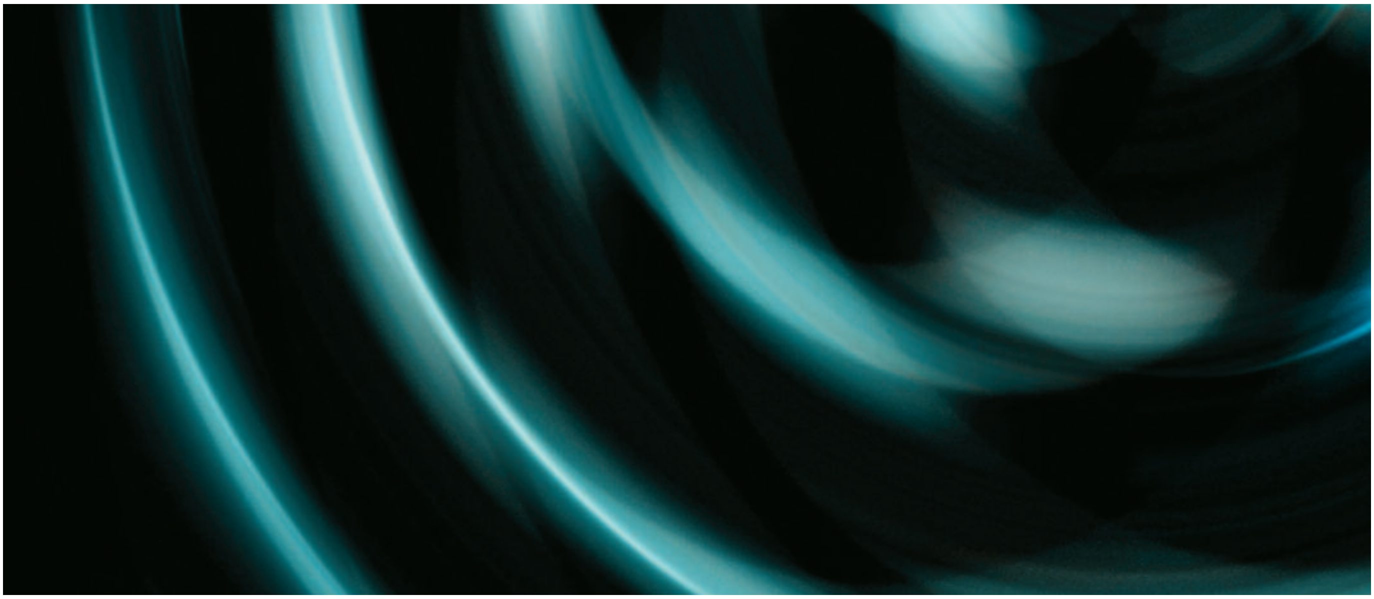

North American One Gigaohm Interlaboratory Comparison: 2006–2008

Jay Klevens

Abstract: Increasingly accurate high resistance measurements are required in electronic measurements. In order to verify these measurements, an interlaboratory comparison (ILC) was conducted at the 1 gigaohm (10^9 ohms) resistance level. Participants in the U. S. and Canada included manufacturers, commercial calibration laboratories, and government laboratories. Six different measurement methods were used; all six methods were validated by the ILC. The National Institute of Standards and Technology performed the opening and closing measurements on the artifacts. NCSL International provided generous support of this ILC. This paper presents the results, the methods, and the participant's associated uncertainties. Some recommendations are offered for developing more consistent uncertainty determinations for various measurement techniques and for developing a better understanding of leakage currents at high resistance measurements and guarding against them.

1. Introduction

A good method of assuring a measurement is to compare results with another laboratory. A single comparison with another laboratory will give an idea if one or the other laboratory is getting valid results, but there is a possibility that both labs are reporting similar errors. Comparing measurements with a number of other laboratories improves the probability of identifying errors. Using measurement results obtained by a national metrology institute (NMI) insures that the measurements are traceable to fundamental SI units.

Commercial proficiency test providers are excellent resources for many measurement parameters, but for unusual or little-used measurements, there are often no commercial proficiency tests available. This was the case at the 1 gigaohm ($1 \times 10^9\ \Omega$) resistance level. Thus an interlaboratory comparison (ILC) was initiated, with the support of NCSL International, to survey and to evaluate the state of measurement at this level in North America.

Not that long ago, measurements at the 1 gigaohm level were a rough, pass-fail sort of test, used in insulation and dielectric proving. Measurements with an uncertainty of 1 % were close

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to practicing state of the art. But the need to measure very small currents in ever smaller electronics, along with increasingly accurate high voltage systems, created a necessity for improved accuracies at high resistance. After several decades of development, high resistance measurements have approached parts-per-million uncertainties.

2. Proposal

The ILC was designed following *NCSLI's Recommended Practice RP-15* [1], titled, "Recommended Practice for Interlaboratory Comparisons." A comparable publication dealing with interlaboratory comparisons is *ISO 17043,* "Conformity assessment — General requirements for proficiency testing," [2] which may be purchased from the International Standards Organization (ISO). Much the same guidance for structuring an ILC is freely available on the National Institute of Standards and Technology (NIST) website. [3]

A draft proposal was developed that outlined the intent and structure of the ILC, the region (U. S. and Canada), the timeframe (2006-2007), and the nature and purpose (assisting participants in measurement at the 1 GΩ level). The author volunteered to serve as the pivot laboratory and to provide the resistors that were used as artifacts.

It is important to anticipate and, if possible, to plan in advance for the behavior of the artifacts over the projected course of the ILC. This is because an ILC may take many months to complete, and because the artifacts will be repeatedly shipped to various laboratories, as well as to the pivot laboratory. The typical problems encountered with resistors are drift over time, changes caused by physical shocks, or damage from misuse.

Because the artifacts used in the ILC were newly manufactured resistors, it was important to keep close watch on their performance. Therefore, to monitor drift over the duration of the ILC, a 'modified petal' ILC structure was chosen. In this case, the artifacts were returned to the pivot laboratory for checks after every two or three participant's measurements. While this ILC structure would lengthen the duration of the ILC, it was hoped that it would hold the artifacts under tighter measurement control.

Each participant paid the cost of shipping the artifacts to the next laboratory; otherwise the coordinator paid the costs of the ILC. NIST was chosen as the reference laboratory to provide resistance measurements at the beginning and end of the ILC (the opening and closing measurements). NCSLI was solicited for sponsorship and also to assist with the cost of the NIST measurements.

To be able to participate, the pivot laboratory and coordinator would operate 'blind,' without access to the NIST measurement data until the conclusion of the ILC.

3. Charter

Participants for the ILC were solicited at the 2006 Measurement Science Conference (MSC) and at the 2006 NCSLI Conference. The ILC charter and proposal were circulated to the various participants, with a request for comments or suggestions. These were gratefully received and were incorporated into the final charter and proposal (see appendix for charter and list of participants).

The charter defined the ILC's scope and goal, provided references, explained the sponsorship and expenses, and outlined the overall ILC structure. (See Appendix.) To protect the confidentiality of the participants' results, the charter referenced 'Level II' confidentiality, as defined in NCSLI's Recommended Practice (*RP-15,* Sections 4.3 and 4.4). In essence, the participants' results would remain anonymous. Each participant laboratory would know its own result, but not that of the other laboratories. To provide anonymity, all laboratories (except for NIST) were assigned letter codes.

4. Artifacts

The pivot laboratory provided two commercially available 1 gigaohm resistance standards. The measurement connections were via BPO (British Post Office) coaxial panel plugs mounted in fluoropolymer (PTFE) discs. As many laboratories did not have mating BPO jacks, the artifacts included accessory adaptors to BNC male and female connectors.

The standards contained a thermistor in close proximity to the internal resistor shell. The thermistor had a nominal value of 10 kΩ at 25 °C. Participants were instructed to measure the thermistor at the time of test, in order to provide an indication of the temperature inside the resistance standard's case.

The two artifacts, identified with serial numbers 6074 and 6075, were packed in a clamshell type foam filled carrying case, which was then surrounded by cushioning material and packed in a larger cardboard box for transit.

5. Instructions

Once the charter and proposal had been finalized, the participant list was closed. A draft of the ILC instructions and the proposed measurement worksheet were circulated to the participants for review and comment. After incorporating some helpful comments, the ILC instructions and worksheet were finalized, and no subsequent changes were made during the ILC.

In the instructions, participants were asked to take less than two weeks to complete the measurements and documentation. However, most participants took longer than the requested time, which resulted in the ILC extending for approximately twice its originally planned duration. This was the fault of the coordinator, who failed to adequately supervise the schedule. It is important for an ILC coordinator to press the participants to keep an ILC on schedule.

The instructions included a checklist for receiving inspection. If everything arrived in good condition, the artifacts were to be placed in a 23 °C laboratory environment. Participants noted the hours elapsed for temperature stabilization and the temperature of the artifacts at the time of test.

Participants were cautioned to use a guarded measurement system and to connect the case terminal of the artifacts to ground. The thermistor resistance was noted at the time of measurement, as well as the power to the thermistor.

Participants were asked to measure each resistor at 10 volts and at 100 volts. Not all participants were able to measure at

Date	Lab	6074 10 V (Ω)	Linear Values 10 V (Ω)	6074 100 V (Ω)	Linear Values 100 V (Ω)
9/12/2006	NIST	—–	1 000 001 150.	—–	1 000 000 900.
10/23/2006	Pivot	1 000 000 890.	1 000 001 640.	1 000 003 120.	1 000 001 281.
2/22/2007	Pivot	999 999 610.	1 000 003 098.	999 997 110.	1 000 002 413.
5/20/2007	Pivot	999 998 410.	1 000 004 137.	999 992 050.	1 000 003 221.
10/3/2007	Pivot	1 000 001 450.	1 000 005 762.	1 000 001 500.	1 000 004 484.
2/1/2008	Pivot	1 000 008 110.	1 000 007 208.	1 000 010 340.	1 000 005 607.
3/4/2008	Pivot	1 000 011 520.	1 000 007 590.	1 000 011 400.	1 000 005 904.
6/30/2008	NIST	—–	1 000 009 000.	—–	1 000 007 000.

Table 1. Reference and uncorrected pivot laboratory measurements for artifact 6074.

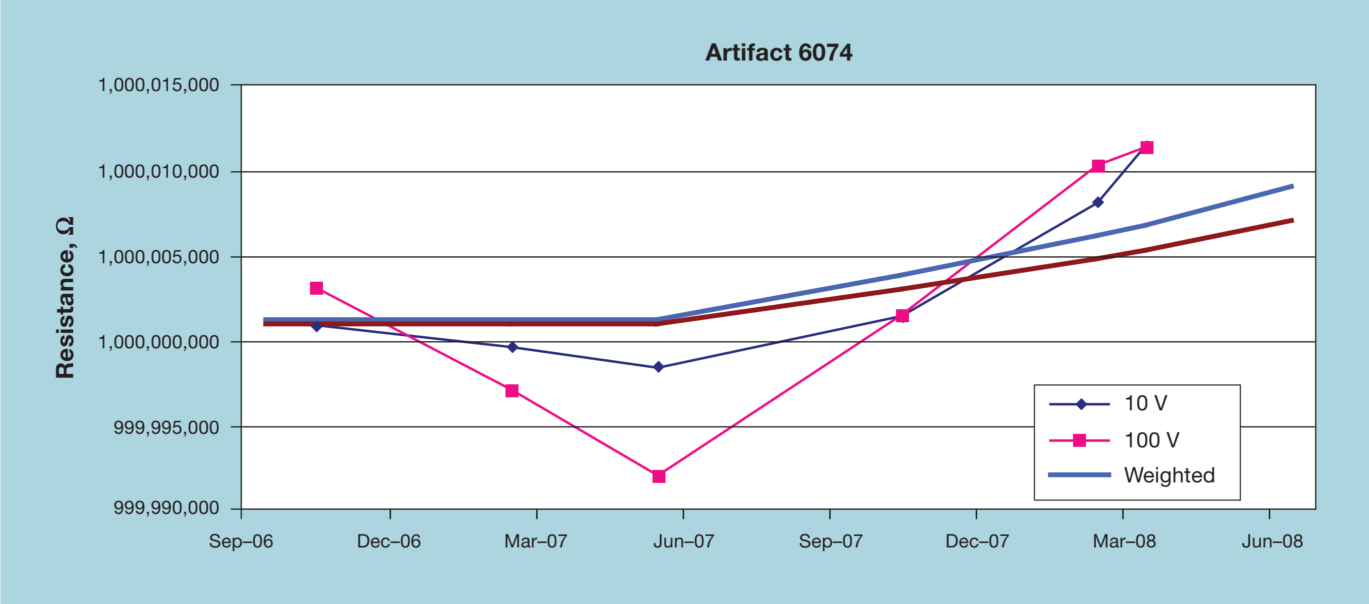

Figure 1. Reference and uncorrected pivot laboratory measurements for artifact 6074 showing the linear interpolation of the NIST data, as well as the weighted reference values.

both voltage levels. Participants were asked to provide their uncertainty budgets; this information was used to assist in working towards some uniformity in the uncertainty components unique to high resistance measurement. All but one participant filled out the uncertainty sections of the ILC worksheet. Several participants submitted extensive uncertainty analyses.

The coordinator requested electronic transmittal of all documents for the ILC. Electronic copies of the participants' documents have been archived by the coordinator, should the participants wish to see a copy of their originals.

6. Results

After all participants had reviewed their data, and after NIST had completed the closing measurements, the coordinator reviewed and analyzed the measurement results.

Tables and Figs. 1 and 2 show the NIST opening and closing data, together with the uncorrected pivot laboratory measurements. These illustrate the drift of the artifacts over the course of the ILC. The linear values shown in the tables were calculated from a linear interpolation between the opening and closing NIST measurements; they are provided for comparison purposes.

Comparing these two data sets shows that the artifacts and the pivot lab measurement system remained in control through the ILC. No widely outlying measurements appeared. The trend of the measured values appears to roughly agree with the linear values between opening and closing NIST measurements.

The data show that the resistance of each artifact varied over the 22 month time period time of the ILC. For artifact 6074, based on NIST's measurements, the resistance increased about 7 µΩ/Ω. For artifact 6075, the resistance increased about 21 µΩ/Ω. One approach to determining reference values for each laboratory's measurements is to linearly interpolate between the opening and closing NIST measurements. However, the drift of one artifact did not appear to be linear, as evidenced from the pivot laboratory's data. Therefore, instead of a linear interpolation, the coordinator chose to weight one artifact's drift based on the date and value of the intermediate pivot laboratory measurements.

Artifact 6074 appears to have dropped by a few µΩ/Ω

Date	Lab	6075 10 V (Ω)	Linear Values 10 V (Ω)	6075 100 V (Ω)	Linear Values 100 V (Ω)
9/12/2006	NIST	—–	999 999 600.	—–	999 999 200.
10/23/2006	Pivot	999 996 000.	1 000 000 935.	1 000 000 140.	1 000 000 498.
2/22/2007	Pivot	1 000 012 470.	1 000 004 909.	1 000 006 440.	1 000 004 360.
5/21/2007	Pivot	1 000 009 310.	1 000 007 776.	1 000 008 060.	1 000 007 146.
10/2/2007	Pivot	1 000 011 690.	1 000 012 140.	1 000 0116700.	1 000 011 389.
2/2/2008	Pivot	1 000 020 600.	1 000 016 147.	1 000 017 740.	1 000 015 283.
3/5/2008	Pivot	1 000 017 770.	1 000 017 189.	1 000 022 570.	1 000 016 296.
6/30/2008	NIST	—–	1 000 021 000.	—–	1 000 020 000.

Table 2. Reference and uncorrected pivot laboratory measurements for artifact 6075.

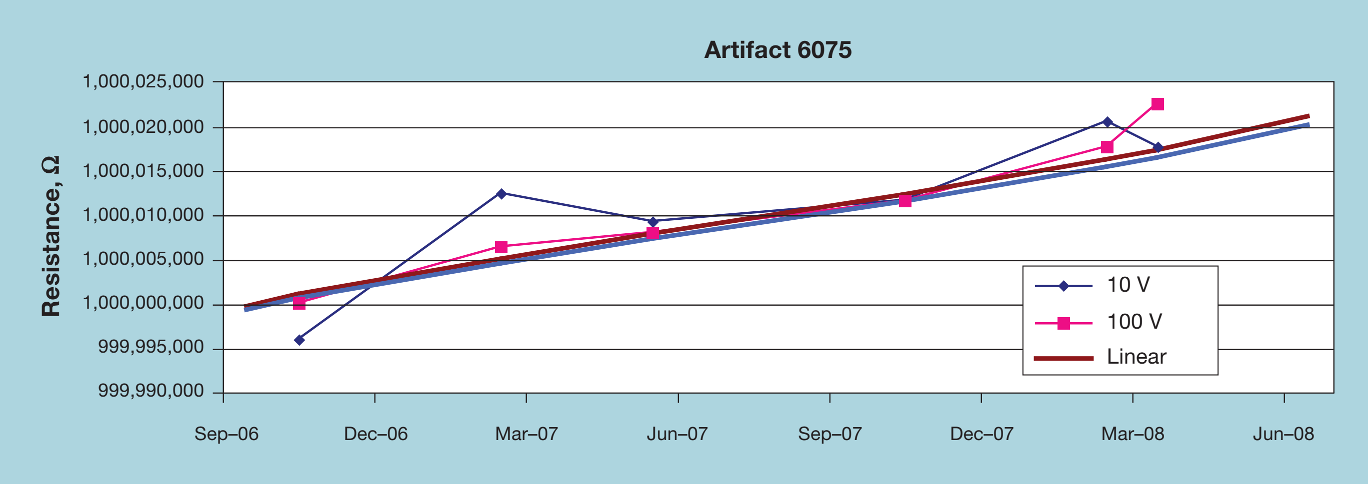

Figure 2. Reference and uncorrected pivot laboratory measurements for artifact 6075, showing the linear interpolation of the NIST data.

through the first half of the ILC, then to have drifted upwards during the second half of the ILC. Based on these data, a reference value for this artifact was derived by assigning a fixed resistance value through the first half of the ILC, and linearly interpolating the rise, fit using the opening and closing NIST measurements, through the second half of the ILC.

Artifact 6075 appears to have drifted upwards roughly linearly through the ILC. Therefore, the reference value of this artifact can be defined as a linear interpolation between the opening and closing NIST measurements. These two weighted sets of resistance values will be used as the laboratory's reference values, against which participant's results can be compared.

These weighted reference values and the participants' results are shown in Figs. 3 to 6 and Tables 3 to 6. For artifact number 6074, using the above weighting as a zero reference line, the participant's measured deviation, in μΩ/Ω, are shown in Figs. 3 and 4. For artifact number 6075, the weighted reference values were again used and results are shown in Figs. 5 and 6. Also shown in the figures are the uncertainties estimated by participants as error bars for $k = 2$. The first and last points are the opening and closing NIST measurements. Note that at both 10 V and 100 V, most of the participant's results agreed with the reference value to within about ±20 μΩ/Ω.

Where there are no results above a laboratory code, the participant did not report a measurement at that point. One participant reported excessive noise with one artifact at one measurement voltage, and this measurement was suppressed from the report. The varying horizontal spacing between measurement points indicates the elapsed days between participant's measurements. For clarity, pivot laboratory measurements are not shown in these figures.

From these figures, it is clear that nearly all participants measured the artifacts well within their claimed uncertainties. However, there were a couple of outlying measurements. Overall, the participants should be pleased with their measurement proficiency and with the general state of measurement competency at the 1 gigaohm level.

7. Proficiency Evaluation

A quantitative evaluation of measurement proficiency can be obtained by comparing the difference with the reference value to the combined uncertainty of the reference value and the uncertainty of each participant laboratory value. [2] The resulting number, E_n, is obtained by dividing the difference between a participant measurement, x, and the reference value, X, by the square root of the sum of the participant laboratory uncertainty,

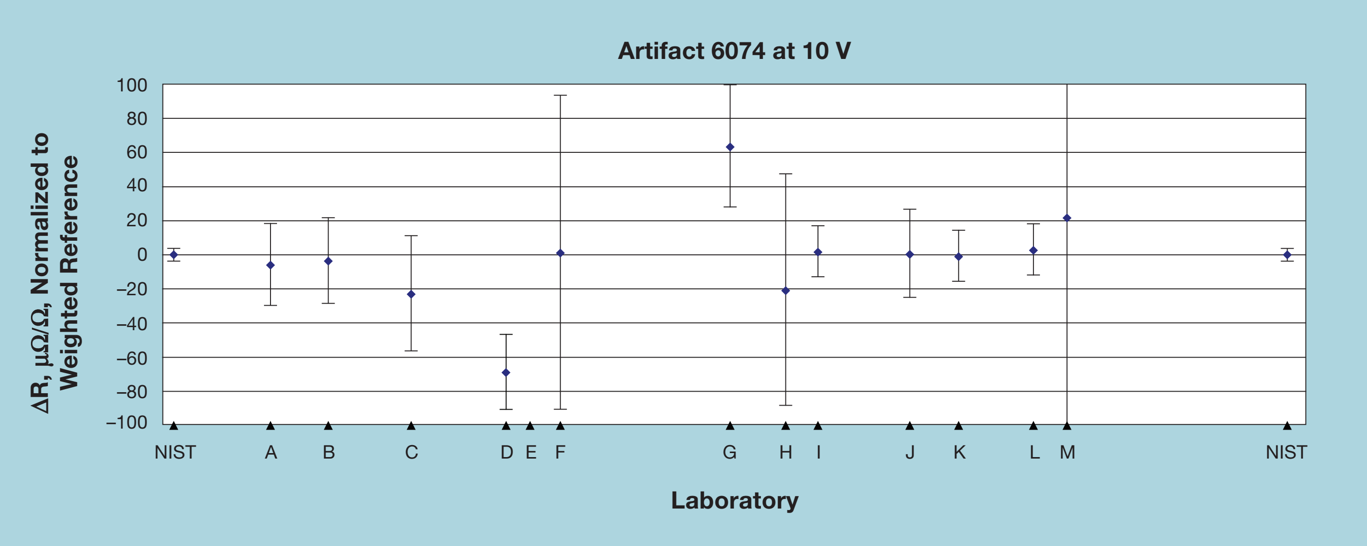

Figure 3. Variation in the participant's measurements of artifact 6074 at 10 V, normalized to weighted reference values listed in Table 3.

Date	Lab	6074 10 V (Ω)	Uncertainty (μΩ/Ω) $k = 2$	Weighted Reference (Ω)	Deviation From Ref. (Ω)	E_n
9/12/2006	NIST	1 000 001 150.	6.8	1 000 001 150.	0.	0 00
11/8/2006	A	999 995 000.	24.0	1 000 001 150.	–6 150.	–0.25
12/12/2006	B	999 997 501.	25.0	1 000 001 150.	–3 650.	–0.14
1/30/2007	C	999 978 010.	33.5	1 000 001 150.	–23 140.	–0.68
3/27/2007	D	999 932 000.	22.0	1 000 001 150.	–69 150.	–3.07
4/10/2007	E	—–	—–	1 000 001 150.	—–	—–
4/28/2007	F	1 000 002 166.	92.0	1 000 001 150.	1 016.	0.01
8/6/2007	G	1 000 064 483.	35.9	1 000 002 130.	62 350.	1.72
9/8/2007	H	999 981 000.	67.9	1 000 003 110.	–22 110.	–0.32
9/27/2007	I	1 000 004 000.	15.0	1 000 004 090.	– 90.	–0.01
11/20/2007	J	1 000 004 000.	25.9	1 000 005 080.	–1 080.	–0.04
12/19/2007	K	1 000 003 300.	15.0	1 000 006 060.	–2 760.	–0.17
2/1/2008	L	1 000 008 110.	15.0	1 000 000 040.	1 070.	0.07
2/21/2008	M	1 000 028 000.	601.4	1 000 008 020.	19 980.	0.03
6/30/20008	NIST	1 000 009 000.	6.8	1 000 009 000.	0.	0.00

Table 3. Measurement results for artifact 6074 at 10 V, showing weighted reference values along with E_n values. Values in red are greater or less than ±1.0.

U_{lab}, and reference laboratory uncertainty, U_{ref}, squared. The equation is:

$$E_n = \frac{x - X}{\sqrt{U^2_{lab} + U^2_{ref}}} \cdot \qquad (1)$$

An E_n within the range ±1.0 means that the participant laboratory value agrees with the reference value, within the bounds of the claimed measurement uncertainties. An E_n of greater than +1.0 or less than −1.0 means that the participant laboratory value lies outside the claimed measurement uncertainty. An E_n of less than ±0.5 shows a comfortable level of measurement uncertainty for the participant laboratory. E_n values of each participant are shown in Figs. 7 and 8.

8. Temperature Effects

The precious-metal oxide resistors used in high resistance stan-

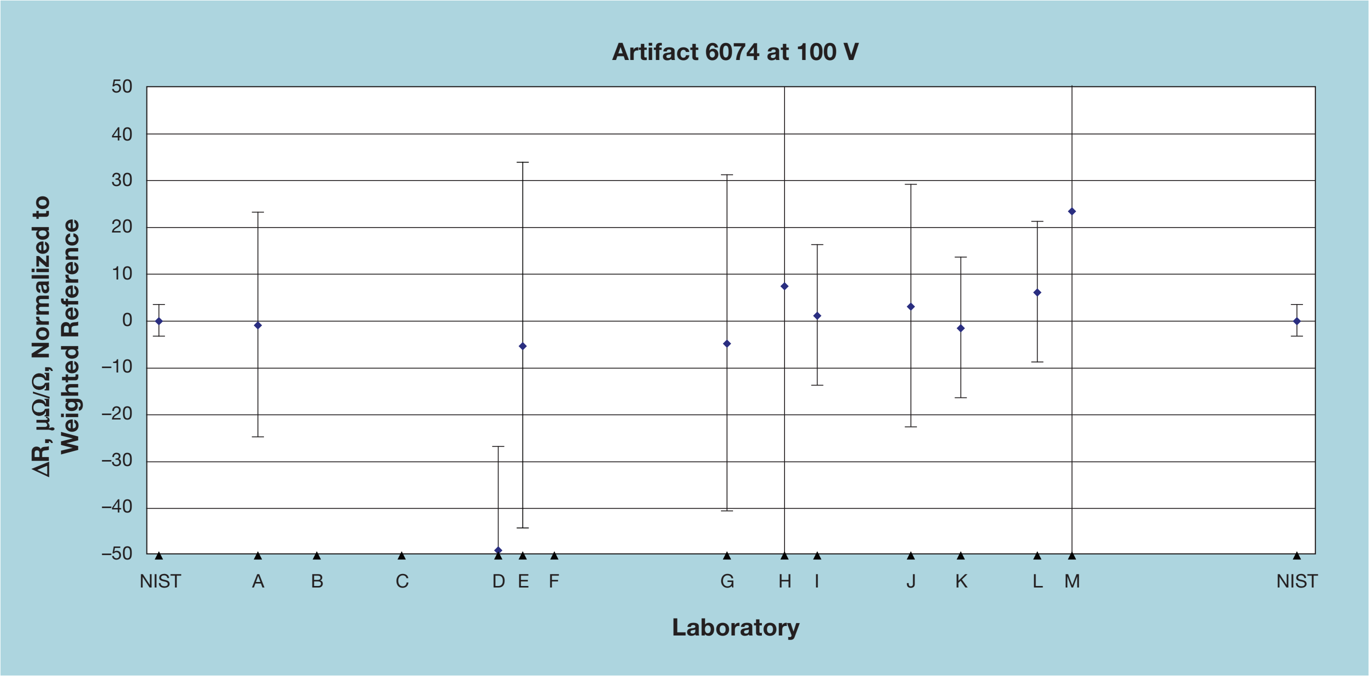

Figure 4. Variation in the participant's measurements of artifact 6074 at 100 V, normalized to weighted reference values listed in Table 4.

Date	Lab	6074 100 V (Ω)	Uncertainty (µΩ/Ω) $k = 2$	Weighted Reference (Ω)	Deviation From Ref. (Ω)	E_n
9/12/2006	NIST	1 000 000 900.	6.8	1 000 000 900.	0.	0 00
11/8/2006	A	1 000 000 000.	24.0	1 000 000 900.	–900.	–0.04
12/12/2006	B	—–	—–	1 000 000 900.	—–	—–
1/30/2007	C	—–	—–	1 000 000 900.	—–	—–
3/27/2007	D	999 952 000.	22.0	1 000 000 900.	–48 900.	–2.17
4/10/2007	E	999 995 610.	39.0	1 000 000 900.	–5 290.	–0.13
4/28/2007	F	—–	—–	1 000 000 900.	—–	—–
8/6/2007	G	999 996 092.	35.9	1 000 001 660.	–5 570.	–0.15
9/8/2007	H	1 000 009 000.	67.9	1 000 002 430.	6 580.	0.10
9/27/2007	I	1 000 003 000.	15.0	1 000 003 190.	–190.	–0.01
11/20/2007	J	1 000 006 000.	25.9	1 000 003 950.	2 050.	0.08
12/19/2007	K	1 000 001 900.	15.0	1 000 004 710.	–2 810.	–0.18
2/1/2008	L	1 000 010 340.	15.0	1 000 005 480.	4 870.	0.31
2/21/2008	M	1 000 028 000.	601.4	1 000 006 240.	21 760.	0.04
6/30/20008	NIST	1 000 007 000.	6.8	1 000 007 000.	0.	0.00

Table 4. Measurement results for artifact 6074 at 100 V, showing weighted reference values along with E_n values. Values in red are greater or less than ±1.0.

dards tend to have higher temperature coefficients of resistance (TCR) than most wire wound standard resistors. Due to the higher TCR for these standards, significant errors might be introduced by variation in the temperature of the artifact at the time of test. The artifacts in this ILC had a temperature coefficient of resistance of about +20 µΩ/Ω / °C. (Note that newer standards have lower TCR values than this value.)

Comparing the reported resistance with the reported tempera-

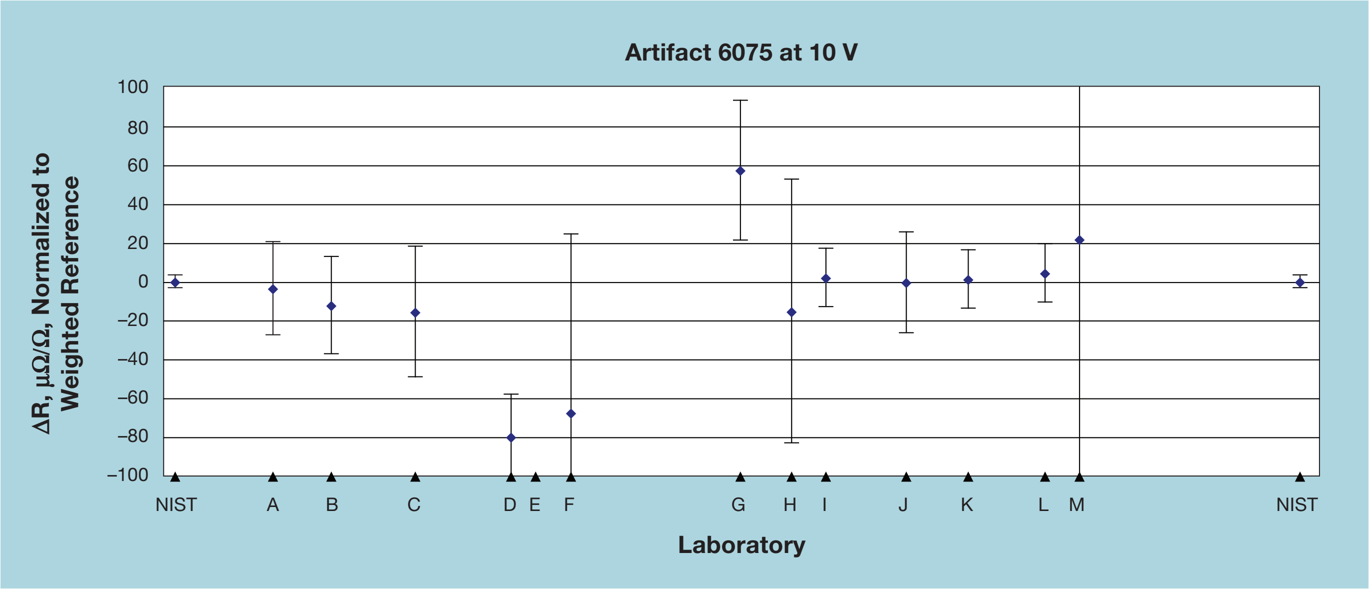

Figure 5. Variation in the participant's measurements of artifact number 6075 at 10 V, normalized to weighted reference values listed in Table 5.

Date	Lab	6075 10 V (Ω)	Uncertainty (μΩ/Ω) $k = 2$	Weighted Reference (Ω)	Deviation From Ref. (Ω)	E_n
9/12/2006	NIST	999 999 600.	6.8	999 999 600.	0.	0 00
11/8/2006	A	999 998 000.	24.0	1 000 001 460.	–3 460.	–0.14
12/12/2006	B	999 990 405.	25.0	1 000 002 560.	–12 160.	–0.48
1/30/2007	C	999 988 570.	33.5	1 000 004 160.	–15 590.	–0.46
3/27/2007	D	999 926 000.	22.0	1 000 005 980.	–79 980.	–3.55
4/10/2007	E	–––	–––	1 000 006 440.	–––	–––
4/28/2007	F	999 939 547.	92.0	1 000 007 120.	–67 580.	–0.73
8/6/2007	G	1 000 067 545.	35.9	1 000 010 350.	57 200.	1.58
9/8/2007	H	999 996 000.	67.9	1 000 011 330.	–15 300.	–0.23
9/27/2007	I	1 000 014 000.	15.0	1 000 011 980.	2 018.	0.13
11/20/2007	J	1 000 013 000.	25.9	1 000 013 510.	–510.	–0.02
12/19/2007	K	1 000 015 900.	15.0	1 000 014 680.	1 200.	0.08
2/1/2008	L	1 000 020 600.	15.0	1 000 016 150.	4 450.	0.28
2/21/2008	M	1 000 038 600.	601.4	1 000 016 800.	21 800.	0.04
6/30/20008	NIST	1 000 021 000.	6.8	1 000 021 000.	0.	0.00

Table 5. Measurement results for artifact 6075 at 10 V, showing weighted reference values along with E_n values. Values in red are outside the range ±1.0.

ture might show the temperature dependence of the artifact. However, there does not appear to be a correlation shown by the data, as seen in Figs. 9 and 10. One laboratory reported a temperature as low as 20.2 °C but the reported value was quite close to the predicted value. The temperature distribution versus resistance deviation appears to be random. Figures 9 and 10 superimpose the weighted reference resistance to 23 °C in order to show the relative measured deviation and temperature differences.

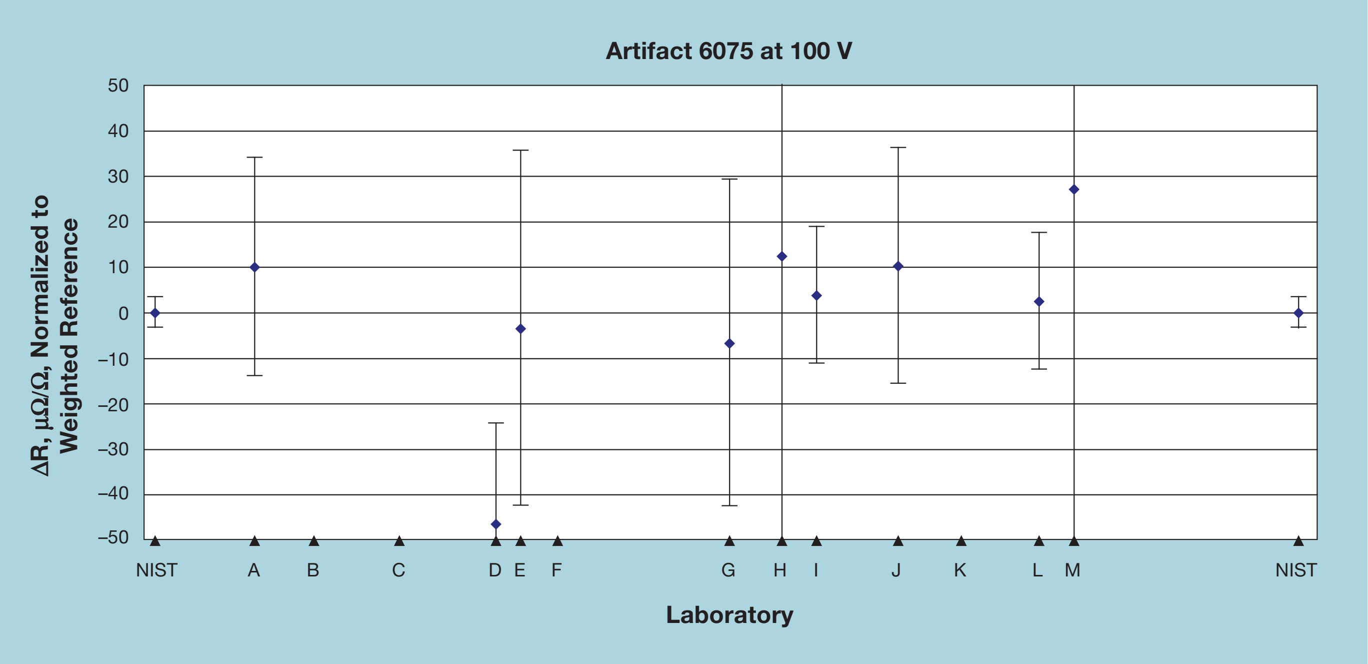

Figure 6. Variation in the participant's measurements of artifact number 6075 at 100 V, normalized to weighted reference values listed in Table 6.

Date	Lab	6075 100 V (Ω)	Uncertainty (μΩ/Ω) $k = 2$	Weighted Reference (Ω)	Deviation From Ref. (Ω)	E_n
9/12/2006	NIST	999 999 200.	6.8	999 999 200.	0.	0 00
11/8/2006	A	1 000 011 000.	24.0	1 000 001 000.	10 000.	0.41
12/12/2006	B	——	——	1 000 002 080.	——	——
1/30/2007	C	——	——	1 000 003 630.	——	——
3/27/2007	D	999 959 000.	22.0	1 000 005 410.	–46 410.	–2.06
4/10/2007	E	1 000 002 370.	39.0	1 000 005 850.	–3 480.	–0.09
4/28/2007	F	——	——	1 000 006 510.	——	——
8/6/2007	G	1 000 002 922.	35.9	1 000 009 650.	–6 728.	–0.19
9/8/2007	H	1 000 023 000.	67.9	1 000 010 600.	12 400.	0.18
9/27/2007	I	1 000 015 000.	15.0	1 000 011 230.	3 770.	0.24
11/20/2007	J	1 000 023 000.	25.9	1 000 012 720.	10 280.	0.39
12/19/2007	K	Excessive Noise	N/A	1 000 013 860.	——	——
2/1/2008	L	1 000 017 740.	15.0	1 000 015 280.	2 460.	0.16
2/21/2008	M	1 000 043 100.	601.4	1 000 015 920.	27 180.	0.05
6/30/20008	NIST	1 000 020 000.	6.8	1 000 020 000.	0.	0.00

Table 6. Measurement results for artifact 6075 at 100 V, showing weighted reference values along with E_n values. Values in red are greater or less than ±1.0.

9. Measurement Methods and Uncertainty Components

It is interesting to note that the participants used six different measurement methods, and that all six methods yielded valid results. The various methods were: (1) commercially available Cutkosky divider bridge (Measurements International MI 6000); (2 & 3) commercially available teraohmmeter (Guildline) using both the direct measurement method and the substitution method; (4) active arm (or dual source) bridge; (5) unbalanced Wheatstone bridge; and (6) substitution method

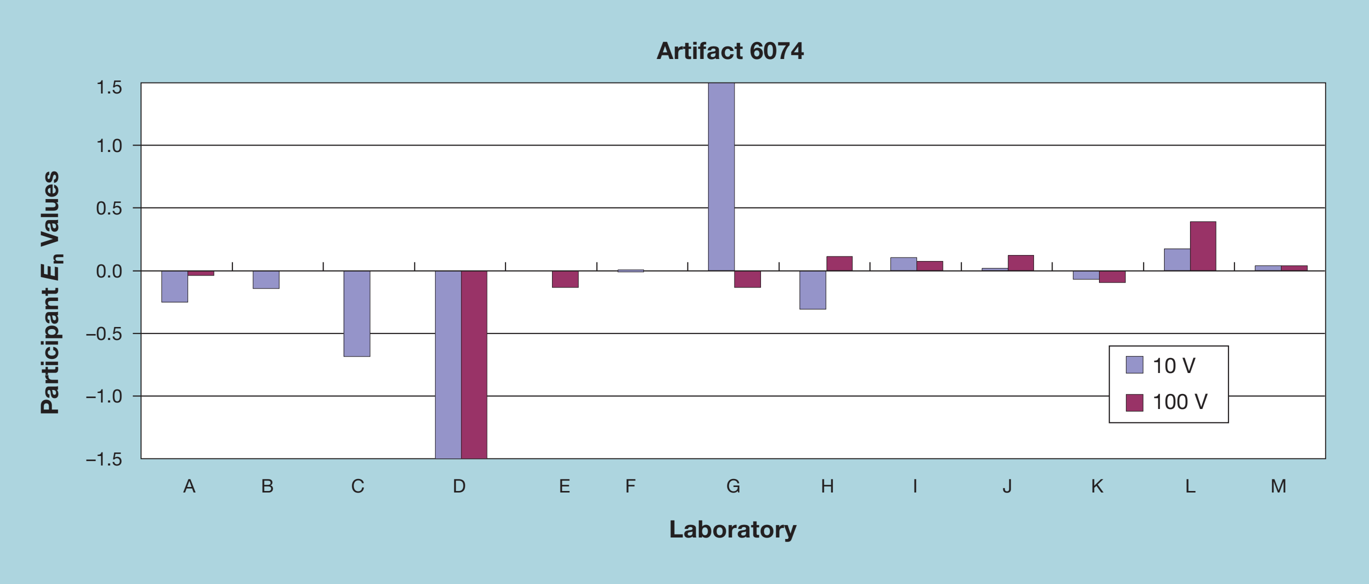

Figure 7. Participant E_n values when measuring artifact 6074 at both 10 V and 100 V.

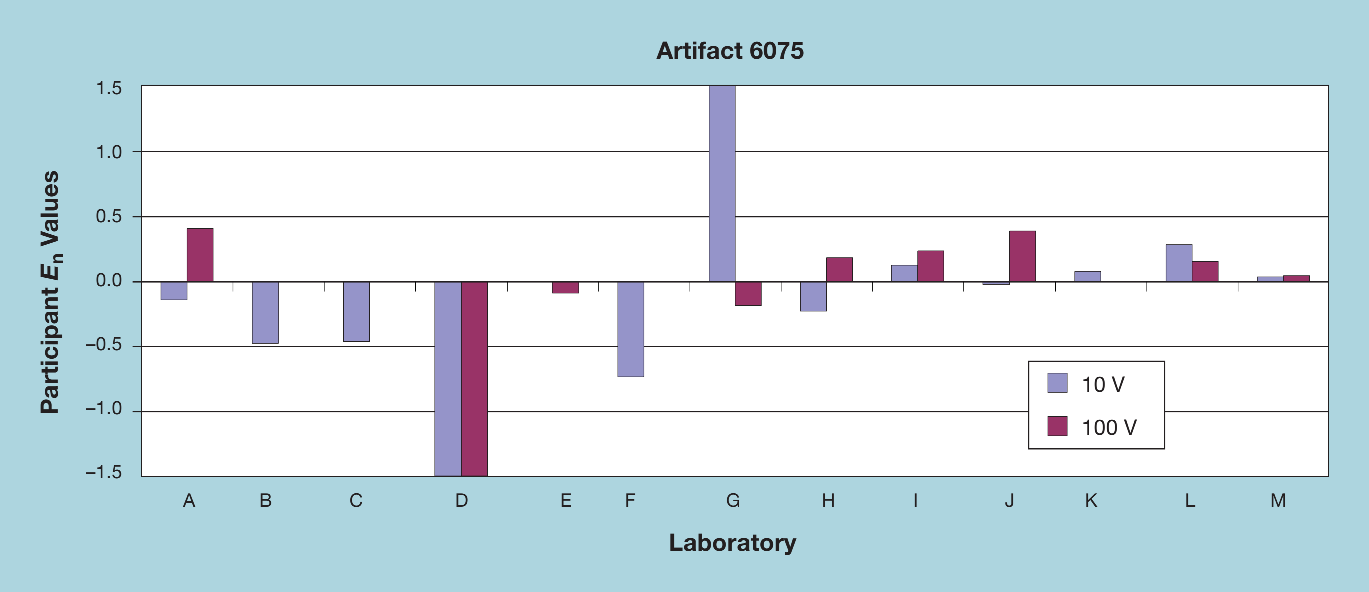

Figure 8. Participant E_n when measuring artifact 6075 at both 10 V and 100 V.

using a long-scale meter.[1] These measurement methods are listed in Table 7.

A Cutkosky divider is an R-R2 circuit suited to binary voltage division [4]; in a bridge it is used as an adjustable voltage divider to null against the measurement nodes of a standard and unknown resistor connected in series as a fixed voltage divider. An active arm bridge places a standard and an unknown resistor in series and applies positive voltage to one and negative to the other, proportioned such that roughly zero volts is present at the junction of the two resistors. The ratio of the positive and negative voltages is proportional to the ratio of the two resistances. A teraohmmeter measures how long a capacitor requires to discharge through a resistor. The unbalanced Wheatstone bridge was specially built by one participant; its results were well within its claimed uncertainty. The meter was a long-scale digital multimeter. These methods all proved satisfactory for measuring at the 1 GΩ level.

Although there was general consistency in the measurement results, the measurement uncertainties show less consistency. Twelve of the thirteen participants submitted uncertainty budgets, and all twelve budgets were different. The similarities and differences therefore warrant discussion.

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[1] Certain commercial equipment, instruments, or materials are identified in this paper in order to adequately describe the experimental procedure. Such identification does not imply recommendation or endorsement by the author or NCSL International, nor does it imply that the materials or equipment identified are the only or best available for the purpose.

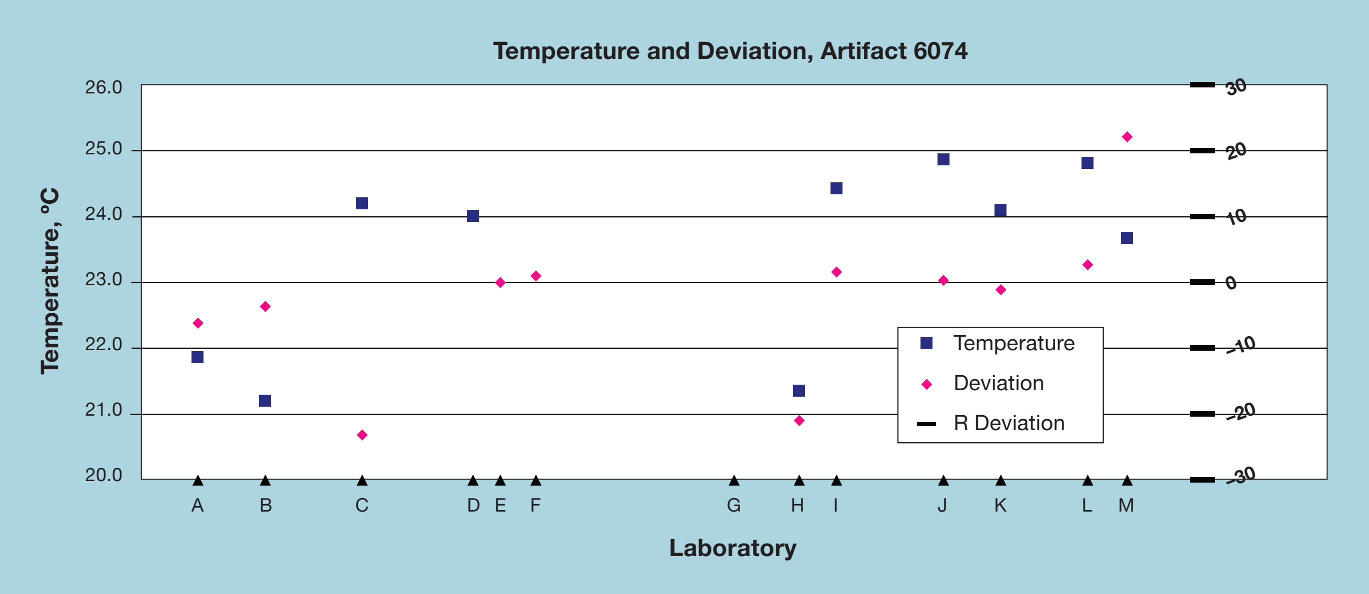

Figure 9. Temperature and resistance deviation from weighted reference value for artifact 6074.

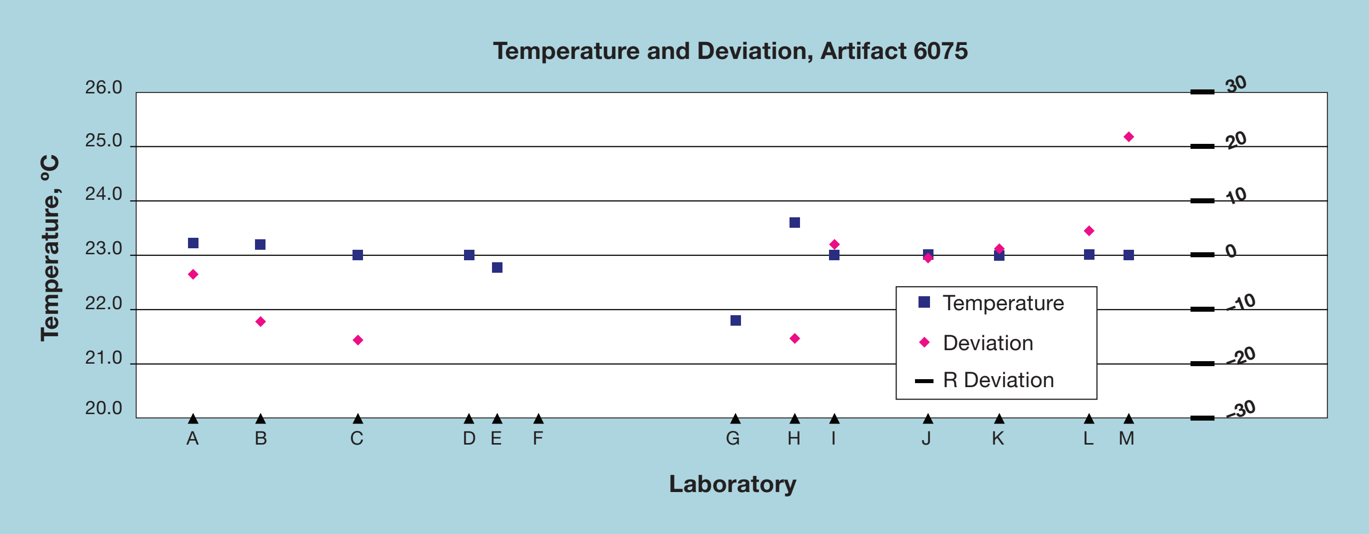

Figure 10. Temperature and resistance deviation from weighted reference value for artifact 6075.

NIST used an active arm bridge; the uncertainty analysis for this method is described in *NIST Technical Note 1458,* "NIST Measurement Service for DC Standard Resistors." [5]

NIST transfers the intrinsic standard of a quantum Hall resistor (around 12.906 kΩ) using a cryogenic current comparator to the 1 megohm level. From there, 100:1 Hamon-type transfer standards build up to the 10^{12} ohms level. NIST's uncertainty components, including Type A and Type B components at 1 GΩ, using an active arm bridge, are listed in Table 8. Note that the two major sources of uncertainty are the working standard and temperature (2 μΩ/Ω) each. The overall expanded uncertainty at $k = 2$ for NIST was 6.8 μΩ/Ω.

One participant with an active arm bridge did not provide uncertainty components. The pivot laboratory used an active arm bridge and followed the scheme of NIST's uncertainty budget, but with higher uncertainty components, mostly for the values of the Reference Standard and the Working Standard uncertainties. The reported uncertainty of the pivot laboratory was 15 μΩ/Ω at $k = 2$.

A majority of the participants (eight) used a Measurements International 6000 bridge. There were notable variations in their uncertainty budgets. These uncertainty components are tabulated in Table 9 for comparison. Note that the reported Bridge uncertainty varied from 1 μΩ/Ω to 20 μΩ/Ω. All but one laboratory included the standard deviation of the measurements. One did not included the uncertainty of the Bridge and the uncertainty of the Working Standard used. Only four included the temperature uncertainty of the 1 GΩ resistors; only three included a leakage current uncertainty.

These eight participants reported final combined (root sum square) measurement uncertainties ($k = 2$) ranging between 15 μΩ/Ω and 67 μΩ/Ω. Given the similarity of their systems and methods, one would expect this range to be lower. Some recommendations are discussed in the next section.

Date	Lab	Measurement Method
9/12/2006	NIST	Active Arm Bridge
11/8/2006	A	MI 6000B
12/12/2006	B	MI 6000A
1/30/2007	C	MI 6000A
3/27/2007	D	MI 6000
4/10/2007	E	Fluke 8508A Meter - Substitution Method
4/28/2007	F	MI 6000A
8/6/2007	G	MI 6000B
9/8/2007	H	Wheatstone Bridge (10 V) MI 6000B (100 V)
9/27/2007	I	Active Arm Bridge
11/20/2007	J	Teraohmmeter – Substitution Method
12/19/2007	K	MI 6000
2/1/2008	L	Active Arm Bridge
2/21/2008	M	Teraohmmeter – Direct Measure
6/30/20008	NIST	Active Arm Bridge

Table 7. Measurement methods used by the participant laboratories and NIST.

10. Recommendations for Uncertainty Budget and Measurement Practice

It might be helpful to review the major significant uncertainty components associated with high resistance measurements.

Type A components are random, occurring only at the time of test. The standard deviation of a series of measurements is a Type A component. If there is measurement history on a unit under test, and if there is regression analysis on its drift, the projected drift of the artifact over the calibration interval can also be considered a Type A component. Generally, these are the only Type A components.

Type B components are built in to the measurement system. For any method using comparison to a standard, the uncertainty of the working standard, R_s, must be included. The uncertainty due to temperature of the working standard should also be listed, either separately or included as part of the uncertainty assigned to the standard. The temperature uncertainty is how much R_s might vary based on its temperature coefficients and on the temperature stability of its environment during a measurement. For an active arm bridge, the NIST uncertainty components listed above may be used. For a high resistance bridge, the manufacturer's specification for the bridge ratio uncertainty should be listed as a Type B component. For the MI 6000 bridge, this is 5 μΩ/Ω at 1 GΩ.

At resistance values above 1 megohm, leakage currents can be a significant source of error. Parasitic current paths act as shunt resistors, giving falsely low results; this error increases as the measurement voltage and resistance increases. To reduce leakage currents, low voltage measurement connections should be shielded at ground potential; higher voltage measurement cables should be physically separated from ground. In addition, the shield of the higher voltage measurement cable should be driven at the measurement voltage. This voltage acts as an electrostatic barrier (a guard) against leakage paths; it should extend to (and into) the resistor being measured. High measurement guards should never be grounded. Low measurement guards and the cases of both the standard and unit under test should be grounded to reduce noise.

Laboratories using a teraohmmeter or a long-scale DMM should include as a Type B uncertainty component either the manufacturer's specification for resistance measurements or a characterized uncertainty provided by a calibration report. For meters used in the direct-measurement method, the measurement uncertainty budget is usually fairly simple: the Type A component is the standard deviation of a series of measurements; the Type B component is the manufacturer's accuracy specification for the measurement device.

The substitution method first measures a calibrated working standard with a meter, then a unit under test, and finally the working standard a second time in order to verify repeatability and sensitivity. The difference between the working standard and the unit under test is thus measured with lower uncertainty than a direct measurement of the unit under test using the meter. In this method, Type B components include the transfer uncertainty of the meter and the working standard.

All participants using these methods properly assigned their uncertainty components and all achieved E_n values of less than 0.5. Based on these results, if less than state-of-the-art uncertainties are adequate to meet a laboratory's needs, direct or substitution methods using a meter appear to be valid at the 1 GΩ level.

To summarize: high resistance measurement uncertainty should include Type A components of measurement repeatability. Type B components should include the working standard (R_s), bridge ratio, temperature of the unit under test, and leakage current. The working standard uncertainty should include these components as they accrue from lower resistance levels. The Type A and Type B components should be combined in a root sum square (RSS). This sum should be doubled ($k = 2$) to provide approximately 95 % statistical coverage of the result.

Leakage in a high resistance measurement system may be evaluated by disconnecting the unit under test and taking a measurement of 'open' unit-under-test terminals with a teraohmmeter or high resistance isolation tester. All terminals and connections should be kept clean. High measurement guards should be driven at measurement potential. High resistance measurements are susceptible to interference from electrical noise caused by equipment switching or personnel walking in the area. More stable measurements are achieved in areas and at times of lower activity. Observing these basic precautions will improve high resistance measurement confidence.

Type A uncertainty; Assumed to be about 1 μΩ/Ω.								
Type B uncertainty at 10^9 Ohms, in μΩ/Ω (RSS total includes type A value of 1)								
Reference Standard	**Working Standard**	**Bridge Ratio**	**Bridge Stability**	**Detector**	**Temperature**	**Leakage**	**System Repeatability**	**RSS Total A + B**
0.50	2.0	1.0	0.50	0.10	2.0	0.10	1.0	3.4

Table 8. NIST uncertainty components for the measurement of 1 GΩ standards.

Reported uncertainty components at 1 GΩ, using a MI 6000 bridge							
Lab 1	**Lab 2**	**Lab 3**	**Lab 4**	**Lab 5**	**Lab 6**	**Lab 7**	**Lab 8**
Type A							
(None)	Std Dev	Std Dev	Std Dev	Std Dev ———————— Working Standard	Std Dev ———————— Stability	Std Dev	Std Dev
Type B							
Bridge 10 μΩ/Ω	Bridge 1 μΩ/Ω	Bridge 20 μΩ/Ω	Bridge 2.5 μΩ/Ω	(none)	Bridge 2.9 μΩ/Ω	Bridge 5 μΩ/Ω	Bridge 2.5 μΩ/Ω
Working Standard	Working Standard	Working Standard	Working Standard		Working Standard	Working Standard	Working Standard
	Temp		Temp	Temp			Temp
Leakage					Leakage		Leakage
Leakage2							
			Temp 2				
			Resolution				
				Working Standard Drift			
					Buildup		

Table 9. Reported uncertainty components for eight different laboratories using the same measurement method.

11. Conclusions

The 1 GΩ North American ILC surveyed thirteen laboratories and evaluated six different measurement methods. Most participants' results agreed with the reference value and were below one half of their claimed uncertainties. Therefore, the overall state of precision high resistance measurements at 1 GΩ appears to be good.

The six measurement methods all appear to be suited to valid measurement at the 1 GΩ level. Understanding and guarding against leakage, and applying uniform uncertainty budgets, appear to be areas for improvement.

The coordinator would like to thank and congratulate all the participants and wishes to extend particular thanks to NCSLI for generous sponsorship of this ILC.

12. References

[1] "Recommended Practice for Interlaboratory Comparisons," *NCSLI Recommended Practice RP-15,* NCSL International, Boulder, CO 80301.

[2] "Conformity assessment — General requirements for proficiency testing," *ISO 17043,* International Standards Organization, Geneva, Switzerland.

[3] See NIST Weights and Measures web site: http://ts.nist.gov/WeightsAndMeasures/Metrology/roundrobins.cfm

[4] R.D. Cutkosky, "A New Switching Technique for Binary Resistive Dividers," *IEEE Trans. Instrum. Meas.,* vol IM-27, no. 4, pp. 421–422, 1978.

[5] R.E. Elmquist et al., "NIST Measurement Service for DC Standard Resistors," *NIST Technical Note 1458,* National Institute of Standards and Technology, December 2003.

13. Appendix

13.1 Final Charter

1. *Scope & Goal:* This charter is for an inter-laboratory comparison of two one gigaohm standards. The ILC is designed to assist in providing each participant confidence in their measurement at the one gigaohm (1×10^9 Ω) level.
2. *References:* This ILC is structured according to *NCSL RP-15,* "Guide for Interlaboratory Comparisons," March 1999.
3. *Sponsorship & Expenses:* NCSLI will sponsor this ILC by contributing towards the cost of NIST's initial and closing measurements. Any balance of the NIST measurement cost

will be borne by the coordinator. Each participant will be responsible for the cost of shipping the artifacts to the next laboratory. Air shipment is recommended.

4. *Structure:* A modified petal structure will be used.
5. *Confidentiality:* Confidentiality will be governed by *NCSL RP-15,* sec. 4.3 & 4.4. The ILC will operate at Level 2 (see *RP-15* section 4.3). Participants will be assigned anonymous lab codes (except NIST, which will be identified as the reference lab). Participants are expected to maintain the confidentiality of all information and data.
6. *Publication and Distribution:* A final report (subject to the above confidentiality restrictions) will be reviewed by all participants and then submitted to NCSLI for publication in the journal *Measure*. Each participant will receive a copy of the final report.
7. *Reference Laboratory:* NIST will perform initial and closing measurements at two voltage levels.
8. *Pivot Laboratory:* The ILC coordinator will perform intermediate checks.
9. *ILC Coordinator:* Jay Klevens, Ohm-Labs, Inc.
10. *Participants:* The ILC participants are laboratories with low measurement uncertainties at the 1 GΩ level; participation is limited to approximately a dozen laboratories to insure a reasonable time limit to the ILC.

13.2 List of Participants

Organization	Contact	Telephone	City	State	Zip
NIST	Dean Jarrett	301-975-4240	Gaithersburg	MD	20899
Boeing	Phil Johnson	206-662-4262	Seattle	WA	98108
Fluke Electronics	Gary Mote	972-406-1000 x766	Carrollton	TX	75006
Fluke Corp.	Dave Deaver; Jorge Martins	425-466-6434	Everett	WA	98203
Guildline	Mike McCain	613-283-3000 x119	Smiths Falls	ON	K7A 4S9
GCS	Mike Frisz	407-333-3327	LakeMary	FL	32746
Keithley	Helga Alexander	440-498-3056	Cleveland	OH	44139
Measurements International	Duane Brown	613-925-5934 x108	Prescott	ON	K0E 1T0
Northrop Grumman	Bill Cross	310-812-7439	Redondo Beach	CA	90278
Ohm-Lab	Jay Klevens	412-431-0640	Pittsburgh	PA	15203
Process Instruments	Karl Klevens	412-431-4600	Pittsburgh	PA	15203
Sandia National Laboratories	Jim Novak; Harold Parks	505-284-3957	Albuquerque	NM	87185
US Army TMDE	Vernon Love	256-876-5364	Redstone Arsenal	AL	35898
Wyle Labs	Paul Reese	321-494-7907	Patrick AFB	FL	32925