FINAL REPORT

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

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Abstract. An international comparison of dc resistance at 10 MΩ and 1GΩ was organized under the auspices of the Comité Consultatif d'Électricité et Magnétisme (CCEM) and piloted by the National Institute of Standards and Technology (NIST). This CCEM comparison began in August of 1996 and was completed in March of 2000 with 14 other national metrology institutes (NMIs) participating. The traveling package included three wirewound 10 MΩ standards and three film-type 1 GΩ standards in special containers designed by NIST. Results indicate that the differences at 10 MΩ and 1 GΩ between each laboratory's value, and the respective reference value, are all within each laboratory's expanded relative uncertainty at a coverage factor $k = 2$.

1. Introduction

Since January 1, 1990, the SI (Système International d'Unités) representation of the ohm has been based on the quantum Hall effect in which a measured resistance value is equal to the von Klitzing constant R_K (believed to be equal to h/e^2) divided by an integer i of the quantum Hall state [1]. The value at a quantized Hall resistance (QHR) plateau is used to assign a value to one or more transfer standards which in turn assign values to banks of working standards through a resistance scaling process. The buildup scaling process to 10 MΩ or 1 GΩ may take a sequence of several measurement steps utilizing many different types of resistance bridges and resistance-ratio transfer devices. Although ratios are dimensionless quantities and need not in principle be traceable to SI standards, establishing accurate ratios can be difficult if care is not taken to reduce errors caused by the effects of ambient conditions, lead and contact resistances, loading, and leakage currents.

Previously, key international comparisons of resistance standards were carried out at 1 Ω and 10 kΩ. At its 20th meeting in 1995, the CCEM (formerly CCE) decided to extend the scope of some key comparisons to demonstrate equivalence of NMIs' standards more effectively, and identified dc resistance $\geq 10^9$ Ω as one of the critical measurement areas. NIST volunteered to be the pilot for this key comparison and recommended using wirewound 10 MΩ and film-type 1 GΩ standards as the traveling resistors. 1GΩ wirewound resistors were not at the disposal of the pilot laboratory, although, in general, they are more stable than film types. Thus, it was decided to include wirewound 10 MΩ standards in the comparison in the event that problems arose with the traveling 1 GΩ standards. Also, the comparison at two different resistance levels would be a check on a NMI's resistance scaling process.

2. Participating Laboratories

Table 1 lists the participants in chronological order and the mean dates of their measurements of the traveling standards along with all of the dates of the NIST measurements.

National Institute of Standards and Technology (NIST), Gaithersburg, MD 20899-8112, U. S. A.

Table 1. List of participants and measurement dates.

Acronym	National Metrology Institute	Mean Date of Measurements
NIST	National Institute of Standards and Technology (Pilot), U. S. A.	1996-08-24
NRC	National Research Council, Canada	1996-10-20
NIST	National Institute of Standards and Technology (Pilot), U. S. A.	1996-12-08
BNM-LCIE	Bureau National de Métrologie- Laboratorie Central des Industries Électriques, France	1997-03-04
NPL	National Physical Laboratory, U. K.	1997-05-06
PTB	Physikalisch-Technische Bundesanstalt, Germany	1997-07-01
NIST	National Institute of Standards and Technology (Pilot), U. S. A.	1997-08-13
CSIRO-NML	Commonwealth Scientific and Industrial Research Organization- National Measurement Laboratory, Australia	1997-10-25
MSL	Measurements Standards Laboratory, New Zealand	1998-01-12
CSIR-NML	Council for Scientific and Industrial Research- National Measurement Laboratory, South Africa	1998-02-15
NIST	National Institute of Standards and Technology (Pilot), U. S. A.	1998-04-30
SP	Swedish National Testing and Research Institute, Sweden	1998-06-27
OFMET	Office Fédéral de Métrologie, Switzerland	1998-08-11
IEN	Istituto Elettrotecnico Nazionale, Italy	1998-09-28
NMi-VSL	Nederlands Meetinstituut- Van Swinden Laboratorium, The Netherlands	1998-12-30
NIST	National Institute of Standards and Technology (Pilot), U. S. A.	1999-02-22
KRISS	Korea Reasearch Institute of Standards and Science, The Republic of Korea	1999-05-23
NIST	National Institute of Standards and Technology (Pilot), U. S. A.	1999-08-07
NIM	National Institute of Metrology, China	1999-11-14
VNIIM	D. I. Mendeleyev Institute for Metrology, Russia	2000-01-10
NIST	National Institute of Standards and Technology (Pilot), U. S. A.	2000-03-12

3. Traveling Standards

The traveling standards consist of three 10 MΩ wirewound resistors (S/Ns HR7550, HR7551, and HR7552) and three 1 GΩ film-type resistors (S/Ns HR9101, HR9102, and HR9106). The resistance elements are hermetically sealed in metal containers and shock-mounted in aluminium enclosures using isolation pads made of highly damped visco-elastic material which is electrically insulated from the resistor containers by polytetrafluoroethylene (PTFE) tape [2]. The resistor terminations of the standards are coaxial 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 of a standard. This allows the resistor container of a standard to be operated either in a floating mode, a grounded mode, or driven at a guard potential.

The standards are designed to be measured in an air environment, preferably at 23 °C. The temperature coefficients of resistance (TCRs) of the 10 MΩ traveling standards at 23 °C are +(1.1 ± 0.2) (x 10^{-6})/°C, +(3.0 ± 0.2) (x 10^{-6})/°C, and +(1.6 ± 0.2) (x 10^{-6})/°C, respectively, for S/Ns HR7550, HR7551, and HR7552. The TCRs of the 1 GΩ traveling standards at 23 °C are −(28 ± 1) (x 10^{-6})/°C, −(31 ± 1) (x 10^{-6})/°C, and −(25 ± 1) (x 10^{-6})/°C, respectively, for S/Ns HR9101, HR9102, and HR9106. Calibrated thermistors are mounted within each enclosure to monitor the temperature of the standards. The voltage coefficients of resistance of the film-type 1 GΩ standards are approximately −0.1 (x 10^{-6})/V.

4. Measurement Procedures

Each participating NMI was requested to complete its measurements of the traveling standards within a two-month period. All were requested to measure the standards at 10 V and 100 V at a preferred ambient temperature of 23 °C, and also to measure the resistance values of the thermistors during the measurement run. Each participating NMI was to report these data along with the measurement date, ambient temperature and humidity, combined standard uncertainties, and the ground/guard configuration of the traveling standards during the measurement run to the pilot laboratory.

The pilot laboratory did not specify to the participants the measurement method to use to measure the traveling standards. It was assumed that each participant would measure the traveling standards using its normal measurement method, as if the traveling standards were part of the normal workload of the laboratory. This allows for a more realistic assessment of the quality of the NMI's measurement process. At NIST, the traveling standards were measured by two different measurement systems that are used on a regular basis to calibrate customer high-resistance standards. One method is a guarded Wheatstone bridge system [3], and the other is a guarded dual-voltage-source bridge system [4]. Both systems use the same standards whose values are based on the QHR. The scaling process at NIST from the QHR to 10 kΩ utilizes cryogenic current comparator bridges [5], and from 10 kΩ to 10 MΩ or 1 GΩ resistance scaling is done with Hamon transfer standards [6].

Below is a listing of the measurement systems that the NMIs indicated they used to measure the traveling standards.

a) Wheatstone bridge with resistive arms: BNM-LCIE (10 MΩ and 1 GΩ), VNIIM, CSIRO-NML, NIST
b) Bridge with dual-voltage-source arms [7]: MSL, NRC, NPL, SP, OFMET (1GΩ), KRISS, PTB, NMi-VSL, NIST
c) Automated bridge with binary voltage divider [8]: BNM-LCIE (10 MΩ), PTB, OFMET (10 MΩ), NIM
d) Teraohmmeter [9]: CSIR-NML
e) Digital multimeter method [10]: IEN

5. Measurement Results at 10 MΩ

The measurement results of the individual NMIs for the 10 MΩ traveling standards and including all of the NIST measurements are listed in Table 2. Also listed in the table are the individual NMIs' expanded relative uncertainties with the coverage factor k = 2, the root-sum-of-squares (RSS) Type A and Type B standard uncertainties, and the mean dates of the measurements. When reporting results, Rule B was applied to the rounding of numbers which always rounds up a number whose least-significant figure is 5 [11]. The uncertainty budget at 10 MΩ for each NMI is listed in Appendix A.

The resistor corrections listed in the table for KRISS were increased by 1.1 x 10^{-6} from the original values listed in the first draft. Mistakenly, KRISS twice applied the correction to its 1 MΩ reference bank to base its value on the QHR. The Type A standard uncertainty for PTB reported in Appendix A does not correspond to that of the initially submitted uncertainty budget. The discrepancy was found to be a transmission error, the reported uncertainty remains unchanged. The expanded relative uncertainties, with the coverage factor k = 2, initially submitted by CSIR-NML were estimated at 100 x 10^{-6} for both the 10 MΩ and 1 GΩ because the uncertainty budgets were not available or required when the results were reported to the pilot laboratory. The uncertainty budgets submitted after the initial results increased the expanded relative uncertainties, with the coverage factor k = 2, to 104 x 10^{-6} and 600 x 10^{-6}, for 10 MΩ and 1 GΩ, respectively. Since the uncertainties reported by CSIR-NML are an order of magnitude larger than those reported by the other NMIs, this increase in uncertainty has negligible effect on the computation of X_{KCRV} and U_{KCRV} for both 10 MΩ and 1 GΩ.

Only some of the NMIs measured the 10 MΩ traveling standards at both 10 V and 100 V; some measured them only at 10 V, others at 50 V or 91 V. In this report, results reported by NMIs are not corrected for voltage. The maximum loading error of these standards, when measured at 100 V, is expected to be < 0.05 x 10^{-6}, based on a temperature rise of 10 °C/watt specification for this type of resistor. Since this effect is insignificant and, in most cases, one would expect an improvement in the signal-to-noise ratio, the results at 100 V are listed in the table wherever possible.

The results in Table 2 are corrected to a nominal temperature of 23 °C based on reported thermistor readings or, if not available, reported ambient temperatures. Temperatures indicated by the calibrated thermistor probes would provide for a more consistent reference temperature. It is assumed that in stationary temperature fields, the differences between the thermistor-indicated temperatures and the temperatures indicated by a calibrated thermometer (with a combined standard uncertainty of 0.005 °C) placed on the top of the resistors cases does not exceed ±0.05 °C. In most cases the temperature corrections to the traveling standards amounted to a few tenths of 1 x 10^{-6} or less. However, two NMIs (NIM and VNIIM) measured the standards at an ambient temperature of 20 °C, and consequently, the temperature corrections were significant.

5.1 Reference Values at 10 MΩ

A time-dependent reference value is calculated for each 10 MΩ traveling resistor. It is based on a least-squares linear regression of the NIST values listed in Table 2.

The reference values, $x_{i\mathrm{P}}$'s, for the three 10 MΩ traveling resistors are as follows:

For S/N HR7550: $x_{i\mathrm{P}} = 30.334 \times 10^{-6} + (1.739 \times 10^{-6}/\mathrm{year})(t - 1996.65)$.

For S/N HR7551: $x_{i\mathrm{P}} = 5.992 \times 10^{-6} + (1.060 \times 10^{-6}/\mathrm{year})(t - 1996.65)$.

For S/N HR7552: $x_{i\mathrm{P}} = 21.161 \times 10^{-6} + (4.529 \times 10^{-6}/\mathrm{year})(t - 1996.65)$,

where t is the measurement date expressed in years, and 1996.65 is the reference date of the first set of NIST measurements.

The data listed in Table 2 are plotted in Figures 1, 2, and 3 for S/Ns HR7550, HR7551,and HR7552, respectively. The y-axis error bars correspond to the individual NMI's expanded relative uncertainties (k = 2) listed in the table. The solid line in each figure is the fitted linear least-squares regression line of the NIST data for a particular resistor.

Table 3 lists the reference values for the various measurement dates and the differences, D_i's, of the individual NMI values from the reference values, i.e.,

$$D_i = x_i - x_{i\mathrm{P}}.$$

The differences for each of the three traveling standards are combined as a weighted average and listed in the table as $D_{i\mathrm{COMB}}$, where the weights are determined from the variances of the residuals of the linear fit. The assumption is that the resistors drift in a linear fashion. Any non-linear effects are caused probably by severe physical or mechanical changes during the transportation process. Since the first draft, several other analysis models have been applied to the data to determine if a linear least-squares regression is the best choice to model the resistors' behavior. One model considered was to split the data into two subsets for linear least-squares regressions since there is indication of a travel incident between the fourth and fifth sets of measurements by the pilot laboratory. The two least-squares regressions did yield reduced uncertainties but there was no ideal approach for modeling the transport standards behavior between the fourth and fifth sets of measurements by the pilot laboratory. The error bars for the NMIs and the key comparison reference value (KCRV) did overlap for both the single and dual regression line models showing that choice of model was within the expanded relative uncertainties. The consensus of the review subgroup was that the resistors had experience some type of nonlinear behavior during transport, that it would be difficult to model the behavior without more information, and that a single linear regression was an acceptable drift model for each resistor for this key comparison.

The residual standard deviations, $\sigma_r(j)$, of the three linear fits are 1.9×10^{-6}, 1.1×10^{-6}, and 3.4×10^{-6} for HR7550, HR7551, and HR7552, respectively. The expanded relative uncertainty ($k = 2$) for each NMI, $U_{i\mathrm{COMB}}$, listed in the table are defined as

$$U_{i\mathrm{COMB}} = 2 * \sqrt{\mathrm{Var}\left[D_{i\mathrm{COMB}}\right]}.$$

For the non-pilot lab NMIs, the variance of $D_{i\mathrm{COMB}}$ is defined as

$$\mathrm{Var}\left[D_{i\mathrm{COMB}}\right] = \sigma^2_{\mathrm{x,B},i} + \sigma^2_{\mathrm{x,A},i} \cdot \frac{\sum_{j=1}^{3} \frac{1}{\sigma^4_{\mathrm{r}}(j)}}{\left(\sum_{j=1}^{3} \frac{1}{\sigma^2_{\mathrm{r}}(j)}\right)^2} + \frac{1 + \frac{1}{n} + \frac{\left(t_i - \bar{t}_{\mathrm{NIST}}\right)^2}{\sum_{k=1}^{n} \left(t_{\mathrm{NIST},k} - \bar{t}_{\mathrm{NIST}}\right)^2}}{\sum_{j=1}^{3} \frac{1}{\sigma^2_{\mathrm{r}}(j)}}$$

where $\sigma_{\mathrm{x,A},i}$ and $\sigma_{\mathrm{x,B},i}$ are the root-sum-of-squares of the individual NMI's Type A and Type B uncertainties, $\sigma_r(j)$ are the residual standard deviations of the linear fits for the j^{th} resistor, ($j = 1, 2, 3$), n is the number of times the resistors were measured by the pilot laboratory, t_i is the date corresponding to the i^{th} non-pilot NMI, $t_{\mathrm{NIST},k}$ is the date corresponding to the k^{th} measurement by the pilot lab, and "$_{\mathrm{NIST}}$ is the average pilot lab measurement date. This analysis allows multiple standards to reduce the Type A standard uncertainty component for each NMI when the three standards are used to determine a $D_{i\mathrm{COMB}}$ for each NMI. Since the pilot lab measured the resistors multiple times during the comparison, the variance of the mean $D_{i\mathrm{COMB}}$, for the pilot lab is defined as

$$\mathrm{Var}\left[\mathrm{AVE}\left(D_{\mathrm{NIST},i\mathrm{COMB}}\right)\right] = \sigma^2_{x,\mathrm{B,NIST}} + \frac{\sigma^2_{x,\mathrm{A,NIST}}}{n} \cdot \frac{\sum_{j=1}^{3} \frac{1}{\sigma^4_{\mathrm{r}}(j)}}{\left(\sum_{j=1}^{3} \frac{1}{\sigma^2_{\mathrm{r}}(j)}\right)^2}.$$

where $\sigma_{\mathrm{x,A,NIST}}$ and $\sigma_{\mathrm{x,B,NIST}}$ are the root-sum-of-squares of the pilot laboratory's Type A and Type B standard uncertainties.

In earlier drafts of this report, a transport uncertainty was calculated based on the weighted average of the residual standard deviations of the linear fits for the three resistors. Since the variance for each resistor is used to determine the $U_{i\mathrm{COMB}}$ for each NMI, this includes the transport uncertainty in each $U_{i\mathrm{COMB}}$. After statistical review, the above approach was recommended for determining $U_{i\mathrm{COMB}}$.

5.2 Key Comparison Reference Value at 10 MΩ

The key comparison reference value, X_{KCRV}, and the uncertainty of the key comparison reference value, U_{KCRV}, is defined as the weighted mean of the $D_{i\text{COMB}}$, where the $U_{i\text{COMB}}$'s for each NMI are used as weights. The mean $D_{i\text{COMB}}$ and $U_{i\text{COMB}}$ of the pilot lab were used in the computation

$$X_{\text{KCRV}} = U_{\text{KCRV}}^2 \cdot \sum_{i=1}^{15} \frac{D_{i\text{COMB}}}{U_{i\text{COMB}}^2} \qquad U_{\text{KCRV}} = \frac{1}{\sqrt{\sum_{i=1}^{15} \frac{1}{U_{i\text{COMB}}^2}}}.$$

of the X_{KCRV} and the U_{KCRV}. The mean $D_{i\text{COMB}}$ of the pilot lab is zero by definition. The formulas are

The weighted mean method of determining the X_{KCRV} does have the possibility that if some NMIs have $D_{i\text{COMB}}$s significantly larger than their corresponding $U_{i\text{COMB}}$s, the X_{KCRV} could be biased. For 10 MΩ, each $D_{i\text{COMB}}$ is smaller than the corresponding $U_{i\text{COMB}}$; therefore, NMIs with relatively small $U_{i\text{COMB}}$ will not bias the X_{KCRV} for this key comparison. The values X_{KCRV} = 0.346 x 10^{-6} and U_{KCRV} = 0.859 x 10^{-6} were computed for the 10 MΩ resistance level.

5.3 Equivalence at 10 MΩ

The matrix of equivalence at 10 MΩ is shown in Table 4. It gives the degree of equivalence of an individual NMI with the reference value and between pairs of NMIs. The degree of equivalence with the reference value is given by the $D_{i\text{KCRV}}$**'s** which are defined as

$$D_{i\text{KCRV}} = D_{i\text{COMB}} - X_{\text{KCRV}}.$$

The uncertainty $U_{i\text{KCRV}}$ for each NMI, which includes the U_{KCRV}, is defined as

$$U_{i\text{KCRV}} = \sqrt{U_{i\text{COMB}}^2 - U_{\text{KCRV}}^2}$$

The $D_{i\text{KCRV}}$ along with the expanded relative uncertainties, $U_{i\text{KCRV}}$'s, calculated using a coverage factor of 2, for the individual NMIs are listed in Table 4. Figure 4 is a chart in chronological order of the $D_{i\text{KCRV}}$**'s** for the individual NMIs. The y-axis error bars refer to the $U_{i\text{KCRV}}$'s.

The degree of equivalence between pairs of NMIs given in Table 4 is equal to

$$D_{ij} = D_{i\text{KCRV}} - D_{j\text{KCRV}},$$

where the matrix rows correspond to Laboratory i and the matrix columns to Laboratory j. The expanded relative uncertainty in the degree of equivalence between pairs of NMIs is determined by

$$U_{ij} = 2 * \sqrt{\text{Var}[D_{ij}]}$$

where for two non-pilot NMIs,

$$\mathrm{Var}\left[D_{ij}\right]=\sigma^2_{\mathrm{x,B},i}+\sigma^2_{\mathrm{x,B},j}+\left(\sigma^2_{\mathrm{x,A},i}+\sigma^2_{\mathrm{x,A},j}\right)\cdot\frac{\sum_{k=1}^{3}\frac{1}{\sigma^4_{\mathrm{r}}(k)}}{\left(\sum_{k=1}^{3}\frac{1}{\sigma^2_{\mathrm{r}}(k)}\right)^2}+\frac{2-\frac{\left(t_i-t_j\right)^2}{\sum_{k=1}^{n}\left(t_{\mathrm{NIST},k}-\bar{t}_{\mathrm{NIST}}\right)^2}}{\sum_{k=1}^{3}\frac{1}{\sigma^2_{\mathrm{r}}(k)}}$$

and where one of the NMIs is the pilot,

$$Var\left[D_{\mathrm{NIST},j}\right]=\sigma^2_{x,\mathrm{B,NIST}}+\sigma^2_{x,\mathrm{B,j}}+\left(\sigma^2_{x,\mathrm{A,j}}+\frac{\sigma^2_{x,\mathrm{A,NIST}}}{n}\right)\cdot\frac{\sum_{k=1}^{3}\frac{1}{\sigma^4_{\mathrm{r}}(k)}}{\left(\sum_{k=1}^{3}\frac{1}{\sigma^2_{\mathrm{r}}(k)}\right)^2}+\frac{1+\frac{1}{n}+\frac{\left(t_j-\bar{t}_{\mathrm{NIST}}\right)^2}{\sum_{k=1}^{n}\left(t_{\mathrm{NIST},k}-\bar{t}_{\mathrm{NIST}}\right)^2}}{\sum_{k=1}^{3}\frac{1}{\sigma^2_{\mathrm{r}}(k)}}$$

In previous drafts of this report, the U_{ij} was determined by a root-sum-of –squares of the U_i and U_j for each laboratory. After statistical review, it was recommended that the above approach be applied to the calculation of U_{ij} for each pair in the matrix of equivalence.

6. Measurement Results at 1 GΩ

The notation and analysis of the data for the 1 GΩ traveling standards are similar to that given in section 5 for the 10 MΩ traveling standards. The measurement results of the individual NMIs for the 1 GΩ traveling standards, and including all of the NIST measurements, are listed in Table 5. Also listed in the table are the expanded relative uncertainties (k = 2) for the individual NMIs, the root-sum-of-squares (RSS) Type A and Type B standard uncertainties, and the mean dates of the measurements. The uncertainty budget at 1 GΩ for each NMI is listed in Appendix A. Again, the resistor corrections listed in the table for KRISS were increased by 1.1 x 10^{-6} from the original values listed in the first draft for the reasons given in the previous section. The previous section also describes changes to the uncertainty budgets for PTB and CSIR-NML. Results are given for the highest voltage applied by a NMI to measure the standards. The results in the table are corrected to a nominal temperature of 23 °C based first on reported thermistor readings or, if not available, reported ambient temperatures. The temperature corrections were significant for the two NMIs (NIM and VNIIM) that measured the standards at an ambient temperature of 20 °C.

6.1 Reference Values at 1 GΩ

Similar to the 10 MΩ analysis, a time-dependent reference value is calculated for each 1 GΩ traveling resistor based on a least-squares linear regression of the NIST data listed in Table 5. The reference values, $x_{i\mathrm{P}}$'s, for the three 1 GΩ traveling resistors are as follows:

For S/N HR9101: $x_{i\mathrm{P}} = 16.32 \times 10^{-6} + (6.266 \times 10^{-6}/\mathrm{year})(t - 1996.65)$.

For S/N HR9102: $x_{i\mathrm{P}} = -103.45 \times 10^{-6} + (9.700 \times 10^{-6}/\mathrm{year})(t - 1996.65)$.

For S/N HR9106: $x_{i\mathrm{P}} = 740.97 \times 10^{-6} + (7.615 \times 10^{-6}/\mathrm{year})(t - 1996.65)$,

where t is the measurement date expressed in years, and 1996.65 is the reference date of the first set of NIST measurements.

The data listed in Table 5 are plotted in Figures 5, 6, and 7 for S/Ns HR9101, HR9102, and HR9106, respectively. The y-axis error bars correspond to the individual NMI's expanded relative uncertainty listed in the table. The solid line in each figure is the fitted linear least-squares regression line of the NIST data for a particular resistor.

Table 6 lists the reference values for the various measurement dates and the differences, D_i's, of the individual NMI values from the reference values. The differences for each of the three traveling standards are combined as a weighted average and listed in the table as D_{iCOMB}, where the weights are determined from the standard deviations, $\sigma_r(j)$, of the residuals of the linear fit. The residual standard deviations of the three linear fits are 5.1×10^{-6}, 5.0×10^{-6}, and 4.2×10^{-6} for HR9101, HR9102, and HR9106, respectively. The expanded relative uncertainties, $U_{i\mathrm{COMB}}$'s, listed in the table are calculated as described for the 10 MΩ resistors in the previous section.

6.2 Key Comparison Reference Value at 1 GΩ

The weighted mean method of determining the X_{KCRV} does have the possibility that if some NMIs have $D_{i\mathrm{COMB}}$s significantly larger than their corresponding $U_{i\mathrm{COMB}}$s, the X_{KCRV} could be biased. For 1 GΩ, each $D_{i\mathrm{COMB}}$ is smaller than the corresponding $U_{i\mathrm{COMB}}$; therefore, NMIs with relatively small $U_{i\mathrm{COMB}}$ will not bias the X_{KCRV} for this key comparison. The values $X_{\mathrm{KCRV}} = 0.099 \times 10^{-6}$ and $U_{\mathrm{KCRV}} = 3.19 \times 10^{-6}$ were computed for the 1 GΩ resistance level.

6.3 Equivalence at 1 GΩ

The matrix of equivalence at 1 GΩ is shown in Table 7. It gives the degree of equivalence of an individual NMI with the reference value and between pairs of NMIs along with the combination of the standard uncertainties between pairs of NMIs. Figure 8 is a chart in chronological order of the $D_{i\mathrm{KCRV}}$'s for the individual NMIs.

7. Conclusion

The results of this key international comparison indicate good agreement among the 15 participating NMIs at 10 MΩ and 1 GΩ. Agreement is well within the level of confidence of 95%. The traveling standards appeared to have functioned satisfactorily during the 43-month period of this comparison.

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Table 2

MEASURAND : Resistance
NOMINAL VALUE : 10 MΩ

x_i : result of measurement of 10 MΩ resistors carried out by laboratory i, and corrected to a nominal temperature of 23 EC

A_i : root-sum-of-squares of Type A standard uncertainty

B_i : root-sum-of-squares of Type B standard uncertainty

U_i : expanded relative uncertainty (k = 2) of x_i

Lab i	x_i (x 10^{-6})	x_i (x 10^{-6})	x_i (x 10^{-6})	A_i (x 10^{-6})	B_i (x 10^{-6})	U_i (x 10^{-6})	Mean Date of Measurements
	S/N HR7550	S/N HR7551	S/N HR7552				
NIST	28.2	4.6	18.6	0.2	1.5	3.0	1996-08-24
NRC*	31	5	20	1.9	2.3	6.0	1996-10-20
NIST	30.8	6.7	20.2	0.2	1.5	3.0	1996-12-08
BNM-LCIE	31.49	6.97	23.04	0.5	0.4	1.4	1997-03-04
NPL	30.8	7.1	23.8	0.5	0.6	1.7	1997-05-06
PTB	31.6	7.5	24.8	1.0	2.2	5.0	1997-07-01
NIST	32.7	8.1	28.4	0.2	1.5	3.0	1997-08-13
CSIRO-NML	32.3	7.3	27.0	0.1	2.6	5.0	1997-10-25
MSL	32.5	7.3	28.6	0.04	0.6	1.2	1998-01-11
CSIR-NML*	50	-20	30	50	14	104	1998-02-18
NIST	36.3	8.9	34.5	0.2	1.5	3.0	1998-04-30
SP	34.3	8.7	32.8	0.2	1.8	3.6	1998-06-27
OFMET*	34.7	8.9	33.2	0.4	0.6	1.4	1998-08-14
IEN*	35.0	9.4	33.7	0.8	2.5	5.4	1998-09-28
NMi-VSL	35.4	9.1	35.0	0.8	3.0	6.0	1998-12-25
NIST	34.9	7.8	31.7	0.2	1.5	3.0	1999-02-22
KRISS	32.7	7.1	30.8	0.3	3	6.0	1999-05-23
NIST	35.5	8.5	33.3	0.2	1.5	3.0	1999-08-07
NIM**	36.9	10.2	38.1	0.1	0.8	2.0	1999-11-14
VNIIM***	36	10	37	0.3	1	1.7	2000-01-10
NIST	34.7	10.0	35.5	0.2	1.5	3.0	2000-03-12

*Measurements at 10 V, **measurements at 91 V, ***measurements at 50 V, all other measurements at 100 V.

Table 3. Reference values at 10 MΩ

x_{iP} = Reference values based on predicted values from a linear regression of NIST data.

For S/N HR7550: $x_{iP} = 30.334 \times 10^{-6} + (1.739 \times 10^{-6}/\text{year})(t - 1996.65)$

For S/N HR7551: $x_{iP} = 5.992 \times 10^{-6} + (1.060 \times 10^{-6}/\text{year})(t - 1996.65)$

For S/N HR7552: $x_{iP} = 21.161 \times 10^{-6} + (4.529 \times 10^{-6}/\text{year})(t - 1996.65)$, **where t is the measurement date expressed in years.**

$D_i = x_i - x_{iP}$

$D_{i\,COMB}$: weighted combined average of D_i's

$U_{i\,COMB}$: expanded relative uncertainty (k = 2) of $D_{i\,COMB}$

Lab i	Mean Date of Measurements	S/N HR7550 x_{iP} (x 10^{-6})	S/N HR7550 D_i (x 10^{-6})	S/N HR7551 x_{iP} (x 10^{-6})	S/N HR7551 D_i (x 10^{-6})	S/N HR7552 x_{iP} (x 10^{-6})	S/N HR7552 D_i (x 10^{-6})	$D_{i\,COMB}$ (x 10^{-6})	$U_{i\,COMB}$ (x 10^{-6})
NIST	1996.65	30.3	-2.1	6.0	-1.4	21.2	-2.6	-1.6	3.0
NRC	1996.80	30.6	0.4	6.2	-1.2	21.9	-1.9	-0.8	5.8
NIST	1996.94	30.8	0.0	6.3	0.4	22.5	-2.3	0.1	3.0
BNM-LCIE	1997.17	31.2	0.3	6.5	0.4	23.5	-0.5	0.3	2.3
NPL	1997.35	31.5	-0.7	6.7	0.4	24.3	-0.5	0.1	2.5
PTB	1997.50	31.8	-0.2	6.9	0.6	25.0	-0.2	0.4	5.0
NIST	1997.62	32.0	0.7	7.0	1.1	25.5	2.9	1.1	3.0
CSIRO-NML	1997.82	32.4	-0.1	7.2	0.1	26.5	0.5	0.1	5.5
MSL	1998.03	32.7	-0.2	7.5	-0.2	27.4	1.2	-0.1	2.3
CSIR-NML	1998.13	33	17	8	-28	28	2	-15.4	79
NIST	1998.33	33.3	3.0	7.8	1.1	28.8	5.7	1.9	3.0
SP	1998.49	33.5	0.8	7.9	0.8	29.5	3.3	0.9	4.1
OFMET	1998.62	33.8	0.9	8.1	0.8	30.1	3.1	1.0	2.3
IEN	1998.74	34.0	1.0	8.2	1.2	30.6	3.1	1.3	5.5
NMi-VSL	1998.98	34.4	1.0	8.5	0.6	31.7	3.3	0.9	6.5
NIST	1999.15	34.7	0.2	8.6	-0.8	32.5	-0.8	-0.6	3.0
KRISS	1999.39	35.1	-2.4	8.9	-1.8	33.6	-2.8	-2.0	6.3
NIST	1999.60	35.5	0.0	9.1	-0.6	34.5	-1.2	-0.5	3.0
NIM	1999.87	35.9	1.0	9.4	0.8	35.7	2.4	0.9	2.7
VNIIM	2000.03	36.2	-0.2	9.6	0.4	36.5	0.5	0.3	3.0
NIST	2000.20	36.5	-1.8	9.8	0.2	37.2	-1.7	-0.4	3.0
NIST(Mean)	1998.35	33.3	0.0	7.8	0.0	28.9	0.0	0.0	3.0

Table 4. Matrix of Equivalence at 10 MΩ
(k = 2)

Key comparison CCEM-K2

MEASURAND: Resistance **NOMINAL VALUE: 10 MΩ**

The key comparison reference value for this comparison is obtained from the weighted average of the participants. The key comparison reference value is X_{KCRV} = 0.346 x 10^{-6} and the expanded relative uncertainty is U_{KCRV} = 0.859 x 10^{-6} for the 10 MΩ resistance level.

The degree of equivalence of each laboratory with respect to the reference value is given by a pair of numbers: $D_{i\,KCRV} = D_{i\,COMB} - X_{KCRV}$ and the expanded relative uncertainty $U_{i\,KCRV} = (U_{i\,COMB}^2 - U_{KCRV}^2)^{1/2}$ where D_{iCOMB} is the weighted mean of the three 10 MΩ traveling standards differences from a least-squares linear regression of the NIST values for each traveling standard. The calculation of the $D_{i\,COMB}$s and $U_{i\,COMB}$s are described in detail in the report.

The degree of equivalence between two laboratories is given by a pair of numbers: $D_{ij} = D_{i\,KCRV} - D_{j\,KCRV}$ and the expanded relative uncertainty U_{ij} which calculation is described in detail in the report.

Lab *i* ↓ \ Lab *j* →	$D_{i\,KCRV}$ (x 10^{-6})	$U_{i\,KCRV}$ (x 10^{-6})	NIST D_{ij} (x 10^{-6})	NIST U_{ij}	NRC D_{ij} (x 10^{-6})	NRC U_{ij}	BNM-LCIE D_{ij} (x 10^{-6})	BNM-LCIE U_{ij}	NPL D_{ij} (x 10^{-6})	NPL U_{ij}	PTB D_{ij} (x 10^{-6})	PTB U_{ij}	CSIRO-NML D_{ij} (x 10^{-6})	CSIRO-NML U_{ij}	MSL D_{ij} (x 10^{-6})	MSL U_{ij}	CSIR-NML D_{ij} (x 10^{-6})	CSIR-NML U_{ij}
NIST	-0.3	2.9			0.8	6.5	-0.3	3.8	-0.1	3.9	-0.4	5.9	-0.1	6.3	0.1	3.8	15	79
NRC	-1.2	5.7	-0.8	6.5			-1.2	6.0	-0.9	6.1	-1.2	7.5	-0.9	7.8	-0.8	6.0	15	79
BNM-LCIE	0.0	2.1	0.3	3.8	1.2	6.0			0.3	3.1	0.0	5.4	0.3	5.8	0.4	2.9	16	79
NPL	-0.3	2.3	0.1	3.9	0.9	6.1	-0.3	3.1			-0.3	5.5	0.0	5.9	0.1	3.1	15	79
PTB	0.0	5.0	0.4	5.9	1.2	7.5	0.0	5.4	0.3	5.5			0.3	7.3	0.4	5.4	16	79
CSIRO-NML	-0.3	5.4	0.1	6.3	0.9	7.8	-0.3	5.8	0.0	5.9	-0.3	7.3			0.1	5.8	15	79
MSL	-0.4	2.1	-0.1	3.8	0.8	6.0	-0.4	2.9	-0.1	3.1	-0.4	5.4	-0.1	5.8			15	79
CSIR-NML	-16	79	-15	79	-15	79	-16	79	-15	79	-16	79	-15	79	-15	79		
SP	0.6	4.0	0.9	5.1	1.8	6.9	0.6	4.5	0.9	4.6	0.6	6.4	0.9	6.7	1.0	4.5	16	79
OFMET	0.7	2.1	1.0	3.8	1.9	6.0	0.7	2.9	1.0	3.1	0.6	5.4	0.9	5.8	1.1	3.1	16	79
IEN	0.9	5.5	1.3	6.3	2.1	7.8	1.0	5.8	1.2	5.9	0.9	7.4	1.2	7.7	1.4	5.9	17	79
NMi-VSL	0.6	6.4	0.9	7.2	1.8	8.5	0.6	6.7	0.9	6.8	0.5	8.1	0.8	8.4	1.0	6.8	16	79
KRISS	-2.3	6.3	-2.0	7.0	-1.2	8.3	-2.3	6.5	-2.1	6.6	-2.4	7.9	-2.1	8.3	-1.9	6.6	13	79
NIM	0.6	2.5	0.9	4.0	1.8	5.9	0.6	2.8	0.9	3.1	0.6	5.4	0.9	5.8	1.0	3.1	16	79
VNIIM	-0.1	2.8	0.3	4.2	1.1	6.0	0.0	3.1	0.2	3.3	-0.1	5.5	0.2	6.0	0.4	3.3	16	79

Lab *i* ↓ \ Lab *j* →	$D_{i\,KCRV}$ (x 10^{-6})	$U_{i\,KCRV}$ (x 10^{-6})	SP D_{ij} (x 10^{-6})	SP U_{ij}	OFMET D_{ij} (x 10^{-6})	OFMET U_{ij}	IEN D_{ij} (x 10^{-6})	IEN U_{ij}	NMi-VSL D_{ij} (x 10^{-6})	NMi-VSL U_{ij}	KRISS D_{ij} (x 10^{-6})	KRISS U_{ij}	NIM D_{ij} (x 10^{-6})	NIM U_{ij}	VNIIM D_{ij} (x 10^{-6})	VNIIM U_{ij}
NIST	-0.3	2.9	-0.9	5.1	-1.0	3.8	-1.3	6.3	-0.9	7.2	2.0	7.0	-0.9	4.0	-0.3	4.2
NRC	-1.2	5.7	-1.8	6.9	-1.9	6.0	-2.1	7.8	-1.8	8.5	1.2	8.3	-1.8	5.9	-1.1	6.0
BNM-LCIE	0.0	2.1	-0.6	4.5	-0.7	2.9	-1.0	5.8	-0.6	6.7	2.3	6.5	-0.6	2.8	0.0	3.1
NPL	-0.3	2.3	-0.9	4.6	-1.0	3.1	-1.2	5.9	-0.9	6.8	2.1	6.6	-0.9	3.1	-0.2	3.3
PTB	0.0	5.0	-0.6	6.4	-0.6	5.4	-0.9	7.4	-0.5	8.1	2.4	7.9	-0.6	5.4	0.1	5.5
CSIRO-NML	-0.3	5.4	-0.9	6.7	-0.9	5.8	-1.2	7.7	-0.8	8.4	2.1	8.3	-0.9	5.8	-0.2	6.0
MSL	-0.4	2.1	-1.0	4.5	-1.1	3.1	-1.4	5.9	-1.0	6.8	1.9	6.6	-1.0	3.1	-0.4	3.3
CSIR-NML	-16	79	-16	79	-16	79	-17	79	-16	79	-13	79	-16	79	-16	79
SP	0.6	4.0			-0.1	4.6	-0.4	6.8	0.0	7.6	2.9	7.4	0.0	4.6	0.6	4.8
OFMET	0.7	2.1	0.1	4.6			-0.3	5.9	0.1	6.8	3.0	6.6	0.1	3.2	0.7	3.4
IEN	0.9	5.5	0.4	6.8	0.3	5.9			0.4	8.5	3.3	8.3	0.3	6.0	1.0	6.1
NMi-VSL	0.6	6.4	0.0	7.6	-0.1	6.8	-0.4	8.5			2.9	9.0	0.0	6.9	0.6	7.0
KRISS	-2.3	6.3	-2.9	7.4	-3.0	6.6	-3.3	8.3	-2.9	9.0			-2.9	6.7	-2.3	6.8
NIM	0.6	2.5	0.0	4.6	-0.1	3.2	-0.3	6.0	0.0	6.9	2.9	6.7			0.7	3.7
VNIIM	-0.1	2.8	-0.6	4.8	-0.7	3.4	-1.0	6.1	-0.6	7.0	2.3	6.8	-0.7	3.7		

Table 5

MEASURAND : Resistance
NOMINAL VALUE : 1 GΩ

x_i: result of measurement of 1 GΩ resistors carried out by laboratory *i*, and corrected to a nominal temperature of 23 °C

A_i: root-sum-of-squares of Type A standard uncertainty

B_i: root-sum-of-squares of Type B standard uncertainty

U_i: expanded relative uncertainty (k = 2) of x_i

Lab *i*	x_i ($\times 10^{-6}$)	x_i ($\times 10^{-6}$)	x_i ($\times 10^{-6}$)	A_i ($\times 10^{-6}$)	B_i ($\times 10^{-6}$)	U_i ($\times 10^{-6}$)	Mean Date of Measurements
	S/N HR9101	S/N HR9102	S/N HR9106				
NIST	8.7	-109.4	734.4	2.0	4.6	10.0	1996-08-24
NRC	15	-102	743	3.8	9.2	20.0	1996-10-11
NIST	20.3	-102.0	744.8	2.0	4.6	10.0	1996-12-08
BNM-LCIE	17	-101	745	2.9	8.4	18	1997-02-18
NPL	10	-97	737	1.5	4.8	10.0	1997-05-08
PTB	27	-89	748	2.5	5.8	15.0	1997-07-12
NIST	27.6	-88.8	752.3	2.0	4.6	10.0	1997-08-12
CSIRO-NML	25	-89	752	2.0	33	70.0	1997-10-25
MSL	30	-84	755	0.9	2.2	5.3	1998-01-11
CSIR-NML	-40	-130	700	50	289	600	1998-02-15
NIST	31.9	-81.0	758.2	2.0	4.6	10.0	1998-04-29
SP	25.5	-86.9	754.0	0.5	4.4	8.8	1998-06-27
OFMET	32.4	-81.0	758.2	4.2	10.8	23.0	1998-08-15
IEN	31.2	-79.9	760.4	3.5	9.1	19.5	1998-10-17
NMi-VSL	1	-111	724	8.0	17	40.0	1999-01-03
NIST	31.0	-77.4	759.9	2.0	4.6	10.0	1999-02-22
KRISS	32	-76	759	0.7	5.6	11.8	1999-05-23
NIST	31.4	-77.5	762.4	2.0	4.6	10.0	1999-08-07
NIM*	35.0	-74.5	766.9	1.0	3.1	6.6	1999-11-14
VNIIM**	38	-72	768	1.0	2.3	4.5	2000-01-23
NIST	38.1	-72.3	765.6	2.0	4.6	10.0	2000-03-13

*Measurements at 91 V, **measurements at 50 V,
all other measurements at 100 V.

Table 6. Reference values at 1 GΩ

x_{iP} = Reference values based on predicted values from a linear regression of NIST data.

For S/N HR9101: $x_{iP} = 16.32 \times 10^{-6} + (6.266 \times 10^{-6}/\text{year})(t - 1996.65)$

For S/N HR9102: $x_{iP} = -103.45 \times 10^{-6} + (9.700 \times 10^{-6}/\text{year})(t - 1996.65)$

For S/N HR9106: $x_{iP} = 740.97 \times 10^{-6} + (7.615 \times 10^{-6}/\text{year})(t - 1996.65)$,
where t is the measurement date expressed in years.

$D_i = x_i - x_{iP}$

D_{iCOMB}: weighted combined average of D_i's

U_{iCOMB}: expanded relative uncertainty (k = 2) of D_{iCOMB}

Lab i	Mean Date of Measurements	S/N HR9101 x_{iP} (x 10^{-6})	S/N HR9101 D_i	S/N HR9102 x_{iP} (x 10^{-6})	S/N HR9102 D_i	S/N HR9106 x_{iP} (x 10^{-6})	S/N HR9106 D_i	D_{iCOMB} (x 10^{-6})	U_{iCOMB}
NIST	1996.65	16.3	-7.6	-103.5	-5.9	741.0	-6.6	-6.7	9.3
NRC	1996.78	17.1	-2.1	-102.2	0.2	742.0	1.0	-0.1	20.0
NIST	1996.94	18.1	2.2	-100.6	-1.4	743.2	1.6	0.9	9.3
BNM-LCIE	1997.13	19.3	-2.3	-98.8	-2.2	744.6	0.4	-1.2	18.3
NPL	1997.35	20.7	-10.7	-96.6	-0.4	746.3	-9.3	-7.1	11.4
PTB	1997.53	21.8	5.2	-94.9	5.9	747.7	0.3	3.4	13.4
NIST	1997.61	22.3	5.3	-94.1	5.3	748.3	4.0	4.8	9.3
CSIRO-NML	1997.82	23.6	1.4	-92.1	3.1	749.9	2.1	2.2	66.9
MSL	1998.03	25.0	5.0	-90.1	6.1	751.5	3.5	4.7	7.3
CSIR-NML	1998.14	26	-66	-89	-41	752	-52	-52.7	581
NIST	1998.33	26.8	5.1	-87.2	6.2	753.7	4.5	5.1	9.3
SP	1998.49	27.9	-2.4	-85.6	-1.3	755.0	-1.0	-1.5	10.5
OFMET	1998.62	28.7	3.7	-84.3	3.3	756.0	2.2	3.0	23.0
IEN	1998.79	29.7	1.5	-82.7	2.8	757.3	3.1	2.6	19.5
NMi-VSL	1999.01	31.1	-30.1	-80.6	-30.4	758.9	-34.9	-32.2	36.4
NIST	1999.15	32.0	-1.0	-79.2	1.8	760.0	-0.1	0.2	9.3
KRISS	1999.39	33.5	-1.5	-76.9	0.9	761.9	-2.9	-1.4	12.8
NIST	1999.60	34.8	-3.4	-74.8	-2.7	763.4	-1.0	-2.2	9.3
NIM	1999.87	36.5	-1.5	-72.2	-2.3	765.5	1.4	-0.5	8.9
VNIIM	2000.06	37.7	0.3	-70.3	-1.7	767.0	1.0	0.1	8.0
NIST	2000.20	38.5	-0.4	-69.0	-3.3	768.0	-2.4	-2.1	9.3
NIST(Mean)	1998.35	27.0	0.0	-86.9	0.0	753.9	0.0	0.0	9.3

Table 7. Matrix of Equivalence at 1 GΩ
(k = 2)

Key comparison CCEM-K2

MEASURAND: Resistance **NOMINAL VALUE: 1 GΩ**

The key comparison reference value for this comparison is obtained from the weighted average of the participants. The key comparison reference value is $X_{KCRV} = 0.099 \times 10^{-6}$ and the expanded relative uncertainty is $U_{KCRV} = 3.19 \times 10^{-6}$ for the 1 GΩ resistance level.

The degree of equivalence of each laboratory with respect to the reference value is given by a pair of numbers: $D_{i\,KCRV} = D_{i\,COMB} - X_{KCRV}$ and the expanded relative uncertainty $U_{i\,KCRV} = (U_{i\,COMB}^2 - U_{KCRV}^2)^{1/2}$ where D_{iCOMB} is the weighted mean of the three 1 GΩ traveling standards differences from a least-squares linear regression of the NIST values for each traveling standard. The calculation of the $D_{i\,COMB}$s and $U_{i\,COMB}$s are described in detail in the report.

The degree of equivalence between two laboratories is given by a pair of numbers: $D_{ij} = D_{i\,KCRV} - D_{j\,KCRV}$ and the expanded relative uncertainty U_{ij} which calculation is described in detail in the report.

Lab *i* ↓ / Lab *j* →	$D_{i\,KCRV}$ (x 10⁻⁶)	$U_{i\,KCRV}$ (x 10⁻⁶)	NIST D_{ij}	NIST U_{ij}	NRC D_{ij}	NRC U_{ij}	BNM-LCIE D_{ij}	BNM-LCIE U_{ij}	NPL D_{ij}	NPL U_{ij}	PTB D_{ij}	PTB U_{ij}	CSIRO-NML D_{ij}	CSIRO-NML U_{ij}	MSL D_{ij}	MSL U_{ij}	CSIR-NML D_{ij}	CSIR-NML U_{ij}
			(x 10⁻⁶)		(x 10⁻⁶)		(x 10⁻⁶)		(x 10⁻⁶)		(x 10⁻⁶)		(x 10⁻⁶)		(x 10⁻⁶)		(x 10⁻⁶)	
NIST	-0.1	8.6			0.1	22.1	1.2	20.5	7.1	14.7	-3.4	16.3	-2.2	67.5	-4.7	11.8	53	581
NRC	-0.2	19.8	-0.1	22.1			1.0	26.7	6.9	22.7	-3.5	23.7	-2.3	69.7	-4.8	20.9	53	581
BNM-LCIE	-1.3	18.0	-1.2	20.5	-1.0	26.7			5.9	21.2	-4.5	22.3	-3.4	69.3	-5.9	19.3	52	581
NPL	-7.2	11.0	-7.1	14.7	-6.9	22.7	-5.9	21.2			-10.4	17.2	-9.2	67.8	-11.8	13.1	46	581
PTB	3.3	13.0	3.4	16.3	3.5	23.7	4.5	22.3	10.4	17.2			1.2	68.1	-1.3	14.9	56	581
CSIRO-NML	2.1	66.8	2.2	67.5	2.3	69.7	3.4	69.3	9.2	67.8	-1.2	68.1			-2.5	67.2	55	585
MSL	4.6	6.6	4.7	11.8	4.8	20.9	5.9	19.3	11.8	13.1	1.3	14.9	2.5	67.2			57	581
CSIR-NML	-53	581	-53	581	-53	581	-52	581	-46	581	-56	581	-55	585	-57	581		
SP	-1.6	10.0	-1.5	14.0	-1.3	22.1	-0.3	20.7	5.6	15.1	-4.8	16.6	-3.7	67.7	-6.2	12.5	51	581
OFMET	2.9	22.8	3.0	24.8	3.1	30.1	4.2	29.0	10.0	25.4	-0.4	26.3	0.8	70.7	-1.7	23.9	56	581
IEN	2.5	19.3	2.6	21.6	2.7	27.5	3.7	26.3	9.6	22.2	-0.8	23.3	0.4	69.6	-2.2	20.6	55	581
NMi-VSL	-32.3	36.3	-32.2	37.6	-32.1	41.2	-31.1	40.5	-25.2	37.9	-35.6	38.6	-34.4	76.1	-36.9	37.0	20	582
KRISS	-1.5	12.4	-1.4	15.8	-1.2	23.0	-0.2	21.6	5.7	16.4	-4.7	17.9	-3.5	68.0	-6.1	14.2	51	581
NIM	-0.6	8.3	-0.5	12.9	-0.4	20.8	0.6	19.3	6.5	13.3	-3.9	15.1	-2.7	67.3	-5.2	10.5	52	581
VNIIM	0.0	7.3	0.1	12.2	0.2	20.3	1.2	18.8	7.1	12.5	-3.3	14.4	-2.1	67.2	-4.7	9.5	53	581

Lab *i* ↓ / Lab *j* →	$D_{i\,KCRV}$ (x 10⁻⁶)	$U_{i\,KCRV}$ (x 10⁻⁶)	SP D_{ij}	SP U_{ij}	OFMET D_{ij}	OFMET U_{ij}	IEN D_{ij}	IEN U_{ij}	NMi-VSL D_{ij}	NMi-VSL U_{ij}	KRISS D_{ij}	KRISS U_{ij}	NIM D_{ij}	NIM U_{ij}	VNIIM D_{ij}	VNIIM U_{ij}
			(x 10⁻⁶)		(x 10⁻⁶)		(x 10⁻⁶)		(x 10⁻⁶)		(x 10⁻⁶)		(x 10⁻⁶)		(x 10⁻⁶)	
NIST	-0.1	8.6	1.5	14.0	-3.0	24.8	-2.6	21.6	32.2	37.6	1.4	15.8	0.5	12.9	-0.1	12.2
NRC	-0.2	19.8	1.3	22.1	-3.1	30.1	-2.7	27.5	32.1	41.2	1.2	23.0	0.4	20.8	-0.2	20.3
BNM-LCIE	-1.3	18.0	0.3	20.7	-4.2	29.0	-3.7	26.3	31.1	40.5	0.2	21.6	-0.6	19.3	-1.2	18.8
NPL	-7.2	11.0	-5.6	15.1	-10.0	25.4	-9.6	22.2	25.2	37.9	-5.7	16.4	-6.5	13.3	-7.1	12.5
PTB	3.3	13.0	4.8	16.6	0.4	26.3	0.8	23.3	35.6	38.6	4.7	17.9	3.9	15.1	3.3	14.4
CSIRO-NML	2.1	66.8	3.7	67.7	-0.8	70.7	-0.4	69.6	34.4	76.1	3.5	68.0	2.7	67.3	2.1	67.2
MSL	4.6	6.6	6.2	12.5	1.7	23.9	2.2	20.6	36.9	37.0	6.1	14.2	5.2	10.5	4.7	9.5
CSIR-NML	-53	581	-51	581	-56	581	-55	581	-20	582	-51	581	-52	581	-53	581
SP	-1.6	10.0			-4.5	25.1	-4.0	22.0	30.8	37.8	-0.1	16.2	-1.0	13.1	-1.5	12.3
OFMET	2.9	22.8	4.5	25.1			0.4	30.0	35.2	42.9	4.3	26.1	3.5	24.3	2.9	23.9
IEN	2.5	19.3	4.0	22.0	-0.4	30.0			34.8	41.2	3.9	23.1	3.1	21.0	2.5	20.6
NMi-VSL	-32.3	36.3	-30.8	37.8	-35.2	42.9	-34.8	41.2			-30.9	38.4	-31.7	37.2	-32.3	37.0
KRISS	-1.5	12.4	0.1	16.2	-4.3	26.1	-3.9	23.1	30.9	38.4			-0.8	15.0	-1.4	14.4
NIM	-0.6	8.3	1.0	13.1	-3.5	24.3	-3.1	21.0	31.7	37.2	0.8	15.0			-0.6	11.0
VNIIM	0.0	7.3	1.5	12.3	-2.9	23.9	-2.5	20.6	32.3	37.0	1.4	14.4	0.6	11.0		

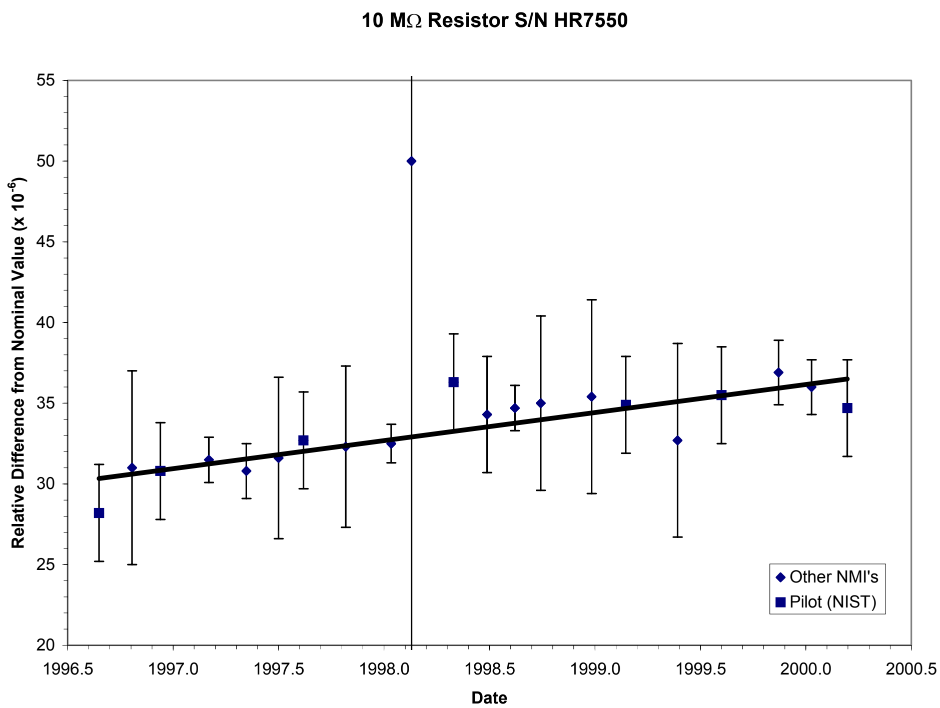

Figure 1. Measurements of 10 MΩ standard S/N HR7550 by all participants. Error bars denote individual NMI's expanded relative uncertainty using $k = 2$. Least-squares linear regression line based only on the pilot laboratory measurements.

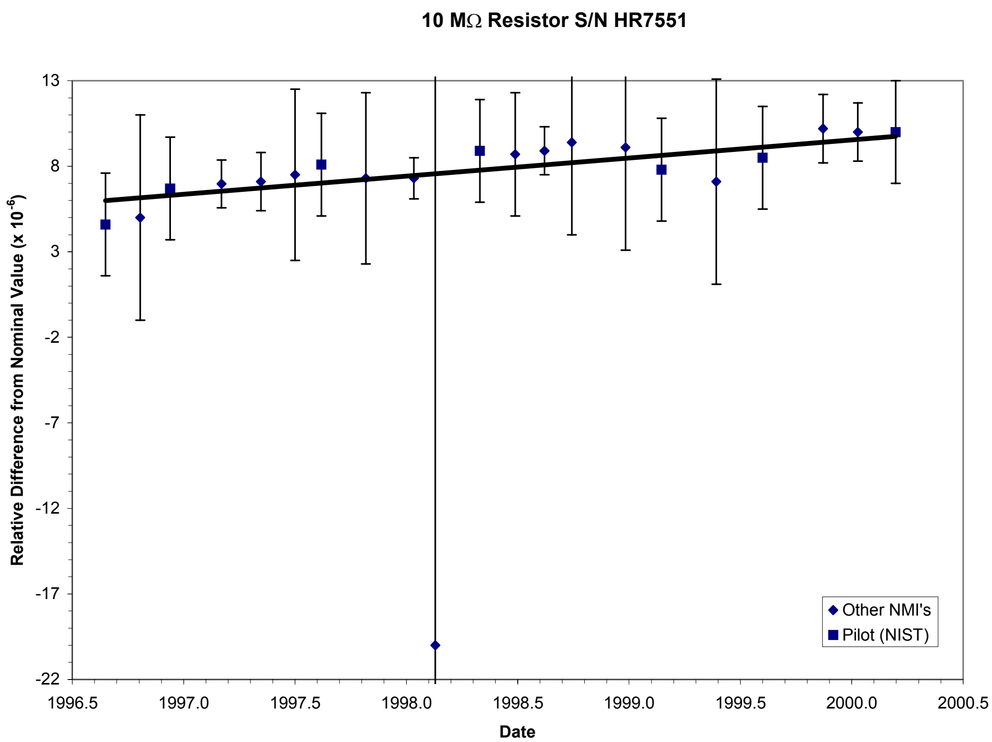

Figure 2. Measurements of 10 MΩ standard S/N HR7551 by all participants. Error bars denote individual NMI's expanded relative uncertainty using $k = 2$. Least-squares linear regression line based only on the pilot laboratory measurements.

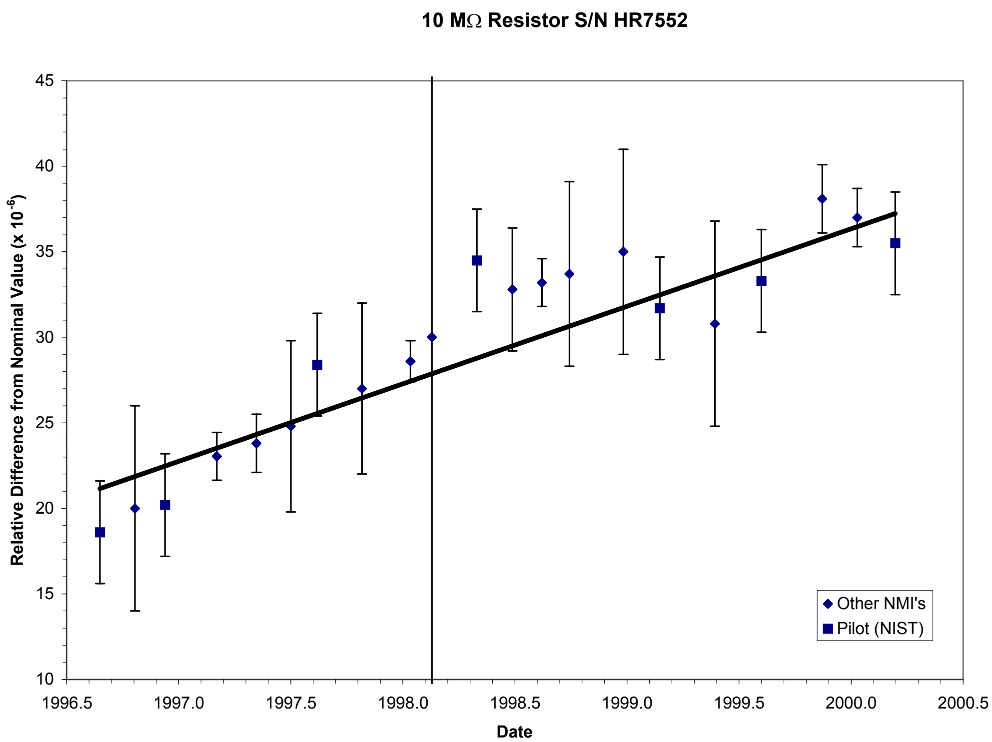

Figure 3. Measurements of 10 MΩ standard S/N HR7552 by all participants. Error bars denote individual NMI's expanded relative uncertainty using $k = 2$. Least-squares linear regression line based only on the pilot laboratory measurements.

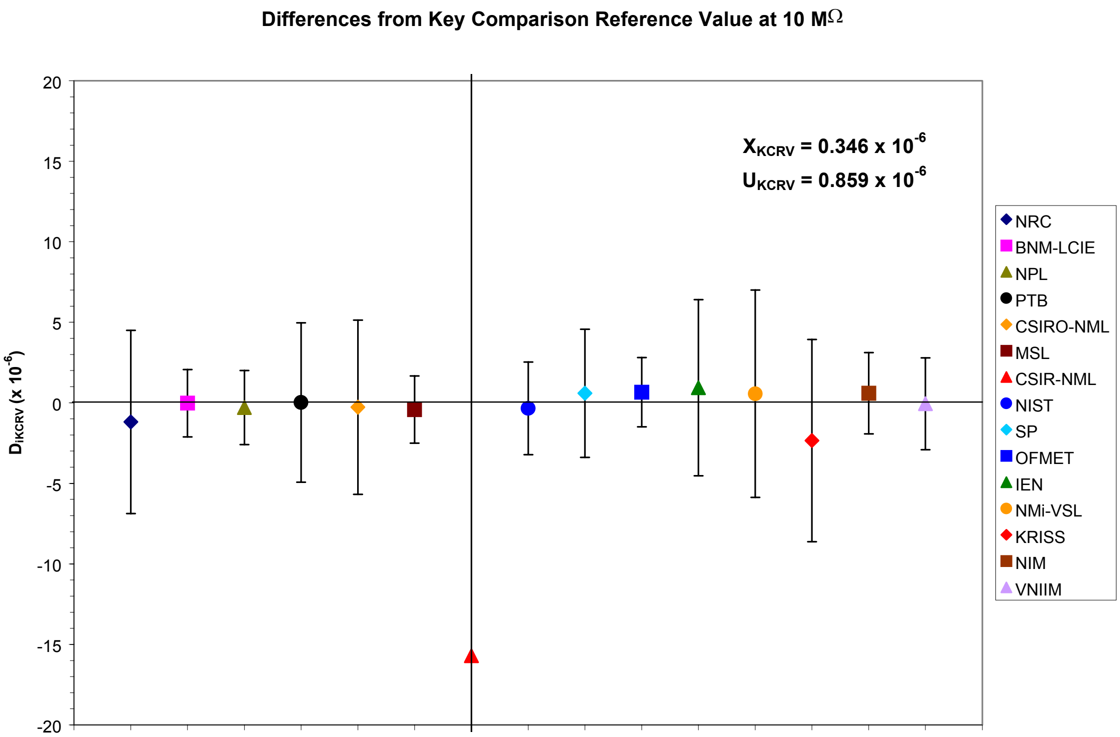

Figure 4. Differences from key comparison reference value, $D_{i\text{KCRV}}$, at 10 MΩ. Error bars denote ± expanded relative uncertainty, $U_{i\text{KCRV}}$, for the individual NMIs using $k = 2$, which includes the U_{KCRV}.

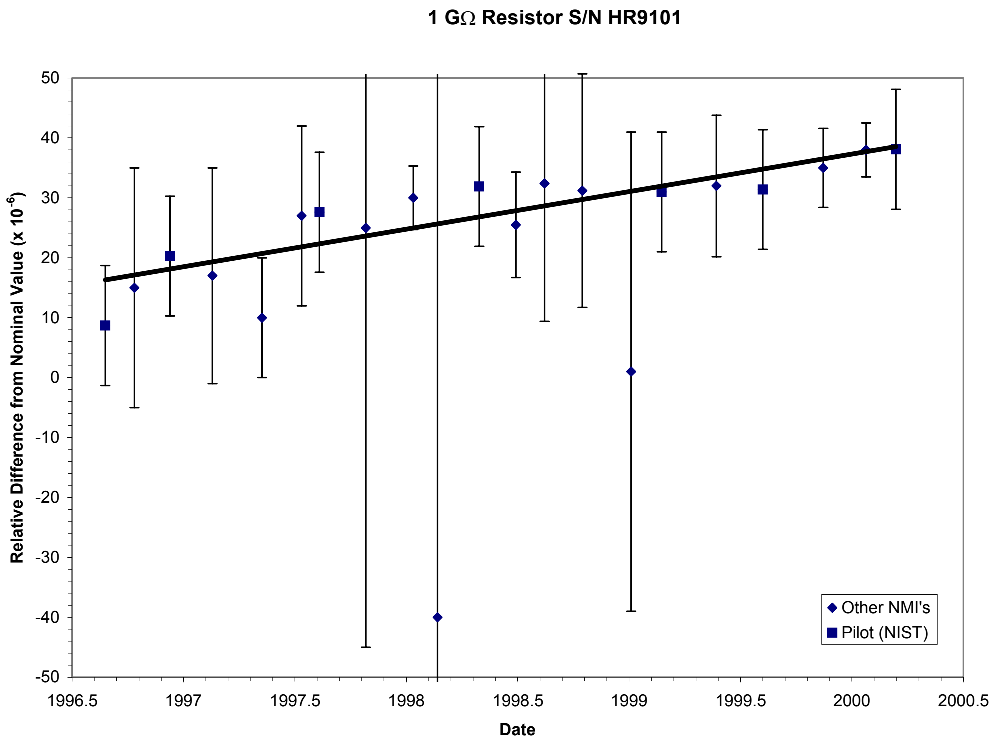

Figure 5. Measurements of 1 GΩ standard S/N HR9101 by all participants. Error bars denote individual NMI's expanded relative uncertainty using $k = 2$. Least-squares linear regression line based only on the pilot laboratory measurements.

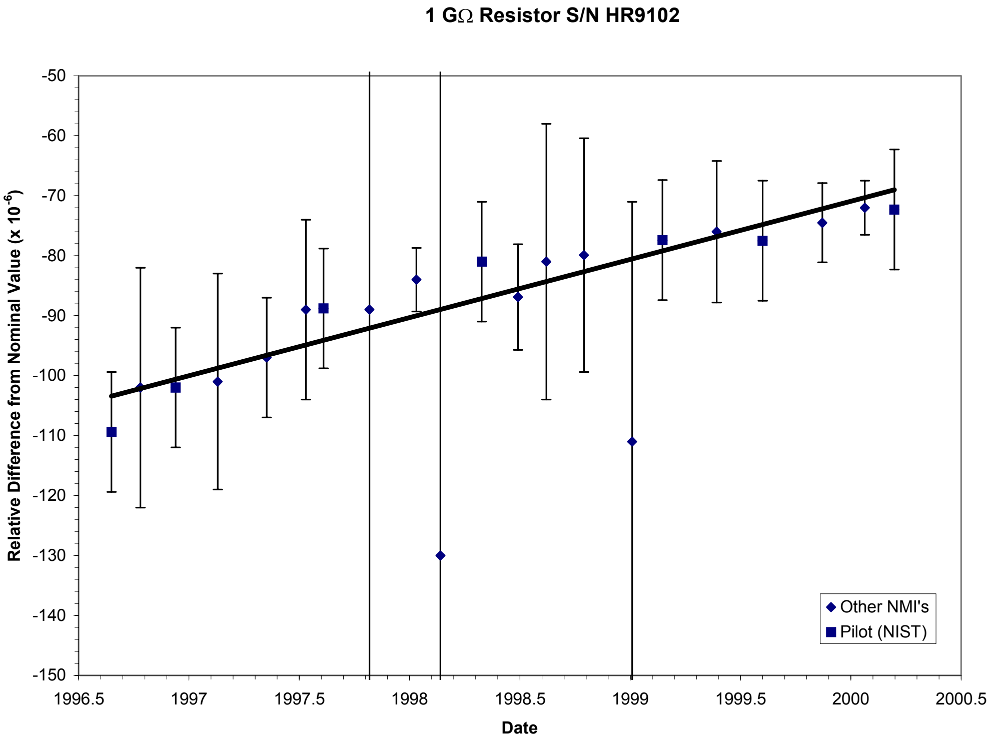

Figure 6. Measurements of 1 GΩ standard S/N HR9102 by all participants. Error bars denote individual NMI's expanded relative uncertainty using $k = 2$. Least-squares linear regression line based only on the pilot laboratory measurements.

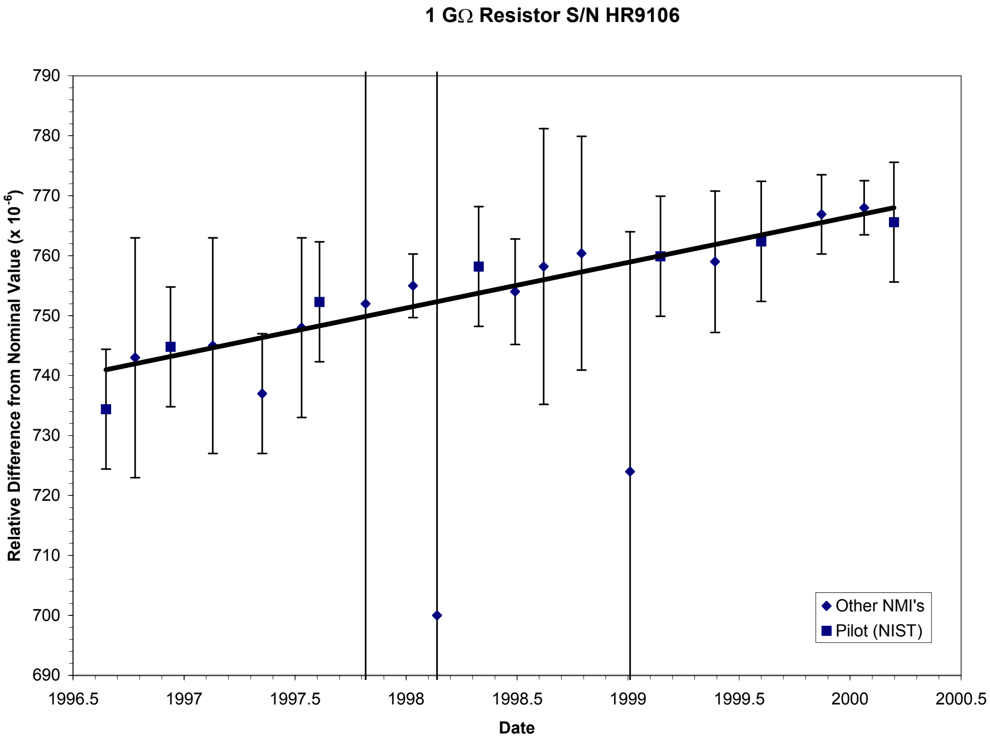

Figure 7. Measurements of 1 GΩ standard S/N HR9106 by all participants. Error bars denote individual NMI's expanded relative uncertainty using $k = 2$. Least-squares linear regression line based only on the pilot laboratory measurements.

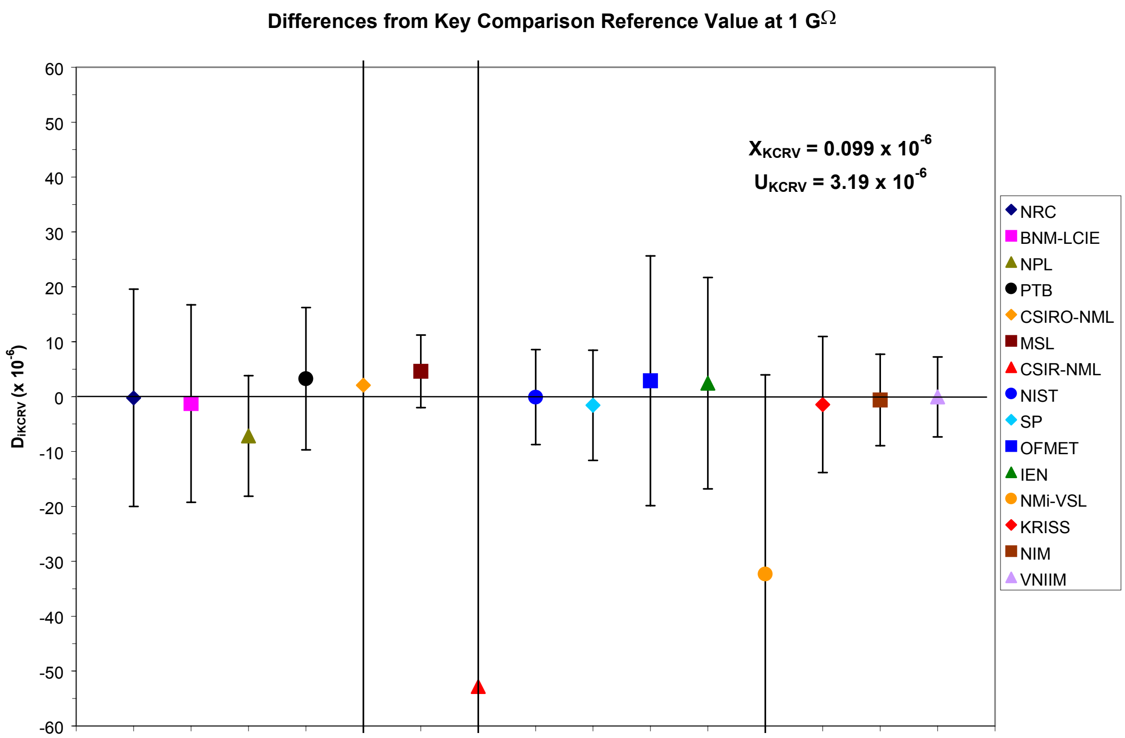

Figure 8. Differences from key comparison reference value, $D_{i\text{KCRV}}$, at 1 GΩ. Error bars denote ± expanded relative uncertainty, $U_{i\text{KCRV}}$, for the individual NMIs using $k = 2$, which includes the U_{KCRV}.

Appendix A

Unless otherwise stated, the uncertainty budgets are for measurements made at 100 volts. The uncertainty budgets provided to the pilot laboratory by the various NMIs were varied in format, detail, complexity, and content. In this appendix, a general template has been utilized for reporting the uncertainty budgets of all NMIs to provide a consistent format. The pilot laboratory has made the assumption that the uncertainty analysis provided by the participating NMIs have been determined by the best means possible and are equally trustworthy. Several of the participating NMIs included probability distributions, degrees of freedom, formulas, and detailed comments in their uncertainty analysis. Since most participating NMIs did not include detailed information in their uncertainty analysis such as probability distributions, degrees of freedom, formulas, and detailed comments are not reported in this appendix.

BNM-LCIE uncertainty budget

Source of Uncertainty	Type	Relative Standard Uncertainty, in 10^{-6}	
		10 MΩ	1 GΩ
Type A	A	0.5	2.9
Calibration of the standard resistance (10 MΩ)	B	0.16	N/A
Calibration of the standard resistance (10 MΩ) for guarded Wheatstone bridge (arm P)	B	N/A	0.65
Calibration of the standard resistance (100 kΩ) for guarded Wheatstone bridge (arm Q)	B	N/A	0.15
Calibration of the standard resistance (10 MΩ) for guarded Wheatstone bridge (arm R)	B	N/A	0.65
Drift of the standard resistance (10 MΩ)	B	Negligible	Negligible
Effect of temperature	B	0.12	N/A
Effect of temperature (arm P)	B	N/A	6.4
Effect of temperature (arm Q)	B	N/A	0.4
Effect of temperature (arm R)	B	N/A	5
Effect of power	B	Negligible	Negligible
Leakage resistances	B	0.015	N/A
Sensibility of the detector, including noise	B	0.29	2
Coefficient of temperature of the resistance under calibration	B	0.01	0.1
RSS of Type A standard uncertainties		0.50	2.90
RSS of Type B standard uncertainties		0.35	8.43
Combined standard uncertainty (1 σ)		0.61	8.91
Expanded relative uncertainty (k = 2)		1.22	17.82
Reported uncertainty		1.4	18

CSIR-NML uncertainty budget

Source of Uncertainty	Type	Relative Standard Uncertainty, in 10^{-6}	
		10 MΩ	1 GΩ
Repeatability	A	50	50
Reference standard (Fluke 742A-10M) uncertainty	B	11.5	N/A
Accuracy of Guildline 9520	B	N/A	288.7
Resolution of Guildline 9520	B	5.8	5.8
Temperature	B	4.1	12.2
RSS of Type A standard uncertainties		50	50
RSS of Type B standard uncertainties		13.52	289.02
Combined standard uncertainty (1 σ)		51.79	293.31
Expanded relative uncertainty (k = 2)		103.59	586.62
Reported uncertainty		104	600

CSIRO-NML uncertainty budget

Source of Uncertainty	Type	Relative Standard Uncertainty, in 10^{-6}	
		10 MΩ	1 GΩ
Type A	A	0.07	2.18
NML STD value at last calibration	B	0.05	0.05
NML STD value extrapolation	B	0.05	0.05
Uncertainty °C in temperature of STD (B Wall)	B	0.20	0.20
Uncertainty °C in temperature of TEST (B Wall)	B	0.10	0.10
Bridge balance 10 kΩ STD	B	0.06	0.06
Bridge balance 100 kΩ/step (P)	B	0.06	0.06
Bridge balance 100 kΩ/step (S)	B	0.06	0.06
(P) to (S) 100 kΩ/step (10 kΩ to 1 MΩ)	B	1	1
Bridge balance 1 MΩ/step (SP)	B	0.06	0.06
Bridge balance 1 MΩ/step (S)	B	0.12	0.12
(SP) to (S) 1 MΩ/step (1 MΩ to 10 MΩ)	B	2	2
Bridge balance 10 MΩ TEST	B	0.12	0
Bridge balance 100 MΩ/step (P)	B	0	0.12
Bridge balance 100 MΩ/step (S)	B	0	1.5
(P) to (S) 100 MΩ/step (10 MΩ to 1 GΩ)	B	0	3
Bridge balance 1 GΩ TEST	B	0	1.5
Insulation leakage (TEST)	B	1.2	33
Insulation leakage (100 MΩ/step)	B	0	1
RSS of Type A standard uncertainties		0.07	2.18
RSS of Type B standard uncertainties		2.56	33.30
Combined standard uncertainty (1 σ)		2.56	33.37
Expanded relative uncertainty (k = 2)		5.12	66.73
Reported uncertainty		5.0	70.0

IEN uncertainty budget (10 MΩ measurements at 10 V)

Source of Uncertainty	Type	Relative Standard Uncertainty, in 10^{-6}	
		10 MΩ	1 GΩ
Step-up from 10 kΩ to 100 kΩ standard			
Variability of repeated observation	A	0.25	N/A
Measurement of 10 kΩ reference standard from 1 Ω national standard	B	0.15	N/A
Drift and temperature variation of the 10 kΩ standard	B	0.10	N/A
Thermals and multimeter non-linearity and instability	B	0.60	N/A
Transfer error of the 10 x 10 kΩ transfer box	B	0.50	N/A
Temperature instability and drift of the 10 x 10 kΩ transfer box	B	0.50	N/A
Step-up from 100 kΩ to 10 MΩ travelling standard			
Variability of repeated observation	A	0.75	N/A
Drift of the 100 kΩ standard	B	0.10	N/A
Thermals and multimeter non-linearity and instability	B	1.0	N/A
Transfer error of the 10 x 1 MΩ Hamon box	B	2.0	N/A
Temperature instability and drift of the 10 x 1 MΩ transfer box	B	0.70	N/A
Temperature instability of the 10 MΩ travelling standards	B	0.10	N/A
Calibration of the 1 GΩ travelling standards			
Variability of repeated observation	A	N/A	3.5
Measurement of 1 MΩ reference standard from the 1 Ω national standard	B	N/A	1.5
Drift and temperature variation of the 1 MΩ standard	B	N/A	0.7
Multimeter accuracy in the measurement of the voltage across 1 MΩ (100 mV)	B	N/A	6.5
Multimeter input resistance load	B	N/A	3.0
Instability of thermal voltages and of the multimeter input bias current	B	N/A	1.2
Multimeter accuracy in the measurement of the total voltage (100 V)	B	N/A	4.8
Temperature instability of the 1 GΩ travelling standards	B	N/A	2.0
RSS of Type A standard uncertainties		0.79	3.50
RSS of Type B standard uncertainties		2.53	9.08
Combined standard uncertainty (1 σ)		2.65	9.73
Expanded relative uncertainty (k = 2)		5.30	19.46
Reported uncertainty		5.4	19.5

KRISS uncertainty budget

Source of Uncertainty	Type	Relative Standard Uncertainty, in 10^{-6}	
		10 MΩ	1 GΩ
10:1 ratio	A	0.3	0.7
Ratio accuracy	B	2	2
Temperature variation	B	0.1	1.5
Leakage	B	0.1	1
Detector linearity	B	2	2
Detector stability	B	0.1	1
Reference standards	B	1	4.4
RSS of Type A standard uncertainties		0.30	0.70
RSS of Type B standard uncertainties		3.00	5.62
Combined standard uncertainty (1 σ)		3.02	5.67
Expanded relative uncertainty (k = 2)		6.04	11.33
Reported uncertainty		6.0	11.8

MSL uncertainty budget

Source of Uncertainty	Type	Relative Standard Uncertainty, in 10^{-6}	
		10 MΩ	1 GΩ
Stability of resistor at MSL	A	0.04	0.86
ESI SR1010 10*100 kΩ reference resistor	B	0.30	N/A
H100M*10 Hamon reference made by MSL	B	N/A	2.15
DC voltage ratio correction	B	0.51	0.09
Bridge null	B	0.02	0.304
Lead correction	B	0.00001	0.0
RSS of Type A standard uncertainties		0.04	0.86
RSS of Type B standard uncertainties		0.59	2.17
Combined standard uncertainty (1 σ)		0.59	2.34
Expanded relative uncertainty (k = 2)		1.19	4.67
Reported uncertainty (for 1 GΩ, k = 2.36)		1.2	5.3

NIM uncertainty budget (10 MΩ and 1 GΩ measurements at 91 V)

Source of Uncertainty	Type	Relative Standard Uncertainty, in 10^{-6}	
		10 MΩ	1 GΩ
Type A	A	0.1	1
Standards	B	0.70	1.75
BVD Bridge with ratio 1:1 and 10:1	B	0.3	1
Insulation	B	0.1	0.5
Offset and drift of detector	B	0.1	2
Hamon resistors	B	Negligible	Negligible
Temperature	B	0.3	1
Pressure	B	Negligible	Negligible
VCR	B	N/A	0.5
RSS of Type A standard uncertainties		0.10	1.00
RSS of Type B standard uncertainties		0.83	3.09
Combined standard uncertainty (1 σ)		0.84	3.25
Expanded relative uncertainty ($k = 2$)		1.67	6.50
Reported uncertainty		2.0	6.6

NIST uncertainty budget

Source of Uncertainty	Type	Relative Standard Uncertainty, in 10^{-6}	
		10 MΩ	1 GΩ
Repeatability	A	0.20	2.0
Leakage	B	0.10	1.0
Ambient	B	1.0	2.0
Standards	B	1.0	4.0
Detector	B	0.10	0.2
Linearity	B	0.50	0.5
RSS of Type A standard uncertainties		0.20	2.00
RSS of Type B standard uncertainties		1.51	4.61
Combined standard uncertainty (1 σ)		1.52	5.03
Expanded relative uncertainty ($k = 2$)		3.04	10.06
Reported uncertainty		3.0	10.0

NMi-VSL uncertainty budget

Source of Uncertainty	Type	Relative Standard Uncertainty, in 10^{-6}	
		10 MΩ	1 GΩ
Total uncertainty for different measurement setups (ratios)	A	0.8	8
Reference resistor value	B	1.8	12
Drift of the reference resistor	B	1.5	2.5
Temperature influence on the reference resistor	B	0.2	0.5
Correction factors for bridge errors	B	1.2	12
Temperature influence on the DUT	B	1.5	2.5
RSS of Type A standard uncertainties		0.80	8.00
RSS of Type B standard uncertainties		3.04	17.34
Combined standard uncertainty (1 σ)		3.14	19.10
Expanded relative uncertainty (k = 2)		6.28	38.20
Reported uncertainty		6.0	40.0

NPL uncertainty budget

Source of Uncertainty	Type	Relative Standard Uncertainty, in 10^{-6}	
		10 MΩ	1 GΩ
Step-up from 10 kΩ to 100 kΩ standard			
10 kΩ reference	A	0.011	N/A
Transfer to 10 x 100 kΩ in parallel	A	0.003	N/A
100 kΩ series-parallel value to bridge internal standard	A	0.150	N/A
Transfer of 100 kΩ standard	A	0.150	N/A
10 kΩ reference	B	0.025	N/A
Temperature 10 kΩ standard	B	0.010	N/A
Transfer to 10 x 100 kΩ in parallel	B	0.006	N/A
Accuracy of ratio standard	B	0.030	N/A
Temperature of ratio standard	B	0.010	N/A
100 kΩ series-parallel value to bridge internal standard	B	0.032	N/A
Temperature stability of bridge internal standard	B	0.200	N/A
Transfer of 100 kΩ standard	B	0.032	N/A

<u>Step-up from 100 kΩ to 10 MΩ standards</u>			
Transfer to bridge internal standard	A	0.150	N/A
Transfer to 10 x 1 MΩ in parallel	A	0.150	N/A
Transfer to bridge internal standard	A	0.300	N/A
Transfer to 10 MΩ unknown	A	0.300	N/A
Temperature 100 kΩ standard	B	0.100	N/A
Transfer to bridge internal standard	B	0.007	N/A
Temperature stability of bridge internal standard	B	0.060	N/A
Transfer to 10 x 1 MΩ in parallel	B	0.007	N/A
Accuracy of 100:1 ratio standard	B	0.500	N/A
Temperature stability of ratio standard	B	0.100	N/A
Transfer to bridge internal standard	B	0.007	N/A
Temperature stability of bridge internal standard	B	0.200	N/A
Transfer to 10 MΩ unknown	B	0.100	N/A
<u>Calibration of the 1 GΩ standards</u>			
Transfer to bridge internal standard	A	N/A	0.300
Transfer to 10 x 100 MΩ in parallel	A	N/A	0.300
Transfer to 1 GΩ standard	A	N/A	1.000
Transfer to 1 GΩ unknown	A	N/A	1.000
Transfer to bridge internal standard	B	N/A	0.100
Temperature stability of bridge internal standard	B	N/A	0.200
Transfer to 10 x 100 MΩ in parallel	B	N/A	0.100
Accuracy of 100:1 ratio standard	B	N/A	3.000
Temperature stability of ratio standard	B	N/A	1.000
Transfer to 1 GΩ standard	B	N/A	2.500
Temperature stability of 1 GΩ	B	N/A	0.500
Transfer to 1 GΩ unknown	B	N/A	2.500
RSS of Type A standard uncertainties		0.520	1.476
RSS of Type B standard uncertainties		0.606	4.776
Combined standard uncertainty (1 σ)		0.799	4.999
Expanded relative uncertainty (k = 2)		1.6	10.0
Reported uncertainty		1.7	10.0

NRC uncertainty budget (10 MΩ measurements at 10 V)

Source of Uncertainty	Type	Relative Standard Uncertainty, in 10^{-6}	
		10 MΩ	1 GΩ
Short term variability (DPSB)	A	1.750	2.00
Short term variability of DUT (CCE resistor)	A	0.375	1.50
Short term variability of reference standards (1 MΩ)	A	0.577	N/A
Short term variability of reference standards (100 MΩ)	A	N/A	2.89
Calibration of SR104 – 10 kΩ	B	0.010	0.01
Long term drift of SR104	B	0.041	0.04
Uncertainty of SR104 due to temperature	B	0.020	0.02
Scaling 10 kΩ to 1 MΩ (1 volt)	B	1.000	0.82
Scaling 1 MΩ to 10 MΩ (1 volt and 10 volts)	B	1.225	N/A
Scaling 1 MΩ to 100 MΩ (2 steps, 1 volt and 10 volts)	B	N/A	4.08
Uncertainty due to air bath gradients	B	0.577	1.15
Systematic error of measurement system (DPSB)	B	1.551	N/A
Systematic error of measurement system (DPSB – 10:1)	B	N/A	8.16
RSS of Type A standard uncertainties		1.88	3.82
RSS of Type B standard uncertainties		2.29	9.23
Combined standard uncertainty (1 σ)		2.96	9.99
Expanded relative uncertainty (k = 2)		5.93	19.98
Reported uncertainty		6.0	20.0

OFMET uncertainty budget (10 MΩ measurements at 10 V)

Source of Uncertainty	Type	Relative Standard Uncertainty, in 10^{-6}	
		10 MΩ	1 GΩ
Hamon stepping from 100 kΩ - Meas. at 100 kΩ	A	0.30	N/A
Reference standard 10 MΩ: tracking, temperature, and pressure coefficients	A	0.15	N/A
Power coefficient reference standard	A	0.01	N/A
Reference standard at 100 MΩ – Stepping 100 MΩ	A	N/A	3.30
Reference standard at 100 MΩ – Tracking, influence ambient condition	A	N/A	0.50
Reference standard at 100 MΩ - Power coefficient	A	N/A	0.01
DUT - Temperature corrections	A	0.05	0.48
Reproducibility; experimental standard deviation	A	0.20	2.50
Bridge 1:1 ratio measurement	B	0.09	N/A
Hamon stepping from 100 kΩ - Transfer stability	B	0.29	N/A
Hamon stepping from 100 kΩ - Hamon ratio	B	0.01	N/A
Shunt leakage bridge + connections	B	0.29	N/A
Bridge – Stability voltage sources	B	N/A	5.77
Bridge – Calibration voltage ratios	B	N/A	2.89
Bridge – Detector (electrometer)	B	N/A	8.66
DUT – Leakage	B	0.40	N/A
DUT - Temperature corrections	B	0.06	0.90
RSS of Type A standard uncertainties		0.39	4.20
RSS of Type B standard uncertainties		0.58	10.84
Combined standard uncertainty (1 σ)		0.70	11.62
Expanded relative uncertainty (k = 2)		1.41	23.24
Reported uncertainty		1.4	23.2

PTB uncertainty budget

Source of Uncertainty	Type	Relative Standard Uncertainty, in 10^{-6}	
		10 MΩ	1 GΩ
Type A	A	1	2.5
Leakages	B	0.52	1.15
Linearity	B	0.29	0.29
Detector Resolution	B	0.06	0.06
Calibrator	B	1	1
Temperature Rs	B	0.58	0.35
Temperature Rx	B	1.15	1.73
Scaling	B	0.58	1.73
Standards	B	1.2	5
RSS of Type A standard uncertainties		1.00	2.50
RSS of Type B standard uncertainties		2.19	5.79
Combined standard uncertainty (1 σ)		2.41	6.31
Expanded relative uncertainty (k = 2)		4.81	12.61
Reported uncertainty		5.0	15.0

SP uncertainty budget

Source of Uncertainty	Type	Relative Standard Uncertainty, in 10^{-6}	
		10 MΩ	1 GΩ
Random error (std dev of mean value)	A	0.17	0.49
Traceability 10 kΩ (QHR)	B	0.03	0.03
Step-up 10 kΩ – 10 MΩ	B	1.2	3.5
Stability 10 MΩ reference resistors (residuals from linear regression)	B	0.67	2.1
Measurement system, calibrators, 1:1 ratio	B	0.87	0.87
Measurement system, electrometer, 1:1 ratio	B	0.58	0.58
Uncertainty due to temperature	B	0.46	1.2
RSS of Type A standard uncertainties		0.17	0.49
RSS of Type B standard uncertainties		1.79	4.38
Combined standard uncertainty (1 σ)		1.80	4.41
Expanded relative uncertainty (k = 2)		3.59	8.82
Reported uncertainty		3.6	8.8

VNIIM uncertainty budget (10 MΩ and 1 GΩ measurements at 50 V)

Source of Uncertainty	Type	Relative Standard Uncertainty, in 10^{-6}	
		10 MΩ	1 GΩ
Repeatability	A	0.25	1.0
Traceability of the reference standard	B	0.7	1.1
Not ideal isolation (insulation) of the bridge	B	0.1	0.4
Not ideal screening of the bridge	B	0.1	0.45
Correction for resistance of the connecting cables	B	0.25	0.8
Non equilibrium temperature of the traveling resistors and temperature measurement	B	0.6	1.5
Variation of the comparator constant	B	0.3	0.7
Drift of the null detector	B	0.2	0.4
RSS of Type A standard uncertainties		0.25	1.00
RSS of Type B standard uncertainties		1.03	2.26
Combined standard uncertainty (1 σ)		1.06	2.47
Expanded relative uncertainty (k = 2)		2.12	4.94
Reported uncertainty		1.7	4.5