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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, $P_{\mathrm{in}}(f)$.

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

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.

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

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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)	Dr. 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
Chinese Hong Kong, Standards and Calibration Laboratory (SCL)	Michael Chow	36th Floor, Immigration Tower, 7 Gloucester Road, Wan Chai, Hong Kong, China	wkchow@itc.gov.hk
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The Republic of Korea, *Korea Research Institute of Standards and Science (KRISS)	Dr. 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)	Dr. Yueyan Shan	1 Science Park Drive, 118221, Singapore	shan_yueyan@nmc.a-star.edu.sg
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The Kingdom of Thailand, National Institute of Metrology (NIMT)	Chalit K.	3/4-5 Moo 3, Klong 5, Klong Luang, Pathumthani 12120, Thailand	chalit@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	1 February 2012	6
SCL	Chinese Hong Kong	15 March 2012	6
NML	Malaysia	1 May 2012	6
MSLNZ	New Zealand	15 June 2012	6

*NMIA	Australia	1 August 2012	6
NMISA	South Africa	15 September 2012	6
*NMIJ	Japan	1 November 2012	6
*NMC	Singapore	15 December 2012	6
NPL	India	1 February 2013	6
*KRISS	The Republic of Korea	15 March 2013	6
*NIM	The People's Republic of China	1 May 2013	6
NIMT	The Kingdom of Thailand	15 June 2013	6
*NMIJ	Japan	1 August 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

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

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.

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

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 coefficient $c_i = \frac{\partial K_{DUT}(f)}{\partial x_i}$	Uncertainty contribution $\lvert c_i \rvert u(x_i) = u_i(K_{DUT}(f))$	Degrees of freedom 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 confidence 95%	Effective degrees of freedom 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

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

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 $P_{STD}(f)$ to the power indication of the monitor power meter $P_{m\_STD}(f)$ is recorded. Secondly, the traveling standard is connected to the test port. The ratio of the power indication of the traveling standard power meter $P_{DUT}(f)$ to the power indication of the monitor power meter $P_{m\_DUT}(f)$ is similarly recorded. Finally, the calibration factor of the traveling standard $K_{DUT}(f)$ is given by the following formula.

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

$K_{DUT}(f)$	- 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
$P_{STD}(f)$	- Observed value of power indication of standard power meter
$P_{m\_STD}(f)$	- Observed value of power indication of monitor power meter for standard power meter
$P_{DUT}(f)$	- Observed value of power indication of traveling standard
$P_{m\_DUT}(f)$	- 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)	Dr. 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
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The Republic of India, National Physical Laboratory (NPL)	V. K. Rustagi	Dr. K.S. Krishnan Road, New Delhi-110012, India	rustagi@ mail.nplindia.ernet.in
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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)	Dr. 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 Prozesky	Private Bag X34, Lynnwood Ridge, Pretoria 0040, South Africa	redressler@nmisa.org
The Kingdom of Thailand, National Institute of Metrology (NIMT)	Chalit K.	3/4-5 Moo 3, Klong 5, Klong Luang, Pathumthani 12120, Thailand	chalit@nimt.or.th

* Linking laboratories

A2. Schedule of measurements

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

The quantity $K_{DUT}(f)$ 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
$P_{STD}(f)$	- Observed value of power indication of standard power meter
$P_{m\_STD}(f)$	- Observed value of power indication of monitor power meter for standard power meter
$P_{DUT}(f)$	- Observed value of power indication of traveling standard
$P_{m\_DUT}(f)$	- 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 $\lvert c_i \rvert u(x_i) = u_i(K_{DUT}(f))$	Degrees of free-dom ν_i
$K_{STD}(f)$			B/ normal			
$\delta K_{STD}(f)$			B/ normal			
$P_{STD}(f)$			B/ uniform			
$P_{m\_STD}(f)$			B/ uniform			
$P_{DUT}(f)$			B/ uniform			
$P_{m\_DUT}(f)$			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 ____________ $\times 10^{-4}$ inch
No. 2 ____________ $\times 10^{-4}$ 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 ____________ $\times 10^{-4}$ inch

No. 2 ____________ $\times 10^{-4}$ 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: