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The 2014 North American Josephson Voltage Interlaboratory Comparison

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1. Abstract

The 10th North American Josephson voltage standard (JVS) interlaboratory comparison (ILC) at 10 V was completed in 2014. This year's ILC was unique as it consisted of 2 parts. An on-site comparison was conducted between the National Institute of Standards and Technology (NIST) compact JVS and the pivot laboratory conventional JVS (CJVS) system. A set of four traveling Zener voltage standards then served to transfer traceability from the pivot laboratory to the 12 other participants. In addition to the regular ILC activities, a second on-site comparison was conducted between the NIST compact JVS and the programmable JVS (PJVS) provided by the National Aeronautics and Space Administration (NASA). Due to limited availability of the PJVS, only two labs were selected to make direct comparison between their CJVS systems and NASA's PJVS. The method has been used for the first time in the JVS ILC and has the advantage of using the PJVS as a transfer standard. This allowed the participating lab to make comparisons using its CJVS system against the 10V PJVS in the same manner as the measurements for Zener standards are performed while overcoming limitations of the Zener noise. We give the results from the 2014 ILC.

Keywords: automatic comparison, conventional Josephson voltage standard, programmable Josephson voltage standard, uncertainty, Zener standard

2. Introduction

The 10-V Josephson voltage interlaboratory comparison (ILC), 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 Josephson voltage standard (JVS) Interlaboratory Comparison (ILC) at 10 V sponsored by the National Conference of Standard Laboratories International (NCSLI) started in 1991. Since then every three years a JVS ILC is carried out among the JVS laboratories in North America, including the National Research Council (NRC) of Canada and Centro Nacional de Metrología, (CENAM) of Mexico.

In the last 20 years the uncertainty of the NCSLI JVS ILC has been improved from a few parts in 10^8 to a few parts in 10^{10} at 10 V. The following are the milestones of the development of various protocols that played critical roles to achieve the improvements.

- 1991 1st JVS ILC using Zener standards as transfer standards, uncertainty 5 parts in 10^8.
- 1999 Introducing correction for Zener pressure effect, uncertainty 2 parts in 10^8.
- 2005 Introducing in-situ JVS comparison using a set of Zener standards, uncertainty 2 parts in 10^9.
- 2008 Introducing direct JVS comparison, uncertainty 3 parts in 10^{10}
- 2014 1st JVS ILC using a programmable JVS (PJVS) as a transfer standard.

Comparisons between Josephson voltage systems are much more accurate than using a Zener as a transfer standard. In the recent NCSLI JVS ILCs a direct comparison between NIST and an ILC pivot lab achieved an uncertainty of a 3 parts in 10^{10}. The on-site comparisons were conducted using transportable, conventional Josephson voltage standards (CJVSs) operated by the National Institute of Standards and Technology (NIST). There were 12 participating laboratories (see Table 1) in the 2014 ILC.

Table 1, Participants in the Zener and PJVS artifact comparison

Participants for the 2014 NCSLI Josephson Voltage ILC
Bionetics Corporation, Kennedy Space Center, FL
Boeing, Seattle, WA
Fluke Calibration, Everett, WA
Idaho National Laboratory, Idaho Falls, ID
Keysight Technologies, Loveland, CO (pivot)
Lockheed Martin Technical Operations, Stennis Space Center, MS
Lockheed Martin Mission Services, Denver, CO
National Research Council Canada, Ottawa, ON
Sandia National Laboratories, Albuquerque, NM
U.S. Air Force Primary Standards Laboratory, Heath, OH
U.S. Army Primary Standards Laboratory, Redstone Arsenal, AL
U.S. Navy Primary Standards Laboratory, San Diego, CA

It is still not practical to conduct on-site direct comparisons with each laboratory for an ILC of this size. Therefore, it is the practice of NIST to conduct an on-site comparison with one pivot laboratory (or several pivot laboratories in the case of the 2005 ILC), and a set of four Fluke 732B Zener voltage references[1] was then sent from the pivot laboratories to the participants. The same set of Zener voltage standards has been used in the six NCSLI ILCs performed since 1997 [1], so a great deal of data is available relating to the performance of these standards.

However, the best uncertainty of JVS ILC using a set of Zener standards as transfer standards can only reach a few parts in 10^9, limited by the noise of the Zeners. This may satisfy the needs

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

for a JVS to calibrate other Zener standards, but not sufficient to demonstrate the capability of a fully functioning JVS system. Some of the small errors related to the JVS operation can be caused by improper grounding, leakage of the filter, etc. The magnitude of such small errors are often in the nanovolts range and thus are not detectable by using Zeners as transfer standards for the comparison.

For the 10th NCSLI JVS ILC, in addition to the traveling Zener transfer standards, a 10 V programmable Josephson voltage standard (PJVS) was used for the first time as a transfer standard for direct comparison between PJVS and the participating lab's CJVS. The stable DC quantized voltage step makes it possible for a CJVS to measure the PJVS voltage as if it were a Zener calibration. The existing software used by CJVS is readily used to make PJVS-CJVS direct comparison. The uncertainty for the PJVS-CJVS direct comparison is the same as direct comparison between two CJVSs. NASA's 10 V PJVS was used as a transfer standard to make direct comparisons with three CJVS, including the NIST CJVS. This is the first time a PJVS has been used as a transfer standard in the NCSLI JVS ILC.

3. Direct CJVS Comparison

To support the traditional Zener transfer standard method, an onsite comparison was conducted with the NIST CJVS traveling to the pivot laboratory at Keysight Technologies (KTI). The CJVS employs a Josephson junction array integrated with tens of thousands of superconductor-insulator-superconductor (SIS) junctions. The voltage generated by the array is quantized and calculable, according to:

$$V_{array} = \frac{nhf}{2e}N = \frac{nf}{K_{J-90}}N \qquad (1)$$

where n is an integer representing the quantum state of the array, h is the Planck constant, f is the frequency of the microwave bias, e is the electron charge, and N is the number of junctions in the array. The value used for $2e/h$ is the value of $K_{J\text{-}90}$ = 483 597.9 GHz/V, the Josephson constant adopted worldwide on January 1, 1990. Essentially, the Josephson junction array converts frequency into a quantized DC voltage.

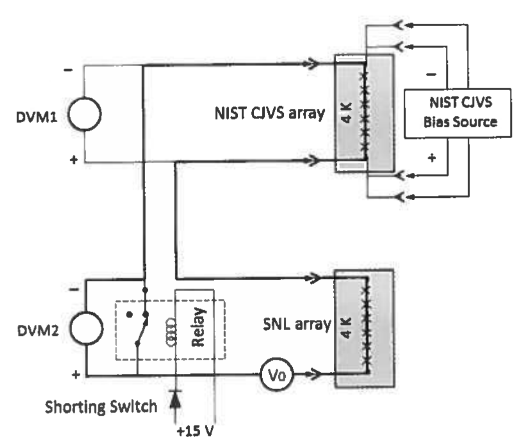


Figure 1. Illustrates the set-up for the NIST-Keysight direct JVS comparison

The basic experimental method (Figure 1) has been reported in [2]. The purpose of the JVS comparison is to determine the quantity V_δ which is the difference between the nominal 10 V outputs of the two arrays that are operated at frequencies f_{NIST} and f_{KTI} and biased on step numbers N_{NIST} and N_{KTI}, respectively from the theoretical voltage difference Δ_{th}.

$$\Delta_{th} = V_{NIST}^{array} - V_{KTI}^{array} \qquad (2)$$

$$N_{NIST} = round\left\{\frac{K_{J-90} * V_{DVM1}}{f_{NIST}}\right\} \qquad (3)$$

$$N_{KTI} = round\left\{\frac{K_{J-90} * (V_{NIST}^{array} - V_{DVM2})}{f_{KTI}}\right\} \qquad (4)$$

where the function *round* is applied to round the result to the nearest integer.

The difference V_δ between each DVM2 measurement and the theoretical difference of the two arrays can be derived as

$$V_\delta = V_{DVM2} - \Delta_{th} \qquad (5)$$

Based on the multiple DVM2 measurements corresponding to the array polarity changes, a difference between the two array systems from their theoretical difference was calculated.

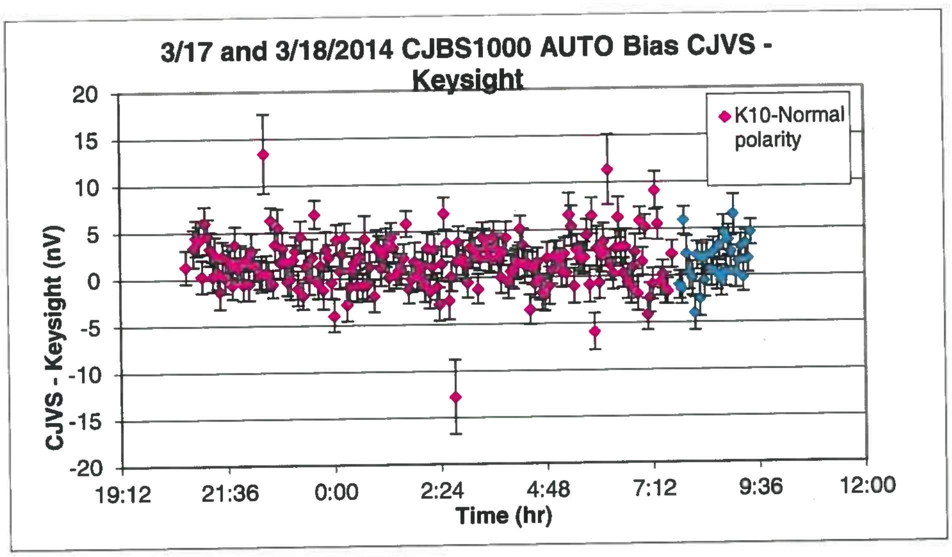


Figure 2. Time trace of measured voltage differences between NIST CJVS and KTI CJVS. Nominal voltage of both CJVS arrays was 10 V. Points near end of trace represent data collected after polarity reversal of both CJVS arrays.

The first automated run of the NIST-KTI CJVS comparison took place on March 17, 2014. A total of 219 measurements were performed as shown in Figure 2. The mean difference of the measurements between the NIST and KTI system was 1.61 nV with a standard deviation of 2.74 nV. It took an average time of 3.0 min to acquire a single data "point". Each such point represents four, sequential measurements, in which the polarity of both arrays is reversed according to {+, -, +, -}. At each step of the sequence, we acquired 10 DVM2 readings, using an integration time of 10 power line cycles per reading. Reversing the polarity in this manner eliminates errors due to thermal EMFs (produced mostly from the leads that are between room temperature and liquid helium temperature) and the DVM zero offset in the measurement loop. The difference V_δ between the two JVS systems was calculated using a least square fit estimation of the entire 40 DVM2 readings. The error bars in Figure 2 reflect the Type A ($k = 1$) uncertainty from 40 DVM measurements.

In this JVS comparison, the difference between the NIST CJVS and the KTI CJVS was found to be 1.61 ± 2.61 nV at 10 V ($k = 2$). The result of this direct JVS comparison achieved an uncertainty level comparable to the international key comparison BIPM.EM.K10.b [2] in the Bureau International des Poids et Mesures (BIPM) Key Comparison Data Base (KCDB). This bilateral JVS comparison has confirmed that Keysight is capable of performing its role as the pivot lab in the NCSLI JVS ILC. The uncertainty of the 2014 direct CJVS comparison is calculated using the following equation,

$$u_c = \sqrt{u_A^2 + u_{freq}^2 + u_{li}^2 + u_{lj}^2 + u_{DVM}^2}$$

where u_A is the Type A uncertainty and the other four items are the Type B components. The standard deviation of the mean of the 219 measurement points from Figure 2 was 0.19 nV, which was lower than the $1/f$ noise floor of the DVM2 that was used to measure the array voltage difference. An independent $1/f$ noise floor measurement was performed using DVM2. The mean Allan deviation for a sampling time that is longer than 50 s was calculated to be 0.33 nV and was used for the estimated Type A uncertainty.

The items u_{freq}, u_{l1}, u_{l2}, and u_{DVM} are the Type B components of uncertainty. The frequency error u_{freq} is dominated by Keysight's Phase Matrix Inc.[1] counter, NIST's system employs a custom phase locked loop and is considered negligible. The timebase error of the 10 MHz reference is common to both systems and therefore does not contribute. The leakage error u_{l1}, u_{l2} of the two systems was measured before the comparison began following [2] and the DVM gain error was measured using a PJVS. All components of uncertainty listed in Table 2 are $k = 1$ with units of nanovolts.

Table 2 Results of the NASA PJVS and NIST CJVS comparison at 10 V

	NIST CJVS	KTI CJVS
NASA - NIST (nV)	1.61	
Number of points	218	
Type A	0.33	
Frequency	0	1.08
Leakage	0.43	0.20
DVM gain	0.50	Not applicable
Expanded U_{95} (nV) ($k = 2$)	2.61	

4. *In Situ* Zener Voltage Standard Comparisons

The direct array-to-array comparison used the bias system and DVM from the NIST CJVS system, and the scanner and software normally used by the KTI's CJVS system was not tested. Therefore, *in situ* comparisons using the traveling Zeners was also conducted, where both NIST and KTI CJVS systems were placed in the same laboratory and to make measurements on the same set of Zener voltage standards. The uncertainty in the system difference was larger in this kind of comparison since we must now contend with the *1/f Zener* voltage standard noise, but this allows the systems to be tested while in the same configuration as for normal use.

An *in-situ* JVS comparison between the NIST CJVS and the Sandia National Laboratories (SNL) JVS via a set of Zener transfer standards at 10 V was carried out. The difference was 12 ± 27.9 nV at 10 V (k = 2). This result is consistent with the results from similar past JVS ILC comparisons.

5. Traveling Zener Voltage Standard Comparisons

The Zeners used in this comparison are quite stable, and have a long, well-documented history [1]. As such, they represent the best artifact standards that most laboratories are likely to calibrate. The procedure used for the artifact comparison is very similar to the six previous North American Josephson comparisons [1, 3-7], all of which used the same four Zener artifacts. Keysight Technologies in Loveland, CO served as the pivot laboratory for this comparison and the 11 other participating laboratories are given in Table 1. The comparison consisted of several sub-loops with the Zeners starting at the pivot lab and traveling to several other labs before returning to the pivot. The original plan was for four sub-loops with two to four labs in each sub-loop. However the "in-cal" light failed after the first participant in the last loop finished the measurements. Normally when this light is off, it indicates that the internal oven has lost temperature control of the voltage reference, perhaps due to a drained battery, and that the Zener value is likely to have shifted. It this case it was found that the problem was with the indicator light itself and no shift was seen in the Zener value. The Zeners were returned to the pivot lab, and a fifth loop was added for the final two participants.

In most cases a lab received the Zeners on a Thursday. The Zeners were allowed to sit over the weekend and measurements were taken on Monday and Tuesday. The only exception was for the 18 July pivot measurements (4^{th} pivot measurement, day 120) where the measurements were started 24 hours after the Zeners were received because the system would not be available following the weekend. Low thermal reversing switches (the same ones used in the five comparisons [1, 3-6]) were attached to the terminals of each Zener. Each lab was instructed to take eight measurements on each Zener 10 V tap with alternating polarity. One lab reported only one measurement at each polarity. The measurements from this lab are included (but marked) in the results. Several labs reported more than eight measurements for each Zener; for these labs only the last eight measurements were included in the analysis.

Four Fluke 732B Zener voltage standards are used as the artifacts. The pressure coefficients of each Zener have been measured previously and they range from -0.7 nV/hPa to -1.7 nV/hPa. Since the ambient pressure in the participating labs ranges from 830 hPa to 1010 hPa, the pressure correction is significant. A pressure sensor traveled with the Zeners and all measurements were corrected to 845 hPa which was the average pressure at the pivot.

Since the Zener values drift with time, the participant-pivot difference is calculated by fitting a line between the pivot bank average measurements immediately before and immediately after the participant measurements and finding the deviation between the participant bank average result and the pivot fit line. The participant (and pivot) bank average result was found by separately fitting a line to the measurements from each Zener, taking the fit prediction from each Zener fit at a common mean time, and averaging the predicted values over the four Zeners. Note that the results of this procedure do not differ significantly from simply averaging the 32 voltage measurements of each participant. The results are shown in Table 3. Note that the ILC charter stipulated a partial anonymity, with the participants listed (Table 1) but with no public identification between the lab and their particular results.

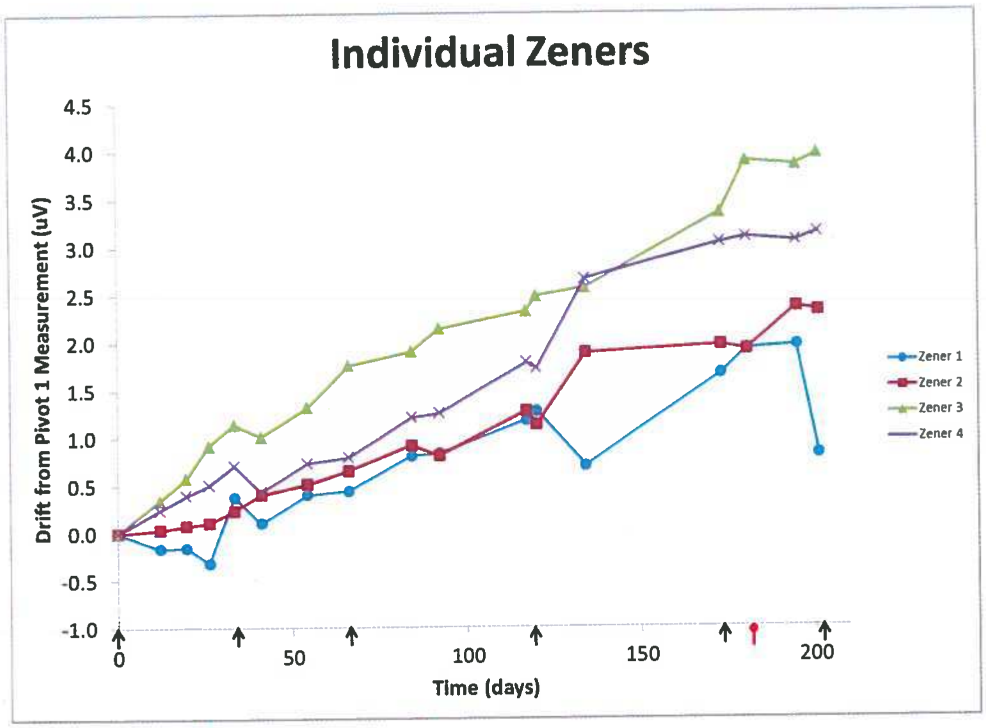
Table 3 Participant–Pivot Differences for the 2014 NCSLI Josephson Voltage ILC

Laboratory	**Mean Date**	**Participant - Pivot Deviation (nV)**
Pivot 1	20-Mar-14	
Lab A	1-Apr-14	-23
Lab B	8-Apr-14	-1
Lab C	15-Apr-14	-182
Pivot 2	22-Apr-14	
Lab D	30-Apr-14	-175
Lab E	13-May-14	-64
Pivot 3	25-May-14	
Lab F	12-Jun-14	58
Lab G	20-Jun-14	-25
Lab H	15-Jul-14	29
Pivot 4	18-Jul-14	
Lab I	1-Aug-14	74
Pivot 5	9-Sep-14	
Lab J*	16-Sep-14	96
Lab K	30-Sep-14	254
Pivot 6	7-Oct-14	

The standard deviation of the deviations (excluding Lab J, which acquired only two measurements instead of eight measurements) is 126 nV. This is slightly larger than the 93 nV standard deviation for the combined results of the last six ILCs conducted from 1999 through 2011, which used the same Zener artifacts and the same measurement and analysis procedures.

As demonstrated by the on-site comparisons performed during this ILC as well as previous on-site comparisons [3, 8-10], uncertainties associated with the Josephson systems themselves amount to only a few nV. The uncertainty in the participant-pivot difference measurement is dominated by the stability of the artifacts even after taking into account the first order drift.

Figure 3 shows the evolution of the individual Zener values as well as the bank mean over the course of the comparison. The Zeners shown in Figure 3 were used in previous comparisons and the numbering of the Zeners is the same as that used in [1] and [3].



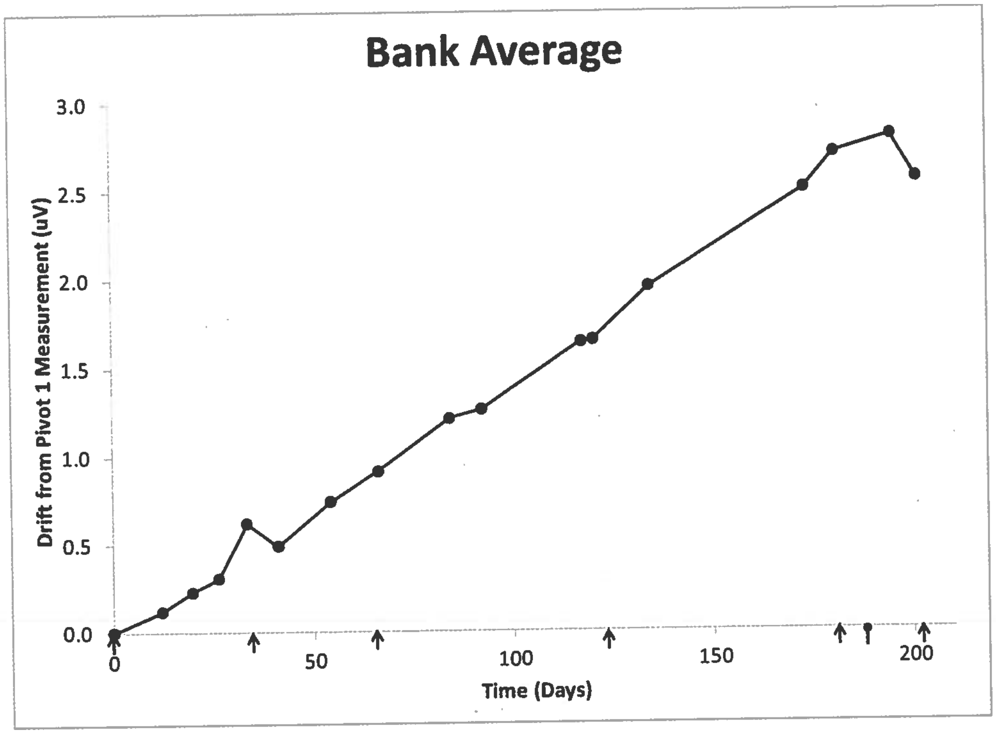


Figure 3. The drifts of the Zener artifacts are shown here. The top plot shows the change in (pressure corrected) value for each of the four Zeners with respect to the values found at the first pivot measurement while the bottom plot shows the drift in the bank mean of all four Zeners. The pivot measurements are indicated by the arrows on the time axis while the measurement from Lab J is indicated by the red tick mark at 181 days.

Zener standards are prone to unpredictable jumps in output voltage, which can make statistical analysis of the results particularly challenging [1]. In [1], the uncertainty interval for the participant-pivot difference (based on a history of five ILC's using the same Zener artifacts as for this comparison) was found to be (-150 nV, +220 nV) at a 95% level of confidence. The results for Labs C, D, and K in Table 3 lie slightly outside this interval. A careful inspection of the data makes it clear that these outlying measurements are due to shifts in the Zeners rather than measurement issues at the participating laboratories.

The general upward trend is consistent with the drift seen in past comparisons. The Lab C and D measurements were taken near days 26 and 41 respectively, immediately before and after the second pivot measurements. Zener 1 shifts immediately before the second pivot measurement and Zeners 3 and 4 shift in unison immediately after that pivot measurement. The result is to put the second pivot measurement well above bank average trend line and cause the lab C and D measurements to be low with respect to the pivot measurements. The outlying result for Lab K is due entirely to a 1 μV shift in Zener 4 immediately after Lab K made the measurements. Note that neither the Zener with the failed in-cal light, Zener 2, nor the pivot measurement where the stabilization time was only 24 hours, pivot 4, is implicated in any of the sudden shifts.

To summarize, the results of this comparison have a slightly higher standard deviation than is typical from past comparisons, and we find three values just outside the (-150 nV, +220 nV) 95%

level of confidence uncertainty interval for the participant-pivot differences. The shifts seen here are not outside those seen in historical experience. We must also keep in mind that, while these shifts are troubling in the context of our uncertainty analysis, the largest participant-pivot deviation in this comparison amounts to a relative error of less than 0.03 μV/V. The tightest uncertainty that the Josephson systems compared here are likely to assign to a device under test in every day operation is on the order of 0.5 μV/V [11].

6. Using the PJVS as a transfer standard for JVS direct comparison

The programmable Josephson voltage standard (PJVS) was first proposed by C. Hamilton at NIST in 1995 [12]. The programmable array is made of superconductor-normal metal-superconductor (SNS) junctions, fabricated by the Quantum Voltage Group at the NIST. Similar work conducted at the Physikalisch-Technische Bundesanstalt (PTB) in Germany uses superconductor-insulator-normal metal-insulator-superconductor (SINIS) junctions [13]. In the PJVS, the quantized voltage step is established by applying a microwave bias as well as a dc current bias. The direction and magnitude of the dc bias allows selection of the quantized voltage steps. The working principle is similar to that of the CJVS, and the relation in Equation 1 may be used. However, in the PJVS the variable n — which represents the step number — is restricted to only the integers +1, 0, and -1. No step jump would happen in the PJVS operation since all the voltage steps must be biased at different currents. Another distinguishing characteristic of the PJVS is that the step width of 1 to 2 mA is almost 100 times larger than that of the CJVS. These two properties have helped to make the PJVS an indispensable tool for precision measurements in noisy environments, such as the Watt balance experiment [REFERENCE?]. Early in its development, the PJVS was limited to maximum voltages of 2 V. Later, in 2010, the first 10 V PJVS was invented, greatly expanding the range of potential applications [14]. The adoption and dissemination of the 10 V PJVS as the precision standard for DC voltage occurred rapidly after its introduction within the United States and around the world. The NASA Metrology and Calibration (MetCal) Program Office, located at the Kennedy Space Center (KSC), was the first organization to use the 10 V PJVS for its various laboratories and centers. The NASA PJVS is shipped from KSC to other NASA locations to calibrate Zener standards, rather than the prior arrangement of sending Zeners to KSC. The uncertainty of Zener calibration is therefore improved by eliminating an uncontrollable process during the shipping. It was proposed at NCSLI 2013 that the PJVS be used as a transfer standard for the next JVS ILC [15]. Since the PJVS is able to provide a quantized voltage step with current margin of approximately 2 mA from −11 V to +11 V, the procedure of a direct comparison between a conventional JVS and 10 V PJVS is remarkably similar to that during a Zener calibration. Therefore, it is possible that the PJVS could replace Zeners as the travelling standard for future ILCs.

7. Operation of NASA PJVS and comparison protocol with CJVS

A comparison between a conventional JVS and the NIST 10V PJVS was first reported in 2012 in order to verify the performance of the NIST 10V PJVS [16]. The mean difference between the two systems at 10 V was found to be −0.49 nV with a combined standard uncertainty of

2.64 nV (k = 2) or a relative combined uncertainty of 2.64 parts in 10^{10}. However, the manual measurement process was very labor-intensive. The polarity of the PJVS must be changed by an operator. In order to make PJVS-CJVS comparison more accessible, NIST developed an automated PJVS-CJVS comparison protocol. The key to make automatic measurement is to set up a local area network (LAN) which provides communication between CJVS and PJVS. The details of the hardware implementation and modifications to the NISTVolt software were reported at the NCSLI Symposium 2013 [15].

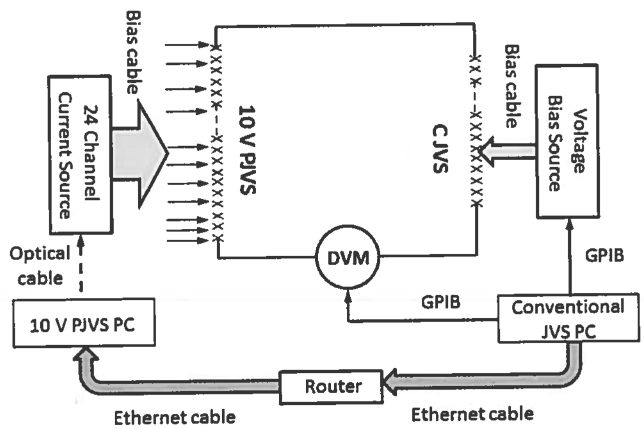


Figure 4. Setup for automated CJVS-PJVS direct comparison

Figure 4 shows the setup for an automatic comparison between a CJVS and the 10 V PJVS. The comparison protocol is similar to Zener calibration by CJVS with modification to the NISTVolt program. In this arrangement, NISTVolt operates as the master controller, initiating commands that are then sent to the (slave) PJVS control software, which is written in LabVIEW. Specifically, NISTVolt writes the desired voltage and polarity data to a file, which is then sent over the network to the PJVS controller via the Data Socket protocol (a method for live data streaming proprietary to National Instruments). The DVM is controlled by the CJVS PC and NISTVolt to measure the voltage difference between the PJVS and CJVS. During the process a step jump may happen due to EMI. As long as the voltage difference between the two systems is less than the maximum voltage for the DVM's range setting (e.g., for our DVM, the maximum voltage is 1.1 mV when the range is set to 1 mV), the data acquisition continues. If the step jump caused the voltage difference between the two systems to be greater than the maximum voltage setting, then re-biasing for the CJVS step will occur until the voltage difference falls back within the setting. Once the CJVS and PJVS systems are tuned up properly, the measurements can continue for days without intervention by the operator. This affords the collection of a large number of data points for subsequent analysis.

8. Results of direct PJVS and CJVS comparison

From February 2014 to June 2014 the NASA PJVS travelled to NIST Gaithersburg, the US Air Force Primary Standards Laboratory and the US Navy Primary Standards Laboratory. Three CJVS systems have been compared directly with the NASA PJVS at 10 V. All three CJVS systems use the protocol described in previous section and NISTVolt software to measure PJVS. The detail of the three comparisons is described [17]. We present here a summary of three CJVS-PJVS comparisons. We also report the challenges encountered in the comparisons, such as noise and ground issues and how to solve these problems.

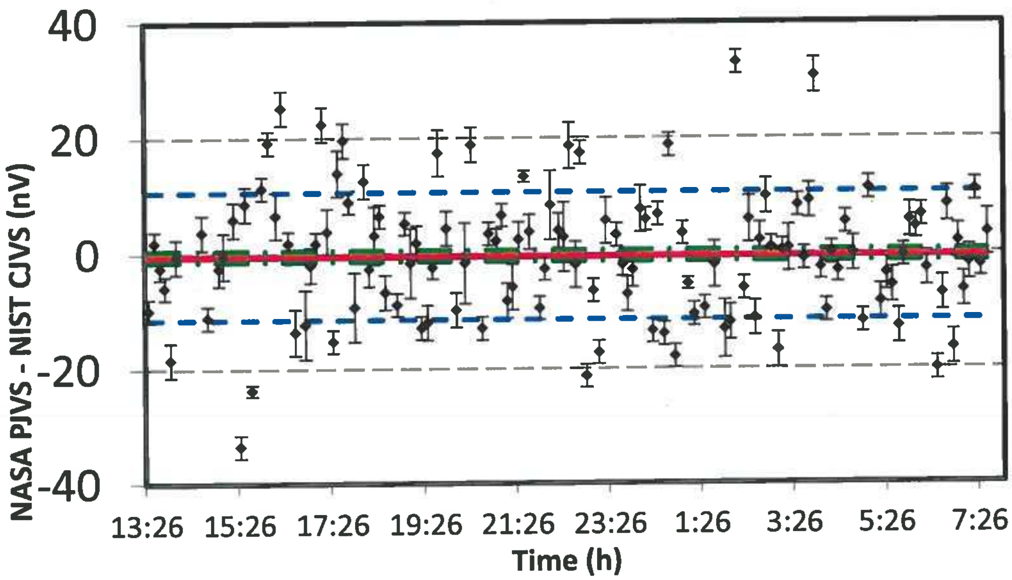


Figure 5. Direct comparison between NASA PJVS and NIST CJVS over 18 hr.

Figure 5 shows the results of a comparison between the NASA PJVS and the NIST JVS on February 25 and February 26, 2014. The acquisition took approximately 18 hr with the DVM at its 1 mV range. The mean difference of 127 measurements between the NASA and NIST systems was –0.40 nV as shown with a red solid line. The dashed lines represent the standard deviation of 11.06 nV. The dotted-dashed lines are the standard deviation of the mean of 0.98 nV. The error bars on individual data points reflect the Type A ($k = 1$) uncertainty from 40 DVM measurements.

The uncertainty of the comparison is calculated using the following equation

$$u_c = \sqrt{u_A^2 + u_{freq}^2 + u_{li}^2 + u_{lj}^2 + u_{DVM}^2}$$

where u_A is the Type A uncertainty and other four items are the Type B components. The standard deviation of the mean of 0.98 nV for the NIST CJVS-NASA PJVS comparison is calculated as the Type A uncertainty. This is justified when the data is randomly distributed as white noise and is higher than the noise floor of the DVM. In some other cases when the data show stochastic serial correlations, the standard deviation of the mean would not be appropriate to represent the Type A uncertainty. The items u_{freq}, u_{l1}, u_{l2}, and u_{DVM} are the Type B components of the frequency, leakage error of two systems and DVM gain error as listed in Table 4. Both NASA and NIST system don't use frequency counter. Therefore, the Type B uncertainty due to the frequency counter in this comparison was not applicable.

Table 4. Results of the NASA PJVS and NIST CJVS comparison at 10 V

	NASA PJVS	NIST CJVS
NASA - NIST (nV)	-0.40	
Number of points	127	
Type A	0.98	
Frequency	0	0
Leakage	0.45	0.43
DVM gain	Not applicable	0.07
Expanded U_{95} (nV) ($k = 2$)	2.33	

The comparison between the Lab1 CJVS and the NASA PJVS was carried out on April 8 and 9, 2014. The comparison between the Lab2 CJVS and the NASA PJVS was carried out from June 2 to June 4, 2014. The comparison results are listed in Table 5.

Table 5. Results of comparisons for Lab1 and Lab2 CJVS with the NASA PJVS

Comparison with NASA PJVS	**Lab 1**	**Lab 2**
Lab – NASA (nV)	2.22	0.08
Number of points	42	112
u_A (nV)	1.07	1.54
u_B (nV)	1.24	1.72
Expanded U_{95} (nV) ($k = 2$)	3.28	4.62

The degree of equivalence of Lab1 and Lab2 with respect to NIST is given by the following relations via the NASA and NIST direct JVS comparison. The link can be extended to BIPM through a comparison between BIPM and NIST in 2009 [2] as shown Table 6.

$$d_{Lab-NIST} = d_{Lab-NASA} + d_{NASA-NIST}$$

$$u^2_{Lab-NIST} = u^2_{Lab-NASA} + u^2_{NASA-NIST}$$

Table 6. Equivalence among JVS systems with respect to NIST and BIPM

Lab	**Reference**	**Lab – Ref (nV)**	u_c **(nV) (*k* = 2)**
NASA	NIST	-0.40	2.34
Lab 1	NIST	1.82	4.03
Lab 2	NIST	-0.32	5.18
NIST	BIPM	-0.8	1.90
NASA	BIPM	-1.20	3.01
Lab 1	BIPM	1.02	4.45
Lab 2	BIPM	-1.12	5.52

Some problems encountered in the PJVS-CJVS direct array comparison are ground loops and EMI. In order to achieve the best results, the two array systems must have their chassis grounded to the same point, in order to avoid ground loop currents, which may arise from different grounding points being at different potentials. The ground loop can create voltage difference in nV scale between the two JVS systems. EMI was also found to be a common problem in the participating laboratories. For example, the CJVS system in one of the laboratories was sharing an ac power supply with several other, unrelated measurement systems. As a result, the voltage steps of the CJVS were very unstable. Connecting the CJVS to an independent and appropriately filtered power supply mitigated the voltage step instability.

9. Conclusion

As in the previous 2011 ILC, an uncertainty on the order of ±3 nV was obtained when two CVJS Josephson voltage systems are compared in the direct array-to-array configuration. The in situ comparison using Zener voltage achieved an uncertainty of ±30 nV, but when the Zener voltage standards are used as traveling standards, the comparison uncertainty is on the order of ±200 nV. This uncertainty is sufficient for most ILC participants and provides traceability to a standard maintained by a national metrology institute. This result has been typical since 2008, however the uncertainty of the overall ILC is dominated by the Zener $1/f$ noise and can be improved by eliminating the Zeners. For the first time a PJVS was used as a transfer standard in the 2014 NSCLI JVS ILC. The PJVS-CJVS direct comparison results have shown the degree of equivalence of all JVS systems to be within a few parts in 10^{10} at 10 V. The experience gained from the three PJVS-CJVS comparisons will provide guidance for future comparisons, especially as the PJVS is increasingly adopted in metrology labs around the world.

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