North American 100 Ampere Interlaboratory Comparison

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Abstract
The base SI unit for electricity is the ampere. At present, there is no intrinsic standard for the ampere, so in practice it is disseminated by measuring voltage across a resistor, using Ohm's Law ($I = E / R$). Higher current is measured with a shunt, which is a high power resistor. Accurate electrical current measurement is critical to the power and electrical test industries. In cooperation with the National Institute of Standards and Technology (NIST) and the NCSLI Utilities Committee, Ohm-Labs performed a North American 100 ampere interlaboratory comparison (ILC). Many measurements did not meet claimed uncertainties, revealing errors in measurement and uncertainty estimation. A second round of measurements was performed. The first and second round results are presented in this paper.

1. Introduction

Interlaboratory comparisons (ILCs) are an important part of measurement assurance programs. At the international level, national metrology institutes (NMI's) regularly circulate artifacts to verify agreement of their measured values. This assures dissemination of standard and derived international units within claimed uncertainties, and is necessary to establish traceability [1]. At the regional level, measurement labs can participate in similar comparisons. Regional ILCs allow laboratories to compare their methods, procedures, uncertainty estimations, and results with other participating laboratories.

Current shunts are low ohmic value resistors designed for high power dissipation. Power is expressed in watts and equals current squared multiplied by resistance ($W = I^2R$). Shunts are calibrated by comparison with a calibrated resistance standard. Calibration of the resistance standard provides traceability to the SI unit of the ampere.

There are several methods for calibrating shunts. Formerly, a Kelvin bridge method was used [2]. The Kelvin bridge subjects both the shunt under test and the standard to equal current. Most resistance standards are not designed to handle high power. This limited the accuracy of shunt measurements to about 0.01 % of measured value. At a time when metrology grade shunts claimed 0.04 % accuracy, this provided a comfortable 4:1 test uncertainty ratio. The Kelvin bridge method is rarely used today.

A second method calibrates shunts by direct comparison. A calibrated standard shunt (R_s) is connected in series with a shunt under test (R_x) so that equal current flows through both. Both shunts are metered (E_s and E_x). The value of R_x will equal (E_s / E_x) * R_s. The accuracy of this method is primarily limited by the calibration uncertainty of the standard shunt, R_s.

A third calibration method involves comparisons using a current comparator bridge. The current comparator bridge has two separate current loops, one through a resistance standard, a second through a resistor under test. Ratio windings allow up to 1,000,000:1 current comparisons. A current comparator system in wide use has 1,000:1 ratio capability, allowing direct comparison of 100 A through a shunt with 100 mA through a resistance standard [3]. Because 100 mA is the nominal measurement current for a 1 Ω resistance standard, it was suggested that the 100 A level was a desirable area for examination. This led to a proposal to perform a 100 A ILC.

2. Proposal and Charter

The ILC followed NCSLI's Recommended Practice RP-15 [4], "Recommended Practice for Interlaboratory Comparisons." As current measurement is integral to electrical utilities, participants were solicited from the NCSLI Utilities Committee. Participants also included manufacturers of current comparator bridge systems, manufacturers of precision current shunts, a U.S. Department of Energy lab, a U.S. Navy lab, and two U.S. Department of Defense prime contractor labs. A total of 16 laboratories participated. Most are accredited to ISO17025 or controlled by nuclear regulatory quality system requirements. NIST provided opening and closing measurements.

A draft proposal, participant list and draft measurement worksheet were circulated for participant review and comment. Suggestions and corrections were incorporated into a final proposal, which was distributed to the participants. The proposal defined the region and scope, identified the coordinator, specified the artifacts, identified potential problems, and outlined the ILC structure and cost. A modified petal structure was used, with the artifacts returning to the pivot lab several times during the ILC for intermediate checks. Participants were requested to bear the cost of outbound shipping to the next participant's lab, and to contribute a share of the NIST measurement cost. Measurement methods and uncertainty estimations were not initially defined, with the objective of surveying and evaluating existing practices.

The proposal formed the basis of the ILC charter. The charter formalized the proposal and specified confidentiality. Each participant was assigned a letter code. The ILC coordinator acted as the pivot lab, and participated blind until the closing measurements were completed. The charter was subsequently modified to include a second round of measurements.

3. Artifacts

NIST provided two artifacts. One was a Leeds & Northrup model 4363 1 mΩ shunt, manufactured in 1980, the other a Rubicon model 1166 10 mΩ shunt of similar vintage. Using older artifacts allowed a depth of measurement history. Using artifacts of different nominal values allowed evaluation of systems at two power levels. Current connection lugs were provided by NIST to accompany the Leeds & Northrup shunt. The coordinator provided a transit container.

4. Instructions

Participants received instructions in the form of a worksheet. The worksheet had check boxes for receiving inspection. Participants reported, for each shunt, the time required to stabilize in the laboratory, the ambient temperature and relative humidity, a photo of the setup for review, the measured resistance, the date of measurement and uncertainty, and a final inspection checklist prior to release to the next laboratory.

A second page on the worksheet requested information on the measurement method and uncertainty calculations. These sections were deliberately left open to the participants' interpretation; reports ranged from brief narrative descriptions to detailed mathematical analysis.

5. Results

The first round of the ILC began on November 29, 2007, following NIST opening measurements. The first round was comprised of 20 measurements, 17 by participants (one of the 16 participants discovered an error and performed a second test), and three intermediate checks. The first round required an average of 2.6 weeks per measurement and concluded on December 2, 2008. Several participants were prompt in their measurements and reporting, but several needed reminders by the coordinator.

NIST concluded the closing measurement of the 1 mΩ shunt on December 15, 2008. The closing measurement showed an upward shift of 342 μΩ/Ω; indicating damage to the artifact. Figure 1 shows measurements of this shunt. For ease of comparing data, charts are scaled for μΩ/Ω. The baseline is a linear interpolation between the opening and closing measurements.

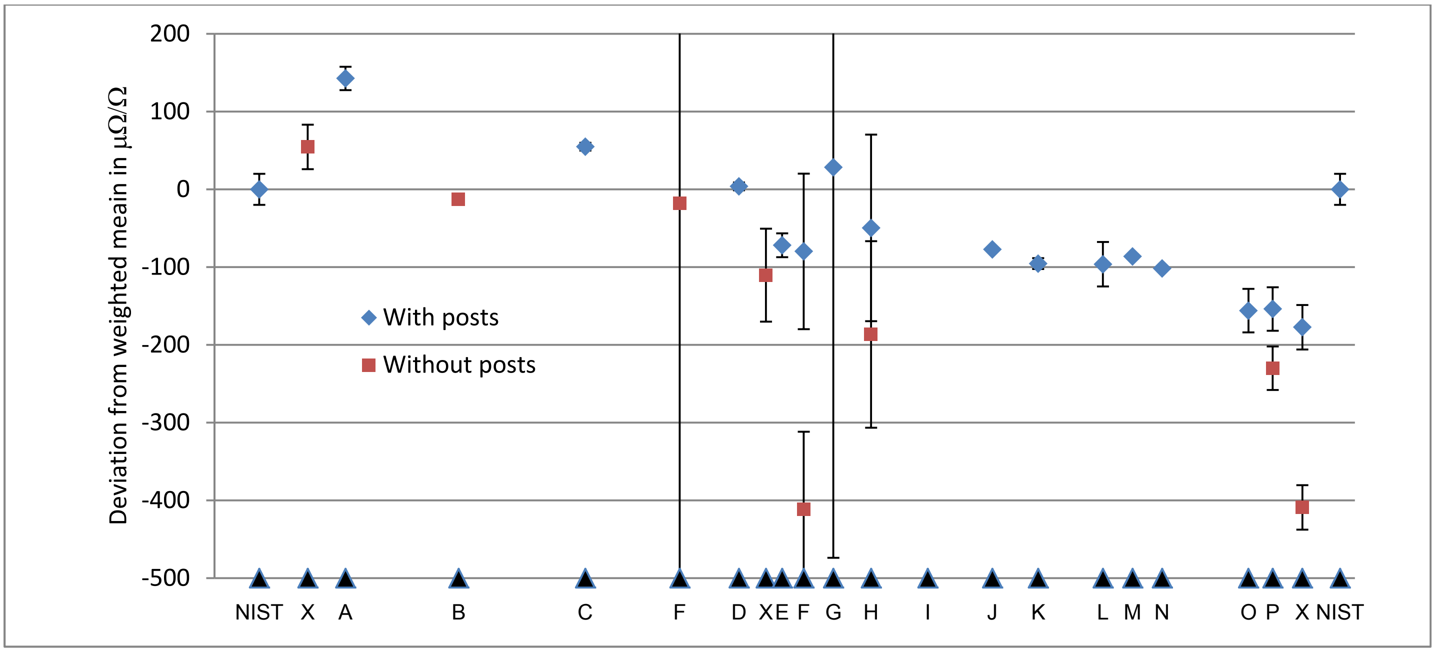

Figure 1. 1 mΩ shunt measurements.

The results illustrate problems with accurate shunt measurement. The artifact shifted. A significant difference in results from connection errors can be seen in data taken both with and without the supplied current posts. The shunt temperature was not reported, so temperature errors are unknown. Stabilization time was not specified, adding to temperature variations caused by varying degrees of thermal stabilization under power. One set of data was not received (Lab code I), and one measurement is off the scale of the chart (Lab code M without posts, -1012.3 μΩ with a claimed uncertainty of 3.0 μΩ/Ω). Finally, uncertainty estimates, often lower than NIST, do not allow for variables and thus nearly all these measurements would fail a proficiency test.

It appears the value shifted in two steps, one after the opening measurement (first point) and one prior to the closing measurement (last point). Because the pivot lab, as a participant, was operating blind, and because of the relative stability of pivot lab measurements through the ILC, this shift was not noticed until the closing.

The blue diamonds indicate measurements made with current connection posts supplied by NIST; the red squares show measurements made without these posts. The connection variations are apparent.

Figure 2 shows a current post installed. The posts are nickel plated solid copper bars, approximately 3 in × 0.75 in in diameter. One end is threaded; the other is machined to closely fit the 0.75 in diameter hole in the shunt. It distributes current more uniformly through the brass current posts on the shunt. Variations in current distribution through brass posts or blocks affects the measured resistance of a shunt. The manufacturer does not note or quantify this error source.

Torque on the connecting bolts and the cleanliness (surface resistivity) of the current connection are also variable factors which cause errors by affecting current distribution through the shunt [9]. The author has observed connection errors on older metrology shunts of this type exceeding 200 μΩ/Ω. Connecting to the top surface instead of inside the holes can cause errors greater than 400 μΩ/Ω. On lower cost metering type shunts, the author has observed connection errors exceeding 1000 μΩ/Ω. A review of photos of the test setups showed a variety of current connections, including some to the top of the current posts.

Figure 2. Current connection lug on 1 mΩ shunt.

NIST concluded closing measurements on the 10 mΩ shunt on January 12, 2009. A linear interpolation between opening and closing values formed a baseline value. Participants' measured values were compared to this baseline value. The drift of this shunt was determined by the difference between the opening and closing measurements, which was -1.6 μΩ/Ω and can be considered negligible.

Figure 3 shows the participants' results. Letter code X represents pivot lab measurements. Red upper and lower limits represent NIST uncertainty. Error bars show participants' claimed uncertainties. All uncertainties were reported at a coverage factor of $k = 2$. One set of readings was not received, and four measurements are off the ±100 μΩ/Ω scale of the chart (Lab A, -619.9, UC 21.3; Lab F, +2038.5, UC 75.8; Lab G -208.0, UC 501; Lab O, -1664.0, UC 27.0. Lab F discovered an error and performed a second measurement as a corrective action.). Figure 3 also illustrates the difference in uncertainty between current comparator systems (smaller error bars) and shunt comparison systems (larger error bars). It also shows many labs claiming a lower uncertainty than NIST.

NIST claimed a uncertainty of 20 μΩ/Ω for the measurement of this shunt. This uncertainty included the standard deviation obtained from multiple measurements. The NIST report and an accompanying fact sheet note the effects of drift, transport, temperature, current and humidity, but not connection variations.

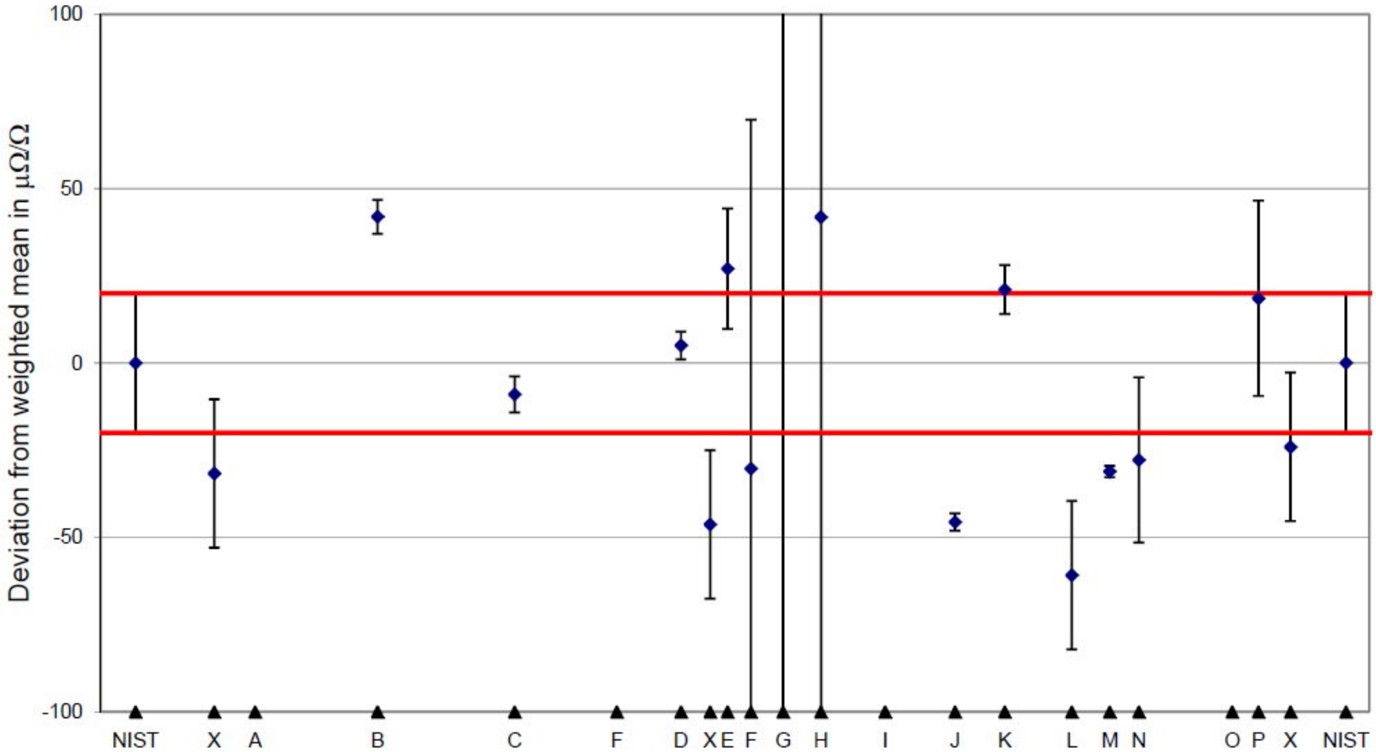

Figure 3. First round of 10 mΩ shunt ILC results.

Due to the number of outlying measurements and the shift of one artifact, the coordinator proposed a second round of measurements. The goal was to minimize problems encountered in the first round [5]. The coordinator requested all participants to continue, drafted a revised charter, and developed new instructions. For the second round, participants performed one measurement using existing procedures, and three subsequent measurements following a procedure defined by the coordinator.

For the second round, the Leeds & Northrop shunt was replaced by a Rubicon 1168 1 mΩ shunt supplied by the coordinator. Copper current connector bars were fabricated and a torque wrench with mating socket was supplied. Type T thermocouples were affixed to the mid-point of both shunts, and a type T thermometer was included with the artifacts. Figure 4 shows the second round items. The 10 mΩ shunt is on the left; the 1 mΩ shunt is on the right.

Figure 4. Artifacts for the second round of the shunt ILC.

Fourteen of the 16 participants agreed to repeat the measurements (one was unable to budget the time, and one went out of business). The opening measurements for the second round were completed on September 20, 2009. Fifteen measurements (13 by participants and two by pivot laboratories) concluded on April 5, 2011. These measurements averaged 5.3 weeks each, roughly twice the duration of the first round measurements. The longer time was partly due to increased measurement requirements.

Closing measurement results were not received from NIST until November 1, 2011, during which time the ILC was idle. After the closing, two participants with prior scheduling conflicts completed second round measurements. These concluded February 17, 2012. The preliminary ILC results were distributed to participants by March 19, 2012.

The 10 mΩ shunt shifted significantly between the opening and closing measurements. The shift in value, as measured by NIST, was -42.5 μΩ/Ω with an uncertainty of 10 μΩ/Ω (k=2). The pivot lab measurements of this shunt agreed within 15 μΩ/Ω after the opening and prior to the closing measurements, compared to a 6 μΩ/Ω agreement for the first round. The larger shift in value calls into question the validity of the second round results, as the artifact instability was greater than many participants' claimed uncertainty.

This artifact was provided by NIST and had a long calibration history. The cause of the change in value is unknown, although being a negative change, in accord with the long term drift of the shunt, it may be partially due to an accelerated downward trend caused by repeated operation at full power during the ILC. This effect, which varies from shunt to shunt, also occurs in resistors, and can be largely attributed to relaxation of stresses in the resistance alloy. To allow for the shift, results for this artifact include both NIST uncertainty and the change in value. The baseline value is a linear interpolation between opening and closing measurements.

Eleven of the fourteen participants submitted standard calibration reports, per the ILC instructions. Figure 5 shows the results of the 11 standard lab calibrations of the 10 mΩ shunt, plus two NIST measurements and four pivot measurements. NIST claimed a measurement uncertainty 10 μΩ/Ω for this shunt. One measurement is off the scale of the chart (Lab A, +699.2, UC 55.0).

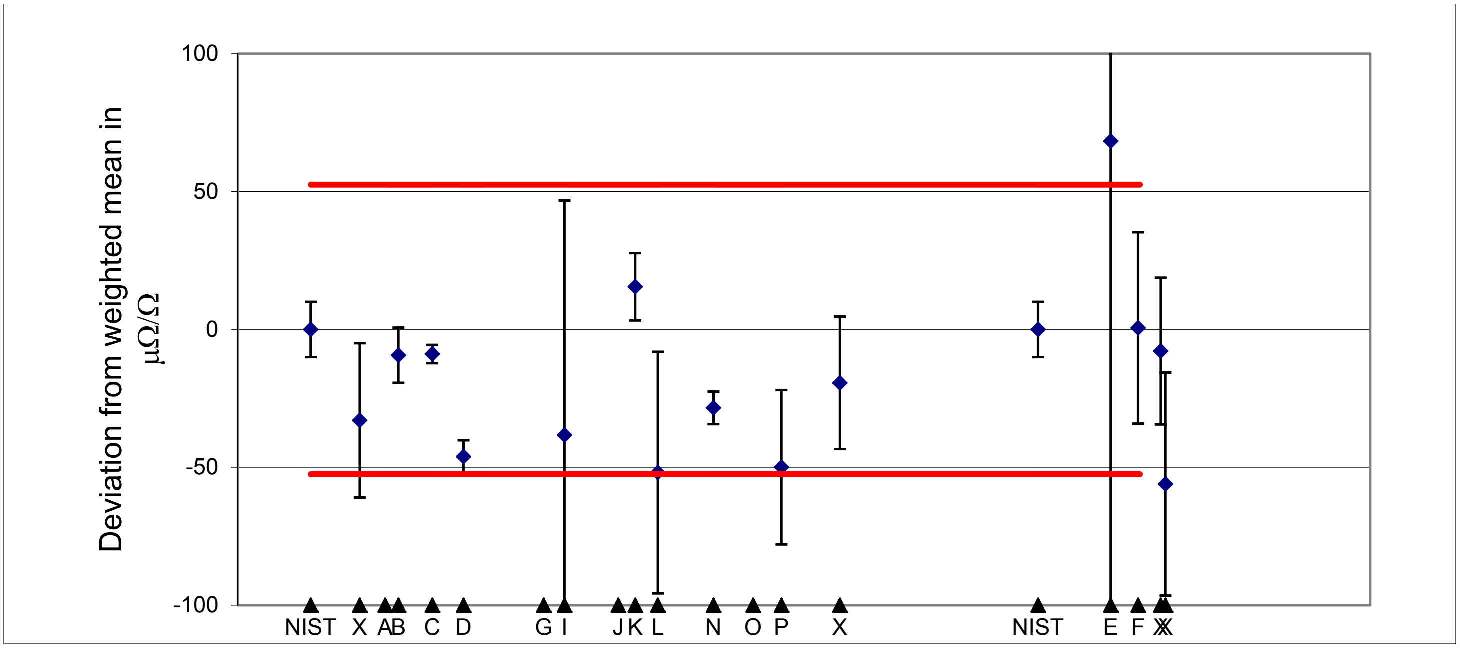

Figure 5. Second round of 10 mΩ shunt comparision using standard laboratory procedure.

After a measurement using the laboratory's standard procedure, participants were instructed to perform three measurements on three separate days, cleaning current connection terminals, connecting the copper bus bars with a torque of 20 newton-meters (15 foot-pounds) using the supplied torque wrench, and recording the shunt temperature with the supplied thermometer. This procedure was designed to reduce connection and temperature variations. All 14 participants provided these measurements. Figure 6 shows the results, including one pivot measurement and the two NIST measurements. An average of the three measurements is shown, along with claimed uncertainty (error bars). Three measurements are off the scale of this chart (Lab A, -682.5, UC 52.0; Lab G, -176.0, UC 556.0; Lab E, -109.1, UC 199.5). A comparison of measurements using both standard lab calibration procedures and the special ILC procedure reveals that four were improved, and eleven were worsened.

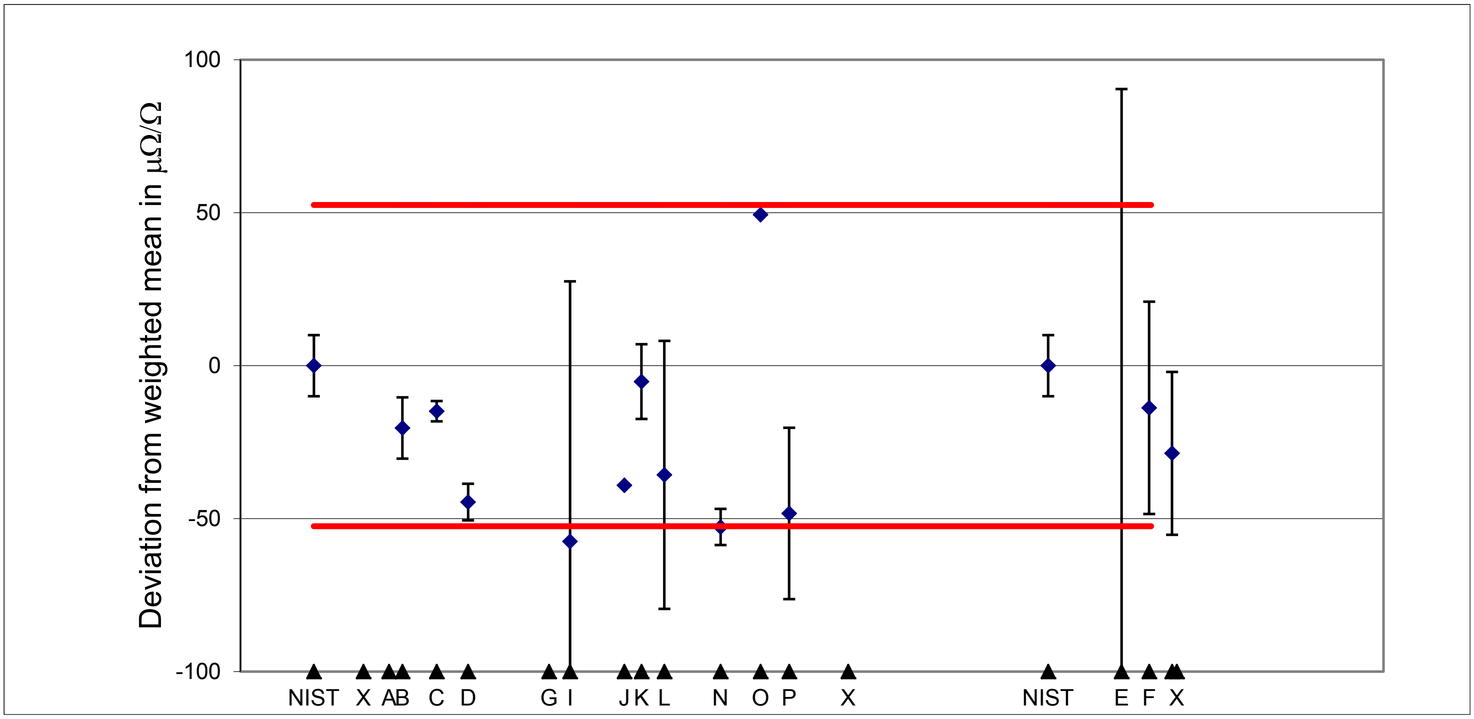

Figure 6. Second round of 10 mΩ shunt comparision using ILC procedure

Participants recorded the shunt temperature at the time of test. Since all metals change resistance with temperature, variations in temperature at the time of measurement may have caused errors. The temperature coefficient of resistance (TCR) of a shunt generally will not change over time. It can be positive or negative, and its curvature can cause a shunt to have both positive and negative areas across its power (or temperature) range. TCR varies from one shunt to another, even in identical models.

The participants recorded temperatures between 53.6 and 63.0 °C during tests. With this shunt, the change in resistance around its mean temperature at 100 A is approximately -20 μΩ/Ω/°C. Figure 7 shows the temperature chart for this shunt.

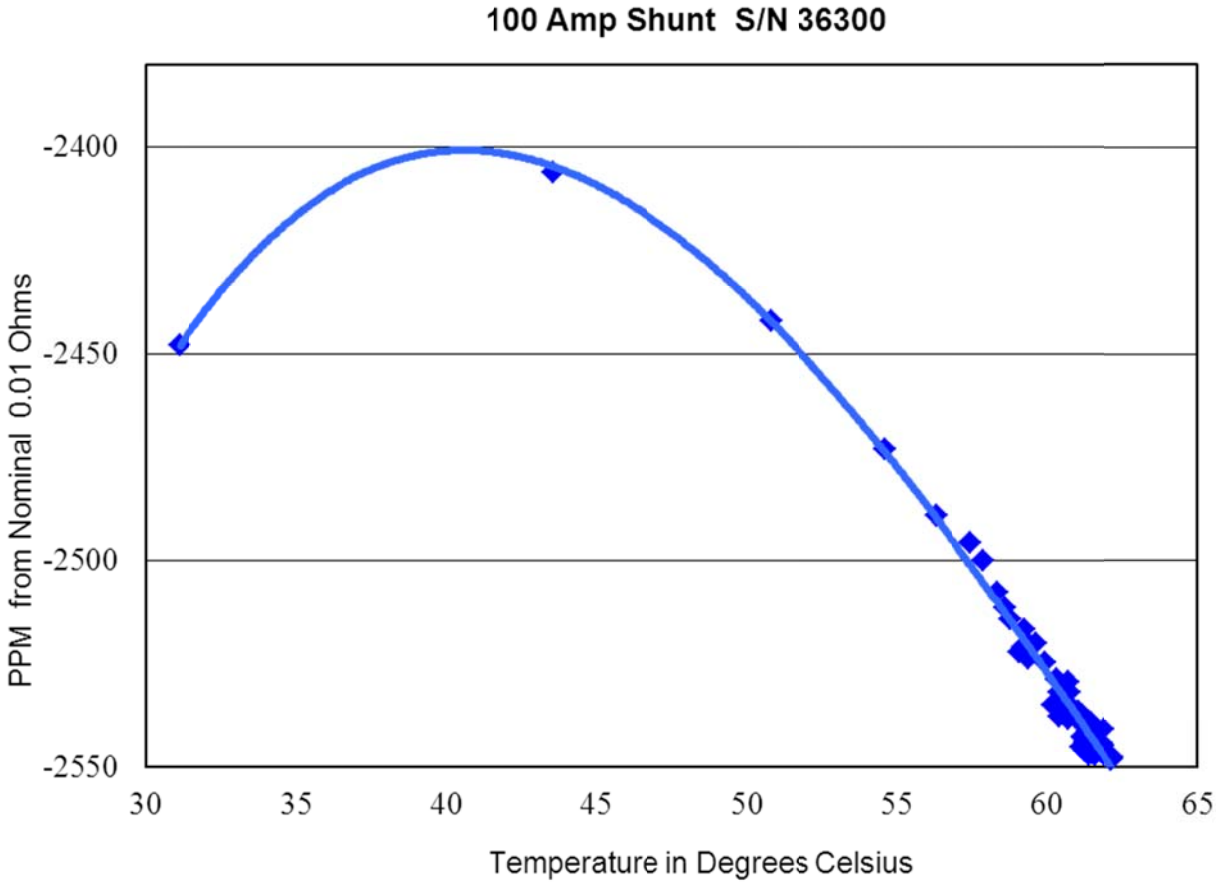

Figure 7. Temperature curve for 10 mΩ ILC shunt.

The difference between the NIST opening measurement at 58.9 °C and the closing measurement at 58.0 °C would cause a resistance difference of approximately +9.2 μΩ/Ω. This difference is a significant proportion of the NIST claimed uncertainty of 10 μΩ/Ω and highlights the difficulty of accurately transferring valid and repeatable shunt measurements. The difference can be factored into the closing measurement to result in a corrected drift of -33.3 μΩ/Ω, but applying this correction does not significantly affect the participants' results. Figure 8 shows the average of participants' three temperature measurements.

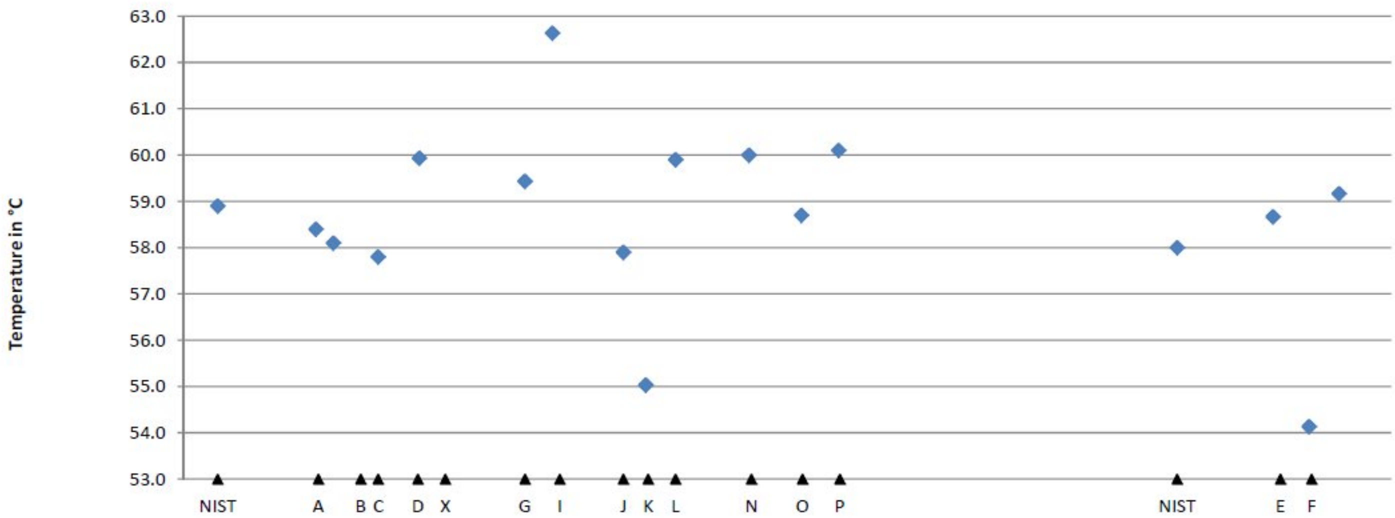

Figure 8. Participants' average reported temperature of 10 mΩ shunt at 100 amperes.

The trendline in Figure 7 is a third order polynomial fit. Although a second order curve is usually used for resistors or shunts, the third order curve better fits the data points. By applying the third order polynomial equation from the curve to the participants' measurements, we can estimate and apply a temperature correction. Figure 9 shows participants' measurements corrected for temperature variation from the mean. However, applying a temperature correction does not significantly alter the participants' results.

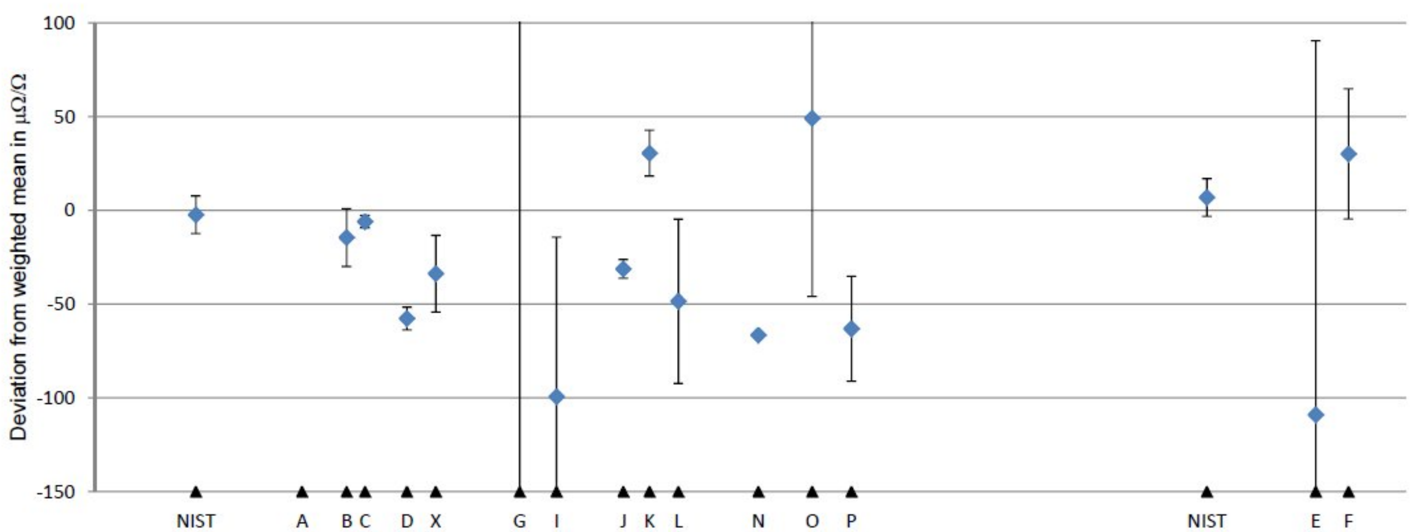

Figure 9. Participants' measurements of 10 mΩ corrected for temperature.

The second shunt, with a resistance of 1 mΩ, heats less than the 10 mΩ shunt. This is due to lower power. Power (W) is the product of resistance (R) and current squared (I^2). At 100 A, I^2R for the 10 mΩ shunt equals 100 W, and for the 1 mΩ shunt it is 10 W. Lower power reduces errors from heating.

This shunt changed in value by +10.0 μΩ/Ω between the opening and closing measurements. This change is within the NIST claimed uncertainty of 20 μΩ/Ω and thus the data is presented without additional correction. As with the 10 mΩ shunt, the baseline value is an interpolation between the opening and closing measurements.

Eleven participants submitted results and uncertainties using their existing calibration procedures. Figure 10 shows results for the 1 mΩ shunt, with two NIST and four pivot measurements.

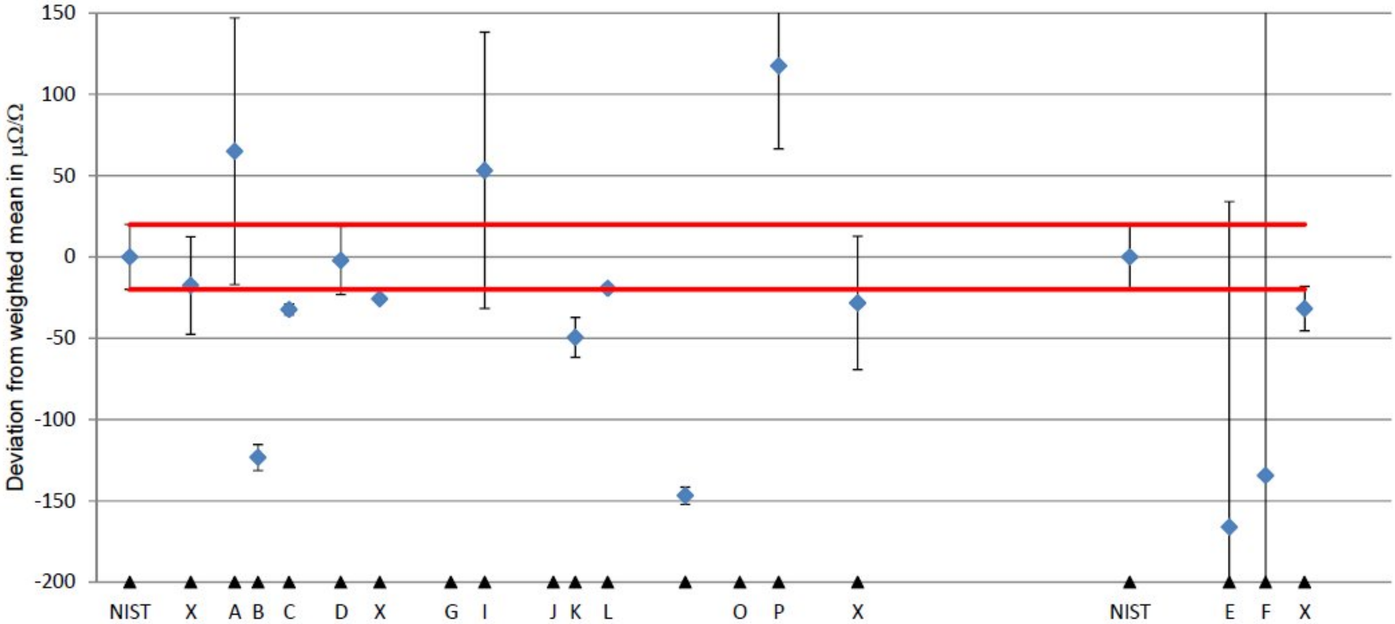

Figure 10. Second round of 1 mΩ shunt comparison, standard procedure.

Participants performed a subsequent set of three measurements on three separate days, following the ILC instructions. As with the 10 mΩ shunt, all 14 participants reported this data. Figure 11 shows the average of these three measurements, including the NIST result and two pivot measurements.

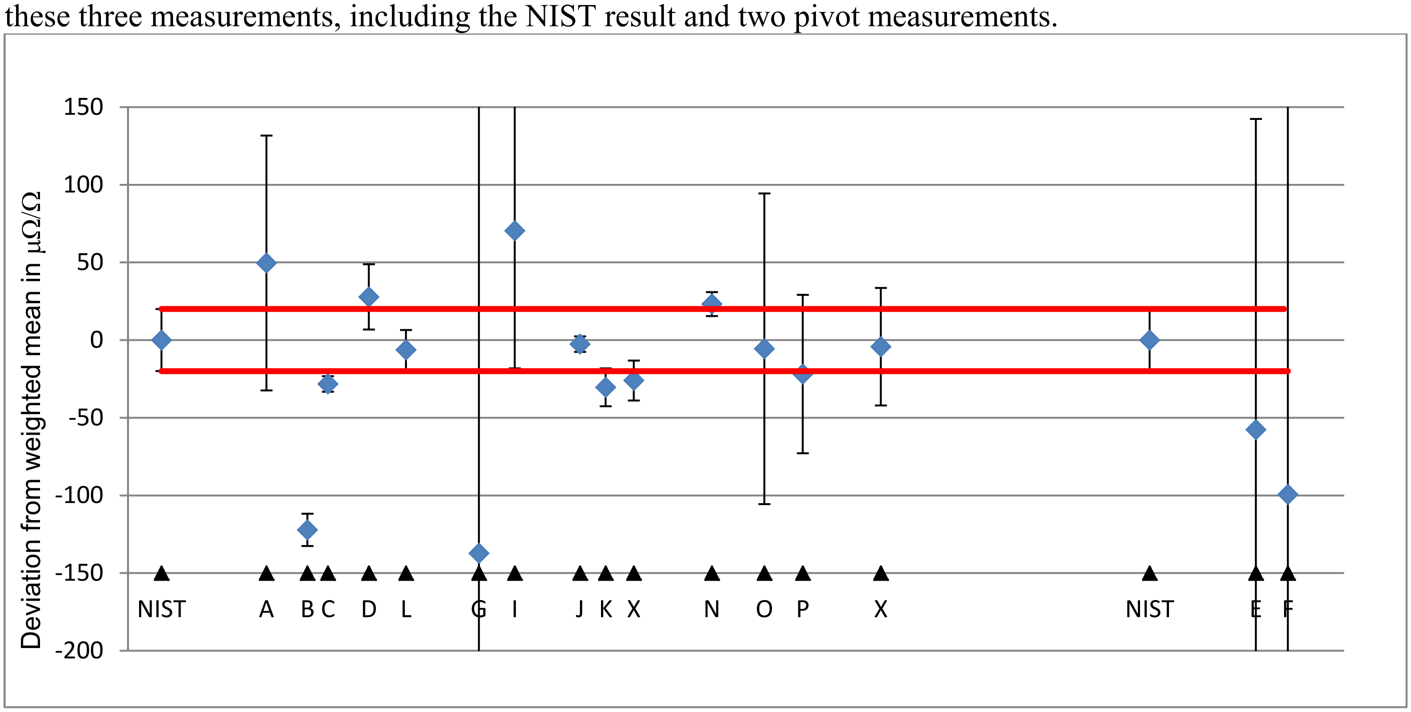

Figure 11. Second round of 1 mΩ shunt comparison, ILC procedure.

Comparing the 16 measurements performed using participants' existing procedures with the ILC procedure shows that 10 were improved by the ILC procedure, and that six were worsened.

6. Evaluation of Results

A useful gauge of a lab's measurement proficiency is to calculate the difference in a lab's measured value with a reference value, and comparing that difference to the relative uncertainties of the two values' uncertainty. The equation for this calculation is

$$E_n = \frac{x - X}{\sqrt{U_{lab}^2 + U_{ref}^2}} \quad . \qquad (1)$$

In Eq. 1, x is the participants' measured value, X is the reference measured value, U is the measurement uncertainty, and E_n is the result. An E_n of >1 shows that a lab has failed to perform a measurement within its claimed uncertainty. An E_n close to 1 can reveal areas of concern. Reported uncertainty is generally calculated by combining Type B ('Built-in') uncertainty components inherent in the lab's system with Type A ('At time of test') components that are unique to the unit under test. Table 1 shows the E_n results for the ILC. Note that the E_n results for the 10 mΩ shunt factor in the shift in value of the artifact and may not be reliable.

Lab	0.01 Ω	0.01 Ω Std Cal	0.01 Ω ILC Cal	0.001 Ω With Posts	0.001 Ω Without Posts	0.001 Ω Std Cal	0.001 Ω ILC Cal
NIST	0.00			0.00			0.00
X	-1.08	-0.55			1.57	-0.49	
A	-10.51	-9.20	-9.24	5.71		0.77	0.59
B	2.04	-0.18	-0.37		-0.63	-5.72	-5.42
C	-0.44	-0.17	-0.28	2.66		-1.60	-1.37
F	26.00				-0.02		
D	0.25	-0.87	-0.84	0.18		-0.08	0.96
X	-1.59	-0.13	-0.51		-1.75	-1.29	-0.27
E	1.02			-2.85			
F	-0.30			-0.78	-4.04		
G	0.41		-0.32	0.06			-0.24
H	0.21			-0.41	-1.53		
I		-0.38	-0.58			0.61	0.78
J	-2.26		-0.74	-3.83			-0.13
K	0.99	0.29	-0.10	-4.50		-2.11	-1.30
L	-2.08	-0.76	-0.52	-2.76		-0.96	-1.09
M	-1.55			-4.27	-50.06		
N	-0.90	-0.54	-1.00	-5.08		-7.09	1.08
O	-49.52		0.45	-4.53			-0.05
P	0.54	-0.84	-0.81	-4.47	-6.68	2.15	-0.40
X	-0.82	-0.34		-5.08	-11.72	-0.62	-0.10
NIST	0.00	0.00	0.00	0.00			0.00
E		0.33	-0.53			-0.83	-0.29
F		0.01	-0.22			-0.39	-0.29
X		-0.85				-1.31	

Table 1. E_n tabulation.

In general, laboratories using the shunt comparison method achieved an E_n of <1, due to larger measurement uncertainty. Laboratories with the highest E_n generally claimed the smallest uncertainty, leaving the least allowance for error.

Performing separate tests on separate days helps to establish repeatability as a Type A uncertainty component. The standard deviation of the participants' three measurements is shown in Fig. 12. Although repeatability is a significant Type A uncertainty component, a comparison of E_n and repeatability does not show a strong correlation. Laboratories with highly repeatable results may be repeating measurements which would fail a proficiency test.

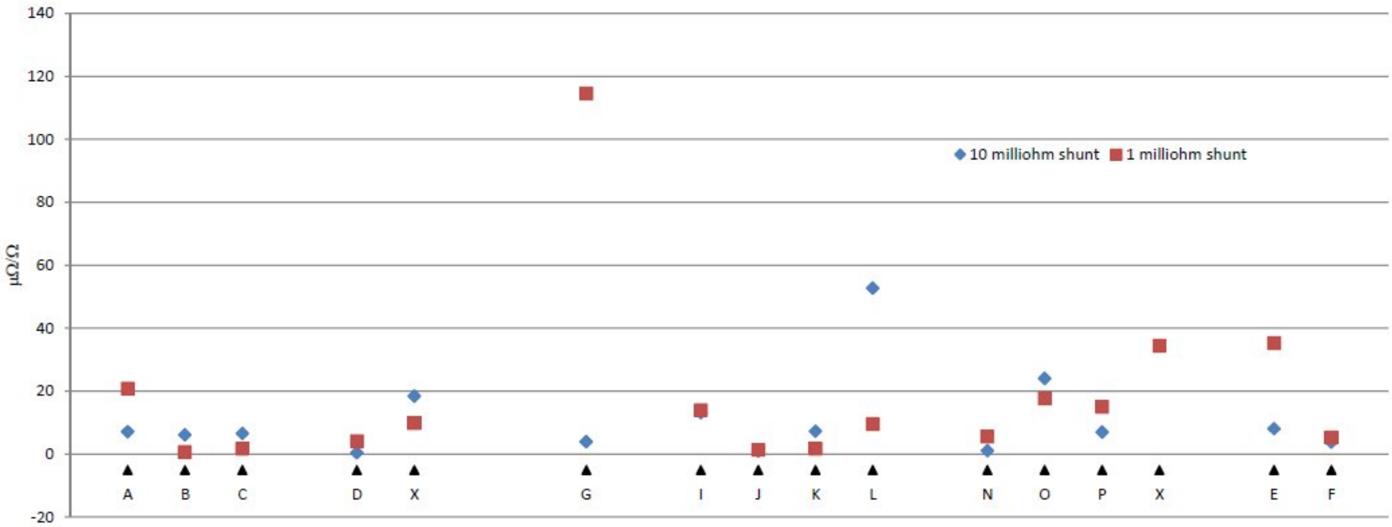

Figure 12. Standard deviation of three measurement runs.

7. Root Cause Error Analysis

NIST reports the measured value of a shunt using a current comparator bridge system. Careful attention is paid to potential and current connections. Shunts with a temperature sensor are allowed to reach thermal stabilization before measurements begin. Shunts without a temperature sensor are allowed 10 to 30 minutes at applied current to approach thermal equilibrium, at which point resistance measurements will show stabilization. Ambient temperature and the rate of air flow across the shunt both affect equilibrium temperature and thus resistance [6]. Figure 13 shows the stabilization time of the 10 mΩ shunt used in the ILC. Figure 14 shows the stabilization time for the 1 mΩ shunt. Both measurement runs were with 100 A applied from a cold condition at a lab temperature of 23 °C.

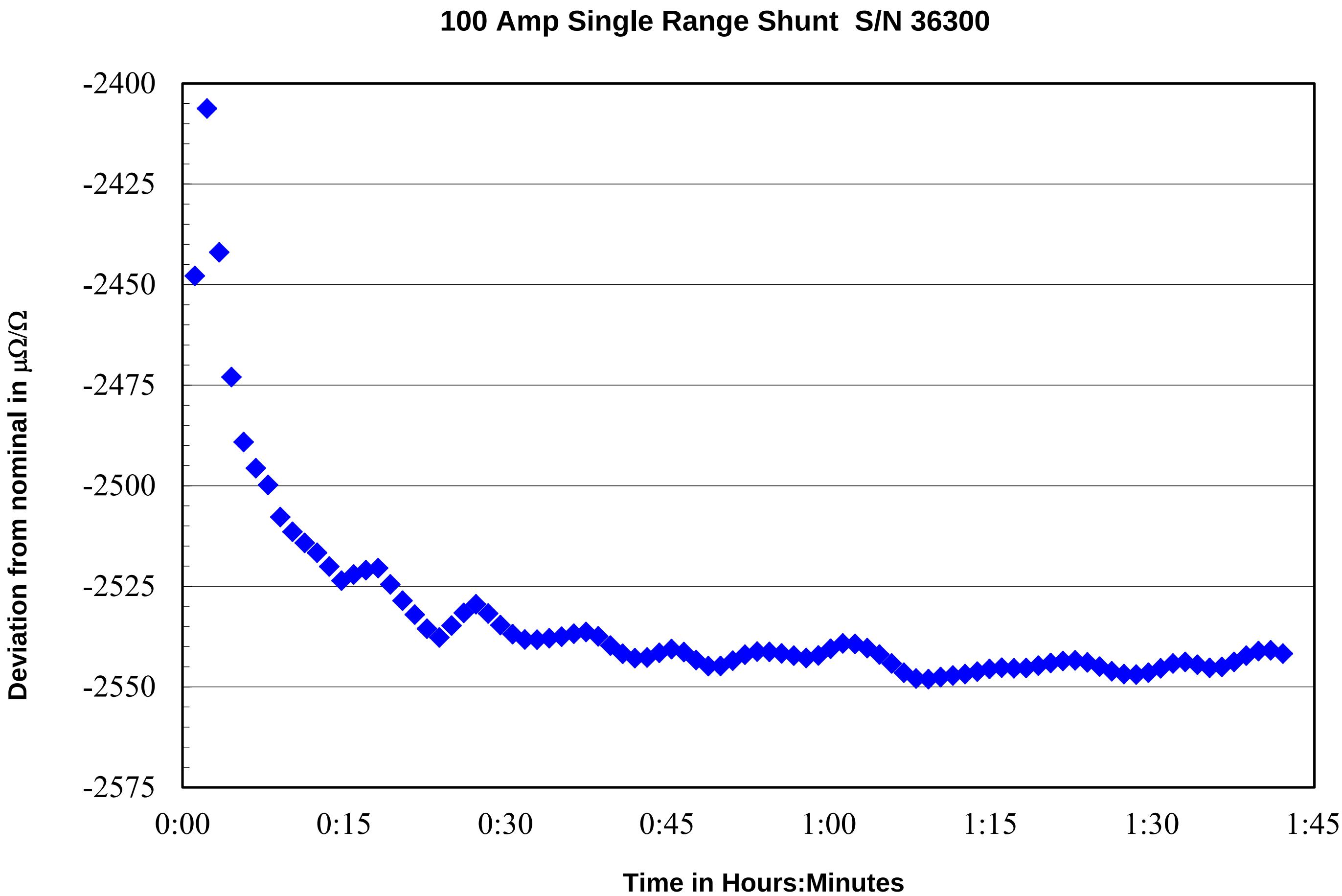

Figure 13. Stabilization time for 10 mΩ shunt.

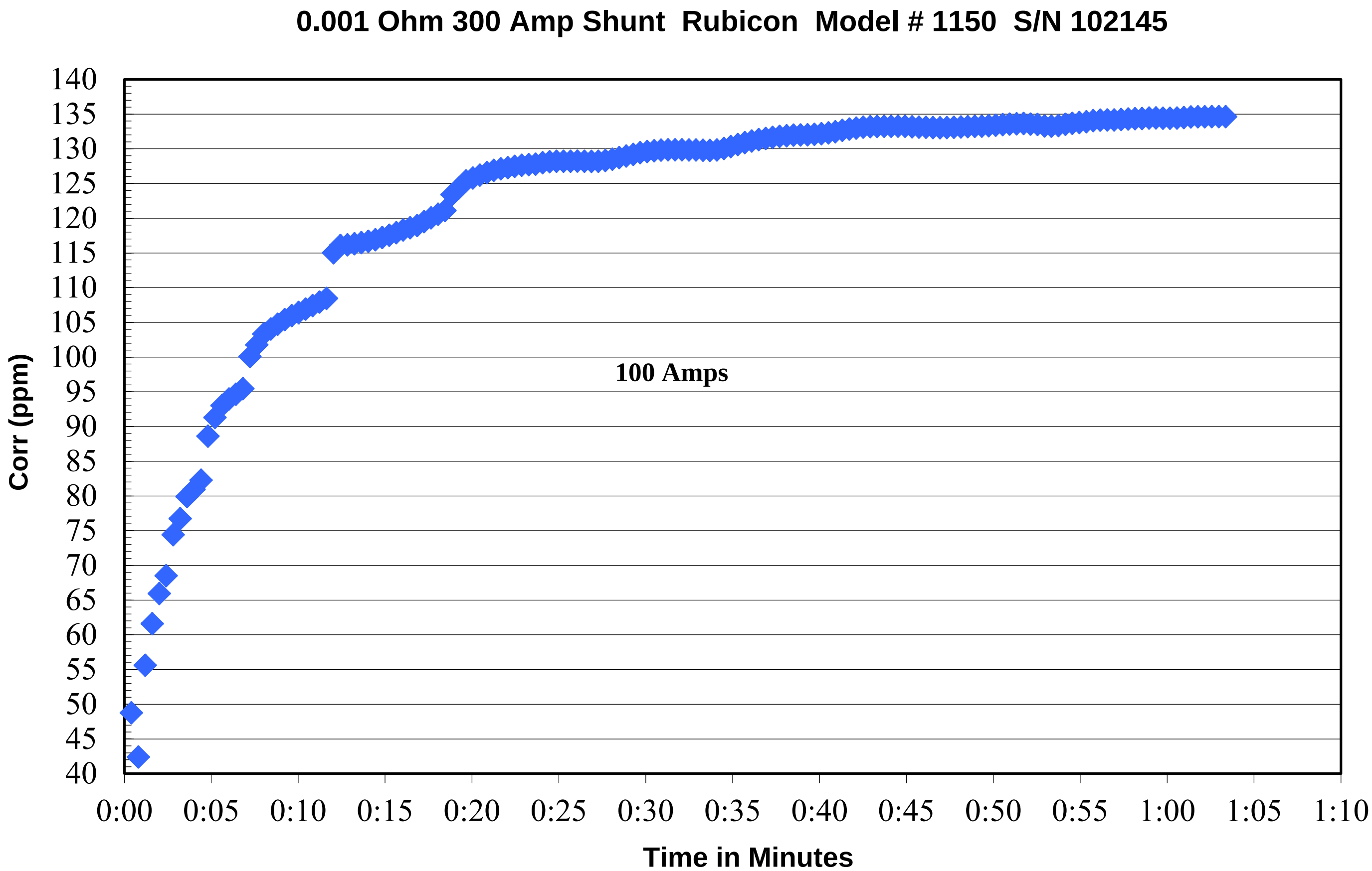

Figure 14. Stabilization time for 1 mΩ shunt.

Both shunts require approximately one hour to reach thermal stability. Due to the temperature coefficient of resistance of these shunts, the most likely error source is due to temperature, which is affected by time of applied current, level of applied current, ambient temperature, air flow, and contributions by the thermal mass of the connectors. Without carefully duplicating all of these environmental conditions, a laboratory may not obtain a measurement in agreement with NIST. [7]

It is important to note the material and design of these shunts. The material is a copper-manganese alloy called Manganin, which was developed in the late 1800's. The design of the L&N shunt dates from the early 1900's, and the Rubicon design (differing only in its current connections) from around 1960. Many laboratories rely on their calibration history for shunts of this design, because the history of shunts of newer designs has not been as well established [8].

The ILC instructions for the second round attempted to minimize connection, temperature and stabilization errors. Drift errors were accounted for by interpolating NIST opening and closing measurements. A review of participants' uncertainty components shows that participants generally understand and applied appropriate elements and calculated them properly.

8. Comparison of Methods

Two measurement methods were used by participants: comparison using a current comparator bridge system and direct comparison with a calibrated shunt. Five participants used the direct comparison method. Twenty of the 24 measurements made using the direct comparison method passed ($E_n < 1$). Of the four that did not pass, one was caught by the participant and subsequently corrected.

Eleven participants used a current comparator bridge system. When properly used to measure resistance standards, these systems can support uncertainties to the μΩ/Ω level. Resistors are usually measured at a power level at or below 10 mW. When measuring current shunts at higher power, additional error factors become increasingly significant, often overwhelming the system's best uncertainty.

NIST claims a type B uncertainty at 10 mΩ of 0.8 μΩ/Ω at a power level of 10 mW. At 100 W, as in this ILC, the NIST type B uncertainty at 10 mΩ is 10 μΩ/Ω. At the 1 mΩ level, the type B uncertainties are 1.2 μΩ/Ω and 20 μΩ/Ω respectively. The higher uncertainty at higher power is derived from experience with shunts.

11. Conclusions

Although many laboratories have experience measuring shunts, errors inherent in higher power measurements may not be specified in manuals for shunts or current comparator bridge systems. Such error factors were absent from earlier publications, such as instruction sheets for the shunts used in this ILC.

An end user must rely on a laboratory's measured value and claimed uncertainty. Laboratories with many years' experience, state of the art equipment, and careful environmental controls, when supported by third party accreditation, are expected to provide reliable calibration results. A comparison of measurements with NIST shows that this is often not the case with current shunts.

12. Acknowledgements

The author acknowledges the contributions and assistance of Marlin Kraft of the Quantum Measurement Division of NIST.

13. References

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14. Appendix: List of Participants

Organization	Contact	City	State/Province
NIST	Marlin Kraft	Gaithersburg	MD
Energy Northwest	John Atkins	Richland	WA
Exelon Power Labs	Cory Peters	Coatesville	PA
First Energy BETA Lab	John Decker	Mayfield Village	OH
FPL Energy Seabrook	Bill Hinton	Seabrook	NH
Guildline Instruments	Cliff Chouinor	Smiths Falls	ON, Canada
High Current Technologies	Dennis Destefan	Broomfield	CO
Lockheed Martin Denver Metrology	Bill Miller	Littleton	CO
Lockheed Martin Tactical Systems	Rod Enke	St. Paul	MN
Measurements International	Duane Brown	Prescott	ON, Canada
Norfolk Naval Shipyard	Scott Smith	Norfolk	VA
Ohm-Labs	Jay Klevens	Pittsburgh	PA
PG&E	Gary Barnes	San Ramon	CA
Process Instruments	Karl Klevens	Pittsburgh	PA
Sandia National Labs	Jim Novak	Albuquerque	NM
Southern CA Edison Metrology	Richard Brenia	Westminster	CA
Southern Texas PNOC	Keith Scoggins	Wadsworth	TX