# Application of a 10 V Programmable Josephson Voltage Standard in Direct Comparison With Conventional Josephson Voltage Standards

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***Abstract*— This paper briefly describes the working principle of the 10 V programmable Josephson voltage standard (PJVS) that was developed at the National Institute of Standards and Technology and how to use it in a direct comparison with a conventional Josephson voltage standard (CJVS). Manual and automatic comparison methods were developed to verify the agreement between the two types of Josephson standards. A 10 V PJVS provided by the National Aeronautics and Space Administration (NASA) was used as a transfer standard in the 2014 Josephson voltage standard Interlaboratory Comparison that is organized by the National Conference of Standards Laboratories International. The results of automatic direct comparisons between a NASA PJVS and three CJVSs are reported. Allan variance is applied to analyze the large number of correlated data for Type A uncertainty.**

***Index Terms*— Allan variance, automated comparison, Josephson arrays, Josephson voltage standards (JVSs), uncertainty, voltage measurement.**

## I. INTRODUCTION

A BREAKTHROUGH in Josephson technology was achieved with the development of the 10 V programmable Josephson junction array in 2010 by scientists at National Institute of Standards and Technology (NIST) [1]. The major difference between the programmable Josephson voltage standard (PJVS) and the conventional Josephson voltage standard (CJVS) is the biasing method. The inherent problem with zero-current-crossing steps provided by a CJVS is that the voltage step can have transition to a different quantum step due to the random behavior of the junction dynamics or being triggered by electromagnetic interference (EMI). The PJVS, on the other hand, uses current-biased voltage steps generated by superconductor–normal metal–superconductor junctions developed at NIST or superconductor–insulator–normal metal–insulator–superconductor junctions developed at the Physikalisch-Technische Bundesanstalt [2]–[4]. The PJVS generates intrinsically stable voltage steps that do not spontaneously switch, but it requires bias currents to produce them. These steps have excellent noise immunity for measurements. The intrinsic stability and noise immunity of the PJVS voltage steps make it possible to compare the PJVS with a CJVS. The CJVS measurement software is used to treat the PJVS voltage in the same manner as it measures a Zener standard. Since the PJVS noise is lower than that of a Zener standard, the statistical measurement uncertainty of the comparison can be improved to a few parts in $10^{10}$ or better at 10 V.

In 2013, the 10th Josephson voltage standard (JVS) Interlaboratory Comparison (ILC) coordinated by the National Conference of Standards Laboratories International (NCSLI JVS ILC) was organized to perform JVS comparisons in 2014. In addition to a typical protocol of using a set of Zener standards as transfer standards for the comparison, NIST and the National Aeronautics and Space Administration (NASA) Metrology and Calibration (MetCal) Program Office, located at the Kennedy Space Center, proposed to use a PJVS as a transfer standard in order to make direct comparisons with the CJVSs of several participating laboratories [5]. In 2014, the NASA 10 V PJVS was shipped to NIST, the U.S. Air Force Primary Standards Laboratory, and the U.S. Navy Primary Standards Laboratory for direct comparisons with the three CJVS at those laboratories.

We present in this paper a newly developed automated measurement protocol for using available CJVS software, typically used for Zener calibrations, to perform direct comparisons with a PJVS. We report the results of three comparisons between CJVS and NASA's traveling PJVS in the 10th NCSLI JVS ILC at a nominal voltage of 10 V. The automated protocol using a local area network (LAN) allows a large amount of data to be collected. We investigate the relationship between the Allan variance of data and the $1/f$ noise floor of the detector used for the comparison. We also report on challenges that arose, such as noise and ground issues, which were encountered during the comparisons and on how we resolved these problems.

## II. WORKING PRINCIPLES OF THE PJVS

The PJVS bias electronics developed at NIST consists of a current source with 24 channels that supplies bias currents to the 23 subarrays with a total number of junctions of approximately 265 000 [1]. The number of junctions in the subarrays varies from 6 to 16 800 junctions. Each current

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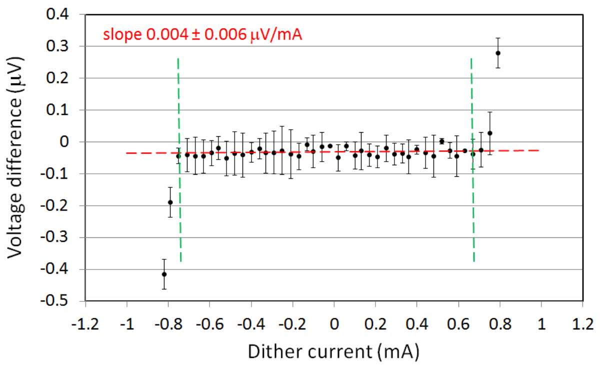

Fig. 1. Flat-spot measurement of the NASA PJVS array that was used for the direct CJVS comparison. The voltage difference is the difference between the measured and theoretical voltages. Two vertical lines define the flat range of the voltage step. The horizontal line is the fit of all measurement points over the flat region of the voltage step. The error bar is the standard deviation of repeated measurements.

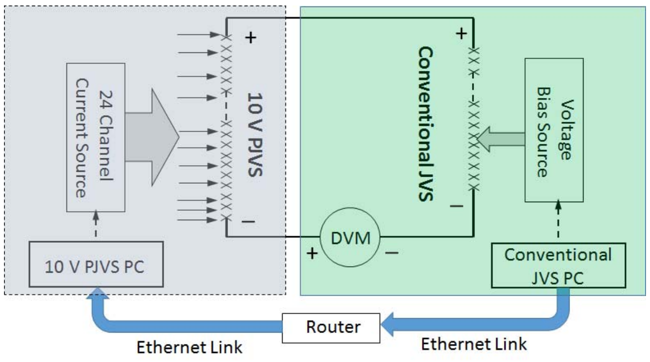

Fig. 2. Setup of an automated comparison between NIST10 (CJVS) and the 10 V PJVS.

source channel uses a 16-bit digital-to-analog converters that yields a set-point accuracy of ±0.02 mA. A synthesizer supplies the microwave bias to the PJVS circuit at frequencies in the range from 18 GHz to 22 GHz. When biased with a 20 GHz signal, a voltage resolution of 248 $\mu$V can be established by selecting different subarrays, which defines the least significant bit. However, an even smaller voltage resolution of 0.5 nV at 20 GHz and 10 V can be achieved by tuning the frequency by 1 Hz. Combinations of selected subarrays with a small number of junctions and the ability to slightly tune the microwave frequency are necessary to attain voltages up to 11 V with an approximately 10-nV resolution. The 10 MHz reference frequency is provided by a Global Positioning System disciplined with either a high-stability oscillator or another precision frequency reference. Sufficient power to drive the array is provided by a microwave power amplifier.

Operation of the NIST-developed PJVS is largely automated with control software written in LabVIEW.[1] In order to obtain the largest current margin for the voltage step, the bias parameters of microwave frequency and power must be optimized for the PJVS circuit. Fig. 1 shows a flat spot measurement of the NASA PJVS that was used in the direct CJVS comparison. The combination of subarrays, which includes most of the largest subarrays, was biased in the sequence pppppp0npnp00npnpnnpnp, where 0 represents a zero step, n is a negative step, and p is a positive step. The operating margin is defined by the range over which the dither current can be varied while the step voltage remains quantized. For this measurement, the current range was −0.75 mA to +0.71 mA. We perform dither current flat-spot measurements before and after each CJVS–PJVS comparison run to make sure that the PJVS voltage step margin remained stable during the comparison [1].

The NIST PJVS can be remotely controlled by the software installed in the CJVS computer via a data socket [6]. The data socket developed by the National Instruments is an Ethernet interface technology based on the transmission control protocol/internet protocol (TCP/IP) protocol that simplifies data exchange between computers and applications. In the PJVS–CJVS comparison, we use the data socket to establish communication between the CJVS PC and the PJVS PC. A network router and setup for the TCP/IP is required.

## III. DIRECT COMPARISON BETWEEN PJVS AND CJVS

Beginning on January 1, 1990, when $K_{J-90}$ was internationally adopted for representation of the Volt in terms of the Josephson relationship $V = nf/K_{J-90}$, JVS comparisons in various forms began to be carried out around the world by the International Bureau of Weights and Measures (BIPM) as BIPM.EM-K10.a and BIPM.EM-K10.b key comparisons [7]. The majority of JVS comparisons used CJVSs up to 10 V in order to establish an equivalence in the framework of the International Committee for Weights and Measures Mutual Recognition Arrangement. In recent years there have been many reports of comparisons between PJVS and CJVS systems [8], [9].

Direct comparison between two CJVS systems is difficult because either CJVS system may randomly switch to a different quantized voltage. In the present ILC, this problem is reduced by using the 10 V PJVS to provide a stable fixed voltage having zero noise. The intercomparison between the CJVS and the PJVS at 10 V is performed with the CJVS Zener calibration software by substituting the PJVS voltage with the Zener voltage.

A manual protocol [9] was initially developed to perform the intercomparison at NIST to verify the equivalence of the two systems. The manual direct JVS comparison was a labor-intensive process. In order to reduce the number of manual adjustments needed to change the PJVS polarity and improve the efficiency of the direct comparison, in 2013 we developed an automated comparison protocol [10], which is shown in Fig. 2. Automation allows the accumulation of a much larger set of data for us to more carefully evaluate and study the Allan variance of the measurements, which was impractical for measurements using the manual protocol.

We change the array voltage polarity by reversing the bias voltage for the CJVS and by reversing the bias current for the PJVS. This method eliminates the use of a mechan-

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

ical switch to reverse the polarity, as is necessary for a Zener measurement. Each PC controls its own JVS operation, setting up its individual voltage and polarity. Coordination among three different software programs is required to perform the comparison. Program #1 controls the PJVS to set its desired voltage and polarity. Program #2 is a modified version of the NISTVolt software that was developed to make Zener calibrations. Program #2 controls the CJVS as well as manages the data acquisition and comparison calculations. The function of the third software package is to receive a command from NISTVolt and send the message via a data socket port to the PJVS. Program #3 was developed specifically for the remote control of the PJVS and is installed on the CJVS PC. The PJVS PC program responds to requests from Program #3 and, in turn, executes the received command to set the PJVS voltage and polarity.

Two ferrite filters are installed in the two precision voltage leads of the PJVS cryoprobe head to provide protection from transient signals such as polarity reversal during the comparison that could cause trapped flux in the PJVS array. Data acquisition was demonstrated to be able to continue for multiple days without trapping flux in either array system.

During the comparison, the measurement circuit is never altered. When the PJVS polarity is reversed, the digital voltmeter (DVM) is momentarily overloaded (1 mV scale used for reading the difference between the two array voltages). The NISTVolt software accordingly sets the bias voltage and corresponding polarity, so as to minimize the Mean Polarized Null Voltage (MPNV) [11]. If the difference between the two array voltages remains within the 1 mV range, then the following data acquisitions are begun after a waiting period of 15 s. The waiting period can be adjusted depending on which filter network design is used for the CJVS.

The rest of the comparison routine is exactly the same as for Zener calibrations performed with the NIST10 CJVS. An Agilent 34420A nanovoltmeter is used for measuring the difference between the two voltages. The range of the DVM was set to 1 mV. During the comparison, a voltage step jump may occur. If the difference between the two arrays is larger than the maximum allowable voltage of 1.1 mV for the DVM 1 mV range (or seven steps off the target voltage set by the 10 V PJVS), the NIST10 rebiases its array so that the difference voltage remains within the 1.1 mV limit of the DVM 1 mV range. The entire process is automatically executed by the NISTVolt software. Four data sets are taken with the voltage polarity sequence of $+ - +-$. Each data set contains 10 points with each point being the average of 10 DVM readings for the number of power line cycles (NPLCs) of 10. The NPLC and the number of DVM readings can be adjusted depending on the noise situation in the measurement loop.

To test the robustness of the automatic comparison protocol, we ran a comparison between NIST10 and the NIST PJVS at 10 V over a 64 hour period without interruption. A total of 367 points were collected from March 1–4, 2013, as shown in Fig. 3. The mean difference between the two systems was determined to be $-1.3$ nV with an expanded total combined uncertainty of 2.6 nV ($k = 2$). No trapped flux occurred in either of the JVS arrays during the comparison. The uncertainty bar of each point represents the Type A uncertainty calculated from 40 DVM points using a least-squares fit line, rather than the mean value of the four data sets. The Type A difference from point to point can be related to the number of step jumps that occur during the data acquisition of the 40 DVM points, small thermal voltage variations in the measurement loop, the noise variations of the DVM itself, etc.

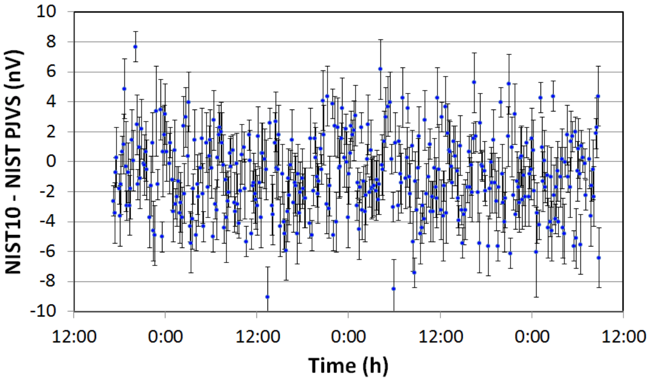

Fig. 3. Automatic comparison between NIST10 and NIST PJVS at 10 V with a total of 367 points collected over a 64 hour period. The error bar is the Type A uncertainty ($k = 1$) for each measurement.

## IV. NCSLI JVS INTERLABORATORY COMPARISON 2014

The 10th JVS ILC sponsored by the NCSLI started in early 2014. This ILC consists of two parts. The first part uses the NASA PJVS 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 in the NCSLI JVS ILC. The second part is to carry out a traditional protocol by shipping and comparing as transfer standards a set of Zeners that were used in the last several ILCs. Fig. 4 shows the process for all of the comparisons of the laboratories participating in the NCSLI JVS ILC 2014. Agilent Technologies (now Keysight Technologies) is the pivot lab for the second part, the traditional JVS ILC. This process started in March 2014 and finished in October 2014. NIST has made a direct JVS comparison with Agilent between the two CJVS systems in order to provide a link to all participating labs. In this report we focus on the direct JVS comparisons using the NASA PJVS as a transfer standard. We also discuss the experience learned from this exercise.

The NASA PJVS is maintained by the NASA MetCal Program Office and is configured as a transportable system. It is shipped to several of NASA's centers on a recurring basis. From February 2014 to June 2014 the NASA PJVS travelled to NIST Gaithersburg, the U.S. Air Force Primary Standards Laboratory, and the U.S. Navy Primary Standards Laboratory. Three CJVS have been compared directly with the NASA PJVS at 10 V.

### A. NASA PJVS Versus NIST JVS

The direct array comparison between the NASA PJVS and the NIST JVS was carried out on February 25 and 26, 2014. The NIST JVS is a transportable system which had been shipped to a dozen of JVS labs in the US as well as

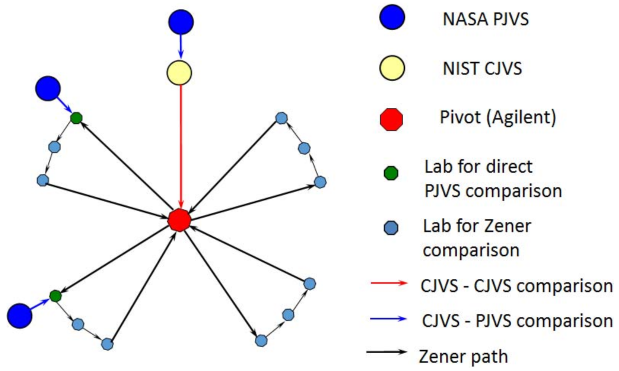

Fig. 4. NCSLI JVS ILC 2014 consists of traditional JVS comparisons using Zeners as transfer standards and direct comparisons using the NASA PJVS as a transfer standard.

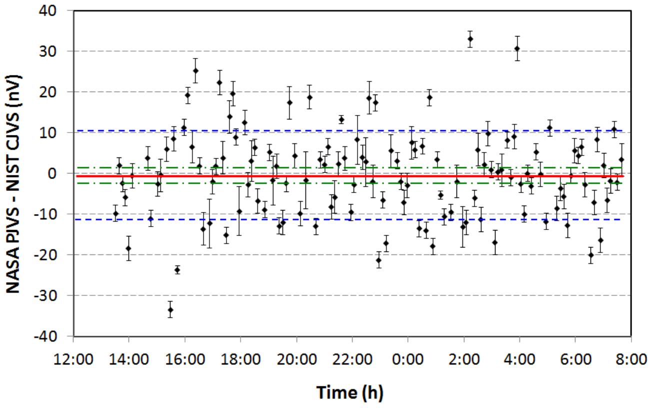

Fig. 5. Direct comparison between the NASA PJVS and the NIST CJVS beginning on February 26 through the morning of February 27, 2014. The error bar is the Type A uncertainty ($k = 1$) of 40 readings for each measurement.

National Metrology Institutes abroad for JVS comparisons in the past. The NIST JVS was also part of the BIPM.EM-K10.b key comparison in [11]. It uses a fixed microwave frequency of 76.76 GHz and integrates the phase-lock circuitry within the cryoprobe. The unique design of the frequency assembly eliminates the need for a frequency counter, thereby reducing the weight of the system and uncertainty B contribution from the frequency counter [12]. Automated intercomparison was carried out on February 26, 2014. Fig. 5 shows the data of the comparison taken from February 26 overnight run through the morning of February 27. The mean difference of 127 measurements between the NASA and NIST systems was $-0.40$ nV as shown by the 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 for each point. The expanded total combined uncertainty ($k = 2$) is 2.33 nV. As an example, Fig. 6 shows 40 DVM measurements for a single point made at 4:38 A.M. on February 27, 2014.

### *B. Lab1 JVS Versus NASA PJVS*

The comparison between the Lab1 JVS and the NASA PJVS was carried out on April 8 and 9, 2014. Because of the limited availability of the Lab1 JVS system, the data acquisition for the comparison was performed only during daytime. The two sets of data shown in Fig. 7 were acquired automatically on April 8 (20 measurements) and April 9 (22 measurements) and they produced essentially the same standard deviations of the mean of 1.51 nV and 1.48 nV, respectively. A $t$-test has shown that these two populations are not significantly statistically different. Therefore, we pooled these two data sets and calculated the difference between Lab1 and the NASA PJVS as being 2.22 nV as shown by the red solid line. The dashed lines represent the standard deviation of 6.95 nV. The dotted-dashed lines represent the standard deviation of the mean of 1.07 nV. The expanded total combined uncertainty ($k = 2$) is 3.28 nV.

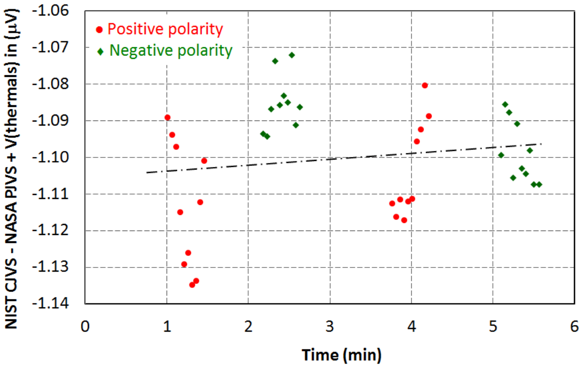

Fig. 6. Comparison between the NASA PJVS and the NIST JVS was taken at 4:38 A.M., February 27, 2014. 40 DVM measurements were taken with the sequence of array polarity $+-+-$. The Type A uncertainty for the comparison was calculated based upon the scatter of DVM measurements relative to the least-squares fit line (dashed line).

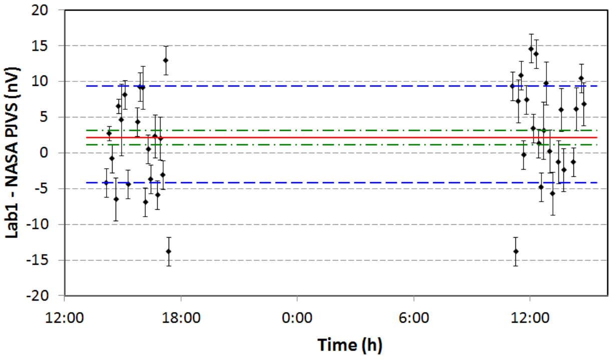

Fig. 7. Direct comparison between the Lab1 JVS and the NASA PJVS taken during daytime on April 8 and 9, 2014. The error bar is the Type A uncertainty ($k = 1$) for each measurement.

### *C. Lab2 JVS Versus NASA PJVS*

The comparison between the Lab2 JVS and the NASA PJVS was carried out from June 2–4, 2014. Two major issues related to EMI had to be resolved before we were able to take measurements. The source of EMI was traced down to the power source that was shared by the two JVS systems and other measurement systems in the lab. An independent Uninterruptable Power Supply was then used to separate the two JVS systems from all other instruments in the same lab. In addition, the negative terminal of the Lab2 JVS was found

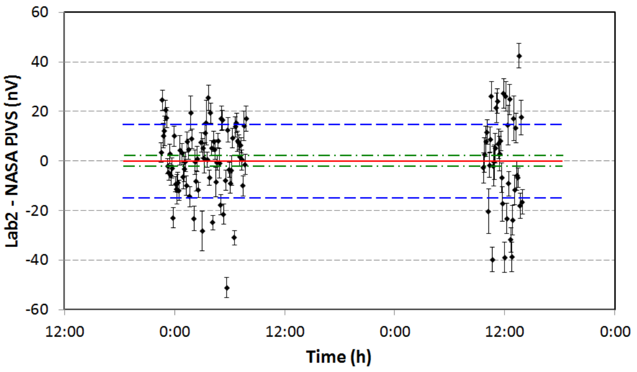

Fig. 8. Direct comparison between the Lab2 JVS and the NASA PJVS taken during June 2–4, 2014. Data taken during the daytime show a higher standard deviation due to the EMI from the environment. The error bar is the Type A uncertainty ($k = 1$) for each measurement.

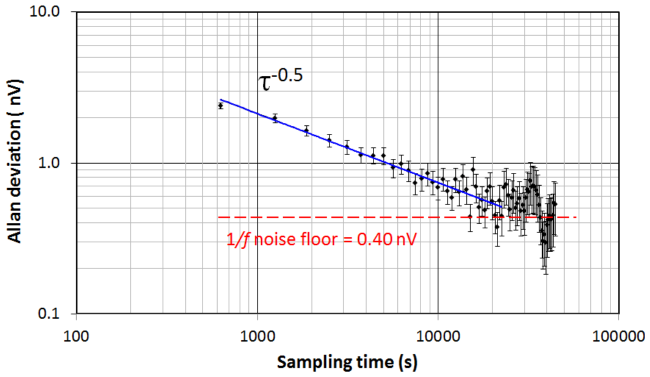

Fig. 9. Allan deviation $\delta$ estimated from voltage differences between the NIST10 and PJVS adjusted to equal time intervals. Solid line is the weighted least-squares fitting in the white noise region and dashed line in $1/f$ noise region. The error bar is the standard deviation of $\delta$ in each block.

to have substantial noise interference, which caused voltage steps of the CJVS to be very unstable. A filter comprised of a parallel inductor of 0.1 mH and a capacitor of 0.1 $\mu$F was used to connect the CJVS and PJVS negative terminals. After these changes were made, the automatic calibration was performed. However, it was still difficult to keep the DVM within the 1 mV range. We finally used the 10 mV range to measure the difference between the two array voltages. Two sets of data were taken with 74 measurements on June 2 (an overnight run) and with 38 measurements on June 4. Fig. 8 shows the results of the two data sets. The larger standard deviation of the June 4 data that were taken during the daytime clearly shows a higher impact of EMI from the surrounding environment on the comparison.

The standard deviations of the mean for the two data sets were 1.6 nV and 3.3 nV, respectively, and a $t$-test assuming unequal variance for the two data sets has confirmed that the two sets were not statistically different. We combined the two sets of data to calculate that the difference between the Lab2 and the NASA PJVS was 0.08 nV as shown by the red solid line. The dashed lines represent the standard deviation of 16.30 nV. The dotted-dashed lines represent the standard deviation of the mean of 1.54 nV. The expanded total combined uncertainty ($k = 2$) is 4.62 nV. The higher standard deviation of the mean of the data set collected during the daytime compared with that of data set collected during the night is a reflection of higher EMI from the surrounding environment during the daytime.

## V. UNCERTAINTY

### *A. Type A Uncertainty*

It has been reported that when analyzing nanovoltmeter measurements, stochastic serial correlations are often ignored and the experimental standard deviation of the mean is assumed to be the Type A uncertainty [13]. This is justified only for white noise. The Type A uncertainty in most of the direct JVS comparisons has been calculated as if the noise were white, usually without presenting evidence to support this assumption.

Using the standard deviation of the mean to represent the Type A uncertainty can sometimes underestimate it due to correlation of the data points. Two methods are introduced to evaluate the Type A uncertainty for this situation.

*1) Analyze the 1/f Noise Based on the Comparison Data:* Allan variance is defined as

$$\mathrm{Avar}(\tau) = \mathrm{Avar}(n\tau_0) = \left\langle \left(\bar{\delta}_{j+1} - \bar{\delta}_j\right)^2 \right\rangle / 2 \qquad (1)$$

where $\tau_0$ is the equal time interval between the data points, $\delta$ being grouped into blocks of $n$ successive points; $\bar{\delta}_j$ is the mean values of $\delta$ in the $j$th group; and the angular brackets indicate the mean as the number of blocks approaches infinity. The sample *Avar* is calculated from the experimental values of $\delta$ and the mean is taken over a finite number of blocks. We used the example from Section III, where 367 points were collected over 64 h, as shown in Fig. 3. The time for a single measurement ranges from 7.0 min to 32.0 min, with a mean time of 10.4 min. We used cubic splines to interpolate the measurement values of $\delta$ and create a time series having a constant interval of 10.4 min. Then, we carried out an Allan variance analysis for all the $\delta$ [14]. The sample variance *Avar* in Fig. 9 suggests a model consisting of white noise and $1/f$ noise as

$$\mathrm{Avar}(\tau) = (h_0/2\tau) + b. \qquad (2)$$

The values of $h_0$ can be determined by a weighted least-squares fitting to a straight line in the white noise region of smaller sampling time (solid line). The value of $b$ is determined by *Avar* in the $1/f$ noise region of larger sampling time shown as the dashed line. It was found that $b = 0.162$ nV$^2$ for the $1/f$ noise floor 0.40 nV at the sampling time of 40 000 s. Fig. 9 shows a clear white noise region for sampling time less than 10 000 s. The Allan deviation became noisier for sampling period larger than 30 000 s. There was only one data set having 367 points that was useful for calculating the Allan variance. It resulted in a relatively large uncertainty in the region of sampling time longer than 30 000 s. However, it is also clear that the Allan deviation is not in the white noise region because the data do not fall on the $\tau^{-0.5}$ line.

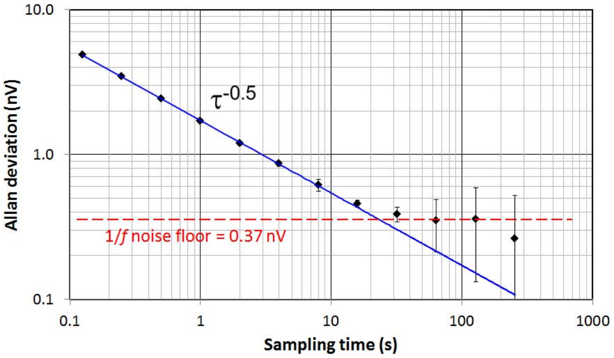

Fig. 10. $1/f$ noise measurement of DVM used as a null detector with a shorted input. The error bar is the standard deviation of 12 repetitive measurements. For the sampling time up to 20 s, the Allan deviation varies as $\tau^{-0.5}$, where $\tau$ is the sampling time. This is the white noise regime.

*2) Analyze 1/f Noise Floor for the Null Detector:* We also made the $1/f$ noise floor measurements for the DVM with a short input on the 1 mV range that was used for measuring the difference between the NIST10 and NIST PJVS. The measurement was carried out on February 15, 2013 before making the JVS direct comparison using the method described in [13]. The same measurements were repeated 12 times in order to reduce the measurement uncertainty. Fig. 10 shows the Allan deviation of the DVM for the sampling time from 0.1 s up to 250 s. It can also be modeled by a combination of white noise for the smaller sampling time and $1/f$ noise for the larger sampling time. The $1/f$ noise floor of 0.37 nV was estimated by averaging the Allan deviation for sampling time from 26 s to 100 s. This result is consistent with the result of noise floor analysis based on all comparison data. The standard deviation of the mean for the 367 points was calculated to be 0.14 nV, which was underestimated for the Type A uncertainty. For this particular data set, we may use the 0.37 nV, $1/f$ noise floor of the DVM or the 0.40 nV noise floor of all the comparison data to express the Type A uncertainty.

The reason for different integration times for reaching the $1/f$ noise floor in two approaches is the totally different sampling time used to obtain the data for analysis. For a single comparison point, the DVM integration time was 4000 PLC $(40 \times 10 \times 10)$ or 67 s which falls into the DVM $1/f$ noise floor region. From the perspective of a series of 367 comparison points, it would take approximately 40 000 s to reach the $1/f$ noise floor. Nevertheless, two approaches led to the same $1/f$ noise floor of approximately 0.4 nV to express the Type A uncertainty in this example.

*3) Type A Uncertainty for NCSLI Direct JVS Comparisons:* Whether standard deviation of the mean or $1/f$ noise floor of the detector (or comparison data) should be used to express the Type A uncertainty depends on the noise level during a direct comparison between JVS systems. Fig. 11 shows an example of the NIST10 and NIST PJVS comparison that was carried out on March 29, 2013. A total of 35 points were taken over a 6 h period. The standard deviation of the mean was calculated to be 0.36 nV, which is very close to the $1/f$ noise floor of the DVM used for the comparison. When the standard deviation of the mean in the comparison reaches the level of the DVMs $1/f$ noise floor, additional measurements will not significantly reduce the Type A uncertainty. The mean difference between the NIST10 and the NIST PJVS was determined to be $-0.8$ nV with an expanded total combined uncertainty of 2.4 nV $(k = 2)$.

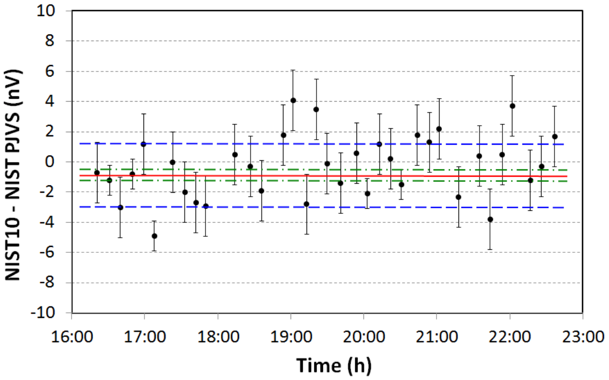

Fig. 11. Automatic comparison between NIST10 and the NIST PJVS at 10 V with a total of 35 points collected over 6 h. The error bar on each point is the Type A uncertainty from 40 readings. The mean difference was $-0.77$ nV as shown by the red solid line. The dashed lines represent the standard deviation of 2.14 nV. The dotted-dashed lines represent the standard deviation of the mean of 0.36 nV, which is approximately the same as the $1/f$ noise floor of the DVM.

The direct comparisons between the NASA PJVS and three CJVS described in Section IV, however, had substantially higher noise, as shown in Figs. 5, 7, and 8. The consequence of the higher noise was increase in the number of measurements needed to reduce the Type A uncertainty. The standard deviations of the mean of the three comparisons were 0.98 nV, 1.07 nV, and 1.54 nV, respectively, all larger than the $1/f$ noise floor of the nanovoltmeter used for the comparisons. Therefore, we used the standard deviation of the mean to represent the Type A uncertainty in all the three comparisons. The source of the higher noise in these comparisons was partially from the environment. There may also be a noise source related to the NASA PJVS system configuration.

### *B. Type B Uncertainty*

The Type B uncertainty includes components for the frequency measurement, leakage error of the cryoprobe, and the detector's gain.

*1) Frequency Measurement:* For the CJVS that uses a frequency counter, we use the specification of ±15 Hz provided by the manufacturer to estimate the frequency-offset uncertainty $u_{\text{frequency}}$ at 10 V as 1.08 nV with an assumed rectangular distribution.

The NIST transportable CJVS and NASA PJVS do not use a frequency counter. The contribution of frequency offset Type B uncertainty for the NIST CJVS and the NASA PJVS is estimated to be less than 0.05 nV at 10 V [15] and has a negligible impact on the total combined uncertainty.

*2) Leakage Error of Cryoprobe:* The leakage resistance $R_l$ for every cryoprobe reported in this paper was measured at the time of the comparison. The method used for measuring the leakage resistance between the two leads for precision voltage measurement of a CJVS cryoprobe is described in

TABLE I

TYPE B UNCERTAINTY COMPONENTS

| | NIST (nV) | NASA (nV) | Lab1 (nV) | Lab2 (nV) |
|---|---|---|---|---|
| Freq. offset $u_{frequency}$ | 0.05 | 0.05 | 1.08 | 1.08 |
| Leakage error $u_l$ | 0.43 | 0.45 | 0.27 | 0.41 |
| DVM gain error $u_{DVM}$ | 0.07 | Not in use | 0.40 | 1.22 |

TABLE II

RESULTS OF DIRECT COMPARISON WITH NASA PJVS

| | **NIST** | **Lab 1** | **Lab 2** |
|---|---|---|---|
| Date in 2014 | Feb. 26-27 | Apr. 8-9 | June 2-4 |
| Lab – NASA (nV) | 0.40 | 2.22 | 0.08 |
| Number of points | 127 | 42 | 112 |
| $u_A$ (nV) | 0.98 | 1.07 | 1.54 |
| $u_B$ (nV) | 0.63 | 1.24 | 1.72 |
| Expanded $u_C$ (nV) ($k = 2$) | 2.33 | 3.28 | 4.62 |

TABLE III

LINK BETWEEN NASA PJVS AND TWO CJVSS TO NIST

| **Lab** | **Reference** | **Lab – Ref (nV)** | **$u_c$ (nV) ($k = 2$)** |
|---|---|---|---|
| NASA | NIST | -0.40 | 2.33 |
| Lab 1 | NIST | 1.82 | 4.03 |
| Lab 2 | NIST | -0.32 | 5.18 |

detail in [11]. The leakage resistance of measurements with the PJVS and its impact on the uncertainty are described in detail in [15].

The uncertainty $u_l$ due to the leakage resistance of the cryoprobe can be calculated using

$$u_l = Vr/\sqrt{3}R_l \tag{3}$$

where $V$ is the output voltage and $r$ is the resistance of the precision voltage leads. The uncertainty component listed in Table II is calculated based on the leakage and leads resistance measurements with an assumed rectangular distribution.

There are two methods for treating the leakage error. In the case that the leakage path is well defined, such as when using a CJVS array not connected to ground and the voltage bias source disconnected from the array during data acquisition, a correction to the JVS voltage output for the leakage error can be made. However, a current bias source with multiple outputs to subarrays is used to obtain a stable voltage for a PJVS. The leakage current path in this case is difficult to identify. Therefore, in all the direct comparisons reported in this paper, no correction for the leakage errors is used. Instead, the leakage errors from both the CJVS and the PJVS are accounted for as Type B uncertainty components.

*3) DVM Gain:* In a direct comparison between a CJVS and PJVS, a DVM is used to measure the difference between the two voltages. The PJVS voltage is fixed and the voltage from a CJVS varies due to the spontaneous step jumps. The uncertainty due to the DVM $u_{\text{DVM}}$ depends on the gain and the voltage being measured

$$u_{\text{DVM}} = (1 - \text{gain})\ \text{MPNV} \tag{4}$$

where MPNV is the mean polarized null voltage [11].

The DVM gain can be measured very accurately using the PJVS. It is preferred to maintain an accurately calibrated voltmeter and to use the 1 mV range for reducing the MPNV. However, for the comparison between the NASA PJVS and Lab2, the DVM range was again set to 10 mV due to EMI during the measurements. As an example, the average of all MPNVs for the NIST10 and NASA PJVS comparison with a total of 127 points was 14.2 $\mu$V. The DVM gain on the 1-mV range was measured to be 0.999995 by the NIST PJVS. The uncertainty due to the DVM gain was 0.07 nV.

Table I summarizes all the Type B components for the three CJVS systems and the NASA PJVS.

The Type B uncertainty is the root-sum-squares (RSS) of all the relevant components

$$u_B = \sqrt{u_{\text{frequency}}^2 + u_{\text{li}}^2 + u_{\text{lj}}^2 + u_{\text{DVM}}^2} \tag{5}$$

where $u_{\text{li}}$ and $u_{\text{lj}}$ are the Type B components from two cryoprobes due to leakage, respectively.

### *C. Total Combined Uncertainty*

The total combined uncertainty $u_c$ for the direct comparison between a CJVS and the PJVS is the RSS of Type A and Type B uncertainties. Table II lists the comparison results of three CJVS systems with the NASA PJVS at 10 V. Through this exercise using the NASA PJVS as a transfer standard for an ILC, we are able to establish a link for the CJVS systems of the participating labs to the NIST CJVS in terms of the equivalence of JVS measurement. Table III lists the degrees of equivalence of the NASA PJVS and the two CJVSs (Lab1 and Lab2) relative to NIST at 10 V with an uncertainty of $u_{\text{lab}-\text{nist}} = [u_{\text{lab}-\text{nasa}}^2 + u_{\text{nasa}-\text{nist}}^2]^{1/2}$.

## VI. CONCLUSION

The purpose of the intercomparison is not just to demonstrate equivalence between the two compared systems, but also to identify possible flaws and to improve the performance of the systems. Because the voltage steps of the PJVS are current biased and intrinsically stable, the CJVS system can measure the PJVS voltage as if measuring the voltage for a Zener standard. The software used for the CJVS can be used with small modification for the direct comparison with the PJVS.

An automated direct comparison protocol has been developed to compare a CJVS and the PJVS using a data socket and LAN to establish communications between the two systems. The automated protocol improves the efficiency of the comparison by reducing the amount of human interaction necessary during the comparison. It also allows the collection of a large number of measurements, which is useful for investigations of Type A uncertainty through Allan variance analysis that determines the $1/f$ noise floor of the comparison data. It was verified that for a direct JVS comparison between a NIST CJVS and a NIST PJVS, the $1/f$ noise floor of the DVM is consistent with that from the Allan variance analysis using all the comparison data points. The number of comparison points required to determine the Type A uncertainty is reached when the standard deviation of the mean is equivalent to the $1/f$ noise floor of the DVM.

The noise levels in the direct PJVS–CJVS comparisons at several locations have shown clear differences. To achieve the best possible comparison, it is important to determine the noise source and then reduce its impact on the JVS systems, for example by adding more effective shielding or suitable filters. We identified some of the noise sources based on the noise levels seen in the data. For one participating laboratory, the comparisons revealed a significant EMI signal. Reduction in this EMI resulted in a significant improvement in the performance of this participant's CJVS.

This is the first time that a PJVS has been used as a transfer standard in the NSCLI JVS ILC. Comparisons with CJVSs at NIST and the other laboratories' CJVS allowed us to determine that the degree of equivalence between these JVSs at 10 V is a few parts in $10^{10}$. We expect that more JVS comparisons will be carried out using PJVS in the future.

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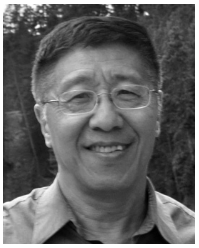

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