   A resistive power splitter system is used with R&S NRV-Z51 power sensor permanently attached to one arm. The device under calibration (DUC) and the standard are attached alternatively to the other arm of the splitter. The reference standard is traceable to NPL-India Primary Standard (Coaxial Microcalorimeter System). The measurements have been repeated for eight times.

   The reflection coefficients of the DUC are measured using Agilent E8257D and Anritsu 37247B Vector network analyzer (VNA). The reflection coefficient measurement using VNA is traceable to Dimensional metrology and DC Resistance Standard at NPL India through transfer standards (Coaxial airlines and Calibration kit components). The uncertainty related to mismatch factors (MF) whose values are assumed to be equal to 1 have been calculated by using equation; $u(MF) = \sqrt{2}|\Gamma_G||\Gamma_X|$, where Γ_G is the reflection coefficient of the RF source and Γ_X (x=STD, DUC) is the reflection coefficient of standard and device under calibration respectively.

3. **Measuring System**

   Direct comparison transfer method is applicable for the calibration of thermistor mounts/power sensors for their calibration factor. In this comparison method, calibration of unknown power sensor (DUC) involves comparing it against the calibrated thermistor mount which acts as a reference standard. The comparison method is based on connecting the reference standard thermistor mount (STD) and an unknown power sensor (DUC) alternately to a matched source of RF power. A power splitter system is used, where a reference power meter is permanently attached to one arm. DUC and the reference standard are attached alternatively to the other arm of the splitter.

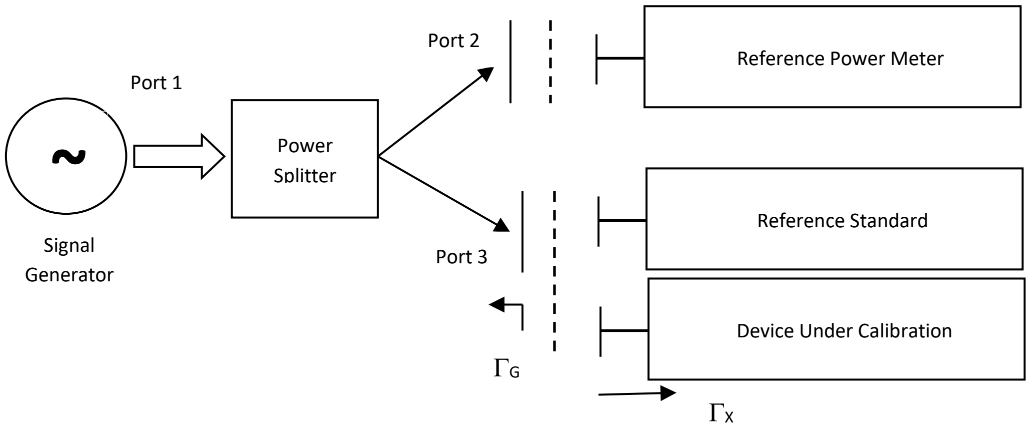


Fig.1: Coaxial Splitter based Power Measurement Setup

The reference standard coaxial thermistor mount (STD) and unknown power sensor (DUC) are used as shown in Fig.1 for the measurement of microwave power. Coaxial thermistor mount, which has been assigned effective efficiency using coaxial microcalorimeter system, is used as reference standard to calibrate unknown power sensor by direct comparison transfer method. The calibration factors K_b of the DUC are calculated using eq. (1)

$$K_{b(DUC)} = K_{b(STD)} \frac{P_{DUC}/P_{ref}}{P_{STD}/P_{ref}} \frac{[1-\Gamma_S\Gamma_G]^2}{[1-\Gamma_D\Gamma_G]^2} \quad \text{------ (1)}$$

Where, $K_{b(DUC)}$ is the calibration factor of the DUC and $K_{b(STD)}$ is the calibration factor of the reference standard. P_{DUC} is the power measured by the device under calibration, P_{STD} is the DC substituted power measured by the reference standard and P_{ref} is the reference power measured at the other arm. In the equation, $\Gamma_{G,}$ Γ_S and Γ_D are the reflection coefficients of the RF Source, reference standard and the device under calibration respectively to calculate the mismatch factor. Reflection coefficient of the DUC is measured at all the desired frequencies using VNA. Based on the above mentioned measurements the calibration factors are assigned to the device under calibration using eq. (1) at all the required frequencies.

4. List of results

Measurement Results DUC - (Sensor 1)

Agilent 8481A

S.No. - US41031012

S.No.	Frequency (GHz)	Calibration Factor *K*	Combined Standard Uncertainty $u_c(K)$ (k=1)	Coverage Factor k @ (95%)
1	0.01	0.9915	0.0043	1.96
2	0.05	1.0009	0.0031	1.96
3	1.0	0.9874	0.0038	1.96
4	4.0	0.9705	0.0046	1.96
5	8.0	0.9532	0.0067	1.96
6	12.0	0.9340	0.0088	1.96
7	15.0	0.9177	0.0092	1.96
8	18.0	0.9093	0.0126	1.96

Measurement Results DUC - (Sensor 2)

Agilent 8481A

S.No. - US41031013

S.No.	Frequency (GHz)	Calibration Factor *K*	Combined Standard Uncertainty $u_c(K)$ (k=1)	Coverage Factor k @ (95%)
1	0.01	0.9919	0.0042	1.96
2	0.05	1.0012	0.0031	1.96
3	1.0	0.9876	0.0038	1.96
4	4.0	0.9714	0.0047	1.96
5	8.0	0.9546	0.0068	1.96
6	12.0	0.9387	0.0084	1.96
7	15.0	0.9210	0.0089	1.96
8	18.0	0.9121	0.0115	1.96

5. Measurement conditions

Ambient temperature (25±1) °C and Relative Humidity (50±10) %

6. Additional Measurements

Measurement Results DUC - (Sensor 1)

Agilent 8481A: S.No. - US41031012

S.No.	Frequency (GHz)	Reflection Coefficient $\lvert\Gamma\rvert$	Combined Standard Uncertainty $u_c(\Gamma)$ (k=1)
1	0.01	0.063	0.006
2	0.05	0.013	0.006
3	1.0	0.008	0.006
4	4.0	0.012	0.008
5	8.0	0.027	0.008
6	12.0	0.035	0.008
7	15.0	0.041	0.008
8	18.0	0.089	0.008

Measurement Results DUC - (Sensor 2)

Agilent 8481A: S.No. - US41031013

S.No.	Frequency (GHz)	Reflection Coefficient $\lvert\Gamma\rvert$	Combined Standard Uncertainty $u_c(\Gamma)$ (k=1)
1	0.01	0.064	0.006
2	0.05	0.014	0.006
3	1.0	0.011	0.006
4	4.0	0.007	0.008
5	8.0	0.025	0.008
6	12.0	0.024	0.008
7	15.0	0.035	0.008
8	18.0	0.073	0.008

7. Uncertainty Budgets:

UNCERTAINTY BUDGET	Calibration Factor HP8481A Power Sensor; Sno. US41031012, APMP.EM.RF-K8.CL						
POINT OF CALCULATION:			10 MHz				
Source of uncertainty	Estimate (Xi)	Limit xi(Xi)	Probability Distribution Type A/B	Standard uncertainty u xi(Xi)	Sensitivity coefficient ci	Uncertainty contribution |ci| uxi(Xi)	Degree of freedom (vi)
Reference Standard $K_{s(f)}$	0.9904	0.0037	Normal Type B 2	0.00185	1	0.00185	∞
Drift in Cal Factor $\delta K_s(f)$	0.001	0.0020	Rectangular Type B √3	0.00115	1	0.00115	∞
Stability 50 MHz ref Source	1	0.0030	Rectangular Type B √3	0.00173	1	0.00173	∞
Instrument Non-Linearity	1	0.0010	Normal Type B 2	0.00050	1	0.00050	∞
Power ratio P_s	1.0069	0.0019	Normal Type B 2	0.00095	1	0.00095	∞
Power ratio P_D	0.9991	0.0018	Normal Type B 2	0.00090	1	0.00090	∞
Mismatch wrt Source to STD	1	0.0025	U Shape Type B √2	0.00179	1	0.00179	∞
Mismatch wrt Source to DUC	1	0.0031	U Shape Type B √2	0.00216	1	0.00216	∞
Repeatability			Type A	0.00044		0.00044	7
Combined Standard Uncertainty $u_c K_{D(f)}$						**0.00422**	
Expanded Uncertainty $UK_{D(f)}$		Coverage Factor @ 95%	k = 1.96	Effective degree of freedom			33918
				0.0083		0.83	%

UNCERTAINTY BUDGET	Calibration Factor HP8481A Power Sensor; Sno. US41031012, APMP.EM.RF-K8.CL						
POINT OF CALCULATION:			50 MHz				
Source of uncertainty	**Estimate (Xi)**	**Limit xi(Xi)**	**Probability Distribution Type A/B**	**Standard uncertainty u xi(Xi)**	**Sensitivity coefficient ci**	**Uncertainty contribution |ci| uxi(Xi)**	**Degree of freedom (vi)**
Reference Standard Ks(f)	1.0006	0.0030	Normal Type B 2	0.00150	1	0.00150	∞
Drift in Cal Factor δKs(f)	0.001	0.0020	Rectangular Type B √3	0.00115	1	0.00115	∞
Stability 50 MHz ref Source	1	0.0030	Rectangular Type B √3	0.00173	1	0.00173	∞
Instrument Non-Linearity	1	0.0010	Normal Type B 2	0.00050	1	0.00050	∞
Power ratio Ps	0.9990	0.0020	Normal Type B 2	0.00100	1	0.00100	∞
Power ratio P_D	0.9995	0.0020	Normal Type B 2	0.00100	1	0.00100	∞
Mismatch wrt Source to STD	1	0.0007	U Shape Type B √2	0.00048	1	0.00048	∞
Mismatch wrt Source to DUC	1	0.0006	U Shape Type B √2	0.00046	1	0.00046	∞
Repeatability			Type A	0.00017		0.00017	7
Combined Standard Uncertainty $u_c K_{D(f)}$						**0.00305**	
Expanded Uncertainty $UK_{D(f)}$		**Coverage Factor @ 95%**	**k = 1.96**	**Effective degree of freedom**			**444711**
				0.0060		0.60	%

UNCERTAINTY BUDGET	Calibration Factor HP8481A Power Sensor; Sno. US41031012, APMP.EM.RF-K8.CL						
POINT OF CALCULATION:			1 GHz				
Source of uncertainty	**Estimate (Xi)**	**Limit xi(Xi)**	**Probability Distribution Type A/B**	**Standard uncertainty u xi(Xi)**	**Sensitivity coefficient ci**	**Uncertainty contribution |ci| uxi(Xi)**	**Degree of freedom (vi)**
Reference Standard $K_{s}(f)$	0.9924	0.0056	Normal Type B 2	0.00280	1	0.00280	∞
Drift in Cal Factor $\delta K_s(f)$	0.001	0.0020	Rectangular Type B √3	0.00115	1	0.00115	∞
Stability 50 MHz ref Source	1	0.0030	Rectangular Type B √3	0.00173	1	0.00173	∞
Instrument Non-Linearity	1	0.0010	Normal Type B 2	0.00050	1	0.00050	∞
Power ratio Ps	0.9996	0.0010	Normal Type B 2	0.00050	1	0.00050	∞
Power ratio P_D	0.9857	0.0010	Normal Type B 2	0.00050	1	0.00050	∞
Mismatch wrt Source to STD	1	0.0014	U Shape Type B √2	0.00097	1	0.00097	∞
Mismatch wrt Source to DUC	1	0.0004	U Shape Type B √2	0.00029	1	0.00029	∞
Repeatability			Type A	0.00065		0.00065	7
Combined Standard Uncertainty $u_c K_D(f)$						**0.00379**	
Expanded Uncertainty $UK_D(f)$		**Coverage Factor @ 95%**	**k = 1.96**	**Effective degree of freedom**			**4688**
				0.0074		0.74	%

UNCERTAINTY BUDGET	Calibration Factor HP8481A Power Sensor; Sno. US41031012, APMP.EM.RF-K8.CL						
POINT OF CALCULATION:			4 GHz				
Source of uncertainty	**Estimate (Xi)**	**Limit xi(Xi)**	**Probability Distribution Type A/B**	**Standard uncertainty u xi(Xi)**	**Sensitivity coefficient ci**	**Uncertainty contribution |ci| uxi(Xi)**	**Degree of freedom (vi)**
Reference Standard $K_{S(f)}$	0.9792	0.0056	Normal Type B 2	0.00280	1	0.00280	∞
Drift in Cal Factor δKs(f)	0.001	0.0020	Rectangular Type B √3	0.00115	1	0.00115	∞
Stability 50 MHz ref Source	1	0.0030	Rectangular Type B √3	0.00173	1	0.00173	∞
Instrument Non-Linearity	1	0.0010	Normal Type B 2	0.00050	1	0.00050	∞
Power ratio Ps	1.0102	0.0006	Normal Type B 2	0.00030	1	0.00030	∞
Power ratio P_D	0.9778	0.0007	Normal Type B 2	0.00035	1	0.00035	∞
Mismatch wrt Source to STD	1	0.0039	U Shape Type B √2	0.00277	1	0.00277	∞
Mismatch wrt Source to DUC	1	0.0008	U Shape Type B √2	0.00059	1	0.00059	∞
Repeatability			Type A	0.00028		0.00028	7
Combined Standard Uncertainty $u_c K_{D(f)}$						**0.00456**	
Expanded Uncertainty $UK_{D(f)}$		**Coverage Factor @ 95%**	**k = 1.96**	**Effective degree of freedom**			**292797**
			0.0089			0.89	%

UNCERTAINTY BUDGET	Calibration Factor HP8481A Power Sensor; Sno. US41031012, APMP.EM.RF-K8.CL						
POINT OF CALCULATION:			**8 GHz**				
Source of uncertainty	**Estimate (Xi)**	**Limit xi(Xi)**	**Probability Distribution Type A/B**	**Standard uncertainty u xi(Xi)**	**Sensitivity coefficient ci**	**Uncertainty contribution |ci| uxi(Xi)**	**Degree of freedom (vi)**
Reference Standard $K_{s(f)}$	0.9654	0.0067	Normal Type B 2	0.00335	1	0.00335	∞
Drift in Cal Factor $\delta K_{s(f)}$	0.001	0.0020	Rectangular Type B √3	0.00115	1	0.00115	∞
Stability 50 MHz ref Source	1	0.0030	Rectangular Type B √3	0.00173	1	0.00173	∞
Instrument Non-Linearity	1	0.0010	Normal Type B 2	0.00050	1	0.00050	∞
Power ratio Ps	1.0104	0.0008	Normal Type B 2	0.00040	1	0.00040	∞
Power ratio P_D	0.9589	0.0007	Normal Type B 2	0.00035	1	0.00035	∞
Mismatch wrt Source to STD	1	0.0070	U Shape Type B √2	0.00498	1	0.00498	∞
Mismatch wrt Source to DUC	1	0.0025	U Shape Type B √2	0.00178	1	0.00178	∞
Repeatability			Type A	0.00061		0.00061	7
Combined Standard Uncertainty $u_c K_{D(f)}$						**0.00667**	
Expanded Uncertainty $UK_{D(f)}$		**Coverage Factor @ 95%**	**k = 1.96**	**Effective degree of freedom**			**56362**
			0.0131			1.31	%

UNCERTAINTY BUDGET	Calibration Factor HP8481A Power Sensor; Sno. US41031012, APMP.EM.RF-K8.CL						
POINT OF CALCULATION:			12 GHz				
Source of uncertainty	Estimate (Xi)	Limit xi(Xi)	Probability Distribution Type A/B	Standard uncertainty u xi(Xi)	Sensitivity coefficient ci	Uncertainty contribution |ci| uxi(Xi)	Degree of freedom (vi)
Reference Standard $K_{S(f)}$	0.9617	0.0072	Normal Type B 2	0.00360	1	0.00360	∞
Drift in Cal Factor $\delta K_{S(f)}$	0.001	0.0020	Rectangular Type B √3	0.00115	1	0.00115	∞
Stability 50 MHz ref Source	1	0.0030	Rectangular Type B √3	0.00173	1	0.00173	∞
Instrument Non-Linearity	1	0.0010	Normal Type B 2	0.00050	1	0.00050	∞
Power ratio Ps	1.0111	0.0009	Normal Type B 2	0.00045	1	0.00045	∞
Power ratio P_D	0.9402	0.0003	Normal Type B 2	0.00016	1	0.00016	∞
Mismatch wrt Source to STD	1	0.0096	U Shape Type B √2	0.00681	1	0.00681	∞
Mismatch wrt Source to DUC	1	0.0049	U Shape Type B √2	0.00348	1	0.00348	∞
Repeatability			Type A	0.00047		0.00047	7
Combined Standard Uncertainty $u_c K_{D(f)}$						**0.00874**	
Expanded Uncertainty $UK_{D(f)}$		Coverage Factor @ 95%	k = 1.96	Effective degree of freedom			482529
				0.0171		1.71	%

UNCERTAINTY BUDGET	Calibration Factor HP8481A Power Sensor; Sno. US41031012, APMP.EM.RF-K8.CL						
POINT OF CALCULATION:			15 GHz				
Source of uncertainty	**Estimate (Xi)**	**Limit xi(Xi)**	**Probability Distribution Type A/B**	**Standard uncertainty u xi(Xi)**	**Sensitivity coefficient ci**	**Uncertainty contribution |ci| uxi(Xi)**	**Degree of freedom (vi)**
Reference Standard $K_{s(f)}$	0.9569	0.0076	Normal Type B 2	0.00380	1	0.00380	∞
Drift in Cal Factor $\delta K_{s(f)}$	0.001	0.0020	Rectangular Type B √3	0.00115	1	0.00115	∞
Stability 50 MHz ref Source	1	0.0030	Rectangular Type B √3	0.00173	1	0.00173	∞
Instrument Non-Linearity	1	0.0010	Normal Type B 2	0.00050	1	0.00050	∞
Power ratio Ps	1.0081	0.0004	Normal Type B 2	0.00020	1	0.00020	∞
Power ratio P_D	0.9211	0.0003	Normal Type B 2	0.00015	1	0.00015	∞
Mismatch wrt Source to STD	1	0.0098	U Shape Type B √2	0.00691	1	0.00691	∞
Mismatch wrt Source to DUC	1	0.0057	U Shape Type B √2	0.00403	1	0.00403	∞
Repeatability			Type A	0.00047		0.00047	7
Combined Standard Uncertainty $u_c K_{D(f)}$						**0.00913**	
Expanded Uncertainty $UK_{D(f)}$		**Coverage Factor @ 95%**	**k = 1.96**	**Effective degree of freedom**			**562296**
			0.0179			1.79	%

UNCERTAINTY BUDGET	Calibration Factor HP8481A Power Sensor; Sno. US41031012, APMP.EM.RF-K8.CL						
POINT OF CALCULATION:			18 GHz				
Source of uncertainty	**Estimate (Xi)**	**Limit xi(Xi)**	**Probability Distribution Type A/B**	**Standard uncertainty u xi(Xi)**	**Sensitivity coefficient ci**	**Uncertainty contribution |ci| uxi(Xi)**	**Degree of freedom (vi)**
Reference Standard Ks(f)	0.9398	0.0094	Normal Type B 2	0.00470	1	0.00470	∞
Drift in Cal Factor δKs(f)	0.001	0.0020	Rectangular Type B √3	0.00115	1	0.00115	∞
Stability 50 MHz ref Source	1	0.0030	Rectangular Type B √3	0.00173	1	0.00173	∞
Instrument Non-Linearity	1	0.0010	Normal Type B 2	0.00050	1	0.00050	∞
Power ratio Ps	1.0288	0.0005	Normal Type B 2	0.00025	1	0.00025	∞
Power ratio P_D	0.9373	0.0003	Normal Type B 2	0.00015	1	0.00015	∞
Mismatch wrt Source to STD	1	0.0103	U Shape Type B √2	0.00730	1	0.00730	∞
Mismatch wrt Source to DUC	1	0.0124	U Shape Type B √2	0.00878	1	0.00878	∞
Repeatability			Type A	0.00044		0.00044	7
Combined Standard Uncertainty $u_c K_{D(f)}$						**0.01254**	
Expanded Uncertainty $UK_{D(f)}$		**Coverage Factor @ 95%**	**k = 1.96**	**Effective degree of freedom**			**2637992**
				0.0246		2.46	%

UNCERTAINTY BUDGET	Calibration Factor HP8481A Power Sensor; Sno. US41031013, APMP.EM.RF-K8.CL						
POINT OF CALCULATION:			10 MHz				
Source of uncertainty	**Estimate (Xi)**	**Limit xi(Xi)**	**Probability Distribution Type A/B**	**Standard uncertainty u xi(Xi)**	**Sensitivity coefficient ci**	**Uncertainty contribution |ci| uxi(Xi)**	**Degree of freedom (vi)**
Reference Standard $K_{S(f)}$	0.9904	0.0037	Normal Type B 2	0.00185	1	0.00185	∞
Drift in Cal Factor δKs(f)	0.001	0.0020	Rectangular Type B √3	0.00115	1	0.00115	∞
Stability 50 MHz ref Source	1	0.0030	Rectangular Type B √3	0.00173	1	0.00173	∞
Instrument Non-Linearity	1	0.0010	Normal Type B 2	0.00050	1	0.00050	∞
Power ratio Ps	1.0049	0.0014	Normal Type B 2	0.00070	1	0.00070	∞
Power ratio P_D	0.9984	0.0010	Normal Type B 2	0.00050	1	0.00050	∞
Mismatch wrt Source to STD	1	0.0025	U Shape Type B √2	0.00179	1	0.00179	∞
Mismatch wrt Source to DUC	1	0.0031	U Shape Type B √2	0.00220	1	0.00220	∞
Repeatability			Type A	0.00044		0.00044	7
Combined Standard Uncertainty $u_c K_{D(f)}$						**0.00412**	
Expanded Uncertainty $UK_{D(f)}$		**Coverage Factor @ 95%**	**k = 1.96**	**Effective degree of freedom**			**30933**
				0.0081		0.81	%

UNCERTAINTY BUDGET	Calibration Factor HP8481A Power Sensor; Sno. US41031013, APMP.EM.RF-K8.CL						
POINT OF CALCULATION:			50 MHz				
Source of uncertainty	**Estimate (Xi)**	**Limit xi(Xi)**	**Probability Distribution Type A/B**	**Standard uncertainty u xi(Xi)**	**Sensitivity coefficient ci**	**Uncertainty contribution |ci| uxi(Xi)**	**Degree of freedom (vi)**
Reference Standard $K_{S(f)}$	1.0006	0.0030	Normal Type B 2	0.00150	1	0.00150	∞
Drift in Cal Factor $\delta K_{S(f)}$	0.001	0.0020	Rectangular Type B √3	0.00115	1	0.00115	∞
Stability 50 MHz ref Source	1	0.0030	Rectangular Type B √3	0.00173	1	0.00173	∞
Instrument Non-Linearity	1	0.0010	Normal Type B 2	0.00050	1	0.00050	∞
Power ratio Ps	0.9968	0.0015	Normal Type B 2	0.00075	1	0.00075	∞
Power ratio P_D	0.9962	0.0022	Normal Type B 2	0.00110	1	0.00110	∞
Mismatch wrt Source to STD	1	0.0007	U Shape Type B √2	0.00048	1	0.00048	∞
Mismatch wrt Source to DUC	1	0.0007	U Shape Type B √2	0.00048	1	0.00048	∞
Repeatability			Type A	0.00017		0.00017	7
Combined Standard Uncertainty $u_c K_{D(f)}$						**0.00302**	
Expanded Uncertainty $UK_{D(f)}$		**Coverage Factor @ 95%**	**k = 1.96**	**Effective degree of freedom**			**424685**
				0.0059		0.59	%

UNCERTAINTY BUDGET	Calibration Factor HP8481A Power Sensor; Sno. US41031013, APMP.EM.RF-K8.CL						
POINT OF CALCULATION:			1 GHz				
Source of uncertainty	Estimate (Xi)	Limit xi(Xi)	Probability Distribution Type A/B	Standard uncertainty u xi(Xi)	Sensitivity coefficient ci	Uncertainty contribution |ci| uxi(Xi)	Degree of freedom (vi)
Reference Standard $K_{s(f)}$	0.9924	0.0056	Normal Type B 2	0.00280	1	0.00280	∞
Drift in Cal Factor $\delta K_{s(f)}$	0.001	0.0020	Rectangular Type B √3	0.00115	1	0.00115	∞
Stability 50 MHz ref Source	1	0.0030	Rectangular Type B √3	0.00173	1	0.00173	∞
Instrument Non-Linearity	1	0.0010	Normal Type B 2	0.00050	1	0.00050	∞
Power ratio Ps	1.0006	0.0007	Normal Type B 2	0.00035	1	0.00035	∞
Power ratio P_D	0.9899	0.0008	Normal Type B 2	0.00040	1	0.00040	∞
Mismatch wrt Source to STD	1	0.0014	U Shape Type B √2	0.00097	1	0.00097	∞
Mismatch wrt Source to DUC	1	0.0005	U Shape Type B √2	0.00039	1	0.00039	∞
Repeatability			Type A	0.00065		0.00065	7
Combined Standard Uncertainty $u_c\ K_{D(f)}$						**0.00377**	
Expanded Uncertainty $UK_{D(f)}$		Coverage Factor @ 95%	k = 1.96	Effective degree of freedom			4591
				0.0074		0.74	%

UNCERTAINTY BUDGET	Calibration Factor HP8481A Power Sensor; Sno. US41031013, APMP.EM.RF-K8.CL						
POINT OF CALCULATION:			4 GHz				
Source of uncertainty	**Estimate (Xi)**	**Limit xi(Xi)**	**Probability Distribution Type A/B**	**Standard uncertainty u xi(Xi)**	**Sensitivity coefficient ci**	**Uncertainty contribution |ci| uxi(Xi)**	**Degree of freedom (vi)**
Reference Standard Ks(f)	0.9792	0.0056	Normal Type B 2	0.00280	1	0.00280	∞
Drift in Cal Factor δKs(f)	0.001	0.0020	Rectangular Type B √3	0.00115	1	0.00115	∞
Stability 50 MHz ref Source	1	0.0030	Rectangular Type B √3	0.00173	1	0.00173	∞
Instrument Non-Linearity	1	0.0010	Normal Type B 2	0.00050	1	0.00050	∞
Power ratio Ps	1.0121	0.0020	Normal Type B 2	0.00100	1	0.00100	∞
Power ratio PD	0.9776	0.0010	Normal Type B 2	0.00050	1	0.00050	∞
Mismatch wrt Source to STD	1	0.0039	U Shape Type B √2	0.00277	1	0.00277	∞
Mismatch wrt Source to DUC	1	0.0005	U Shape Type B √2	0.00033	1	0.00033	∞
Repeatability			Type A	0.00028		0.00028	7
Combined Standard Uncertainty u_c KD(f)						**0.00464**	
Expanded Uncertainty UKD(f)		**Coverage Factor @ 95%**	**k = 1.96**	**Effective degree of freedom**			**315890**
			0.0091			0.91	%

UNCERTAINTY BUDGET	Calibration Factor HP8481A Power Sensor; Sno. US41031013, APMP.EM.RF-K8.CL						
POINT OF CALCULATION:			8 GHz				
Source of uncertainty	**Estimate (Xi)**	**Limit xi(Xi)**	**Probability Distribution Type A/B**	**Standard uncertainty u xi(Xi)**	**Sensitivity coefficient ci**	**Uncertainty contribution |ci| uxi(Xi)**	**Degree of freedom (vi)**
Reference Standard $K_{S(f)}$	0.9654	0.0067	Normal Type B 2	0.00335	1	0.00335	∞
Drift in Cal Factor δKs(f)	0.001	0.0020	Rectangular Type B √3	0.00115	1	0.00115	∞
Stability 50 MHz ref Source	1	0.0030	Rectangular Type B √3	0.00173	1	0.00173	∞
Instrument Non-Linearity	1	0.0010	Normal Type B 2	0.00050	1	0.00050	∞
Power ratio Ps	1.0108	0.0008	Normal Type B 2	0.00040	1	0.00040	∞
Power ratio P_D	0.9580	0.0030	Normal Type B 2	0.00150	1	0.00150	∞
Mismatch wrt Source to STD	1	0.0070	U Shape Type B √2	0.00498	1	0.00498	∞
Mismatch wrt Source to DUC	1	0.0023	U Shape Type B √2	0.00166	1	0.00166	∞
Repeatability			Type A	0.00061		0.00061	7
Combined Standard Uncertainty $u_c K_{D(f)}$						**0.00680**	
Expanded Uncertainty $UK_{D(f)}$		**Coverage Factor @ 95%**	**k = 1.96**	**Effective degree of freedom**			**60747**
				0.0133		1.33	%

UNCERTAINTY BUDGET	Calibration Factor HP8481A Power Sensor; Sno. US41031013, APMP.EM.RF-K8.CL						
POINT OF CALCULATION:			12 GHz				
Source of uncertainty	**Estimate (Xi)**	**Limit xi(Xi)**	**Probability Distribution Type A/B**	**Standard uncertainty u xi(Xi)**	**Sensitivity coefficient ci**	**Uncertainty contribution |ci| uxi(Xi)**	**Degree of freedom (vi)**
Reference Standard $K_{S}(f)$	0.9617	0.0072	Normal Type B 2	0.00360	1	0.00360	∞
Drift in Cal Factor $\delta K_S(f)$	0.001	0.0020	Rectangular Type B √3	0.00115	1	0.00115	∞
Stability 50 MHz ref Source	1	0.0030	Rectangular Type B √3	0.00173	1	0.00173	∞
Instrument Non-Linearity	1	0.0010	Normal Type B 2	0.00050	1	0.00050	∞
Power ratio Ps	1.0089	0.0010	Normal Type B 2	0.00050	1	0.00050	∞
Power ratio P_D	0.9411	0.0009	Normal Type B 2	0.00045	1	0.00045	∞
Mismatch wrt Source to STD	1	0.0096	U Shape Type B √2	0.00681	1	0.00681	∞
Mismatch wrt Source to DUC	1	0.0033	U Shape Type B √2	0.00235	1	0.00235	∞
Repeatability			Type A	0.00047		0.00047	7
Combined Standard Uncertainty $u_c K_D(f)$						**0.00837**	
Expanded Uncertainty $UK_D(f)$		**Coverage Factor @ 95%**	**k = 1.96**	**Effective degree of freedom**			**412220**
			0.0164			1.64	%

UNCERTAINTY BUDGET	Calibration Factor HP8481A Power Sensor; Sno. US41031013, APMP.EM.RF-K8.CL						
POINT OF CALCULATION:			15 GHz				
Source of uncertainty	**Estimate (Xi)**	**Limit xi(Xi)**	**Probability Distribution Type A/B**	**Standard uncertainty u xi(Xi)**	**Sensitivity coefficient ci**	**Uncertainty contribution |ci| uxi(Xi)**	**Degree of freedom (vi)**
Reference Standard Ks(f)	0.9569	0.0076	Normal Type B 2	0.00380	1	0.00380	∞
Drift in Cal Factor δKs(f)	0.001	0.0020	Rectangular Type B √3	0.00115	1	0.00115	∞
Stability 50 MHz ref Source	1	0.0030	Rectangular Type B √3	0.00173	1	0.00173	∞
Instrument Non-Linearity	1	0.0010	Normal Type B 2	0.00050	1	0.00050	∞
Power ratio Ps	1.0079	0.0008	Normal Type B 2	0.00040	1	0.00040	∞
Power ratio PD	0.9236	0.0010	Normal Type B 2	0.00050	1	0.00050	∞
Mismatch wrt Source to STD	1	0.0098	U Shape Type B √2	0.00691	1	0.00691	∞
Mismatch wrt Source to DUC	1	0.0048	U Shape Type B √2	0.00341	1	0.00341	∞
Repeatability			Type A	0.00047		0.00047	7
Combined Standard Uncertainty u_c KD(f)						**0.00889**	
Expanded Uncertainty UKD(f)		**Coverage Factor @ 95%**	**k = 1.96**	**Effective degree of freedom**			**505614**
				0.0174		1.74	%

UNCERTAINTY BUDGET	Calibration Factor HP8481A Power Sensor; Sno. US41031013, APMP.EM.RF-K8.CL						
POINT OF CALCULATION:			18 GHz				
Source of uncertainty	**Estimate (Xi)**	**Limit xi(Xi)**	**Probability Distribution Type A/B**	**Standard uncertainty u xi(Xi)**	**Sensitivity coefficient ci**	**Uncertainty contribution |ci| uxi(Xi)**	**Degree of freedom (vi)**
Reference Standard $K_{s(f)}$	0.9398	0.0094	Normal Type B 2	0.00470	1	0.00470	∞
Drift in Cal Factor δKs(f)	0.001	0.0020	Rectangular Type B √3	0.00115	1	0.00115	∞
Stability 50 MHz ref Source	1	0.0030	Rectangular Type B √3	0.00173	1	0.00173	∞
Instrument Non-Linearity	1	0.0010	Normal Type B 2	0.00050	1	0.00050	∞
Power ratio Ps	1.0301	0.0008	Normal Type B 2	0.00040	1	0.00040	∞
Power ratio P_D	0.9390	0.0008	Normal Type B 2	0.00040	1	0.00040	∞
Mismatch wrt Source to STD	1	0.0103	U Shape Type B √2	0.00730	1	0.00730	∞
Mismatch wrt Source to DUC	1	0.0101	U Shape Type B √2	0.00717	1	0.00717	∞
Repeatability			Type A	0.00044		0.00044	7
Combined Standard Uncertainty $u_c K_{D(f)}$						**0.01149**	
Expanded Uncertainty $UK_{D(f)}$		**Coverage Factor @ 95%**	**k = 1.96**	**Effective degree of freedom**			**1855294**
			0.0225			2.25	%

--------------- END OF REPORT -----------------

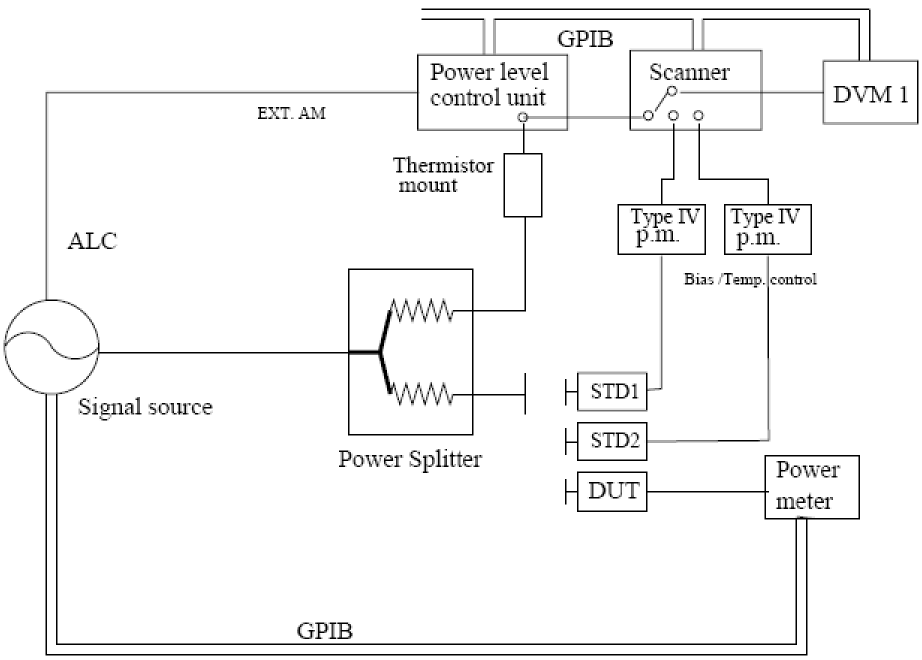
Report on

APMP.EM.RF-K8.CL "Power in 50 Ω coaxial line, frequency: 10 MHz to 18 GHz"

1. Laboratory Identification

Name: JeongIl Park, TaeWeon Kang, Jae-Yong Kwon, JeongHwan Kim
Institute: Korea Research Institute of Standards and Science (KRISS)
Address: P.O.Box 102, Yuseong, Daejeon 305-600, Korea
E-mail: kimjh@kriss.re.kr
TEL: +82-42-868-5170
FAX: +82-42-868-5018

2. Description of measurement



Measurement setup

The traveling standards were calibrated by a direct comparison system with the coaxial transfer standards. The effective efficiencies of the transfer standards are calibrated with the new Type-N microcalorimeter at KRISS.

The reflection coefficients of the traveling standards were measured using a VNA calibrated using the SOSL (Short/Open/Sliding load) technique and a Type-N calibration kit traceable to the impedance standards of the KRISS.

3. Measurement results (Calibration factor)

1) Agilent 8481A thermocouple power sensor (US41031012)

Frequency (GHz)	Calibration factor	Uncertainty 1 standard deviation
0.01	0.9971	0.0018
0.05	0.9919	0.0017
1	0.9750	0.0024
4	0.9669	0.0022
8	0.9515	0.0030
12	0.9287	0.0025
15	0.9141	0.0030
18	0.9169	0.0056

2) Agilent 8481A thermocouple power sensor (US41031013)

Frequency (GHz)	Calibration Factor	Uncertainty 1 standard deviation
0.01	0.9953	0.0017
0.05	0.9912	0.0016
1	0.9751	0.0024
4	0.9671	0.0022
8	0.9511	0.0030
12	0.9286	0.0025
15	0.9136	0.0029
18	0.9159	0.0052

4. Measurement results (Reflection coefficient)

1) Agilent 8481A thermocouple power sensor (US41031012)

Frequency (GHz)	**Reflection coefficient**		Uncertainty 1 standard deviation
	Real	**Imag**	
0.01	0.0076	- 0.0626	0.0061
0.05	- 0.0012	- 0.0134	0.0061
1	0.0096	- 0.0027	0.0061
4	0.0112	0.0105	0.0100
8	- 0.0146	- 0.0118	0.0101
12	- 0.0284	0.0133	0.0103
15	- 0.0112	0.0310	0.0103
18	- 0.0492	0.0566	0.0106

2) Agilent 8481A thermocouple power sensor (US41031013)

Frequency (GHz)	**Reflection coefficient**		Uncertainty 1 standard deviation
	Real	**Imag**	
0.01	0.0085	- 0.0641	0.0062
0.05	0.0002	- 0.0138	0.0061
1	0.0093	- 0.0044	0.0061
4	0.0121	0.0050	0.0100
8	- 0.0165	- 0.0078	0.0101
12	- 0.0206	0.0073	0.0102
15	- 0.0047	0.0201	0.0102
18	- 0.0387	0.0465	0.0105

5. **Uncertainty**

1) Agilent 8481A (US41031012)

US41031012

Frequency : 0.01 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	0.0012	1.0089	0.0012
Calibration factor of the transfer standard 2	B	Normal	0.0012	1.0059	0.0012
Power ratio of the transfer standard 1	B	Normal	0.0006	1.0505	0.0006
Power ratio of the transfer standard 2	B	Normal	0.0007	1.0535	0.0008
Power ratio of the traveling standard	B	Normal	0.0007	1.0631	0.0008
Mismatch between the transfer std. 1 and traveling std.	B	Normal	0.0004	1.0006	0.0004
Mismatch between the transfer std. 2 and traveling std.	B	Normal	0.0004	0.9999	0.0004
Measurement repeatability	A	Normal	0.0008	1.0000	0.0008
Combined uncertainty (1 standard deviation)					0.0018

US41031012

Frequency : 0.05 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	0.0012	0.9956	0.0011
Calibration factor of the transfer standard 2	B	Normal	0.0012	0.9951	0.0011
Power ratio of the transfer standard 1	B	Normal	0.0006	1.0047	0.0006
Power ratio of the transfer standard 2	B	Normal	0.0007	1.0059	0.0007
Power ratio of the traveling standard	B	Normal	0.0007	1.0008	0.0007
Mismatch between the transfer std. 1 and traveling std.	B	Normal	0.0001	0.9918	0.0001
Mismatch between the transfer std. 2 and traveling std.	B	Normal	0.0001	0.9924	0.0001
Measurement repeatability	A	Normal	0.0007	1.0000	0.0007
Combined uncertainty (1 standard deviation)					0.0017

US41031012

Frequency : 1 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	0.0014	0.9873	0.0014
Calibration factor of the transfer standard 2	B	Normal	0.0014	0.9853	0.0014
Power ratio of the transfer standard 1	B	Normal	0.0009	0.9931	0.0009
Power ratio of the transfer standard 2	B	Normal	0.0010	0.9943	0.0010
Power ratio of the traveling standard	B	Normal	0.0011	0.9810	0.0011
Mismatch between the transfer std. 1 and traveling std.	B	Normal	0.0005	0.9759	0.0004
Mismatch between the transfer std. 2 and traveling std.	B	Normal	0.0005	0.9760	0.0005
Measurement repeatability	A	Normal	0.0011	1.0000	0.0011
Combined uncertainty (1 standard deviation)					0.0024

US41031012

Frequency : 4 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	0.0017	0.9884	0.0016
Calibration factor of the transfer standard 2	B	Normal	0.0017	0.9831	0.0017
Power ratio of the transfer standard 1	B	Normal	0.0003	0.9935	0.0003
Power ratio of the transfer standard 2	B	Normal	0.0003	0.9961	0.0003
Power ratio of the traveling standard	B	Normal	0.0003	0.9818	0.0003
Mismatch between the transfer std. 1 and traveling std.	B	Normal	0.0008	0.9677	0.0008
Mismatch between the transfer std. 2 and traveling std.	B	Normal	0.0012	0.9686	0.0012
Measurement repeatability	A	Normal	0.0002	1.0000	0.0002
Combined uncertainty (1 standard deviation)					0.0022

US41031012

Frequency : 8 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	0.0020	0.9884	0.0019
Calibration factor of the transfer standard 2	B	Normal	0.0021	0.9767	0.0020
Power ratio of the transfer standard 1	B	Normal	0.0007	1.0069	0.0007
Power ratio of the transfer standard 2	B	Normal	0.0008	1.0162	0.0008
Power ratio of the traveling standard	B	Normal	0.0010	0.9903	0.0010
Mismatch between the transfer std. 1 and traveling std.	B	Normal	0.0013	0.9494	0.0012
Mismatch between the transfer std. 2 and traveling std.	B	Normal	0.0013	0.9467	0.0013
Measurement repeatability	A	Normal	0.0010	1.0000	0.0010
Combined uncertainty (1 standard deviation)					0.0030

US41031012

Frequency : 12 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	0.0023	0.9781	0.0022
Calibration factor of the transfer standard 2	B	Normal	0.0024	0.9608	0.0023
Power ratio of the transfer standard 1	B	Normal	0.0003	0.9737	0.0003
Power ratio of the transfer standard 2	B	Normal	0.0003	0.9848	0.0002
Power ratio of the traveling standard	B	Normal	0.0003	0.9503	0.0003
Mismatch between the transfer std. 1 and traveling std.	B	Normal	0.0009	0.9310	0.0009
Mismatch between the transfer std. 2 and traveling std.	B	Normal	0.0009	0.9285	0.0008
Measurement repeatability	A	Normal	0.0002	1.0000	0.0002
Combined uncertainty (1 standard deviation)					0.0025

US41031012

Frequency : 15 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	0.0026	0.9776	0.0025
Calibration factor of the transfer standard 2	B	Normal	0.0026	0.9518	0.0025
Power ratio of the transfer standard 1	B	Normal	0.0004	0.9658	0.0004
Power ratio of the transfer standard 2	B	Normal	0.0005	0.9822	0.0005
Power ratio of the traveling standard	B	Normal	0.0006	0.9435	0.0006
Mismatch between the transfer std. 1 and traveling std.	B	Normal	0.0007	0.9165	0.0006
Mismatch between the transfer std. 2 and traveling std.	B	Normal	0.0017	0.9195	0.0015
Measurement repeatability	A	Normal	0.0006	1.0000	0.0006
Combined uncertainty (1 standard deviation)					0.0030

US41031012

Frequency : 18 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	0.0029	0.9940	0.0028
Calibration factor of the transfer standard 2	B	Normal	0.0029	0.9659	0.0028
Power ratio of the transfer standard 1	B	Normal	0.0003	1.0006	0.0003
Power ratio of the transfer standard 2	B	Normal	0.0003	1.0241	0.0003
Power ratio of the traveling standard	B	Normal	0.0003	0.9926	0.0003
Mismatch between the transfer std. 1 and traveling std.	B	Normal	0.0034	0.9167	0.0031
Mismatch between the transfer std. 2 and traveling std.	B	Normal	0.0054	0.9186	0.0049
Measurement repeatability	A	Normal	0.0003	1.0000	0.0003
Combined uncertainty (1 standard deviation)					0.0056

2) Agilent 8481A (US41031013)

US41031013

Frequency : 0.01 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	0.0012	1.0070	0.0012
Calibration factor of the transfer standard 2	B	Normal	0.0012	1.0041	0.0012
Power ratio of the transfer standard 1	B	Normal	0.0006	1.0485	0.0006
Power ratio of the transfer standard 2	B	Normal	0.0007	1.0516	0.0008
Power ratio of the traveling standard	B	Normal	0.0007	1.0592	0.0007
Mismatch between the transfer std. 1 and traveling std.	B	Normal	0.0004	0.9988	0.0004
Mismatch between the transfer std. 2 and traveling std.	B	Normal	0.0004	0.9980	0.0004
Measurement repeatability	A	Normal	0.0008	1.0000	0.0008
Combined uncertainty (1 standard deviation)					0.0017

US41031013

Frequency : 0.05 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	0.0012	0.9949	0.0011
Calibration factor of the transfer standard 2	B	Normal	0.0012	0.9944	0.0011
Power ratio of the transfer standard 1	B	Normal	0.0006	1.0039	0.0006
Power ratio of the transfer standard 2	B	Normal	0.0007	1.0051	0.0007
Power ratio of the traveling standard	B	Normal	0.0007	0.9994	0.0007
Mismatch between the transfer std. 1 and traveling std.	B	Normal	0.0001	0.9911	0.0001
Mismatch between the transfer std. 2 and traveling std.	B	Normal	0.0001	0.9917	0.0001
Measurement repeatability	A	Normal	0.0007	1.0000	0.0007
Combined uncertainty (1 standard deviation)					0.0016

US41031013

Frequency : 1 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	0.0014	0.9873	0.0014
Calibration factor of the transfer standard 2	B	Normal	0.0014	0.9854	0.0014
Power ratio of the transfer standard 1	B	Normal	0.0009	0.9932	0.0009
Power ratio of the transfer standard 2	B	Normal	0.0010	0.9943	0.0010
Power ratio of the traveling standard	B	Normal	0.0011	0.9811	0.0010
Mismatch between the transfer std. 1 and traveling std.	B	Normal	0.0005	0.9760	0.0005
Mismatch between the transfer std. 2 and traveling std.	B	Normal	0.0005	0.9761	0.0005
Measurement repeatability	A	Normal	0.0011	1.0000	0.0011
Combined uncertainty (1 standard deviation)					0.0024

US41031013

Frequency : 4 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	0.0017	0.9886	0.0016
Calibration factor of the transfer standard 2	B	Normal	0.0017	0.9833	0.0017
Power ratio of the transfer standard 1	B	Normal	0.0003	0.9937	0.0003
Power ratio of the transfer standard 2	B	Normal	0.0003	0.9963	0.0003
Power ratio of the traveling standard	B	Normal	0.0004	0.9825	0.0004
Mismatch between the transfer std. 1 and traveling std.	B	Normal	0.0008	0.9681	0.0008
Mismatch between the transfer std. 2 and traveling std.	B	Normal	0.0012	0.9690	0.0012
Measurement repeatability	A	Normal	0.0002	1.0000	0.0002
Combined uncertainty (1 standard deviation)					0.0022

US41031013

Frequency : 8 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	0.0020	0.9880	0.0019
Calibration factor of the transfer standard 2	B	Normal	0.0021	0.9763	0.0020
Power ratio of the transfer standard 1	B	Normal	0.0007	1.0064	0.0007
Power ratio of the transfer standard 2	B	Normal	0.0008	1.0157	0.0008
Power ratio of the traveling standard	B	Normal	0.0010	0.9897	0.0010
Mismatch between the transfer std. 1 and traveling std.	B	Normal	0.0012	0.9494	0.0012
Mismatch between the transfer std. 2 and traveling std.	B	Normal	0.0013	0.9467	0.0012
Measurement repeatability	A	Normal	0.0010	1.0000	0.0010
Combined uncertainty (1 standard deviation)					0.0030

US41031013

Frequency : 12 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	0.0023	0.9779	0.0022
Calibration factor of the transfer standard 2	B	Normal	0.0024	0.9607	0.0023
Power ratio of the transfer standard 1	B	Normal	0.0003	0.9736	0.0003
Power ratio of the transfer standard 2	B	Normal	0.0003	0.9847	0.0002
Power ratio of the traveling standard	B	Normal	0.0003	0.9498	0.0003
Mismatch between the transfer std. 1 and traveling std.	B	Normal	0.0009	0.9306	0.0009
Mismatch between the transfer std. 2 and traveling std.	B	Normal	0.0009	0.9281	0.0008
Measurement repeatability	A	Normal	0.0002	1.0000	0.0002
Combined uncertainty (1 standard deviation)					0.0025

US41031013

Frequency : 15 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	0.0026	0.9771	0.0025
Calibration factor of the transfer standard 2	B	Normal	0.0026	0.9513	0.0025
Power ratio of the transfer standard 1	B	Normal	0.0004	0.9654	0.0004
Power ratio of the transfer standard 2	B	Normal	0.0005	0.9817	0.0005
Power ratio of the traveling standard	B	Normal	0.0005	0.9423	0.0005
Mismatch between the transfer std. 1 and traveling std.	B	Normal	0.0007	0.9158	0.0006
Mismatch between the transfer std. 2 and traveling std.	B	Normal	0.0016	0.9187	0.0014
Measurement repeatability	A	Normal	0.0006	1.0000	0.0006
Combined uncertainty (1 standard deviation)					0.0029

US41031013

Frequency : 18 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	0.0029	0.9937	0.0028
Calibration factor of the transfer standard 2	B	Normal	0.0029	0.9639	0.0028
Power ratio of the transfer standard 1	B	Normal	0.0004	1.0003	0.0004
Power ratio of the transfer standard 2	B	Normal	0.0003	1.0220	0.0003
Power ratio of the traveling standard	B	Normal	0.0003	0.9945	0.0003
Mismatch between the transfer std. 1 and traveling std.	B	Normal	0.0030	0.9195	0.0028
Mismatch between the transfer std. 2 and traveling std.	B	Normal	0.0049	0.9214	0.0045
Measurement repeatability	A	Normal	0.0003	1.0000	0.0003
Combined uncertainty (1 standard deviation)					0.0052

APMP KEY COMPARISON APMP.EM.RF-K8.CL

"Power in 50 Ω coaxial line, frequency: 10 MHz to 18 GHz"

Measurement Report

(1) Organization, country, contact person, and address
National Institute of Metrology (NIM)
The People's Republic of China,
Dr. Yuan Wenze yuanwz@nim.ac.cn
Dr. Liu Xinmeng liuxm@nim.ac.cn
No. 18, Bei San Huan DongLu, Beijing, China
Note: The experiment, data acquisition and processing, and initial draft of the comparison report were all completed independently by Dr. Liu. Due to Dr. Liu's job change, Dr. Yuan completed the report revision and submitted it to the pilot laboratory.

(2) Measurement methods
The measurement method is comparison method. This calibration method has not been modified after CCEM.RF-K8.CL. A RF source, a resistive power splitter, and a monitoring power meter constitute a transfer standard system. The monitoring power meter and the RF source are connected to form a closed-loop feedback system with a constant amplitude output. The output port of the resistive power splitter is the test port of the transfer standard system. The reference standard and the travelling standard are alternately connected to test port of the power transfer standard system. The reference standard is a thermistor power sensor, and its calibration factor is by the effective efficiency measured with the microcalorimeter developed by NIM and the reflection coefficient traceable to national scattering parameter standard at NIM.

The measurement results of travelling standards are calculated according to the formula below:

$$K_u = K_s \frac{P_{bu}}{P_{bs}} \frac{M_u}{M_s}$$

Where K_u is the calibration factor of the travelling standard, K_s is the calibration factor of the reference standard, P_{bu} is the power meter readout of travelling standard, P_{bs} is the power meter readout of reference standard, M_u and M_s are the mismatch factors. In this comparison measurement, no complex mismatch correction was made, and the mismatch factor M_u, M_s follow U-distribution. In the comparison experiment, 6 independent repeated connection measurements were completed.

The uncertainty budget with all uncertainty source is listed in the table 1.

Table 1. The uncertainty budget of the calibration factor K_u

Uncertainty	Quantity	Probability distribution/ method of evaluation (A, B)	Sensitivity coefficient	Degrees of freedom
$u(K_s)$	Calibration factor of reference standard	Normal/B	1	∞
$u(P_{bs})$	Power meter readout of reference standard	Uniform/B	1	∞
$u(P_{bu})$	Power meter readout of travelling standard	Uniform/B	1	∞
$u(M_s)$	Mismatch factor	U-shaped/B	1	∞
$u(M_u)$	Mismatch factor	U-shaped/B	1	∞
$s(K_u)$	Repeatability	Normal/A	1	5

(3) Measuring system

The measurement system is shown Fig.1. The measurement system is composed of a RF source, a resistive power splitter, and a monitoring power meter. The monitoring power meter, connected to the signal source, utilizes closed-loop feedback control to form a stable-amplitude power transfer system. The output port of the power splitter is the test port of the transfer standard system.

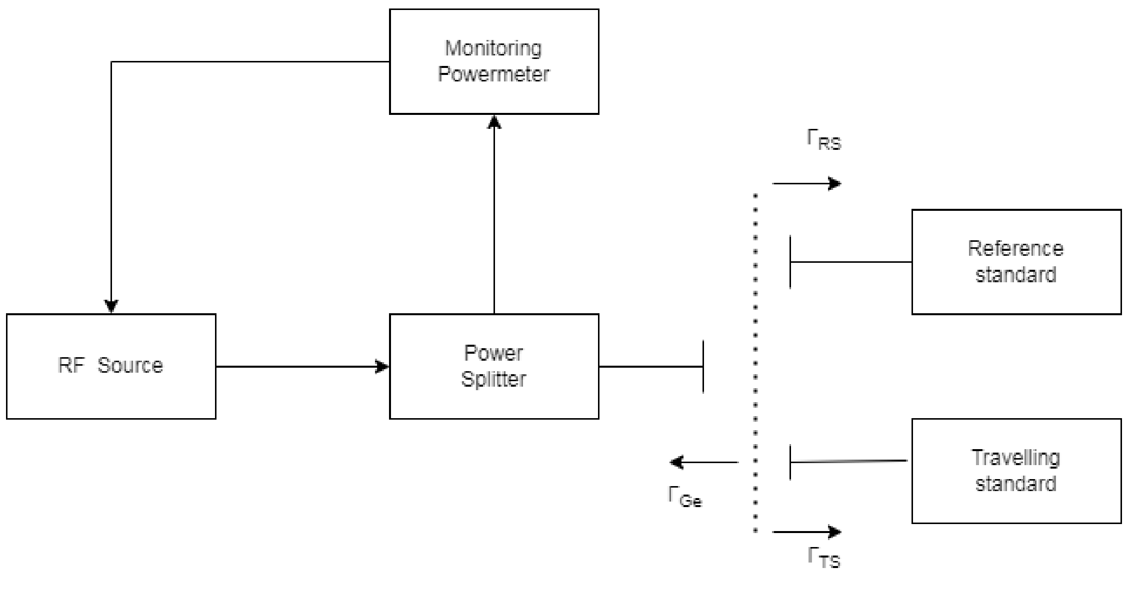


Fig.1　(0.01～18) GHz Type N Connector RF Power Transfer System

(4) Measurement results

Table 2 The calibration factor of No.1 travelling standard

Frequency [GHz]	Calibration factor *K*	Combined standard uncertainty $u_c(K)$	Coverage factor *k* corresponding to a level of confidence of 95 %
0.01	0.9859	0.0049	2
0.05	0.9916	0.0049	2
1	0.9752	0.0048	2
4	0.9655	0.0053	2
8	0.9569	0.0063	2
12	0.9256	0.0064	2
15	0.9065	0.0077	2
18	0.8975	0.0078	2

Table 3 The calibration factor of No.2 travelling standard

Frequency [GHz]	Calibration factor *K*	Combined standard uncertainty $u_c(K)$	Coverage factor *k* corresponding to a level of confidence of 95 %
0.01	0.9870	0.0049	2
0.05	0.9937	0.0048	2
1	0.9773	0.0045	2
4	0.9674	0.0049	2
8	0.9540	0.0052	2
12	0.9267	0.0053	2
15	0.9056	0.0063	2
18	0.9008	0.0071	2

(5) Measurement conditions

Ambient temperature: 23 °C

Humidity: 52 %.

(6) Reflection coefficient

Table 4 The refection coefficient of No.1 travelling standard

Frequency [GHz]	Real component [Lin.]	Imaginary component [Lin.]	Uncertainty of magnitude [Lin.]
0.01	0.007	-0.063	0.009
0.05	-0.001	-0.014	0.009
1	0.008	-0.004	0.016

4	0.011	0.011	0.016
8	-0.012	-0.011	0.017
12	-0.027	0.013	0.017
15	-0.008	0.028	0.017
18	-0.054	0.054	0.009

Table 5 The refection coefficient of No.2 travelling standard

Frequency [GHz]	Real component [Lin.]	Imaginary component [Lin.]	Uncertainty of magnitude [Lin.]
0.01	0.008	-0.064	0.009
0.05	0.000	-0.014	0.009
1	0.008	-0.005	0.016
4	0.012	0.006	0.016
8	-0.015	-0.006	0.017
12	-0.018	0.006	0.016
15	-0.002	0.014	0.017
18	-0.044	0.044	0.009

Appendix

The uncertainty budget of comparison results of No.1

Frequency [GHz]	Calibration factor *K*	Combined standard uncertainty $u_c(K)$ (k = 1)	$u(K_s)$	$u(P_{bs})$	$u(P_{bu})$	$u(M)$	$u(K)$
0.01	0.9859	0.0049	0.0033	0.00173	0.0029	0.00011	0.00142
0.05	0.9916	0.0049	0.0032	0.00173	0.0029	0.00013	0.00161
1	0.9752	0.0048	0.0028	0.00173	0.0029	0.00008	0.00196
4	0.9655	0.0053	0.0033	0.00173	0.0029	0.00024	0.00234
8	0.9569	0.0063	0.0037	0.00173	0.0029	0.00013	0.0038
12	0.9256	0.0064	0.0039	0.00173	0.0029	0.00053	0.0037
15	0.9065	0.0077	0.0053	0.00173	0.0029	0.00048	0.00441
18	0.8975	0.0078	0.0060	0.00173	0.0029	0.0019	0.00312

The uncertainty budget of comparison results of No.2

Frequency [GHz]	Calibration factor *K*	Combined standard uncertainty $u_c(K)$ (k = 1)	$u(K_s)$	$u(P_{bs})$	$u(P_{bu})$	$u(M)$	$u(K)$
0.01	0.9870	0.0049	0.0033	0.00173	0.0029	0.00012	0.00124
0.05	0.9937	0.0048	0.0032	0.00173	0.0029	0.00013	0.00124
1	0.9773	0.0045	0.0028	0.00173	0.0029	0.00009	0.00106
4	0.9674	0.0049	0.0033	0.00173	0.0029	0.00021	0.00125

8	0.9540	0.0052	0.0037	0.00173	0.0029	0.00012	0.00134
12	0.9267	0.0053	0.0039	0.00173	0.0029	0.00034	0.00127
15	0.9056	0.0063	0.0053	0.00173	0.0029	0.00023	0.00079
18	0.9008	0.0071	0.0060	0.00173	0.0029	0.00154	0.00064

National Institute of Metrology (Thailand)
Ministry of Science and Technology

Certificate of Calibration

Certificate No. : EF-14-0013AA

Issued by : RF & Microwave Laboratory, Electrical Metrology Department

MEASUREMENT ITEM	:	Power Sensors and Power Meter
MANUFACTURER	:	Agilent Technologies
MODEL/TYPE	:	8481A and E4419B
SERIAL NUMBER	:	US41031012, US41031013 and MY45100436
CUSTOMER	:	RF & Microwave Laboratory (APMP.EM.RF-K8.CL) Electrical Metrology Department 3/4-5 Moo 3, Klong 5, Klong Luang, Pathumthani 12120
MEASUREMENT DATE	:	5 May 2014

This certificate replaces the certificate number EF-14-0013

Reference:	**Date:**	**Approved by:**	**Performed by:**
MSR No. I-14-195	25 August 2016	(Chalit Kumtawee)	(Sarinya Pasakawee)

Partial reproduction of this certificate is permitted only with a written permission from NIMT.

ENVIRONMENTAL CONDITIONS

The measurement was carried out in an ambient temperature of (23.0 ± 2.0) °C and relative humidity of (50 ± 15) %.

MEASUREMENT METHOD

The power sensors were calibrated by comparing their output settings with the measured values obtained from standards that maintained by NIMT RF & Microwave Laboratory.

UNCERTAINTIES OF MEASUREMENT

The stated measurement uncertainties are the expanded measurement uncertainties obtained from the combined standard measurement uncertainties multiplied by the coverage factor $k = 2$. They are determined in accordance with JCGM 100: 2008 "Evaluation of measurement data - Guide to the expression of uncertainty in measurement". The values of the measurand lie within the assigned range of values with a probability of approximately 95 %.

TRACEABILITY

This certificate provides traceability of measurement to recognized national standards, and to the realization of the International System of Units (SI).

MEASUREMENT RESULTS

Measurement Condition

The calibration factor of the power sensor was measured at a nominal power level of 1 mW at frequency between 10 MHz and 18 000 MHz.

The calibration factor is defined as follows:

$$\textit{Calibration Factor at calibration frequency} = \frac{\textit{Indicated power of the power meter at calibration frequency}}{\textit{RF Power Standard at calibration frequency}} \times 100\%$$

The measured values relate to the performance of the device under test when connected in to a transmission line system having a characteristic impedance of 50 ohm.

MEASUREMENT RESULTS

Power Sensor S/N US41031012 and Power Meter S/N MY 45100436

Frequency	Calibration Factor	Uncertainty
10 MHz	98.9 %	1.3 %
50 MHz	99.6 %	1.2 %
1 000 MHz	98.2 %	1.3 %
4 000 MHz	97.2 %	1.4 %
8 000 MHz	96.3 %	1.9 %
12 000 MHz	93.4 %	2.0 %
15 000 MHz	91.9 %	1.5 %
18 000 MHz	91.8 %	2.4 %

Power Sensor S/N US41031013 and Power Meter S/N MY 45100436

Frequency	Calibration Factor	Uncertainty
10 MHz	98.7 %	1.3 %
50 MHz	99.5 %	1.2 %
1 000 MHz	98.2 %	1.3 %
4 000 MHz	97.1 %	1.4 %
8 000 MHz	96.1 %	1.9 %
12 000 MHz	93.4 %	2.0 %
15 000 MHz	91.8 %	1.4 %
18 000 MHz	91.9 %	2.4 %

End of Certificate of Calibration

Uncertainty budget (NIMT)
Sensor No.1

Freq. (GHz)	Ks	Uncert. [%]	u(Ks1)	D.F.	u(Ks2)	D.F.	u(Ks3)	D.F.	Pdu (mW)	Pds,ave (mW)	u(Pds1) (mW)	D.F.	u(Pds2) (mW)	D.F.	u(Pds3) (mW)	D.F.
0.01	1.0140	0.9	0.0046	α	0.0008	α	5 8E-04	α	0.975	1.000	1 9E-04	4	2.8E-04	α	1.3E-03	5
0.05	0.991	0.9	0.0045	a	0.0013	a	5 8E-04	a	1.005	1.000	2 2E-04	4	2.8E-04	a	1.3E-03	5
1	0.975	1.0	0.0049	a	0.0021	a	5 8E-04	a	1.007	1.000	2 3E-04	4	2.8E-04	a	1.3E-03	5
4	0.955	1.1	0.0053	a	0.0029	a	5 8E-04	a	1.018	1.000	3 5E-04	4	2.8E-04	a	1.3E-03	5
8	0.942	1.7	0.0080	a	0.0028	a	5 8E-04	a	1.022	1.000	3.4E-04	4	2.8E-04	a	1.3E-03	5
12	0.927	1.6	0.0074	a	0.0039	a	5 8E-04	a	1.007	1.000	4.1E-04	4	2.8E-04	a	1.3E-03	5
15	0.927	1.1	0.0051	a	0.0019	a	5 8E-04	a	0.992	1.000	3.4E-04	4	2.8E-04	a	1.3E-03	5
18	0 9160	1.8	0.0082	α	0.0036	α	5 8E-04	α	1.002	1.000	2 3E-04	4	2.8E-04	α	1.3E-03	5
	Calibration Factor calculation at calibration frequency															
	Uncertainty due to RF Power standard (Feedthrough Mount)								Uncertainty due to the Other Error							
	Uncertainty from Upper Std				Secular variation		Linearity		Nominal value	Average value	Repetitive		Resolution of E4419B		Short term stability	
	Calibration Factor	Relative uncertainty	Absolute uncertainty													

Freq. (GHz)	u(Pds4) (mW)	D.F.	u(Pds5) (mW)	D.F.	u(Pds6) (mW)	D.F.	Mu	Γu	Γg	u(Mu)	D.F.	Ku	Ku = Kc/Kr	u_c(Ku)	U(Ku) (%)	Veff	k	CMC (%)
0.01	5 2E-05	5	3.4E-05	2	2 5E-03	α	1	0.074	0.0290	3.0E-03	8	0.989	0.993	0.006	1.3	5E+06	2.00	1.7
0.05	5 2E-05	5	3.4E-05	2	2 5E-03	a	1	0.014	0.0290	5.7E-04	8	0.996	1.000	0.006	1.2	2E+06	2.00	1.7
1	5 2E-05	5	3.4E-05	2	2 5E-03	a	1	0.010	0.0290	4.1E-04	8	0.982	0.986	0.006	1.3	2E+06	2.00	1.8
4	5 2E-05	5	2.4E-06	2	2 5E-03	a	1	0.009	0.0290	3.7E-04	8	0.972	0.976	0.007	1.4	5E+05	2.00	1.8
8	5 2E-05	5	2.4E-06	2	2 5E-03	a	1	0.020	0.0480	1.4E-03	8	0.963	0.967	0.009	1.9	2E+06	2.00	2.3
12	5 2E-05	5	2.4E-06	2	2 5E-03	a	1	0.036	0.0480	2.4E-03	8	0.934	0.938	0.009	2.0	1E+06	2.00	2.3
15	5 2E-05	5	9.0E-06	2	2 5E-03	a	1	0.032	0.0480	2 2E-03	8	0.919	0.923	0.007	1.5	5E+05	2.00	2.0
18	5 2E-05	5	9.0E-06	2	2 5E-03	α	1	0.073	0.0480	5.0E-03	8	0.918	0.922	0.011	2.4	2E+07	2.00	2.5
												Uncertainty of measurement						
							Mismatch Error											
	Long term stability		Spurious power of the SG		Temperature room			Input Reflect of UUT	Output Reflect of RF std	Multiple Reflect calculated from (2*ΓsΓg)/sqrt(2)		CF of UUT absolute	relative	Sum of absolute value	Expand Uncert	Degree of freedom	Coverage factor	

Description

Std	Feedthrough Mount	**Model**	1807A	**S/N**	2246
UUT	Power sensor	**Model**	8481A	**S/N**	US41031012

Uncertainty budget (NIMT)
Sensor No.2

Freq. (GHz)	Ks	Uncert. [%]	u(Ks1)	D.F.	u(Ks2)	D.F.	u(Ks3)	D.F.	Pdu (mW)	Pds,ave (mW)	u(Pds1) (mW)	D.F.
0.01	1.0140	0.9	0.0046	α	0.0008	α	5 8E-04	α	0.973	1.000	5 3E-04	4
0.05	0.991	0.9	0.0045	a	0.0013	a	5 8E-04	a	1.004	1.000	5.1E-04	4
1	0.975	1.0	0.0049	a	0.0021	a	5 8E-04	a	1.007	1.000	5 3E-04	4
4	0.955	1.1	0.0053	a	0.0029	a	5 8E-04	a	1.017	1.000	4 8E-04	4
8	0.942	1.7	0.0080	a	0.0028	a	5 8E-04	a	1.020	1.000	7.1E-04	4
12	0.927	1.6	0.0074	a	0.0039	a	5 8E-04	a	1.007	1.000	6.0E-04	4
15	0.927	1.1	0.0051	a	0.0019	a	5 8E-04	a	0.991	1.000	7 3E-04	4
18	0 9160	1.8	0.0082	α	0.0036	α	5 8E-04	α	1.003	1.000	6 5E-04	4
	Calibration Factor calculation at calibration frequency											
	Uncertainty due to RF Power standard (Feedthrough Mount)								Uncertainty due to the Other Error			
	Uncertainty from Upper Std				Secular variation		Linearity		Nominal value	Average value	Repetitive	
	Calibration Factor	Relative uncertainty	Absolute uncertainty									

Freq. (GHz)	u(Pds2) (mW)	D.F.	u(Pds3) (mW)	D.F.	u(Pds4) (mW)	D.F.	u(Pds5) (mW)	D.F.	u(Pds6) (mW)	D.F.	Mu	Γu	Γg	u(Mu)	D.F.	Ku	Ku = Kc/Kr	u_c(Ku)	U(Ku) (%)	Veff	k	CMC (%)
0.01	2.8E-04	α	1.3E-03	5	5 2E-05	5	3.4E-05	2	2 5E-03	α	1	0.074	0.0290	3.0E-03	8	0.987	0.992	0.006	1.3	8E+04	2.00	1.7
0.05	2.8E-04	a	1.3E-03	5	5 2E-05	5	3.4E-05	2	2 5E-03	a	1	0.014	0.0290	5.7E-04	8	0.995	1.000	0.006	1.2	5E+04	2.00	1.7
1	2.8E-04	a	1.3E-03	5	5 2E-05	5	3.4E-05	2	2 5E-03	a	1	0.010	0.0290	4.1E-04	8	0.982	0.987	0.006	1.3	7E+04	2.00	1.8
4	2.8E-04	a	1.3E-03	5	5 2E-05	5	2.4E-06	2	2 5E-03	a	1	0.006	0.0290	2 5E-04	8	0.971	0.976	0.007	1.4	1E+05	2.00	1.8
8	2.8E-04	a	1.3E-03	5	5 2E-05	5	2.4E-06	2	2 5E-03	a	1	0.018	0.0480	1 2E-03	8	0.961	0.966	0.009	1.9	1E+05	2.00	2.3
12	2.8E-04	a	1.3E-03	5	5 2E-05	5	2.4E-06	2	2 5E-03	a	1	0.026	0.0480	1 8E-03	8	0.934	0.939	0.009	2.0	2E+05	2.00	2.3
15	2.8E-04	a	1.3E-03	5	5 2E-05	5	9.0E-06	2	2 5E-03	a	1	0.022	0.0480	1 5E-03	8	0.918	0.923	0.006	1.4	2E+04	2.00	2.0
18	2.8E-04	α	1.3E-03	5	5 2E-05	5	9.0E-06	2	2 5E-03	α	1	0.069	0.0480	4.7E-03	8	0.919	0.923	0.011	2.4	3E+05	2.00	2.5
																Uncertainty of measurement						
											Mismatch Error											
	Resolution of E4419B		Short term stability		Long term stability		Spurious power of the SG		Temperature room			Input Reflect of UUT	Output Reflect of RF std	Multiple Reflect calculated from (2*ΓsΓg)/sqrt(2)		C F of UUT absolute	relative	Sum of absolute value	Expand Uncert	Degree of freedom	Coverage factor	

Description

Std	Feedthrough Mount	Model	1807A	S/N	2246
UUT	Power sensor	Model	8481A	S/N	US41031013