A Direct Josephson Voltage Standard Comparison between NIST and Lockheed Martin Mission Services

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Abstract

To support the 8th JVS Interlaboratory Comparison (ILC) in 2008, sponsored by the National Conference of Standard Laboratories International (NCSLI), a direct Josephson Voltage Standard (JVS) comparison using the NIST compact JVS (CJVS) was carried out in March 2008 between NIST and Lockheed Martin Mission Services (LMMS). LMMS is the pilot laboratory for the JVS ILC 2008. A comparison between NIST and LMMS will provide all of the JVS ILC participating laboratories with a link to NIST. A protocol designed for the JVS direct comparison is described in the paper. It is possible to use a direct JVS comparison to detect JVS system errors associated with the frequency measurement, cryoprobe leakage correction and the Josephson junction array. These errors are small in magnitude and are not normally detectable by other types of JVS comparisons, such as the Zener Measurement Assurance Program (MAP). The difference between the LMMS JVS and the NIST CJVS at 10 V was found to be 0.71 nV with an expanded uncertainty of 6.87 nV ($k = 2$) or a relative uncertainty of 6.87 parts in 10^{10}, which is a factor of 4 improvement compared to that of the *in situ* indirect JVS comparisons implemented in the NCSLI JVS ILC 2005 and a factor of about 40 improvement compared to the results from the NCSLI JVS ILC 2002. This comparison has verified the LMMS JVS and also has confirmed that LMMS is well prepared to serve as the pivot lab for the NCSLI JVS ILC 2008.

Key words: Compact Josephson voltage standard (CJVS), direct JVS comparison, interlaboratory comparison (ILC), uncertainty

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1. Introduction

The NCSLI has been organizing the JVS ILC at 10 V in North American since 1991, occurring at an interval of every two to three years [1]. The JVS ILC provides the participating laboratories with dc voltage measurement comparisons which meet accreditation or contractual requirements and establishes reliability, confidence, and improved JVS system operation. During the last 17 years, several major changes in the measurement protocol have been implemented to detect small system errors and to improve the uncertainty of the JVS. Most of the NCSLI JVS ILC comparisons have been performed using a set of traveling Zener standards and have attained an uncertainty of a few parts in 10^8. Since the Type B uncertainty of a well maintained JVS usually is in the range of a few parts in 10^{10}, small system errors, from sources such as the cryoprobes leakage and the frequency measurement, cannot be detected by using traveling Zeners. The inability to detect the small errors is due to the characteristics of the Zeners such as non-linear drift, environmental effects and shipping impact. During the NCSLI JVS ILC 2005, NIST served as the pivot lab and made indirect comparisons, *in situ* using a CJVS developed at NIST [2], with 5 sub-pivot participating labs. The measurement protocol involved two JVS systems performing measurements of the same set of transfer Zener standards *in situ* to reduce the effects of non-ideal Zener characteristics. The uncertainty of these JVS comparisons was in the range of 2 to 3 parts in 10^9. A system error in the order of a few parts in 10^9 is detectable by this type of comparison.

NIST has continued its effort to further reduce the uncertainty of JVS comparisons by using the CJVS for a direct array to array comparison. In 2006, NIST and the National Research Council (NRC), Canada carried out a successful direct JVS comparison at NRC. Results from the NIST – NRC JVS comparison has shown that the difference between the NIST CJVS and the NRC JVS was -0.28 nV at 10 V with an expanded uncertainty ($k = 2$) of 2.1 nV or 2.1 parts in 10^{10} [3]. A system error in the order of a few parts in 10^{10}, such as cryoprobe leakage, frequency measurement, and array performance, is usually very difficult to detect using Zeners as transfer standards. The direct JVS comparison is able to detect these small errors.

The 2008 JVS ILC follows the recommendations of ASTM E1301-95, “Standard Guide for Proficiency Testing by Interlaboratory Comparisons,” and is open to all standards laboratories in North America with an operational 10 V Josephson voltage standard. A total of 15 laboratories with 17 JVS systems participate in this activity. The measurement protocol, in which a set of Zeners travel to the labs and is measured by each JVS, was used for the NCSLI JVS ILC 2008 and is similar to the protocol used for the ILC 2002. To reduce the impact of effects such as non-linear drift, the Zeners are returned to the pivot lab after being transported to two or three labs for tracking of the changes in the traveling Zener standards. During the ILC 2008, five such loops are scheduled to be accomplished.

NIST has supported the NCSLI JVS ILC 2008 through a direct JVS comparison with the pivot lab LMMS in Denver, Colorado. This comparison will provide all of the ILC participating labs with a link to NIST through the pivot lab LMMS. Because the uncertainty of the NIST – LMMS JVS comparison is in the range of a few parts in 10^{10}, the uncertainty of a participating JVS lab, relative to the NIST CJVS, would be mainly determined by the comparisons between the pivot lab LMMS and the participating ILC lab. This paper describes the JVS direct comparison protocol using the NIST CJVS and software NISTVolt. The results and uncertainty analysis of the NIST – LMMS direct JVS comparison are also presented.

2. Principle of Direct JVS Comparison and Description of JVS Systems

For convenience of description we will use JVS 1 and JVS 2 to specify two JVS systems for the direct JVS comparison. Each JVS system is equipped to generate a 10 V nominal voltage and has software that performs the data acquisition and analysis. In general, the hardware construction of the JVS system and the associated software can differ from system to system. A complete direct JVS comparison is composed of two stages. During the first stage of the comparison, JVS 1 establishes a voltage at 10 V and JVS 2 uses its software to take a set of measurements of the voltage provided by JVS 1. The second stage of the comparison involves JVS 1 using its software to measure the voltage provided by JVS 2. The two sets of measurement data determine the consistency of the two JVS systems with respect to their claimed uncertainties and the validity of the software used for the data acquisition and analysis.

The CJVS, constructed at NIST, uses a fixed microwave frequency of 76.76 GHz and integrates the microwave frequency assembly with the cryoprobe. The unique design of the frequency assembly eliminates the need of a frequency counter, thereby reducing the weight of the system. This makes the system compact and transportable. The construction of the 76.76 GHz microwave assembly is described in reference [4]. The resistance of the NIST CJVS precision measurement leads is 7.0 Ω (including the filter resistance). The leakage resistance between the two precision measurement leads was 4.0×10^{11} Ω. The voltage drop due to the leakage resistance at 10 V is 0.175 nV. Other details of the CJVS are as follows:

- Precision measurement leads resistance: 7.0 Ω
- Josephson junction array: Hypres[†] 10 V array
- Null detector: Agilent[†] 34420A
- Software : NISTVolt for Windows

The construction of the LMMS JVS system is based on the NIST design described in the NCSLI Recommended Intrinsic / Derived Standards Practice RISP-1 [5]. A Gunn oscillator provides a microwave signal of 77.06 GHz to the Hypres[†] Josephson junction array. An EIP[†] counter is used to measure the microwave frequency. A 10 MHz

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[†] Certain commercial equipment, instruments, or materials are identified in this report in order to facilitate understanding. Such identification does not imply recommendation or endorsement by NIST neither by LMMS, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

frequency from a Cesium clock provides the frequency reference to the LMMS JVS as well as to the NIST CJVS during the comparison. Other details of the LMMS are as follows:

- Precision measurement leads resistance: 3.4 Ω
- Josephson junction array: Hypres† 10 V array
- Null detector: Agilent† 3458A
- Software : NISTVolt for Windows

Fig. 1 shows the setup using the NIST CJVS bias source to measure the difference between the NIST CJVS and the LMMS JVS. The two arrays are connected in series opposition with the difference voltage $V_{LMMS} - V_{CJVS}$ connected to DVM2. DVM1 is connected across V_{CJVS}. The NIST CJVS bias source is used to set both array systems near 10 V when the shorting switch across DVM2 is closed. A shorting switch across DVM2 is used in conjunction with the reversing switch of the CJVS bias source (not shown in the Fig. 1) to change the polarity of both arrays. The shorting switch provides a fast way to put both arrays on steps at nearly the same voltage.

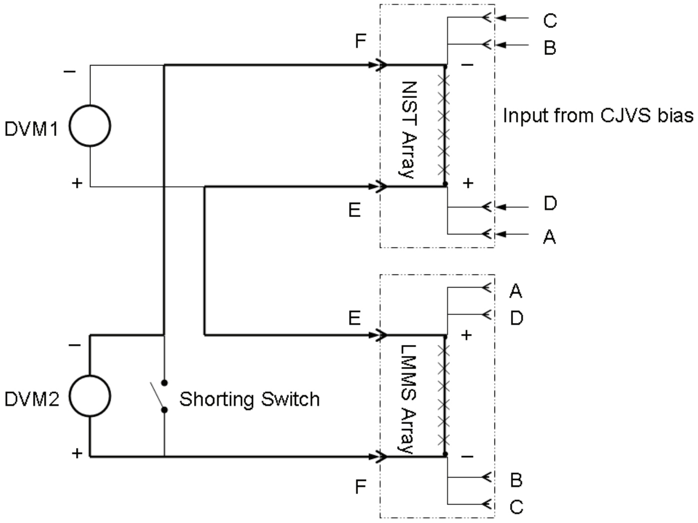

Fig. 1 The setup using the NIST CJVS bias source to measure the difference between the LMMS JVS and the NIST CJVS.

Both JVS systems use the same software program NISTVolt for data acquisition and analysis. This feature allows us to make one comparison to check the consistency of both JVS systems. It is important to understand that a direct array comparison does not test the offset and repeatability of the low potential reversing switches that are normally part of a JVS measurement system and used for measuring Zener standards. A separate *in situ* indirect JVS comparison between the NIST JVS and the LMMS JVS was also carried out to evaluate the reversing switch used for Zener measurements. The protocol of the *in situ* indirect JVS comparison can be found in reference [2] and is not described in this paper.

The result of the *in situ* indirect JVS comparison between the NIST CJVS and LMMS JVS is consistent with those performed between the NIST CJVS and sub-pivot labs during the NCSLI JVS ILC 2005.

3. NISTVolt Protocol for JVS Direct Comparison

In a direct Josephson comparison, the parameter of interest is the amount by which the difference voltage deviates from its theoretical value. Comparisons are made by connecting the standards in series opposition and measuring the difference voltage V_d with a sensitive digital voltmeter (DVM) such that

$$V_\mathrm{d} = V_\mathrm{a1} - V_\mathrm{a2} = (N_1 f_1 - N_2 f_2) \,/\, K_\mathrm{J\text{-}90} \qquad (1)$$

The difference between the theoretical value V_d and the voltmeter's estimate V_m of the actual difference can be modeled by

$$V_\mathrm{d} - V_\mathrm{m} = (V_\mathrm{o} + mt + V_\mathrm{n} + \delta)\ \ (1 + E_\mathrm{g}) \qquad (2)$$

where $V_\mathrm{o} + mt$ represents an offset voltage with a fixed and a linearly drifting component. The offset voltage is assumed to include both the voltmeter offset and thermal emfs in the measurement loop. V_n is the random time dependent noise in the meter readings and any other unaccounted effects such as DVM nonlinearity. E_g is the gain error of the voltmeter. δ is the amount by which the measured voltage between the two standards differs from its theoretical value.

Contributions to δ are:

1. A discrepancy between f_1 or f_2 as used in the equation and the actual frequencies applied to the Josephson arrays.
2. Leakage current I_L that results in a voltage drop across the resistance of the measurement loop.
3. A bias current dependence of the step voltage (sloped steps).
4. Uncorrected thermal offset and drift.
5. Any additional unknown effects. Note that no uncertainty is being ascribed to the value or accuracy of $K_\mathrm{J\text{-}90}$.

Solving Eq. 2 for δ gives

$$\delta = (V_\mathrm{d} - V_\mathrm{m}) \,/\, (1+E_\mathrm{g}) - V_\mathrm{o} - mt - V_\mathrm{n} \qquad (3)$$

The unknowns in this equation are V_o and m and δ. They can be estimated by making sets of measurements with two or more polarity reversals. Rather than using a reversing switch, the polarity of each array is reversed by changing the array bias to reverse the signs of N_1 and N_2 but not the magnitude.

The data set is an array $V_\mathrm{d}(\mathrm{i})$, $V_\mathrm{m}(\mathrm{i})$, $t(\mathrm{i})$, and $P(\mathrm{i})$ for i = 1 to N where $V_\mathrm{d}(\mathrm{i})$ is the i$^{\mathrm{th}}$ theoretical difference in array voltages, $V_\mathrm{m}(\mathrm{i})$ is the i$^{\mathrm{th}}$ meter reading, $t(\mathrm{i})$ is the time of the

i^{th} reading, $P(i)$ is the polarity of V_{a1} and V_{a2} for the i^{th} reading, and N is the total number of readings.

Equation 3 is a model for the data set. Best estimates for V_o and m and δ are computed using a 3 parameter fit that minimizes the RSS sum of the residuals $R(i)$ to the model of Eq. 3 where:

$$R(i) = [V_d(i) - V_m(i)] / (1+E_g) + V_o + mt(i) - \delta \qquad (4)$$

The NISTVolt software implements the measurement protocol described above. In the comparison between the LMMS JVS and NIST CJVS, the array polarity change sequence + – + – + – is used. The polarity change of the arrays was made electronically by the NIST CJVS bias source without using a mechanical switch.

4. Results and Uncertainty

The measurements from comparing the LMMS JVS against the NIST CJVS were made by manually operating the bias source of the NIST CJVS and the DVM2 shorting switch. The bias source was kept on during the measurement so that the possibility of a small error due to sloped steps of either array could be detected. The NISTVolt software was used for the data acquisition and calculation of the difference between the two JVS systems from the theoretical value. The voltage difference between the two arrays was always controlled within 10 mV. Fig. 2 shows the results of comparison between the NIST CJVS and the LMMS JVS. A total of 20 points within a 6 hour period were taken with 10 points using the DVM in the normal polarity position for the measurements and 10 points using the DVM in the reversed polarity position.

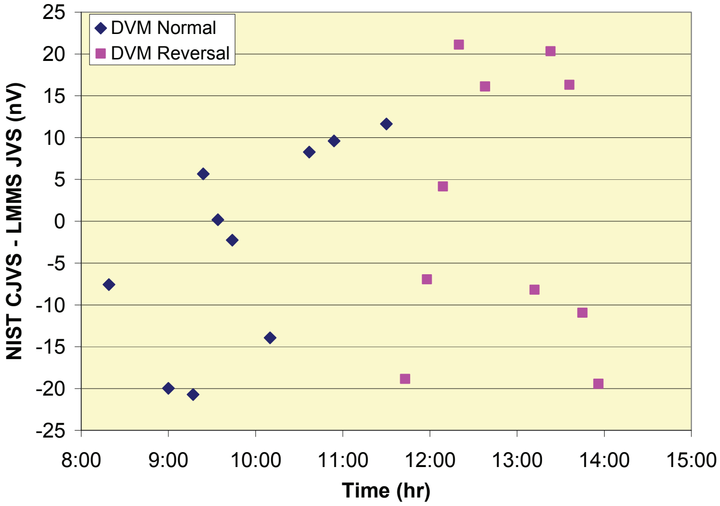

Fig. 2 Measurement results from the direct JVS comparison between the NIST CJVS and the LMMS JVS. Each point is calculated using a fitted value from the 6 iterations of + – + – + – array polarity changes.

The difference D of LMMS – NIST is the mean of the differences of all the measurements calculated as

$$D = \frac{\frac{\sum_i D_i^+}{N_+} + \frac{\sum_i D_i^-}{N_-}}{2} \tag{5}$$

where D_i^+ is the i$^{\text{th}}$ measurement and N_+ is the number of measurements taken with DVM normal polarity, D_i^- is the i$^{\text{th}}$ measurement and N_- is the number of measurements taken with DVM reversed polarity. In the comparison, an equal number of DVM normal polarity and reversed polarity measurements was taken. Type A uncertainty of the measurements is the pooled standard deviation of the mean of all the measurements,

$$u_A = \sqrt{\left({u_A^+}\!/_{2}\right)^2 + \left({u_A^-}\!/_{2}\right)^2} \tag{6}$$

where u_A^+ and u_A^- is the standard deviation of the mean for data sets with normal and reversed DVM polarity, respectively.

Table 1. Differences between the two JVSs and associated Type A uncertainties

LMMS - NIST (nV)	0.71
Number of measurements N_+ (or N_-)	10
Standard Deviation (nV)	10.11
Type A uncertainty u_A (nV)	3.20

Table 2 lists the Type B components from various sources for the JVS systems and measuring device. The leakage resistance between the precision measurement leads of each cryoprobe has been measured. The combined correction of 0.033 nV for the leakage resistance from both cryoprobes is applied to the final calculation. The uncertainty of 0.01 nV was estimated as 20 % of the correction. The DVM gain and linearity was estimated to be 1 nV, considering the range change between 1 mV and 10 mV during the measurements. It is assumed that the bias related to the DVM polarity in the measurements was due to the electromagnetic interference (EMI) in the measurement loop and is estimated as 0.6 nV, based on a similar direct JVS comparison. Lastly, the Type B contribution of the detector offset, impedance, and noise was estimated by a short test using the NIST CJVS to measure a zero voltage (short). The uncertainty contributions from the microwave power rectification, uncorrected thermals, and sloped voltage steps are negligible in this comparison. The Type B is the root sum square (RSS) of all the components listed in Table 2.

Table 2. Type B uncertainty components

NIST CJVS Frequency offset and noise	0.10
LMMS JVS Frequency offset and noise	0.39
Leakage correction	0.01
Detector gain and linearity	1.00
EMI	0.60
Detector offset, impedance and noise	0.15
Type B uncertainty u_B (nV)	1.24

Table 3 lists the differences and associated combined uncertainty as RSS of Type A and Type B uncertainty.

Table 3. The differences with combined uncertainties

LMMS - NIST (nV)	0.71
Type A uncertainty u_A (nV)	3.20
Type B uncertainty u_B (nV)	1.24
Combined uncertainty (nV)	3.43
Expanded combined uncertainty (nV) $k = 2$	6.87

5. Summary

NIST has continually worked on the development of new JVS comparison methods to improve the uncertainty of a JVS comparison. The direct JVS comparison between LMMS and NIST has shown that the difference between the two JVS systems is 0.71 nV with an expanded combined uncertainty of 6.87 nV ($k = 2$) or a relative uncertainty of 6.87 parts in 10^{10}. It is an improvement by a factor of 4 compared to the uncertainty of the *in situ* indirect JVS comparison implemented in the NCSLI JVS ILC 2005 and an improvement by a factor of about 40 compared to the uncertainty from using Zeners as travelling standards in the NCSLI JVS ILC 2002.

The time needed to accomplish a Zener Map comparison, which is statistically significant and has an uncertainty of a few parts in 10^8, is usually several weeks. When the NIST CJVS is implemented in *in situ* indirect JVS comparisons such as in the NCSLI JVS ILC2005, this time period can be reduced to 10 – 16 hours and an uncertainty of few parts in 10^9 can be achieved. A direct JVS comparison needs only a few hours to obtain an uncertainty of a few parts in 10^{10}. A successful direct JVS comparison not only improves the uncertainty for detecting small system errors, but also reduces the time needed for the data acquisition. This new measurement protocol greatly enhances the efficiency and reduces the cost of a JVS comparison.

No errors related to the cryoprobe leakage correction, microwave frequency measurements, and array sloped steps were detected within the uncertainty of the LMMS and NIST direct JVS comparison. This comparison has verified the LMMS JVS and also has confirmed that LMMS is well prepared to serve as the pivot lab for the NCSLI JVS

ILC 2008. The comparison result will be used to establish a link between the participating ILC labs and NIST via the comparison with the pivot lab LMMS.

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