

The North-American Josephson Voltage Interlaboratory Comparison

Harold V. Parks, Yi-hua Tang, Paul Reese, Jeff Gust, and James J. Novak

Abstract—The 9th North-American Josephson voltage standards interlaboratory comparison at 10 V was completed in 2011. An on-site comparison was conducted between the NIST compact Josephson voltage system and the pivot laboratory system. A set of four traveling Zener voltage standards were then shipped from the pivot laboratory to the other participants. We give the results from the 2011 interlaboratory comparison and review recent comparisons which have used the same traveling standards and similar procedures.

Index Terms— Interlaboratory comparison, Josephson voltage standards (JVS), measurement standards, voltage measurement, uncertainty

I. INTRODUCTION

THE 10 V Josephson voltage interlaboratory comparison (ILC), sponsored by the NCSLI, provides the participating laboratories a means of comparing DC voltage measurements to verify the reliability of their systems and to provide an explicit link to a national metrology institute. The highest accuracy comparisons between Josephson voltage systems can only be conducted when both systems are at the same laboratory. Since 2001 some on-site comparisons have been conducted using transportable compact Josephson voltage systems (CJVS) operated by NIST and Sandia National Laboratories [1]–[4]. However these comparisons are time consuming. In each of the four NCSLI ILC's conducted since 2001, between 13 and 17 laboratories have participated [2], [5]–[7]. It is not practical to conduct on site comparisons with each lab for an ILC of this size. So it has been the practice for NIST to conduct an on-site comparison with one (or, in the case of the 2005 ILC, several) pivot labs and a set of four Fluke 732B Zener voltage references¹ are then sent from the pivot labs to the participants. The same set of Zeners has been used in the six NCSLI ILC's performed since 1997 [2], [5]–[10], so a great deal of data is available relating to the performance and of these standards.

Manuscript received June 29, 2012.

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

H.V. Parks and J.J. Novak are with Sandia National Laboratories, Albuquerque, NM 87185 USA (email: hvparks@sandia.gov).

Y. Tang is with National Institute of Standards and Technology (NIST), Gaithersburg, MD 20878 USA.

P. Reese is with Bionetics Corporation, Patrick AFB, FL 32925 USA.

J. Gust is with Fluke Corporation, Everett WA 98206-9090 USA.

TABLE I
PARTICIPANTS IN THE 2011 NCSLI JOSEPHSON VOLTAGE ILC

| |
|---|
| Agilent Technologies, Loveland, CO |
| Bionetics Corporation, Kennedy Space Center, FL |
| Boeing, Seattle, WA |
| Fluke Calibration, Everett, WA |
| Idaho National Laboratory, Idaho Falls, ID |
| Lockheed Martin Technical Operations, Stennis Space Center, MS |
| Los Alamos National Laboratory, Los Alamos, NM |
| NIST, Gaithersburg, MD (on site comparison with the pivot lab only) |
| Sandia National Laboratories, Albuquerque, NM (pivot) |
| U.S. Air Force Primary Standards Laboratory, Heath, OH |
| U.S. Army Primary Standards Laboratory, Redstone Arsenal, AL |
| U.S. Navy Mid Atlantic Regional Calibration Center, Norfolk, VA |
| U.S. Navy Primary Standards Laboratory, San Diego, CA |

The results of the 2011 ILC were reported at the CPEM 2012 conference [7]. There were 13 participating laboratories (see Table I). An on-site comparison was conducted with the NIST CJVS traveling to the pivot lab at Sandia National Laboratories. The traveling Zeners were then shipped to the 11 other participating laboratories in a set of four loops with each laboratory having the Zeners for one week and the Zeners returning to the pivot lab for about three weeks in between each loop.

II. ON SITE COMPARISONS

A. Direct Array-to-Array Comparisons

Comparisons with a very low uncertainty can be performed when the Josephson array of one system is connected directly to the array of another system. Such direct array-to-array comparisons were conducted between the NIST CJVS and the pivot laboratories for the 2008 and 2011 ILC's.

In 2008, the NIST CJVS traveled to the pivot lab at Lockheed Martin Mission Services (LMMS) in Denver [3]. The comparison was conducted with the bias adjusted by hand. The LMMS – NIST difference at 10 V was found to be (0.7 ± 7.5) nV at a 95% level of confidence. The uncertainty was limited by the fact that only a small number of data points could be taken using the manual method in the several days allowed for the comparison.

¹ Certain commercial equipment, instruments, or materials are identified in this report in order to facilitate understanding. Such identification does not imply recommendation or endorsement by the organizations of the authors, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

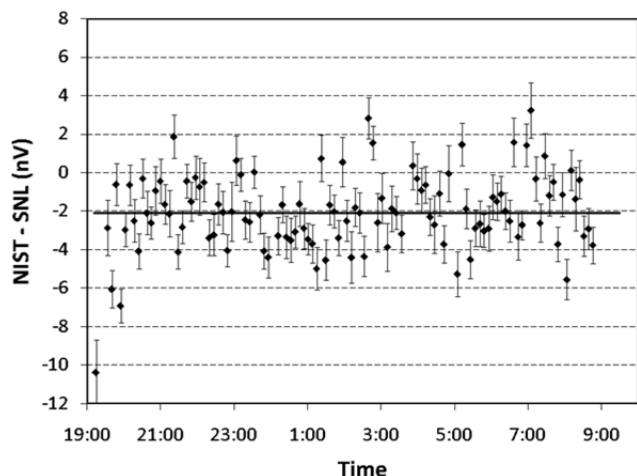


Fig. 1. NIST – Sandia voltage differences at 10 V using the automated direct array to array protocol. Each point represents four sets of data with an alternating (+--+) polarity [4].

For the 2011 ILC, the NIST CJVS traveled to the pivot at Sandia National Laboratories in Albuquerque in December of 2010 [4]. This time an automated protocol was used. Both arrays were connected together and biased (at 10 V) with the NIST CJVS bias system. The bias connect and disconnect and the array difference voltage measurements proceeded automatically. Note that each array is in a separate cryostat and connected to separate microwave sources but are both locked to a common 10 MHz reference.

Some dependence on the time between the bias disconnect and the array voltage measurements was noticed. A first set of runs with a 10 s waiting period between the bias disconnect and the start of the voltage readings found a difference of (-6.5 ± 3.4) nV (at a 95% level of confidence) between the NIST and Sandia systems. Upon further investigation it was decided that dielectric absorption in filter capacitors in the Sandia system was a concern and the waiting period before the voltage measurements was increased to 60 s. A difference of (-2.1 ± 2.9) nV at a 95% level of confidence was now found. This data is summarized in Fig. 1. There is some time correlation in this data so an Allen deviation rather than a standard deviation was used to get a Type A standard uncertainty component of 0.75 nV which was combined with a Type B standard uncertainty of 1.23 nV. The Type B uncertainty contained components for the microwave frequency counters used, by the systems, leakage resistance, and digital voltmeter gain.

B. In-Situ Zener Comparisons

The direct array-to-array comparison uses the bias system and DVM from only one system and the scanners and software normally used by the systems are not tested. So *in-situ* comparisons are also conducted, where both systems are placed in the same lab and make measurements on the same set of Zeners. The uncertainty in the system difference is larger in this kind of comparison since we must now contend with the Zener noise, but this allows the systems to be tested while in the same configuration as for normal use.

TABLE II

A SUMMARY OF THE *IN-SITU* COMPARISONS CARRIED OUT IN NCSLI JOSEPHSON VOLTAGE ILC'S

| Systems Compared | Date | Difference (nV) | U_c (95%) (nV) |
|------------------|------------|-----------------|------------------|
| SNL 1 - NIST | 11/14/2001 | 4 | 12 |
| SNL 1 - SNL 2 | 11/29/2001 | -6 | 15 |
| Lab 1 - NIST | 4/5/2005 | 5 | 27 |
| Lab 2 - NIST | 5/10/2005 | 7 | 19 |
| Lab 3 - NIST | 6/7/2005 | -4 | 27 |
| Lab 4 - NIST | 7/12/2005 | -2 | 25 |
| Lab 5 - NIST | 8/16/2005 | -15 | 25 |
| LMMS - NIST | 3/19/2008 | -16 | 22 |
| SNL 1 - SNL 2 | 5/19/2008 | 7 | 26 |
| SNL 2 - NIST | 12/9/2010 | -12 | 22 |

In the first column of the above table, NIST indicates the NIST CJVS, SNL 1 is a CJVS system operated by Sandia, SNL 2 is a non-portable system at Sandia that was used as the pivot system in the 2002 and 2011 ILC's, and LMMS is the system at Lockheed Martin Mission Services in Denver that was the pivot system for the 1999 and 2008 ILC's. Five laboratories, Lab 1 through Lab 5, conducted comparisons with the NIST CJVS during the 2005 ILC, but the rules of the ILC preclude identifying which laboratory took which measurement. A list of the participating laboratories can be found in [2].

In-situ comparisons using the same set of Zeners that are used for the traveling standards were conducted during the 2002 [1], 2005 [2], 2008 [6], and 2011 ILC's. For the 2002 ILC, a CJVS system owned by Sandia traveled to NIST for a comparison, and the Sandia traveling system was then compared to the non-portable system at Sandia that was used as the pivot for the ILC. During the 2005 ILC, the NIST CJVS system went to five sub-pivot laboratories. In the 2008, and 2011 ILC's, the NIST CJVS was compared to the pivot system with an *in-situ* comparison in addition to the direct array to array comparison. Also in the 2008 ILC, Sandia was a participating laboratory and measured the Zeners with two separate systems during the same week.

The procedure was the same for all of these comparisons, with low thermal reversing switches attached to the 10 V tap of each of the four Zener voltage reference. Four measurements were taken with the switches at each polarity on each of the four Zeners with each system (for a total of 32 measurements from each system).

The results of most recent *in-situ* comparison (conducted on 12/9/2010 at the same time as the direct array-to-array comparison) along with the past comparisons are summarized in Table II. The measured differences are all within the 95% confidence level uncertainties which range from ± 12 nV to ± 27 nV. These uncertainties are dominated by noise in the Zeners. Type B uncertainty components such as leakage currents, time base uncertainty, and DVM errors amount to only a couple of nV.

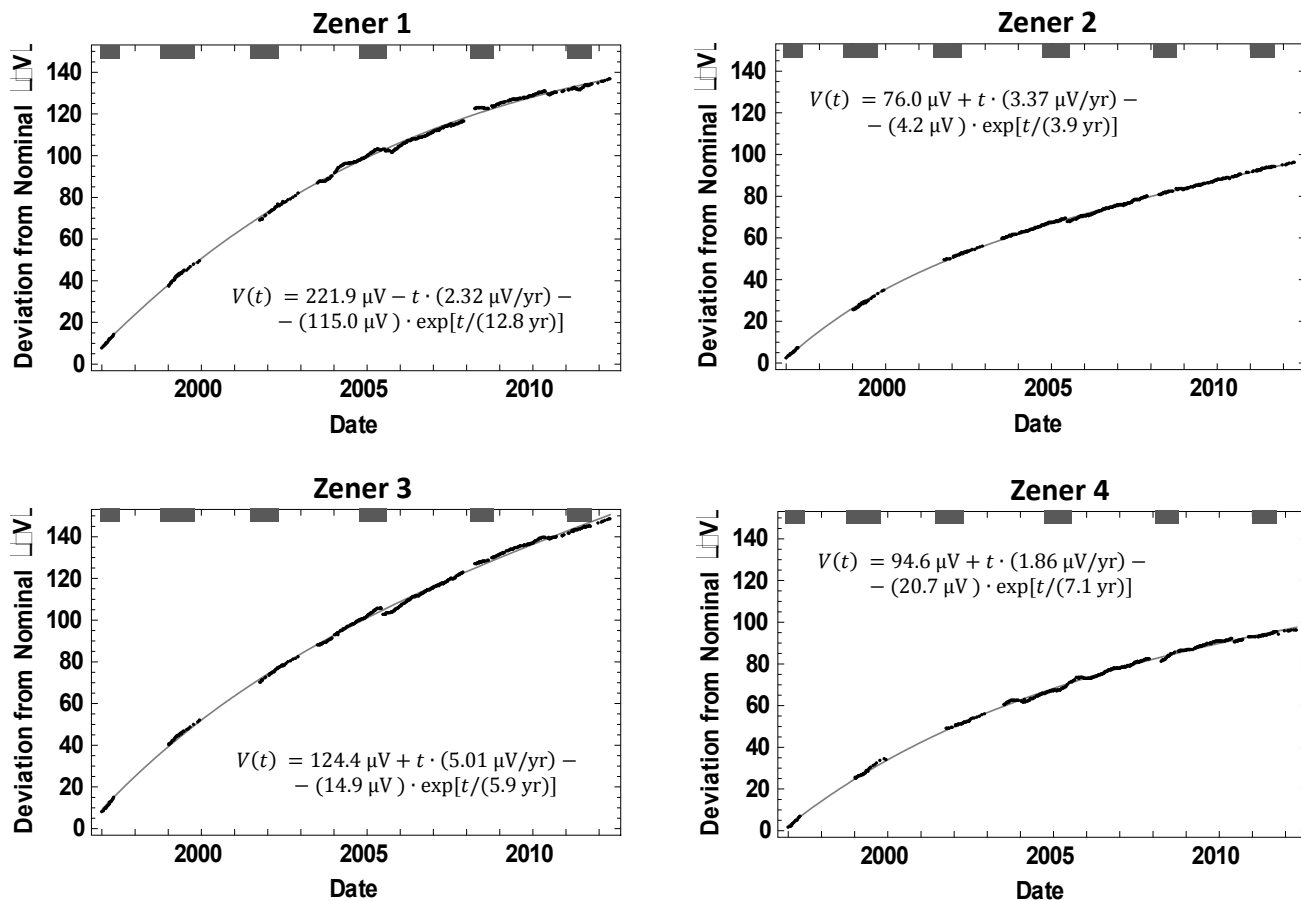


Fig. 2. The pressure corrected deviation from nominal for the 10 V tap of each of the four traveling Zeners plotted from 1997 to 2012. Each point represents the average of data taken in one week. The bars at the top of each frame indicate when the Zeners were traveling for the ILC's. The gray lines are a fit of the data to an exponential plus a linear drift, with the fit equation given on each plot.

III. TRAVELING ZENER COMPARISONS

A. Traveling Zener Measurement Procedure

The same set of Zeners has been used in the NCSLI Josephson voltage ILC's since 1997. The 1997 ILC did not use a pivot lab, and each lab took 16 measurements on each of the four Zeners [8]. In 1999 low thermal reversing switches which mount to the front of the Zeners were added and the same switches have been used ever since. Also since 1999, the number of measurement per Zener from each lab was reduced to 8 (with the reversing switch polarity alternating each measurement). The Zeners normally arrive in a lab on a Thursday, and measurements are taken on the following Monday and Tuesday with the Zeners shipped to the next lab on Wednesday.

The 1999 [9], 2002 [5], 2008 [6] and 2011 ILC's used a single pivot lab. The ILC is arranged as a series of loops where the Zeners would be sent from the pivot to between one and five participant labs before returning to the pivot lab. The 2005 ILC used a variant of this method, where each traveling Zener loop began and ended with a different sub-pivot lab, with each sub-pivot lab conducting *in-situ* comparison with

the NIST CJVS at the start of each loop [2]. The pivot – participant deviation is calculated by assuming a straight line drift of the (pressure corrected) Zener bank mean between the loop opening and closing pivot (or sub-pivot) measurements and calculating the difference between the participant measurement and the pivot line.

B. Zener Performance

The pressure coefficient 732B Zeners are usually close to either -1 nV/hPa or +19 nV/hPa [11], and the Zeners used for this ILC were chosen because they fall into the group with the lower pressure coefficient. The pressure coefficient of these Zeners has been measured in several different pressure chambers, and the coefficient for each Zener was found to be between -0.6 nV/hPa and -1.7 nV/hPa and the bank mean was found to be (-1.11 ± 0.08) nV/hPa at an approximately 95% level of confidence [5]. The ambient pressure at ILC participant labs ranges from 780 hPa to 1010 hPa. The pivot – participant residuals from the 1999, 2002, 2008, and 2011 ILC's were analyzed and a pressure coefficient of (-1.19 ± 0.12) hPa at a 95% level of confidence was found to minimize the standard deviation of the residuals. (The 2005 ILC was not included in this data set since the sub-pivot labs were

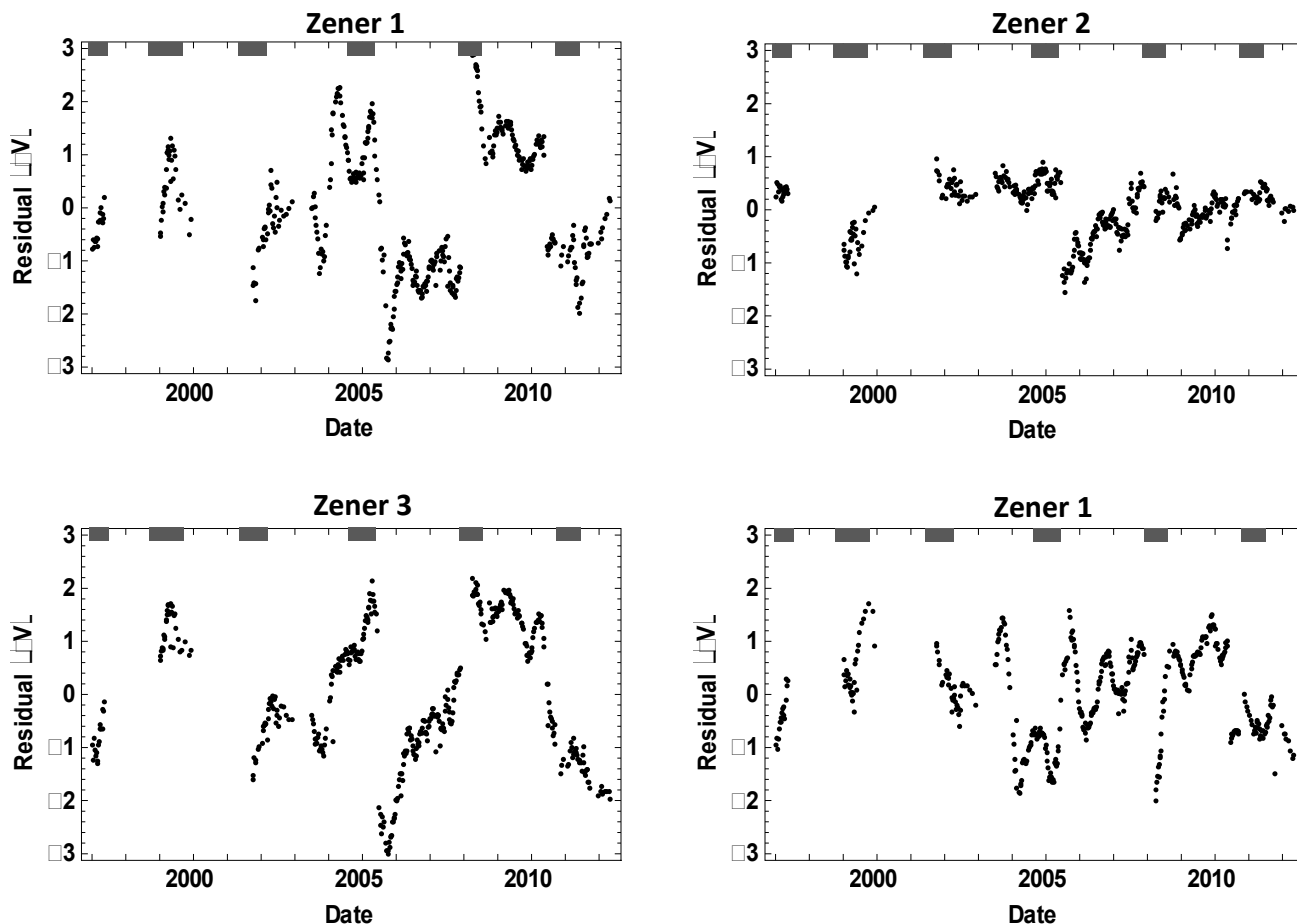


Fig. 3. The residuals of the Zener 10 V tap output when fit to an exponential plus a linear drift. (The data points used to find the fit along with the fit lines are shown in Fig. 2). The bars at the top of each frame indicate when the Zeners were traveling for the ILC's. A large shift in the data is seen in mid-2005, when the Zener batteries died while being held by US Customs. Shifts are also seen in 2008 and 2010 due to the shipping stresses when the Zeners were transported from NIST to the pivot lab prior to an ILC. Seasonal cycling due to humidity effects is also present.

chosen to minimize the altitude difference between the sub-pivot and the participants for the corresponding loop.) The altitude of the pivot labs has been relatively high with the pivot for the 1999 and 2008 ILC at Lockheed Martin Mission Services in Denver, CO with a mean pressure of 823 hPa and the pivot of the 2002 and 2011 ILC at Sandia National Laboratories in Albuquerque, NM with a mean pressure of 834 hPa. However the uncertainty in the pressure corrected Zener voltage due to uncertainty in the pressure coefficient is less than 20 nV even when a lab at sea level is compared to a pivot at Lockheed, Denver or Sandia, Albuquerque.

The Zener output does have dependence on humidity, but the effect can have a time constant of month or more [12]. Since the Zeners move from lab to lab on a weekly basis during the ILC, we do not attempt to make a correction based on humidity. The temperature coefficient of these Zeners were measured for the 2002 ILC and were found to range between -15 nV/ $^{\circ}$ C and $+26$ nV/ $^{\circ}$ C, with the bank mean having a temperature coefficient of (1 ± 10) nV/ $^{\circ}$ C at a 95% level of confidence. (These coefficients are with respect to the environmental temperature, not the internal oven temperature.)

Because the coefficients are small, no temperature corrections are applied to the data.

The drift of the four traveling Zeners from 1997 to 2012 is plotted in Fig. 2. Data taken during all the ILC's since 1997 is plotted (most of the points in red), as well as data taken between ILC's (in blue) while the Zeners were at NIST from 2003 to 2010 and at Sandia in 2002-2003 and 2010-2012. The drifts do not all fit a single exponential well, but they do fit an exponential (with a time constant ranging from 4 to 13 yrs) plus a linear drift on the order of 3 μ V/yr. The fit residuals for the individual Zeners as well as the mean of the residuals are plotted in Figs. 3 and 4. A jump occurs in the middle of the 2005 ILC when the batteries died while the Zeners were being held by US Customs. Jumps also appear in 2008 and 2010 which occurred during transit from NIST to the pivot lab prior to an ILC. In these two cases the batteries never ran low. Seasonal variation due to humidity changes can also be seen in the NIST data. We note that 732B Zeners that have a small pressure coefficient tend to have a drift rate with a higher magnitude (and drift in the positive rather than the negative direction) than the 732B Zeners that have a larger pressure

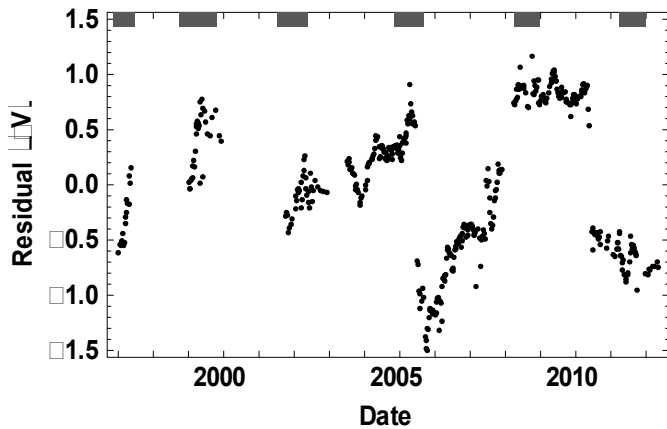


Fig. 4. The behavior of the Zener bank mean after removing the drifts as fit in Fig. 2. The bars at the top indicate when the Zeners were traveling for the ILC's

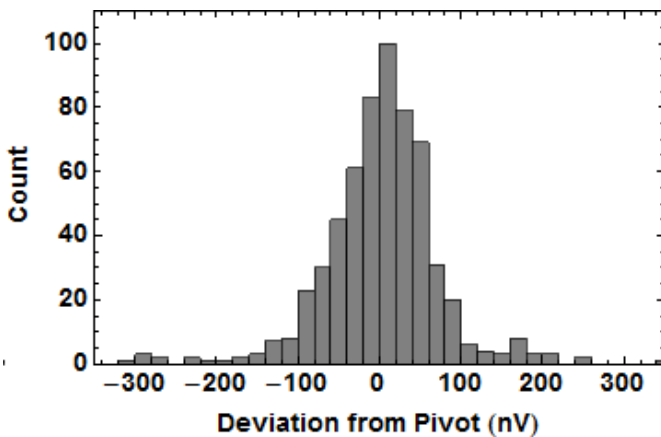


Fig. 5. A histogram of the participant - pivot residuals simulated from the NIST data taken when the Zeners were at NIST. The standard deviation is 73 nV

coefficient. But variations in the drift rate are small, so the average drift rate can be removed from the data.

It can be seen immediately from the scatter in Fig. 4 that, while the drift of the Zeners has been quite predictable over the course of 15 years, the week to week variation of the Zener bank mean is still much larger than the uncertainties of a Josephson voltage system. The spread of the points in Fig. 4, even over short times scales, can be several hundred nV. Based on the direct and *in-situ* comparisons, we would expect the uncertainties of the Josephson systems themselves contribute less than 20 nV to this scatter. To get a feel for the week to week variations, the NIST data from 2003 to 2010 (when the Zeners weren't traveling) was used to simulate ILC data. "Pivot" weeks were arbitrarily selected from the NIST data set which bracketed "participant" points and "participant" - "pivot" differences were calculated following the ILC procedure. Using a four week separation for the pivot points (which is the mean separation for pivot measurements for the 1999 to 2011 ILC's), the 602 possible participant - pivot differences are plotted as a histogram in Fig. 5. The standard deviation is 73 nV, but the 95% confidence interval is slightly asymmetric, with the 2.5% and 97.5% quantiles at -149 nV and +164 nV. The actual ILC data will be expected to have

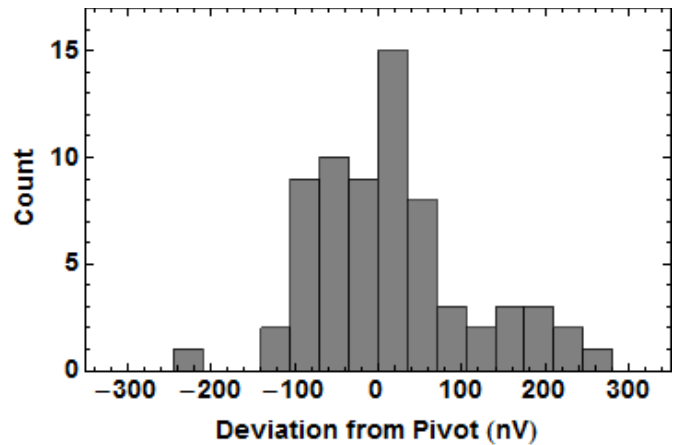


Fig. 6. A histogram of the participant - pivot deviations from the 1999 through 2011 ILC's. The mean is 14 nV and the standard deviation is 93 nV. Not included in this standard deviation is a point at -1.0 μ V from the 2005 ILC where a problem with the participant time base was found. Also excluded are two points at -670 nV and -690 nV taken during the 1999 ILC.

slightly more scatter due to the effects of transportation on the Zeners.

A histogram of the actual participant - pivot deviations from the 1999 through 2011 ILC's is shown in Fig. 6. The standard deviation is 93 nV but the distribution also is skewed towards the positive direction (even though the procedure for calculating the deviations should remove the overall drift of the Zeners that is seen in Fig. 2). This distribution has an Anderson-Darling statistic of 1.1 [13], which indicates that the hypothesis that the data are normally distributed is rejected at a 99% level of confidence. The mechanism behind this non-Gaussian behavior is not known, though the outlying points generally coincide with sudden short term changes in the Zener drift rate. Zeners are prone to sudden changes in response to environmental or transportation stresses, and it is not surprising that this is reflected in the data.

There are 68 data points represented in Fig. 6, which is not quite enough to accurately fix the 95% confidence interval without making assumptions about the shape of the distribution. Fitting the data to a skew-normal distribution we find a skew parameter of 2.3 and 2.5% and 97.5% quantiles at -140 nV and +220 nV. The lower bound is close to but, by chance, slightly narrower than the bound found from the simulation using the NIST data, while the upper bound is significantly wider than the simulation. We take the uncertainty in the participant - pivot differences to be +220 nV -150 nV at a 95% level of confidence. For the lower bound of this uncertainty interval we have used the result from the simulated ILC since there are many more points in the simulated data set and we would not expect the actual data to have less scatter than the simulated case where the Zeners were not subjected to the stresses of transportation. For the upper bound of the uncertainty interval we use the fit of the real ILC data since actual data is more skewed in this direction than the simulated data. The result is not too different from the ± 190 nV 95% confidence interval that would be calculated assuming that the ILC data is normally distributed. In the absence of more data or a detailed model for the mechanism

TABLE III
PARTICIPANT – PIVOT DIFFERENCES FOR THE 2011 NCSLI
JOSEPHSON VOLTAGE ILC.

| Lab | Mean Date | Participant – Pivot Difference (nV) |
|--------|-----------|-------------------------------------|
| Pivot | 3/21/2011 | |
| Lab A | 3/28/2011 | 168 |
| Lab B | 4/5/2011 | 183 |
| Lab C1 | 4/14/2011 | 10 |
| Lab C2 | 4/17/2011 | 15 |
| Pivot | 4/27/2011 | |
| Pivot | 5/9/2011 | |
| Lab D | 5/16/2011 | -71 |
| Pivot | 6/1/2011 | |
| Pivot | 6/20/2011 | |
| Lab E | 6/28/2011 | -40 |
| Lab F | 7/12/2011 | -20 |
| Lab G | 7/19/2011 | 174 |
| Pivot | 7/24/2011 | |
| Pivot | 8/8/2011 | |
| Lab H | 8/16/2011 | 29 |
| Lab I | 8/22/2011 | 44 |
| Lab J | 8/30/2011 | 36 |
| Lab K | 9/7/2011 | 19 |
| Pivot | 9/17/2011 | |

The uncertainty in the participant – pivot differences is ± 220 nV -150 nV at a 95% level of confidence. Lab C, Bionetics Corp. at Kennedy Space Center, FL, made measurements with two systems, a conventional Josephson system (C1) and a programmable Josephson system (C2).

behind the non-Gaussian behavior, this is the best uncertainty estimate that can be obtained.

C. 2011 Results

The results of the 2011 NCSLI Josephson voltage ILC are given in Table III. Note that Lab C (Bionetics Corp. at Kennedy Space Center, FL) measured the Zeners with a conventional Josephson system (denoted C1 in table III) and a programmable Josephson system (denoted C2). Except for C2, all systems in this ILC ran a version of the NISTVolt software. The standard deviation of the participant – pivot differences is 88 nV. The uncertainty of a typical Josephson voltage system is less than 20 nV, as demonstrated by direct array-to array and *in-situ* comparisons, so almost all of this variation is due to the Zener voltage standards used for the comparison. Since the same Zeners and procedures were used for this ILC as for the 1999, 2002, 2005, and 2008 ILC's, we use data from all of these ILC's to estimate the uncertainty in the participant – pivot difference. We find the 95% level of confidence uncertainty interval to be ± 220 nV -150 nV.

IV. CONCLUSION

An uncertainty of several nV may be obtained when Josephson voltage systems are compared with a direct array-to-array comparison. When an *in-situ* comparison using Zeners is conducted, this uncertainty rises to on the order of ± 20 nV. When the Zeners are used as traveling standards, the

comparison uncertainty is on the order of ± 200 nV. Even though the uncertainty using traveling Zener standards is much larger than what can be theoretically obtained with Josephson voltage systems, it is still smaller than the uncertainty assigned to the instruments that are routinely calibrated with these systems. As a practical matter, this type of ILC is a valuable aid in ensuring the traceability to the SI for measurement performed by the participating laboratories.

ACKNOWLEDGMENT

We thank Fluke Calibration for the use of the four Zener traveling standards since 1997 and High Precision Devices for the reversing switches.

REFERENCES

- [1] Y. Tang, S.L. Kupferman, and M.T. Salazar, "An Evaluation of Two Methods for Comparing Josephson Voltage Standards of Two Laboratories", *IEEE Trans. Instrum. Meas.*, vol. 54, no. 1 pp. 398-403, Feb. 2005.
- [2] Y. Tang, C.A. Hamilton, D. Deaver, H. Parks, B.M. Wood, "The Seventh Intercomparison of Josephson Voltage Standards in North America", *IEEE Trans. Instrum. Meas.*, vol. 56, no. 2, pp. 605-609, April 2007.
- [3] Y. Tang, W.B. Miller, and L.P. Pardo, "A Direct Josephson Voltage Standard Comparison between NIST and Lockheed Martin Mission Services for Supporting the NCSLI Intercomparison", *NCSLI Measure*, vol 4, no. 3, pp. 28-32, Sept. 2009.
- [4] Y. Tang, H. Parks, M. Salazar, and J. Novak, "Direct JVS Comparison between NIST and SNL to Support NCSLI JVS ILC 2011", *NCSLI Measure*, vol 6, no. 4, pp. 40-45, Dec. 2011.
- [5] C.A. Hamilton, S.L. Kupferman, M.T. Salazar, D. Deaver, B.M. Wood, "Interlaboratory Comparison at 10 V DC", *IEEE Trans. Instrum. Meas.*, vol. 54, no. 1, pp. 215-221, Feb. 2005.
- [6] H.V. Parks, W.B. Miller, L.P. Pardo, C. Kiser, C.A. Hamilton, and Y. Tang, "The 2008 NCSLI Josephson Voltage Standards Interlaboratory Comparison", *NCSLI Measure*, vol 5, no. 4, pp. 74-78, Dec. 2010.
- [7] H.V. Parks, Y. Tang, P. Reese, J. Gust, and J.J. Novak, "The 2011 North-American Josephson Voltage Interlaboratory Comparison", *Conference on Precision Electromagnetic measurements 2012 Digest*, Washington DC, July 1-6, 2012.
- [8] C.M. Wang and C.A. Hamilton, "The fourth interlaboratory comparison of 10 V Josephson voltage standards in North America", *Metrologia*, vol. 35, no. 1, pp. 33-40, Feb. 1998.
- [9] D. Deaver, W.B. Miller, L. Pardo, K. Jaeger, D. Plowman, C.A. Hamilton, "Interlaboratory Comparison of Josephson Voltage Standards", *IEEE Trans. Instrum. Meas.*, vol. 50, no. 2, pp. 199-202, April 2001.
- [10] Y. Tang and W.B. Miller, "Interlaboratory comparison of Josephson voltage standards between NIST and Lockheed Martin Astronautics", *IEEE Trans. Instrum. Meas.*, vol. 50, no. 2, pp. 210-213, April 2001.
- [11] T.J. Witt, "Pressure Coefficients of Some Zener Diode-Based Electronic Voltage Standards", *IEEE Trans. Instrum. Meas.*, vol. 48, no. 2, pp. 329-332, April 1999.
- [12] C.A. Hamilton and L.W. Tarr, "Projecting Zener DC Reference Performance Between Calibrations", *IEEE Trans. Instrum. Meas.*, vol. 52, no. 2, pp. 454-456, April 2003.
- [13] T.W. Anderson and D.A. Darling, "A Test of Goodness-of-Fit", *Journal of the American Statistical Association*, vol 49, no. 268, pp. 765-769, Dec. 1954.