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Direct JVS Comparison between NIST and SNL to Support NCSLI JVS ILC 2011

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Abstract

The National Conference of Standard Laboratories International (NCSLI) is scheduled to start its 9th Josephson Voltage Standard (JVS) Interlaboratory Comparison (ILC) in March 2011. Sandia National Laboratories (SNL) is the pivot lab for this comparison of JVS systems that are currently in operation at several U.S. companies and national laboratories. In order to ensure the uniformity and traceability of the representation of the volt based on the *Josephson constant 1990* in all the participating labs, the National Institute of Standards and Technology (NIST) DC Volt Lab and SNL performed a direct JVS comparison from December 6, 2010 to December 10, 2010 at the SNL, Albuquerque, NM.

In this JVS comparison, the difference between the NIST CJVS and the SNL JVS was found to be -2.08 nV ± 2.88 nV at 10 V (k = 2). The large number of measurement data points enabled research investigations, such as the evaluation of the impact of the null detector's gain error and the filter network on the comparison result. The team discovered that the polarization of the dielectric material of the SNL cryoprobe filter capacitors could affect the comparison outcome. The difference between the two JVSs was reduced from -6.50 nV to -2.08 nV by extending the waiting period for the capacitor recovery from polarization to equilibrium. An *in-situ* JVS comparison between the NIST CJVS and the SNL JVS via a set of Zener transfer standards at 10 V was also carried out. The difference was 12 nV ± 21 nV at 10 V (k = 2). This result is consistent with the results from similar past JVS ILC comparisons. The same set of Zeners will be used in the JVS ILC that is scheduled to begin in March 2011.

The result of this direct JVS comparison achieved an uncertainty level comparable to the international key comparison BIPM.EM.K10.b in the Bureau International des Poids et Mesures (BIPM) Key Comparison Data Base (KCDB). This bilateral JVS comparison has confirmed that SNL is capable of performing its role as the pivot lab in the upcoming NCSLI JVS ILC. The results of the NCSLI JVS ILC will allow its participants to establish a voltage measurement link to NIST via the pivot lab SNL.

Index terms – alternative protocol, automatic comparison, dielectric polarization, digital voltmeter gain correction, Josephson voltage standard, uncertainty.

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1. Introduction

The 9th Josephson Voltage Standard (JVS) Interlaboratory Comparison (ILC) sponsored by the National Conference of Standard Laboratories International (NCSLI) is scheduled to start in March 2011. Sandia National Laboratories (SNL) is acting as the pivot lab that will perform comparisons with the other participating labs via a set of highly stable and low noise solid-state voltage standards. The 2011 JVS ILC is intended to provide the participating laboratories with a means of comparing their dc voltage measurements in order to verify the reliability and confidence in their JVS system operation. This activity ensures the uniformity and traceability of the representation of the volt based on $K_{J\text{-}90}$, the conventional value of the Josephson constant internationally adopted in 1990 within all the participating labs. In order to establish a link between the participating labs and the National Institute of Standards and Technology (NIST), a direct JVS comparison between NIST and SNL was carried out in December 2010.

During the past few years, NIST has developed an automatic direct JVS comparison protocol which is an alternative method to the BIPM Key comparison protocol - BIPM.EM.K10.b Option A and Option B [1, 2]. An automatic protocol for the direct JVS comparison enables a large number of data points to be collected without an operator's intervention. The validity of the automatic protocol has been verified by a BIPM key comparison between NIST and BIPM [3], where the differences between the NIST Compact JVS (CJVS) and the BIPM JVS using the BIPM protocol Option A, Option B and the NIST automatic protocol were -1.53 nV, -0.07 nV and 1.07 nV with the comparable standard combined uncertainties of 1.07 nV, 1.15 nV and 1.31 nV, respectively. The automatic protocol was also used in a regional supplemental key comparison SIM.EM.BIPM-10.b1 between NIST and the National Institute of Metrology, Standardization and Industrial Quality (INMETRO), Brazil [4].

This is the first time that the automatic protocol for the direct JVS comparison is used in a NCSLI JVS ILC. Past NCSL JVS ILCs utilized several different protocols that were developed by NIST in order to improve the uncertainty of the JVS comparison and resulted in a reduction in the uncertainty from a few parts in 10^8 to a few parts in 10^9. The automatic protocol for the direct JVS comparison is capable of further improvement in the comparison uncertainty to a few parts in 10^{10} at 10 V, and therefore enabling the detection of small system errors in the nanovolt range that cannot be discovered by other means. This paper presents the set-up of the NIST-SNL JVS comparison and the uncertainty analysis of the comparison data. The paper also discusses the important issues that are commonly encountered in the JVS comparison and their impact on the comparison result, such as the gain error of the detector and the filter network that is used in the cryoprobe to suppress the electromagnetic interference (EMI).

2. Direct JVS Comparison Set-up

Since the basic experimental method has been reported in [3] and other publications a brief description of the comparison set-up will be presented. The purpose of the JVS comparison is to determine the quantity δ which is the difference between the nominal 10 V outputs of the two arrays that are operated at frequencies f_{NIST} and f_{SNL} and biased on step numbers N_{NIST} and N_{SNL} respectively from the theoretical voltage difference Δ_{th}. Fig.1 illustrates the set-up for the NIST-SNL direct JVS comparison. The principal features of the set-up are the following:

- DVM1 monitors the nominal 10 V output of the NIST CJVS array in order to determine the step number for the NIST array, as well as the step number for the SNL JVS array along with DVM2 measurement.
- The measurement process continues if the step number of either array spontaneously changes (“jumps”) and causes a DVM2 measurement that is less than 1.1 mV (the maximum voltage for the DVM2 on the 1 mV range) in the absolute value. This feature decreases the time required by the re-biasing of the array voltages when the BIPM protocol Option A or Option B is used and therefore shortens the time for the data acquisition.
- The measurement process is temporarily suspended if the step number of either array spontaneously changes (“jumps”) and causes DVM2 measurement that is larger than 1.1 mV in the absolute value. The CJVS bias source is then reconnected to both arrays with the shorting switch closed. The process is controlled by the NISTVolt software automatically without any operator interference.
- The CJVS provides a common bias source for both arrays. Once the desired bias condition is set, an opto-isolator is used to gradually ramp up the impedance of the bias source. This feature increases the stability of the steps when compared with the conventional on/off switching during the bias removal process.

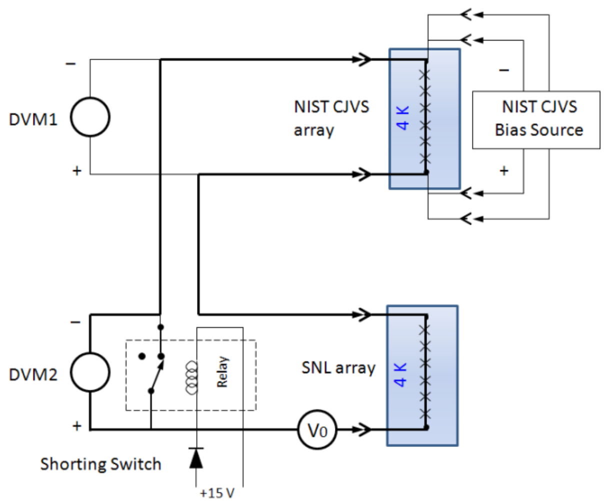

Fig.1 The set-up for a direct JVS comparison between the NIST CJVS and the SNL JVS. The NIST CJVS bias source was used to bias both arrays to a nominal 10 V voltage.

The theoretical difference between the two JVSs, Δ_{th}, can be calculated based on the information obtained from the two DVM readings in Eq. (1) through Eq. (5); where N refers to the step number of the array, V^{array} refers to the theoretical array voltage, f refers to the microwave frequency, V_{DVM} refers to the DVM reading and $K_{J\text{-}90}$ is the Josephson constant. The subscripts and superscripts are self explanatory.

$$N_{NIST} = round\left\{\frac{K_{J-90} * V_{DVM1}}{f_{NIST}}\right\} \qquad (1)$$

$$V_{NIST}^{array} = \frac{N_{NIST} * f_{NIST}}{K_{J-90}} \qquad (2)$$

$$N_{SNL} = round\left\{\frac{K_{J-90} * (V_{NIST}^{array} - V_{DVM2})}{f_{SNL}}\right\} \qquad (3)$$

$$V_{SNL}^{array} = \frac{N_{SNL} * f_{SNL}}{K_{J-90}} \qquad (4)$$

$$\Delta_{th} = V_{NIST}^{array} - V_{SNL}^{array} \qquad (5)$$

In order to find the measured difference between the two array voltages four array voltage polarity reversals following the sequence + - + - were performed in order to subtract the thermal voltage (produced mostly from the leads that are between room temperature and liquid helium temperature) and the DVM zero offset in the measurement loop. The array voltage polarity changes were also controlled automatically by the NISTVolt software and the bias source. At each polarity, 10 or 15 voltage readings were taken with DVM2, using an integration time of 10 power line cycles for each measurement. The difference V_j between each DVM2 measurement and the theoretical difference of the two arrays can be derived as

$$V_j = V_{DVM2} - \Delta_{th} \qquad (6)$$

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 using various mathematical models, such as the least square fit or simple average method that is described later.

3. Impact of the DVM Gain Error on the JVS Comparison

For the direct JVS comparison, the uncertainty is usually in the range of a few parts in 10^{10} at 10 V. Any error in the nanovolt range could affect the comparison result. For the NIST-SNL direct JVS comparison, an Agilent 34420A[‡] digital voltmeter (DVM2) on the 1 mV range was used to measure the difference between the two array voltages. The NISTVolt software keeps track of the Mean Polarized Null Voltage (MPNV), which is defined as Σ P(Set) x V_{DVM2}(Set), where P(Set) is the polarity of the measurement (either +1 or -1) and V_{DVM2}(Set) is the null voltage from that set. The difference between the two JVS systems should be independent from the MPNV. Fig.2 shows the result of the NIST-SNL comparison that was performed on December 9, 2010 with respect to the MPNV. The difference between the two JVS systems was calculated based on the raw DVM2 measurements without making any meter gain corrections. The slope of the difference vs. the MPNV was -8.9 nV/mV, indicating a strong correlation between the measured difference and the MPNV.

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

The DVM2 gain error was measured in the NIST lab before the NIST-SNL comparison with a programmable JVS (PJVS) which provided quantized voltage steps between the -1 mV and + 1 mV. The gain error of the DVM2 on the 1 mV range was calculated by the difference between the DVM2 reading and the known PJVS voltage. The gain error was measured at a number of voltages between -1 mV and +1 mV. The mean value 6.6 μV/V is used to represent the gain error for the DVM2 on the 1 mV range.

Fig.3 shows the result of the NIST-SNL comparison that was performed on December 9, 2010 versus the MPNV, now with all of the DVM2 measurements adjusted by the 6.6 μV/V DVM2 gain error. Consequently, the MPNV and the reported difference between the NIST and SNL JVS systems changed slightly. The slope of the difference vs. the MPNV decreased to -2.4 nV/mV, indicating a significant reduction in the correlation between the measured difference and the MPNV. In the data analysis for the final report, we applied the gain correction of 6.6 μV/V to all of the DVM2 measurements. This caused the final reported difference between the two JVS systems from -1.15 nV (without the DVM gain correction) to -2.08 nV (with the DVM gain correction).

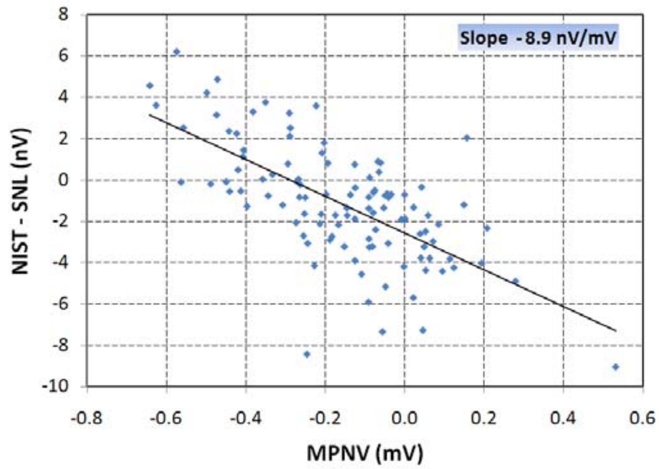

Fig.2 The strong correlation between the two JVSs difference and the Mean Polarized Null Voltage (MPNV) without the DVM2 gain error correction.

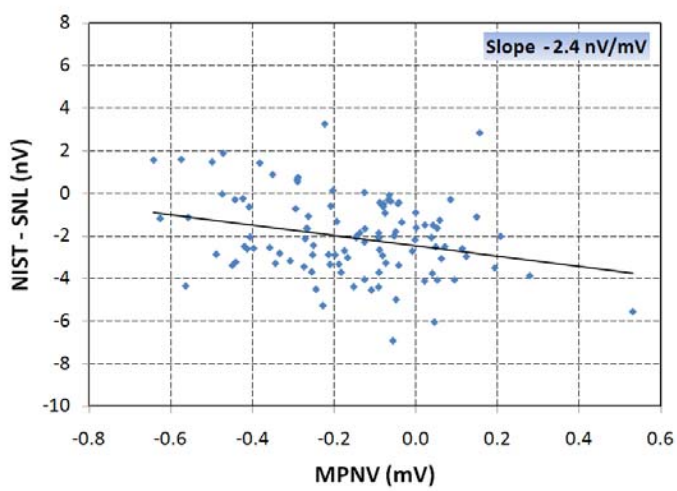

Fig.3 The correlation between the two JVSs difference and the Mean Polarized Null Voltage (MPNV) is significantly reduced when the DVM2 gain error correction of 6.6 μV/V is applied.

4. Impact of the Dielectric Discharge Process on the JVS Comparison

The first automatic run of the NIST-SNL JVS comparison took place on December 8, 2010. The frequencies of the microwaves used by the NIST CJVS and SNL JVS were 76.76 GHz and 75.4172 GHz, respectively. The data acquisition was initiated at 7 PM and terminated at 8:45 AM the next day. During that time period, the comparison was automatically controlled by the NISTVolt software. A total of 277 measurements were performed as shown in Fig.4. It took an average time of 3.0 m to finish a single measurement point. Each measurement point was made following the array polarity sequence + - + - at a nominal voltage of 9.997 V. Each measurement set included 10 DVM2 readings. The difference between the two JVS systems was calculated using a least square fit estimation of the entire 40 DVM2 readings. The error bar is the standard deviation of the 40 points from the fit. The mean difference between the NIST and SNL JVS systems using all of the 277 measurements was -6.50 nV with a combined expanded uncertainty of 3.36 nV (k = 2). The fact that the mean difference is larger than the expanded uncertainty indicates that there may be other error sources that affect the comparison.

We also analyzed the data using the simple average method to calculate the difference δ between the two JVS systems. The final difference for each measurement point following the array polarity sequence + - + - was

$$\delta = \{\sum_{i=1}^{4}[\sum_{j=1}^{J} P(i) * V_j(i)/J]\}/4 \qquad (7)$$

where $V_j(i)$ for each DVM measurement of Set i is calculated from Eq. (6), and J is the number of the measurement for each polarity set. The mean difference using all of the 277 measurements and calculated using this method was -6.46 nV with the same expanded uncertainty as the least square fit model, indicating that the two mathematical models generate essentially the same result.

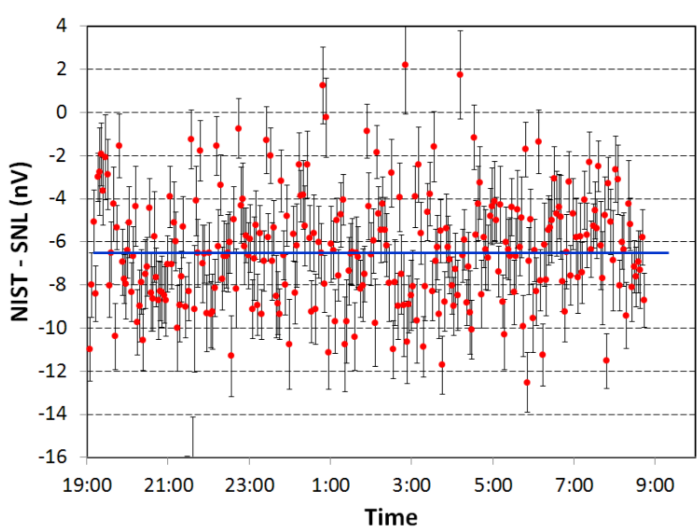

Fig.4 Data acquisition initiated after the polarity change for both arrays with 10 s waiting period. The larger than expected difference between the two JVSs was due to the polarization of the dielectric material that was used in the filter capacitors.

The larger than expected difference was traced to the filter capacitors that were used in the SNL cryoprobe. We discovered that the polarization of the dielectric material in the capacitors could affect the outcome of the comparison. The long relaxation time of the dielectric material required a sufficient waiting period in order to reach an equilibrium state after the arrays were biased to the nominal 10 V voltage. For the comparison shown in Fig.4, the data acquisition began approximately 10 s after the bias was disconnected from the arrays. The second run began at 7 PM on December 9, 2010 and ended at 9 AM the next day. We increased the waiting period before the start of the data acquisition by 60 s. We also increased the number of DVM2 measurements for each polarity set from 10 to 15. The average measurement time for a single point took 7.3 m. The mean difference between the NIST and SNL JVS systems using all of the 108 points as shown in Fig.5 was -2.08 nV with a combined expanded uncertainty of -2.88 nV (*k* = 2) using the NISTVolt software least square fit procedure. The mean difference using the simple average method from Eq. 7 was -2.28 nV with the same uncertainty.

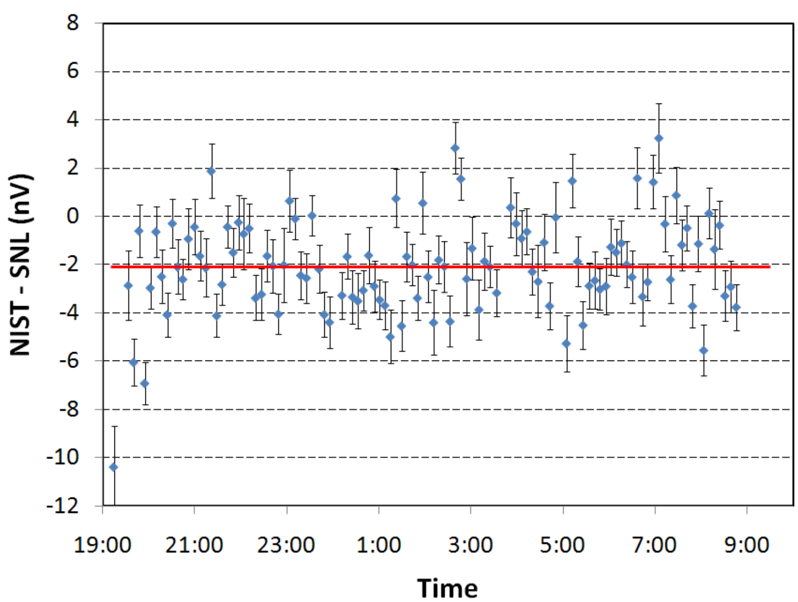

Fig.5 Automatic run made on December 9, 2010. Data acquisition started 60 s after the polarity change for both arrays. NISTVolt software least square fit procedure was used to calculate the difference between the two array systems.

5. Uncertainty Analysis

Table 1 summarizes the result of the NIST-SNL direct JVS comparison. When a large number of data points are collected from measurements like the NIST-SNL JVS comparison, serial correlations among the repetitive measurements can significantly impact the statistical or Type A uncertainty [5]. With repetitive measurements the standard deviation of the mean is often used to specify the Type A uncertainty. But this can lead to underestimation from the assumption that the data are uncorrelated. In the NIST-SNL JVS comparison, more than a hundred of data points were taken. The standard deviation of the mean of the 108 measurement points from Fig.5 was 0.20 nV, which was much 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 with input of DVM2 shorted as shown in Fig.6 and is based on the method introduced by T.J. Witt [6]. For a short sampling time, 0.3 s to 10 s, the Allan deviation varies $\tau^{-0.5}$ with white noise behavior, where τ is the sampling time. For a long sampling time, greater than 10 s, the Allan deviation deviates from the $\tau^{-0.5}$ line, exhibiting 1/*f* noise behavior. The mean Allan deviation for a sampling time that is longer than 10 s was calculated to be 0.75 nV, and we used this for the estimated Type A uncertainty.

Table 1 Result of the NIST-SNL direct JVS comparison at a nominal voltage of 9.997 V

Mean difference (NIST-SNL) (nV)	-2.08
Degrees of Freedom	107
Type A uncertainty (nV)	0.75
Type B uncertainty (nV)	1.23
Combined standard uncertainty (nV)	1.44
Expanded Uncertainty (nV) $k = 2$	2.88

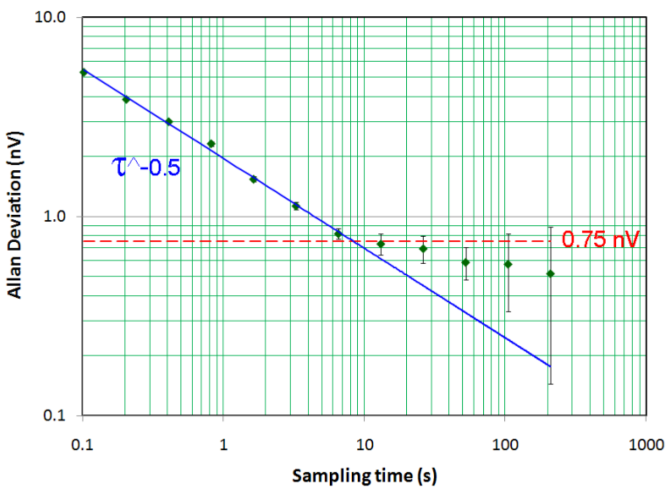

Fig. 6 Allan deviation for the DVM2 used for the NIST-SNL direct JVS comparison. For the sampling time longer than 10 s, the mean Allan deviation was 0.75 nV.

The Type B uncertainty components from both JVS systems are listed in Table 2. The leakage resistances were measured after the comparison and were found to be 8.3×10^{10} Ω and 2.0×10^{11} Ω for the NIST and SNL cryoprobe, respectively. The resistances of the precision voltage leads for the NIST and SNL cryoprobe were 5.9 Ω and 15.0 Ω. The voltage drop in the precision leads that was caused by the leakage resistance at the nominal comparison voltages generated by the NIST and SNL JVS systems was 0.71 nV and 0.75 nV. These corrections have been included in the reported difference. However, we estimated the uncertainty of the leakage correction to be 0.25 nV for each cryoprobe and included them as the Type B components in the final budget.

We also applied the DVM2 gain correction obtained from the data analysis with the uncertainty of the gain error measurement estimated to be 0.50 nV. We reported the combined Type B uncertainty as 1.23 nV.

Table 2. Type B uncertainty components of each JVS system

Type B uncertainty component	NIST (nV)	SNL (nV)
Frequency counter	0.10	1.06
Leakage resistance	0.25	0.25
DVM2 gain	0.50	N/A
Combined Type B uncertainty (nV)	1.23	

The comparison between the SNL and participating labs will be performed via a set of low noise transfer Zener standards. For this reason an *in-situ* JVS comparison between the NIST CJVS and the SNL JVS was also carried out using same set of Zener standards and the protocol developed by NIST and SNL [7]. The difference was found to be 12 nV ± 21 nV at 10 V (k = 2) or a relative uncertainty of 2.1 parts in 10^9. This result is consistent with the results from similar past JVS ILC comparisons [8].

6. Conclusion

We performed the NIST-SNL direct JVS comparison using the automatic protocol in order to support the NCSMI JVS ILC 2011. The difference between the NIST CJVS and NSL JVS was found to be -2.08 nV with an expanded uncertainty of 2.88 nV (k = 2) or a relative uncertainty of 2.88 parts in 10^{10} at the nominal voltage 9.997 V. The DVM gain error correction of 6.6 μV/V was applied to the measurement data. We found the dielectric discharge time of the filter capacitors had a significant impact on the comparison. The effect was significantly reduced by increasing the waiting period for the discharging process to reach an equilibrium state. We also reported that the standard deviation of the mean was not an appropriate estimation of the Type A uncertainty for the correlated data produced by this comparison. We decided to use the DVM 1/f noise floor to represent the Type A uncertainty for a large number of correlated data points.

The result of this direct JVS comparison achieved an uncertainty level that was comparable to the international key comparison BIPM.EM.K10.b in the BIPM KCDB. This bilateral JVS comparison has confirmed that SNL is capable of performing its role as the pivot lab in the upcoming NCSLI JVS ILC. The results of the NCSLI JVS ILC will allow each of its participants to establish a voltage measurement link to NIST via the pivot lab SNL.

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