FINAL REPORT

CCEM-K2.2012 Key Comparison of Resistance Standards at 10 MΩ and 1 GΩ

Carlos Sanchez and Kai Wendler

National Research Council Canada

1200 Montreal Road, Ottawa K1A 0R6, Ontario

Canada

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Abstract. An international comparison of dc resistance at 10 MΩ and 1 GΩ was carried out under the framework of the Mutual Recognition Arrangement (MRA) of the *Comité Consultatif d'Électricité et Magnétisme* (CCEM). The comparison was piloted by the National Research Council of Canada (NRC) with the participation of 12 National Metrology Institutes (NMIs). Two 10 MΩ resistors (Measurements International, model 9331) and two 1 GΩ resistors (Measurements International, model 9331S) were used as travelling standards. Although the uncertainty at 10 MΩ was limited by the stability of the travelling standards, the comparison achieved a reduction in the uncertainties of the degrees of equivalence relative to the 2002 CCEM-K2 comparison, especially at 1 GΩ where the improvement was quite significant.

1. Introduction

The MRA states that its technical basis is a set of results obtained in the course of time through key comparisons carried out by the Consultative Committees (CCs) of the *Comité International des Poids et Mesures* (CIPM), the *Bureau International des Poids et Mesures* (BIPM) and the Regional Metrology Organizations (RMOs). As part of this process, the Consultative Committee on 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].

In subsequent years SIM [2], EURAMET [3] and APMP have each carried out a similar comparison, and the published results are linked in the KCDB of the BIPM. Since the original CCEM-K2 of 2002 many laboratories have enhanced their measurement capabilities in the ranges in question. At the meeting in 2009 the CCEM decided to repeat the CCEM-K2 comparison to improve the precision of the link between RMOs. The National Research Council of Canada agreed to pilot this comparison.

2. Travelling Standards

The 10 MΩ standards are manufactured by Measurements International Ltd. (CA), model 9331. The resistance elements are hermetically sealed in metal containers. The four resistor terminations of the standards are tellurium copper binding posts. A separate ground terminal is included for screening.

The 1 GΩ standards are manufactured by Measurements International Ltd. (CA), model 9331S. The resistance elements are housed in a double shielded enclosure. The two resistor terminations of the standards are BPO coaxial connectors mounted directly on the outer enclosure. The inner enclosure containing the resistive element is isolated from the external enclosure. It is connected to the guard terminal and may be operated either in floating mode, a grounded mode, or driven at a guard potential.

3. Participants

Since the principal aim of this comparison was to provide a link between RMOs at the smallest possible level of uncertainty, the participating laboratories were chosen only from those maintaining an independent realization of impedance or resistance units with a small uncertainty (e.g. calculable capacitor, quantized Hall resistance/cryogenic current comparator). The participating institutes are listed in chronological order in table 1.

Table 1. List of participants and measurement dates

Acronym	National Metrology Institute	Mean date of measurements
NRC	National Research Council, Canada (pilot)	2012-08-25
NIST	National Institute for Standards and Technology, U.S.A.	2012-10-03
CENAM	Centro Nacional de Metrologia, Mexico	2012-11-12
INTI	Instituto Nacional de Tecnologia Industrial, Argentina	2013-03-05
NRC	National Research Council, Canada (pilot)	2013-08-02
NRC	National Research Council, Canada (pilot)	2014-02-05
PTB	Physikalisch-Technische Bundesanstalt, Germany	2014-03-12
NPL	National Physical Laboratory, United Kingdom	2014-04-12
METAS	Federal Institute of Metrology METAS	2014-05-25
VSL	VSL Dutch Metrology Institute, Netherlands	2014-06-26
NRC	National Research Council, Canada (pilot)	2014-10-27
NMISA	National Metrology Institute of South Africa, South Africa	2014-12-04
NRC	National Research Council, Canada (pilot)	2015-10-01
NIM	National Institute of Metrology, China	2015-12-23
VNIIM	D.I. Mendeleyev Research Institute for Metrology, Russian Federation	2016-03-28
KRISS	Korea Research Institute of Standards and Science, The Republic of Korea	2016-09-02
NRC	National Research Council, Canada (pilot)	2016-12-08

4. Measurement procedure

The nominal conditions specified for the comparison were a temperature of 23 °C and a measurement voltage of 10 V for the 10 MΩ resistors and 100 V for the 1 GΩ resistors. Whenever the actual measurement conditions reported by the participants departed from the nominal conditions, corrections were applied using the temperature, voltage and pressure coefficients determined by the pilot laboratory.

The participants were asked to report the following:

- Description of the measuring set-up including the ground/guard configuration.
- Traceability scheme.
- Brief description of the measurement procedure.
- The measurement results: mean resistance value, with uncertainty, for each standard and the corresponding mean date of measurement.
- The test voltages chosen for the measurements.
- The ambient conditions of the measurement: the temperature and humidity with limits of variation.
- A complete uncertainty budget in accordance with the principles of the ISO Guide to the Expression of Uncertainty in Measurement.

Except for NMISA, which had traceability to 1 Ω resistors calibrated at BIPM, all the participants obtained traceability through their Quantum Hall Resistance standard (QHR). The protocol did not specify the measurement method. It was assumed that the participants would use the normal measurement procedures. The participants reported using the following measurement systems:

- Cryogenic Current Comparator (CCC): NRC (QHR – 100 kΩ), NIST (QHR – 10 MΩ), CENAM (10 kΩ – 100 MΩ), INTI (1 MΩ – 10 MΩ), NPL (QHR – 1 GΩ), METAS (QHR – 1 MΩ), NIM (QHR – 10 kΩ) and KRISS (QHR – 1 MΩ).
- Hamon standards: NIST, CENAM, METAS, VSL, NIM and VNIIM.
- Binary divider resistance bridge: NRC, CENAM, PTB, METAS, VSL, NMISA and NIM.
- Dual source bridge: NRC, NIST, CENAM, METAS, VSL, NIM and KRISS.
- Potentiometric method: INTI.
- Wheatstone bridge: VNIIM.

The comparison had been planned to take place within a time frame of a little more than one year, between September 2012 and December 2013. This required a measurement time of five weeks for each participant, including transportation time. The comparison ended up being delayed significantly due to a number of problems:

- The first loop proceeded with a few minor delays related to shipping and customs. However, upon return of the package from the SIM loop the 1 GΩ resistors seemed to be unstable, possibly due to mishandling during shipping, and it was decided to allow a period of several months for them to stabilize before continuing with the comparison.

Fortunately there is no evidence of a change in the value of the resistors once they reached stability.

- The second loop of the comparison was carried out without any problems and was completed in July, 2014. The third loop started in November 2014 with the shipment of the resistors to NMISA. This loop included the participation of KRISS, Korea but their technical expert was on extended leave and they were unable to measure the resistors for at least one year. At the informal meeting of the CCEM Working group on DC and Low Frequency Quantities at the 2014 Conference on Precision Electromagnetic Measurements (CPEM) in Rio de Janeiro, Brazil, it was decided to add another NMI from the *Asia Pacific Metrology Programme* (APMP) to replace KRISS. The Measurement Standards Laboratory (MSL) of New Zealand kindly agreed to participate in the comparison. The traveling standards were scheduled to be sent to VNIIM after being measured at NMISA but the documentation and the Carnet were not adequate to clear Russian customs. After a couple of months, in February 2015, the problem with the documentation could not be resolved and it was decided to modify the schedule and send the resistors to MSL. This was during the summer vacations in New Zealand and it was understood that they wouldn’t be able to measure the resistors right away but they agreed to receive the package then because no other NMI was available at that time to continue with the comparison.
- An additional delay occurred at MSL due to some difficulties while doing the measurements. The resistors were received back at NRC at the end of June, 2015.
- The last loop of the comparison proceeded very slowly. The standards were sent to NIM at the end of October, 2015, then to VNIIM in February, 2016 and finally to KRISS at the end of June, 2016. The eventual re-inclusion of KRISS meant that the MSL participation in the comparison was not deemed necessary and, due to a heavy workload, they decided not to report their results.
- The effect of atmospheric pressure was not anticipated to affect the comparison. However, tests made after all the legs of the comparison were completed indicated that the pressure coefficient of the resistors was significant and it was decided to make careful measurements to evaluate this effect and correct for it. The pressure chamber needed for this had a leak and it took a few months for the repair and the measurements to be completed.
- Finally, it is acknowledged that there were periods of time throughout the comparison when the pilot laboratory was overwhelmed with a heavy workload and this also contributed to the slow completion of the measurements and the analysis.

5. Measurement results at 10 MΩ.

The results reported by the participants were corrected to nominal conditions (T=23 °C, V=10 V) using the parameters shown in table 2. These parameters were determined by the pilot laboratory in the temperature range between 19 °C and 27 °C and for voltages between 10 V and 100 V. For both resistors, a linear model with a simple temperature coefficient α_T and a voltage coefficient α_V was deemed adequate.

Additionally, the pressure coefficient α_P was found to be significant for laboratories at high altitude and the data were corrected to the nominal atmospheric pressure of the pilot laboratory (101.4 kPa). The atmospheric pressure was either reported by the participants or it was obtained from the data logger which was included with the travelling standards. The reported and corrected data are summarized in tables 3 (S/N 1100405) and 4 (S/N 1101333).

Table 2. Temperature, voltage and pressure coefficients for the 10 MΩ resistors. The reported uncertainties are standard uncertainties.

Resistor	α_T (ppm / °C)	u (α_T) (ppm / °C)	α_V (ppm / V)	u (α_V) (ppm / V)	α_P (ppm/kPa)	u (α_P) (ppm/kPa)
1100405	0.01	0.02	-0.0023	0.0018	-0.041	0.009
1101333	0.73	0.02	-0.0036	0.0017	-0.044	0.011

Table 3. Reported results, measurement conditions and corrected values for resistor 1100405. $X_{05} = \Delta R/R$ is the relative resistance deviation from the nominal value expressed in parts in 10^6 (ppm). Uncertainties have a coverage factor k = 2.

	Reported data								Corrected data	
Lab	Date	X_{05} (ppm)	u_{TOTAL} (ppm)	U_{A} (ppm)	T (°C)	$U(T)$ (°C)	V (V)	P (kPa)	X_{05} (ppm)	U_{TOTAL} (ppm)
NRC	16-Feb-12	-0.12	0.58	0.31	23.05	0.06	10	101.4	-0.12	0.58
NRC	10-May-12	-0.29	0.68	0.15	22.95	0.06	10	101.4	-0.29	0.68
NRC	26-Aug-12	0.06	0.49	0.13	23.02	0.06	10	101.4	0.06	0.49
NIST	3-Oct-12	0.83	0.50	0.22	23.00	0.10	10	99.96	0.77	0.50
CENAM	25-Nov-12	2.50	0.82	0.36	23.00	0.02	9.1	81.08	1.66	0.84
INTI	4-Mar-13	3.00	0.60	0.16	23.00	0.10	9.954	101.4	3.00	0.60
NRC	2-Aug-13	3.32	0.71	0.14	22.88	0.08	10	101.4	3.32	0.71
NRC	5-Feb-14	3.94	0.42	0.11	22.92	0.06	10	101.4	3.94	0.42
PTB	12-Mar-14	3.40	1.00	0.58	23.02	0.10	10	101.38	3.40	1.00
NPL	11-Apr-14	4.06	0.15	0.02	23.01	0.20	10	101.73	4.08	0.15
METAS	25-May-14	4.32	0.48	0.1	23.00	0.10	10	95.26	4.07	0.48
VSL	29-Jun-14	6.35	0.42	0.08	23.00	0.02	9.09	101.70	6.36	0.42
NRC	25-Oct-14	5.73	0.50	0.13	22.98	0.08	10	101.4	5.73	0.50
NMISA	4-Dec-14	4.00	5.00	0.66	22.90	0.60	91	86.62	3.58	5.00
NRC	9-Oct-15	10.69	0.51	0.14	22.99	0.12	10	101.4	10.69	0.51
NIM	23-Dec-15	10.90	1.50	0.09	23.00	0.01	10	102.0	10.92	1.50
VNIIM	28-Mar-16	11.40	1.56	1.16	19.98	0.02	61.6	100.61	11.52	1.56
KRISS	2-Sep-16	9.00	0.58	0.26	23.00	0.04	50	100.2	9.04	0.58
NRC	29-Nov-16	13.03	0.46	0.23	23.03	0.06	10	101.4	13.03	0.46

Table 4. Reported results, measurement conditions and corrected values for resistor 1101333. $X_{33} = \Delta R/R$ is the relative resistance deviation from the nominal value expressed in parts in 10^6 (ppm). Uncertainties have a coverage factor k = 2.

	Reported data								Corrected data	
Lab	Date	X_{33} (ppm)	U_{TOTAL} (ppm)	U_{A} (ppm)	T (°C)	$u(T)$ (°C)	V (V)	P (kPa)	X_{33} (ppm)	U_{TOTAL} (ppm)
NRC	22-Feb-12	1.04	0.46	0.08	22.97	0.06	10	101.4	1.06	0.46
NRC	8-May-12	1.08	0.59	0.24	22.93	0.06	10	101.4	1.13	0.59
NRC	25-Aug-12	2.33	0.64	0.10	23.02	0.06	10	101.4	2.32	0.64
NIST	3-Oct-12	2.79	0.50	0.22	23.00	0.1	10	99.96	2.73	0.51
CENAM	25-Nov-12	4.94	0.80	0.28	23.00	0.028	9.1	81.08	4.05	0.83
INTI	5-Mar-13	5.70	0.60	0.16	23.00	0.1	9.954	101.4	5.70	0.60
NRC	2-Aug-13	5.56	0.73	0.21	22.90	0.06	10	101.4	5.63	0.73
NRC	5-Feb-14	5.61	0.54	0.38	22.92	0.06	10	101.4	5.67	0.54
PTB	12-Mar-14	5.40	1.00	0.58	23.02	0.1	10	101.38	5.38	1.00
NPL	12-Apr-14	6.19	0.16	0.03	22.99	0.2	10	101.73	6.21	0.21
METAS	25-May-14	6.52	0.48	0.10	23.00	0.1	10	95.26	6.25	0.49
VSL	26-Jun-14	8.67	0.42	0.08	23.00	0.018	9.09	101.70	8.68	0.42
NRC	27-Oct-14	7.94	0.48	0.06	22.94	0.06	10	101.4	7.98	0.48
NMISA	4-Dec-14	7.00	5.00	1.09	22.90	0.6	91	86.62	6.72	5.03
NRC	1-Oct-15	13.54	0.49	0.08	22.99	0.06	10	101.4	13.55	0.49
NIM	23-Dec-15	13.20	1.50	0.08	23.00	0.012	10	102.0	13.22	1.50
VNIIM	28-Mar-16	11.70	1.68	1.16	19.98	0.02	61.6	100.61	14.05	1.69
KRISS	2-Sep-16	12.40	0.58	0.26	23.00	0.04	50	100.2	12.49	0.60
NRC	8-Dec-16	15.41	0.48	0.08	22.98	0.06	10	101.4	15.42	0.48

U_{A} and U_{B} stand for type A and type B uncertainty components. Figures 1 and 2 show the corrected measurements for resistors 1100405 and 1101333 respectively. The plots also show a linear fit to the pilot laboratory data and the regression parameters are summarized in table 5. It seems clear that the measurements show significant departures with respect to a linear trend over the full time of the comparison but it's difficult to know if or when the resistors suffered abrupt changes over relatively short periods of time. After considering several types of analysis, it was decided to analyze the data in three separate segments, as shown in figure 3. This approach is thought to minimize the impact of the instability of the resistors and yield the best estimate of the differences between laboratories.

First the measurements from the two travelling standards were combined to obtain a single result X_{i} for each NMI. This was done by taking the weighted mean:

$$X_i = v_{05}\, X_{05} + v_{33}\, X_{33}\,, \tag{1}$$

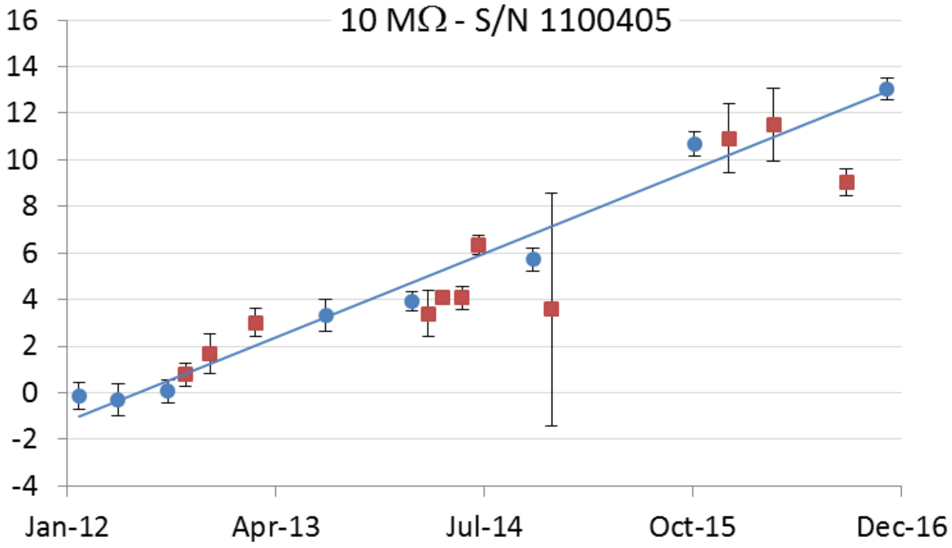

Figure 1. Corrected measurements of the 10 MΩ resistor, S/N 1100405. The pilot laboratory measurements are shown in blue circles, all other measurements shown as red squares. The uncertainty bars are the k=2 uncertainties reported by the laboratories. The vertical scale is the deviation from the nominal value, expressed in ppm.

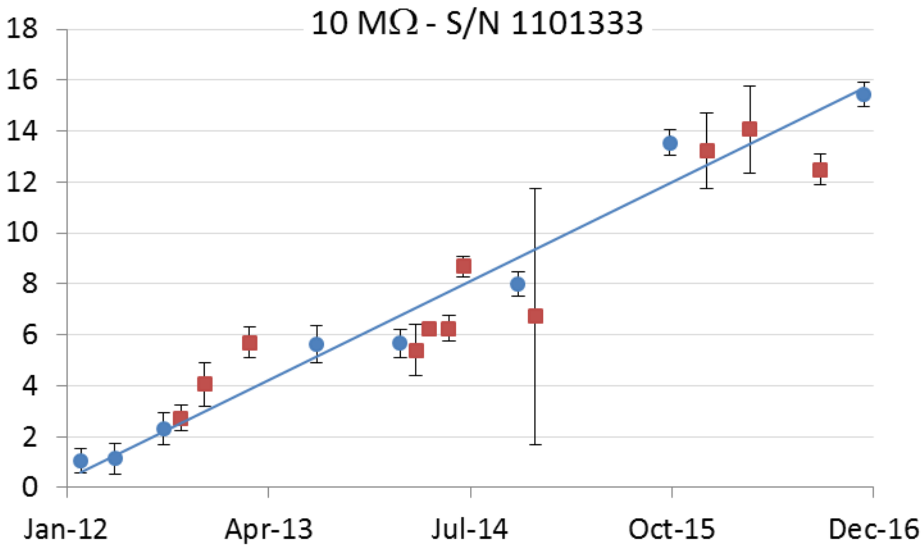

Figure 2. Corrected measurements of the 10 MΩ resistor, S/N 1101333. The pilot laboratory measurements are shown in blue circles, all other measurements shown as red squares. The uncertainty bars are the k=2 uncertainties reported by the laboratories. The vertical scale is the deviation from the nominal value, expressed in ppm.

Table 5. Fit parameters for the 10 MΩ resistors.

Resistor	σ (ppm)	Slope (ppm/year)	Correlation coefficient
1100405	0.82	2.91	0.87
1101333	0.95	3.15	
Combined	0.85	3.02	

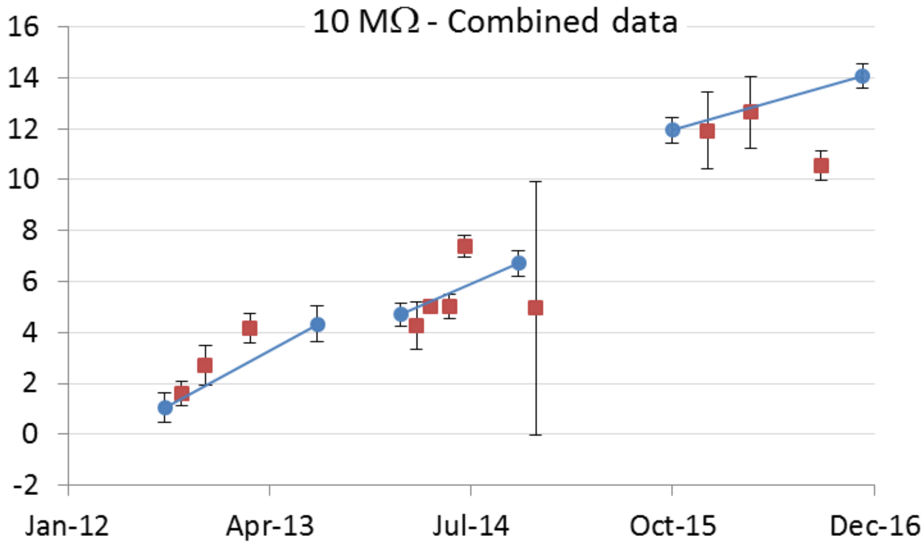

Figure 3. Combined measurement results calculated from the weighted mean of the corrected values of the two travelling standards. Error bars are the k=2 uncertainties.

with the weights v_{05} and v_{33} given by:

$$v_{05} = \frac{\frac{1}{\sigma_{05}^2}}{\frac{1}{\sigma_{05}^2} + \frac{1}{\sigma_{33}^2}} = 0.56 \tag{2}$$

$$v_{33} = \frac{\frac{1}{\sigma_{33}^2}}{\frac{1}{\sigma_{05}^2} + \frac{1}{\sigma_{33}^2}} = 0.44 \tag{3}$$

where σ_{05} and σ_{33} are the regression standard deviations shown in table 5.

The uncertainty of the combined result was calculated as:

$$U^2(X_i) = U_B^2(X_i) + v_{05}^2\, U_{A-05}^2 + v_{33}^2\, U_{A-33}^2 \tag{4}$$

The combined results and uncertainties are shown in table 6.

Table 6. Combined measurement results and uncertainties expressed in ppm. The uncertainty has a coverage factor of k=2.

Lab	Date	X_i (ppm)	$U(X_\mathrm{i})$ (ppm)
NRC	25-Aug-12	1.04	0.56
NIST	3-Oct-12	1.62	0.48
CENAM	25-Nov-12	2.70	0.78
INTI	4-Mar-13	4.18	0.59
NRC	2-Aug-13	4.33	0.71
NRC	5-Feb-14	4.69	0.43
PTB	12-Mar-14	4.26	0.92
NPL	11-Apr-14	5.01	0.15
METAS	25-May-14	5.02	0.48
VSL	27-Jun-14	7.37	0.42
NRC	26-Oct-14	6.71	0.49
NMISA	4-Dec-14	4.95	4.97
NRC	5-Oct-15	11.93	0.50
NIM	23-Dec-15	11.92	1.50
VNIIM	28-Mar-16	12.64	1.41
KRISS	2-Sep-16	10.54	0.56
NRC	3-Dec-16	14.07	0.46

Next, for each of the three subgroups, the difference between each NMI and the pilot lab $D_{i\text{-}NRC}$ was obtained by interpolating the pilot lab results (blue line in figure 3) to the time of the NMI measurements. The k=2 uncertainties of these differences were calculated as:

$$U^2(D_{i-NRC}) = U_i^2 + (2\sigma_{10M})^2\,, \tag{5}$$

where σ_{10M} = 0.85 ppm is the standard deviation of the regression of the combined pilot laboratory data, shown on table 5. The use of σ_{10M} in equation 5 tends to overestimate the uncertainty of the comparison for several laboratories but its use was deemed appropriate to account for the possibility of abrupt changes in the resistors at various times. Note that σ_{10M} is not smaller than both individual standard deviations in table 5 due to the high degree of correlation between the two resistors. The differences between each NMI and the pilot lab and the corresponding uncertainties are shown in table 7. The uncertainty entry for NRC in table 7 was calculated as:

$$U^2(D_{1-NRC}) = U_{NRC}^2 + (2\sigma_{10M})^2, \tag{6}$$

where U_{NRC} is the pooled standard deviation of all the NRC measurements shown in table 6, assuming equal degrees of freedom.

Table 7. Difference between each NMI and the pilot lab and the corresponding uncertainty, expressed in ppm. The uncertainty has a coverage factor of $k=2$.

Lab	$D_{i\text{-NRC}}$ (ppm)	$U(D_{i\text{-NRC}})$ (ppm)
NRC	0.00	1.78
NIST	0.21	1.76
CENAM	0.78	1.87
INTI	1.30	1.80
PTB	-0.70	1.93
NPL	-0.19	1.70
METAS	-0.51	1.76
VSL	1.58	1.75
NMISA	-2.06	5.25
NIM	-0.41	2.26
VNIIM	-0.17	2.21
KRISS	-3.07	1.79

The reference value X_{KCRV} was calculated as:

$$X_{KCRV} = \sum_i w_i D_{i-NRC} = -0.11\, ppm, \tag{7}$$

with the weights w_i given by:

$$w_i = \frac{\frac{1}{[U(D_{i-NRC})]^2}}{\sum_j \frac{1}{\left[U\left(D_{j-NRC}\right)\right]^2}} \quad . \tag{8}$$

The observed value of chi-squared,

$$\chi_{obs}^2 = \sum_i \frac{(D_{i-NRC} - X_{KCRV})^2}{[u(D_{i-NRC})]^2} = 19.4\,, \tag{9}$$

yields a probability of $\chi^2(\nu) > \chi^2_{obs}$ of 5.4 % (ν = 11) and hence, the consistency check is passed. The uncertainty in equation 9 is the standard uncertainty.

The uncertainty of X_{KCRV} was calculated as:

$$U^2_{KCRV} = \frac{1}{\sum \frac{1}{U^2_{i,1}}} = (0.55\, ppm)^2. \tag{10}$$

The degrees of equivalence

$$D_i = D_{i-NRC} - X_{KCRV} \tag{11}$$

and corresponding uncertainties

$$U^2(D_i) = U^2(D_{i-NRC}) - U^2(X_{KCRV}), \tag{12}$$

are shown in table 8 and figure 4.

Table 8. Degrees of equivalence and corresponding expanded uncertainty (k=2), expressed in ppm.

Lab	D_{i} (ppm)	$U(D_{\mathrm{i}})$ (ppm)
NRC	0.1	1.7
NIST	0.3	1.7
CENAM	0.9	1.8
INTI	1.4	1.7
PTB	-0.6	1.8
NPL	-0.1	1.6
METAS	-0.4	1.7
VSL	1.7	1.7
NMISA	-2.0	5.2
NIM	-0.3	2.2
VNIIM	-0.1	2.1
KRISS	-3.0	1.7

The degrees of equivalence between pairs of laboratories

$$D_{i,j} = D_i - D_j \tag{13}$$

and the corresponding uncertainty

$$U^2(D_{i,j}) = U^2(X_i) + U^2(X_j) + (2\sigma_{10M})^2, \tag{14}$$

are shown in tables 9 and 10 respectively.

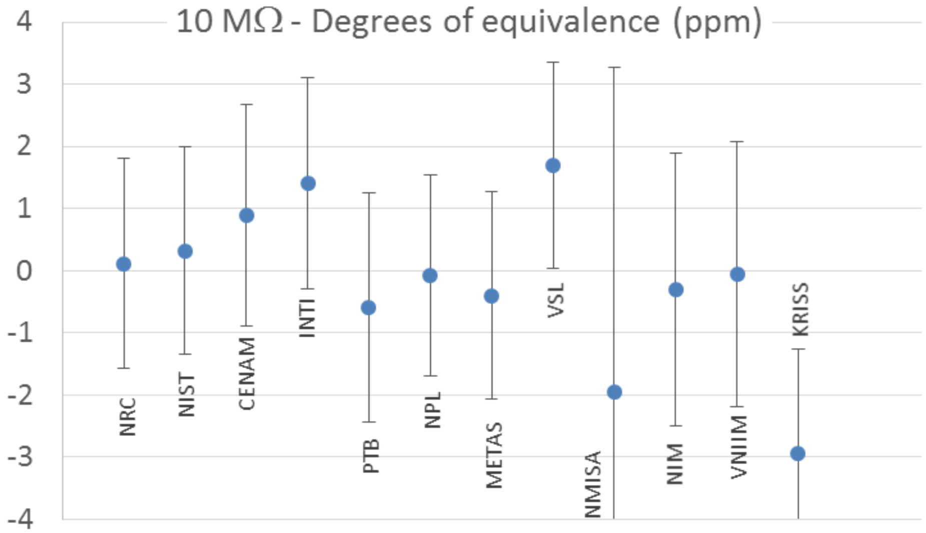

Figure 4. Degrees of equivalence at 10 MΩ and corresponding uncertainty (k=2), expressed in ppm.

Table 9. Degrees of equivalence $D_{i,j}$ between pairs of laboratories, expressed in ppm.

j i	NRC	NIST	CENAM	INTI	PTB	NPL	METAS	VSL	NMISA	NIM	VNIIM	KRISS
NRC		-0.2	-0.8	-1.3	0.7	0.2	0.5	-1.6	2.1	0.4	0.2	3.1
NIST	0.2		-0.6	-1.1	0.9	0.4	0.7	-1.4	2.3	0.6	0.4	3.3
CENAM	0.8	0.6		-0.5	1.5	1.0	1.3	-0.8	2.8	1.2	1.0	3.8
INTI	1.3	1.1	0.5		2.0	1.5	1.8	-0.3	3.4	1.7	1.5	4.4
PTB	-0.7	-0.9	-1.5	-2.0		-0.5	-0.2	-2.3	1.4	-0.3	-0.5	2.4
NPL	-0.2	-0.4	-1.0	-1.5	0.5		0.3	-1.8	1.9	0.2	0.0	2.9
METAS	-0.5	-0.7	-1.3	-1.8	0.2	-0.3		-2.1	1.6	-0.1	-0.3	2.6
VSL	1.6	1.4	0.8	0.3	2.3	1.8	2.1		3.6	2.0	1.8	4.6
NMISA	-2.1	-2.3	-2.8	-3.4	-1.4	-1.9	-1.6	-3.6		-1.7	-1.9	1.0
NIM	-0.4	-0.6	-1.2	-1.7	0.3	-0.2	0.1	-2.0	1.7		-0.2	2.7
VNIIM	-0.2	-0.4	-1.0	-1.5	0.5	0.0	0.3	-1.8	1.9	0.2		2.9
KRISS	-3.1	-3.3	-3.8	-4.4	-2.4	-2.9	-2.6	-4.6	-1.0	-2.7	-2.9	

Table 10. Uncertainty of the degrees of equivalence between pairs of laboratories, k=2, expressed in ppm.

j i	NRC	NIST	CENAM	INTI	PTB	NPL	METAS	VSL	NMISA	NIM	VNIIM	KRISS
NRC		1.8	1.9	1.9	2.0	1.8	1.8	1.8	5.3	2.3	2.3	1.9
NIST	1.8		1.9	1.9	2.0	1.8	1.8	1.8	5.3	2.3	2.3	1.9
CENAM	1.9	1.9		2.0	2.1	1.9	1.9	1.9	5.3	2.4	2.3	2.0
INTI	1.9	1.9	2.0		2.0	1.8	1.9	1.8	5.3	2.3	2.3	1.9
PTB	2.0	2.0	2.1	2.0		1.9	2.0	2.0	5.3	2.4	2.4	2.0
NPL	1.8	1.8	1.9	1.8	1.9		1.8	1.8	5.3	2.3	2.2	1.8
METAS	1.8	1.8	1.9	1.9	2.0	1.8		1.8	5.3	2.3	2.3	1.9
VSL	1.8	1.8	1.9	1.8	2.0	1.8	1.8		5.3	2.3	2.2	1.8
NMISA	5.3	5.3	5.3	5.3	5.3	5.3	5.3	5.3		5.5	5.4	5.3
NIM	2.3	2.3	2.4	2.3	2.4	2.3	2.3	2.3	5.5		2.7	2.3
VNIIM	2.3	2.3	2.3	2.3	2.4	2.2	2.3	2.2	5.4	2.7		2.3
KRISS	1.9	1.9	2.0	1.9	2.0	1.8	1.9	1.8	5.3	2.3	2.3	

6. Measurement results at 1 GΩ.

For the 1 GΩ measurements the specified nominal conditions were a V=100 V and T=23 °C. The parameters shown in table 11, which were determined by the pilot laboratory in the temperature range between 19 °C and 27 °C and for voltages between 50 V and 150 V, were used to correct the results to nominal conditions. A simple voltage coefficient α_V and a quadratic temperature dependence, expressed as

$$R(T) = R(23) + \alpha_T(T - 23) + \beta_T(T - 23)^2, \tag{15}$$

were deemed adequate.

Additionally, as with the 10 MΩ resistors, the pressure dependence of the resistors was evaluated by the pilot laboratory between 78 kPa and 109 kPa and the measurement results reported by the participants were corrected to the nominal pressure of the pilot laboratory (101.4 kPa). Resistor 1100037 was well described by a linear pressure coefficient, α_P, while 1101485 showed a quadratic dependence which was modelled as:

$$R(P) = R(101.4) + \alpha_P(P - 101.4) + \beta_P(P - 101.4)^2, \tag{16}$$

The reported and corrected data are summarized in tables 12 (S/N 1100037) and 13 (S/N 1101485).

Table 11. Temperature, Voltage and Pressure coefficients for the 1 GΩ resistors. The reported uncertainties are standard uncertainties.

Resistor	α_T	$u\ (\alpha_T)$	β_T	$u\ (\beta_T)$	α_V	$u\ (\alpha_V)$	α_P	$u\ (\alpha_P)$	β_P	$u\ (\beta_P)$
	(ppm/°C)		(ppm/°C^2)		(ppm/V)		(ppm/kPa)		(ppm/kPa^2)	
1100037	3.805	0.028	-0.076	0.011	-0.003	0.006	0.038	0.012	-	-
1101485	3.782	0.036	-0.017	0.014	-0.011	0.007	0.193	0.010	0.0041	0.0006

Table 12. Reported results, measurement conditions and corrected values for resistor 1100037. $X_{37} = \Delta R/R$ is the relative resistance difference from the nominal value expressed in parts in 10^6 (ppm). Uncertainties have a coverage factor k = 2.

	Reported data							Corrected data	
Lab	Date	X_{37} (ppm)	U_{TOTAL} (ppm)	U_{A} (ppm)	T (°C)	$U(T)$ (°C)	V (V)	P (kPa)	X_{37} (ppm)	U_{TOTAL} (ppm)
NRC	3-Apr-12	-5.07	3.90	0.57	22.99	0.03	100	101.4	-5.03	3.91
NIST	1-Oct-12	-2.76	1.90	1.62	23.00	0.05	100	99.96	-2.71	1.94
CENAM	26-Nov-12	1.80	7.60	0.20	22.97	0.04	100	81.08	2.68	7.65
INTI	9-Mar-13	9.80	6.00	2.76	23.00	0.05	99.9992	101.4	9.80	6.01
NRC	11-Aug-13	0.58	3.83	0.15	23.04	0.03	100	101.4	0.43	3.84
NRC	6-Feb-14	-1.40	3.80	0.07	22.99	0.03	100	101.4	-1.36	3.81
PTB	8-Mar-14	-4.00	5.00	1.12	23.01	0.05	100	101.38	-4.04	5.01
NPL	14-Apr-14	0.47	0.64	0.46	23.03	0.10	100	101.73	0.35	0.99
METAS	22-May-14	-0.30	5.30	0.80	23.00	0.05	100	95.26	-0.07	5.32
VSL	29-Jun-14	6.30	2.00	0.62	22.91	0.01	99.5	101.70	6.64	2.00
NRC	22-Sep-14	1.13	3.90	0.74	23.02	0.03	100	101.4	1.05	3.91
NMISA	30-Nov-14	-7.00	10.00	7.64	22.90	0.30	91	86.62	-6.08	10.27
NRC	23-Sep-15	2.44	3.90	0.72	22.99	0.03	100	101.4	2.48	3.91
NIM	25-Dec-15	-0.40	4.30	0.31	23.00	0.00	100	102.0	-0.42	4.30
VNIIM	5-Apr-16	-7.40	5.60	4.20	20.02	0.01	58.5	100.61	4.53	5.61
KRISS	27-Aug-16	7.90	3.20	1.60	23.00	0.02	100	100.2	7.95	3.20
NRC	9-Mar-17	3.37	4.00	1.02	22.99	0.03	100	101.4	3.41	4.01

Table 13. Reported results, measurement conditions and corrected values for resistor 1101485. $X_{85} = \Delta R/R$ is the relative resistance difference from the nominal value expressed in parts in 10^6 (ppm). Uncertainties have a coverage factor k = 2.

	Reported data								Corrected data	
Lab	Date	X_{85} (ppm)	U_{TOTAL} (ppm)	U_{A} (ppm)	T (°C)	$U(T)$ (°C)	V (V)	P (kPa)	X_{85} (ppm)	U_{TOTAL} (ppm)
NRC	3-Apr-12	-11.72	4.20	1.86	22.97	0.03	100	101.4	-11.61	4.21
NIST	1-Oct-12	-10.91	1.40	1.00	23.00	0.05	100	99.96	-10.64	1.48
CENAM	26-Nov-12	-8.10	7.60	0.40	22.99	0.08	100	81.08	-5.83	8.74
INTI	9-Mar-13	-3.00	5.60	2.76	23.00	0.05	99.9992	101.4	-2.99	5.61
NRC	11-Aug-13	-9.56	3.87	0.29	23.07	0.03	100	101.4	-9.82	3.88
NRC	6-Feb-14	-9.82	3.90	0.97	22.99	0.03	100	101.4	-9.78	3.91
PTB	8-Mar-14	-13.00	5.00	1.12	23.01	0.05	100	101.38	-13.03	5.01
NPL	14-Apr-14	-8.65	0.87	0.75	23.03	0.10	100	101.73	-8.84	1.15
METAS	22-May-14	-10.00	5.30	0.80	23.00	0.05	100	95.26	-8.97	5.45
VSL	29-Jun-14	-4.60	2.00	0.62	22.90	0.01	99.5	101.70	-4.27	2.00
NRC	22-Sep-14	-7.32	4.30	1.71	23.03	0.03	100	101.4	-7.43	4.31
NMISA	30-Nov-14	-24.00	10.00	7.72	22.90	0.30	91	86.62	-21.77	10.68
NRC	23-Sep-15	-5.68	3.80	0.55	22.99	0.03	100	101.4	-5.64	3.81
NIM	25-Dec-15	-10.20	4.30	0.16	23.00	0.00	100	102.0	-10.32	4.30
VNIIM	5-Apr-16	-17.90	4.60	2.60	20.01	0.01	58.5	100.61	-6.74	4.62
KRISS	27-Aug-16	16.80	3.20	1.60	23.00	0.02	100	100.2	17.03	3.21
NRC	9-Mar-17	-6.13	4.10	1.66	23.01	0.03	100	101.4	-6.17	4.11

Figures 5 and 6 show the corrected measurements for resistors 1100037 and 1101485 respectively and a linear fit to the pilot laboratory data.

Both resistors showed a very predictable linear trend. As with the 10 MΩ case, the first step of the analysis was to combine the measurements from the two travelling standards to obtain a single result X_{i} for each NMI by taking the weighted mean:

$$X_i(\,t_i) = v_{37}\,X_{37} + v_{85}\,X_{85}\,, \tag{17}$$

with the weights v_{37} and v_{85} given by:

$$v_{37} = \frac{\frac{1}{\sigma_{37}^2}}{\frac{1}{\sigma_{37}^2} + \frac{1}{\sigma_{85}^2}} = 0.35 \tag{18}$$

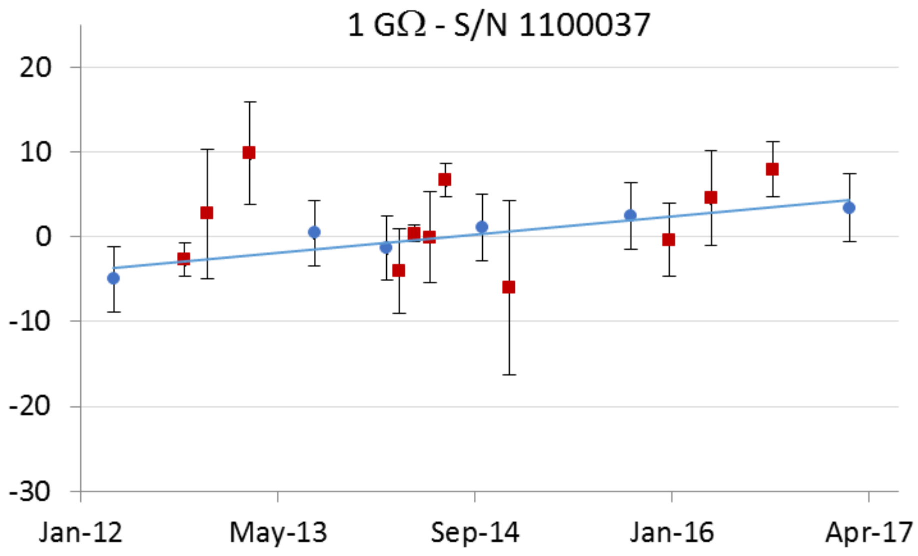

Figure 5. Corrected measurements of the 1 GΩ resistor, S/N 1100037. The pilot laboratory measurements are shown in blue circles, all other laboratories shown as red squares. The uncertainty bars are the k=2 uncertainties reported by the laboratories. The vertical scale is the deviation from the nominal value, expressed in ppm.

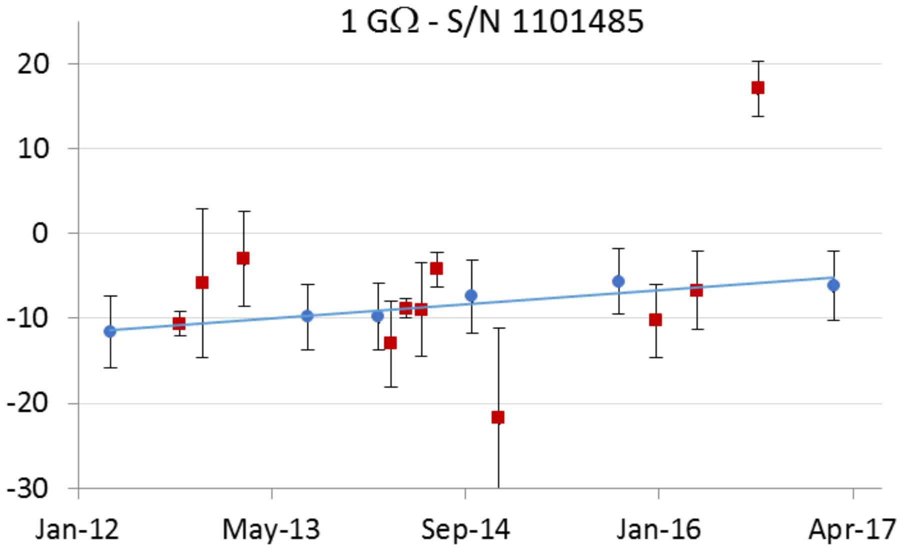

Figure 6. Corrected measurements of the 1 GΩ resistor, S/N 1101485. The pilot laboratory measurements are shown in blue circles, all other laboratories shown as red squares. The uncertainty bars are the k=2 uncertainties reported by the laboratories. The vertical scale is the deviation from the nominal value, expressed in ppm.

and

$$v_{85} = \frac{\frac{1}{\sigma_{85}^2}}{\frac{1}{\sigma_{37}^2} + \frac{1}{\sigma_{85}^2}} = 0.65 \tag{19}$$

σ_{37} and σ_{85} are the regression standard deviations shown in table 14 which were calculated using the pilot laboratory data.

The uncertainty of the combined result was calculated as:

$$U_i^2[X_i(t_i)] = U_{i_B}^2[X_i(t_i)] + v_{37}^2\, U_{i_{A-37}}^2 + v_{85}^2\, U_{i_{A-85}}^2 \tag{20}$$

A linear regression was calculated using the six combined results of the pilot laboratory. The standard deviation σ_{1G} and slope m_{1G} of the combined data regression are also shown in table 14.

Table 14. Fit parameters for the 1 GΩ resistors.

Resistor	σ (ppm)	Slope (ppm/year)	Correlation coefficient
1100037	1.38	1.62	0.49
1101485	1.02	1.27	
Combined	0.99	1.40	

The slope m_{1G} was used to correct the NMI combined results to the average time ($t=0$) of the pilot laboratory:

$$X_i(t=0) = X_i(t_i) - m_{1G}\, t_i \tag{21}$$

The uncertainty $u_i(0)$ of the drift-corrected values $X_i(t=0)$ was calculated as:

$$U_i^2[X_i(0)] = U^2[X_i(t_i)] + (2\sigma_{1G})^2 + [2u(m_{1G})t_i]^2 \tag{22}$$

where $u(m_{1G})$ = 0.26 ppm/year is the standard uncertainty of the slope on the regression of the combined pilot laboratory data. For the pilot laboratory, the value shown in table 15 at $t=0$ is given by the intercept parameter of the regression and the uncertainty was calculated as:

$$U^2[X_i(0)] = U_{1_B}^2 + (2\sigma_{1G})^2\left(1+\frac{1}{K}\right), \tag{23}$$

where K is the number of measurements made by the pilot laboratory and is equal to 6.

Table 15. Combined measurement results and uncertainties at $t=t_i$ and $t=0$.

Lab	Date	$X_i(t_i)$ (ppm)	$U[X_i(t_i)]$ ($k=2$) (ppm)	$X_i(0)$ (ppm)	$U[X_i(0)]$ ($k=2$) (ppm)
NRC	9-Aug-14	-5.38	3.91	-5.38	4.31
NIST	1-Oct-12	-7.84	1.38	-5.25	2.60
CENAM	25-Nov-12	-2.83	8.19	-0.45	8.48
INTI	9-Mar-13	1.52	5.50	3.51	5.90
PTB	8-Mar-14	-9.86	4.96	-9.26	5.34
NPL	13-Apr-14	-5.60	1.02	-5.14	2.24
METAS	22-May-14	-5.83	5.36	-5.52	5.71
VSL	29-Jun-14	-0.42	1.96	-0.26	2.79
NMISA	30-Nov-14	-16.23	9.11	-16.66	9.33
NIM	25-Dec-15	-6.82	4.30	-8.74	4.79
VNIIM	5-Apr-16	-2.76	4.39	-5.07	4.89
KRISS	3-Sep-16	13.82	3.02	10.93	3.77

The last point in figure 7 was considered an outlier (with an offset of more than 7σ). Excluding this point, the reference value X_{KCRV} was calculated as:

$$X_{KCRV} = \sum_{i \neq 12} w_i X_i(0) = -4.5\, ppm, \tag{24}$$

with the weights w_{i} given by:

$$w_i = \frac{\frac{1}{U_i^2[X_i(\,0)]}}{\sum_j \frac{1}{U_j^2\left[X_j(\,0)\right]}}\,. \tag{25}$$

The uncertainty of X_{KCRV} ($k=2$) was calculated as:

$$u_{KCRV}^2 = \frac{1}{\sum[U(X_i(0))]^{-2}} = (1.2\, ppm)^2. \tag{26}$$

The degrees of equivalence

$$D_i = X_i(0) - X_{KCRV} \tag{27}$$

and corresponding uncertainties

$$U^2(D_i) = U^2[X_i(\,0)] \mp U^2(X_{KCRV}), \tag{28}$$

are shown in table 16 and figure 7. The plus sign in equation 28 was used for the laboratory that was excluded from the calculation of the KCRV and the minus sign applies to all other laboratories.

Table 16. Degrees of equivalence and corresponding uncertainty (k=2), expressed in ppm.

Lab	D_i	$U(D_\mathrm{i})$, (k=2)
NRC	-0.9	4.2
NIST	-0.8	2.3
CENAM	4.1	8.4
INTI	8.0	5.8
PTB	-4.8	5.2
NPL	-0.6	1.9
METAS	-1.0	5.6
VSL	4.2	2.5
NMISA	-12.2	9.3
NIM	-4.2	4.6
VNIIM	-0.6	4.8
KRISS	15.4	4.0

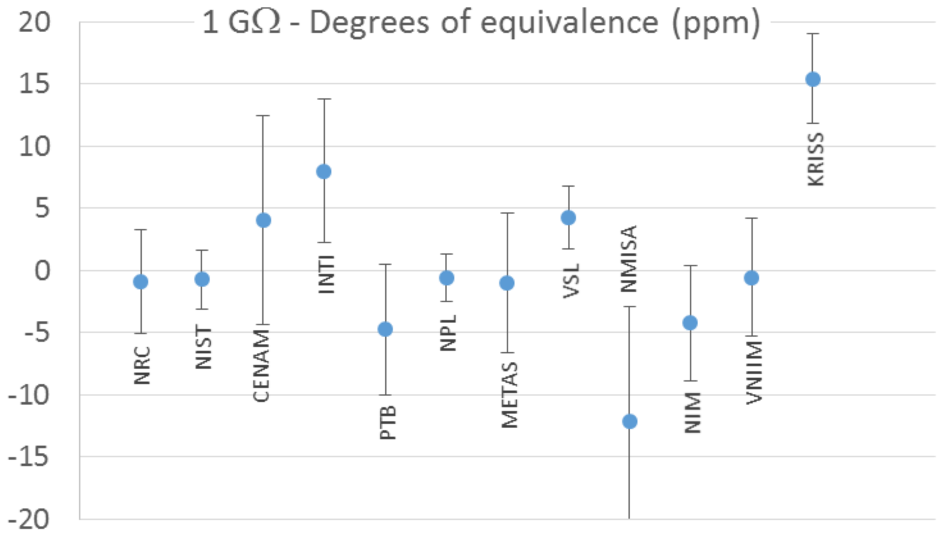

Figure 7. Degrees of equivalence and corresponding uncertainty at 1 GΩ (k=2).

This analysis failed a chi-squared consistency check with χ^2_{obs}= 31.7, ν = 10, and P [$\chi^2(\nu) > \chi^2_{obs}$] = 0.05 % and therefore X_KCRV should be regarded as an arbitrary reference. The degrees of equivalence between pairs of laboratories

$$D_{i,j} = D_i - D_j \tag{29}$$

and the corresponding uncertainty

$$U^2[D_i - D_j] = U^2[X_i(t_i)] + U^2[X_j(t_j)] + (2\sigma_{1G})^2 + [2U(m_{1G})(t_i - t_j)]^2 \tag{30}$$

are shown in tables 17 and 18 respectively.

Table 17. Degrees of equivalence $D_{i,j}$ between pairs of laboratories, expressed in ppm.

j i	NRC	NIST	CENAM	INTI	PTB	NPL	METAS	VSL	NMISA	NIM	VNIIM	KRISS
NRC		-0.1	-4.9	-8.9	3.9	-0.2	0.1	-5.1	11.3	3.4	-0.3	-16.3
NIST	0.1		-4.8	-8.8	4.0	-0.1	0.3	-5.0	11.4	3.5	-0.2	-16.2
CENAM	4.9	4.8		-4.0	8.8	4.7	5.1	-0.2	16.2	8.3	4.6	-11.4
INTI	8.9	8.8	4.0		12.8	8.7	9.0	3.8	20.2	12.3	8.6	-7.4
PTB	-3.9	-4.0	-8.8	-12.8		-4.1	-3.7	-9.0	7.4	-0.5	-4.2	-20.2
NPL	0.2	0.1	-4.7	-8.7	4.1		0.4	-4.9	11.5	3.6	-0.1	-16.1
METAS	-0.1	-0.3	-5.1	-9.0	3.7	-0.4		-5.3	11.1	3.2	-0.4	-16.5
VSL	5.1	5.0	0.2	-3.8	9.0	4.9	5.3		16.4	8.5	4.8	-11.2
NMISA	-11.3	-11.4	-16.2	-20.2	-7.4	-11.5	-11.1	-16.4		-7.9	-11.6	-27.6
NIM	-3.4	-3.5	-8.3	-12.3	0.5	-3.6	-3.2	-8.5	7.9		-3.7	-19.7
VNIIM	0.3	0.2	-4.6	-8.6	4.2	0.1	0.4	-4.8	11.6	3.7		-16.0
KRISS	16.3	16.2	11.4	7.4	20.2	16.1	16.5	11.2	27.6	19.7	16.0	

Table 18. Uncertainty of the degrees of equivalence between pairs of laboratories, $U(D_{i,j})$, expressed in ppm, $k=2$.

j i	NRC	NIST	CENAM	INTI	PTB	NPL	METAS	VSL	NMISA	NIM	VNIIM	KRISS
NRC		4.7	9.3	7.1	6.6	4.5	6.9	4.8	10.1	6.2	6.3	5.4
NIST	4.7		8.5	6.0	5.6	2.7	5.9	3.2	9.5	5.2	5.3	4.4
CENAM	9.3	8.5		10.1	9.8	8.5	10.0	8.7	12.5	9.6	9.7	9.2
INTI	7.1	6.0	10.1		7.7	6.0	8.0	6.2	10.9	7.4	7.5	6.8
PTB	6.6	5.6	9.8	7.7		5.4	7.6	5.7	10.6	6.9	7.0	6.3
NPL	4.5	2.7	8.5	6.0	5.4		5.8	3.0	9.4	4.9	5.0	4.0
METAS	6.9	5.9	10.0	8.0	7.6	5.8		6.0	10.8	7.2	7.3	6.6
VSL	4.8	3.2	8.7	6.2	5.7	3.0	6.0		9.5	5.2	5.3	4.3
NMISA	10.1	9.5	12.5	10.9	10.6	9.4	10.8	9.5		10.3	10.3	9.8
NIM	6.2	5.2	9.6	7.4	6.9	4.9	7.2	5.2	10.3		6.5	5.6
VNIIM	6.3	5.3	9.7	7.5	7.0	5.0	7.3	5.3	10.3	6.5		5.7
KRISS	5.4	4.4	9.2	6.8	6.3	4.0	6.6	4.3	9.8	5.6	5.7	

7. Comments on specific NMI results

The comments in sections 7.1 and 7.2 were provided by VSL and KRISS respectively.

7.1 VSL results

Following the distribution of the Draft A report to the participants, VSL has performed an extensive evaluation of its comparison results. At the time of the comparison measurements, the VSL results showed good agreement with an independent verification using Hamon devices, so the VSL comparison DoE values were not as expected.

In the evaluation of the 10 MΩ comparison results, it was finally found that the self-calibration of the binary divider of the VSL measurement bridge used for scaling from 10 kΩ to 10 MΩ was performed with too short settling times. This resulted in a +0.5 ppm error per 1:10 scaling step, culminating in a +1.5 μΩ/Ω deviation at 10 MΩ. This very well explains the +1.7 μΩ/Ω DoE of VSL at 10 MΩ. Verification of the 10 x 100 kΩ Hamon device used during the 2014 comparison measurements with the now correctly functioning measurement bridge reveals a -1.1 ppm error in the 1:100 ratio of this Hamon device. Apparently, the VSL measurement bridge and the verification Hamon device had exactly compensating errors in the 1:100 scaling during the comparison measurements.

No deviations were found in the evaluation of the 1:100 scaling from 10 MΩ to 1 GΩ level. However, during the 2014 comparison measurements, one of the voltage sources in the VSL dual source voltage bridge started showing unexpected behaviour; it was finally replaced after the comparison measurements. With the present VSL system, the 1:100 scaling ratio measured with the VSL dual source measurement bridge agrees within (0.2 ± 0.4) ppm with that of a 10 x 100 MΩ Hamon device. Before the comparison start, a similar verification was performed with (+0.9 ± 1.5) ppm (k = 2) as result. So likely, the additional VSL deviation in the 1 GΩ comparison results is caused by a voltage source that started to malfunction during the comparison measurements.

The above evaluation of the VSL comparison results was verified by measurements early 2019 of a 10 MΩ and 1 GΩ resistor by both VSL and NPL. This bilateral verification showed excellent results. The respective differences between the VSL and NPL results are (k = 2 uncertainties):

• 10 M resistance:	(+0.3 ± 0.5) μΩ/Ω,
• 1:100 scaling from 10 MΩ to 1 GΩ:	(-0.4 ± 1.0) μΩ/Ω,
• 1 GΩ resistance:	(-0.1 ± 1.1) μΩ/Ω.

It is noted that this bilateral exercise allowed verification of NMI measurement capabilities to a significantly better level than the formal comparison. This may be a good motivation to move to a star-type comparison for future resistance comparisons, similar to the recent CCEM-K4 capacitance comparison.

7.2 KRISS results

When the travelling standards of the CCEM Key Comparison were measured at KRISS, the ground noise from the outside was severe. Thus, in order to reduce the noise, we tried a new ground connection, different from the old one, which is proven to be ok by APMP.EM-K2 and 2017 peer review. This new ground connection resulted in the discrepancy of the measurement from the reference value. We later confirmed this by comparing two measurements with old and new ground connection of standard resistors which have similar internal structures as the ones used in the Key Comparison. We are now using the old ground connection.

8. Conclusions

The CCEM-K2.2012 key comparison has partially satisfied the stated purpose of assessing the improved measurement capabilities of the participating NMIs since the original CCEM-K2 comparison in 2002.

For the 10 MΩ results the measurement uncertainties reported by most laboratories are smaller than the uncertainty due to the long term variability of the resistors. It is worth noting that the variability of the resistors in this comparison was comparable to that of the standards used in 2002 and that resistors with significantly better long term behavior would be necessary to yield better results under the same circumstances. Nevertheless, the comparison achieved a reduction in the uncertainties in the degrees of equivalency relative to those of the 2002 comparison and, for some laboratories, the reduction is quite significant. The uncertainty of future comparisons could be reduced, for example, by a star design where the participating NMIs send their own standards to the pilot laboratory to be measured within a short timeframe.

At 1 GΩ the behavior of the travelling standards was satisfactory since their variability was smaller than the reported measurement uncertainties (with the exception of two laboratories). For most participants, these results provides strong support for their measurement capabilities while the uncertainties of the degrees of equivalency are significantly smaller than those reported in 2002. However, it should be noted that the failed chi-squared test at 1 GΩ suggests that some laboratories are underestimating their uncertainty.

Finally, this comparison also provides a better KCRV link for the RMO comparison EURAMET.EM-K2 at 1 GΩ although, this was not achieved at 10 MΩ.

Acknowledgements

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References

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Appendix A

NRC uncertainty budget – 10 MΩ – S/N 1100405

Source of Uncertainty	Type	Relative Standard uncertainty / 10^{-6}
Measurement scatter	A	0.15
Value of the 1 MΩ standard resistor	B	0.13
Leakage on the 6000B bridge	B	0.1
Bridge 10:1 ratio calibration	B	0.07
Bridge linearity	B	0.01
Combined standard uncertainty		0.23
Expanded relative uncertainty ($k=2$)		0.46
Reported uncertainty		**0.46**

NRC uncertainty budget – 1 GΩ – S/N 1100037

Source of Uncertainty	Type	Relative Standard uncertainty / 10^{-6}
Measurement scatter	A	0.51
Value of the 10 MΩ standard resistor	B	1.37
Bridge source 1 (100 V)	B	0.58
Bridge source 2 (10 V)	B	0.29
Current meter accuracy	B	0.01
3458 temperature coefficient	B	0.08
3458 linearity (100 V range)	B	0.60
Leakage	B	1.00
Combined standard uncertainty		1.98
Expanded relative uncertainty ($k=2$)		3.96
Reported uncertainty		**3.96**

NIST uncertainty budget – 10 MΩ – S/N 1101333

Source of Uncertainty	Type	Relative Standard uncertainty / 10^{-6}
Standard deviation	A	0.11
Scaling / Traceability	B	0.09
Reference standards	B	0.07
Measuring apparatus	B	0.02
Leakage effects	B	0.01
Ambient temperature	B	0.10
Repeatability	B	0.14
Combined standard uncertainty		0.23
Expanded relative uncertainty ($k=2$)		0.47
Reported uncertainty		**0.47**

NIST uncertainty budget – 1 GΩ – S/N 1101485

Source of Uncertainty	Type	Relative Standard uncertainty / 10^{-6}
Standard deviation	A	0.50
Scaling / Traceability	B	0.27
Reference standards	B	0.07
Measuring apparatus	B	0.40
Leakage effects	B	0.10
Ambient temperature	B	0.11
Repeatability	B	0.02
Combined standard uncertainty		0.7
Expanded relative uncertainty ($k=2$)		1.4
Reported uncertainty		**1.4**

CENAM uncertainty budget – 10 MΩ – S/N 1101333

Source of Uncertainty	Type	Relative Standard uncertainty / 10^{-6}
Scaling from the QHR to 1 MΩ	B	0.34
Drift of reference resistor	B	0.10
Reference resistor temperature stability	B	0.02
Bridge 10:1 ratio error	B	0.06
Leakage in the measurement system	B	0.10
Repeatability	A	0.14
Combined standard uncertainty		0.40
Expanded relative uncertainty ($k=2$)		0.80
Reported uncertainty		**0.80**

CENAM uncertainty budget – 1 GΩ – S/N 1100037

Source of Uncertainty	Type	Relative Standard uncertainty / 10^{-6}
Scaling from the QHR to 100 MΩ	B	0.8
Drift of reference resistor	B	0.2
Reference resistor temperature stability	B	1.0
Calibration of source V_x	B	2.0
Drift of source V_x	B	0.2
Calibration of source V_s	B	2.0
Drift of source V_s	B	0.2
Detector resolution	B	0.6
Leakage in the measurement system	B	2.0
Repeatability	A	0.1
Combined standard uncertainty		3.8
Expanded relative uncertainty ($k=2$)		7.6
Reported uncertainty		**7.6**

INTI uncertainty budget – 10 MΩ – S/N 1101333

Source of Uncertainty	Type	Relative Standard uncertainty / 10^{-6}
Scaling / traceability	B	0.28
Reference standard	B	0.03
Measuring apparatus	B	0.02
Standard deviation	A	0.08
Combined standard uncertainty		0.29
Expanded relative uncertainty ($k=2$)		0.58
Reported uncertainty		**0.58**

INTI uncertainty budget – 1 GΩ – S/N 1100037

Source of Uncertainty	Type	Relative Standard uncertainty / 10^{-6}
Scaling / traceability	B	0.28
Reference standard	B	0.03
Measuring apparatus	B	2.65
Standard deviation	A	1.38
Combined standard uncertainty		3.01
Expanded relative uncertainty ($k=2$)		6.02
Reported uncertainty		**6.02**

PTB uncertainty budget – 10 MΩ

Source of Uncertainty	Type	Relative Standard uncertainty / 10^{-6}
Reference resistor	B	0.05
Bridge ratio	A	0.02
Ratio correction	B	0.054
Temperature correction for standard resistor	B	0.029
Drift correction for standard resistor	B	0.12
Repeatibility	A	0.29
Combined standard uncertainty		0.32
Expanded relative uncertainty ($k=2$)		0.65
Reported uncertainty		**1.0**

PTB uncertainty budget – 1 GΩ

Source of Uncertainty	Type	Relative Standard uncertainty / 10^{-6}
Reference resistor	B	0.78
Bridge ratio	A	0.019
Ratio correction	B	0.054
Temperature correction for standard resistor	B	0.029
Drift correction for standard resistor	B	0.12
Repeatibility	A	0.56
Combined standard uncertainty		0.969
Expanded relative uncertainty ($k=2$)		1.938
Reported uncertainty		**5.0**

NPL uncertainty budget – 10 MΩ

Source of Uncertainty	Type	Relative Standard uncertainty / 10^{-6}
CCC	B	< 0.001
Leakage	B	< 0.001
Standard resistor type A	A	0.027
Standard resistor type B	B	0.052
Temperature of the standard	B	0.050
Standard power coefficient	B	0.005
Unknown resistor	A	0.063
Combined standard uncertainty		0.100
Expanded relative uncertainty (k=2)		0.200
Reported uncertainty		**0.2**

NPL uncertainty budget – 1 GΩ

Source of Uncertainty	Type	Relative Standard uncertainty / 10^{-6}
CCC	B	< 0.012
Leakage	B	< 0.001
SQUID linearity	B	0.2
Series resistance	B	0.02
Standard resistor type A	A	0.027
Standard resistor type B	B	0.052
Temperature of the standard	B	0.050
Standard power coefficient	B	0.050
Unknown resistor	A	0.141
Combined standard uncertainty		0.26
Expanded relative uncertainty (k=2)		0.52
Reported uncertainty		**0.52**

METAS uncertainty budget – 10 MΩ

Source of Uncertainty	Type	Relative Standard uncertainty / 10^{-6}
Step-up QHR to 10 MΩ	A	0.11
10 MΩ reference: stability temperature and loading	A	0.11
1:1 bridge ratio: accuracy, interchange effects	A	0.09
Leakage effects	B	0.10
Temperature dependence of the device under test	B	0.11
Reproducibility, measurement of unknown resistor	A	0.05
Combined standard uncertainty		0.24
Expanded relative uncertainty ($k=2$)		0.48
Reported uncertainty		**0.48**

METAS uncertainty budget – 1 GΩ

Source of Uncertainty	Type	Relative Standard uncertainty / 10^{-6}
Step-up QHR to 100 MΩ	A	1.40
100 MΩ reference: stability temperature and loading	A	0.44
Reference voltage dependence	A	1.00
Bridge: 10:1 voltage ratio calibration	A	050
Bridge: 10:1 voltage ratio stability	B	1.75
Uncompensated offset; burden voltage	B	0.50
Temperature dependence of the device under test	B	0.22
Reproducibility, measurement of unknown resistor	A	0.40
Combined standard uncertainty		2.63
Expanded relative uncertainty ($k=2$)		5.3
Reported uncertainty		**5.3**

VSL uncertainty budget – 10 MΩ – S/N 1100405

Source of Uncertainty	Type	Relative Standard uncertainty / 10^{-6}
10 MΩ to 1 MΩ ratio measurement	A	0.04
Uncertainty of the 10 MΩ to 1 MΩ ratio	B	0.12
Power / voltage effect in the 1 MΩ transfer resistor	B	0.029
Leakage effects (bridge, cables, reference and DUT)	B	0.12
10 kΩ to 1 MΩ ratio measurement	A	0.1
Uncertainty of the 10 kΩ to 1 MΩ ratio	B	0.069
Temperature effect on the unknown 10 MΩ resistor	B	0.006
10 kΩ reference resistor	B	0.025
Temperature effect on the reference resistor	B	0.006
Drift of the temperature resistor	A	0.01
Power effect in the 10 kΩ reference resistor	B	0.006
Combined standard uncertainty		0.21
Expanded relative uncertainty ($k=2$)		0.42
Reported uncertainty		**0.42**

VSL uncertainty budget – 1 GΩ – S/N 1100037

Source of Uncertainty	Type	Relative Standard uncertainty / 10^{-6}
Value of the 10 MΩ reference resistor	A	0.200
Power and/or voltage effect of reference resistor	B	0.029
Temperature effect of reference resistor	B	0.023
Measured ratio in 10 MΩ - 1 GΩ measurement	A	0.003
3458A DVM voltage ratio calibration	A	0.310
Drift in the voltage sources since last calibration	B	0.400
3458A DVM non-linearity	B	0.520
Linearity of the R_s voltage source	B	0.290
Null detector gain error	B	0.012
Effect of bridge sensitivity	B	0.012
Difference in values measured with +V or -V	B	0.020
Insufficient waiting time	B	0.017
Leakage (bridge, cables, reference resistor, DUT)	B	0.580
Combined standard uncertainty		1.0
Expanded relative uncertainty ($k=2$)		2.0
Reported uncertainty		**2.0**

NMISA uncertainty budget – 10 MΩ – S/N 1100405

Source of Uncertainty	Type	Relative Standard uncertainty / 10^{-6}
Accuracy of the 6000B bridge	B	0.05
Linearity of the 6000B bridge	B	0.005
Short term drift of the 6000B bridge	B	0.1
Thermal emf of the 4220A scanner	B	0.0005
Contact resistance error of the 4220A scanner	B	0.0025
Leakage resistance error of measurement system	B	0.6
Reference standard calibration uncertainty	B	2.0
Reference standard drift since last calibration	B	0.033
Standard deviation of measurement results	A	0.332
Combined standard uncertainty		2.12
Expanded relative uncertainty ($k=2$)		4.24
Reported uncertainty		**5.0**

NMISA uncertainty budget – 1 GΩ – S/N 1100037

Source of Uncertainty	Type	Relative Standard uncertainty / 10^{-6}
Accuracy of the 6000B bridge	B	0.05
Linearity of the 6000B bridge	B	0.005
Short term drift of the 6000B bridge	B	0.1
Thermal emf of the 4220A scanner	B	0.0005
Contact resistance error of the 4220A scanner	B	0.0025
Leakage resistance error of measurement system	B	0.6
Reference standard calibration uncertainty	B	3.0
Reference standard drift since last calibration	B	0.0495
Reference standard voltage coefficient	B	0.05
Standard deviation of measurement results	A	3.82
Combined standard uncertainty		4.9
Expanded relative uncertainty ($k=2$)		9.8
Reported uncertainty		**10.0**

NIM uncertainty budget – 10 MΩ – S/N 1100405

Source of Uncertainty	Type	Relative Standard uncertainty / 10^{-6}
Repeatability	A	0.046
Standard resistors	B	0.532
Leakage	B	0.058
Nonlinearity	B	0.005
Bridge calibration	B	0.050
Voltage source stability (8 hours)	B	0.500
Null detector (noise, drift and offset)	B	0.115
Hamon resistors		negligible
Temperature coefficient	B	0.017
Combined standard uncertainty		0.74
Expanded relative uncertainty ($k=2$)		1.48
Reported uncertainty		**1.5**

NIM uncertainty budget – 1 GΩ – S/N 1100037 – Binary Voltage Divider Bridge

Source of Uncertainty	Type	Relative Standard uncertainty / 10^{-6}
Repeatability	A	0.37
Standard resistors	B	1.44
Leakage	B	0.005
Nonlinearity	B	2.5
Bridge calibration	B	0.5
Voltage source stability (8 hours)	B	0.115
Null detector (noise, drift and offset)	B	0.017
Temperature coefficient	B	1.44
Combined standard uncertainty		3.15
Expanded relative uncertainty ($k=2$)		6.3

NIM uncertainty budget – 1 GΩ – S/N 1100037 – Dual Source Bridge

Source of Uncertainty	Type	Relative Standard uncertainty / 10^{-6}
Repeatability	A	0.117
Standard resistors	B	1.085
Voltage ratio accuracy	B	2.71
Null detector (noise, drift and offset)	B	0.115
Temperature coefficient	B	0.017
Combined standard uncertainty		2.93
Expanded relative uncertainty ($k=2$)		5.9

NIM combined uncertainty– 1 GΩ – S/N 1100037

Reported uncertainty	**4.3**

VNIIM uncertainty budget – 10 MΩ – S/N 1100405

Source of Uncertainty	Type	Relative Standard uncertainty / 10^{-6}
Reference standard (100 kΩ)	B	0.31
Hamon transfer standard	B	0.09
Instability of the Hamon transfer standard	B	0.22
Leakage in the Wheatstone bridge	B	0.18
Balance of the Wheatstone bridge	A	0.58
Temperature instability	B	0.29
Combined standard uncertainty		0.78
Expanded relative uncertainty ($k=2$)		1.58
Reported uncertainty		**0.78**

VNIIM uncertainty budget – 1 GΩ – S/N 1101485

Source of Uncertainty	Type	Relative Standard uncertainty / 10^{-6}
Reference standard (10 MΩ)	B	0.31
Hamon transfer standard	B	1.2
Instability of the Hamon transfer standard	B	0.7
Leakage in the Wheatstone bridge	B	0.8
Balance of the Wheatstone bridge	A	1.3
Temperature instability	B	0.9
Combined standard uncertainty		2.3
Expanded relative uncertainty ($k=2$)		4.6
Reported uncertainty		**2.3**

KRISS uncertainty budget – 10 MΩ

Source of Uncertainty	Type	Relative Standard uncertainty / 10^{-6}
Voltage ratio (linearity, stability)	A	0.25
Detector stability	B	0.06
Leakage effects	B	0.01
Temperature effects	B	0.02
1 MΩ reference resistor	B	0.05
Repeatability	A	0.13
Combined standard uncertainty		0.29
Expanded relative uncertainty ($k=2$)		0.58
Reported uncertainty		**0.29**

KRISS uncertainty budget – 1 GΩ

Source of Uncertainty	Type	Relative Standard uncertainty / 10^{-6}
Voltage ratio (linearity, stability)	A	0.25
Detector stability	B	0.58
Leakage effects	B	0.58
Temperature effects	B	0.11
1 GΩ reference resistor	B	1.02
Repeatability	A	0.8
Combined standard uncertainty		1.56
Expanded relative uncertainty ($k=2$)		3.1
Reported uncertainty		**1.6**