APMP.EM-K2, 10 MΩ and 1 GΩ

RMO KEY COMPARISON FINAL REPORT

Kwang Min Yu and Wan Seop Kim

2010.07 – 2014.07 High Resistance standards comparison between APMP Laboratories

Pilot Laboratory: Korea Research Institute of Standards and Science, Yuseong, Daejeon, Republic of Korea

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1. Introduction

The technical basis of the Mutual Recognition Arrangement (MRA) is a set of results obtained in a course of time through key comparisons carried out by the Consultative Committees (CCs) of the International Committee for Weights and Measures (CIPM), the International Bureau of Weights and Measures (BIPM) and the Regional Metrology Organizations (RMOs). As a part of this process, the CIPM Consultative Committee for Electricity and Magnetism (CCEM) carried out the key comparison CCEM-K2 of resistance standards at 10 MΩ and 1 GΩ. This comparison was piloted by the National Institute for Standards and Technology and approved by the CCEM for full equivalence in January 2002 [1,2]. Also, the EUROMET.EM-K2 comparison was carried out between 2005 and 2007[3].

In order to link the National Metrology Institutes (NMI) organized in Asia Pacific Metrology Programme (APMP) to the key comparison CCEM-K2, the APMP Technical Committee for Electricity and Magnetism (TCEM) decided at its October 2008 meeting to carry out the corresponding APMP.EM-K2 comparison. The Korea Research Institute of Standards and Science (KRISS) acted as a pilot institute. By means of procedures for linking key comparison data [4], the APMP.EM-K2 comparisons will help to provide assurance of equality in measurements between the nations organized in APMP and the participants in the CCEM key comparisons. The analysis included in this report specifically provides methods for calculating the degrees of equivalence and their uncertainties between the national measurement standards of the participating laboratories (Appendix B).

2. Participants and Organization of the comparison

2.1 Pilot laboratory and supporting Group

The pilot laboratory for the comparison is the Korea Research Institute of Standards and Science (KRISS).

Coordinator: Kwang Min Yu (KRISS), e-mail: kmyu@kriss.re.kr

Support group:

Laurie Christian(MSL), New Zealand, e-mail: L.christian@irl.cri.nz

Yuri Semenov(VNIIM), Russia, e-mail: Y.P.Semenov@vniim.ru

Leigh Johnson(NMIA), Australia, e-mail: Heather.Johnson@measurement.gov.au

2.2 List of participants

The proposed participating institutes are listed in the following Table 1. The contact details are given in Annex A1.

Table 1 List of participants

Country	**Institute**	**Acronym**
Australia	National Measurement Institute, Australia	NMIA$^{*)}$
China	National Institute of Metrology	NIM$^{*)}$
Chinese Taipei	Center for Measurement Standards	CMS
Hong Kong, China	Standards and Calibration Laboratory	SCL
Japan	National Metrology Institute of Japan	NMIJ
Korea, The Republic of	Korea Research Institute of Standards and Science	KRISS$^{*)}$
Malaysia	National Metrology Laboratory SIRIM	NML-SIRIM
New Zealand	Measurement Standards Laboratory	MSL$^{*)}$
Russian Federation	D.I.Mendeleyev Institute for Metrology	VNIIM$^{*)}$
Singapore	National Metrology Center, A*STAR	NMC
South Africa	National Metrology Institute of South Africa	NMISA$^{*)}$
Thailand	National Institute of Metrology, Thailand	NIMT
Kazakhstan	Republic State Enterprise ″Kazakhstan Institute of Metrology″	KazInMetr

*: These laboratories participated in CCEM-K2

2.3 Comparison schedule

The circulation of the standards started in June 2010 and was planned to end in August 2011. However, owing to the earthquake in Japan, a terminal problem with one 10 MΩ resistor, measurement system problems, holidays and customs problems and the time limit of ATA Carnet, the entire measurement schedule was much delayed from the original schedule. The detailed time schedule for the comparison is given in Table 2. A period of four weeks was allowed for the measurements in each laboratory, including the time necessary for transportation. Participants were asked to conduct measurements for up to four weeks beginning as soon as possible after receiving the inter-comparison shipment. In agreeing with the proposed circulation time schedule, each participating laboratory confirms that it is capable of performing the measurements in the limited time period allocated in the time schedule. If, for some reasons, the measurement facility was not ready or customs clearance took too much time, the laboratory was requested to contact immediately the coordinator in the pilot laboratory. As soon as possible after the completion of the measurements, the transport package was to be transported to the next participant and the participant should have indicated that all measurements have been completed. If an unavoidable delay occurs, the coordinators were to inform the participants and revise the time schedule if necessary.

2.4 Organization of the comparison

KRISS made the initial measurements of the comparison between January and July 2010. In order to minimize shipping over the great distances between the NMIs, the participants in adjacent countries were grouped together. The travelling standards circulated in each of the three loops in succession. The comparison was completed with closing measurements at KRISS between March 2014 and July 2014. The final measurements included temperature and voltage coefficients as well as resistance measurements. Four weeks of measurement time was assigned to each NMI. The traveling standards were transported in a larger wooden case by air cargo using an ATA Carnet for customs clearance where possible. A small temperature and humidity monitor and a shock monitor were also enclosed in the transport case to monitor the environmental change during the transportation. During the circulation, it seems that no abnormal behavior was appeared in the travelling standards.

2.5 Unexpected incidents

During the measurements at the NMIA, there was an issue that the low terminal BPO shield of one 10 MΩ standard, HR7552, was not connected to the metal container used as a guard. Fortunately, no significant problems except a little noise were resulted during the circulation measurements and the insulation resistance between terminals, or between one terminal and the case was measured to be higher than 100 TΩ. In addition, owing to unexpected measurement system problems, holidays and customs problems, the limit of the ATA Carnet validity, and the late participation of one NMI, the entire measurement schedule was significantly delayed.

3. Travelling standards and measurement instructions

3.1 Description of the standards

Three NIST-designed wire-wound resistors as 10 MΩ standards and three NIST-designed film resistors as 1 GΩ standards are used as the traveling standards:

The resistance elements are hermetically sealed in metal containers. The two resistor terminations of the standards are coaxial BPO connectors mounted on grooved PTFE circular plates on the top panel of the enclosures. The resistor containers are electrically isolated from the enclosures and electrically connected to the shield of one of the coaxial connectors. This allows the resistor container of the standard to be operated either in floating mode, in grounded mode, or driven at a guard potential. There are internal 10 kΩ thermistor temperature sensors that may be measured with the provided LEMO-to-banana plug leads provided in case of large temperature effects.

Table 2 Comparison schedule for participants

Institute	**Country**	**Receipt and dispatch date**	**Time for measurements and transport**	**Reasons for delay**
Pilot (KRISS)	Korea	Jan to July 2010	-	First measurements
CMS	Taiwan	Aug.-Sept. 2010	4 weeks	
NIMT	Thailand	Sep.-Oct. 2010	4 weeks	Customs problem
NML-SIRIM	Malaysia	Nov. 2010	4 weeks	
NMC	Singapore	Dec. 2010	4 weeks	
Pilot (KRISS)	Korea	Jan-Feb 2011	-	
NMIJ	Japan	March-April 2011	4 weeks	Earthquake and transport problem(including NMIA holidays)
NMIA	Australia	May-July 2011	4 weeks	HR7552 terminal problem
MSL	New Zealand	Aug.-Oct. 2011	-	Needs re-measurement owing to failure of a Pt sensor of MSL reference resistor problem
Pilot (KRISS)	Korea	Nov-Dec 2011	-	Rescheduling by holidays of NIM and SCL
NMISA	South Africa	Jan.-Feb 2012	4 weeks	
NIM	China	March-May 2012	4 weeks	System(Bridge) problem
VNIIM	Russian Federation	June-Sep. 2012	4 weeks	Customs problem

SCL	Hong Kong	Sep.-Nov. 2012	4 weeks	Overlapped with public holidays in October and SCL Laboratory Accreditation Audit
KazInMetr	Kazakhstan	Nov. 2012-Jan. 2013	-	Needs re-measurement owing to customs problem & limit of ATA Carnet due time
Pilot (KRISS)	Korea	Jan.-March 2013	-	
KazInMetr	Kazakhstan	April-June 2013	4 weeks	System problem
Pilot (KRISS)	Korea	July-Aug. 2013	-	Summer holidays
MSL	New Zealand	Sept.-Nov. 2013	4 weeks	System problem
Pilot (KRISS)	Korea	Dec.2013-July 2014	-	Final measurements and temp. and voltage coeff. measurements

The packing list of the standards is as follows:

-Three 10 MΩ standard resistors:
  - NIST-designed, Serial Number HR7550, Size 250 mm x 80 mm x 80 mm, Weight 1259 g
  - NIST-designed, Serial Number HR7551, Size 250 mm x 80 mm x 80 mm, Weight 1268 g
  - NIST-designed, Serial Number HR7552, Size 250 mm x 80 mm x 80 mm, Weight 1261 g

-Three 1 GΩ standard resistors:
  - NIST-designed, Serial Number HR9101, Size 250 mm x 80 mm x 80 mm, Weight 1455 g
  - NIST-designed, Serial Number HR9102, Size 250 mm x 80 mm x 80 mm, Weight 1519 g
  - NIST-designed, Serial Number HR9106, Size 250 mm x 80 mm x 80 mm, Weight 1511 g

-12 BPO-BNC adapters

-6 cables, 2.75 m long for reading the 10 kΩ thermistors installed in the six standards

-2 ambient conditions recorders, CENTER 342 and HiGee. These recorders are used to monitor the temperature and humidity and to monitor any mechanical shock of the standards during transport.

-Instruction manual

3.2 Quantities to be measured and conditions of measurement

Resistance of the 10 MΩ and 1 GΩ standards is measured at the following conditions:

Test voltage: $10\ \mathrm{V} \leq V_{\mathbf{test}} \leq 100\ \mathrm{V}$;

Ambient or air bath temperature: (23 ± 2.0) °C

Ambient relative humidity: (45 ± 15) %.

The measurements may also be performed at an ambient temperature of (20 ± 2.0) °C. In such a case, the results will be corrected to 23 °C using their temperature coefficients.

3.3 Measurement instructions

Pre-conditioning: The standards should be installed in a thermostatic air bath, regulated at the chosen working temperature, at least 48 h before starting the measurements. Also, the standards should be conditioned to air-bath or ambient laboratory conditions for at least 24 h.

Measurand: The resistance value of the traveling standards should be measured at DC, expressed in terms of the conventional value of the von Klitzing constant $R_{\text{K-90}} = 25812.807\ \Omega$ or the SI ohm via a calculable capacitor.

Measurements: The measurements should be repeated at least twice each week during the period allocated to the participating laboratory, approximately three to four weeks. The average value and standard deviation of each set of measurements should be recorded, along with the environmental parameters at the time of measurement.

3.4 Deviations from the protocol

The measurement schedule was changed by several issues described in the above section 2.5 and the addition of Kazakhstan NMI, RSE ″KazInMetr″ as a participant.

4. Methods of measurement

The measurement method was not specified. It is assumed that every participant laboratory has used its best normal measurement process. The method and the traceability scheme were described in the laboratory’s measurement report. The detailed methods are described in Appendix A. The methods of measurement are summarized as follows.

1) Binary Voltage Divider Bridge: NIM, NMIA, NMC, NIMT, NMISA
2) Dual-Voltage Source bridge and Hamon Transfer Standards: CMS, KRISS, MSL, SCL(1 GΩ)

3) Direct Current Comparator Bridge with Hamon Transfer and Modified Wheatstone Bridge: NML-SIRIM
4) Injected voltage type High Resistance Bridge based on Wheatstone bridge: NMIJ
5) Direct Current Comparator Bridge & Teraohmmeter Substitution: RSE ″KazInMetr″
6) Wheatstone Bridge and Hamon Transfer Standards: VNIIM
7) Kelvin type resistance ratio bridge and Hamon Transfer Standards: SCL(10 MΩ)

5. Pilot laboratory measurement results

5.1 Temperature and voltage dependence

Temperature and voltage dependence of the travelling standards were determined using a dual voltage source bridge (or a modified Wheatstone bridge)[5,8] and a potentiometric method[6]. The results are shown in Table 3.

Table 3 Temperature and voltage dependence of the travelling standards

Model	TCR(10^{-6}/℃) (20 ℃ ~ 23 ℃)	VCR(10^{-6}/V) Up to 100 V
HR 7550(10 MΩ)	+1.2(0.4)	+0.0001(39)
HR 7551(10 MΩ)	+3.2(0.4)	+0.0007(13)
HR 7552(10 MΩ)	+1.2(0.4)	+0.0001(8)
HR 9101(1 GΩ)	-28.2(1.0)	+0.002(6)
HR 9102(1 GΩ)	-30.9(0.7)	+0.007(3)
HR 9106(1 GΩ)	-24.9(0.5)	+0.006(9)

(*Parentheses mean one-standard deviations)

5.2 Drift behaviour of the travelling standards

The pilot laboratory made resistance measurements before starting the comparison, in the middle of the loops and at the end and the results were used to establish the drift behaviour of the travelling standards. Due to thermal stress, the resistance value generally changes with time, generally. Step-like resistance changes can be produced after temperature shocks or mechanical shocks. As shown in Figures 1 to 6, all other standards except HR7552 showed linear drifts in time. The HR7552 showed a nonlinear drift trend and it is shown that a second order polynomial fit is sufficient to describe the resistance change over time for this purpose. For the drift trends of the six standards, the reference date $t0$ was chosen as 1 January 2010 and the fitted results are shown in Table 4. In the graphs below, solid lines represent the fit functions.

Table 4 The time drift of travelling standards by linear and second order polynomial fittings

Travelling Standard		α_0(x10^{-6})	α_1(x10^{-6}/y)	α_2(x10^{-6}/y^2)	Residual Standard Deviation(x10^{-6})
10 MΩ	HR7550	60.25(0.34)	2.42(0.14)		0.88
	HR7551	20.73(0.21)	1.43(0.09)		0.54
	HR7552	47.15(0.32)	5.80(0.43)	-1.01(0.10)	0.62
1 GΩ	HR9101	74.91(1.03)	6.97(0.44)		2.18
	HR9102	-51.73(0.60)	1.96(0.26)		1.30
	HR9106	781.97(0.83)	2.77(0.36)		1.79

(*Parentheses mean one-standard deviations)

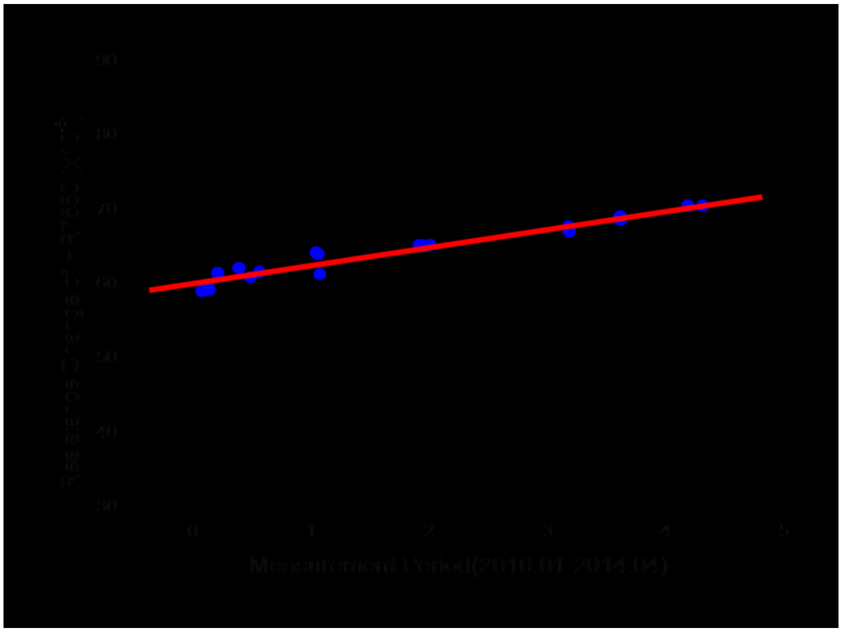

Figure 1 Drift behaviour of the 10 MΩ HR7550 standard

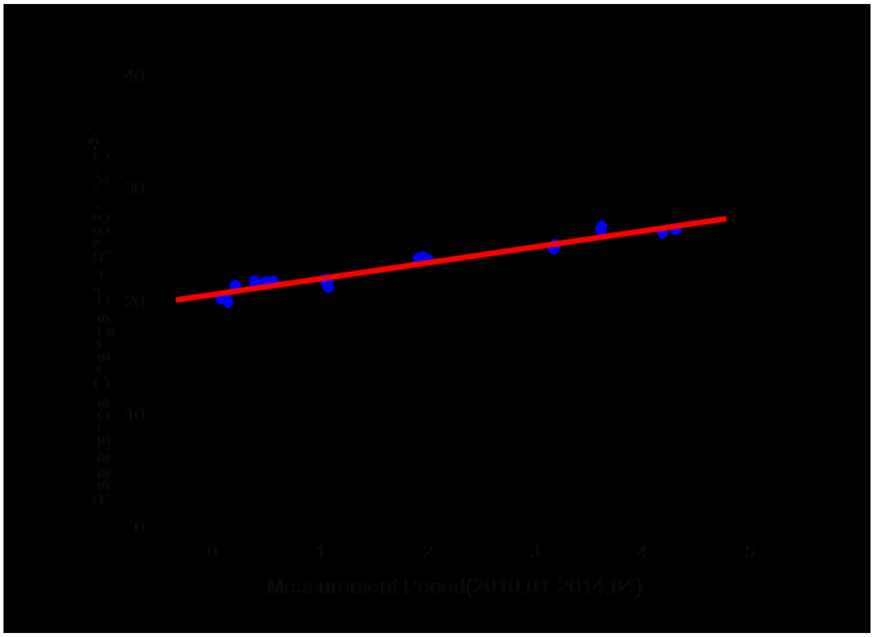

Figure 2 Drift behaviour of the 10 MΩ HR7551 standard

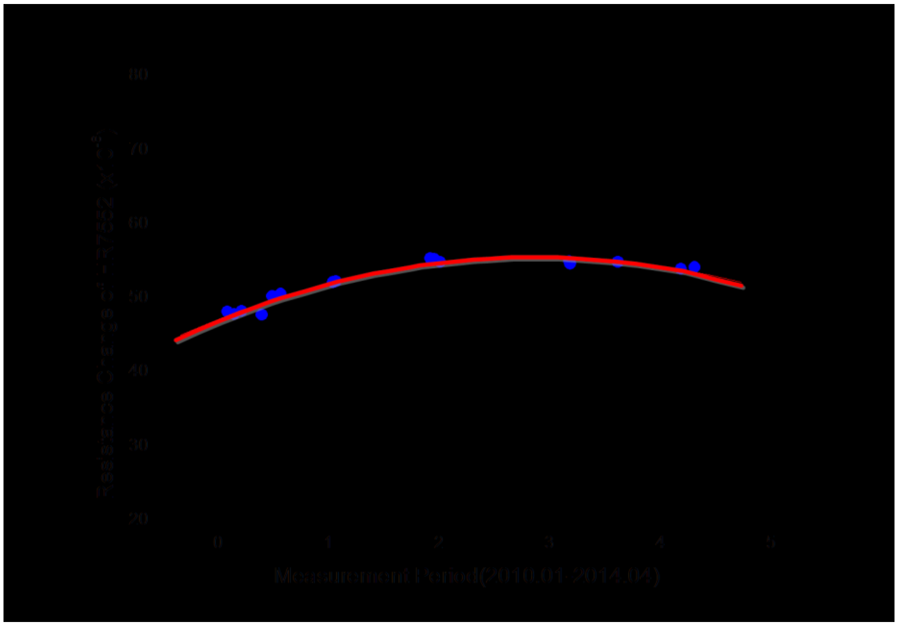

Figure 3 Drift behaviour of the 10 MΩ HR7552 standard

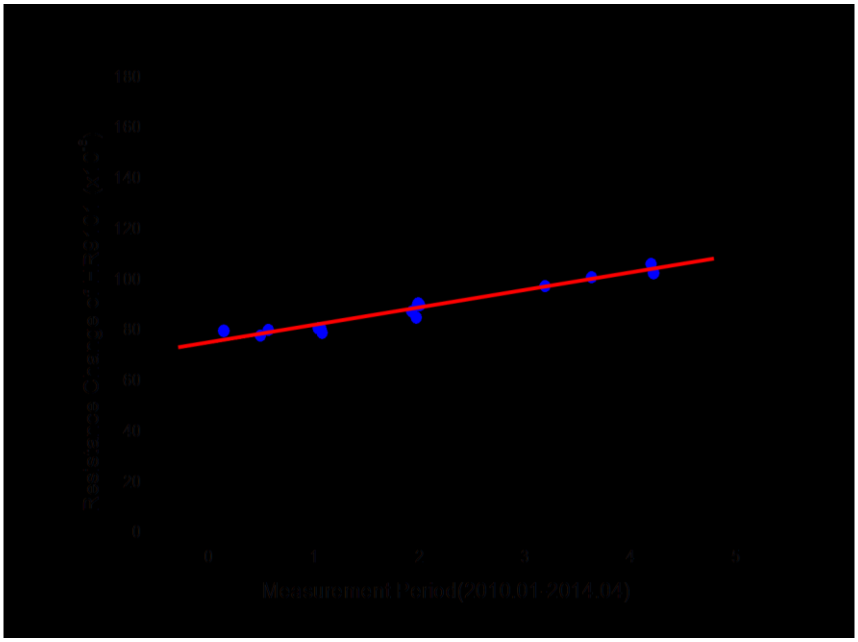

Figure 4 Drift behaviour of the 1 GΩ HR9101 standard

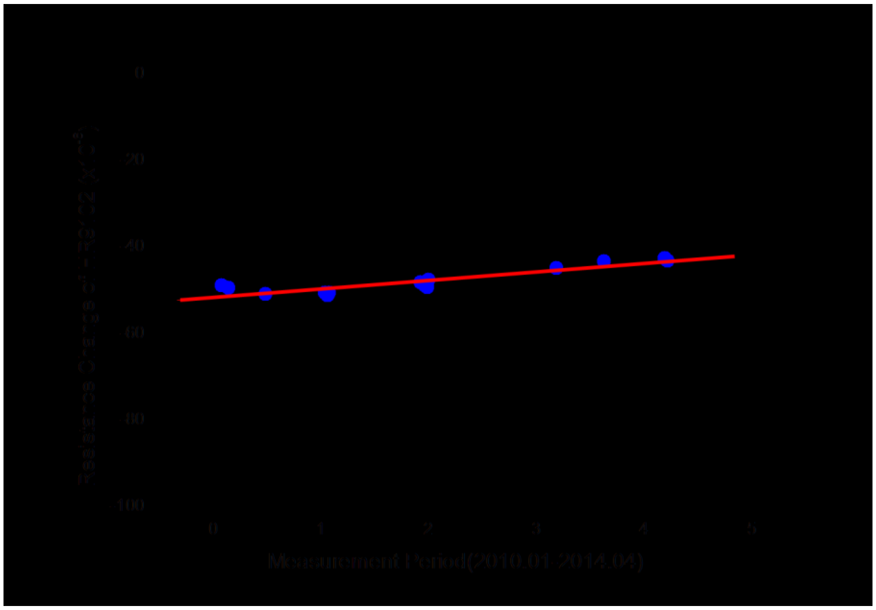

Figure 5 Drift behaviour of the 1 GΩ HR9102 standard

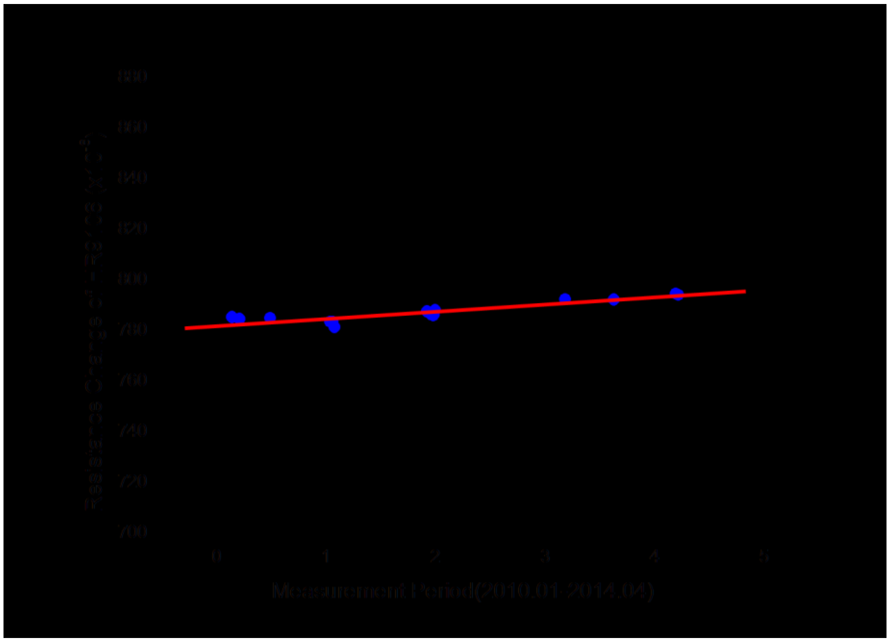

Figure 6 Drift behaviour of the 1 GΩ HR9106 standard

6. Measurement results

6.1 Results of the participating institutes

Each result reported by the participants can be expressed by

$$R_{p,k}(t, T, V)=R_{nom}(1+M_{p,k})=R_{nom}\{1+M_{p,k}(t_{p,k}, T_{p,k}, V_{p,k})\} \tag{1}$$

Here the notation in the subscript means:

- p: Index for the participant, k: Index for the travelling standard, nom: Nominal value of each travelling standard
- $M_{p,k}$: Deviation from the nominal value, reported at time $t_{p,k}$, temperature $T_{p,k}$ and test voltage $V_{p,k}$

The values $M_{p,k}$ and the associated type A and type B standard uncertainty are given in Tables 5 and 6.

6.2 Normalization of the results

6.2.1 Corrections to the standard conditions for the reported NMI results at different temperature and voltages

In a first step, temperature(T) and voltage(V) corrections were applied to the reported results. The corrected results to 23 ℃ and zero applied voltage are in a linear approximation given by the following equation and shown in table 7.

$$M_{p,k}(t_{p,k}) = M_{p,k}(t_{p,k}, T_{p,k}, V_{p,k}) - \alpha_T(T-T_0) - \beta_V(V-V_0) \qquad (2)$$

Here, T_0 and V_0 mean 23 ℃ and zero applied voltage. Also, α_T and β_V mean temperature and voltage coefficients shown in Table 3. The uncertainty by temperature and voltage corrections for each participant was estimated by applying the law of propagation of uncertainty which is expressed in ISO GUM to the last two terms of equation (2) and is shown in section 6.2.3.

6.2.2 Time drift corrections

In a second step, the time dependence of the standards taken from the results of the pilot laboratory is removed from the temperature and voltage-corrected results shown in Table 7 using equation (3). The normalized results (after temperature, voltage and time drift corrections) $M_{p,k}$ are given in Tables 8 and 9.

$$M_{p,k} = M_{p,k}(t_{p,k}) - f(t_{p,k}) \qquad (3)$$

$f(t_{p,k})$ is the model function fitted to the results of the pilot laboratory and are shown in Table 4.

The standards were measured before and after the loop and four times during the loop. For every of these six measurement periods a mean value (n = 1 to 6) is calculated for every standard. A smooth fitting line (straight line or 2nd order polynomial) is then fitted for every standard through the six data points. The residuals to the fit curve are an average measure for the step-like changes which may have occurred during transport. The transport uncertainty for standard *a* is then estimated using equation (4)[7] and is shown in Tables 10 and 11.

$$u_{tr-a}{}^2 = \frac{\sum(M_{1,a,i} - f_a(t_i))^2}{(5-\nu_a)} \qquad (4)$$

$fa(t_i)$ is the overall fitting curve and v the number of degrees of freedom (=2 for a straight line and 3 for a 2nd order polynomial).

Table 5 Measurement results and the associated standard uncertainty for 10 MΩ travelling standards

Mean date of measure-ments	NMI	$M_{p,k}(t_{p,k}, T_{p,k}, V_{p,k})$ **(reported resistance in 10^{-6})**								
		HR 7550	**Standard uncertainty (10^{-6})**		**HR 7551**	**Standard uncertainty (10^{-6})**		**HR 7552**	**Standard uncertainty (10^{-6})**	
			Type A	**Type B**		**Type A**	**Type B**		**Type A**	**Type B**
2010.04.30 (0.33)	**KRISS**	**60.8(10V) 23.00(3)℃**	**0.10**	**0.58**	**21.3(10V) 23.00(3)℃**	**0.10**	**0.58**	**48.8(10V) 23.00(3)℃**	**0.10**	**0.58**
2010.08.17 (0.63)	**CMS**	**56.6(50V) 23.10(3)℃**	**0.17**	**2.26**	**20.6(50V) 23.10(3)℃**	**0.17**	**2.26**	**51.2(50V) 23.10(3)℃**	**0.17**	**2.26**
2010.10.02 (0.75)	**NIMT**	**69.1(10V) 23.15(20)℃**	**1.01**	**3.06**	**29.8(10V) 22.85(20)℃**	**1.35**	**3.06**	**55.9(10V) 23.15(20)℃**	**0.84**	**3.06**
2010.11.11 (0.86)	**NML-SIRIM**	**60.4(100V) 23.2(2)℃**	**0.06**	**6.66**	**23.1(100V) 23.2(2)℃**	**0.10**	**6.88**	**54.9(100V) 23.3(2)℃**	**0.12**	**6.69**
2010.12.18 (0.96)	**NMC**	**62.3(10V) 23.02(1)℃**	**0.19**	**0.73**	**22.0(10V) 23.02(1)℃**	**0.14**	**0.60**	**51.7(10V) 23.02(1)℃**	**0.15**	**0.59**
2011.01.30 (1.08)	**KRISS**	**63.3(10V) 23.00(3)℃**	**0.10**	**0.58**	**21.8(10V) 23.00(3)℃**	**0.10**	**0.58**	**53.1(10V) 23.00(3)℃**	**0.10**	**0.58**
2011.04.15 (1.29)	**NMIJ**	**61.8(100V) 23.07(1)℃**	**0.30**	**0.47**	**23.3(100V) 23.07(1)℃**	**0.30**	**0.47**	**56.3(100V) 23.07(1)℃**	**0.30**	**0.47**
2011.05.31 (1.41)	**NMIA**	**64.34(91V) 64.72(50V) 22.90(6)℃**	**0.03**	**0.63**	**21.70(91V) 21.79(50V) 22.90(6)℃**	**0.03**	**0.65**	**50.48(50V) 22.90(6)℃**	**0.03**	**0.63**
2011.12.30 (2.00)	**KRISS**	**65.1(10V) 23.00(3)℃**	**0.10**	**0.58**	**23.9(10V) 23.00(3)℃**	**0.10**	**0.58**	**55.1(10V) 23.00(3)℃**	**0.10**	**0.58**
2012.02.11 (2.11)	**NMISA**	**65(91V) 23.55(2)℃**	**1.2**	**2.12**	**24(91V) 23.53(2)℃**	**1.2**	**2.12**	**49(91V) 23.52(2)℃**	**1.45**	**2.13**
2012.05.15 (2.37)	**NIM**	**61.4(100V) 19.98(2)℃**	**0.27**	**0.63**	**14.1(100V) 19.98(0)℃**	**0.24**	**0.64**	**51.2(100V) 20.04(2)℃**	**0.17**	**0.63**

2012.07.30 (2.58)	VNIIM	64.0(91V) 23.10(1)℃	0.15	0.59	24.7(91V) 23.10(1)℃	0.16	0.59	55.1(89V) 23.02(4)℃	0.22	0.59
2012.10.21 (2.81)	SCL	68.8(100V) 22.97(5)℃	0.07	2.50	23.7(100 V) 22.98(5)℃	0.13	2.50	50.5(100V) 22.97(5)℃	0.23	2.49
2013.03.30 (3.25)	KRISS	67.2(10V) 23.00(3)℃	0.10	0.58	24.5(10 V) 23.00(3)℃	0.10	0.58	54.8(10V) 23.00(3)℃	0.10	0.58
2013.06.15 (3.46)	KazIn- Metr	35.9(100V) 22.95(5)℃	5.0	23.5	26.3(100V) 22.95(5)℃	5.0	23.5	58.4(100V) 22.95(5)℃	5.0	23.5
2013.08.30 (3.67)	KRISS	69.1(10V) 23.00(3)℃	0.10	0.58	26.5(10V) 23.00(3)℃	0.10	0.58	54.8(10V) 23.00(3)℃	0.10	0.58
2013.11.10 (3.86)	MSL	62.00(10V) 64.69(100V) 20.75(2)℃	0.68(10V) 0.25(100V)	5.05 0.31	16.52(10V) 16.37(100V) 20.75(2)℃	0.68(10V) 0.25(100V)	0.57 0.30	52.63(10V) 51.74(100V) 20.75(2)℃	0.68(10V) 0.25(100V)	0.99 0.50
2014.04.30 (4.33)	KRISS	70.6(10V) 23.00(3)℃	0.10	0.58	26.4(10V) 23.00(3)℃	0.10	0.58	54.0(10V) 23.00(3)℃	0.10	0.58

Table 6 Measurement results and the associated standard uncertainty for 1 GΩ travelling standards

Mean date of measure-ments	NMI	$M_{p,k}(t_{p,k}, T_{p,k}, V_{p,k})$ (reported resistance in 10^{6})								
		HR 9101	Standard uncertainty (10^{-6})		HR 9102	Standard uncertainty (10^{-6})		HR 9106	Standard uncertainty (10^{-6})	
			Type A	Type B		Type A	Type B		Type A	Type B
2010.04.30 (0.33)	KRISS	79.3(100 V) 23.00(3)℃	0.50	1.33	-49.8(100 V) 23.00(3)℃	3.0	1.33	784.9(100 V) 23.00(3)℃	3.0	1.33
2010.08.28 (0.66)	CMS	79.1(100V) 23.14(3)℃	1.49	4.30	-54.0(100V) 23.14(3)℃	1.49	4.30	784.1(100V) 23.14(3)℃	1.49	4.30
2010.10.12 (0.78)	NIMT	539(100V) 23.05(20)℃	1.82	59.97	394(100V) 23.00(20)℃	3.62	59.99	1,241(100V) 23.10(20)℃	7.34	59.95
2010.11.14 (0.88)	NML- SIRIM	77(100V) 23.3(2)℃	0.01	22.37	-53(100V) 23.5(2)℃	0.01	22.58	781(100V) 23.4(2)℃	0.01	22.53
2010.12.21	NMC	71.5(100V)	4.47	3.37	-57.6(100V)	5.91	3.36	788.9(100V)	5.39	3.26

(0.98)		23.02(1)℃			23.02(1)℃			23.02(1)℃		
2011.01.30 (1.08)	KRISS	80.0(100V) 23.00(3)℃	0.50	1.33	-51.2(100V) 23.00(3)℃	3.0	1.33	782.7(100V) 23.00(3)℃	3.0	1.33
2011.04.15 (1.29)	NMIJ	85.9(100V) 23.07(1)℃	1.0	1.25	-45.4(100V) 23.07(1)℃	1.0	1.25	791.0(100V) 23.07(1)℃	1.0	1.25
2011.06.01 (1.42)	NMIA	85.1(91V) 22.90(6)℃	0.50	2.67	-48.7(91V) 22.90(6)℃	0.50	2.73	790.8(91V) 22.90(6)℃	0.50	2.56
2011.12.30 (2.00)	KRISS	88.7(100 V) 23.00(3)℃	0.50	1.33	-48.7(100 V) 23.00(3)℃	3.0	1.33	786.7(100 V) 23.00(3)℃	3.0	1.33
2012.02.11 (2.12)	NMISA	82(91V) 23.49(2)℃	1.10	3.96	-64(91V) 23.64(2)℃	1.23	3.96	777(91V) 23.66(2)℃	0.95	3.96
2012.05.17 (2.37)	NIM	174.1(100V) 19.99(1)℃	1.04	3.24	+42.6(100V) 19.98(2)℃	1.46	3.18	864.1(100V) 19.97(0)℃	0.45	3.17
2012.08.07 (2.60)	VNIIM	101.1(95V) 22.97(2)℃	1.65	1.74	-44.2(97V) 22.99(1)℃	0.85	1.81	793.2(96V) 23.00(1)℃	0.8	1.83
2012.10.19 (2.80)	SCL	94(100V) 23.00(3)℃	0.13	6.00	-44(100V) 23.00(3)℃	0.11	6.00	792(100V) 23.00(3)℃	0.11	6.00
2013.03.30 (3.25)	KRISS	97.5(100V) 23.00(3)℃	0.50	1.33	-45.0(100V) 23.00(3)℃	3.0	1.33	792.4(100V) 23.00(3)℃	3.0	1.33
2013.06.20 (3.47)	KazIn-Mter	338(100V) 23.00(3)℃	7.0	70.7	167(100V) 23.00(3)℃	7.8	70.6	1,024(100V) 23.00(3)℃	10.9	71.2
2013.08.30 (3.67)	KRISS	100.9(100 V) 23.00(3)℃	0.50	1.33	-43.4(100 V) 23.00(3)℃	3.0	1.33	792.2(100 V) 23.00(3)℃	3.0	1.33
2013.11.11 (3.86)	MSL	170.47(10V) 168.76(100V) 20.76(2)℃	1.42(10V) 0.34(100V)	1.78 0.52	29.60(10V) 28.23(100V) 20.75(2)℃	1.42(10V) 0.34(100V)	2.26 0.42	856.27(10V) 854.87(100V) 20.66(17)℃	1.42(10V) 0.34(100V)	2.37 1.05
2014.04.30 (4.33)	KRISS	106.0(100 V) 23.00(3)℃	0.50	1.33	-41.1(100 V) 23.00(3)℃	3.0	1.33	795.9(100 V) 23.00(3)℃	3.0	1.33

Table 7 Corrected results to the standard conditions

NMI	$M_{p,k}(t_{p,k})$, 10 MΩ (T, V corrections, x10^{-6})			$M_{p,k}(t_{p,k})$, 1 GΩ (T, V corrections, x10^{-6})		
	HR 7550	HR 7551	HR 7552	HR9101	HR9102	HR9106
KRISS	60.8	21.3	48.8	79.1	-50.5	784.3
CMS	56.5	20.3	51.1	82.8	-50.4	787.0
NIMT	68.9	30.3	55.7	540.2	393.3	1,242.9
NML-SIRIM	60.2	22.5	54.5	85.5	-37.5	791.0
NMC	62.3	21.9	51.7	71.9	-57.7	788.8
KRISS	63.3	21.8	53.1	79.8	-51.9	782.1
NMIJ	61.9	23.1	56.2	87.7	-43.9	792.1
NMIA	64.2(91V) 64.7(50V)	21.4(91V) 22.1(50V)	50.6(50V)	82.1	-52.4	787.8
KRISS	65.1	23.9	55.1	88.5	-49.4	786.1
NMISA	64.3	22.3	48.4	95.6	-44.8	792.9
NIM	65.0	23.7	54.8	89.0	-51.4	788.1
VNIIM	63.9	24.4	55.1	100.1	-45.2	792.6
SCL	68.8	23.7	50.5	93.8	-44.7	791.4
KRISS	67.2	24.5	54.8	97.3	-45.7	791.8
KazInMetr	36.0	26.5	58.5	338	168	1,025
KRISS	69.1	26.5	54.8	100.7	-44.1	791.6
MSL	64.7(10V) 67.4(100V)	23.7(10 V) 23.4(100V)	55.3(10V) 54.4(100V)	107.5(10V) 105.8(100V)	-39.7(10V) -41.1(100V)	798.2(10V) 796.8(100V)
KRISS	70.6	26.4	54.0	105.8	-41.8	795.3

Table 8 The normalized results for the 10 MΩ standards after temperature, voltage and time drift corrections

Mean date of measurements	NMI	$M_{p,k}$ (after T, V and time drift corrections, x10^{-6})		
		HR 7550	HR 7551	HR7552
2010.04.30 (0.33)	KRISS	-0.25	0.10	-0.15
2010.08.17 (0.63)	CMS	-5.27	-1.33	0.70
2010.10.02 (0.75)	NIMT	6.83	8.50	4.77
2010.11.11 (0.86)	NML-SIRIM	-2.13	0.54	3.11
2010.12.18 (0.96)	NMC	-0.27	-0.20	0.00
2011.01.30 (1.08)	KRISS	0.44	-0.47	0.86
2011.04.15 (1.29)	NMIJ	-1.47	0.53	3.25
2011.05.31 (1.41)	NMIA	1.04	-0.65	-2.72
2011.12.30 (2.00)	KRISS	0.01	0.31	0.39

2012.02.11 (2.11)	NMISA	-1.06	-1.45	-6.49
2012.05.15 (2.37)	NIM	-0.99	-0.42	-0.42
2012.07.30 (2.58)	VNIIM	-2.59	-0.02	-0.29
2012.10.21 (2.81)	SCL	1.75	-1.05	-4.97
2013.03.30 (3.25)	KRISS	-0.92	-0.88	-0.53
2013.06.15 (3.46)	KazInMetr	-32.62	0.82	3.37
2013.08.30 (3.67)	KRISS	-0.03	0.52	-0.03
2013.11.10 (3.86)	MSL	-2.19	-2.85	-0.09
2014.04.30 (4.33)	KRISS	-0.13	-0.52	0.67

Table 9 The normalized results for the 1 GΩ standards after temperature, voltage and time drift corrections

Mean date of measurements	NMI	$M_{p,k}$ (after T, V and time drift corrections, x10^{-6})		
		HR9101	HR 9102	HR 9106
2010.04.30 (0.33)	KRISS	1.89	0.58	1.42
2010.08.28 (0.66)	CMS	3.29	0.04	3.20
2010.10.12 (0.78)	NIMT	459.85	443.50	458.77
2010.11.14 (0.88)	NML-SIRIM	4.46	12.51	6.59
2010.12.21 (0.98)	NMC	-9.84	-7.89	4.12
2011.01.30 (1.08)	KRISS	-2.64	-2.29	-2.86
2011.04.15 (1.29)	NMIJ	3.80	5.30	6.56
2011.05.31 (1.42)	NMIA	-2.71	-3.45	1.90
2011.12.30 (2.00)	KRISS	-0.35	-1.59	-1.41
2012.02.11 (2.12)	NMISA	5.91	2.77	5.06
2012.05.15 (2.37)	NIM	-2.50	-4.33	-0.46
2012.08.07 (2.60)	VNIIM	7.07	1.43	3.43
2012.10.19 (2.80)	SCL	-0.63	1.54	1.67
2013.03.30 (3.25)	KRISS	-0.26	-0.34	0.83
2013.06.20 (3.47)	KazInMetr	238.90	212.93	233.42
2013.08.30 (3.67)	KRISS	0.21	0.44	-0.54
2013.11.10 (3.86)	MSL	3.99	3.06	4.14
2014.04.30 (4.33)	KRISS	0.71	1.44	1.34

6.2.3 Reproducibility of results

The reproducibility of results was estimated from the repeatability and temperature/voltage correction uncertainty of results, and transport uncertainty of travelling standards. The transport uncertainty was taken from the residual standard deviation of least square fittings for the standards and the reproducibility was shown in table 10 and 11.

Table 10 The reproducibility of results for the 10 MΩ standards

NMI	$u_{r,k}$ ($\times10^{-6}$) (NMI repeatability)			$u_{TV,k}$ ($\times10^{-6}$) (NMI T,V corrections)			$u_{tr,k}$ ($\times10^{-6}$) (transport uncertainty)			$u_{rp,p,k}$ ($\times10^{-6}$) (reproducibility)		
	HR7550	HR7551	HR7552	HR7550	HR7551	HR7552	HR7550	HR7551	HR7552	HR7550	HR7551	HR7552
KRISS	0.1	0.1	0.1	0.053	0.097	0.037	0.88	0.54	0.62	0.887	0.558	0.629
CMS	0.17	0.17	0.17	0.202	0.123	0.067	0.88	0.54	0.62	0.919	0.579	0.646
NIMT	1.01	1.35	0.84	0.25	0.643	0.248	0.88	0.54	0.62	1.363	1.590	1.073
NML-SIRIM	0.06	0.1	0.12	0.271	0.651	0.268	0.88	0.54	0.62	0.923	0.852	0.686
NMC	0.185	0.136	0.153	0.042	0.035	0.016	0.88	0.54	0.62	0.900	0.558	0.639
NMIJ	0.3	0.3	0.3	0.391	0.137	0.086	0.88	0.54	0.62	1.009	0.633	0.694
NMIA	0.032	0.032	0.032	0.364	0.229	0.11	0.88	0.54	0.62	0.953	0.587	0.630
NMISA	1.2	1.17	1.45	0.418	0.258	0.233	0.88	0.54	0.62	1.546	1.314	1.594
NIM	0.273	0.244	0.174	1.27	1.217	1.211	0.88	0.54	0.62	1.569	1.354	1.372
VNIIM	0.54	0.62	0.86	0.357	0.129	0.084	0.88	0.54	0.62	1.092	0.832	1.064
SCL	0.07	0.13	0.23	0.395	0.207	0.101	0.88	0.54	0.62	0.967	0.593	0.669
KazInMetr	5	5	5	0.395	0.207	0.102	0.88	0.54	0.62	5.092	5.033	5.039
MSL	0.25	0.25	0.25	0.981	0.912	0.904	0.88	0.54	0.62	1.341	1.089	1.124

Table 11 The reproducibility of results for the 1 GΩ standards

NMI	$u_{r,k}$ (NMI repeatability)			$u_{TV,k}$ (NMI T,V corrections)			$u_{tr,k}$ (transport uncertainty)			$u_{rp,p,k}$ ($\times10^{-6}$) (reproducibility)		
	HR9101	HR9102	HR9106	HR9101	HR9102	HR9106	HR9101	HR9102	HR9106	HR9101	HR9102	HR9106
KRISS	0.5	0.5	0.5	1.037	0.974	1.170	2.18	1.30	1.79	2.465	1.700	2.196
CMS	1.49	1.49	1.49	1.047	0.979	1.172	2.18	1.30	1.79	2.841	2.206	2.607
NIMT	1.82	3.62	7.34	5.672	6.187	5.061	2.18	1.30	1.79	6.343	7.285	9.094
NML-SIRIM	0.01	0.01	0.01	5.694	6.197	5.065	2.18	1.30	1.79	6.097	6.332	5.372
NMC	4.47	5.91	5.39	0.663	0.431	0.934	2.18	1.30	1.79	5.017	6.067	5.756
NMIJ	1	1	1	0.667	0.433	0.934	2.18	1.30	1.79	2.489	1.696	2.253
NMIA	0.503	0.503	0.503	1.781	1.875	1.704	2.18	1.30	1.79	2.860	2.336	2.522
NMISA	1.102	1.228	0.952	0.925	0.811	1.014	2.18	1.30	1.79	2.612	1.964	2.267
NIM	1.04	1.46	0.45	0.663	0.687	0.934	2.18	1.30	1.79	2.505	2.072	2.069
VNIIM	2.9	1.3	1.2	0.802	0.421	0.989	2.18	1.30	1.79	3.716	1.886	2.371
SCL	0.13	0.11	0.11	1.037	0.974	1.170	2.18	1.30	1.79	2.418	1.628	2.141
KazInMetr	6.991	7.81	10.926	1.037	0.974	1.170	2.18	1.30	1.79	7.396	7.977	11.133
MSL	0.355	0.355	0.355	2.396	1.718	1.558	2.18	1.30	1.79	3.259	2.183	2.399

6.3 Calculation of the reference value, its uncertainty and Degree of Equivalence (DOE)

The weighted mean value (M_P) and standard uncertainty (u_C) of the three results for the same nominal value obtained by each participant is estimated by the following equations and is shown in Table 12 and Table 13.

$$\mathrm{Mp} = \frac{\sum_{k=1}^{3}\frac{M_{p,k}}{{u_{rp,p,k}}^2}}{\sum_{k=1}^{3}\frac{1}{{u_{rp,p,k}}^2}} \ , \ u_C\left(M_p\right) = \sqrt{({u_{rp,p}}^2 + {u_{sys,p}}^2)} \qquad (5)$$

, where ${u_{rp,p}}^2 = (\frac{1}{3})\sum_{k=1}^{3} {u_{rp,p,k}}^2$, ${u_{rp,p,k}}^2 = {u_{r,k}}^2 + {u_{TV,k}}^2 + {u_{tr,k}}^2$ and ${u_{sys,p}}^2 = (\frac{1}{3})\sum_{k=1}^{3} {u_{sys,p,k}}^2$

, where $u_{rp,p,k}$ means the reproducibility for each travelling standard shown in table 10 and 11, $u_{sys,p,k}$ means type B standard uncertainty of each NMI shown in Tables 5 and 6 and *k* means the number of travelling standards.

From the weighted mean and the standard uncertainty of each participant, CRV, DoE and associated standard uncertainties of the entire participant's results are determined by the following equations and are shown in Table 12 and Table 13. In case of MSL, the results at 10 V and 100 V for 10 MΩ are given but the Mp and DoE difference is given to be $0.3 \cdot 10^{-6}$ and the associated uncertainties for u_c(Mp) and u(CRV) are almost the same so that they are not influenced on the entire result. So, in Table 12 and the following graphs the results at 100 V are shown. In case of NMIA, the results at 50 V for 10 MΩ are used because the result for HR7552 is given at 50 V and the results for HR7550 and HR7551 at 50 V and 91 V are the same within the uncertainty so that they are not influenced on other results. The method proposed in [2] is used to calculate the comparison reference value(CRV). The degrees of equivalence(DoE) with respect to the CRV at 10 MΩ and 1 GΩ are shown in Figure 7 and Figure 8. Also, the pairwise DoEs with respect to the CRV at 10 MΩ and 1 GΩ are shown in Table 15 and 16.

$$\mathrm{CRV} = \frac{\sum_{p=1}^{N}\omega_P \cdot M_P}{\sum_{p=1}^{N}\omega_P}, \quad \omega_P = \frac{1}{{u_C}^2(M_P)} \ , \ u^2(CRV) = \sqrt{\frac{1}{\sum_{p=1}^{N}\frac{1}{{u_C}^2(M_P)}}} \ ,$$

$$(DoE)_P = \mathrm{di} = M_P - \mathrm{CRV} \ , u(DoE)_P = \sqrt{{u_C}^2(M_P) + u^2(CRV)} \ , U(DoE)_P = 2 \cdot u(DoE)_P \ , \qquad (6)$$

$$\mathrm{dij} = \mathrm{di} - \mathrm{dj} \ , \mathrm{U(dij)} = 2 \cdot \mathrm{u(dij)} \ , u^2(dij) = u^2(di) + u^2(dj)$$

, where ω_P means weight which shows the standard deviation associated with M_P and CRV means the weighted mean value of the participants' results.

The NML-SIRIM measured the travelling standards using the reference multimeter 8508A with Calibration Platform Resistance and also using a DCC Bridge and Modified Wheatstone Bridge on measurement. For the draft A report, the first one was submitted and the second one was submitted to properly support the CMC claims for the draft B report. It is shown in the draft B report that the revised results do not have influence on CRV, KCRV and other NMI's results.

For an overall consistency check of the results, chi-squared test was applied using the following equation and test results are shown in Table 14.

$$\chi^2{}_{obs} = \sum_{p=1}^{N} \frac{(M_P - CRV)^2}{u_C{}^2(M_P)} = \sum_{p=1}^{N} \frac{(DoE)_P{}^2}{u_C{}^2(M_P)} \tag{7}$$

where N means number of participants.

The consistency check is failed if $[\Pr[\chi^2(\mathrm{v}) > \chi^2{}_{obs}] < 0.05$. Here, Pr denotes "probability of". If the consistency check does not fail, accept the weighted mean value and standard uncertainty of the participants' measurements as the CRV and the standard uncertainty u_{CRV} associated with the CRV[2]. From calculation of CRV, |di|-U(di) value for p=12 is much larger than other NMI's values and so it is regarded as providing a discrepant measurement by chi square test. Therefore, the NMI's result is excluded to calculate the CRV of 1 GΩ measurements shown in Table 13.

Table 12 The CRV, DoE and associated standard uncertainties of the entire participant's results for 10 MΩ

NMI	10 M Weighted Mean (M_P, x10^{-6})	$u_C(M_P)$	CRV	u(CRV)	DOE(p) or di	|di|	u(di)	U(di)	|di|-U(di)
KRISS	-0.03	0.91	-0.20	0.40	0.17	0.17	0.82	1.64	-1.47
CMS	-1.30	2.37	-0.20	0.40	-1.10	1.10	2.34	4.67	-3.57
NIMT	6.20	3.35	-0.20	0.40	6.40	6.40	3.33	6.65	-0.25
NML-SIRIM	1.04	3.47	-0.20	0.40	1.24	1.24	3.45	6.89	-5.65
NMC	-0.14	0.96	-0.20	0.40	0.06	0.06	0.87	1.75	-1.69
NMIJ	1.19	0.92	-0.20	0.40	1.39	1.39	0.83	1.66	-0.27
NMIA	-1.16	0.98	-0.20	0.40	-0.96	0.96	0.89	1.79	-0.83
NMISA	-2.76	2.59	-0.20	0.40	-2.56	2.56	2.56	5.12	-2.56
NIM	-0.58	1.57	-0.20	0.40	-0.38	0.38	1.52	3.04	-2.66
VNIIM	-0.78	1.16	-0.20	0.40	-0.58	0.58	1.09	2.18	-1.60
SCL	-1.99	2.61	-0.20	0.40	-1.79	1.79	2.58	5.16	-3.37
KazInMetr	-9.31	24.04	-0.20	0.40	-9.11	9.11	24.04	48.07	-38.96
MSL	-1.69	3.22	-0.20	0.40	-1.49	1.49	3.20	6.39	-4.90

Table 13 The CRV, DoE and associated standard uncertainties of the entire participant's results for 1 GΩ

NMI	1 G Weighted Mean (M_P, x10^{-6})	$u_C(M_P)$	CRV	u(CRV)	DOE(p) or di	|di|	u(di)	U(di)	|di|-U(di)
KRISS	-0.22	2.52	1.81	1.14	-2.03	2.03	2.25	4.51	-2.48
CMS	1.86	5.01	1.81	1.14	0.05	0.05	4.88	9.75	-9.70
NML-SIRIM	7.63	12.73	1.81	1.14	5.82	5.82	12.68	25.36	-19.54
NMC	-4.95	6.54	1.81	1.14	-6.76	6.76	6.44	12.88	-6.12
NMIJ	5.31	2.51	1.81	1.14	3.50	3.50	2.23	4.46	-0.96
NMIA	-1.44	3.70	1.81	1.14	-3.25	3.25	3.52	7.05	-3.80
NMISA	4.28	4.58	1.81	1.14	2.47	2.47	4.43	8.87	-6.40
NIM	-2.42	3.90	1.81	1.14	-4.23	4.23	3.72	7.45	-3.22
VNIIM	2.87	3.30	1.81	1.14	1.06	1.06	3.09	6.19	-5.13
SCL	1.09	6.35	1.81	1.14	-0.72	0.72	6.25	12.50	-11.78
KazInMetr	228.15	71.40	1.81	1.14	226.34	226.34	71.39	142.79	83.55
MSL	3.64	3.42	1.81	1.14	1.83	1.83	3.22	6.44	-4.61

Table 14 Chi-squared test results for an overall consistency check of the participants' results

CRV (10 MΩ)	χ_{obs}^2	Degree of freedom	Pr		
-0.20	9.4	12	>0.5		pass
CRV (1 GΩ)	χ_{obs}^2		Pr		
1.85	34.2	12	<0.05		fail
1.79	16.6	11	>0.1	exclude p=12 from CRV calculation	pass

Table 15 Pairwise DOEs with respect to the CRV at 10 MΩ

10 MΩ			KRISS		CMS		NIMT		NML-SIRIM		NMC		NMIJ		NMIA		NMISA		NIM		VNIIM		SCL		KazInMetr		MSL	
Lab i	di	$u(d_i)$	dij	U(dij)	dij	U(dij)	dij	U(dij)	dij	U(dij)	dij	U(dij)	dij	U(dij)	dij	U(dij)	dij	U(dij)	dij	U(dij)	dij	U(dij)	dij	U(dij)	dij	U(dij)	dij	U(dij)
KRISS	0.19	0.82	-	-	1.27	4.96	-6.23	6.86	-1.07	7.09	0.11	2.39	-1.22	2.33	1.13	2.42	2.73	5.38	0.55	3.45	0.75	2.73	1.96	5.41	9.28	48.11	1.66	6.61
CMS	-1.08	2.34	-1.27	4.96	-	-	-7.50	8.14	-2.34	8.34	-1.16	4.99	-2.49	4.97	-0.14	5.01	1.46	6.94	-0.72	5.58	-0.52	5.16	0.69	6.97	8.01	48.31	0.39	7.93
NIMT	6.42	3.33	6.23	6.86	7.50	8.14	-	-	5.16	9.59	6.34	6.88	5.01	6.86	7.36	6.89	8.96	8.40	6.78	7.32	6.98	7.01	8.19	8.43	15.51	48.54	7.89	9.24
NML-SIRIM	1.26	3.45	1.07	7.09	2.34	8.34	-5.16	9.59	-	-	1.18	7.12	-0.15	7.10	2.20	7.13	3.80	8.59	1.62	7.54	1.82	7.24	3.03	8.62	10.35	48.57	2.73	9.41
NMC	0.08	0.87	-0.11	2.39	1.16	4.99	-6.34	6.88	-1.18	7.12	-	-	-1.33	2.40	1.02	2.49	2.62	5.41	0.44	3.50	0.64	2.79	1.85	5.45	9.17	48.11	1.55	6.63
NMIJ	1.41	0.83	1.22	2.33	2.49	4.97	-5.01	6.86	0.15	7.10	1.33	2.40	-	-	2.35	2.43	3.95	5.38	1.77	3.46	1.97	2.74	3.18	5.42	10.50	48.11	2.88	6.61
NMIA	-0.94	0.89	-1.13	2.42	0.14	5.01	-7.36	6.89	-2.20	7.13	-1.02	2.49	-2.35	2.43	-	-	1.60	5.42	-0.58	3.52	-0.38	2.81	0.83	5.46	8.15	48.11	0.53	6.64
NMISA	-2.54	2.56	-2.73	5.38	-1.46	6.94	-8.96	8.40	-3.80	8.59	-2.62	5.41	-3.95	5.38	-1.60	5.42	-	-	-2.18	5.95	-1.98	5.56	-0.77	7.27	6.55	48.35	-1.07	8.20
NIM	-0.36	1.52	-0.55	3.45	0.72	5.58	-6.78	7.32	-1.62	7.54	-0.44	3.50	-1.77	3.46	0.58	3.52	2.18	5.95	-	-	0.20	3.74	1.41	5.99	8.73	48.18	1.11	7.09
VNIIM	-0.56	1.09	-0.75	2.73	0.52	5.16	-6.98	7.01	-1.82	7.24	-0.64	2.79	-1.97	2.74	0.38	2.81	1.98	5.56	-0.20	3.74	-	-	1.21	5.60	8.53	48.13	0.91	6.76
SCL	-1.77	2.58	-1.96	5.41	-0.69	6.97	-8.19	8.43	-3.03	8.62	-1.85	5.45	-3.18	5.42	-0.83	5.46	0.77	7.27	-1.41	5.99	-1.21	5.60	-	-	7.32	48.36	-0.30	8.22
KazInMetr	-9.09	24.04	-9.28	48.11	-8.01	48.31	-15.51	48.54	-10.35	48.57	-9.17	48.11	-10.50	48.11	-8.15	48.11	-6.55	48.35	-8.73	48.18	-8.53	48.13	-7.32	48.36	-	-	-7.62	48.50
MSL	-1.47	3.20	-1.66	6.61	-0.39	7.93	-7.89	9.24	-2.73	9.41	-1.55	6.63	-2.88	6.61	-0.53	6.64	1.07	8.20	-1.11	7.09	-0.91	6.76	0.30	8.22	7.62	48.50	-	-

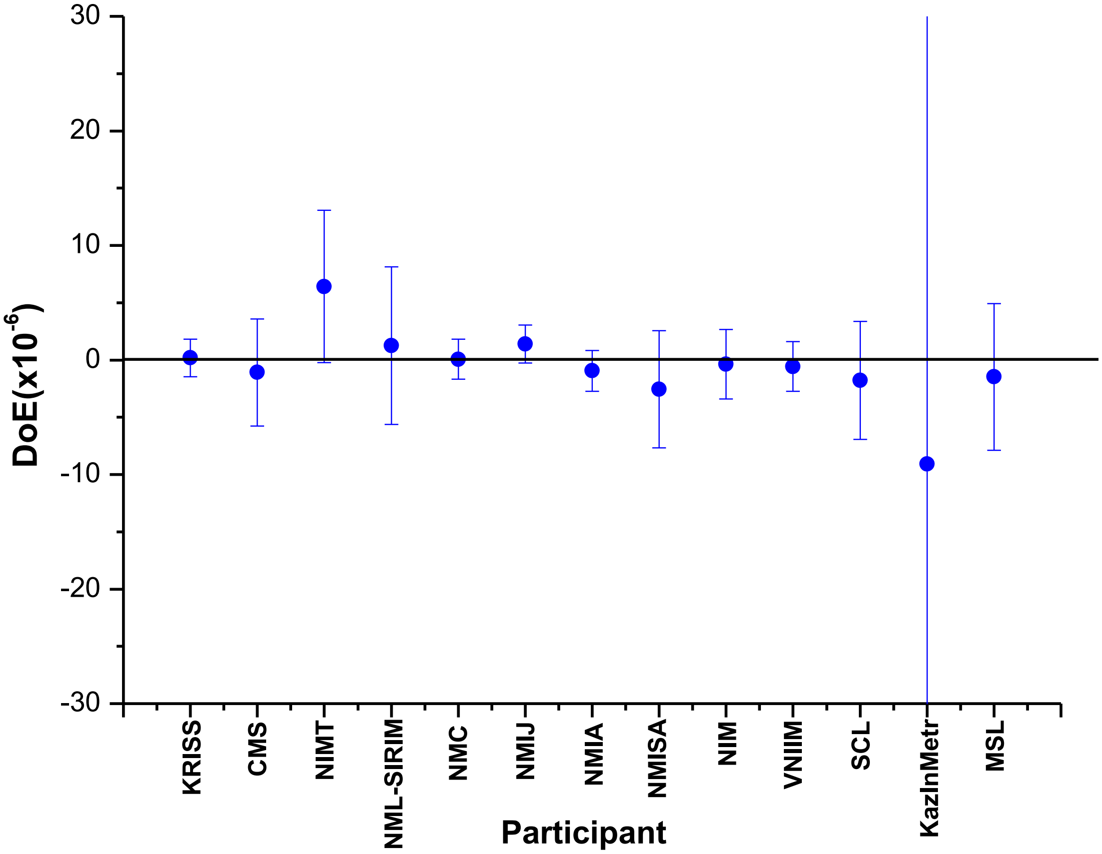

Figure 7 Degrees of equivalence with respect to the CRV at 10 MΩ

Table 16 Pairwise DOEs with respect to the CRV at 1 GΩ

1 GΩ			KRISS		CMS		NML-SIRIM		NMC		NMIJ		NMIA		NMISA		NIM		VNIIM		SCL		KazInMetr		MSL	
Lab i	di	$u_C(d_i)$	dij	U(dij)	dij	U(dij)	dij	U(dij)	dij	U(dij)	dij	U(dij)	dij	U(dij)	dij	U(dij)	dij	U(dij)	dij	U(dij)	dij	U(dij)	dij	U(dij)	dij	U(dij)
KRISS	-2.06	2.25	-	-	-2.16	10.75	-7.93	25.76	4.65	13.64	-5.61	6.34	1.14	8.36	-4.58	9.94	2.12	8.70	-3.17	7.64	-1.39	13.29	-228.45	142.85	-3.94	7.86
CMS	0.1	4.88	2.16	10.75	-	-	-5.77	27.17	6.81	16.16	-3.45	10.73	3.30	12.03	-2.42	13.18	4.28	12.27	-1.01	11.55	0.77	15.86	-226.29	143.11	-1.78	11.69
NML-SIRIM	5.87	12.68	7.93	25.76	5.77	27.17	-	-	12.58	28.44	2.32	25.75	9.07	26.32	3.35	26.86	10.05	26.43	4.76	26.10	6.54	28.27	-220.52	145.01	3.99	26.16
NMC	-6.71	6.44	-4.65	13.64	-6.81	16.16	-12.58	28.44	-	-	-10.26	13.63	-3.51	14.68	-9.23	15.63	-2.53	14.87	-7.82	14.29	-6.04	17.95	-233.10	143.36	-8.59	14.40
NMIJ	3.55	2.23	5.61	6.34	3.45	10.73	-2.32	25.75	10.26	13.63	-	-	6.75	8.33	1.03	9.92	7.73	8.67	2.44	7.62	4.22	13.27	-222.84	142.85	1.67	7.83
NMIA	-3.2	3.52	-1.14	8.36	-3.30	12.03	-9.07	26.32	3.51	14.68	-6.75	8.33	-	-	-5.72	11.32	0.98	10.24	-4.31	9.37	-2.53	14.35	-229.59	142.95	-5.08	9.54
NMISA	2.52	4.43	4.58	9.94	2.42	13.18	-3.35	26.86	9.23	15.63	-1.03	9.92	5.72	11.32	-	-	6.70	11.57	1.41	10.80	3.19	15.32	-223.87	143.05	0.64	10.95
NIM	-4.18	3.72	-2.12	8.70	-4.28	12.27	-10.05	26.43	2.53	14.87	-7.73	8.67	-0.98	10.24	-6.70	11.57	-	-	-5.29	9.67	-3.51	14.55	-230.57	142.97	-6.06	9.84
VNIIM	1.11	3.09	3.17	7.64	1.01	11.55	-4.76	26.10	7.82	14.29	-2.44	7.62	4.31	9.37	-1.41	10.80	5.29	9.67	-	-	1.78	13.94	-225.28	142.91	-0.77	8.93
SCL	-0.67	6.25	1.39	13.29	-0.77	15.86	-6.54	28.27	6.04	17.95	-4.22	13.27	2.53	14.35	-3.19	15.32	3.51	14.55	-1.78	13.94	-	-	-227.06	143.33	-2.55	14.06
KazInMetr	226.39	71.39	228.45	142.85	226.29	143.11	220.52	145.01	233.10	143.36	222.84	142.85	229.59	142.95	223.87	143.05	230.57	142.97	225.28	142.91	227.06	143.33	-	-	224.51	142.93
MSL	1.88	3.22	3.94	7.86	1.78	11.69	-3.99	26.16	8.59	14.40	-1.67	7.83	5.08	9.54	-0.64	10.95	6.06	9.84	0.77	8.93	2.55	14.06	-224.51	142.93	-	-

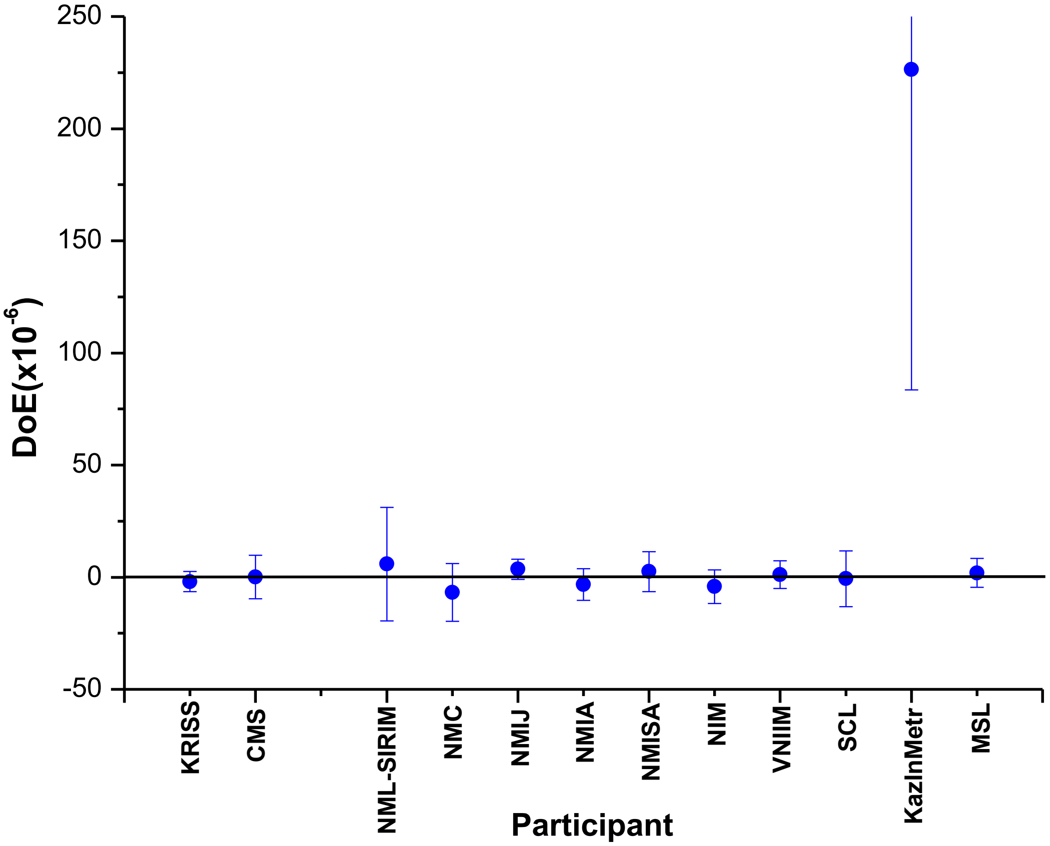

Figure 8 Degrees of equivalence with respect to the CRV at 1 GΩ

7. Link to the CCEM KC and DOEs[1],[3],[4]

It is assumed that a linking laboratory performed similarly in the CCEM and in the RMO comparison. The difference between its unilateral DoE d_i in the CCEM and RMO comparison can thus be taken as the correction Δ_i which needs to be applied to the RMO values.

$$\Delta_i = d_i^{CCEM} - d_i^{RMO} \tag{8}$$

with i indicating the linking laboratory. For more than one linking laboratory it is reasonable to determine a weighted average of all linking labs as the overall correction Δ

$$\Delta = \sum_i \omega_i \, \Delta_i = \frac{\sum_i \frac{\Delta_i}{u^2(\Delta_i)}}{\sum_i \frac{1}{u^2(\Delta_i)}} \tag{9}$$

with

$$u^2(\Delta_i) = u^2\left({d_i}^{CCEM}\right) + u^2\left({d_i}^{RMO}\right)$$

and

$$u^2(\Delta) = \frac{1}{\sum_i \frac{1}{u^2(\Delta_i)}} \tag{10}$$

i denotes that the sum is over the linking laboratory only.

The correction to the DoEs of those who participated exclusively in the RMO comparison can then be written as

$${d_i}^{CCEM} = {d_i}^{APMP} + \Delta \tag{11}$$

with uncertainties

$$u^2\left({d_i}^{CCEM}\right) = u^2\left({d_i}^{APMP}\right) + u^2(\Delta)$$

i indicates the laboratories that participated in the RMO comparison only, whereas the linking laboratories will simply keep the DoEs determined in the CCEM comparison.

For the bilateral DoEs ${d_{ij}}^{CCEM}$ one can use

$${d_{ij}}^{CCEM} = {d_i}^{CCEM} - {d_j}^{CCEM} \tag{12}$$

with uncertainties

$$u^2\left({d_{ij}}^{CCEM}\right) = u^2\left({d_i}^{CCEM}\right) + u^2\left({d_j}^{CCEM}\right)$$

The bilateral DoEs ${d_{ij}}^{CCEM}$ are only calculated between laboratories that participated in the RMO comparison and those which participated not in the RMO comparison, i.e. the bilateral DoEs determined within the RMO comparison are used unaltered as the CCEM values.

Table 17 shows degrees of equivalence of the linking labs with respect to the CCEM as well as the APMP and correction values and the uncertainties for linking to the CCEM results. Furthermore, Table 18 and Table 19 show degree of equivalence with respect to the Key Comparison Reference Value (KCRV) and pairwise degree of equivalence for 10 MΩ and 1 GΩ.

Table 17 Unilateral degrees of equivalence of the linking labs with respect to the CCEM and the APMP and correction values and the uncertainties for linking to the CCEM results

10 MΩ	**CCEM**			**APMP**			**Δi**	**u(Δi)**		**Δ**	**u(Δ)**
	di(=DOE)	ui(DOE)		di(=DOE)	ui(DOE)						
KRISS	-2.3	3.15		0.17	0.82		-2.47	3.25		0.35	1.15
MSL	-0.4	1.05		-1.49	3.20		1.09	3.37			
NIM	0.6	1.25		-0.38	1.52		0.98	1.97			
VNIIM	-0.1	1.4		-0.58	1.09		0.48	1.77			
1 GΩ	**CCEM**			**APMP**			**Δi**	**u(Δi)**		**Δ**	**u(Δ)**
	di(=DOE)	ui(DOE)		di(=DOE)	ui(DOE)						
KRISS	-1.5	6.2		-2.03	2.25		0.53	6.60		1.46	2.62
MSL	4.6	3.3		1.83	3.22		2.77	4.61			
NIM	-0.6	4.15		-4.23	3.72		3.63	5.57			
VNIIM	0.0	3.65		1.06	3.09		-1.06	4.78			

Table 18 Degrees of equivalence with respect to the KCRV and pairwise degree of equivalence at 10 MΩ

			Lab j																					
	10 MΩ		**NIST**		**NRC**		**LNE**		**NPL**		**PTB**		**NMIA**		**MSL**		**NMISA**		**SP**		**METAS**		**INRIM**	
Lab i	di	U(di)	**dij**	**U(dij)**	**dij**	**U(dij)**	**dij**	**U(dij)**	**dij**	**U(dij)**	**dij**	**U(dij)**	**dij**	**U(dij)**	**dij**	**U(dij)**	**dij**	**U(dij)**	**dij**	**U(dij)**	**dij**	**U(dij)**	**dij**	**U(dij)**
NIST	-0.3	2.9	-		0.9	6.4	-0.3	3.6	0.0	3.7	-0.3	5.8	0.0	6.1	0.1	3.6	15.7	79.1	-0.9	4.9	-1.0	3.6	-1.2	6.2
NRC	-1.2	5.7	-0.9	6.4			-1.2	6.1	-0.9	6.1	-1.2	7.6	-0.9	7.9	-0.8	6.1	14.8	79.2	-1.8	7.0	-1.9	6.1	-2.1	7.9
LNE	0.0	2.1	0.3	3.6	1.2	6.1			0.3	3.1	0.0	5.4	0.3	5.8	0.4	3.0	16.0	79.0	-0.6	4.5	-0.7	3.0	-0.9	5.9
NPL	-0.3	2.3	0.0	3.7	0.9	6.1	-0.3	3.1			-0.3	5.5	0.0	5.9	0.1	3.1	15.7	79.0	-0.9	4.6	-1.0	3.1	-1.2	6.0
PTB	0.0	5.0	0.3	5.8	1.2	7.6	0.0	5.4	0.3	5.5			0.3	7.4	0.4	5.4	16.0	79.2	-0.6	6.4	-0.7	5.4	-0.9	7.4
NMIA	-0.3	5.4	0.0	6.1	0.9	7.9	-0.3	5.8	0.0	5.9	-0.3	7.4			0.1	5.8	15.7	79.2	-0.9	6.7	-1.0	5.8	-1.2	7.7
MSL	-0.4	2.1	-0.1	3.6	0.8	6.1	-0.4	3.0	-0.1	3.1	-0.4	5.4	-0.1	5.8			15.6	79.0	-1.0	4.5	-1.1	3.0	-1.3	5.9
NMISA	-16.0	79.0	-15.7	79.1	-14.8	79.2	-16.0	79.0	-15.7	79.0	-16.0	79.2	-15.7	79.2	-15.6	79.0			-16.6	79.1	-16.7	79.0	-16.9	79.2
SP	0.6	4.0	0.9	4.9	1.8	7.0	0.6	4.5	0.9	4.6	0.6	6.4	0.9	6.7	1.0	4.5	16.6	79.1			-0.1	4.5	-0.3	6.8
METAS	0.7	2.1	1.0	3.6	1.9	6.1	0.7	3.0	1.0	3.1	0.7	5.4	1.0	5.8	1.1	3.0	16.7	79.0	0.1	4.5			-0.2	5.9
INRIM	0.9	5.5	1.2	6.2	2.1	7.9	0.9	5.9	1.2	6.0	0.9	7.4	1.2	7.7	1.3	5.9	16.9	79.2	0.3	6.8	0.2	5.9		
VSL	0.6	6.4	0.9	7.0	1.8	8.6	0.6	6.7	0.9	6.8	0.6	8.1	0.9	8.4	1.0	6.7	16.6	79.3	0.0	7.5	-0.1	6.7	-0.3	8.4
KRISS	-2.3	6.3	-2.0	6.9	-1.1	8.5	-2.3	6.6	-2.0	6.7	-2.3	8.0	-2.0	8.3	-1.9	6.6	13.7	79.3	-2.9	7.5	-3.0	6.6	-3.2	8.4
NIM	0.6	2.5	0.9	3.8	1.8	6.2	0.6	3.3	0.9	3.4	0.6	5.6	0.9	6.0	1.0	3.3	16.6	79.0	0.0	4.7	-0.1	3.3	-0.3	6.0
VNIIM	-0.1	2.8	0.2	4.0	1.1	6.4	-0.1	3.5	0.2	3.6	-0.1	5.7	0.2	6.1	0.3	3.5	15.9	79.0	-0.7	4.9	-0.8	3.5	-1.0	6.2
CMS	-0.8	4.8	-0.5	5.6	0.4	7.5	-0.8	5.2	-0.5	5.3	-0.8	6.9	-0.5	7.2	-0.4	5.2	15.2	79.1	-1.4	6.2	-1.5	5.2	-1.7	7.3
NIMT	6.8	6.7	7.1	7.3	8.0	8.8	6.8	7.0	7.1	7.1	6.8	8.4	7.1	8.6	7.2	7.0	22.8	79.3	6.2	7.8	6.1	7.0	5.9	8.7
NML-SIRIM	1.6	7.0	1.9	7.6	2.8	9.0	1.6	7.3	1.9	7.4	1.6	8.6	1.9	8.8	2.0	7.3	17.6	79.3	1.0	8.1	0.9	7.3	0.7	8.9
NMC	0.4	2.1	0.7	3.6	1.6	6.1	0.4	3.0	0.7	3.1	0.4	5.4	0.7	5.8	0.8	3.0	16.4	79.0	-0.2	4.5	-0.3	3.0	-0.5	5.9
NMIJ	1.7	2.0	2.0	3.5	2.9	6.0	1.7	2.9	2.0	3.0	1.7	5.4	2.0	5.8	2.1	2.9	17.7	79.0	1.1	4.5	1.0	2.9	0.8	5.9
NMIA	-0.6	2.1	-0.3	3.6	0.6	6.1	-0.6	3.0	-0.3	3.1	-0.6	5.4	-0.3	5.8	-0.2	3.0	15.4	79.0	-1.2	4.5	-1.3	3.0	-1.5	5.9
NMISA	-2.2	5.2	-1.9	6.0	-1.0	7.7	-2.2	5.6	-1.9	5.7	-2.2	7.2	-1.9	7.5	-1.8	5.6	13.8	79.2	-2.8	6.6	-2.9	5.6	-3.1	7.6
SCL	-1.4	5.3	-1.1	6.0	-0.2	7.8	-1.4	5.7	-1.1	5.8	-1.4	7.3	-1.1	7.6	-1.0	5.7	14.6	79.2	-2.0	6.6	-2.1	5.7	-2.3	7.6
KazInMetr	-8.8	48.1	-8.5	48.2	-7.6	48.4	-8.8	48.1	-8.5	48.2	-8.8	48.4	-8.5	48.4	-8.4	48.1	7.2	92.5	-9.4	48.3	-9.5	48.1	-9.7	48.4

			Lab j																								
	10 MΩ		**VSL**		**KRISS**		**NIM**		**VNIIM**		**CMS**		**NIMT**		**NML-SIRIM**		**NMC**		**NMIJ**		**NMIA**		**NMISA**		**SCL**		**KazInMetr**	
Lab i	di	U(di)	**dij**	**U(dij)**	**dij**	**U(dij)**	**dij**	**U(dij)**	**dij**	**U(dij)**	**dij**	**U(dij)**	**dij**	**U(dij)**	**dij**	**U(dij)**	**dij**	**U(dij)**	**dij**	**U(dij)**	**dij**	**U(dij)**	**dij**	**U(dij)**	**dij**	**U(dij)**	**dij**	**U(dij)**
NIST	-0.3	2.9	-0.9	7.0	2.0	6.9	-0.9	3.8	-0.2	4.0	0.5	5.6	-7.1	7.3	-1.9	7.6	-0.7	3.6	-2.0	3.5	0.3	3.6	1.9	6.0	1.1	6.0	8.5	48.2
NRC	-1.2	5.7	-1.8	8.6	1.1	8.5	-1.8	6.2	-1.1	6.4	-0.4	7.5	-8.0	8.8	-2.8	9.0	-1.6	6.1	-2.9	6.0	-0.6	6.1	1.0	7.7	0.2	7.8	7.6	48.4
LNE	0	2.1	-0.6	6.7	2.3	6.6	-0.6	3.3	0.1	3.5	0.8	5.2	-6.8	7.0	-1.6	7.3	-0.4	3.0	-1.7	2.9	0.6	3.0	2.2	5.6	1.4	5.7	8.8	48.1
NPL	-0.3	2.3	-0.9	6.8	2.0	6.7	-0.9	3.4	-0.2	3.6	0.5	5.3	-7.1	7.1	-1.9	7.4	-0.7	3.1	-2.0	3.0	0.3	3.1	1.9	5.7	1.1	5.8	8.5	48.2
PTB	0	5	-0.6	8.1	2.3	8.0	-0.6	5.6	0.1	5.7	0.8	6.9	-6.8	8.4	-1.6	8.6	-0.4	5.4	-1.7	5.4	0.6	5.4	2.2	7.2	1.4	7.3	8.8	48.4
NMIA	-0.3	5.4	-0.9	8.4	2.0	8.3	-0.9	6.0	-0.2	6.1	0.5	7.2	-7.1	8.6	-1.9	8.8	-0.7	5.8	-2.0	5.8	0.3	5.8	1.9	7.5	1.1	7.6	8.5	48.4
MSL	-0.4	2.1	-1.0	6.7	1.9	6.6	-1.0	3.3	-0.3	3.5	0.4	5.2	-7.2	7.0	-2.0	7.3	-0.8	3.0	-2.1	2.9	0.2	3.0	1.8	5.6	1.0	5.7	8.4	48.1
NMISA	-16	79	-16.6	79.3	-13.7	79.3	-16.6	79.0	-15.9	79.0	-15.2	79.1	-22.8	79.3	-17.6	79.3	-16.4	79.0	-17.7	79.0	-15.4	79.0	-13.8	79.2	-14.6	79.2	-7.2	92.5
SP	0.6	4	0.0	7.5	2.9	7.5	0.0	4.7	0.7	4.9	1.4	6.2	-6.2	7.8	-1.0	8.1	0.2	4.5	-1.1	4.5	1.2	4.5	2.8	6.6	2.0	6.6	9.4	48.3
METAS	0.7	2.1	0.1	6.7	3.0	6.6	0.1	3.3	0.8	3.5	1.5	5.2	-6.1	7.0	-0.9	7.3	0.3	3.0	-1.0	2.9	1.3	3.0	2.9	5.6	2.1	5.7	9.5	48.1
INRIM	0.9	5.5	0.3	8.4	3.2	8.4	0.3	6.0	1.0	6.2	1.7	7.3	-5.9	8.7	-0.7	8.9	0.5	5.9	-0.8	5.9	1.5	5.9	3.1	7.6	2.3	7.6	9.7	48.4
VSL	0.6	6.4			2.9	9.0	0.0	6.9	0.7	7.0	1.4	8.0	-6.2	9.3	-1.0	9.5	0.2	6.7	-1.1	6.7	1.2	6.7	2.8	8.2	2.0	8.3	9.4	48.5
KRISS	-2.3	6.3	-2.9	9.0			-2.9	6.8	-2.2	6.9	-1.5	7.9	-9.1	9.2	-3.9	9.4	-2.7	6.6	-4.0	6.6	-1.7	6.6	-0.1	8.2	-0.9	8.2	6.5	48.5
NIM	0.6	2.5	0.0	6.9	2.9	6.8			0.7	3.8	1.4	5.4	-6.2	7.2	-1.0	7.4	0.2	3.3	-1.1	3.2	1.2	3.3	2.8	5.8	2.0	5.9	9.4	48.2
VNIIM	-0.1	2.8	-0.7	7.0	2.2	6.9	-0.7	3.8			0.7	5.6	-6.9	7.3	-1.7	7.5	-0.5	3.5	-1.8	3.4	0.5	3.5	2.1	5.9	1.3	6.0	8.7	48.2
CMS	-0.8	4.8	-1.4	8.0	1.5	7.9	-1.4	5.4	-0.7	5.6			-7.6	8.2	-2.4	8.5	-1.2	5.2	-2.5	5.2	-0.2	5.2	1.4	7.1	0.6	7.2	8.0	48.3
NIMT	6.8	6.7	6.2	9.3	9.1	9.2	6.2	7.2	6.9	7.3	7.6	8.2			5.2	9.7	6.4	7.0	5.1	7.0	7.4	7.0	9.0	8.5	8.2	8.5	15.6	48.6
NML-SIRIM	1.6	7.0	1.0	9.5	3.9	9.4	1.0	7.4	1.7	7.5	2.4	8.5	-5.2	9.7			1.2	7.3	-0.1	7.3	2.2	7.3	3.8	8.7	3.0	8.8	10.4	48.6
NMC	0.4	2.1	-0.2	6.7	2.7	6.6	-0.2	3.3	0.5	3.5	1.2	5.2	-6.4	7.0	-1.2	7.3			-1.3	2.9	1.0	3.0	2.6	5.6	1.8	5.7	9.2	48.1
NMIJ	1.7	2.0	1.1	6.7	4.0	6.6	1.1	3.2	1.8	3.4	2.5	5.2	-5.1	7.0	0.1	7.3	1.3	2.9			2.3	2.9	3.9	5.6	3.1	5.7	10.5	48.1
NMIA	-0.6	2.1	-1.2	6.7	1.7	6.6	-1.2	3.3	-0.5	3.5	0.2	5.2	-7.4	7.0	-2.2	7.3	-1.0	3.0	-2.3	2.9			1.6	5.6	0.8	5.7	8.2	48.1
NMISA	-2.2	5.2	-2.8	8.2	0.1	8.2	-2.8	5.8	-2.1	5.9	-1.4	7.1	-9.0	8.5	-3.8	8.7	-2.6	5.6	-3.9	5.6	-1.6	5.6			-0.8	7.4	6.6	48.4
SCL	-1.4	5.3	-2.0	8.3	0.9	8.2	-2.0	5.9	-1.3	6.0	-0.6	7.2	-8.2	8.5	-3.0	8.8	-1.8	5.7	-3.1	5.7	-0.8	5.7	0.8	7.4			7.4	48.4
KazInMetr	-8.8	48.1	-9.4	48.5	-6.5	48.5	-9.4	48.2	-8.7	48.2	-8.0	48.3	-15.6	48.6	-10.4	48.6	-9.2	48.1	-10.5	48.1	-8.2	48.1	-6.6	48.4	-7.4	48.4		

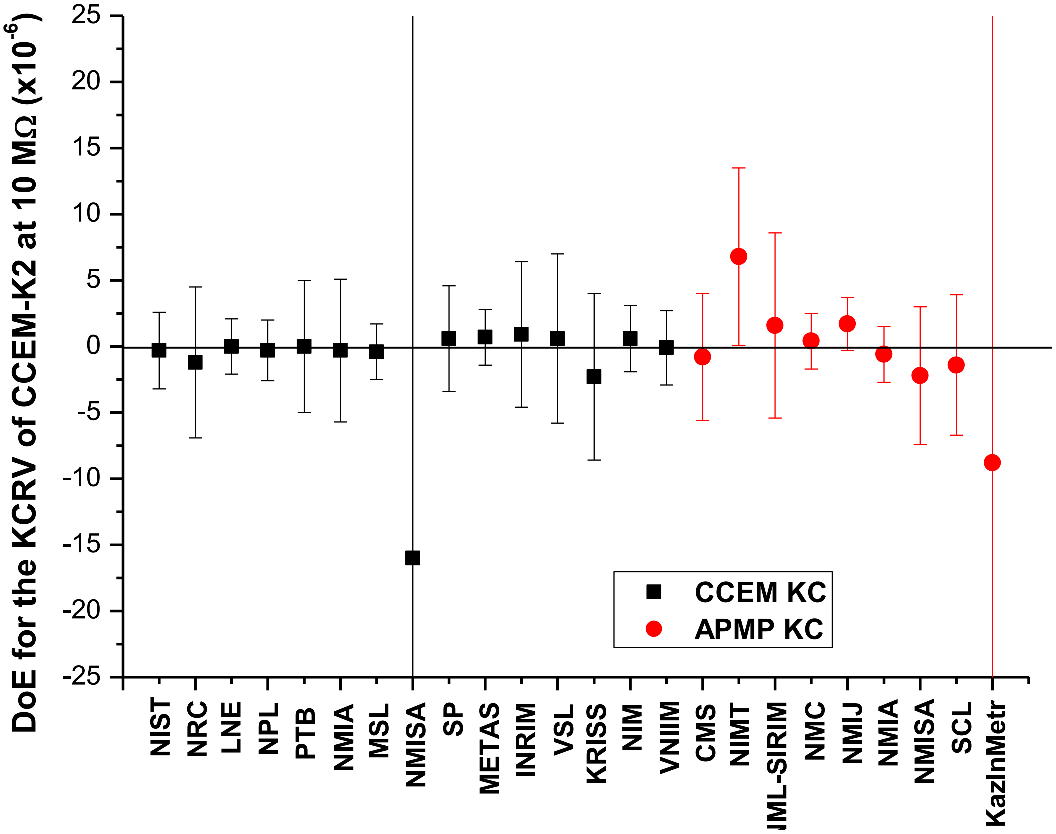

Figure 9 Degrees of equivalence with respect to the KCRV at 10 MΩ

Table 19 Degrees of equivalence with respect to the KCRV and pairwise degree of equivalence at 1 GΩ

			Lab j																					
	1 GΩ		**NIST**		**NRC**		**LNE**		**NPL**		**PTB**		**NMIA**		**MSL**		**NMISA**		**SP**		**METAS**		**INRIM**	
Lab i	di	u_C(di)	**dij**	**U(dij)**	**dij**	**U(dij)**	**dij**	**U(dij)**	**dij**	**U(dij)**	**dij**	**U(dij)**	**dij**	**U(dij)**	**dij**	**U(dij)**	**dij**	**U(dij)**	**dij**	**U(dij)**	**dij**	**U(dij)**	**dij**	**U(dij)**
NIST	-0.1	8.6	-		0.1	21.6	1.2	19.9	7.1	14.0	-3.4	15.6	-2.2	67.4	-4.7	10.8	52.9	581.1	1.5	13.2	-3.0	24.4	-2.6	21.1
NRC	-0.2	19.8	-0.1	21.6			1.1	26.8	7.0	22.7	-3.5	23.7	-2.3	69.7	-4.8	20.9	52.8	581.3	1.4	22.2	-3.1	30.2	-2.7	27.7
LNE	-1.3	18.0	-1.2	19.9	-1.1	26.8			5.9	21.1	-4.6	22.2	-3.4	69.2	-5.9	19.2	51.7	581.3	0.3	20.6	-4.2	29.0	-3.8	26.4
NPL	-7.2	11.0	-7.1	14.0	-7.0	22.7	-5.9	21.1			-10.5	17.0	-9.3	67.7	-11.8	12.8	45.8	581.1	-5.6	14.9	-10.1	25.3	-9.7	22.2
PTB	3.3	13.0	3.4	15.6	3.5	23.7	4.6	22.2	10.5	17.0			1.2	68.1	-1.3	14.6	56.3	581.1	4.9	16.4	0.4	26.2	0.8	23.3
NMIA	2.1	66.8	2.2	67.4	2.3	69.7	3.4	69.2	9.3	67.7	-1.2	68.1			-2.5	67.1	55.1	584.8	3.7	67.5	-0.8	70.6	-0.4	69.5
MSL	4.6	6.6	4.7	10.8	4.8	20.9	5.9	19.2	11.8	12.8	1.3	14.6	2.5	67.1			57.6	581.0	6.2	12.0	1.7	23.7	2.1	20.4
NMISA	-53.0	581.0	-52.9	581.1	-52.8	581.3	-51.7	581.3	-45.8	581.1	-56.3	581.1	-55.1	584.8	-57.6	581.0			-51.4	581.1	-55.9	581.4	-55.5	581.3
SP	-1.6	10.0	-1.5	13.2	-1.4	22.2	-0.3	20.6	5.6	14.9	-4.9	16.4	-3.7	67.5	-6.2	12.0	51.4	581.1			-4.5	24.9	-4.1	21.7
METAS	2.9	22.8	3.0	24.4	3.1	30.2	4.2	29.0	10.1	25.3	-0.4	26.2	0.8	70.6	-1.7	23.7	55.9	581.4	4.5	24.9			0.4	29.9
INRIM	2.5	19.3	2.6	21.1	2.7	27.7	3.8	26.4	9.7	22.2	-0.8	23.3	0.4	69.5	-2.1	20.4	55.5	581.3	4.1	21.7	-0.4	29.9		
VSL	-32.3	36.3	-32.2	37.3	-32.1	41.3	-31.0	40.5	-25.1	37.9	-35.6	38.6	-34.4	76.0	-36.9	36.9	20.7	582.1	-30.7	37.7	-35.2	42.9	-34.8	41.1
KRISS	-1.5	12.4	-1.4	15.1	-1.3	23.4	-0.2	21.9	5.7	16.6	-4.8	18.0	-3.6	67.9	-6.1	14.0	51.5	581.1	0.1	15.9	-4.4	26.0	-4.0	22.9
NIM	-0.6	8.3	-0.5	12.0	-0.4	21.5	0.7	19.8	6.6	13.8	-3.9	15.4	-2.7	67.3	-5.2	10.6	52.4	581.1	1.0	13.0	-3.5	24.3	-3.1	21.0
VNIIM	0.0	7.3	0.1	11.3	0.2	21.1	1.3	19.4	7.2	13.2	-3.3	14.9	-2.1	67.2	-4.6	9.8	53.0	581.0	1.6	12.4	-2.9	23.9	-2.5	20.6
CMS	1.6	10.1	1.7	13.3	1.8	22.2	2.9	20.6	8.8	14.9	-1.7	16.5	-0.5	67.6	-3.0	12.1	54.6	581.1	3.2	14.2	-1.3	24.9	-0.9	21.8
NML-SIRIM	7.3	25.5	7.4	26.9	7.5	32.3	8.6	31.2	14.5	27.8	4.0	28.6	5.2	71.5	2.7	26.3	60.3	581.6	8.9	27.4	4.4	34.2	4.8	32.0
NMC	-5.3	13.1	-5.2	15.7	-5.1	23.7	-4.0	22.3	1.9	17.1	-8.6	18.5	-7.4	68.1	-9.9	14.7	47.7	581.1	-3.7	16.5	-8.2	26.3	-7.8	23.3
NMIJ	5.0	5.2	5.1	10.0	5.2	20.5	6.3	18.7	12.2	12.2	1.7	14.0	2.9	67.0	0.4	8.4	58.0	581.0	6.6	11.3	2.1	23.4	2.5	20.0
NMIA	-1.8	7.5	-1.7	11.4	-1.6	21.2	-0.5	19.5	5.4	13.3	-5.1	15.0	-3.9	67.2	-6.4	10.0	51.2	581.0	-0.2	12.5	-4.7	24.0	-4.3	20.7
NMISA	4.0	9.2	4.1	12.6	4.2	21.8	5.3	20.2	11.2	14.3	0.7	15.9	1.9	67.4	-0.6	11.3	57.0	581.1	5.6	13.6	1.1	24.6	1.5	21.4
SCL	0.8	12.8	0.9	15.4	1.0	23.6	2.1	22.1	8.0	16.9	-2.5	18.2	-1.3	68.0	-3.8	14.4	53.8	581.1	2.4	16.2	-2.1	26.1	-1.7	23.2
KazInMetr	227.8	142.8	227.9	143.1	228.0	144.2	229.1	143.9	235.0	143.2	224.5	143.4	225.7	157.7	223.2	143.0	280.8	598.3	229.4	143.1	224.9	144.6	225.3	144.1

			Lab j																					
	1 GΩ		**VSL**		**KRISS**		**NIM**		**VNIIM**		**CMS**		**NML-SIRIM**		**NMC**		**NMIJ**		**NMIA**		**NMISA**		**SCL**		**KazInMetr**	
Lab i	di	u_C(di)	**dij**	**U(dij)**	**dij**	**U(dij)**	**dij**	**U(dij)**	**dij**	**U(dij)**	**dij**	**U(dij)**	**dij**	**U(dij)**	**dij**	**U(dij)**	**dij**	**U(dij)**	**dij**	**U(dij)**	**dij**	**U(dij)**	**dij**	**U(dij)**	**dij**	**U(dij)**
NIST	-0.1	8.6	32.2	37.3	1.4	15.1	0.5	12.0	-0.1	11.3	-1.7	13.3	-7.4	26.9	5.2	15.7	-5.1	10.0	1.7	11.4	-4.1	12.6	-0.9	15.4	-227.9	143.1
NRC	-0.2	19.8	32.1	41.3	1.3	23.4	0.4	21.5	-0.2	21.1	-1.8	22.2	-7.5	32.3	5.1	23.7	-5.2	20.5	1.6	21.2	-4.2	21.8	-1.0	23.6	-228.0	144.2
LNE	-1.3	18	31.0	40.5	0.2	21.9	-0.7	19.8	-1.3	19.4	-2.9	20.6	-8.6	31.2	4.0	22.3	-6.3	18.7	0.5	19.5	-5.3	20.2	-2.1	22.1	-229.1	143.9
NPL	-7.2	11	25.1	37.9	-5.7	16.6	-6.6	13.8	-7.2	13.2	-8.8	14.9	-14.5	27.8	-1.9	17.1	-12.2	12.2	-5.4	13.3	-11.2	14.3	-8.0	16.9	-235.0	143.2
PTB	3.3	13	35.6	38.6	4.8	18.0	3.9	15.4	3.3	14.9	1.7	16.5	-4.0	28.6	8.6	18.5	-1.7	14.0	5.1	15.0	-0.7	15.9	2.5	18.2	-224.5	143.4
NMIA	2.1	66.8	34.4	76.0	3.6	67.9	2.7	67.3	2.1	67.2	0.5	67.6	-5.2	71.5	7.4	68.1	-2.9	67.0	3.9	67.2	-1.9	67.4	1.3	68.0	-225.7	157.7
MSL	4.6	6.6	36.9	36.9	6.1	14.0	5.2	10.6	4.6	9.8	3.0	12.1	-2.7	26.3	9.9	14.7	-0.4	8.4	6.4	10.0	0.6	11.3	3.8	14.4	-223.2	143.0
NMISA	-53	581	-20.7	582.1	-51.5	581.1	-52.4	581.1	-53.0	581.0	-54.6	581.1	-60.3	581.6	-47.7	581.1	-58.0	581.0	-51.2	581.0	-57.0	581.1	-53.8	581.1	-280.8	598.3
SP	-1.6	10	30.7	37.7	-0.1	15.9	-1.0	13.0	-1.6	12.4	-3.2	14.2	-8.9	27.4	3.7	16.5	-6.6	11.3	0.2	12.5	-5.6	13.6	-2.4	16.2	-229.4	143.1
METAS	2.9	22.8	35.2	42.9	4.4	26.0	3.5	24.3	2.9	23.9	1.3	24.9	-4.4	34.2	8.2	26.3	-2.1	23.4	4.7	24.0	-1.1	24.6	2.1	26.1	-224.9	144.6
INRIM	2.5	19.3	34.8	41.1	4.0	22.9	3.1	21.0	2.5	20.6	0.9	21.8	-4.8	32.0	7.8	23.3	-2.5	20.0	4.3	20.7	-1.5	21.4	1.7	23.2	-225.3	144.1
VSL	-32.3	36.3			-30.8	38.4	-31.7	37.2	-32.3	37.0	-33.9	37.7	-39.6	44.4	-27.0	38.6	-37.3	36.7	-30.5	37.1	-36.3	37.4	-33.1	38.5	-260.1	147.3
KRISS	-1.5	12.4	30.8	38.4			-0.9	14.9	-1.5	14.4	-3.1	16.0	-8.8	28.4	3.8	18.0	-6.5	13.4	0.3	14.5	-5.5	15.4	-2.3	17.8	-229.3	143.3
NIM	-0.6	8.3	31.7	37.2	0.9	14.9			-0.6	11.1	-2.2	13.1	-7.9	26.8	4.7	15.5	-5.6	9.8	1.2	11.2	-4.6	12.4	-1.4	15.3	-228.4	143.0
VNIIM	0	7.3	32.3	37.0	1.5	14.4	0.6	11.1			-1.6	12.5	-7.3	26.5	5.3	15.0	-5.0	9.0	1.8	10.5	-4.0	11.7	-0.8	14.7	-227.8	143.0
CMS	1.6	10.1	33.9	37.7	3.1	16.0	2.2	13.1	1.6	12.5			-5.7	27.4	6.9	16.5	-3.4	11.4	3.4	12.6	-2.4	13.7	0.8	16.3	-226.2	143.2
NML-SIRIM	7.3	25.5	39.6	44.4	8.8	28.4	7.9	26.8	7.3	26.5	5.7	27.4			12.6	28.7	2.3	26.0	9.1	26.6	3.3	27.1	6.5	28.5	-220.5	145.1
NMC	-5.3	13.1	27.0	38.6	-3.8	18.0	-4.7	15.5	-5.3	15.0	-6.9	16.5	-12.6	28.7			-10.3	14.1	-3.5	15.1	-9.3	16.0	-6.1	18.3	-233.1	143.4
NMIJ	5.0	5.2	37.3	36.7	6.5	13.4	5.6	9.8	5.0	9.0	3.4	11.4	-2.3	26.0	10.3	14.1			6.8	9.1	1.0	10.6	4.2	13.8	-222.8	142.9
NMIA	-1.8	7.5	30.5	37.1	-0.3	14.5	-1.2	11.2	-1.8	10.5	-3.4	12.6	-9.1	26.6	3.5	15.1	-6.8	9.1			-5.8	11.9	-229.6	143.0	-1.8	7.5
NMISA	4.0	9.2	36.3	37.4	5.5	15.4	4.6	12.4	4.0	11.7	2.4	13.7	-3.3	27.1	9.3	16.0	-1.0	10.6	5.8	11.9			4.0	9.2	4.0	9.2
SCL	0.8	12.8	33.1	38.5	2.3	17.8	1.4	15.3	0.8	14.7	-0.8	16.3	-6.5	28.5	6.1	18.3	-4.2	13.8	2.6	14.8	-3.2	15.8			-227.0	143.4
KazInMetr	227.8	142.8	260.1	147.3	229.3	143.3	228.4	143.0	227.8	143.0	226.2	143.2	220.5	145.1	233.1	143.4	222.8	142.9	229.6	143.0	223.8	143.1	227.0	143.4		

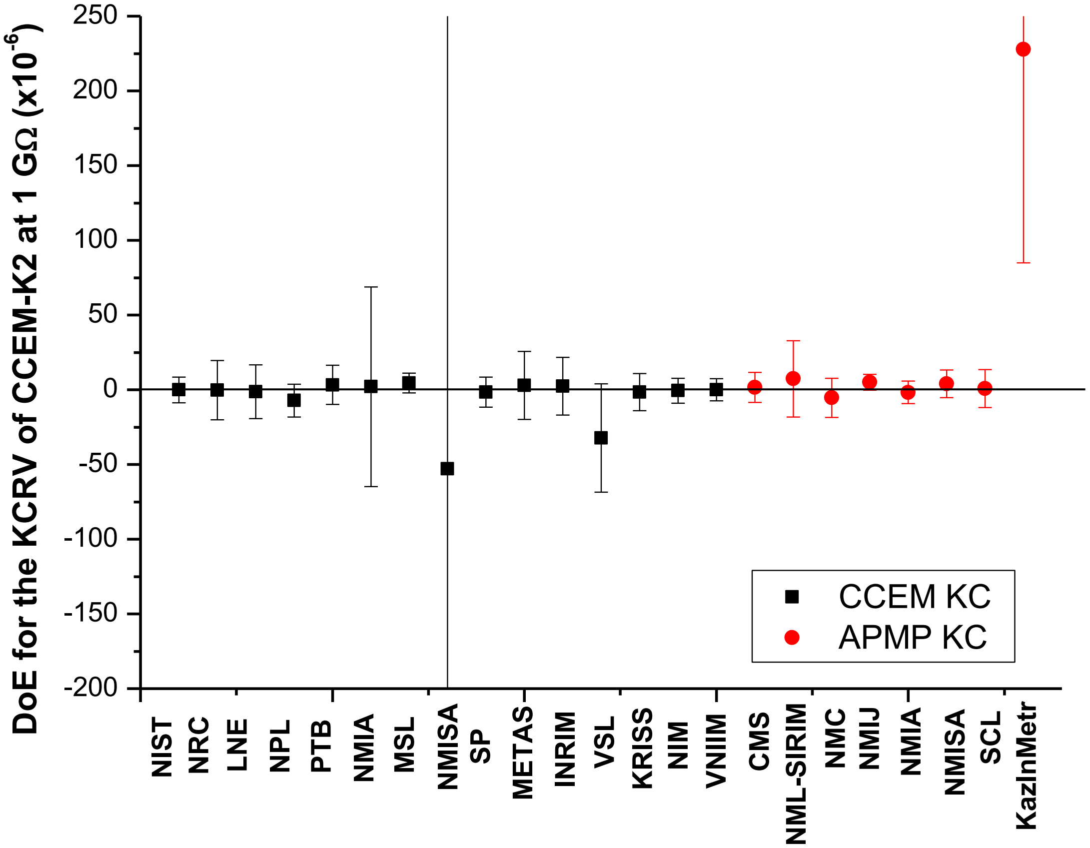

Figure 10 Degrees of equivalence with respect to the KCRV at 1 GΩ

8. Withdrawals of results

One participant had a big difference from other participants for the 1 GΩ measurement results and it is clearly shown in chi square test for the CRV consistency. The participant found system errors in the calibration system after the artefact measurement were done and reported. After that, the participant withdrew the measurement results.

9. Follow-up comparison

The NMI that decided to withdraw the 1 GΩ results will be participated in bilateral comparison with another NMI which has already participated in this APMP comparison.

10. Summary and conclusion

The results of this key comparison for 10 MΩ and 1 GΩ standards indicate good agreement among the 13 participating NMIs despite the long comparison period. Agreement is well within the level of confidence of 95%. The traveling standards appeared to have functioned satisfactorily during the 4 year period of this comparison. The second CCEM-K2 comparison report, CCEM-K2.2012 was completed several years after APMP.EM-K2. Rather than link these results to CCEM-K2.2012, a more likely outcome would be to link a future APMP comparison to CCEM-K2.2012.

11. Reference

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[3] Jeckelmann B and Zeier M, "Final report on RMO key comparison EUROMET.EM-K2: comparison of resistance standards at 10 MΩ and 1 GΩ," *Metrologia,* 47**,** 01006, 2010.

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12. Impact of the comparison on the calibration and measurements capabilities of the participating laboratories

According with the CCEM KC Guideline(2004 version), through the persons responsible for the comparison, the participating laboratories declare in writing that they have checked their results – may be with the help of the pilot institute – against their CMC claims and state whether or not these claims are supported by their results. If not, they describe the measures to be taken to remove this inconsistency.

Since the first CCEM.EM-K2 key comparison, the uncertainty of most NMIs is much improved. Thus, the result and expanded uncertainty of each NMI participated in this key comparison is considered to be reasonable with comparing to its CMC as shown in Table 20 and Table 21.

Table 20 The DOE and CMC uncertainty of the participating laboratories for 10 MΩ

Lab	U(DOE, APMP) (Expanded uncertainty, *k*=2, μΩ/Ω)	U(CMC) (Expanded uncertainty, *k*=2, μΩ/Ω)
KRISS	1.6	6
CMS	4.7	13
NIMT	6.7	32
NML-SIRIM	6.9	5
NMC	1.8	5
NMIJ	1.7	1.1
NMIA	1.8	1
NMISA	5.1	6
NIM	3.0	2
VNIIM	2.2	2
SCL	5.2	10
KazInMetr	48.1	Firstly participated
MSL	6.4	0.97

Table 21 The DOE and CMC uncertainty of the participating laboratories for 1 GΩ

Lab	U(DOE, APMP) (Expanded uncertainty, *k*=2, μΩ/Ω)	U(CMC) (Expanded uncertainty, *k*=2, μΩ/Ω)
KRISS	4.5	12
CMS	9.8	180
NML-SIRIM	25.4	17
NMC	12.9	16
NMIJ	4.5	3.2
NMIA	7.1	5
NMISA	8.9	9
NIM	7.5	7
VNIIM	6.2	5
SCL	12.5	46
KazInMetr	142.8	Firstly participated
MSL	6.4	7.7

Appendix A. Methods of measurement

Serial No	NMI	Method and Traceability
1	KRISS	KRISS QHR-traceable 1 MΩ to 10 MΩ and 10 MΩ to 10 MΩ travelling standards using a modified Wheatstone bridge/potentiometric method, 10 MΩ to 1 GΩ and 1 GΩ to 1 GΩ travelling standards using 10 to 1 ratios of a modified Wheatstone bridge/potentiometric method
2	CMS	CMS QHR-traceable 10 kΩ to 1 kΩ (parallel mode of 10 kΩ/step HTS) using a DCC bridge, 100 kΩ (series mode of 10 kΩ/step HTS) to 100 kΩ(parallel mode of 1 MΩ/step HTS) to using a multimeter, 10 MΩ(series mode of 1 MΩ/step HTS) to 10 MΩ travelling standards using a dual-source bridge, 10 MΩ(series mode of 1 MΩ/step HTS) to 10 MΩ(parallel mode of 100 MΩ/step HTS) using a dual-source bridge, 1 GΩ(series mode of 100 MΩ/step HTS) to 1 GΩ travelling standards using a dual-source bridge. The inner containers of travelling standard are connected to ground of measurement set-up at each measurement level.
3	NIMT	BIPM QHR-traceable 10 kΩ to 1 GΩ using 10 to 1 ratios of an automatic high resistance bridge
4	NML-SIRIM	BIPM QHR-traceable 10 kΩ to 10 MΩ using a DCC bridge, 10 MΩ to 1 GΩ using 10 to 1 ratios of a modified Wheatstone bridge
5	NMC	BIPM QHR-traceable10 kΩ scalling to 1MΩ to compare with 10 MΩ and 1 GΩ using 10 to 1 ratios of a potentiometric high resistance bridge. For the travelling standards, the inner guard for high was connected to the V-guard of the bridge driven by external guard potential(DVM's guard); the inner guard for low was grounded to the copper plate of the bridge
6	NMIJ	NMIJ QHR to 10 kΩ(parallel value of 100 kΩ/step HTS) using a CCC bridge, 1 MΩ(series value of 100 kΩ/step HTS) to 1 MΩ using the NMIJ-made injected voltage type high resistance bridge(NMIJ-HRB), 1 MΩ to 10 MΩ and 10 MΩ to 1 GΩ using 10 to 1 ratios of the NMIJ-HRB
7	NMIA	NMIA-Calculable Cross Capacitor-traceable 10 kΩ to 10 MΩ and 10 MΩ to 1 GΩ using 10 to 1 ratios of a high resistance ratio bridge. The comparison resistors were connected to the bridge using 3 m triaxial cables. The inner conductor of each lead was connected to the sense terminal of the bridge, the first outer conductor was connected to the source terminal of the bridge and the second outer conductor of the lead was connected to the bridge ground. At the resistor, the triaxial cable was terminated at a BPO connector. The inner and first outer conductors of the triaxial lead were joined together and connected to the inner terminal of the BPO connector. The second outer conductor was connected to the outer terminal of the BPO connector. The second outer conductor was also connected to a wire terminated in a spade lug to connect the terminal marked "CASE"

		to the bridge ground. For all measurements reported here, both the terminal marked "CASE" and the outers of the BPO connectors of each of the resistor terminations were connected to the bridge ground.
8	NMISA	A 1 MΩ reference standard to 10 MΩ and 10 MΩ to 1 GΩ using an automatic high resistance bridge
9	NIM	NIM QHR-traceable 10 kΩ to 10 MΩ and 10 MΩ to 1 GΩ using an automatic high resistance bridge
10	VNIIM	VNIIM QHR-traceable 10 kΩ to 100 kΩ using an automatic resistance bridge, 100 kΩ to 10 MΩ using a Wheatstone bridge and parallel mode of 1 MΩ/step HTS, 10 MΩ to 1 GΩ using a Wheatstone bridge and parallel mode of 100 MΩ/step HTS
11	SCL	NPL-traceable 100 Ω to 10 KΩ using the SCL CCC bridge, resistance scaling from 1 kΩ to 10 MΩ and from 10 kΩ to 100 MΩ using 1:100 ratio HTS and Kelvin Type Resistance Ratio Bridge, 100 MΩ to 1 GΩ using an automatic high resistance bridge
12	KazInMetr	KazInMetr QHR-traceable 10 kΩ to 10 MΩ using a DCC bridge, VNIIM-calibrated 1 GΩ to 1 GΩ travelling standards using a teraohmmeter substitution method
13	MSL	The measurement circuit consisted of a modified Wheatstone bridge, consisting of two voltage sources and two digital voltage meters; one acting as a null detector and the other to monitor the source voltages at the potential connections of the resistors, via a computer-controlled switch box. the four-terminal DC resistance of each standard was measured with the right-hand terminal (as viewed with the identification label upright) maintained close to ground potential, while the energizing potential was applied to the left terminal and left terminal guard. The right terminal guard and case were connected directly to the ground of the measurement apparatus.

*HTS means Hamon Transfer Standard

Appendix B. Uncertainty budgets for 10 MΩ

1. Detailed uncertainty budget, KRISS

Quantity X_i	Relative standard uncertainty, $u(x_i)$ $\times 10^{-6}$	Probability distribution /method of evaluation (A,B)	Sensitivity coefficient c_i	Relative uncertainty contribution, $u(R_i)$ $\times 10^{-6}$	Degree of freedom ν_i
Reference standard (1 MΩ)	0.28	Normal/B	1	0.28	∞
10 to 1 ratio	0.36	Rectangular/B	1	0.36	∞
Repeatability	0.2	Normal/A	1	0.2	10
Temperature effect (reference 10 MΩ)	0.15	Rectangular/B	1	0.15	∞
resistance stability (10 MΩ)	0.24	Rectangular/B	1	0.24	∞
1 to 1 ratio repeatability (10 MΩ to 10 MΩ)	0.1	Normal/A	1	0.1	10
Temperature effect (travelling standard)	0.1	Rectangular/B	1	0.1	∞
	Relative combined standard uncertainty:			0.59	
	Effective degrees of freedom:			641.5	
	Relative expanded uncertainty (95% confidence level, coverage factor k=2):			1.18	

Measurement Condition:

Temperature: The reference standards and comparison standards were measured in an air bath maintained at 23.00 °C±0.03 °C.

Test voltage: DC 10 V at 10 MΩ and 100 V at 1 GΩ.

Typical pressure: 102 kPa.

Humidity: 45 % ± 10 % r.h.

2. Detailed uncertainty budget, CMS

Quantity X_i	Estimate x_i		Relative Standard uncertainty $u(x_i)$		Probability distribution/ Method of evaluation(A,B)	Sensitivity coefficient c_i	Uncertainty contribution $u(R_i)$		Degree of freedom v_i
Step-up from 10 kΩ to 100 kΩ standard									
Repeatability			1.35	μΩ/Ω	Normal/Type A	1	1.35	μΩ/Ω	3
Measurement of 10×10 kΩ in parallel from 10 kΩ reference standard			0.108	μΩ/Ω	Normal/Type B	1	0.108	μΩ/Ω	520
Parallel to Series of 10×10 kΩ (1 kΩ transfers to 100 kΩ)			1	μΩ/Ω	Normal/Type B	1	10	μΩ/Ω	∞
Temperature instability of 10×10 kΩ			0.026	μΩ/Ω	Rectangle/Type B	1	0.026	μΩ/Ω	∞
Non-linearity of multimeter			0.1	μΩ/Ω	Rectangle/Type B	1	0.1	μΩ/Ω	∞
Resolution of multimeter			0.058	μΩ/Ω	Rectangle/Type B	1	0.058	μΩ/Ω	∞
Measurement of the 10 MΩ travelling standard									
Repeatability			0.17	μΩ/Ω	Normal/Type A	1	0.17	μΩ/Ω	2
Parallel to Series of 10×1 MΩ (100 kΩ transfers to 10 MΩ)			0.1	μΩ/Ω	Normal/Type B	1	0.1	μΩ/Ω	∞
Temperature instability of 10×1 MΩ			0.16	μΩ/Ω	Rectangle/Type B	1	0.16	μΩ/Ω	∞
Temperature corrections of 10MΩ traveling standard			0.013	μΩ/Ω	Rectangle/Type B	1	0.013	μΩ/Ω	∞
1:1 Dual-source bridge			1.5	μΩ/Ω	Normal/Type B	1	1.5	μΩ/Ω	∞
Combined relative standard uncertainty and effective degrees of freedom							2.27	μΩ/Ω	2.41×10^{25}
Relative expanded uncertainty (95 % coverage factor)							4.55	μΩ/Ω	

Measurement Condition:

Temperature: 23.09 °C~23.11 °C ±0.027 °C.

Test voltage: DC 50 V at 10 MΩ.

Humidity: 50.8 % ~ 51.0 % (± 0.3) % r.h.

3. Detailed uncertainty budget, NIMT

1) HR7550

Quantity X_i	Estimate xi	Relative standard uncertainty, $u(x_i)$ $\times 10^{-6}$	Probability distribution	Sensitivity coefficient c_i	Relative uncertainty contribution, $u(R_i)$ $\times 10^{-6}$	Degree of freedom ν_i
r	*10.00020946*	1.01	Normal	1	1.01	9
R_S	*1000048.151*	1.55	Normal	1	1.55	∞
δR_{Sd}		2.5	Rectangular	1	2.5	∞
δr_{acc}		0.6	Rectangular	1	0.6	∞
δr_{ii}		0.006	Rectangular	1	0.006	∞
δr_{rs}		0.03	Rectangular	1	0.03	∞
δr_{st}		0.06	Rectangular	1	0.06	∞
δlek		0.577	Rectangular	1	0.577	∞
δR_{temp}		0.06	Rectangular	1	0.06	∞
R_X	*10000690.98*					
		Relative combined standard uncertainty:			3.22	
		Effective degrees of freedom:			∞	
		Relative expanded uncertainty (95% confidence level, coverage factor k=2):			6.4	

Measurement Condition:

Temperature: 23.15 °C ±2.0 °C.

Test voltage: DC 10 V.

Humidity: 49 % (± 15) % r.h.

2) HR7551

Quantity X_i	Estimate xi	Relative standard uncertainty, $u(x_i)$ $\times 10^{-6}$	Probability distribution	Sensitivity coefficient c_i	Relative uncertainty contribution, $u(R_i)$ $\times 10^{-6}$	Degree of freedom ν_i
r	9.999816285	1.35	Normal	1	1.35	9
R_S	1000048.151	1.55	Normal	1	1.55	∞
δR_{Sd}		2.5	Rectangular	1	2.5	∞
δr_{acc}		0.6	Rectangular	1	0.6	∞
δr_{ii}		0.006	Rectangular	1	0.006	∞
δr_{rs}		0.03	Rectangular	1	0.03	∞
δr_{st}		0.06	Rectangular	1	0.06	∞
δlek		0.577	Rectangular	1	0.577	∞
δR_{temp}		0.06	Rectangular	1	0.06	∞
R_X	10000297.79					
		Relative combined standard uncertainty:			3.34	
		Effective degrees of freedom:			∞	
		Relative expanded uncertainty (95% confidence level, coverage factor k=2):			6.7	

Measurement Condition:

Temperature: 22.85 °C ±2.0 °C.

Test voltage: DC 10 V.

Humidity: 48 % (± 15) % r.h.

3) HR7552

Quantity	Estimate	Relative standard uncertainty, $u(x_i)$	Probability distribution	Sensitivity coefficient	Relative uncertainty contribution, $u(R_i)$	Degree of freedom ν_i
X_i	xi	$\times 10^{-6}$		c_i	$\times 10^{-6}$	
r	10.00007762	0.843	Normal	1	0.843	9
R_S	1000048.151	1.55	Normal	1	1.55	∞
δR_{Sd}		2.5	Rectangular	1	2.5	∞
δr_{acc}		0.6	Rectangular	1	0.6	∞
δr_{ii}		0.006	Rectangular	1	0.006	∞
δr_{rs}		0.03	Rectangular	1	0.03	∞
δr_{st}		0.06	Rectangular	1	0.06	∞
δlek		0.577	Rectangular	1	0.577	∞
δR_{temp}		0.06	Rectangular	1	0.06	∞
R_X	10000559.13					
		Relative combined standard uncertainty:			3.17	
		Effective degrees of freedom:			∞	
		Relative expanded uncertainty (95% confidence level, coverage factor k=2):			6.3	

Measurement Condition:

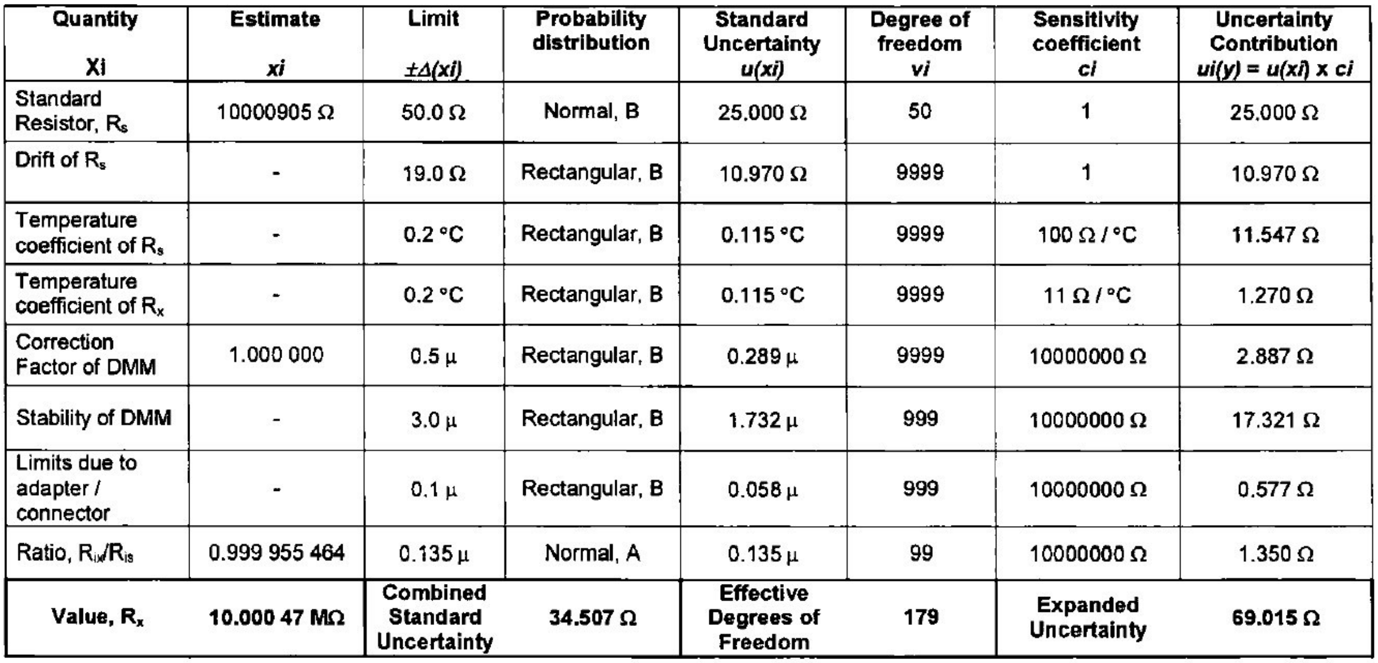
Temperature: 23.15 °C ±2.0 °C.

Test voltage: DC 10 V.

Humidity: 49 % (± 15) % r.h.

4. Detailed uncertainty budget, NML-SIRIM

1) HR7550



Quantity Xi	Estimate *xi*	Limit *±Δ(xi)*	Probability distribution	Standard Uncertainty *u(xi)*	Degree of freedom *vi*	Sensitivity coefficient *ci*	Uncertainty Contribution *ui(y) = u(xi) x ci*
Standard Resistor, R_s	10000905 Ω	50.0 Ω	Normal, B	25.000 Ω	50	1	25.000 Ω
Drift of R_s	-	19.0 Ω	Rectangular, B	10.970 Ω	9999	1	10.970 Ω
Temperature coefficient of R_s	-	0.2 °C	Rectangular, B	0.115 °C	9999	100 Ω / °C	11.547 Ω
Temperature coefficient of R_x	-	0.2 °C	Rectangular, B	0.115 °C	9999	11 Ω / °C	1.270 Ω
Correction Factor of DMM	1.000 000	0.5 µ	Rectangular, B	0.289 µ	9999	10000000 Ω	2.887 Ω
Stability of DMM	-	3.0 µ	Rectangular, B	1.732 µ	999	10000000 Ω	17.321 Ω
Limits due to adapter / connector	-	0.1 µ	Rectangular, B	0.058 µ	999	10000000 Ω	0.577 Ω
Ratio, R_{ix}/R_{is}	0.999 955 464	0.135 µ	Normal, A	0.135 µ	99	10000000 Ω	1.350 Ω
Value, R_x	**10.000 47 MΩ**	**Combined Standard Uncertainty**	**34.507 Ω**	**Effective Degrees of Freedom**	**179**	**Expanded Uncertainty**	**69.015 Ω**

Measurement Condition: *Temperature:* 23.3 °C ±1.0 °C, *Test voltage:* DC 10 V, *Humidity:* 55 % (± 10) % r.h.

2) HR7551

Quantity Xi	Estimate *xi*	Limit *±Δ(xi)*	Probability distribution	Standard Uncertainty *u(xi)*	Degree of freedom *vi*	Sensitivity coefficient *ci*	Uncertainty Contribution *ui(y) = u(xi) x ci*
Standard Resistor, R_s	10000905 Ω	50.0 Ω	Normal, B	25.000 Ω	50	1	25.000 Ω
Drift of R_s	-	19.0 Ω	Rectangular, B	10.970 Ω	9999	1	10.970 Ω
Temperature coefficient of R_s	-	0.2 °C	Rectangular, B	0.115 °C	9999	100 Ω / °C	11.547 Ω
Temperature coefficient of R_x	-	0.2 °C	Rectangular, B	0.115 °C	9999	30 Ω / °C	3.464 Ω
Correction Factor of DMM	1.000 000	0.5 μ	Rectangular, B	0.289 μ	9999	10000000 Ω	2.887 Ω
Stability of DMM	-	3.0 μ	Rectangular, B	1.732 μ	999	10000000 Ω	17.321 Ω
Observe different due to adapter	-	0.1 μ	Rectangular, B	0.058 μ	999	10000000 Ω	0.577 Ω
Ratio, R_{ix}/R_{is}	0.999 917 645	0.141 μ	Normal, A	0.141 μ	99	10000000 Ω	1.410 Ω
Value, R_x	**10.000 09 MΩ**	**Combined Standard Uncertainty**	**34.660 Ω**	**Effective Degrees of Freedom**	**183**	**Expanded Uncertainty**	**69.320 Ω**

Measurement Condition: *Temperature:* 23.3 °C ±1.0 °C, *Test voltage:* DC 10 V, *Humidity:* 55 % (± 10) % r.h.

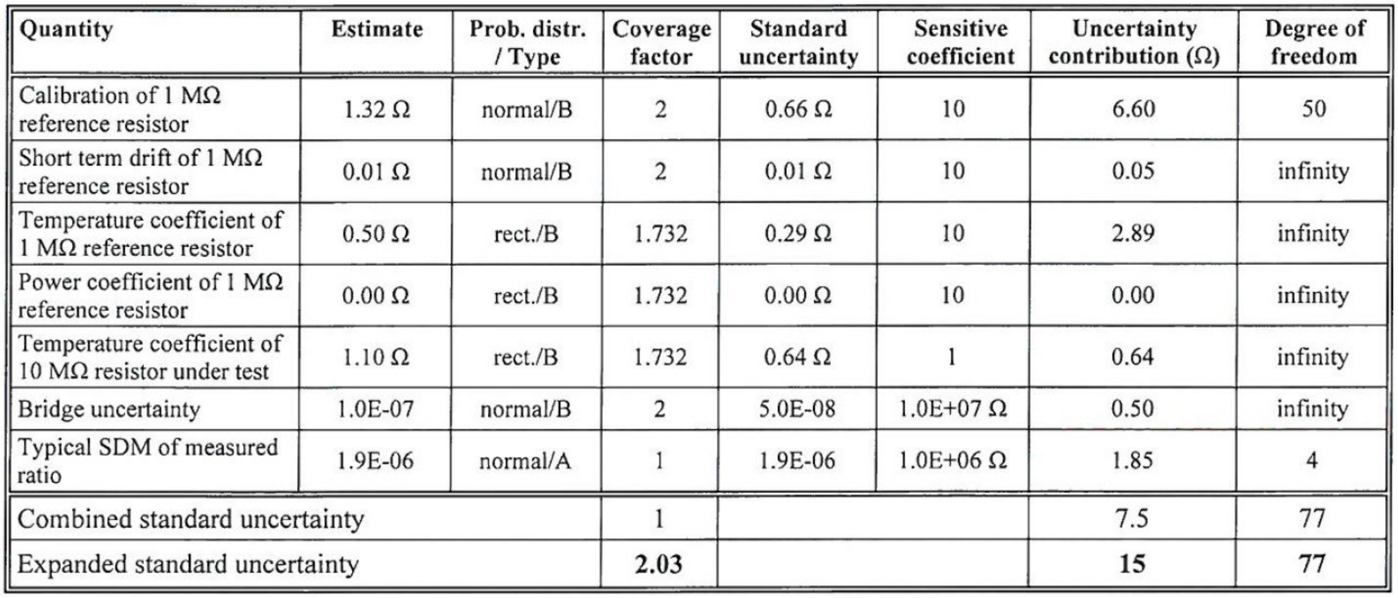
3) HR7552

Quantity Xi	Estimate *xi*	Limit *±Δ(xi)*	Probability distribution	Standard Uncertainty *u(xi)*	Degree of freedom *vi*	Sensitivity coefficient *ci*	Uncertainty Contribution *ui(y) = u(xi) x ci*
Standard Resistor, R_s	10000905 Ω	50.0 Ω	Normal, B	25.000 Ω	50	1	25.000 Ω
Drift of R_s	-	19.0 Ω	Rectangular, B	10.970 Ω	9999	1	10.970 Ω
Temperature coefficient of R_s	-	0.2 °C	Rectangular, B	0.115 °C	9999	100 Ω / °C	11.547 Ω
Temperature coefficient of R_x	-	0.2 °C	Rectangular, B	0.115 °C	9999	16 Ω / °C	1.848 Ω
Correction Factor of DMM	1.000 000	0.5 μ	Rectangular, B	0.289 μ	9999	10000000 Ω	2.887 Ω
Stability of DMM	-	3.0 μ	Rectangular, B	1.732 μ	999	10000000 Ω	17.321 Ω
Observe different due to adapter	-	0.1 μ	Rectangular, B	0.058 μ	999	10000000 Ω	0.577 Ω
Ratio, R_{ix}/R_{is}		0.115 μ	Normal, A	0.115 μ	99	10000000 Ω	1.150 Ω
Value, R_x	**10.000 46 MΩ**	**Combined Standard Uncertainty**	**35.526 Ω**	**Effective Degrees of Freedom**	**180**	**Expanded Uncertainty**	**69.053 Ω**

Measurement Condition: *Temperature:* 23.2 °C ±1.0 °C, *Test voltage:* DC 10 V, *Humidity:* 55 % (± 10) % r.h.

5. Detailed uncertainty budget, NMC

1) HR7550



Quantity	Estimate	Prob. distr. / Type	Coverage factor	Standard uncertainty	Sensitive coefficient	Uncertainty contribution (Ω)	Degree of freedom
Calibration of 1 MΩ reference resistor	1.32 Ω	normal/B	2	0.66 Ω	10	6.60	50
Short term drift of 1 MΩ reference resistor	0.01 Ω	normal/B	2	0.01 Ω	10	0.05	infinity
Temperature coefficient of 1 MΩ reference resistor	0.50 Ω	rect./B	1.732	0.29 Ω	10	2.89	infinity
Power coefficient of 1 MΩ reference resistor	0.00 Ω	rect./B	1.732	0.00 Ω	10	0.00	infinity
Temperature coefficient of 10 MΩ resistor under test	1.10 Ω	rect./B	1.732	0.64 Ω	1	0.64	infinity
Bridge uncertainty	1.0E-07	normal/B	2	5.0E-08	1.0E+07 Ω	0.50	infinity
Typical SDM of measured ratio	1.9E-06	normal/A	1	1.9E-06	1.0E+06 Ω	1.85	4
Combined standard uncertainty			1			7.5	77
Expanded standard uncertainty			**2.03**			**15**	**77**

Measurement Condition: *Temperature:* 23.02 °C ±0.01 °C, *Test voltage:* DC 10 V, *Humidity:* 57.3 % (± 2.0) % r.h.

2) HR7551

Quantity	Estimate	Prob. distr. / Type	Coverage factor	Standard uncertainty	Sensitive coefficient	Uncertainty contribution (Ω)	Degree of freedom
Calibration of 1 MΩ reference resistor	1.00 Ω	normal/B	2	0.50 Ω	10	5.00	50
Short term drift of 1 MΩ reference resistor	0.01 Ω	normal/B	2	0.01 Ω	10	0.05	infinity
Temperature coefficient of 1 MΩ reference resistor	0.50 Ω	rect./B	1.732	0.29 Ω	10	2.89	infinity
Power coefficient of 1 MΩ reference resistor	0.00 Ω	rect./B	1.732	0.00 Ω	10	0.00	infinity
Temperature coefficient of 10 MΩ resistor under test	3.00 Ω	rect./B	1.732	1.73 Ω	1	1.73	infinity
Bridge uncertainty	1.0E-07	normal/B	2	5.0E-08	1.0E+07 Ω	0.50	infinity
Typical SDM of measured ratio	1.4E-06	normal/A	1	1.4E-06	1.0E+06 Ω	1.36	4
Combined standard uncertainty			1			6.2	111
Expanded standard uncertainty			**2.02**			**13**	**111**

Measurement Condition:
Temperature: 23.03 C ±0.01 C, *Test voltage:* DC 10 V, *Humidity:* 57.2 % (± 2.0) % r.h.

3) HR7552

Quantity	Estimate	Prob. distr. / Type	Coverage factor	Standard uncertainty	Sensitive coefficient	Uncertainty contribution (Ω)	Degree of freedom
Calibration of 1 MΩ reference resistor	1.00 Ω	normal/B	2	0.50 Ω	10	5.00	50
Short term drift of 1 MΩ reference resistor	0.01 Ω	normal/B	2	0.01 Ω	10	0.05	infinity
Temperature coefficient of 1 MΩ reference resistor	0.50 Ω	rect./B	1.732	0.29 Ω	10	2.89	infinity
Power coefficient of 1 MΩ reference resistor	0.00 Ω	rect./B	1.732	0.00 Ω	10	0.00	infinity
Temperature coefficient of 10 MΩ resistor under test	1.60 Ω	rect./B	1.732	0.92 Ω	1	0.92	infinity
Bridge uncertainty	1.0E-07	normal/B	2	5.0E-08	1.0E+07 Ω	0.50	infinity
Typical SDM of measured ratio	1.5E-06	normal/A	1	1.5E-06	1.0E+06 Ω	1.53	4
Combined standard uncertainty			1			6.1	98
Expanded standard uncertainty			**2.03**			**12**	**98**

Measurement Condition:

Temperature: 23.02 °C ±0.01 °C, *Test voltage:* DC 10 V, *Humidity:* 55.6 % (± 2.0) % r.h.

Remarks:

1) The calibration uncertainty of reference standard is the total uncertainty of step-up from 10 kΩ to 1 MΩ.
2) The bridge uncertainty is the total uncertainty associated to the bridge, including ratio error, voltage source stability, resolution and offset of system detector.
3) The typical standard deviation of the mean(SDM) of measured ratio is defined as the median value of SDM values among the data sets used to calculate the final reported value.

6. Detailed uncertainty budget, NMIJ

Source x_i	$u(x_i)$	Distribution	Sensitivity coefficient c_i	$c_i \times u(x_i)$ [μΩ/Ω]	Degree of freedom
Calibration of 1-MΩ resistor	0.31	Normal (Type B)	1	0.31	110
Voltage divider	0.35	Rectangular (Type B)	1	0.35	∞
Voltage division of injected voltage	0.005	Rectangular (Type B)	1	0.005	∞
Resistance of lead wire	0.05	Rectangular (Type B)	1	0.05	∞
Scattering observed in measurements	0.3	Normal (Type A)	1	0.3	99
Temperature coefficient of resistor	0.01	Rectangular (Type A)	1	0.01	∞
Humidity coefficient of resistor	0.02	Rectangular (Type B)	1	0.02	∞
Combined standard uncertainty and effective degree of freedom				0.56	600
Expanded uncertainty (coverage factor k = 2 at level of confidence of 95%) and effective degree of freedom				1.1	600

Table 2. Ambient conditions.

	Date (yyyy-mm-dd)	Air bath temperature [°C]			Air bath humidity [%RH]		
		Measured value	Uncertainty (k = 2)	Range of validation (k = 1)	Measured value	Uncertainty (k = 2)	Range of validation (k = 1)
	2011-04-06	23.025	0.008	0.001	43.0	1.0	0.0
	2011-04-25	23.039		0.001	43.4		0.1
Mean value	2011-04-15	23.032	0.008	0.001	43.2	1.0	0.1

7. Detailed uncertainty budget(HR7550 at 91 V), NMIA

	Quantity **X_i**	**Estimate** **x_i** **(μΩ/Ω)**	**Standard uncertainty** **$u(x_i)$** **(μΩ/Ω)**	**Units**	**Method of evaluation**	**Probability distribution**	**Sensitivity coefficient** **c_i**	**Uncertainty contribution** **$u(x_i)$ x c_i** **(μΩ/Ω)**	**Degrees of freedom** **v**
SI Determi-nation	SI value of four 1 Ω resistors determined with reference to the NMIA calculable capacitor	-	0.082	μΩ/Ω	A and B	N	1	0.082	45
10 kΩ reference standard	Calibrated value of 10 kΩ reference standard	4.900	0.026	μΩ/Ω	A and B	N	1	0.026	10
	Estimated drift in value of 10 kΩ between calibration and use as reference standard	0.101	0.050	μΩ/Ω	B	N	1	0.050	6
	Temperature difference of 10 kΩ between calibration and use as reference standard	-0.030	0.050	°C	A and B	N	0.2	0.010	20
Build-up: 10 kΩ to 1 MΩ	Ratio of 1 MΩ to 10 kΩ reference standard	-3.307	0.095	μΩ/Ω	A	N	1	0.095	14
	10:1 bridge ratio error at 20 V (applied twice)*	0.000	0.346	μΩ/Ω	B	N	1.4	0.490	133
	Estimate of change in value of 100 kΩ resistor between two ratio measurements	0.000	0.300	μΩ/Ω	B	N	1	0.300	10
	Temperature difference of 1 MΩ between calibration and use as reference standard	0.000	0.044	°C	A and B	R	0.02	0.001	2594
	Estimated drift in value of 1 MΩ between calibration and use as reference standard	0.000	0.050	μΩ/Ω	B	N	1	0.050	10
Test resistor	Ratio of 10 MΩ test resistor to 1 MΩ reference standard	62.676	0.032	μΩ/Ω	A	N	1	0.032	10
	10:1 bridge ratio error at 100 V *	0.000	0.175	μΩ/Ω	B	N	1	0.175	1237
	Lead leakage resistance	0.000	0.009	μΩ/Ω	B	R	1	0.009	50
	Measurement of temperature of test resistor	0.000	0.054	°C	B	N	1.1	0.059	616
	Deviation from nominal	**64.340**						**0.622**	**119**

Measurement Condition: The ambient temperature in the resistance laboratory was in the range 19.7 °C to 20 °C. The humidity in the laboratory was between 45% and 55% except for the last two days when it fell to 35%.

All six of the comparison resistors were placed in a temperature-controlled air bath set to 23 °C. The humidity was not separately controlled and was somewhat affected by changes in the ambient laboratory humidity.

The temperature and humidity of the air bath was continuously monitored and recorded. Separate measurements of the temperature variation within the air bath, and of the difference between the resistors' thermistors and the temperature monitor, were used to adjust the recorded temperature for each resistor.

Note: The range of temperature and humidity variation is the range of variation between the measurement period start date and the measurement period finish date. It therefore includes spikes in temperature and humidity that occurred between measurements when the air bath (set at 23 °C) was opened to the laboratory ambient temperature at 20 °C to change leads etc.

8. Detailed uncertainty budget, NMISA

The 10 MΩ travelling standards were measured against a 1 MΩ standard in a 10:1 ratio using a automatic high resistance bridge and a low thermal scanner, with 100 V applied across a series connection of a 1 MΩ standard and a 10 MΩ travelling standard using a multifunction calibrator.

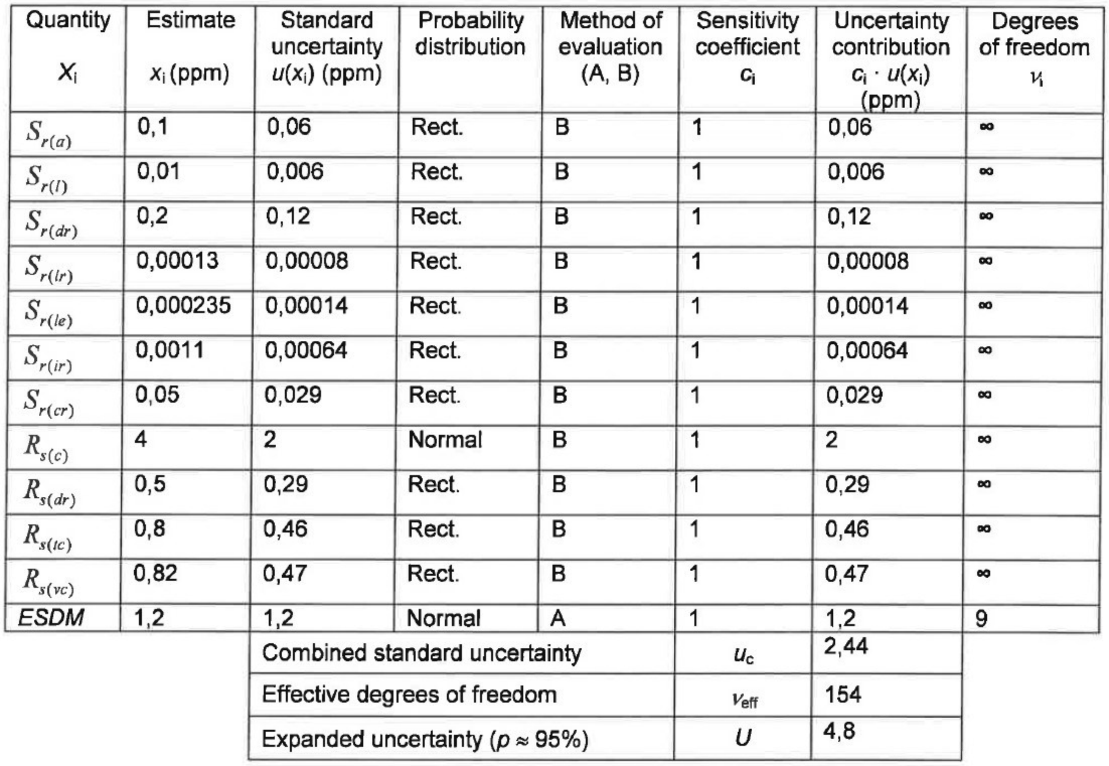
The reported resistance of each 10 MΩ travelling standard was assigned using the formula:

$$R_x = \left(S_r + S_{r(a)} + S_{r(l)} + S_{r(dr)} + S_{r(lr)} + S_{r(le)} + S_{r(ir)} + S_{r(cre)}\right) * (R_{s(cal)} + R_{s(dr)} + R_{s(lc)} + R_{s(vc)})$$

Where:

R_x	is the assigned resistance of the travelling standard.
S_r	is the system calculated ratio between reference standard and travelling standard.
$S_{r(a)}$	is the accuracy of the bridge.
$S_{r(l)}$	is the linearity of the bridge.
$S_{r(dr)}$	is the short-term drift of the bridge.
$S_{r(lr)}$	is the measurement system leakage resistance.
$S_{r(le)}$	is the loading error of the system digital multimeter.
$S_{r(ir)}$	is the insulation resistance error of the system scanner.
$S_{r(cre)}$	is the contact resistance error of the system scanner.
R_s	is the reference standard value.
$R_{s(cal)}$	is the reference standard calibration uncertainty.
$R_{s(dr)}$	is the estimated drift of the reference standard since last calibration.
$R_{s(lc)}$	is the temperature coefficient correction of the reference standard.
$R_{s(vc)}$	is the voltage coefficient correction of the reference standard.

1) HR7550



Quantity X_i	Estimate x_i (ppm)	Standard uncertainty $u(x_i)$ (ppm)	Probability distribution	Method of evaluation (A, B)	Sensitivity coefficient c_i	Uncertainty contribution $c_i \cdot u(x_i)$ (ppm)	Degrees of freedom ν_i
$S_{r(a)}$	0,1	0,06	Rect.	B	1	0,06	∞
$S_{r(l)}$	0,01	0,006	Rect.	B	1	0,006	∞
$S_{r(dr)}$	0,2	0,12	Rect.	B	1	0,12	∞
$S_{r(lr)}$	0,00013	0,00008	Rect.	B	1	0,00008	∞
$S_{r(le)}$	0,000235	0,00014	Rect.	B	1	0,00014	∞
$S_{r(ir)}$	0,0011	0,00064	Rect.	B	1	0,00064	∞
$S_{r(cr)}$	0,05	0,029	Rect.	B	1	0,029	∞
$R_{s(c)}$	4	2	Normal	B	1	2	∞
$R_{s(dr)}$	0,5	0,29	Rect.	B	1	0,29	∞
$R_{s(tc)}$	0,8	0,46	Rect.	B	1	0,46	∞
$R_{s(vc)}$	0,82	0,47	Rect.	B	1	0,47	∞
ESDM	1,2	1,2	Normal	A	1	1,2	9
		Combined standard uncertainty			u_c	2,44	
		Effective degrees of freedom			ν_{eff}	154	
		Expanded uncertainty ($p \approx 95\%$)			U	4,8	

2) HR7551

Quantity X_i	Estimate x_i (ppm)	Standard uncertainty $u(x_i)$ (ppm)	Probability distribution	Method of evaluation (A, B)	Sensitivity coefficient c_i	Uncertainty contribution $c_i \cdot u(x_i)$ (ppm)	Degrees of freedom ν_i
$S_{r(a)}$	0,1	0,06	Rect.	B	1	0,06	∞
$S_{r(l)}$	0,01	0,006	Rect.	B	1	0,006	∞
$S_{r(dr)}$	0,2	0,12	Rect.	B	1	0,12	∞
$S_{r(lr)}$	0,00013	0,00008	Rect.	B	1	0,00008	∞
$S_{r(le)}$	0,000235	0,00014	Rect.	B	1	0,00014	∞
$S_{r(ir)}$	0,0011	0,00064	Rect.	B	1	0,00064	∞
$S_{r(cr)}$	0,05	0,029	Rect.	B	1	0,029	∞
$R_{s(c)}$	4	2	Normal	B	1	2	∞
$R_{s(dr)}$	0,5	0,29	Rect.	B	1	0,29	∞
$R_{s(tc)}$	0,8	0,46	Rect.	B	1	0,46	∞
$R_{s(vc)}$	0,82	0,47	Rect.	B	1	0,47	∞
ESDM	1,2	1,2	Normal	A	1	1,2	9
		Combined standard uncertainty			u_c	2,44	
		Effective degrees of freedom			ν_{eff}	154	
		Expanded uncertainty ($p \approx 95\%$)			U	4,8	

3) HR7552

Quantity X_i	Estimate x_i (ppm)	Standard uncertainty $u(x_i)$ (ppm)	Probability distribution	Method of evaluation (A, B)	Sensitivity coefficient c_i	Uncertainty contribution $c_i \cdot u(x_i)$ (ppm)	Degrees of freedom ν_i
$S_{r(a)}$	0,1	0,06	Rect.	B	1	0,06	∞
$S_{r(l)}$	0,01	0,006	Rect.	B	1	0,006	∞
$S_{r(dr)}$	0,2	0,12	Rect.	B	1	0,12	∞
$S_{r(lr)}$	0,00013	0,00008	Rect.	B	1	0,00008	∞
$S_{r(le)}$	0,000235	0,00014	Rect.	B	1	0,00014	∞
$S_{r(ir)}$	0,0011	0,00064	Rect.	B	1	0,00064	∞
$S_{r(cr)}$	0,05	0,029	Rect.	B	1	0,029	∞
$R_{s(c)}$	4	2	Normal	B	1	2	∞
$R_{s(dr)}$	0,5	0,29	Rect.	B	1	0,29	∞
$R_{s(tc)}$	0,8	0,46	Rect.	B	1	0,46	∞
$R_{s(vc)}$	0,82	0,47	Rect.	B	1	0,47	∞
ESDM	1,45	1,45	Normal	A	1	1,45	9
		Combined standard uncertainty			u_c	2,58	
		Effective degrees of freedom			ν_{eff}	90	
		Expanded uncertainty ($p \approx 95\%$)			U	5,1	

9. Detailed uncertainty budget, NIM

1) HR7550

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution/method of evaluation(A,B)	Sensitivity coefficient c_i	Uncertainty contribution $u(R_i)$	Degree of freedom v_i
Repeatability	0.273	0.273	A	1	0.273	9
Standard resistors	0.966	0.483	B	1	0.483	∞
Insulation	0.100	0.0577	B	1	0.058	∞
Unlinearity	0.01	0.005	B	1	0.005	∞
Bridge Calibration	0.1	0.05	B	1	0.050	∞
Stability of the voltage source（/24hours)including the noise	0.755	0.38	B	1	0.377	∞
Null indicator resolution noise, drift and offset	0.2	0.115	B	1	0.115	∞
Temperature coefficient(0.03℃)	0.033	0.019	B	1	0.019	∞
voltage coefficient	0	0	B	1	0.000	∞
R_X						
Combined standard uncertainty and effective degrees of freedom:$u_c(R_X)$					0.69	357.6
Expanded uncertainty (95% coverage factor): *U*					1.3	

Measurement Condition:

Temperature : mean value 19.98 ℃, range of variation 20.00 ℃ ~ 19.97 ℃

Test voltage: DC 100 V, Humidity : 40 % RH ~ 45 % RH

2) HR7551

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution/method of evaluation(A,B)	Sensitivity coefficient c_i	Uncertainty contribution $u(R_i)$	Degree of freedom v_i
Repeatability	0.244	0.244	A	1	0.244	9
Standard resistors	0.966	0.483	B	1	0.483	∞
Insulation	0.100	0.0577	B	1	0.058	∞
Unlinearity	0.01	0.005	B	1	0.005	∞
Bridge Calibration	0.1	0.05	B	1	0.050	∞
Stability of the voltage source （/24hours)including the noise	0.755	0.38	B	1	0.377	∞
Null indicator resolution noise, drift and offset	0.2	0.115	B	1	0.115	∞
Temperature coefficient(0.03℃)	0.09	0.052	B	1	0.052	∞
voltage coefficient	0	0	B	1	0.000	∞
R_X						
Combined standard uncertainty and effective degrees of freedom:$u_\mathrm{c}(\mathrm{R_X})$					0.68	530.6
Expanded uncertainty (95% coverage factor): U					1.3	

Measurement Condition:

Temperature : mean value 19.98 ℃, range of variation 19.98 ℃ ~ 19.98 ℃

Test voltage: DC 100 V

Humidity : 40 % RH ~ 45 % RH

3) HR7552

QuantityX_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution/method of evaluation(A,B)	Sensitivity coefficient c_i	Uncertainty contribution $u(R_i)$	Drgree of freedom v_i
Repeatability	0.174	0.174	A	1	0.174	9
Standard resistors	0.966	0.483	B	1	0.483	∞
Insulation	0.100	0.0577	B	1	0.058	∞
Unlinearity	0.01	0.005	B	1	0.005	∞
Bridge Calibration	0.1	0.05	B	1	0.050	∞
Stability of the voltage source（/24hours)including the noise	0.755	0.38	B	1	0.377	∞
Null indicator resolution noise, drift and offset	0.2	0.115	B	1	0.115	∞
Temperature coefficient(0.03℃)	0.048	0.028	B	1	0.028	∞
voltage coefficient	0	0	B	1	0.000	∞
R_X						
Combined standard uncertainty and effective degrees of freedom:$u_c(R_X)$					0.65	1781.2
Expanded uncertainty (95% coverage factor): U					1.3	

Measurement Condition:

Temperature : mean value 20.04 ℃, range of variation 20.05 ℃ ~ 20.02 ℃

Test voltage: DC 100 V

Humidity : 40 % RH ~ 45 % RH

10. Detailed uncertainty budget(HR7551, 91 V, 23.09°C), VNIIM

The model for the measurement of **10 MΩ** standard is:

$R\,(10M)_x = R_{s1}\cdot N_H\cdot(1+\delta R_{x1})\cdot(1+\delta_{H1}+\delta_{H2}+\delta_{leak1}+\delta_{Wb1}+\delta_{t1}))\cdot(1+c_{cab})$

The components are: ((

$R(10M)_x$: the unknown resistor,

R_{s1}: the reference standard 100 kΩ,

N_H: nominal ratio of the series-parallel transfer of the 1 MΩ per step Hamon standard $(N_H=100)$,

δR_{x1}: reading (ratio) of Wheatstone bridge,

c_{cab} **:** a correction of shunt effect of an insulation resistance of connecting cables (c_{cab} =- $2,8\times10^{-6}$ for measured resistance standards, $c_{cab}=0$ for reference resistance;standards);

δ_{H1}: the relative uncertainty due to imperfect series-parallel transfer of the Hamon standard;

δ_{H2}: the relative uncertainty due to the instability of the Hamon standard

δ_{leak1}: the relative uncertainty due to leakage resistance from node points of the Wheatstone bridge,

δ_{Wb1}: the relative uncertainty due to balancing of the Wheatstone bridge for 10 MΩ resistors (sensitivity, repeatability),

δ_{t1}: the relative uncertainty due to instability temperature of the resistors.

The relative standard uncertainty is evaluated by means of equation:

$$\frac{u(R(10M)_x)}{R(10M)_x}=\sqrt{\left(\frac{u(R_{s1})}{R_{s1}}\right)^2+\sum_1^5(\delta_i^2)}$$

Quantity X_i	Estimate x_i	Relative standard uncertainty, $u(x_i)$ $\times10^{-7}$	Probability distribution /method of evaluation (A,B)	Sensitivity coefficient c_i	Relative uncertainty contribution, $u(R_i)$ $\times10^{-7}$	Degree of freedom ν_i
R_{s1}	99.99908 kΩ	3.8	Normal/B	1.0	3.8	24
N_{H1}	100	-	-	-	-	-
δR_{x1}	$368\cdot10^{-7}$	-				
δ_{H1}	0	0.8	Rectangular/B	1.0	0.8	Inf

δ_{H2}	0	2.5	Rectangular/B	1.0	2.5	Inf
δ_{leak}	0	1.8	Rectangular/B	1.0	2.2	Inf
δ_{Wb1}	0	26.2	Normal/A	1.0	6.2	18
δ_{t1}	0	2.7	Rectangular/B	1.0	2.9	Inf
c_{cab}	$- 2,8\times10^{-}$	2,8	Rectangular/B	1,0	2,8	Inf.
R_x	10.000248 MΩ					
		Relative combined standard uncertainty:			$9.0\cdot10^{-7}$	
		Effective degrees of freedom:			80	
		Relative expanded uncertainty (95% coverage factor):			18.410^{-7} (k = 2.04)	

Measurement conditions for 10 MΩ and 1 GΩ

Temperature:

The comparison standards were measured in an air bath maintained at nominal 23°C. The reference standards were measured in an air bath maintained at nominal 20°C; measurement uncertainty does not exceed 0,01°C.

Voltage:

The test voltage for the comparison and the reference standard was set within a range (86 – 97)V.

***Ambient conditions (in the laboratory room)*:**

Temperature: Mean value 19.9˚C, measurement uncertainty 0.1˚C, range of variation ± 0.2˚C

Pressure: Typical barometric pressure was 101,4 kPa, measurement uncertainty 0,1 kPa, range of variation ± 0,8 kPa

Humidity: Relative humidity in the laboratory averaged 44 %, measurement uncertainty 4%, range of variation ± 6%

11. Detailed uncertainty budget, SCL

Serial No.	Mean Date of Measurement	Test Voltage	Ambient Conditions				
			Temperature			Relative Humidity	
			Mean Value	Expanded Measurement Uncertainty	Range of Variation	Mean Value	Range of Variation
HR7550	21 October 2012	100 V	22.97 °C	0.05 °C	0.2 °C	45.3 %	3.9 %
HR7551	21 October 2012	100 V	22.98 °C	0.05 °C	0.2 °C	45.8 %	1.7 %
HR7552	21 October 2012	100 V	22.97 °C	0.05 °C	0.2 °C	45.6 %	2.3 %

1) HR7550

Quantity X_i	Estimate x_i MΩ	Relative standard uncertainty $u(x_i)$ μΩ/Ω	Probability distribution /Method	Sensitivity coefficient c_i	Relative uncertainty contribution $u(R_i)$ μΩ/Ω	Degrees of freedom ν_i
Uncertainty in the 10 MΩ reference standard	10	0.5	Normal/B	1	0.5	50
Stability of the 10 MΩ reference standard	0	0.5	Rectangular /B	1	0.29	∞
Allowance for the power coefficient for the reference standard	0	1	Rectangular /B	1	0.58	∞
Temperature effect on bridge for ± 1°C variation	0	3.5	Rectangular /B	1	2.02	∞
Temperature effect on unknown resistor	0	0.1	Rectangular /B	1	0.06	∞
Bridge resolution in measuring reference	0	1.5	Rectangular /B	1	0.87	∞
Bridge resolution in measuring unknown	0	1.5	Rectangular /B	1	0.87	∞
Type A uncertainty (Repeatability)	0	0.07	Normal/A	1	0.07	18
R_x	10.000 688					
Combined standard measurement uncertainty (Effective degrees of freedom)					2.5	31299
95 % Coverage factor					2.0	
Expanded relative measurement uncertainty					5.0	

2) HR7551

Quantity X_i	Estimate x_i MΩ	Relative standard uncertainty $u(x_i)$ μΩ/Ω	Probability distribution /Method	Sensitivity coefficient c_i	Relative uncertainty contribution $u(R_i)$ μΩ/Ω	Degrees of freedom ν_i
Uncertainty in the 10 MΩ reference standard	10	0.5	Normal/B	1	0.5	50
Stability of the 10 MΩ reference standard	0	0.5	Rectangular /B	1	0.29	∞
Allowance for the power coefficient for the reference standard	0	1	Rectangular /B	1	0.58	∞
Temperature effect on bridge for ± 1°C variation	0	3.5	Rectangular /B	1	2.02	∞
Temperature effect on unknown resistor	0	0.3	Rectangular /B	1	0.17	∞
Bridge resolution in measuring reference	0	1.5	Rectangular /B	1	0.87	∞
Bridge resolution in measuring unknown	0	1.5	Rectangular /B	1	0.87	∞
Type A uncertainty (Repeatability)	0	0.13	Normal/A	1	0.13	18
R_x	10.000 237					
Combined standard measurement uncertainty (Effective degrees of freedom)					2.5	31323
95 % Coverage factor					2.0	
Expanded relative measurement uncertainty					5.0	

3) HR7552

Quantity X_i	Estimate x_i MΩ	Relative standard uncertainty $u(x_i)$ μΩ/Ω	Probability distribution /Method	Sensitivity coefficient c_i	Relative uncertainty contribution $u(R_i)$ μΩ/Ω	Degrees of freedom ν_i
Uncertainty in the 10 MΩ reference standard	10	0.5	Normal/B	1	0.5	50
Stability of the 10 MΩ reference standard	0	0.5	Rectangular /B	1	0.29	∞
Allowance for the power coefficient for the reference standard	0	1	Rectangular /B	1	0.58	∞
Temperature effect on bridge for ± 1°C variation	0	3.5	Rectangular /B	1	2.02	∞
Temperature effect on unknown resistor	0	0.2	Rectangular /B	1	0.12	∞
Bridge resolution in measuring reference	0	1.5	Rectangular /B	1	0.87	∞
Bridge resolution in measuring unknown	0	1.5	Rectangular /B	1	0.87	∞
Type A uncertainty (Repeatability)	0	0.23	Normal/A	1	0.23	18
R_x	10.000 505					
Combined standard measurement uncertainty (Effective degrees of freedom)					2.5	28385
95 % Coverage factor					2.0	
Expanded relative measurement uncertainty					5.0	

12. **Detailed uncertainty budget,** KazInMetr

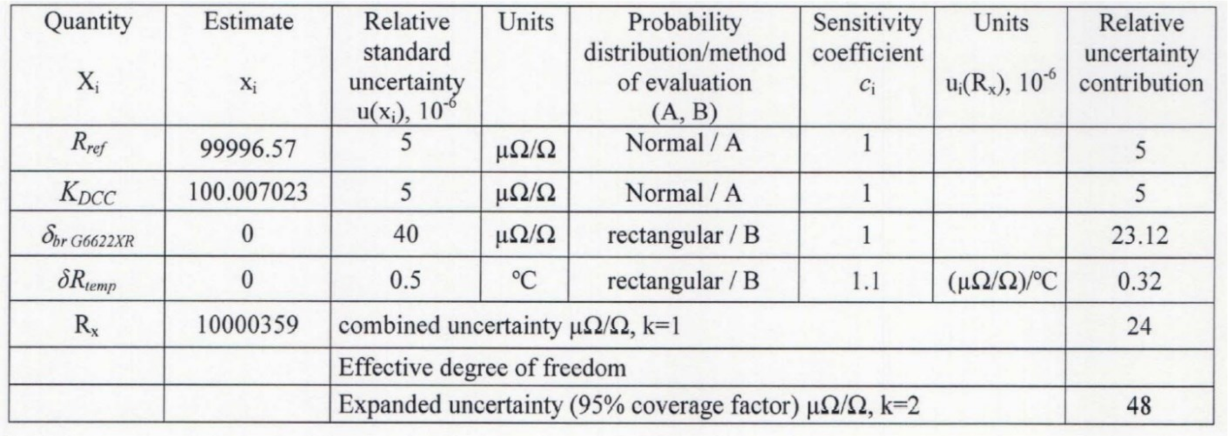
The measurement consists in a 100 kΩ:10 MΩ comparison ($R_{1:100}$) against a reference standard R_s calibrated in terms of the quantized Hall resistance. The step up to 100 kΩ is carried out using a DCC bridge. The model for the 1:100 comparison at 10 MΩ can be simplified to:

$$R_x = R_{Ref} * \left(1 + \delta_{Ref} + K_{Temper}\right) * K_{DCC}(1 + k_{br}) * (1 + \delta_{Xt} * K_{Xt})$$

The following sources of uncertainty are taken into account:

R_{Ref} is the actual value of reference resistor
δ_{Ref} is the relative error of the reference resistor from calibration
K_{Temper} is the relative error due temperature of reference resistor
K_{DCC} is the nominal ratio of the bridge
k_{br} is specified 1 σ uncertainty of the bridge ratio for that range
δ_{Xt} is temperature difference of the measured resistor
K_{Xt} is expected relative temperature coefficient of the measured resistor

1) **HR7550**



Quantity X_i	Estimate x_i	Relative standard uncertainty $u(x_i)$, 10^{-6}	Units	Probability distribution/method of evaluation (A, B)	Sensitivity coefficient c_i	Units $u_i(R_x)$, 10^{-6}	Relative uncertainty contribution
R_{ref}	99996.57	5	μΩ/Ω	Normal / A	1		5
K_{DCC}	100.007023	5	μΩ/Ω	Normal / A	1		5
$\delta_{br\ G6622XR}$	0	40	μΩ/Ω	rectangular / B	1		23.12
δR_{temp}	0	0.5	°C	rectangular / B	1.1	(μΩ/Ω)/°C	0.32
R_x	10000359	combined uncertainty μΩ/Ω, k=1					24
		Effective degree of freedom					
		Expanded uncertainty (95% coverage factor) μΩ/Ω, k=2					48

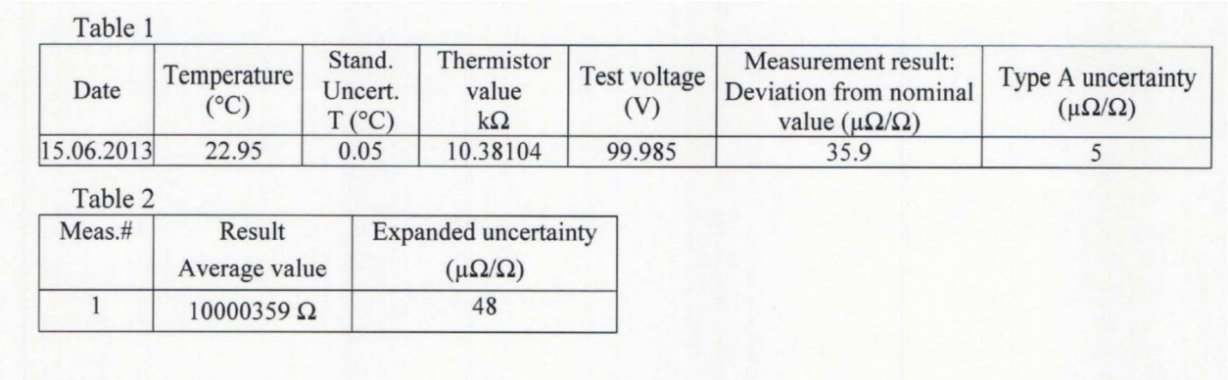


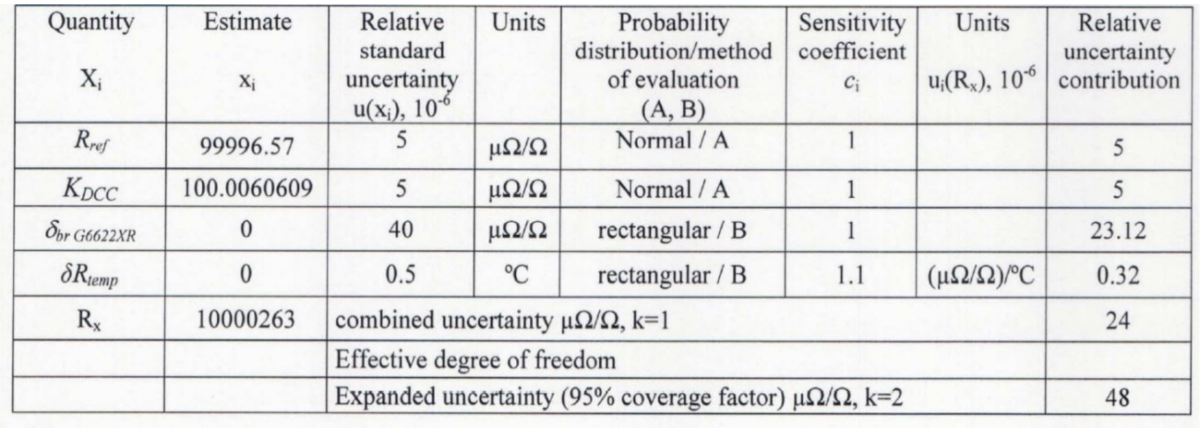
Table 1

Date	Temperature (°C)	Stand. Uncert. T (°C)	Thermistor value kΩ	Test voltage (V)	Measurement result: Deviation from nominal value (μΩ/Ω)	Type A uncertainty (μΩ/Ω)
15.06.2013	22.95	0.05	10.38104	99.985	35.9	5

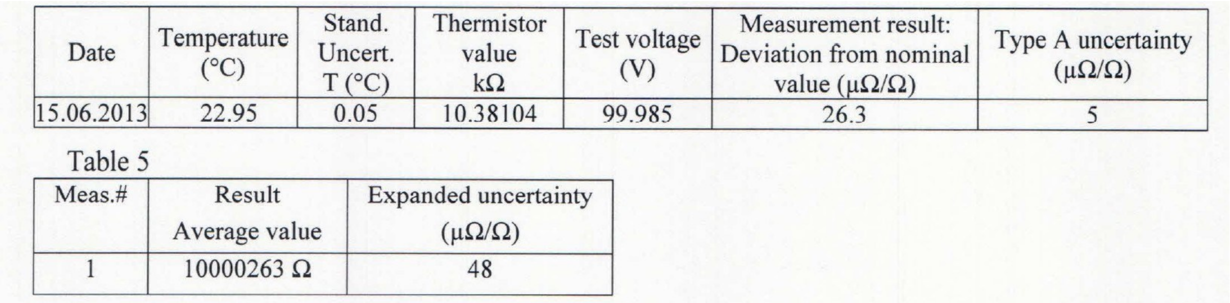
Table 2

Meas.#	Result Average value	Expanded uncertainty (μΩ/Ω)
1	10000359 Ω	48

2) HR7551



Quantity X_i	Estimate x_i	Relative standard uncertainty $u(x_i)$, 10^{-6}	Units	Probability distribution/method of evaluation (A, B)	Sensitivity coefficient c_i	Units $u_i(R_x)$, 10^{-6}	Relative uncertainty contribution
R_{ref}	99996.57	5	μΩ/Ω	Normal / A	1		5
K_{DCC}	100.0060609	5	μΩ/Ω	Normal / A	1		5
$\delta_{br\ G6622XR}$	0	40	μΩ/Ω	rectangular / B	1		23.12
δR_{temp}	0	0.5	°C	rectangular / B	1.1	(μΩ/Ω)/°C	0.32
R_x	10000263	combined uncertainty μΩ/Ω, k=1					24
		Effective degree of freedom					
		Expanded uncertainty (95% coverage factor) μΩ/Ω, k=2					48

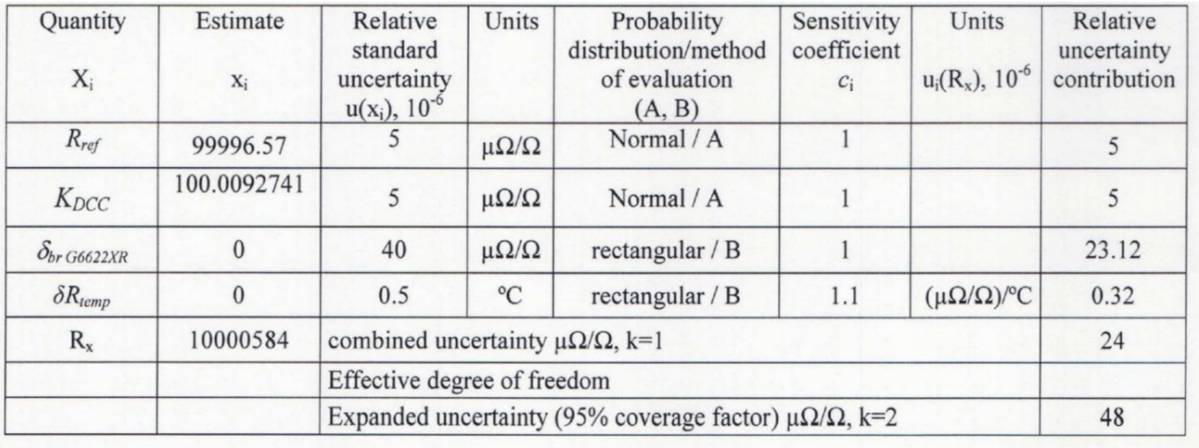


Date	Temperature (°C)	Stand. Uncert. T (°C)	Thermistor value kΩ	Test voltage (V)	Measurement result: Deviation from nominal value (μΩ/Ω)	Type A uncertainty (μΩ/Ω)
15.06.2013	22.95	0.05	10.38104	99.985	26.3	5

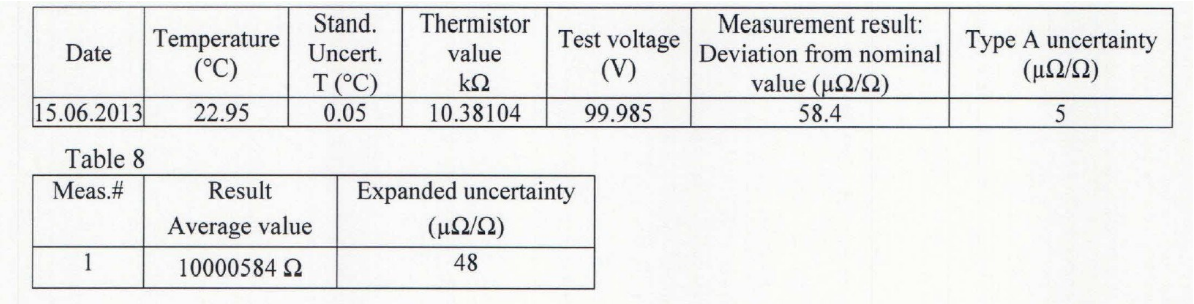
Table 5

Meas.#	Result Average value	Expanded uncertainty (μΩ/Ω)
1	10000263 Ω	48

3) HR7552



Quantity X_i	Estimate x_i	Relative standard uncertainty $u(x_i)$, 10^{-6}	Units	Probability distribution/method of evaluation (A, B)	Sensitivity coefficient c_i	Units $u_i(R_x)$, 10^{-6}	Relative uncertainty contribution
R_{ref}	99996.57	5	μΩ/Ω	Normal / A	1		5
K_{DCC}	100.0092741	5	μΩ/Ω	Normal / A	1		5
$\delta_{br\ G6622XR}$	0	40	μΩ/Ω	rectangular / B	1		23.12
δR_{temp}	0	0.5	°C	rectangular / B	1.1	(μΩ/Ω)/°C	0.32
R_x	10000584	combined uncertainty μΩ/Ω, k=1					24
		Effective degree of freedom					
		Expanded uncertainty (95% coverage factor) μΩ/Ω, k=2					48



Date	Temperature (°C)	Stand. Uncert. T (°C)	Thermistor value kΩ	Test voltage (V)	Measurement result: Deviation from nominal value (μΩ/Ω)	Type A uncertainty (μΩ/Ω)
15.06.2013	22.95	0.05	10.38104	99.985	58.4	5

Table 8

Meas.#	Result Average value	Expanded uncertainty (μΩ/Ω)
1	10000584 Ω	48

13. Detailed uncertainty budget, MSL

Illustrative uncertainty budgets at each resistance level and each test voltage are presented in the tables below. Only significant contributions are listed. All contributing uncertainties have been assessed as Gaussian probability distributions.

Glossary of terms:

Repeatability - Standard deviation in multiple measurements of a single resistor.

Rlink - Link resistance, as described in Section 4.

Rs0 - Calibration value of Rs under defined conditions (T0, V0).

T0 - Reference temperature of Rs for temperature coefficient corrections.

Ta - Temperature of reference resistor (Rs). Uncertainty in **Ta** combines all type A uncertainties.

Tb - Zero-valued parameter whose uncertainty combines all type B uncertainties in temperature of Rs.

V0 - Reference voltage for voltage coefficient corrections.

V1m - Negative-polarity voltage applied to Rx during voltage reversal sequence.

V1p - First positive-polarity voltage applied to Rx during voltage reversal sequence.

V1pp - Second positive-polarity voltage applied to Rx during voltage reversal sequence.

V2m - Positive-polarity voltage applied to Rs during voltage reversal sequence.

V2p - First negative-polarity voltage applied to Rs during voltage reversal sequence.

V2pp - Second negative-polarity voltage applied to Rs during voltage reversal sequence.

V2ppp - Third negative-polarity voltage, plus small perturbation, applied to Rs during voltage reversal sequence.

Vdm - Null voltage measured when negative-polarity voltage is applied to Rx during voltage reversal sequence.

Vdp - Null voltage measured when first positive-polarity voltage is applied to Rx during voltage reversal sequence.

Vdpp - Null voltage measured when second positive-polarity voltage is applied to Rx during voltage reversal sequence.

Vdppp - Null voltage measured when third positive-polarity voltage is applied to Rx during voltage reversal sequence.

Vdrift1 - Voltage drift term used in calculation of the gain G.

Vdrift2 - Voltage drift term used in calculation of mean null voltage $\overline{V_d}$**.**

Vlin1 - Voltage linearity term used in calculation of the gain G.

Vlin2 - Voltage linearity term used in calculation of mean null voltage $\overline{V_d}$**.**

Alpha - First-order temperature coefficient of Rs.

Beta - Second-order temperature coefficient of Rs.

Gamma - Voltage coefficient of Rs.

Tmc - Temperature correction of meter used to measure the temperature of Rs.

Vrc - Voltage ratio correction of gain errors between volt meter ranges of DVM1 (see Figure 1).

1) HR7551 at 10 V

Quantity, X_i	Value, x_i	Standard Uncertainty $u(x_i)$	Effective Dof, ν_i	Sensitivity Coefficient, c_i	Uncertainty Contribution, $u(R_i)$	Method of Evaluation
gamma	3.3E-08 Ω/(Ω.V)	1.6E-07	15.0	-9.00E+07 Ω.V	14.8 Ω	A
Repeatability	0 Ω	5.9	15.0	1 Ω/Ω	5.9 Ω	A
T0	20.627 °C	0.060	17.0	-54.6 Ω/°C	3.3 Ω	A
Vdrift2	0 V	2.9E-07	8.0	-1.10E+07 Ω/V	3.2 Ω	B
Vdm	-1.06E-06 V	4.6E-07	9.0	5.50E+06 Ω/V	2.5 Ω	A
Rs0	1000066.13 Ω	0.19	7.0	9.9995 Ω/Ω	1.9 Ω	B
Vdp	3.52E-06 V	5.4E-07	9.0	-2.75E+06 Ω/V	1.5 Ω	A
Vdpp	2.61E-06 V	4.6E-07	9.0	-2.75E+06 Ω/V	1.3 Ω	A
Tb	0 °C	0.019	11.8	54.60 Ω/°C	1.1 Ω	B
tmc	-5.0E-04 °C/°C	8.0E-04	8.0	1135 Ω.°C/°C	0.9 Ω	B
vrc	2.22E-07 V/V	9.0E-08	7.0	1.00E+07 Ω.V/V	0.9 Ω	A
V2pp	-1.00005395 V	5.0E-08	9.0	2.50E+06 Ω/V	0.1 Ω	A
V2p	-1.00005399 V	4.6E-08	9.0	2.50E+06 Ω/V	0.1 Ω	A
V2m	1.00005105 V	1.5E-08	9.0	-5.00E+06 Ω/V	0.1 Ω	A
V1m	-10.00004647 V	9.4E-08	9.0	-5.00E+05 Ω/V	0.05 Ω	A
V1pp	10.00004302 V	9.9E-08	9.0	2.50E+05 Ω/V	0.03 Ω	A
V1p	10.00004364 V	9.3E-08	9.0	2.50E+05 Ω/V	0.02 Ω	A
Vlin2	0 V	2.0E-09	8.0	-1.10E+07 Ω/V	0.02 Ω	B
alpha	5.558E-06 Ω/(Ω.°C)	1.0E-08	8.0	1.42E+06 Ω.°C	0.01 Ω	B
Combined standard uncertainty (of all contributions):					17.2 Ω	

2) HR7551 at 100 V

Quantity, X_i	Value, x_i	Standard Uncertainty $u(x_i)$	Effective Dof, ν_i	Sensitivity Coefficient, c_i	Uncertainty Contribution, $u(R_i)$	Method of Evaluation
T0	20.627 °C	0.060	17.0	-54.6 Ω.°C	3.3 Ω	A
Rs0	1000066.13 Ω	0.19	7.0	9.9995 Ω/Ω	1.9 Ω	B
Repeatability	0 Ω	2.3	13.0	1 Ω/Ω	2.3 Ω	A
vrc	4.809E-07 V/V	1.8E-07	7.0	1.00E+07 Ω.V/V	1.8 Ω	A
Tb	0 °C	0.019	11.8	54.59 Ω/°C	1.1 Ω	B
tmc	-5.0E-04 °C/°C	8.0E-04	8.0	1134 Ω.°C/°C	0.9 Ω	B
Vdm	-6.29E-06 V	6.0E-07	9.0	5.50E+05 Ω/V	0.3 Ω	A
Vdrift2	0 V	2.4E-07	8.0	-1.10E+06 Ω/V	0.3 Ω	B
Vdp	1.167E-05 V	5.4E-07	9.0	-2.75E+05 Ω/V	0.1 Ω	A
Vdpp	1.039E-05 V	5.1E-07	9.0	-2.76E+05 Ω/V	0.1 Ω	A
V1m	-100.0002735 V	2.5E-06	9.0	-5.00E+04 Ω/V	0.1 Ω	A
V1p	100.0002956 V	2.8E-06	9.0	2.50E+04 Ω/V	0.1 Ω	A
V1pp	100.0002882 V	2.8E-06	9.0	2.50E+04 Ω/V	0.07 Ω	A
V2m	10.00052552 V	8.3E-08	9.0	-5.00E+05 Ω/V	0.04 Ω	A
V2pp	-10.00052974 V	7.3E-08	9.0	2.51E+05 Ω/V	0.02 Ω	A
V2p	-10.00052906 V	7.2E-08	9.0	2.50E+05 Ω/V	0.02 Ω	A
alpha	5.558E-06 Ω/(Ω.°C)	1.0E-08	8.0	1.43E+06 Ω.°C	0.01 Ω	B
Combined standard uncertainty (of all contributions):					5.0 Ω	

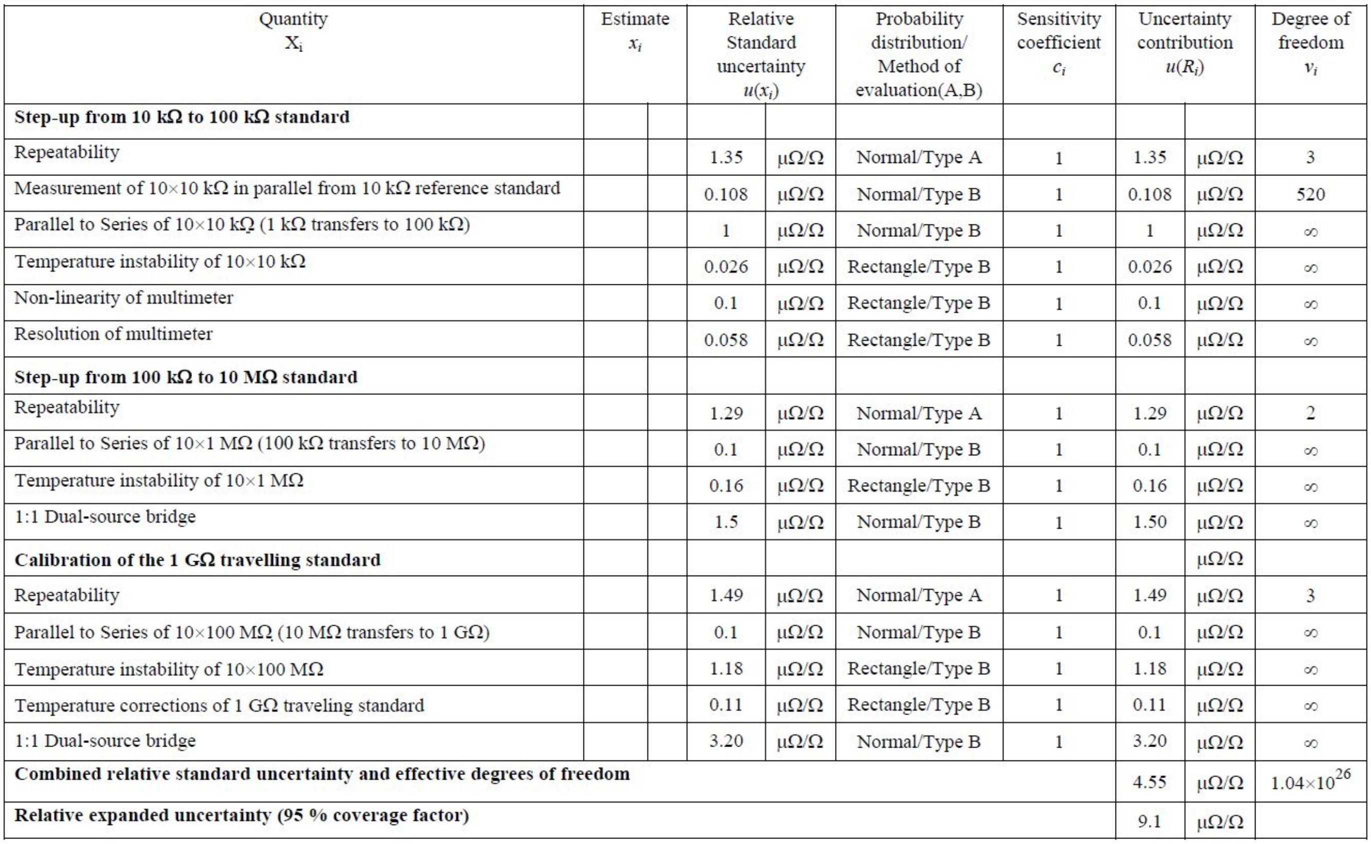
Measurement Condition: The resistors were maintained in air at a mean temperature and relative humidity of 20.7 °C and 45 %. The expanded uncertainty in these mean values is 0.2 °C and 9 %, respectively, calculated using a coverage factor of 1.96 for a 95 % level of confidence. The range of variation in temperature was 20.4 °C to 20.9 °C, and in relative humidity, 38 % to 57 %.

Appendix C. Uncertainty budgets for 1 GΩ

1. Detailed uncertainty budget, KRISS

Quantity X_i	Relative standard uncertainty, $u(x_i)$ $\times 10^{-6}$	Probability distribution /method of evaluation (A,B)	Sensitivity coefficient c_i	Relative uncertainty contribution, $u(R_i)$ $\times 10^{-6}$	Degree of freedom ν_i
Reference standard (10 MΩ)	0.57	Normal/B	1	0.57	∞
10 to 1 ratio (10 MΩ to 100 MΩ)	0.2	Rectangular/B	1	0.2	∞
Rpeatability (10 MΩ to 100 MΩ)	0.22	Normal/A	1	0.22	10
10 to 1 ratio (100 MΩ to 1 GΩ)	0.7	Rectangular/B	1	0.7	∞
Repeatability (100 MΩ to 1 GΩ)	0.2	Normal/A	1	0.2	10
Temperature effect (1 GΩ reference)	0.15	Rectangular/B	1	0.15	∞
1 to 1 ratio (1 GΩ to 1 GΩ)	0.5	Normal/A	1	0.5	10
Temperature effect (travelling standard)	0.9	Rectangular/B	1	0.9	∞
	Relative combined standard uncertainty:			1.42	
	Effective degrees of freedom:			555.9	
	Relative expanded uncertainty (95% confidence level, coverage factor k=2):			2.85	

2. Detailed uncertainty budget, CMS



Quantity X_i	Estimate x_i		Relative Standard uncertainty $u(x_i)$		Probability distribution/ Method of evaluation(A,B)	Sensitivity coefficient c_i	Uncertainty contribution $u(R_i)$		Degree of freedom v_i
Step-up from 10 kΩ to 100 kΩ standard									
Repeatability			1.35	μΩ/Ω	Normal/Type A	1	1.35	μΩ/Ω	3
Measurement of 10×10 kΩ in parallel from 10 kΩ reference standard			0.108	μΩ/Ω	Normal/Type B	1	0.108	μΩ/Ω	520
Parallel to Series of 10×10 kΩ (1 kΩ transfers to 100 kΩ)			1	μΩ/Ω	Normal/Type B	1	1	μΩ/Ω	∞
Temperature instability of 10×10 kΩ			0.026	μΩ/Ω	Rectangle/Type B	1	0.026	μΩ/Ω	∞
Non-linearity of multimeter			0.1	μΩ/Ω	Rectangle/Type B	1	0.1	μΩ/Ω	∞
Resolution of multimeter			0.058	μΩ/Ω	Rectangle/Type B	1	0.058	μΩ/Ω	∞
Step-up from 100 kΩ to 10 MΩ standard									
Repeatability			1.29	μΩ/Ω	Normal/Type A	1	1.29	μΩ/Ω	2
Parallel to Series of 10×1 MΩ (100 kΩ transfers to 10 MΩ)			0.1	μΩ/Ω	Normal/Type B	1	0.1	μΩ/Ω	∞
Temperature instability of 10×1 MΩ			0.16	μΩ/Ω	Rectangle/Type B	1	0.16	μΩ/Ω	∞
1:1 Dual-source bridge			1.5	μΩ/Ω	Normal/Type B	1	1.50	μΩ/Ω	∞
Calibration of the 1 GΩ travelling standard								μΩ/Ω	
Repeatability			1.49	μΩ/Ω	Normal/Type A	1	1.49	μΩ/Ω	3
Parallel to Series of 10×100 MΩ (10 MΩ transfers to 1 GΩ)			0.1	μΩ/Ω	Normal/Type B	1	0.1	μΩ/Ω	∞
Temperature instability of 10×100 MΩ			1.18	μΩ/Ω	Rectangle/Type B	1	1.18	μΩ/Ω	∞
Temperature corrections of 1 GΩ traveling standard			0.11	μΩ/Ω	Rectangle/Type B	1	0.11	μΩ/Ω	∞
1:1 Dual-source bridge			3.20	μΩ/Ω	Normal/Type B	1	3.20	μΩ/Ω	∞
Combined relative standard uncertainty and effective degrees of freedom							4.55	μΩ/Ω	1.04×10^{26}
Relative expanded uncertainty (95 % coverage factor)							9.1	μΩ/Ω	

Measurement Condition:

Temperature: 23.13 °C~23.15 °C ±0.027 °C.

Test voltage: DC 100 V at 1 GΩ.

Humidity: 51.2 % (± 0.3) % r.h.

3. Detailed uncertainty budget, NIMT

1) HR9101

Quantity	Estimate	Relative standard uncertainty, $u(x_i)$	Probability distribution	Sensitivity coefficient	Relative uncertainty contribution, $u(R_i)$	Degree of freedom ν_i
X_i	xi	$\times 10^{-6}$		c_i	$\times 10^{-6}$	
r	*10.0050307*	1.82	Normal	1	1.82	9
R_S	*100007084.7*	11	Normal	1	11	∞
δR_{Sd}		11.5	Rectangular	1	11.5	∞
δr_{acc}		2.9	Rectangular	1	2.9	∞
δr_{ii}		0.006	Rectangular	1	0.006	∞
δr_{rs}		0.03	Rectangular	1	0.03	∞
δr_{st}		0.27	Rectangular	1	0.27	∞
δlek		57.7	Rectangular	1	57.7	∞
δR_{temp}		1.44	Rectangular	1	1.44	∞
R_X	*1000573953*					
		Relative combined standard uncertainty:			60.0	
		Effective degrees of freedom:			∞	
		Relative expanded uncertainty (95% confidence level, coverage factor k=2):			120	

Measurement Condition:

Temperature: 23.05 °C ±2.0 °C.

Test voltage: DC 100 V.

Humidity: 49 % (± 15) % r.h.

2) HR9102

Quantity	Estimate	Relative standard uncertainty, $u(x_i)$	Probability distribution	Sensitivity coefficient	Relative uncertainty contribution, $u(R_i)$	Degree of freedom ν_i
X_i	xi	$\times 10^{-6}$		c_i	$\times 10^{-6}$	
r	*10.0035741*	3.62	Normal	1	3.62	9
R_S	*100007084.7*	11	Normal	1	11	∞
δR_{Sd}		11.5	Rectangular	1	11.5	∞
δr_{acc}		2.9	Rectangular	1	2.9	∞
δr_{ii}		0.006	Rectangular	1	0.006	∞
δr_{rs}		0.03	Rectangular	1	0.03	∞
δr_{st}		0.27	Rectangular	1	0.27	∞
δlek		57.7	Rectangular	1	57.7	∞
δR_{temp}		1.44	Rectangular	1	1.44	∞
R_X	*1000428282*					
		Relative combined standard uncertainty:			60.1	
		Effective degrees of freedom:			∞	
		Relative expanded uncertainty (95% confidence level, coverage factor k=2):			120	

Measurement Condition:

Temperature: 23.00 °C ±2.0 °C.

Test voltage: DC 100 V.

Humidity: 49 % (± 15) % r.h.

3) HR9106

Quantity	Estimate	Relative standard uncertainty, $u(x_i)$	Probability distribution	Sensitivity coefficient	Relative uncertainty contribution, $u(R_i)$	Degree of freedom ν_i
X_i	xi	$\times10^{-6}$		c_i	$\times10^{-6}$	
r	*10.0120454*	7.34	Normal	1	7.34	9
R_S	*100007084.7*	11	Normal	1	11	∞
δR_{Sd}		11.5	Rectangular	1	11.5	∞
δr_{acc}		2.9	Rectangular	1	2.9	∞
δr_{ii}		0.006	Rectangular	1	0.006	∞
δr_{rs}		0.03	Rectangular	1	0.03	∞
δr_{st}		0.27	Rectangular	1	0.27	∞
δlek		57.7	Rectangular	1	57.7	∞
δR_{temp}		1.44	Rectangular	1	1.44	∞
R_X	*1001275472*					
		Relative combined standard uncertainty:			60.4	
		Effective degrees of freedom:			∞	
		Relative expanded uncertainty (95% confidence level, coverage factor k=2):			121	

Measurement Condition:

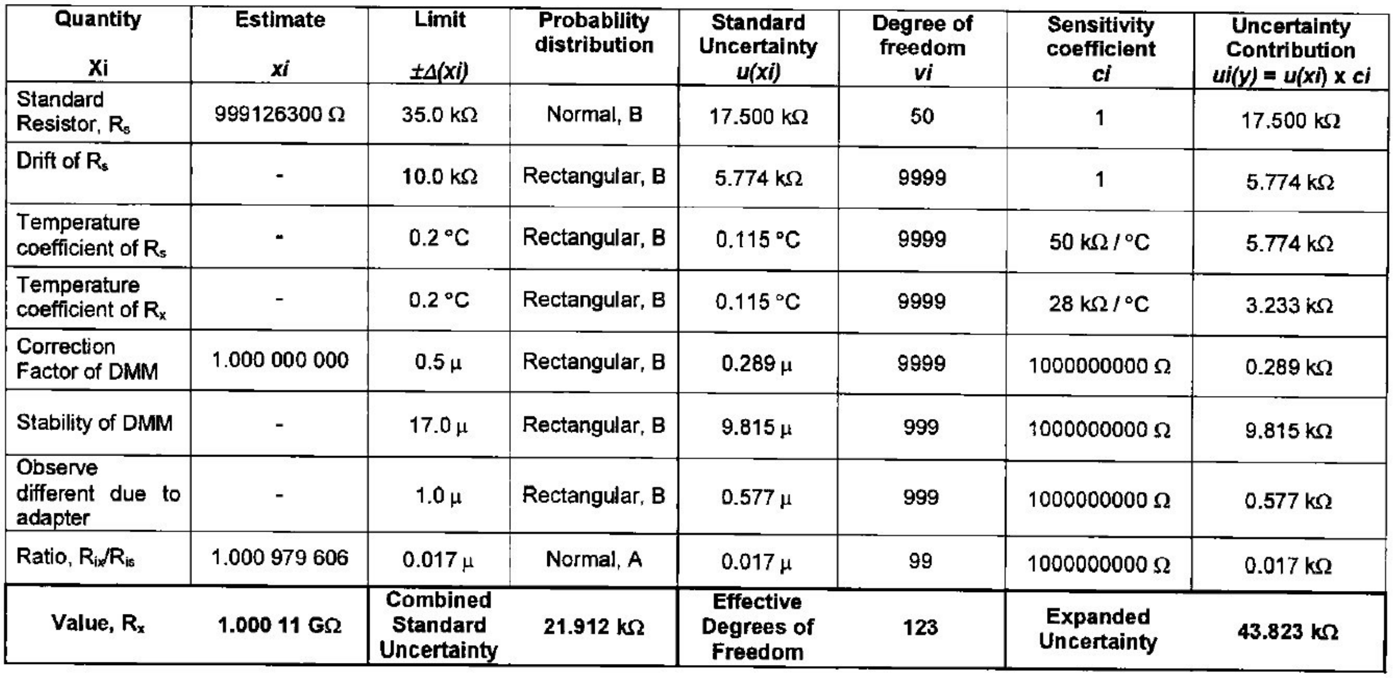
Temperature: 23.10 °C ±2.0 °C.

Test voltage: DC 100 V.

Humidity: 51 % (± 15) % r.h.

4. Detailed uncertainty budget, NML-SIRIM

1) HR9101



Quantity Xi	Estimate *xi*	Limit *±Δ(xi)*	Probability distribution	Standard Uncertainty *u(xi)*	Degree of freedom *vi*	Sensitivity coefficient *ci*	Uncertainty Contribution *ui(y) = u(xi)* x *ci*
Standard Resistor, R_s	999126300 Ω	35.0 kΩ	Normal, B	17.500 kΩ	50	1	17.500 kΩ
Drift of R_s	-	10.0 kΩ	Rectangular, B	5.774 kΩ	9999	1	5.774 kΩ
Temperature coefficient of R_s	-	0.2 °C	Rectangular, B	0.115 °C	9999	50 kΩ / °C	5.774 kΩ
Temperature coefficient of R_x	-	0.2 °C	Rectangular, B	0.115 °C	9999	28 kΩ / °C	3.233 kΩ
Correction Factor of DMM	1.000 000 000	0.5 μ	Rectangular, B	0.289 μ	9999	1000000000 Ω	0.289 kΩ
Stability of DMM	-	17.0 μ	Rectangular, B	9.815 μ	999	1000000000 Ω	9.815 kΩ
Observe different due to adapter	-	1.0 μ	Rectangular, B	0.577 μ	999	1000000000 Ω	0.577 kΩ
Ratio, R_{ix}/R_{is}	1.000 979 606	0.017 μ	Normal, A	0.017 μ	99	1000000000 Ω	0.017 kΩ
Value, R_x	**1.000 11 GΩ**	**Combined Standard Uncertainty**	**21.912 kΩ**	**Effective Degrees of Freedom**	**123**	**Expanded Uncertainty**	**43.823 kΩ**

Measurement Condition: *Temperature:* 23.5 °C ±1.0 °C, *Test voltage:* DC 100 V, *Humidity:* 55 % (± 10) % r.h.

2) HR9102

Quantity Xi	Estimate *xi*	Limit *±Δ(xi)*	Probability distribution	Standard Uncertainty *u(xi)*	Degree of freedom *vi*	Sensitivity coefficient *ci*	Uncertainty Contribution *ui(y) = u(xi) x ci*
Standard Resistor, R_s	999126300 Ω	35.0 kΩ	Normal, B	17.500 kΩ	50	1	17.500 kΩ
Drift of R_s	-	10.0 kΩ	Rectangular, B	5.774 kΩ	9999	1	5.774 kΩ
Temperature coefficient of R_s	-	0.2 °C	Rectangular, B	0.115 °C	9999	50 kΩ / °C	5.774 kΩ
Temperature coefficient of R_x	-	0.2 °C	Rectangular, B	0.115 °C	9999	31 kΩ / °C	3.580 kΩ
Correction Factor of DMM	1.000 000	0.5 µ	Rectangular, B	0.289 µ	9999	1000000000 Ω	0.289 kΩ
Stability of DMM	-	17.0 µ	Rectangular, B	9.815 µ	999	1000000000 Ω	9.815 kΩ
Observe different due to adapter	-	1.0 µ	Rectangular, B	0.577 µ	999	1000000000 Ω	0.577 kΩ
Ratio, R_{ix}/R_{is}	1.000 844 970	0.017 µ	Normal, A	0.017 µ	99	1000000000 Ω	0.0174 kΩ
Value, R_x	**0.999 97 GΩ**	**Combined Standard Uncertainty**	**21.965 kΩ**	**Effective Degrees of Freedom**	**124**	**Expanded Uncertainty**	**43.931 kΩ**

Measurement Condition:

Temperature: 23.5 °C ±1.0 °C, *Test voltage:* DC 100 V, *Humidity:* 55 % (± 10) % r.h.

3) HR9106

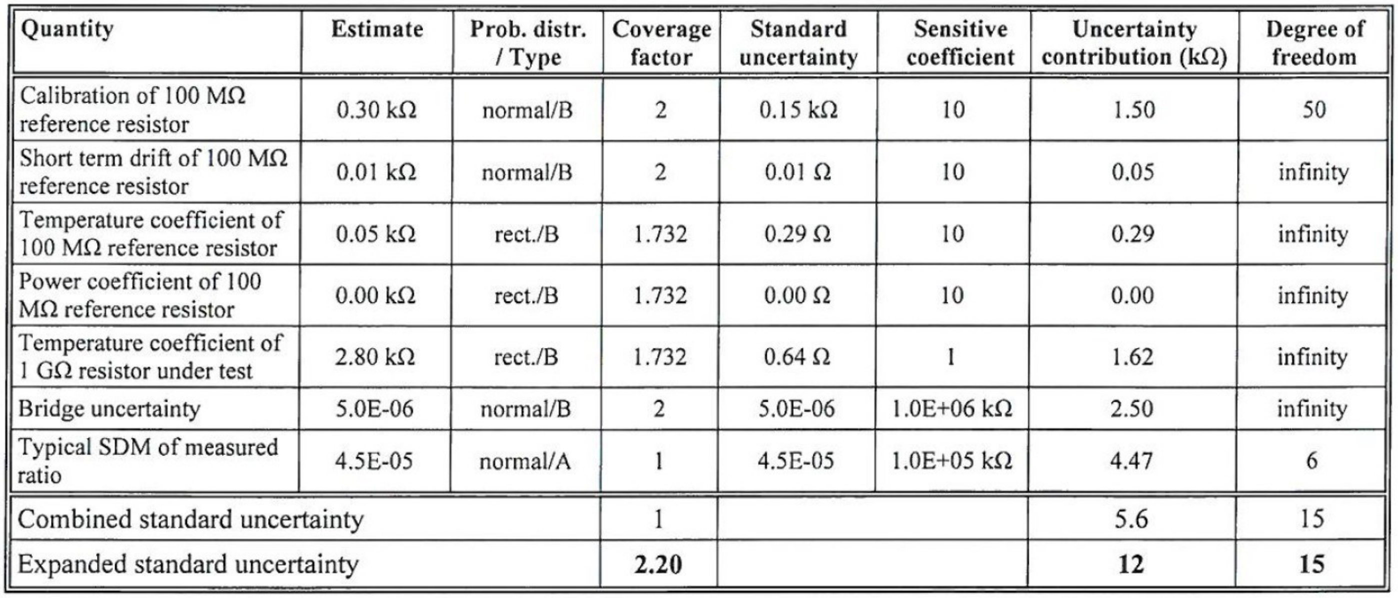
Quantity Xi	Estimate *xi*	Limit *±Δ(xi)*	Probability distribution	Standard Uncertainty *u(xi)*	Degree of freedom *vi*	Sensitivity coefficient *ci*	Uncertainty Contribution *ui(y) = u(xi) x ci*
Standard Resistor, R_s	999126300 Ω	35.0 kΩ	Normal, B	17.500 kΩ	50	1	17.500 kΩ
Drift of R_s	-	10.0 kΩ	Rectangular, B	5.774 kΩ	9999	1	5.774 kΩ
Temperature coefficient of R_s	-	0.2 °C	Rectangular, B	0.115 °C	9999	50 kΩ / °C	5.774 kΩ
Temperature coefficient of R_x	-	0.2 °C	Rectangular, B	0.115 °C	9999	25 kΩ / °C	2.886 kΩ
Correction Factor of DMM	1.000 000	0.5 µ	Rectangular, B	0.289 µ	9999	1000000000 Ω	0.289 kΩ
Stability of DMM	-	17.0 µ	Rectangular, B	9.815 µ	999	1000000000 Ω	9.815 kΩ
Observe different due to adapter	-	1.0 µ	Rectangular, B	0.577 µ	999	1000000000 Ω	0.577 kΩ
Ratio, R_{ix}/R_{is}	1.001 681 468	0.070 µ	Normal, A	0.070 µ	99	1000000000 Ω	0.070 kΩ
Value, R_x	**1.000 81 GΩ**	**Combined Standard Uncertainty**	**21.863 kΩ**	**Effective Degrees of Freedom**	**122**	**Expanded Uncertainty**	**43.727 kΩ**

Measurement Condition:

Temperature: 23.4 °C ±1.0 °C, *Test voltage:* DC 100 V, *Humidity:* 55 % (± 10) % r.h.

5. Detailed uncertainty budget, NMC

1) HR9101

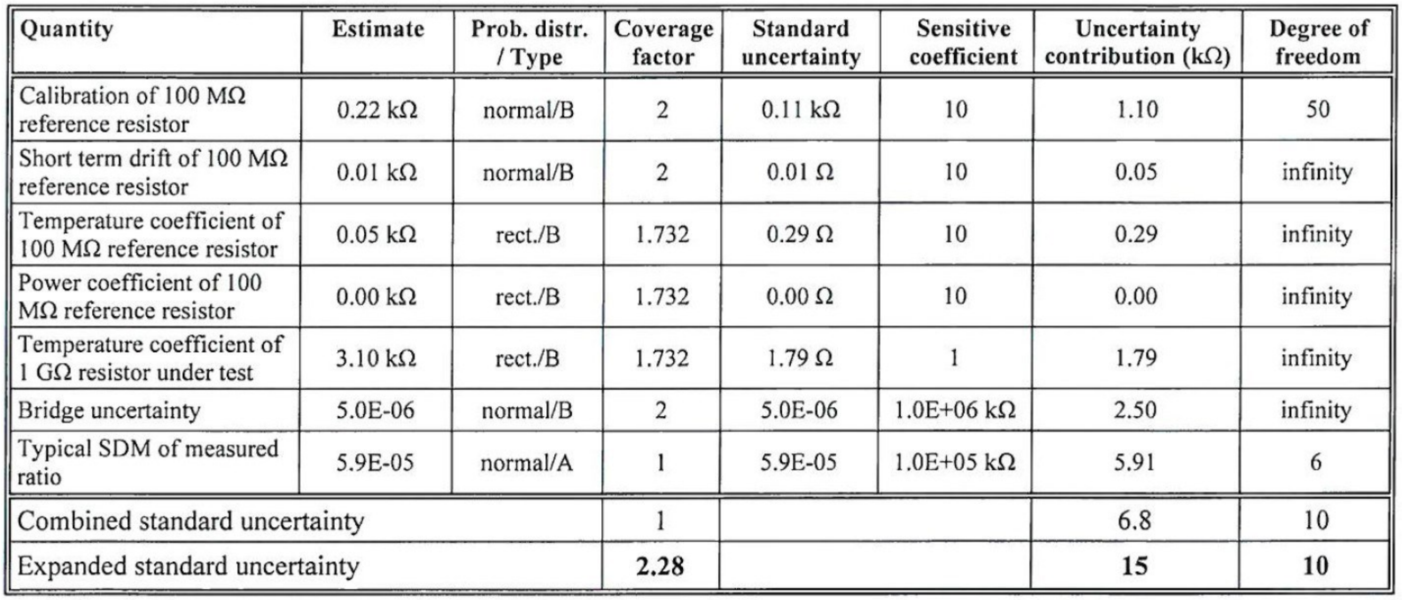


Quantity	Estimate	Prob. distr. / Type	Coverage factor	Standard uncertainty	Sensitive coefficient	Uncertainty contribution (kΩ)	Degree of freedom
Calibration of 100 MΩ reference resistor	0.30 kΩ	normal/B	2	0.15 kΩ	10	1.50	50
Short term drift of 100 MΩ reference resistor	0.01 kΩ	normal/B	2	0.01 Ω	10	0.05	infinity
Temperature coefficient of 100 MΩ reference resistor	0.05 kΩ	rect./B	1.732	0.29 Ω	10	0.29	infinity
Power coefficient of 100 MΩ reference resistor	0.00 kΩ	rect./B	1.732	0.00 Ω	10	0.00	infinity
Temperature coefficient of 1 GΩ resistor under test	2.80 kΩ	rect./B	1.732	0.64 Ω	1	1.62	infinity
Bridge uncertainty	5.0E-06	normal/B	2	5.0E-06	1.0E+06 kΩ	2.50	infinity
Typical SDM of measured ratio	4.5E-05	normal/A	1	4.5E-05	1.0E+05 kΩ	4.47	6
Combined standard uncertainty			1			5.6	15
Expanded standard uncertainty			**2.20**			**12**	**15**

Measurement Condition:

Temperature: 23.02 °C ±0.01 °C, *Test voltage:* DC 100 V, *Humidity:* 57.6 % (±2.0) % r.h.

2) HR9102

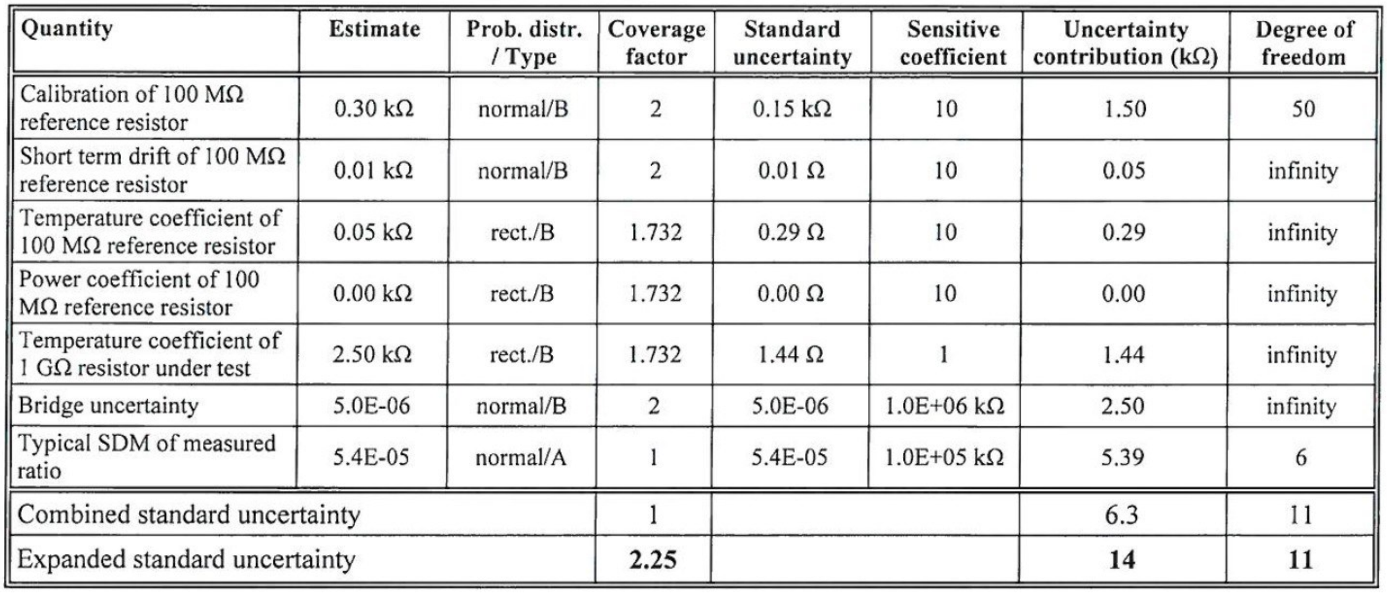


Quantity	Estimate	Prob. distr. / Type	Coverage factor	Standard uncertainty	Sensitive coefficient	Uncertainty contribution (kΩ)	Degree of freedom
Calibration of 100 MΩ reference resistor	0.22 kΩ	normal/B	2	0.11 kΩ	10	1.10	50
Short term drift of 100 MΩ reference resistor	0.01 kΩ	normal/B	2	0.01 Ω	10	0.05	infinity
Temperature coefficient of 100 MΩ reference resistor	0.05 kΩ	rect./B	1.732	0.29 Ω	10	0.29	infinity
Power coefficient of 100 MΩ reference resistor	0.00 kΩ	rect./B	1.732	0.00 Ω	10	0.00	infinity
Temperature coefficient of 1 GΩ resistor under test	3.10 kΩ	rect./B	1.732	1.79 Ω	1	1.79	infinity
Bridge uncertainty	5.0E-06	normal/B	2	5.0E-06	1.0E+06 kΩ	2.50	infinity
Typical SDM of measured ratio	5.9E-05	normal/A	1	5.9E-05	1.0E+05 kΩ	5.91	6
Combined standard uncertainty			1			6.8	10
Expanded standard uncertainty			**2.28**			**15**	**10**

Measurement Condition:

Temperature: 23.02 °C ±0.01 °C, *Test voltage:* DC 100 V, *Humidity:* 56.0 % (±2.0) % r.h.

3) HR9106



Quantity	Estimate	Prob. distr. / Type	Coverage factor	Standard uncertainty	Sensitive coefficient	Uncertainty contribution (kΩ)	Degree of freedom
Calibration of 100 MΩ reference resistor	0.30 kΩ	normal/B	2	0.15 kΩ	10	1.50	50
Short term drift of 100 MΩ reference resistor	0.01 kΩ	normal/B	2	0.01 Ω	10	0.05	infinity
Temperature coefficient of 100 MΩ reference resistor	0.05 kΩ	rect./B	1.732	0.29 Ω	10	0.29	infinity
Power coefficient of 100 MΩ reference resistor	0.00 kΩ	rect./B	1.732	0.00 Ω	10	0.00	infinity
Temperature coefficient of 1 GΩ resistor under test	2.50 kΩ	rect./B	1.732	1.44 Ω	1	1.44	infinity
Bridge uncertainty	5.0E-06	normal/B	2	5.0E-06	1.0E+06 kΩ	2.50	infinity
Typical SDM of measured ratio	5.4E-05	normal/A	1	5.4E-05	1.0E+05 kΩ	5.39	6
Combined standard uncertainty			1			6.3	11
Expanded standard uncertainty			**2.25**			**14**	**11**

Measurement Condition:

Temperature: 23.02 °C ±0.01 °C, *Test voltage:* DC 100 V, *Humidity:* 58.0 % (±2.0) % r.h.

Remarks:

1) The calibration uncertainty of reference standard is the total uncertainty of step-up from 10 kΩ to 100 MΩ.
2) The bridge uncertainty is the total uncertainty associated to the bridge, including ratio error, voltage source stability, resolution and offset of system detector.
3) The typical standard deviation of the mean(SDM) of measured ratio is defined as the median value of SDM values among the data sets used to calculate the final reported value.

6. Detailed uncertainty budget, NMIJ

Source x_i	$u(x_i)$	Distribution	Sensitivity coefficient c_i	$c_i \times u(x_i)$ [μΩ/Ω]	Degree of freedom
Calibration of 100-MΩ resistor	0.66	Normal (Type B)	1	0.66	1300
Voltage divider (addition because the same voltage divider is used three times)	1.05	Rectangular (Type B)	1	1.05	∞
Voltage division of injected voltage	0.05	Rectangular (Type B)	1	0.05	∞
Resistance of lead wire	0.005	Rectangular (Type B)	1	0.005	∞
Scattering observed in measurements	1.0	Normal (Type A)	1	1.0	99
Temperature coefficient of resistor	0.01	Rectangular (Type A)	1	0.01	∞
Humidity coefficient of resistor	0.02	Rectangular (Type B)	1	0.02	∞
Combined standard uncertainty and effective degree of freedom				1.6	630
Expanded uncertainty (coverage factor k = 2 at level of confidence of 95%) and effective degree of freedom				3.2	630

7. Detailed uncertainty budget(HR9101 at 91 V), NMIA

	Quantity X_i	Estimate x_i (μΩ/Ω)	Standard uncertainty $u(x_i)$ (μΩ/Ω)	Units	Method of evaluation	Probability distribution	Sensitivity coefficient c_i	Uncertainty contribution $u(x_i) \times c_i$ (μΩ/Ω)	Degrees of freedom v
SI Determi-nation	SI value of four 1 Ω resistors determined with reference to the NMIA calculable capacitor	-	0.082	μΩ/Ω	A and B	N	1	0.082	45
10 kΩ reference standard	Calibrated value of 10 kΩ reference standard	4.900	0.026	μΩ/Ω	A and B	N	1	0.026	10
	Estimated drift in value of 10 kΩ between calibration and use as reference standard	0.101	0.050	μΩ/Ω	B	N	1	0.050	6
	Temperature difference of 10 kΩ between calibration and use as reference standard	-0.030	0.050	°C	A and B	N	0.2	0.010	20
Build-up: 10 kΩ to 100 MΩ	Ratio of 1 MΩ to 10 kΩ reference standard	-3.307	0.095	μΩ/Ω	A	N	1	0.095	14
	Ratio of 10 MΩ to 1 MΩ reference standard	-2.490	0.019	μΩ/Ω	A	N	1	0.019	14
	Ratio of 100 MΩ to 10 MΩ reference standard	0.967	0.199	μΩ/Ω	A	N	1	0.199	11
	10:1 bridge ratio error* at 20 V (applied twice): 1 MΩ to 10 kΩ	0.000	0.346	μΩ/Ω	B	N	1.4	0.490	133
	10:1 bridge ratio error* at 100 V: 10 MΩ to 1 MΩ	0.000	0.175	μΩ/Ω	B	N	1	0.175	1237
	10:1 bridge ratio error* at 100 V: 100 MΩ to 10 MΩ	0.000	0.336	μΩ/Ω	B	N	1	0.336	91
	Estimate of change in value of 100 kΩ resistor between two ratio measurements	0.000	0.300	μΩ/Ω	B	N	1	0.300	10
	Estimate of change in value of 1 MΩ resistor between two ratio measurements	0.000	0.050	μΩ/Ω	B	N	1	0.050	10
	Estimate of change in value of 10 MΩ resistor between two ratio measurements	0.000	0.050	μΩ/Ω	B	N	1	0.050	10
	Estimated change in value of 100 MΩ between calibration and use as reference standard	0.000	0.050	μΩ/Ω	B	N	1	0.050	10
Test resistor	Ratio of 1 GΩ test resistor to 100 MΩ reference standard	84.962	0.503	μΩ/Ω	A	N	1	0.503	5

	10:1 bridge ratio error at 100 V: 1 GΩ to 100 MΩ	0.000	2.007	μΩ/Ω	B	N	1	2.007	10
	Leads correction due to leakage resistance between potential leads	0.000	0.520	μΩ/Ω	B	R	1	0.520	50
	Measurement of temperature of test resistor	0.000	0.054	°C	B	N	28	1.512	616
	Deviation from nominal	**85.103**						**2.716**	**34**

8. Detailed uncertainty budget, NMISA

The 1 GΩ travelling standards were measured against a 1 GΩ standard. The travelling standards and the 1 GΩ reference standard were first measured against a 100 MΩ standard in a 10:1 ratio using an automatic high resistance bridge and a low thermal scanner, with 100 V applied across a series connection of a 100 MΩ and a 1 GΩ standard using a multifunction calibrator. Thereafter, the travelling standard values assigned using substitution method.

The reported resistance of each 1 GΩ travelling standard was assigned using the formula:

$$R_x = \frac{R_{x(rd)}}{R_{s(rd)}} * (R_{s(cal)} + R_{s(dr)} + R_{s(lc)} + R_{s(vc)})$$

Where:

R_x is the assigned resistance of the travelling standard.

$R_{x(rd)}$ is the travelling standard measured resistance.

$R_{s(rd)}$ is the reference standard measured resistance.

R_s is the reference standard value.

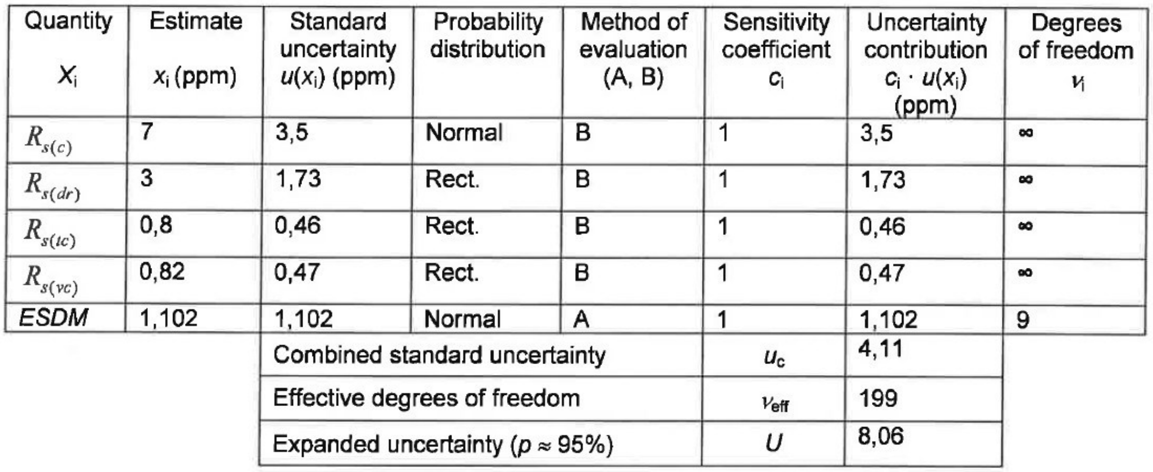
$R_{s(cal)}$ is the reference standard calibration uncertainty.

$R_{s(dr)}$ is the estimated drift of the reference standard since last calibration.

$R_{s(lc)}$ is the temperature coefficient correction of the reference standard.

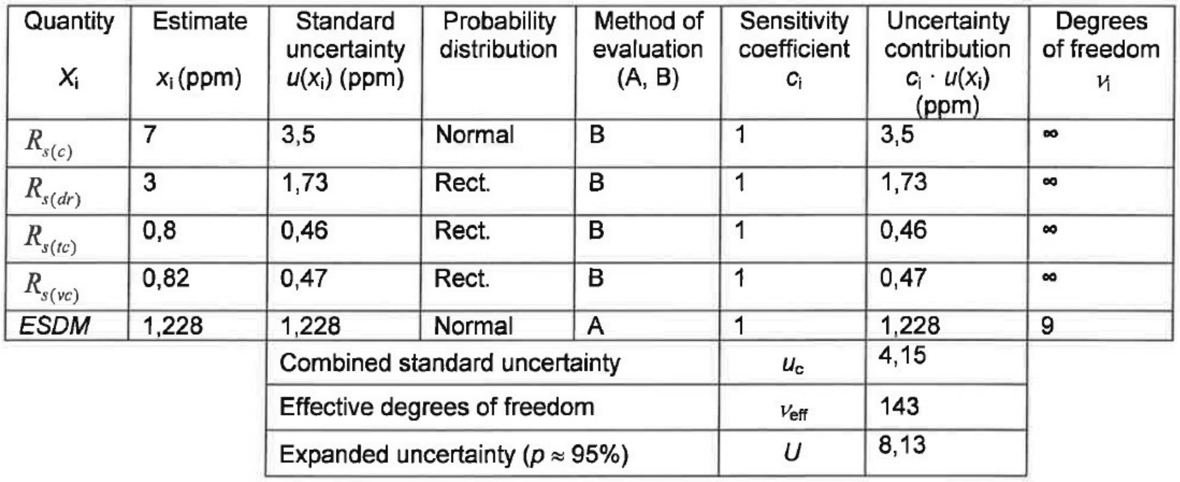
$R_{s(vc)}$ is the voltage coefficient correction of the reference standard.

1) HR9101



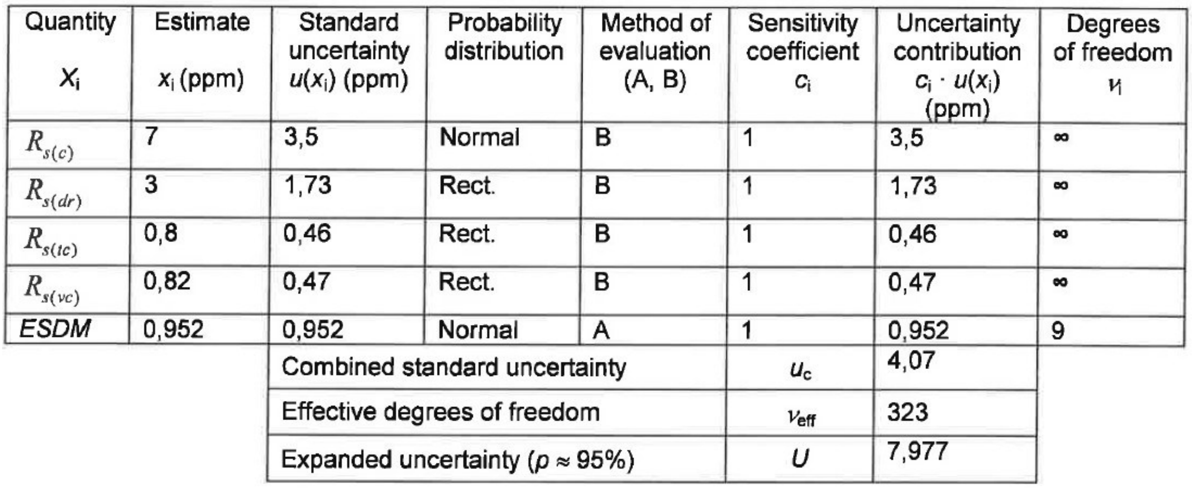
Quantity X_i	Estimate x_i (ppm)	Standard uncertainty $u(x_i)$ (ppm)	Probability distribution	Method of evaluation (A, B)	Sensitivity coefficient c_i	Uncertainty contribution $c_i \cdot u(x_i)$ (ppm)	Degrees of freedom ν_i
$R_{s(c)}$	7	3,5	Normal	B	1	3,5	∞
$R_{s(dr)}$	3	1,73	Rect.	B	1	1,73	∞
$R_{s(lc)}$	0,8	0,46	Rect.	B	1	0,46	∞
$R_{s(vc)}$	0,82	0,47	Rect.	B	1	0,47	∞
ESDM	1,102	1,102	Normal	A	1	1,102	9
		Combined standard uncertainty			u_c	4,11	
		Effective degrees of freedom			ν_{eff}	199	
		Expanded uncertainty ($p \approx 95\%$)			U	8,06	

2) HR9102



Quantity X_i	Estimate x_i (ppm)	Standard uncertainty $u(x_i)$ (ppm)	Probability distribution	Method of evaluation (A, B)	Sensitivity coefficient c_i	Uncertainty contribution $c_i \cdot u(x_i)$ (ppm)	Degrees of freedom ν_i
$R_{s(c)}$	7	3,5	Normal	B	1	3,5	∞
$R_{s(dr)}$	3	1,73	Rect.	B	1	1,73	∞
$R_{s(tc)}$	0,8	0,46	Rect.	B	1	0,46	∞
$R_{s(vc)}$	0,82	0,47	Rect.	B	1	0,47	∞
ESDM	1,228	1,228	Normal	A	1	1,228	9
		Combined standard uncertainty			u_c	4,15	
		Effective degrees of freedom			ν_{eff}	143	
		Expanded uncertainty ($p \approx 95\%$)			U	8,13	

3) HR9106



Quantity X_i	Estimate x_i (ppm)	Standard uncertainty $u(x_i)$ (ppm)	Probability distribution	Method of evaluation (A, B)	Sensitivity coefficient c_i	Uncertainty contribution $c_i \cdot u(x_i)$ (ppm)	Degrees of freedom ν_i
$R_{s(c)}$	7	3,5	Normal	B	1	3,5	∞
$R_{s(dr)}$	3	1,73	Rect.	B	1	1,73	∞
$R_{s(tc)}$	0,8	0,46	Rect.	B	1	0,46	∞
$R_{s(vc)}$	0,82	0,47	Rect.	B	1	0,47	∞
ESDM	0,952	0,952	Normal	A	1	0,952	9
		Combined standard uncertainty			u_c	4,07	
		Effective degrees of freedom			ν_{eff}	323	
		Expanded uncertainty ($p \approx 95\%$)			U	7,977	

Measurement Conditions:

Table 1. Temperature

Minimum	Average	Maximum
22,8 °C	23,4 °C	23,8 °C

Table 2. Temperature uncertainty budget calculation

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Method of evaluation (A, B)	Sensitivity coefficient c_i	Uncertainty contribution $c_i \cdot u(x_i)$	Degrees of freedom ν_i
T_s	0,4 °C	0,23 °C	Rect.	B	1	0,23 °C	∞
s	0,3 °C	0,3 °C	Normal	A	1	0,3 °C	9
		Combined standard uncertainty			u_c	0,3 °C	
		Effective degrees of freedom			ν_{eff}	9	
		Expanded uncertainty ($p \approx 95\%$)			U	0,68 °C	

Table 3. Relative humidity

Minimum	Average	Maximum
52,4 %RH	55,2 %RH	58,0 %RH

Table 4. Relative humidity uncertainty budget calculation

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Method of evaluation (A, B)	Sensitivity coefficient c_i	Uncertainty contribution $c_i \cdot u(x_i)$	Degrees of freedom ν_i
$\%RH_s$	0,4 %RH	0,23 %RH	Rect.	B	1	0,23 %RH	∞
s	1,8 %RH	1,8 %RH	Normal	A	1	1,8 %RH	9
		Combined standard uncertainty			u_c	1,81 %RH	
		Effective degrees of freedom			ν_{eff}	45	
		Expanded uncertainty ($p \approx 95\%$)			U	3,64 %RH	

9. Detailed uncertainty budget, NIM

1) HR9101

QuantityX_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution/method of evaluation (A,B)	Sensitivity coefficient c_i	Uncertainty contribution $u(R_i)$	Drgree of freedom v_i
Repeatability	1.04	1.04	A	1	1.04	9
Standard resistors	1.959	0.980	B	1	0.980	∞
Insulation	4.5	2.60	B	1	2.60	∞
Unlinearity	0.01	0.005	B	1	0.005	∞
Bridge Calibration	3	1.5	B	1	1.500	∞
Stability of the voltage source（/24hours)including the noise	0.755	0.38	B	1	0.377	∞
Null indicator resolution noise, drift and offset	0.2	0.115	B	1	0.115	∞
Temperature coefficient(0.03℃)	0.84	0.485	B	1	0.485	∞
voltage coefficient	0.1	0.058	B	1	0.058	∞
R_X						
Combined standard uncertainty and effective degrees of freedom:$u_\mathrm{c}(\mathrm{R_X})$					3.4	1006.1
Expanded uncertainty (95% coverage factor): U					6.6	

Measurement Condition:

Temperature : mean value 19.99 ℃, range of variation 19.98 ℃ ~ 20.00 ℃

Test voltage: DC 100 V

Humidity : 40 % RH ~ 45 % RH

2) HR9102

QuantityX_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution/method of evaluation(A,B)	Sensitivity coefficient c_i	Uncertainty contribution $u(R_i)$	Drgree of freedom v_i
Repeatability	1.46	1.46	A	1	1.46	9
Standard resistors	1.959	0.980	B	1	0.980	∞
Insulation	4.5	2.60	B	1	2.60	∞
Unlinearity	0.01	0.005	B	1	0.005	∞
Bridge Calibration	3	1.5	B	1	1.500	∞
Stability of the voltage source (/24hours)including the noise	0.755	0.38	B	1	0.377	∞
Null indicator resolution noise, drift and offset	0.2	0.115	B	1	0.115	∞
Temperature coefficient(0.03℃)	0.93	0.537	B	1	0.537	∞
voltage coefficient	0.1	0.058	B	1	0.058	∞

R_X						
Combined standard uncertainty and effective degrees of freedom:$u_c(R_X)$					3.5	311.4
Expanded uncertainty (95% coverage factor): U					6.9	

Measurement Condition:

Temperature : mean value 19.98 ℃, range of variation 19.96 ℃ ~ 19.99 ℃

Test voltage: DC 100 V

Humidity : 40 % RH ~ 45 % RH

3) HR9106

QuantityX_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution/method of evaluation(A,B)	Sensitivity coefficient c_i	Uncertainty contribution $u(R_i)$	Drgree of freedom v_i
Repeatability	0.45	0.45	A	1	0.45	9
Standard resistors	1.959	0.980	B	1	0.980	∞
Insulation	4.5	2.60	B	1	2.60	∞
Unlinearity	0.01	0.005	B	1	0.005	∞
Bridge Calibration	3	1.5	B	1	1.500	∞
Stability of the voltage source （/24hours)including the noise	0.755	0.38	B	1	0.377	∞

Null indicator resolution noise, drift and offset	0.2	0.115	B	1	0.115	∞
Temperature coefficient(0.03℃)	0.75	0.433	B	1	0.433	∞
voltage coefficient	0.1	0.058	B	1	0.058	∞
R_X						
Combined standard uncertainty and effective degrees of freedom:$u_c(R_X)$					3.2	24238.4
Expanded uncertainty (95% coverage factor): U					6.4	

Measurement Condition:

Temperature : mean value 19.97 ℃, range of variation 19.97 ℃ ~ 19.97 ℃

Test voltage: DC 100 V

Humidity : 40 % RH ~ 45 % RH

10. Detailed uncertainty budget(HR9102, 97.4 V, 22.98°C), VNIIM

The model for the measurement of **1 GΩ** standard is:

$R\ (1G)_x = R_{s2}\cdot N_H\cdot(1+\delta R_{x2})\cdot(1+\delta_{H1}+\delta_{H2}+\delta_{leak1}+\delta_{Wb1}+\delta_{t1})\ )\cdot(1+c_{cab})$

The components are:

$R(10M)_x$: the unknown resistor,

R_{s2}: the reference standard 10 MΩ,

N_H: nominal ratio of the series-parallel transfer of the 100 MΩ per step Hamon standard *(N_H=100),*

δR_{x2}: reading (ratio) of Wheatstone bridge,

c_{cab} **:** a correction of shunt effect of an insulation resistance of connecting cables (c_{cab} =- *2,8*×10^{-6} for measured resistance standards, c_{cab} = 0 for reference resistance;standards);

δ_{H1} : the relative uncertainty due to imperfect series-parallel transfer of the Hamon standard;

δ_{H2} : the relative uncertainty due to the instability of the Hamon standard

δ_{leak1}: the relative uncertainty due to leakage resistance from node points of the Wheatstone bridge,

δ_{Wb1}: the relative uncertainty due to balancing of the Wheatstone bridge for 1 GΩ resistors (sensitivity, repeatability),

δ_{t1}: the relative uncertainty due to instability temperature of the resistors.

The relative standard uncertainty is evaluated by means of equation:

$$\frac{u(R(1G)_x)}{R(1G)_x} = \sqrt{\left(\frac{u(R_{s2})}{R_{s2}}\right)^2 + \sum_1^5\left(\delta_j^2\right)}$$

Quantity X_i	Estimate x_i	Relative standard uncertainty, $u(x_i)$ ×10^{-6}	Probability distribution /method of evaluation (A,B)	Sensitivity coefficient c_i	Relative uncertainty contribution, $u(R_i)$ ×10^{-6}	Degree of freedom ν_i
R_{s2}	10.002583MΩ	0.38	Normal/B	1.0	0.4	130
N_{H1}	100	-	-	-	-	-
δR_{x2}	- 2997·10^{-7}	-				

δ_{H1}	0	1.6	Rectangular/B	1.0	1.6	Inf
δ_{H2}	0	0.5	Rectangular/B	1.0	0.5	Inf
δ_{leak}	0	0.8	Rectangular/B	1.0	0.8	Inf
δ_{Wb1}	0	4.63	Normal/A	1.0	1.3	12
δ_{t1}	0	0.9	Rectangular/B	1.0	0.9	Inf
c_{cab}	$-2,8\times10^{-}$	0,28	Rectangular/B	1,0	0,28	Inf.
R_x	9.999558 GΩ					
		Relative combined standard uncertainty:			$2.5\cdot10^{-6}$	
		Effective degrees of freedom:			16.4	
		Relative expanded uncertainty (95% coverage factor):			$5.4\cdot10^{-6}$ (k = 2.17)	

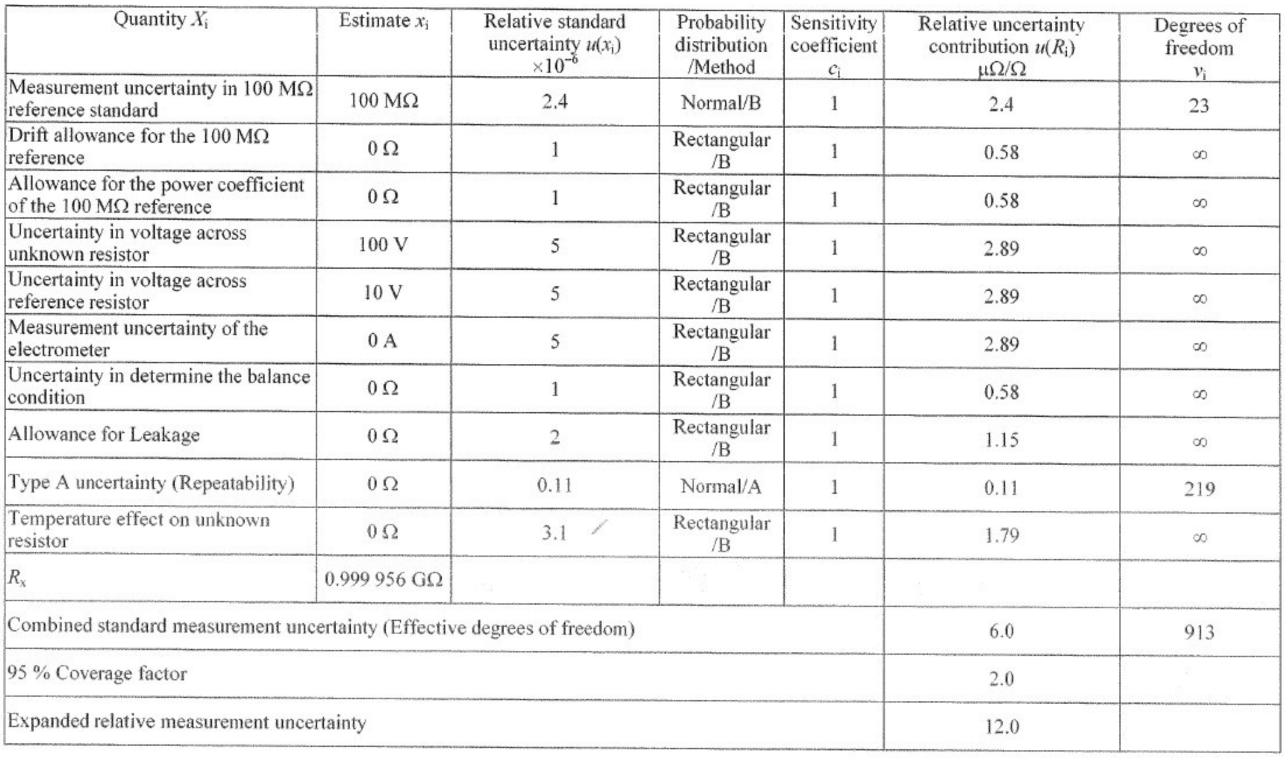
11. Detailed uncertainty budget, SCL

Serial No.	Mean Date of Measurement	Test Voltage	Ambient Conditions				
			Temperature			Relative Humidity	
			Mean Value	Expanded Measurement Uncertainty	Range of Variation	Mean Value	Range of Variation
HR9101	19 Oct 2012	100 V	23.00 °C	0.03 °C	0.06 °C	46.7 %	3.5 %
HR9102	19 Oct 2012	100 V	23.00 °C	0.03 °C	0.05 °C	46.8 %	3.6 %
HR9106	19 Oct 2012	100 V	23.00 °C	0.03 °C	0.07 °C	46.9 %	3.4 %

1) HR9101

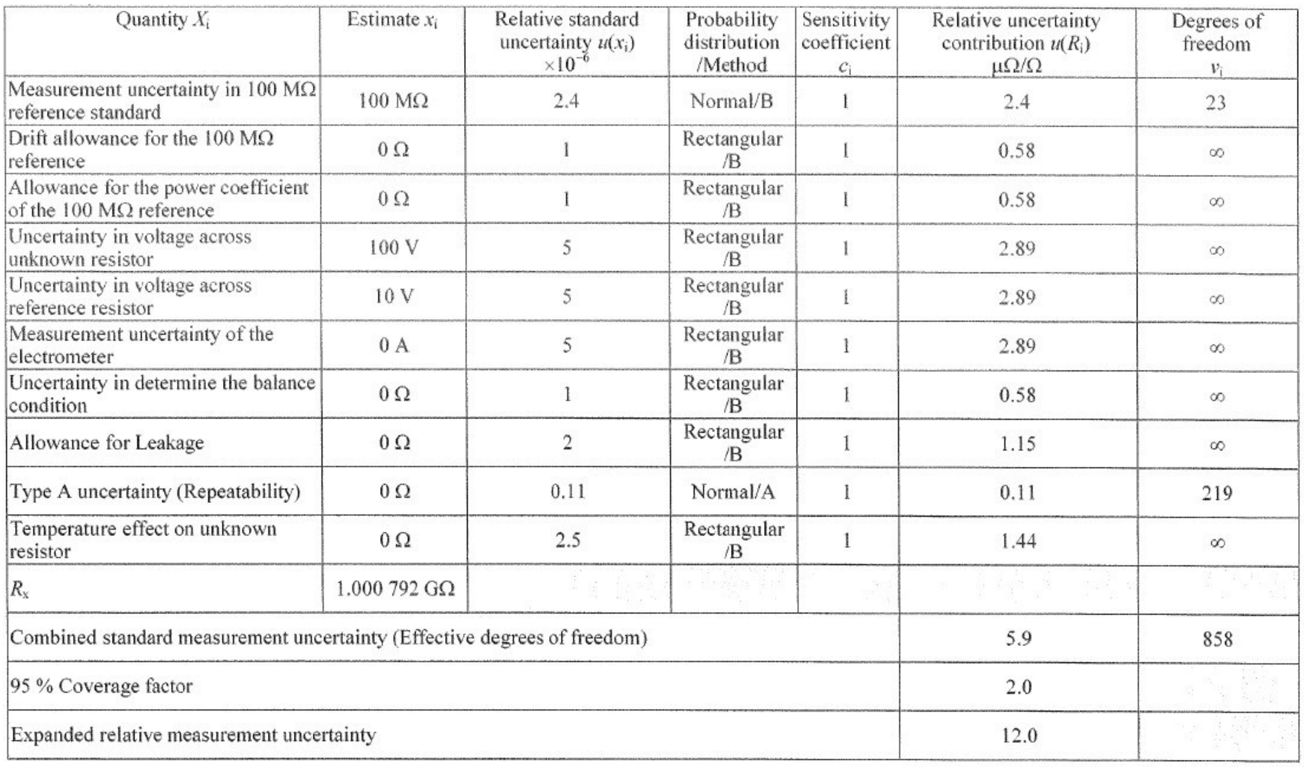
Quantity X_i	Estimate x_i	Relative standard uncertainty $u(x_i)$ $\times 10^{-6}$	Probability distribution /Method	Sensitivity coefficient c_i	Relative uncertainty contribution $u(R_i)$ μΩ/Ω	Degrees of freedom ν_i
Measurement uncertainty in 100 MΩ reference standard	100 MΩ	2.4	Normal/B	1	2.4	23
Drift allowance for the 100 MΩ reference	0 Ω	1	Rectangular /B	1	0.58	∞
Allowance for the power coefficient of the 100 MΩ reference	0 Ω	1	Rectangular /B	1	0.58	∞
Uncertainty in voltage across unknown resistor	100 V	5	Rectangular /B	1	2.89	∞
Uncertainty in voltage across reference resistor	10 V	5	Rectangular /B	1	2.89	∞
Measurement uncertainty of the electrometer	0 A	5	Rectangular /B	1	2.89	∞
Uncertainty in determine the balance condition	0 Ω	1	Rectangular /B	1	0.58	∞
Allowance for Leakage	0 Ω	2	Rectangular /B	1	1.15	∞
Type A uncertainty (Repeatability)	0 Ω	0.13	Normal/A	1	0.13	229
Temperature effect on unknown resistor	0 Ω	2.8	Rectangular /B	1	1.62	∞
R_x	1.000 094 GΩ					
Combined standard measurement uncertainty (Effective degrees of freedom)					6.0	884
95 % Coverage factor					2.0	
Expanded relative measurement uncertainty					12.0	

2) HR9102



Quantity X_i	Estimate x_i	Relative standard uncertainty $u(x_i)$ $\times 10^{-6}$	Probability distribution /Method	Sensitivity coefficient c_i	Relative uncertainty contribution $u(R_i)$ μΩ/Ω	Degrees of freedom ν_i
Measurement uncertainty in 100 MΩ reference standard	100 MΩ	2.4	Normal/B	1	2.4	23
Drift allowance for the 100 MΩ reference	0 Ω	1	Rectangular /B	1	0.58	∞
Allowance for the power coefficient of the 100 MΩ reference	0 Ω	1	Rectangular /B	1	0.58	∞
Uncertainty in voltage across unknown resistor	100 V	5	Rectangular /B	1	2.89	∞
Uncertainty in voltage across reference resistor	10 V	5	Rectangular /B	1	2.89	∞
Measurement uncertainty of the electrometer	0 A	5	Rectangular /B	1	2.89	∞
Uncertainty in determine the balance condition	0 Ω	1	Rectangular /B	1	0.58	∞
Allowance for Leakage	0 Ω	2	Rectangular /B	1	1.15	∞
Type A uncertainty (Repeatability)	0 Ω	0.11	Normal/A	1	0.11	219
Temperature effect on unknown resistor	0 Ω	3.1	Rectangular /B	1	1.79	∞
R_x	0.999 956 GΩ					
Combined standard measurement uncertainty (Effective degrees of freedom)					6.0	913
95 % Coverage factor					2.0	
Expanded relative measurement uncertainty					12.0	

3) HR9106



Quantity X_i	Estimate x_i	Relative standard uncertainty $u(x_i)$ $\times 10^{-6}$	Probability distribution /Method	Sensitivity coefficient c_i	Relative uncertainty contribution $u(R_i)$ µΩ/Ω	Degrees of freedom ν_i
Measurement uncertainty in 100 MΩ reference standard	100 MΩ	2.4	Normal/B	1	2.4	23
Drift allowance for the 100 MΩ reference	0 Ω	1	Rectangular /B	1	0.58	∞
Allowance for the power coefficient of the 100 MΩ reference	0 Ω	1	Rectangular /B	1	0.58	∞
Uncertainty in voltage across unknown resistor	100 V	5	Rectangular /B	1	2.89	∞
Uncertainty in voltage across reference resistor	10 V	5	Rectangular /B	1	2.89	∞
Measurement uncertainty of the electrometer	0 A	5	Rectangular /B	1	2.89	∞
Uncertainty in determine the balance condition	0 Ω	1	Rectangular /B	1	0.58	∞
Allowance for Leakage	0 Ω	2	Rectangular /B	1	1.15	∞
Type A uncertainty (Repeatability)	0 Ω	0.11	Normal/A	1	0.11	219
Temperature effect on unknown resistor	0 Ω	2.5	Rectangular /B	1	1.44	∞
R_x	1.000 792 GΩ					
Combined standard measurement uncertainty (Effective degrees of freedom)					5.9	858
95 % Coverage factor					2.0	
Expanded relative measurement uncertainty					12.0	

12. **Detailed uncertainty budget,** KazInMetr

The principle of measurement applied was the substitution method. The measurand is described by the equation

$$R_X = R_S + (R_{XM} - R_{SM})$$

If this equation is expanded in order to include relevant deviation of the input quantities, it becomes:

$$R_X = (R_S + (R_{XM} - R_{SM})) * (1 + \delta R_{S6520} + \delta R_{X6520} + \delta R_{ST} + \delta R_{XT})$$

measurement consists in a 100 kΩ:10 MΩ comparison ($R_{1:100}$) against a reference standard R_s calibrated in terms of the quantized Hall resistance. The step up to 100 kΩ is carried out using a DCC bridge. The model for the 1:100 comparison at 10 MΩ can be simplified to:

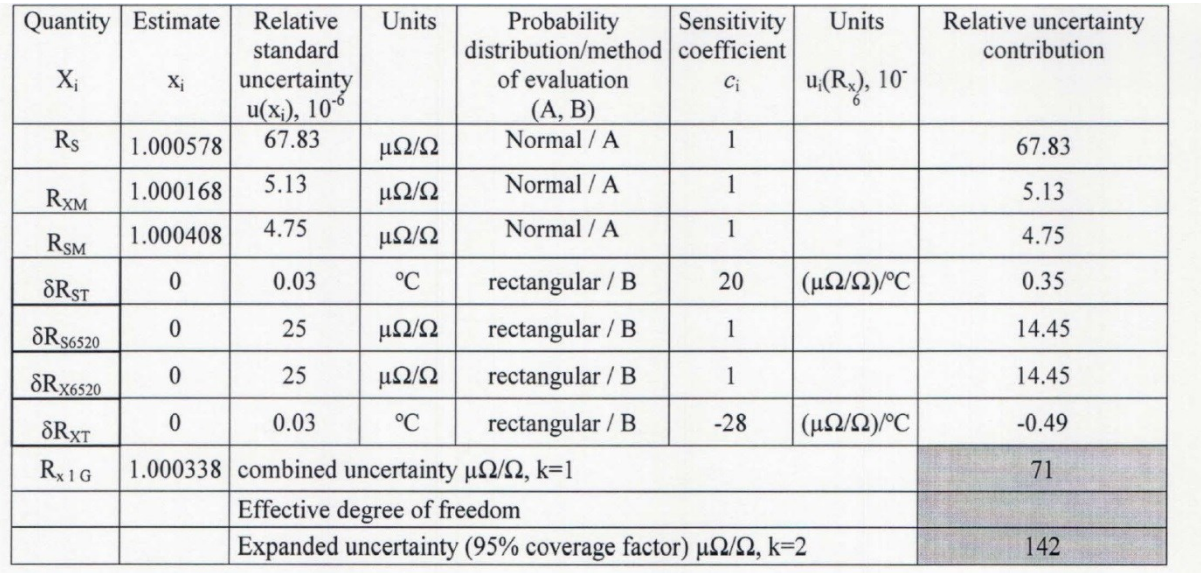
$$R_x = R_{Ref} * \left(1 + \delta_{Ref} + K_{Temper}\right) * K_{DCC}(1 + k_{br}) * (1 + \delta_{Xt} * K_{Xt})$$

The following sources of uncertainty are taken into account:

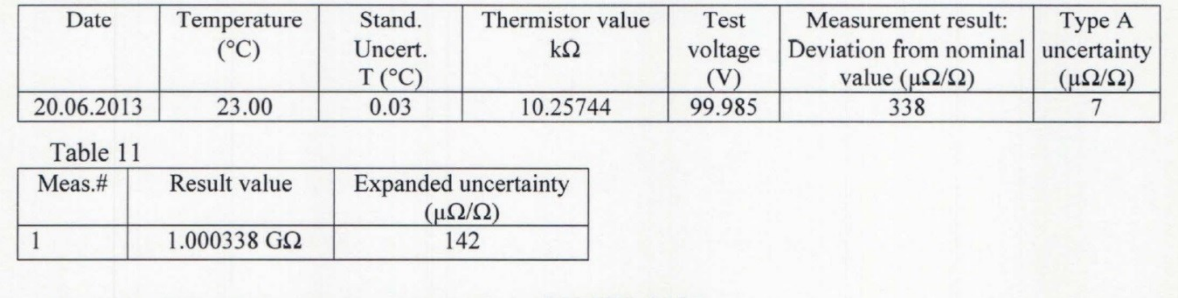
R_{Ref}	is the actual value of reference resistor
δ_{Ref}	is the relative error of the reference resistor from calibration
K_{Temper}	is the relative error due temperature of reference resistor
K_{DCC}	is the nominal ratio of the bridge
k_{br}	is specified 1 σ uncertainty of the bridge ratio for that range
δ_{Xt}	is temperature difference of the measured resistor

K_{Xt} is expected relative temperature coefficient of the measured resistor

1) HR9101



Quantity X_i	Estimate x_i	Relative standard uncertainty $u(x_i)$, 10^{-6}	Units	Probability distribution/method of evaluation (A, B)	Sensitivity coefficient c_i	Units $u_i(R_x)$, 10^{-6}	Relative uncertainty contribution
R_S	1.000578	67.83	μΩ/Ω	Normal / A	1		67.83
R_{XM}	1.000168	5.13	μΩ/Ω	Normal / A	1		5.13
R_{SM}	1.000408	4.75	μΩ/Ω	Normal / A	1		4.75
δR_{ST}	0	0.03	°C	rectangular / B	20	(μΩ/Ω)/°C	0.35
δR_{S6520}	0	25	μΩ/Ω	rectangular / B	1		14.45
δR_{X6520}	0	25	μΩ/Ω	rectangular / B	1		14.45
δR_{XT}	0	0.03	°C	rectangular / B	-28	(μΩ/Ω)/°C	-0.49
$R_{x\,1\,G}$	1.000338	combined uncertainty μΩ/Ω, k=1					71
		Effective degree of freedom					
		Expanded uncertainty (95% coverage factor) μΩ/Ω, k=2					142

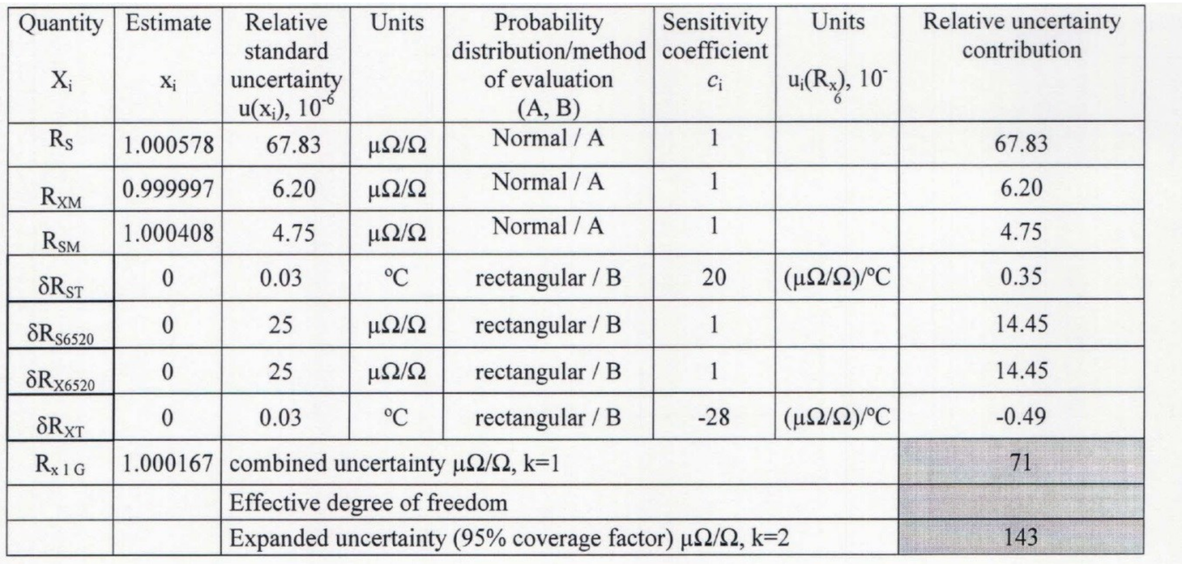


Date	Temperature (°C)	Stand. Uncert. T (°C)	Thermistor value kΩ	Test voltage (V)	Measurement result: Deviation from nominal value (μΩ/Ω)	Type A uncertainty (μΩ/Ω)
20.06.2013	23.00	0.03	10.25744	99.985	338	7

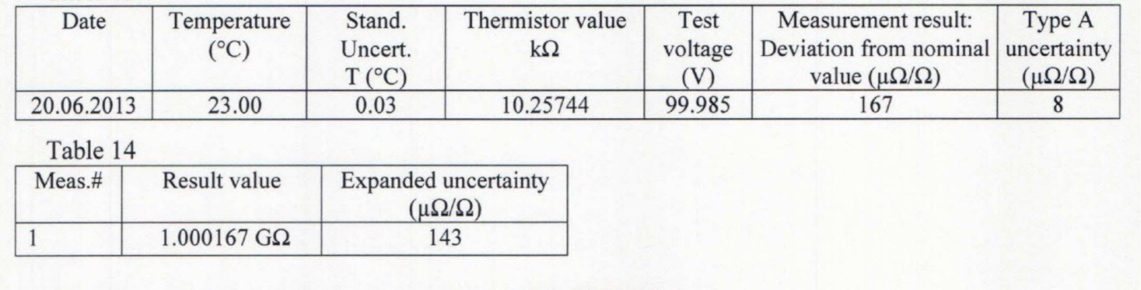
Table 11

Meas.#	Result value	Expanded uncertainty (μΩ/Ω)
1	1.000338 GΩ	142

2) HR9102



Quantity X_i	Estimate x_i	Relative standard uncertainty $u(x_i)$, 10^{-6}	Units	Probability distribution/method of evaluation (A, B)	Sensitivity coefficient c_i	Units $u_i(R_x)$, 10^{-6}	Relative uncertainty contribution
R_S	1.000578	67.83	μΩ/Ω	Normal / A	1		67.83
R_{XM}	0.999997	6.20	μΩ/Ω	Normal / A	1		6.20
R_{SM}	1.000408	4.75	μΩ/Ω	Normal / A	1		4.75
δR_{ST}	0	0.03	ºC	rectangular / B	20	(μΩ/Ω)/ºC	0.35
δR_{S6520}	0	25	μΩ/Ω	rectangular / B	1		14.45
δR_{X6520}	0	25	μΩ/Ω	rectangular / B	1		14.45
δR_{XT}	0	0.03	ºC	rectangular / B	-28	(μΩ/Ω)/ºC	-0.49
$R_{x\,1\,G}$	1.000167	combined uncertainty μΩ/Ω, k=1					71
		Effective degree of freedom					
		Expanded uncertainty (95% coverage factor) μΩ/Ω, k=2					143

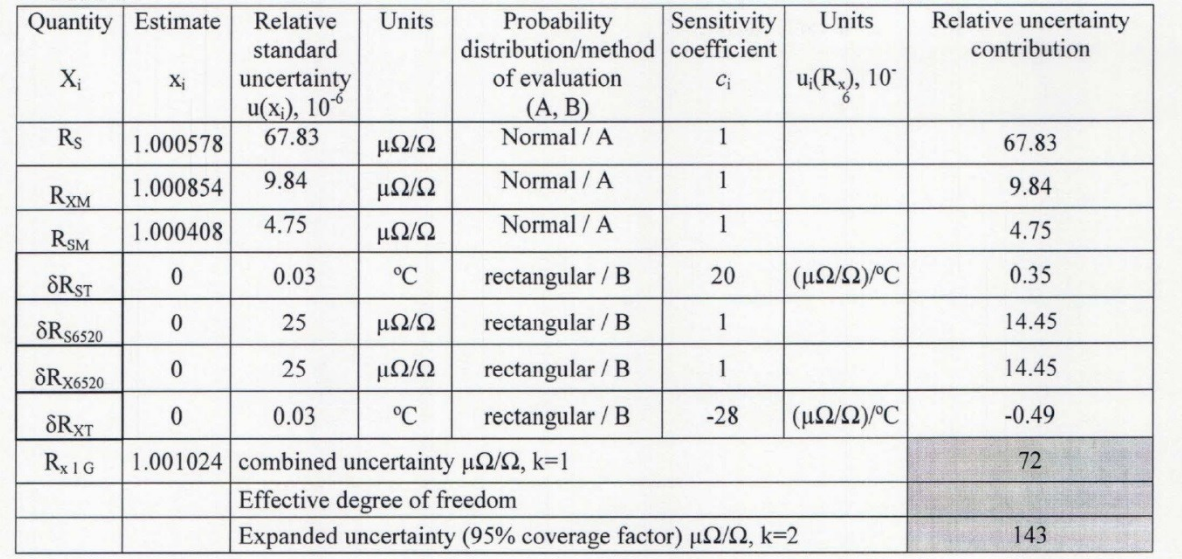


Date	Temperature (°C)	Stand. Uncert. T (°C)	Thermistor value kΩ	Test voltage (V)	Measurement result: Deviation from nominal value (μΩ/Ω)	Type A uncertainty (μΩ/Ω)
20.06.2013	23.00	0.03	10.25744	99.985	167	8

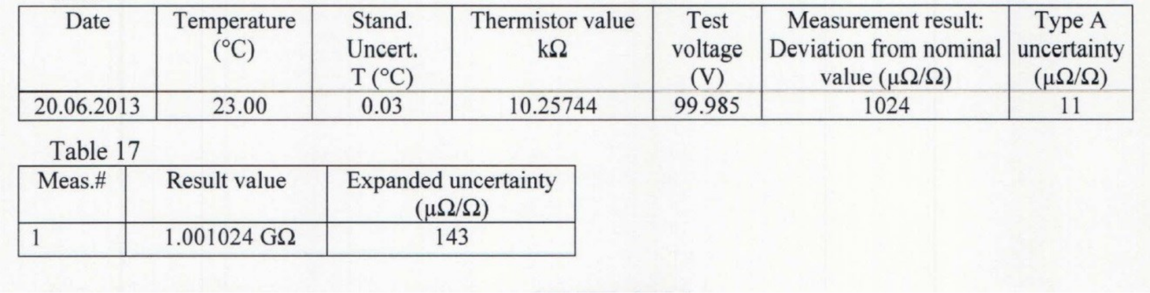
Table 14

Meas.#	Result value	Expanded uncertainty (μΩ/Ω)
1	1.000167 GΩ	143

3) HR9106



Quantity X_i	Estimate x_i	Relative standard uncertainty $u(x_i)$, 10^{-6}	Units	Probability distribution/method of evaluation (A, B)	Sensitivity coefficient c_i	Units $u_i(R_x)$, 10^{-6}	Relative uncertainty contribution
R_S	1.000578	67.83	μΩ/Ω	Normal / A	1		67.83
R_{XM}	1.000854	9.84	μΩ/Ω	Normal / A	1		9.84
R_{SM}	1.000408	4.75	μΩ/Ω	Normal / A	1		4.75
δR_{ST}	0	0.03	°C	rectangular / B	20	(μΩ/Ω)/°C	0.35
δR_{S6520}	0	25	μΩ/Ω	rectangular / B	1		14.45
δR_{X6520}	0	25	μΩ/Ω	rectangular / B	1		14.45
δR_{XT}	0	0.03	°C	rectangular / B	-28	(μΩ/Ω)/°C	-0.49
$R_{x\,1\,G}$	1.001024	combined uncertainty μΩ/Ω, k=1					72
		Effective degree of freedom					
		Expanded uncertainty (95% coverage factor) μΩ/Ω, k=2					143



Date	Temperature (°C)	Stand. Uncert. T (°C)	Thermistor value kΩ	Test voltage (V)	Measurement result: Deviation from nominal value (μΩ/Ω)	Type A uncertainty (μΩ/Ω)
20.06.2013	23.00	0.03	10.25744	99.985	1024	11

Table 17

Meas.#	Result value	Expanded uncertainty (μΩ/Ω)
1	1.001024 GΩ	143

13. Detailed uncertainty budget, MSL

Illustrative uncertainty budgets at each resistance level and each test voltage are presented in the tables below. Only significant contributions are listed. All contributing uncertainties have been assessed as Gaussian probability distributions.

Glossary of terms:

Repeatability - Standard deviation in multiple measurements of a single resistor.
Rlink - Link resistance, as described in Section 4.
Rs0 - Calibration value of Rs under defined conditions (T0, V0).
T0 - Reference temperature of Rs for temperature coefficient corrections.
Ta - Temperature of reference resistor (Rs). Uncertainty in **Ta** combines all type A uncertainties.
Tb - Zero-valued parameter whose uncertainty combines all type B uncertainties in temperature of Rs.
V0 - Reference voltage for voltage coefficient corrections.
V1m - Negative-polarity voltage applied to Rx during voltage reversal sequence.
V1p - First positive-polarity voltage applied to Rx during voltage reversal sequence.
V1pp - Second positive-polarity voltage applied to Rx during voltage reversal sequence.
V2m - Positive-polarity voltage applied to Rs during voltage reversal sequence.
V2p - First negative-polarity voltage applied to Rs during voltage reversal sequence.
V2pp - Second negative-polarity voltage applied to Rs during voltage reversal sequence.
V2ppp - Third negative-polarity voltage, plus small perturbation, applied to Rs during voltage reversal sequence.
Vdm - Null voltage measured when negative-polarity voltage is applied to Rx during voltage reversal sequence.
Vdp - Null voltage measured when first positive-polarity voltage is applied to Rx during voltage reversal sequence.
Vdpp - Null voltage measured when second positive-polarity voltage is applied to Rx during voltage reversal sequence.
Vdppp - Null voltage measured when third positive-polarity voltage is applied to Rx during voltage reversal sequence.
Vdrift1 - Voltage drift term used in calculation of the gain G.
Vdrift2 - Voltage drift term used in calculation of mean null voltage $\overline{V_d}$.
Vlin1 - Voltage linearity term used in calculation of the gain G.
Vlin2 - Voltage linearity term used in calculation of mean null voltage $\overline{V_d}$.
Alpha - First-order temperature coefficient of Rs.
Beta - Second-order temperature coefficient of Rs.

Gamma - Voltage coefficient of Rs.

Tmc - Temperature correction of meter used to measure the temperature of Rs.

Vrc - Voltage ratio correction of gain errors between volt meter ranges of DVM1 (see Figure 1).

1) HR9191 at 10 V

Quantity, X_i	Value, x_i	Standard Uncertainty $u(x_i)$	Effective Dof, ν_i	Sensitivity Coefficient, c_i	Uncertainty Contribution, $u(R_i)$	Method of Evaluation
Repeatability	0 Ω	1516	12.0	1 Ω/Ω	1516 Ω	A
Vdm	-1.075E-03 V	1.1E-05	9.0	1.00E+08 Ω/V	1107 Ω	A
Vdrift2	0 V	4.3E-06	8.0	-2.00E+08 Ω/V	859 Ω	B
Vdp	-1.182E-03 V	1.4E-05	9.0	-5.01E+07 Ω/V	711 Ω	A
Vdpp	-1.170E-03 V	1.1E-05	9.0	-4.98E+07 Ω/V	555 Ω	A
Rs0	1000123678 Ω	355	9.0	1.000 Ω/Ω	355 Ω	B
T0	20.438 °C	0.012	19.0	-6801 Ω/°C	82 Ω	A
Tb	0 °C	0.010	4.0	6826 Ω/°C	68 Ω	B
alpha	6.80E-06 Ω/(Ω.°C)	1.0E-07	8.0	3.14E+08 Ω.°C	31 Ω	B
Ta	20.680 °C	2.6E-03	3.0	6826 Ω/°C	19 Ω	A
Vdppp	1.326E-03 V	1.3E-05	9.0	-2.62E+05 Ω/V	7 Ω	A
V1m	-10.000046049 V	8.3E-08	9.0	-5.00E+07 Ω/V	4 Ω	A
V2m	9.999702293 V	7.3E-08	9.0	-5.00E+07 Ω/V	4 Ω	A
V1pp	10.000041471 V	8.9E-08	9.0	2.50E+07 Ω/V	2 Ω	A
Vdrift1	0 V	4.3E-06	8.0	-2.62E+05 Ω/V	2 Ω	B
V1p	10.000041896 V	8.4E-08	9.0	2.50E+07 Ω/V	2 Ω	A
V2pp	-9.999705261 V	8.0E-08	9.0	2.49E+07 Ω/V	2 Ω	A
V2p	-9.999705673 V	7.3E-08	9.0	2.50E+07 Ω/V	2 Ω	A
Vlin2	0 V	2.0E-09	8.0	-2.00E+08 Ω/V	0.4 Ω	B
Combined standard uncertainty (of all contributions):					2337 Ω	

2) HR9101 at 100 V

Quantity, X_i	Value, x_i	Standard Uncertainty $u(x_i)$	Effective Dof, ν_i	Sensitivity Coefficient, c_i	Uncertainty Contribution, $u(R_i)$	Method of Evaluation
Rs0	1000123678 Ω	355	9.0	1.000 Ω/Ω	355 Ω	B
Repeatability	0 Ω	342	12.0	1 Ω/Ω	342 Ω	A
Vdrift2	0 V	1.2E-05	8.0	-1.99E+07 Ω/V	245 Ω	B
Vdm	-5.25E-04 V	1.8E-05	9.0	9.97E+06 Ω/V	180 Ω	A
Vdp	-1.67E-03 V	1.8E-05	9.0	-4.98E+06 Ω/V	91 Ω	A
Vdpp	-1.67E-03 V	1.9E-05	9.0	-4.60E+06 Ω/V	87 Ω	A
T0	20.438 °C	0.012	19.0	-6801 Ω/°C	82 Ω	A
Tb	0 °C	0.010	4.0	6826 Ω/°C	68 Ω	B
alpha	6.80E-06 Ω/(Ω.°C)	1.0E-07	8.0	3.21E+08 Ω.°C	32 Ω	B
Ta	20.686 °C	2.0E-03	3.0	6826 Ω/°C	14 Ω	A
V2m	99.997125 V	2.4E-06	9.0	-5.00E+06 Ω/V	12 Ω	A
V1m	-100.000272 V	2.1E-06	9.0	-5.00E+06 Ω/V	10 Ω	A
Vdppp	3.35E-03 V	1.9E-05	9.0	-3.85E+05 Ω/V	7 Ω	A
V2p	-99.997108 V	2.8E-06	9.0	2.50E+06 Ω/V	7 Ω	A
V2pp	-99.997096 V	2.8E-06	9.0	2.31E+06 Ω/V	6 Ω	A
V1p	100.000289 V	2.5E-06	9.0	2.50E+06 Ω/V	6 Ω	A
V1pp	100.000276 V	2.3E-06	9.0	2.50E+06 Ω/V	6 Ω	A
Vdrift1	0 V	1.2E-05	8.0	-3.85E+05 Ω/V	5 Ω	B
V2ppp	-99.987092 V	2.8E-06	9.0	1.94E+05 Ω/V	0.6 Ω	A
Combined standard uncertainty (of all contributions):					625 Ω	

Appendix D. Technical Protocol

RMO Key Comparison APMP.EM-K2:

Comparison of Resistance Standards at 10 MΩ and 1 GΩ

2010 - 2011 Resistance Comparison between APMP Laboratories

Pilot Laboratory: Korea Research Institute of Standards and Science, 1 Doryong-Dong, Yuseong-Gu, Daejeon 305-340, Republic of Korea

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1. Introduction

The Mutual Recognition Arrangement (MRA) states that its technical basis is a set of results obtained in a course of time through key comparisons carried out by the Consultative Committees (CCs) of the CIPM, the BIPM and the Regional Metrology Organizations (RMOs). As part of this process, the CIPM Consultative Committee for Electricity and Magnetism (CCEM) carried out the key comparison CCEM K2 of resistance standards at 10 M and 1 G . This comparison was piloted by the National Institute of Standards and Technology and approved by the CCEM for full equivalence in January 2002 [1,2].

By means of this proposed comparison of resistance standards, the APMP Technical Committee for Electricity and Magnetism will provide a link between the National Metrology Institutes organized in APMP and the CCEM key comparison results.

The procedures outlined in this document should allow for a clear and unequivocal comparison of the measurement results. The protocol was prepared following the CCEM guidelines for planning, organizing, conducting and reporting key, supplementary and pilot comparisons.

2. Traveling standards

2.1 Description of the standards

Three NIST-designed wire-wound resistors as 10 M standards and three NIST-designed film resistors as 1 G standards are used as traveling standards:

The resistance elements are hermetically sealed in metal containers. The two resistor terminations of the standards are coaxial BPO connectors mounted on grooved PTFE circular plates on the top panel of the enclosures. The resistor containers are electrically isolated from the enclosures and electrically connected to the shield of one of the coaxial connectors. This allows the resistor container of the standard to be operated either in floating mode, a grounded mode, or driven at a guard potential. There are internal 10 k thermistor temperature sensors that may be measured with the provided LEMO to banana plug leads in case of large temperature effects.

2.2 Quantities to be measured at the time of each test

Resistance of the 10 M and 1 G standards at the following conditions:
test voltage: 10 V $\le \boldsymbol{V}_{\textbf{test}} \le$ 100 V;
ambient or air bath temperature: (23 ± 2.0) °C
ambient relative humidity: (45 ± 15) %.

The measurements may also be performed at an ambient temperature of (20 ± 2.0) °C. In such a case, the results will be corrected to 23 °C using their temperature coefficients.

2.3 Method of computation of the reference value

The APMP regional comparison reference value (RRV) will be evaluated following the principles described in [3]. A generalized version of the procedures described in [4, 5] will be applied to account for the drift of the traveling standards. The proposed principles of the analysis are:

-The results obtained by the pilot laboratory will be used to determine the drift behavior of the traveling standards;

-The results provided by the participants will be corrected to the nominal temperatures (23 °C) and the nominal test voltage (DC 100 V) using the sensitivity coefficients already determined;

-For the calculation of the RRV, the weighted mean over the laboratories will be used. If for a result, the uncertainty contribution due to the traceability to another NMI participating in the comparison amounts to a substantial part of the overall uncertainty value, the result will not be taken into account in the calculation of the RRV;

3. Organization

3.1 Coordinators and members of the support group

The pilot laboratory for the comparison is the Korea Research Institute of Standards and Science (KRISS).

Coordinator of the pilot laboratory:

Kwang Min Yu (KRISS), e-mail: kmyu@kriss.re.kr

Proposed support group:
Laurie Christian(MSL), New Zealand, e-mail: L.christian@irl.cri.nz
Yuri Semenov(VNIIM), Russia, e-mail: Y.P.Semenov@vniim.ru
Leigh Johnson(NMIA), Australia, e-mail: Heather.Johnson@measurement.gov.au

3.2 Participants

The proposed participating institutes are listed in the following table. The contact details are given in Annex A1.

Table 1: Participants

No	Country	Institute	Acronym
1	Australia	National Measurement Institute, Australia	NMIA$^{*)}$

2	China	National Institute of Metrology	NIM*)
3	Chinese Taipei	Center for Measurement Standards	CMS
4	Hong Kong, China	Standards and Calibration Laboratory	SCL
5	Japan	National Metrology Institute of Japan	NMIJ
6	Korea, The Republic of	Korea Research Institute of Standards and Science	KRISS*)
7	Malaysia	National Metrology Laboratory SIRIM	NML-SIRIM
8	New Zealand	Measurement Standards Laboratory	MSL*)
9	Russian Federation	D.I.Mendeleyev Institute for Metrology	VNIIM*)
10	Singapore	National Metrology Center, A*STAR	NMC
11	South Africa	National Metrology Institute of South Africa	NMISA*)
12	Thailand	National Institute of Metrology, Thailand	NIMT
13	Kazakhstan	Republic State Enterprise ″Kazakhstan Institute of Metrology″	KazInMetr

*) These laboratories participated in CCEM-K2

3.3 Time schedule

The circulation of the standards starts in June 2010 and is planned to end in August 2011. The detailed time schedule for the comparison is given in Annex A2.

A period of four weeks is allowed for the measurements in each laboratory, including the time necessary for transportation. Participants will be asked to conduct measurements for up to four weeks beginning as soon as possible after receiving the intercomparison shipment. Upon agreement between the coordinators and the participant laboratory, the measurements could be concluded in less than four weeks if the stability of the results is reasonably good and sufficient statistical data for the intercomparison has been obtained.

In agreeing with the proposed circulation time schedule, each participating laboratory confirms that it is capable of performing the measurements in the limited time period allocated in the time schedule. If, for some reasons, the measurement facility is not ready or custom clearance should take too much time, the laboratory is requested to contact immediately the coordinator in the pilot laboratory.

As soon as possible after the completion of the measurements, the transport package is to be transported to the next participant and the participant should indicate that all measurements have been completed.

If unavoidable delay occurs, the coordinators shall inform the participants and may revise the time schedule.

3.4 Transportation

Transportation is at each laboratory‘s own responsibility and cost. Due to the time constraints, a recognized customs broker and shipping agent guaranteeing an adequate delivery time, inclusive of the time for customs procedure, should be used. Customs procedures have to be examined in advance of the transport, and the customs brokers acting in behalf of each participant should coordinate the transport process with great care. *The shipping agent has to be informed that the transport case should not be exposed to extreme temperatures or mechanical shock*s.

Six resistors will be shipped in one container, attached to a larger pallet to ensure that the container remains upright. These traveling standards will consist of three 10 M standards (NIST design) and three sealed film-type 1 G standards (NIST design). The original shipping container and pallet should be re-used for each shipment. The container should be transported by the safest means possible with shipping charges prepaid, and by prior arrangement with the shipping and customs agents of the receiving laboratory. Any shipping or import charges due upon receipt will be paid by the receiving laboratory.

A carnet may be included with the transport package. If so, the carnet must be included with the other forwarding documents so that the shipping agent can obtain customs clearance. *In no case should the carnet be packed inside the case*. The carnet must be stored in the laboratory very carefully because a loss of the carnet may cause a serious delay in the comparison schedule.

On receipt of the transport package, the participant shall inform the pilot laboratory by sending the receipt form given in Annex A5 by fax or e-mail to the coordinator, and should receive a reply (confirmation) e-mail from the pilot lab.

Immediately after the completion of the measurements, the case is to be transported to the next participant. It is advisable to organize this transport beforehand. The pilot laboratory has to be informed through the form given in Annex 6 about the dispatch of the case. The next participant should be informed as well.

3.5 Unpacking, handling, packing

The transport case contains the following items:

Packing list

-Three 10 M standard resistors:

- NIST-designed, Serial Number HR7550, Size 250 mm x 80 mm x 80 mm, Weight 1259 g
- NIST-designed, Serial Number HR7551, Size 250 mm x 80 mm x 80 mm, Weight 1268 g
- NIST-designed, Serial Number HR7552, Size 250 mm x 80 mm x 80 mm, Weight 1261 g

-Three 1 G standard resistors:

- NIST-designed, Serial Number HR9101, Size 250 mm x 80 mm x 80 mm, Weight 1455 g
- NIST-designed, Serial Number HR9102, Size 250 mm x 80 mm x 80 mm, Weight 1519 g
- NIST-designed, Serial Number HR9106, Size 250 mm x 80 mm x 80 mm, Weight 1511 g

-12 BPO-BNC adapters

-6 cables, 2.75 m long for reading 10 k thermistors installed in the six standards

-2 ambient conditions recorders, CENTER 342 & HiGee. These recorders are used to monitor the temperature and humidity and to monitor any mechanical shock of the standards during transport.

-Instruction manual

On receipt of the case, unpack the standards carefully and check for any damage and the completeness of the audit pack according to the packing list. The ambient conditions recorders should not be removed from the transport case. If possible, the transport case should be stored in the laboratory. Any damage of the standards or missing item shall be reported on the receipt form in Annex A5, to be sent to the coordinator.

Before sending the case out, check the packing list and ensure everything is enclosed. The standards should be packed in the original transport case as illustrated in the instruction manual.

Ensure that the ATA carnet (where applicable) is packed outside the case for easy access by customs.

3.6 Failure of the traveling standard

Should one of the standards be damaged during the comparison, the pilot laboratory has to be informed immediately.

3.7 Financial aspects, insurance

Each participating laboratory covers the costs of the measurements, transportation and customs duties as well as for any damage that may occur within its country. The overall costs for the organization of the comparison are covered by the pilot laboratory. The pilot laboratory has no insurance for any loss or damage of the standards during transportation.

4. Measurement instructions

Please refer to the information in separate “instruction Manual” concerning TCR, VCR, stability and the structure of the traveling standards.

4.1 Test before measurements

No initial tests are required. However, the ambient laboratory conditions of temperature and humidity should be maintained within the range given in section 2.2 during the measurements and for periods of at least eight hours before measurements.

4.2 Measurement performance

Pre-conditioning: Air-type standards should be conditioned to air-bath or ambient laboratory conditions, regulated at the chosen working temperature for at least 24 hours. Keep the specified voltage and do not immerse the standards in the oil.

Measurand: The resistance value of the traveling standards should be measured at DC, expressed in terms of the conventional value of the von Klitzing constant R_{K-90} =25812.807 or in terms of the SI ohm. The uncertainty budget of the measurement should be developed using the template provided in Annex A3.

Test voltage: 10 V $\leq V_{test} \leq$ 100 V

Temperature: (23 ± 2.0) °C preferred, or (20 ± 2.0) °C

Humidity: (45 ± 15) %.

Measurements: The measurements should be repeated several times during the whole period allocated to the participating laboratory.

4.3 Method of measurement

The measurement method is not specified. It is assumed that every participant uses its best normal measurement process. The method and the traceability scheme have to be described in the measurement report (see below). The choice of using the ground/guard configuration is left to the participants. Section 2.1 describes the internal configuration of the ground/guard terminals in the resistance standards.

5. Uncertainty of measurement

5.1 Main uncertainty components

A detailed uncertainty budget in accordance with the ISO Guide to the Expression of Uncertainty in Measurement shall be reported for one resistor of each nominal value.

To have a comparable uncertainty evaluation, principal uncertainty contributions are listed as below. Depending on the measuring methods this list may be changed:

1) Scaling procedure and/or traceability path (total at time of reference standard calibration)

2) Reference standard(s) (total due to drift, TCR, PCR, VCR)

3) Measuring apparatus (ratio, resolution, stability, gain and offset effects, configuration)

4) Leakage effects

5) Temperature variation effects

6) Typical standard deviation of a measurement set, defined as the median standard deviation value among the data sets used to calculate the final reported value.

5.2 Format of the uncertainty budget

A proposed format for the uncertainty budget is given in Annex A3.

6. Measurement report

Each participant is asked to submit a final printed and signed report by mail within 6 weeks after completing the measurements. A copy of the report may also be sent by e-mail. In the case of differences between electronic and paper versions of the report, the signed paper form is considered to be the valid version. The report should contain at least the following (see also Appendix A4):

-Description of the measuring set-up used for each level, including the ground/guard configuration;

-Traceability scheme. If the traceability to the SI is provided by another NMI, the name of the NMI should be stated (needed to identify possible sources of correlation);

-Description of the measurement procedure used for each level;

-The test voltage used for the measurements;
-The ambient conditions of the measurement: the mean temperature and humidity;
-The measurement results: Mean resistance value for every standard and the corresponding mean date of measurement; individual results in the form described in Annex A4;
-A complete uncertainty budget in accordance with the principles of the ISO Guide to the Expression of Uncertainty in Measurement, including degrees of freedom for every component and calculation of the coverage factor. Such an analysis is a prerequisite to be considered in the calculation of the comparison reference value. It is also an essential part of the final report which will appear in the BIPM Key Comparison Database.

The pilot laboratory will inform a participating laboratory if there is a substantial deviation between the results of the laboratory and the preliminary reference values. No other information will be communicated before the completion of the circulation.

7. Report of the comparison

The pilot laboratory will prepare the draft A report within three months after completion of the circulation. This report will be prepared with the aid of the support group and will be sent to all participants for comments.

Included in the final report will be calculated values of the degree of equivalence with the RRV for each participant at each resistance level where results are submitted. The degree of equivalence between the participants will be presented in table form.

References

[1] R.F. Dziuba and D. G. Jarett, Final report on key comparison CCEM-K2 of resistance standards at 10 M and 1 G , Metrologia, 39, Tech. Suppl., 01001, 2002.

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[3] M. G. Cox, The evaluation of key comparison data, Metrologia 39, pp. 589-95, 2002.

[4] N. F. Zhang, H.-K. Liu, N. Sedransk and W. E. Straderman, Statistical analysis of key comparisons with linear trends, Metrologia, 41, pp. 231-7, 2004.

[5] Zhang, N. F., Strawderman, W. E., Liu, Hung-kung, and Sedransk, N., Statistical analysis for multiple artifact problem in key comparisons with linear trends, to appear in Metrologia, 42 (2005)

[6] F. Delahaye and T. J. Witt, Linking the results of key comparison CCEM-K4 with the 10 pF results of EUROMET.EM-K4, Metrologia 39, Tech. Suppl. 01005, 2002.

[7] CCEM Guidelines for Planning, Organizing, Conducting and Reporting Key, Attached, Supplementary and Pilot Comparisons, Annex 5, The BIPM key comparison database, August 2002.

[8] ISO/IEC Guide 98-3:2008, Uncertainty of measurement-Part 3: Guide to the expression of uncertainty in measurement(GUM:1995), 2008

A1. Detailed list of participants

Institute (Acronym)	Contact person	Address	Telephone, Telefax	e-mail

National Measurement Institute(NMIA), Australia	Leigh Johnson	National Measurement Institute, Australia PO Box 264 Lindfield NSW 2070 Australia	Phone: +61 2 8467 3524 Fax: +61 2 8467 3752	Heather.Johnson@measurement.gov.au
National Institute of Metrology(NIM), China	Liangbo	Electricity and Quantum Div., National Institute of Metrology, No. 18, Bei San Huan Dong Rd., Beijing, 100013 China	Phone: +86 10 8425 1573 Fax: +86 10 6421 8629	liangbo@nim.ac.cn
Center for Measurement Standards(CMS), Chinese Taipei	Jimmy Chun-Ming Hsu	Electric & Electromagnetic Measurement Lab. CMS/ITRI E100, Bldg. 16, No. 321 Kuang Fu Road, Section 2, Hsinchu, Taiwan 30042, R.O.C.	Phone: +886 3 5743726 Fax: +886 3 5726445	jimmychsu@itri.org.tw
Standards and Calibration Laboratory(SCL), Hong Kong, China	Steven Yang	7 Gloucester Road 36/F Immigration Tower Wanchai, Hong Kong	Phone: +852 2829 4832 Fax: +852 2824 1302	Steven.yang@itc.gov.hk
National Metrology Institute of Japan(NMIJ), Japan	Takehiko Oe	National Metrology Institute of Japan, AIST Tsukuba Central 3-1, 1-1-1 Umezono, Tsukuba Ibaraki 305-8563, JAPAN	Phone: +81 29 861 4244 Fax: +81 29 861 3469	t.oe@aist.go.jp CC: nobuhisa.kaneko@aist.go.jp
Korea Research Institute of Standards and Science(KRISS), Korea, The republic of	Kwang Min Yu	Electromagnetic Metrology Center, Div. of Physical Metrology, Korea Research Institute of Standards and Science, 1 Doryong-Dong, Yuseong-Gu, Daejeon 305-340, Rep. of Korea	Phone: +82 42 868 5153 Fax: +82 42 868 5018	kmyu@kriss.re.kr
National Metrology Laboratory SIRIM (NML-SIRIM), Malaysia	NIRUL IRWANI BINTI ISHAK	Lot PT 4803, Bandar Baru, Salak Tinggi, 43900 Sepang, Selangor Darul Ehsan, Malaysia	Phone: +60 3 8778 1664 Fax: +60 3 8778 1661	nirul@sirim.my
Measurement Standards Laboratory(MSL), New Zealand	Laurie Christian Murray Early	Industrial Research Ltd, PO Box 31310, Lower Hutt 5040, New Zealand	Phone: +64 4 9313110 Fax: +64 4 9313194	L.Christian@irl.cri.nz Murray.Early@callaghaninnovation.govt.nz
D.I.Mendeleyev Institute for Metrology(VNIIM), Russian Federation	Yuri Semenov	19 Moskovsky pr., St. Petersburg 198005 Russia	Tel/Fax: 7 812 323 96 21	Y.P.Semenov@vniim.ru

National Metrology Center(NMC)-A*STAR, Singapore	Chua Sze Wey	1 Science Park Drive Singapore 118221	Phone: +65 6279 1909 Fax: +65 6279 1995	chua_sze_wey @nmc.a-star.edu.sg
National Metrology Institute of South Africa(NMISA), South Africa	Alexander Matlejoane	PO Box 395, Pretoria 0001, South Africa	Phone: +27 12 841 4343 Fax: +27 12 841 2131	amatlejoane@nmisa.org
National Institute of Metrology(NIMT), Thailand	Chalit Kumtawee, (Mr. Chaiwat Jessadajin, Ms. Natenapit Chookunhom)	Department of Electrical Metrology, Ministry of Science and Technology, 3/4-5 Moo 3, Klong 5, Klong Luang, Pathumthani 12120 Thailand	Phone: +66 2 577 5100 Fax: +66 2 577 3658	chalit@nimt.or.th
RSE(Republican State Enterprise) “KazInMetr”(Kazakhstan an Institute of Metrology), The Rebublic of Kazakhstan	Danat Termirkhanov	010000, Astana city, Orynbor str., Building No 11, “Standards Center”	Phone: +7 7172 793252 Fax: +7 7172 793299	dako.87@mail.ru

A2. Schedule of the measurements

Institute	**Country**	**Start date**	**Time for measurements and transport**
Pilot (KRISS)	Korea	June 2010	4 weeks
CMS	Taiwan	July 2010	4 weeks

NIMT	Thailand	August 2010	4 weeks
NML-SIRIM	Malaysia	September 2010	4 weeks
NMC	Singapore	October 2010	4 weeks
Pilot (KRISS)	Korea	November 2010	4 weeks
NMIJ	Japan	December 2010	4 weeks
MSL	New Zealand	January 2011	4 weeks
NMIA	Australia	February 2011	4 weeks
Pilot (KRISS)	Korea	March 2011	4 weeks
NIM	China	April 2011	4 weeks
VNIIM	Russian Federation	May 2011	4 weeks
SCL	Hong Kong	June 2011	4 weeks
NMISA	South Africa	July 2011	4 weeks
Pilot (KRISS)	Korea	August 2011	4 weeks
KazInMetr	Kazakhstan	Participated later	4 weeks

A3. Typical scheme for an uncertainty budget

The detailed uncertainty has to be provided in this form for one standard of each nominal value with including main uncertainty components of the Section 5.1.

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution/method of evaluation(A, B)	Sensitivity coefficient c_i	Uncertainty contribution $u(R_i)$	Degree of freedom ν_i

R_x		▨	▨	▨	▨	▨
Combined standard uncertainty and effective degrees of freedom:						
Expanded uncertainty (95% coverage factor):						▨

A4. Layout of the final measurement report

1. Measurand (nominal value, manufacturer, and serial number of artifact)
2. Measurement set-up and traceability scheme
3. Measurement procedure
4. Results (as required for each range in section 2.2)

a. Mean date of measurement

b. Test voltage

c. Ambient conditions (Temperature: mean value, uncertainty and range of variation; Humidity: mean value, uncertainty and range of variation)

d. Mean resistance value, combined standard uncertainty and expanded uncertainty

5. Detailed uncertainty budget
6. Signature and title of laboratory representative

A5. Confirmation note of receipt

To: kmyu@kriss.re.kr

From: (participating laboratory):

....

Re: **APMP.EM-K2 - Receipt of traveling standards**

We confirm having received the traveling standards of the APMP.EM-K2 key comparison on ….(date)….

After visual inspection:

No damage of the transport package and the traveling standards has been noticed (or) The following damage(s) must be reported (if possible add a picture):

....

....

....

Date: .... Name............................

A6. Confirmation note of dispatch

To: kmyu@kriss.re.kr

From: (participating laboratory):

....

Re: **APMP.EM-K2 - Dispatch of traveling standards**

We have informed the next participant on …(date)… that we will send the traveling standards to them.

We confirm having sent the traveling standards of the APMP.EM-K2 key comparison
on .... to the next participant.

Additional informations:

....
....
....

Date: ....   Signature ....

A7. Linkage between CCEM-K2 and APMP.EM-K2

To build a linkage between a key comparison and a RMO comparison, the normal linking procedure that determine a correction value from the NMIs which participated in both of the CCEM KC and the RMO comparison[6,7] will be used. Degrees of equivalence between any two labs, each of which participated in either or both comparisons, and the corresponding uncertainties will be calculated according to the Annex 5 of CCEM Guidelines.