The 2008 NCSLi Josephson Voltage Standards Interlaboratory Comparison

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Abstract

Josephson voltage standards (JVS) provide a highly accurate representation of the volt. Although the Josephson Effect provides an intrinsic standard of voltage, inter-comparisons between different systems are important to insure that potential sources of systematic error are under control and to provide an explicit link to the volt as maintained by a national metrology institute. We present results from the 8th Josephson voltage standards inter-laboratory comparison (ILC) at 10 V sponsored by the National Conference of Standards Laboratories International (NCSLi). The inter-laboratory comparison was conducted between March and July 2008 with 14 participating labs in North America. It began with a direct array to array comparison between the National Institute of Standards and Technology (NIST) compact Josephson voltage standard (CJVS) system and the system at the pivot lab at Lockheed Mission Services in Denver. The two systems agreed to well within the $k = 2$ uncertainty of the comparison of 6.6 nV at 10 V [1]. Once the NIST-pivot lab comparison was complete, four traveling Zeners were sent from the pivot lab to the participant labs in a series of four loops with a pivot lab measurement between the loops. The standard deviation of the 10 V bank average as measured by the participants with respect to the drift line established by the pivot lab was 68 nV. There are some indications of non-normal behavior in the residuals and we adopt an expanded uncertainty for the comparison of 190 nV at a 95% level of confidence.

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Introduction

Regular inter-laboratory comparisons (ILC's) between Josephson voltage systems (JVS's) in North America have been performed with the sponsorship of the NSCLi about once every two to three years since 1991 [2]. This comparison performed between March and July 2008 represents the eighth such ILC. Including NIST and the pivot laboratory there were 14 participants as shown in table I.

The 2008 comparison used a set of four Zener references as traveling standards. This means that the uncertainty of the comparison is limited by the Zener noise to a few parts in 10^8, while the systematic uncertainty of a well maintained Josephson voltage system can be as low as a few parts in 10^{10}. In-situ Zener comparisons, where two Josephson systems are brought to the same place to measure the Zeners can reach an uncertainty of a few parts in 10^9, and direct array to array comparisons can reach an uncertainty of less than a part in 10^9. However considerable time, effort, and expense are required for these direct comparisons in order to transport a Josephson system and operator from one laboratory to another.

We must also remember that Zener references, whether standalone or in a precision digital multi-meters represent almost all of the workload for a typical JVS laboratory. The uncertainty of this comparison, about 2 parts in 10^8, is as tight as is ever demanded from a typical laboratory outside of a direct array-to-array comparison. So any systematic errors serious enough to affect the data quality will likely be revealed. These exercises also allow participants the chance to prove to assessors that they can produce high quality data and can show a direct link to national standards.

NIST – Pivot Laboratory Preliminary Inter-Comparison

One week before the opening of the main part of the ILC, an intercomparsion at 10 V was performed between the NIST compact Josephson voltage standard (CJVS) system and the pivot laboratory system at Lockheed Martin Mission Services. The NIST system was shipped to the Lockheed laboratory in Denver and a direct array-to-array comparison was performed. The difference between the Lockheed and NIST systems at 10 V was found to be 0.71 nV with an expanded uncertainty of 6.6 nV (at $k = 2$). A detailed account can be found in reference [1].

Since the array to array comparison does not test the scanner or the software used by the pivot lab, a comparison was also performed using four Zeners (the same ones used in the rest of the ILC) as transfer standards. The uncertainty of this comparison was larger due to the noise in the Zeners. Here the Lockheed - NIST difference was found to be -16 nV at 10 V with a type A uncertainty of 22 nV (at $k = 2$).

Procedure

The 2008 ILC used the same set of well characterized Fluke 732B Zener traveling references as used in the 1993 [3], 1997 [4], 1999 [5], 2002 [6], and 2005 [7] ILC's. The traveling references are sent in a daisy pattern from the pivot laboratory (Lockheed Mission Services, Denver, CO) to two or three participant laboratories and back to the pivot laboratory, for a total of five loops. Measurements were performed by a different laboratory every week of the ILC, with only one week (between the last participant measurement and the final pivot measurement) with no data taken. With one exception, the Zeners were shipped on Wednesday and received on Thursday. Measurements were then taken on Monday and Tuesday.

A low thermal reversing switch traveled with the Zeners, and on Monday each laboratory made four measurements of each Zener alternately the reversing switch between the "plus" and "minus" positions. On Tuesday the four +-+- measurements on each Zener were repeated for a total of 32 measurements over two days. With the exception of one pivot point that consisted of 26 individual measurements, all labs sent at least 32 measurements. Several labs sent more data, however in this case only 32 measurements were selected for the analysis. The labs also recorded the atmospheric pressure on the measurement days from a pressure sensor that traveled with the Zeners.

Data Analysis

Though the Zeners used in this ILC do exhibit drift over time that is approximately linear, the nonlinear component is significant over the course of the entire ILC. So we adopt a method of fitting linear segments between pivot laboratory measurements.

For each participant, the data from each Zener is corrected to the pressure of the pivot laboratory using the pressure coefficients for each Zener measured previously [6]. The data for that week is fit to a line, and the fit is used to calculate the mean voltage of all four Zeners at the mean time of measurement for that lab. A straight line is then fit between each of the five pivot laboratory measurements. The residual between each laboratory mean value and the pivot laboratory line is then taken to be the participant minus pivot laboratory deviation.

This method of taking the residual from line segments joining pivot laboratory measurements was used in the 1999 [5], and 2006 [6] ILC's. The 2005 ILC did not used a single pivot lab, but used a system of five sub-pivot labs each of which was compared to the NIST portable system with an in-situ comparison [7]. However, the traveling Zeners were sent in a loop to two or three other participants from each sub-pivot lab. A model with line segments joining the sub-pivot measurements was then used. The comparison uncertainty was much reduced for the sub-pivot labs that participated in in-situ comparisons. But for other participants, the week-to-week Zener drift dominated the uncertainty budget. So the residuals from the participants that received the Zeners as traveling standards are directly comparable to the residuals of the 2008 ILC.

Results and Discussion

The deviations of the participant labs from the pivot lines are listed in Table II and plotted in Fig. 1. There are two points at 5/19/08 since participant F used both a laboratory JVS and a portable JVS to measure the Zeners on the same week. To more accurately reflect the week-to-week variation, we average the two points on 5/19/08 and find the standard deviation of the residuals to be 68 nV. This is almost identical to the 68 nV standard deviation reported for the 1999 ILC (after removing two 700 nV outliers where hardware problems were suspected). It is also comparable to the 2002 ILC which had a 99 nV standard deviation. The 2005 ILC (traveling Zener standard component) had a slightly larger standard deviation of 150 nV due to the failure of the batteries in all four Zeners resulting from a shipping delay half way through the ILC (one data point where hardware problems were suspected and which has a residual of 1000 nV was removed).

A plot of the drift of each of the Zeners with respect to its initial value is shown in Fig. 2. One Zener voltage increased in value by 4 μV over the four months of the ILC, while two Zeners increased by 1 μV and the final Zener remained within 0.5 μV.

At first glance it looks like the value reported by laboratory G (NRC Canada) is an outlier. Excluding laboratory G, the standard deviation is 41 nV, making the laboratory G value 4.5 standard deviations from the mean. However a closer look at the data reveals a more complicated picture. As difficulty had been experienced in the past in shipping the Zeners from Canada to the Unites States, Laboratory G shipped the Zeners on Tuesday rather than Wednesday as was the procedure for the other participants. And in fact, the Zeners delivery to laboratory H was delayed until that Friday due to customs issues. The Zeners were without power for 3½ days. All the “In Cal” lights were still illuminated upon arrival at laboratory H, indicating that the batteries supplying power to the temperature stabilizing ovens had not completely run out. However there is still some indication that the stress of this delay did affect the Zeners. The voltages of all four Zeners with the offset and linear drift removed are plotted in Fig. 3. As can be seen in this figure, between the measurements of laboratory G on 6/1/08 and the measurements of laboratory H on 6/9/08, three of the four Zeners took a nearly identical shift down of several hundred nanovolts and the drift rate of these Zeners also changed noticeably. This correlated kick to the Zeners due to the shipping stress causes our analysis procedure to assign a larger residual to the laboratory G measurements than we would expect from purely Gaussian statistics.

Over the past four ILC’s, which used the same Zeners and analysis technique, we have a total of 27 pivot laboratory measurements and 58 participant residuals (excluding two values in 1999 and one in 2005 where actual hardware problems were suspect and the residuals were over 500 nV). These measurements have a standard deviation of 96 nV. The cumulative distribution of the residuals is plotted in Fig. 4. There is, in fact, an unusually large cluster of residuals near +150 nV. The Anderson-Darling statistic for this data is 0.97 indicating that the hypothesis that the residuals follow exactly a normal distribution can be rejected with over a 98% level of confidence. Even if the two outliers at -265 nV and 277 nV are removed, the Anderson-Darling statistic only drops to 0.87, still indicating that the distribution is non-normal to over a 97% level of confidence.

This non-normal behavior makes the usual procedure of combining the standard deviation of the residuals with the other sources of uncertainty and multiplying by a student-t factor somewhat suspect for this ILC. However, we do notice from Fig. 4, that an interval of twice the standard deviation of the 1999 to 2008 data, which is equal to 190 nV, does include the majority of the data, including the most of the cluster near 150 nV. Therefore, an expanded uncertainty for the 2008 ILC of 190 nV, $k = 2$ at a 95% level of confidence does seem reasonable. Though the statistics are thin we do note that about 95% of the residuals since 1999 (55 of 58) do lie within our expanded interval.

Uncertainties other than the week-to-week drift of the Zeners contribute negligibly to the total uncertainty. Though not specifically required in the ILC instructions, all but two labs reported a type A uncertainty for each of the 32 data points that they reported. These uncertainties ranged from 10 to 50 nV (at $k = 1$). When the 32 data points are combined this short term noise contributes 6 to 11 nV of standard uncertainty to the mean voltage from each lab. Systematic uncertainties such as leakage current corrections and time base uncertainties add only a couple of nanovolts at most for a typical JVS system. Uncertainties related to the pressure correction add up to 10 nV of standard uncertainty to the values for labs near sea level (which differ most in pressure from the Denver pivot lab). All of these uncertainty sources together result in less than a 2 % inflation in the combined uncertainty and can be safely neglected. Any adjustment due to finite effective degrees of freedom would be of the same level (and as we have seen the statistics here are not quite normal) so this is ignored as well.

References

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[3] K.M. Rodriguez and L. Huntley, “U.S. Intercomparision of Josephson Array Voltage Standards”, *IEEE Trans. Intsr. Meas.*, vol. 44, pp. 215-218, 1995.

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Agilent Technologies, Loveland, CO
Boeing, Seattle, WA
Fluke Corporation, Everett, WA
Idaho National Lab, Idaho Falls, ID
Lockheed Martin Mission Services, Denver, CO (pivot)
Lockheed Martin Technical Operations, Stennis Space Center, MS
Los Alamos National Lab, Los Alamos, NM
Mid Atlantic Regional Calibration Center (Navy), Norfolk, VA
National Research Council, Ottawa, On, Canada
Sandia National Labs, Albuquerque, NM
U.S. Air Force Primary Standards Lab, Heath, OH
U.S. Army Primary Standards Lab, Redstone Arsenal, AL
Wyle Labs, Kennedy Space Center, FL
NIST, Gaithersburg, MD (indirect participant: comparison at Lockheed Denver)

Table I. Participants in the 2008 ILC

Laboratory	**Date**	**Laboratory - Pivot Residual (nV)**
Pivot 1	4/1/08	
A	4/7/08	-48
B	4/15/08	-45
C	4/22/08	-72
Pivot 2	4/29/08	
D	5/6/08	-83
E	5/12/08	-13
F - L	5/19/08	30
F- P	5/19/08	37
Pivot 3	5/27/08	
G	6/1/08	178
H	6/9/08	2
I	6/16/08	-23
Pivot 4	6/23/08	
J	6/30/08	30
K	7/8/08	23
L	7/14/08	12
Pivot 5	7/28/08	

Table II. Residuals for the participants from a straight line fit between the pivot points.

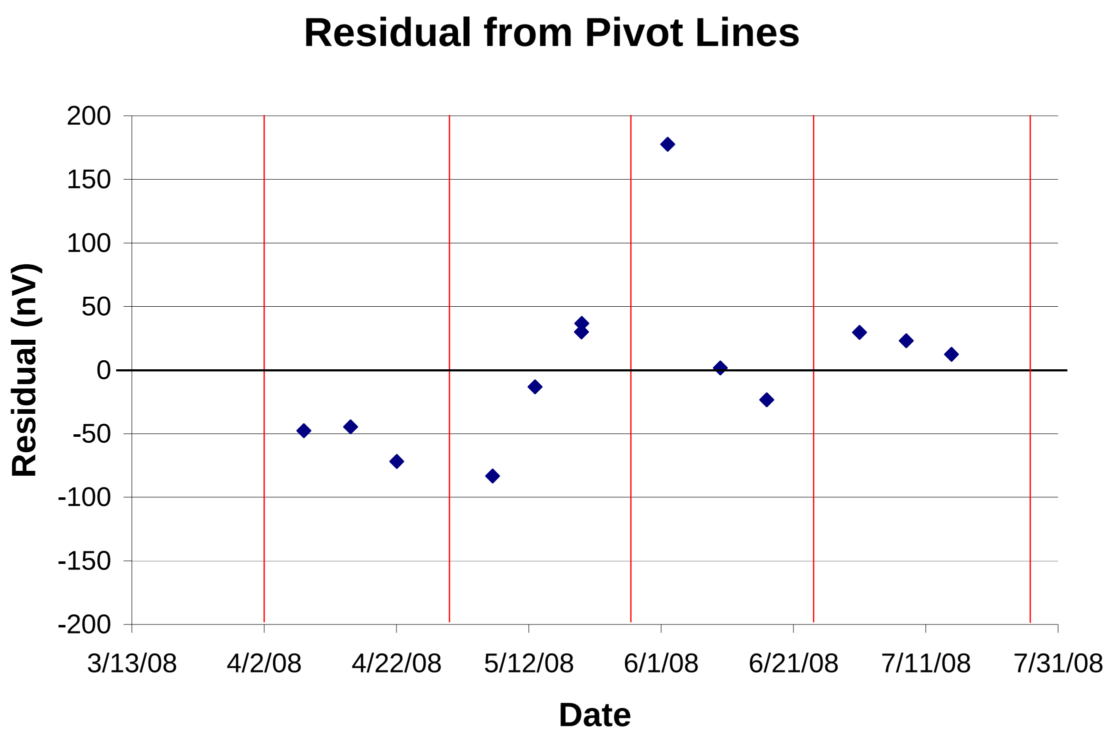

Fig. 1. A plot of the participant minus the pivot residuals as given in table II. Pivot measurements are marked by the vertical gridlines.

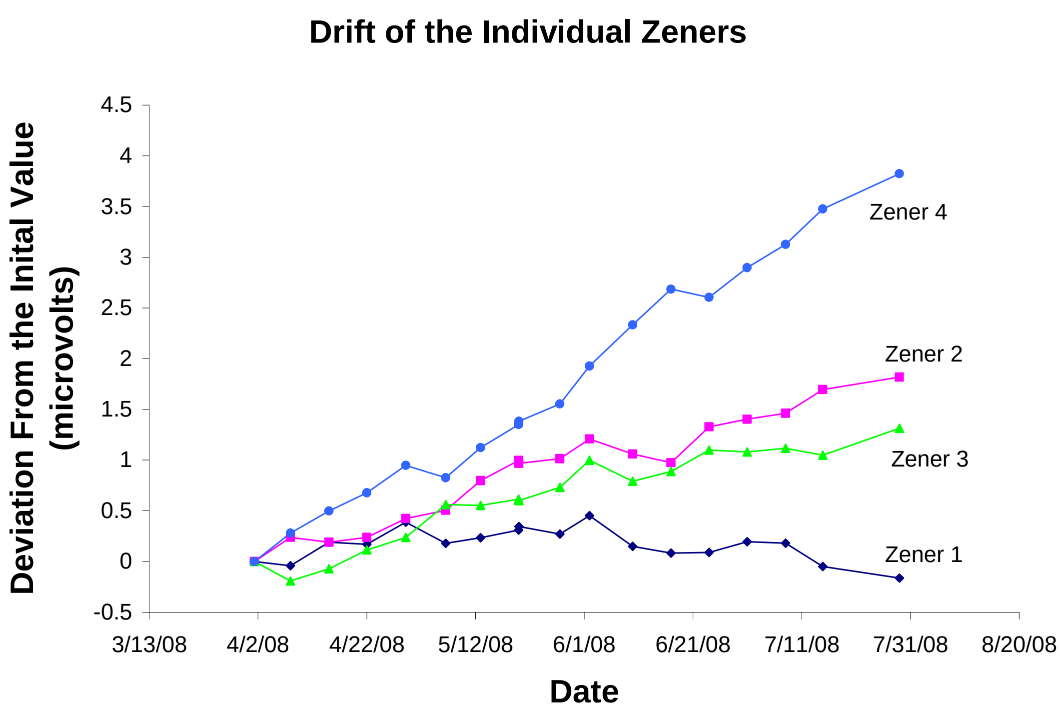

Fig. 2. The values reported from each laboratory (including pivot measurements) for each Zener, with respect to the first pivot measurement.

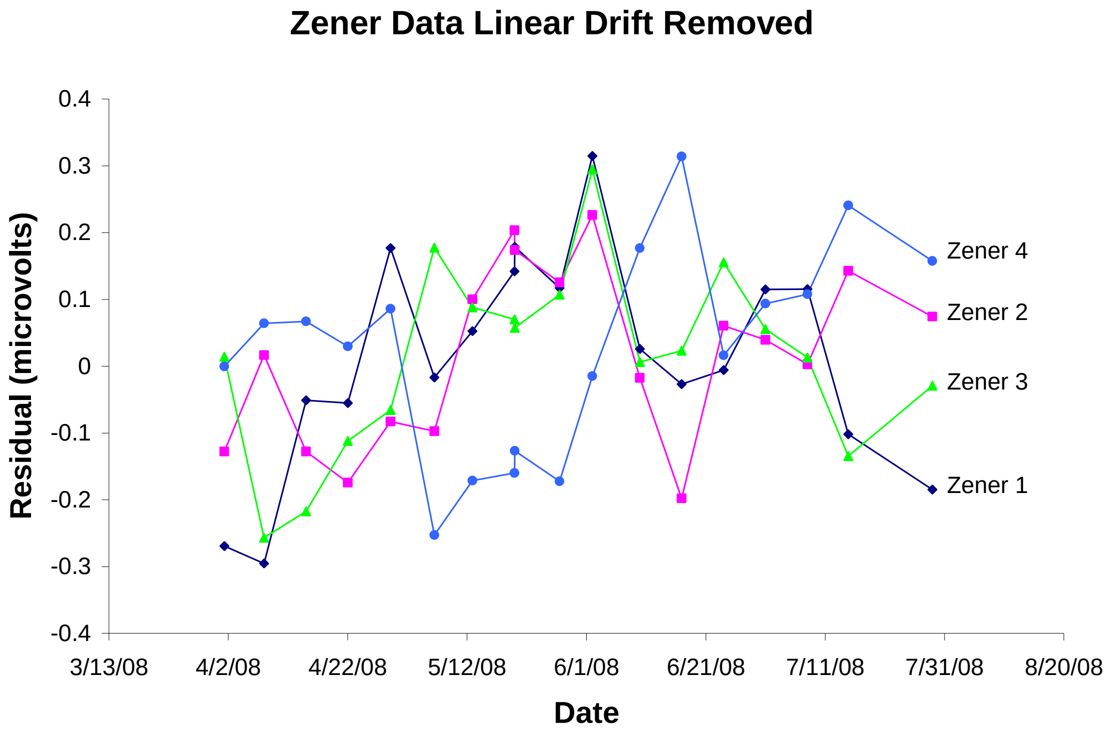

Fig. 3. The values for each Zener reported by the participants (including the pivot laboratory points) with an offset and linear drift removed. Between the measurements of 6/1/08 and 6/9/08 the Zeners were delayed in customs for 3½ days and a shift is noticeable in the Zeners 1-3 data.

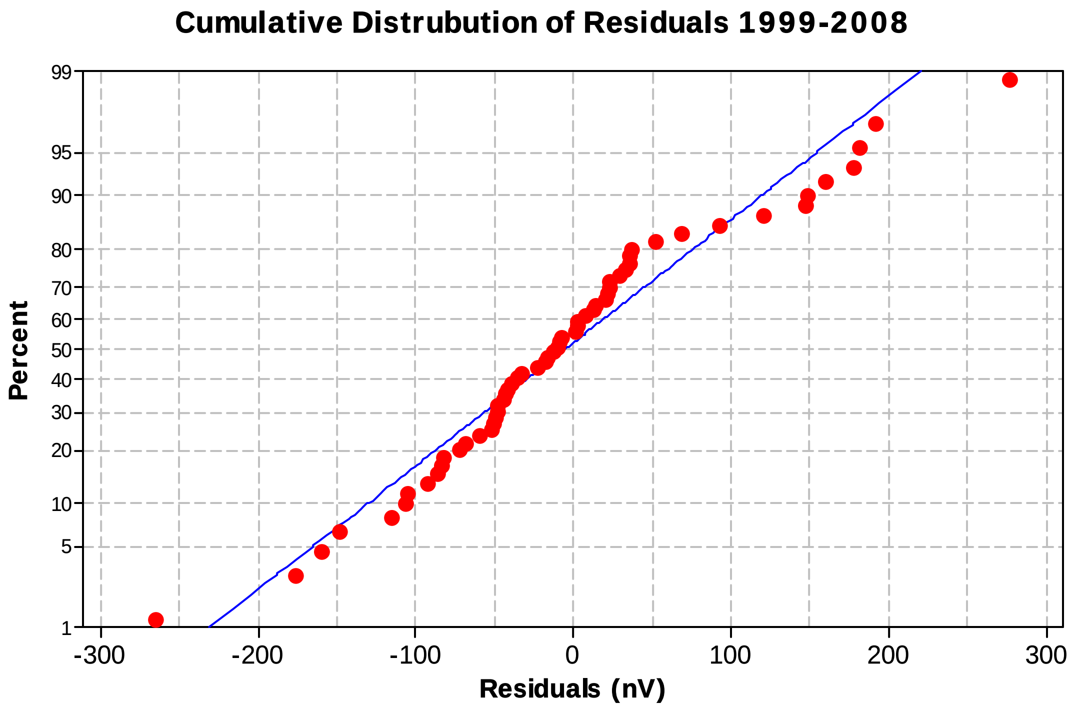

Fig. 4. The cumulative distribution of the residuals from the 1999, 2002, 2005, and 2008 ILC's. The vertical axis is scaled so that a normal distribution with a standard deviation of 96 nV would fall along the straight line. An unusually large cluster of points between +100 and +200 nV is noticeable.