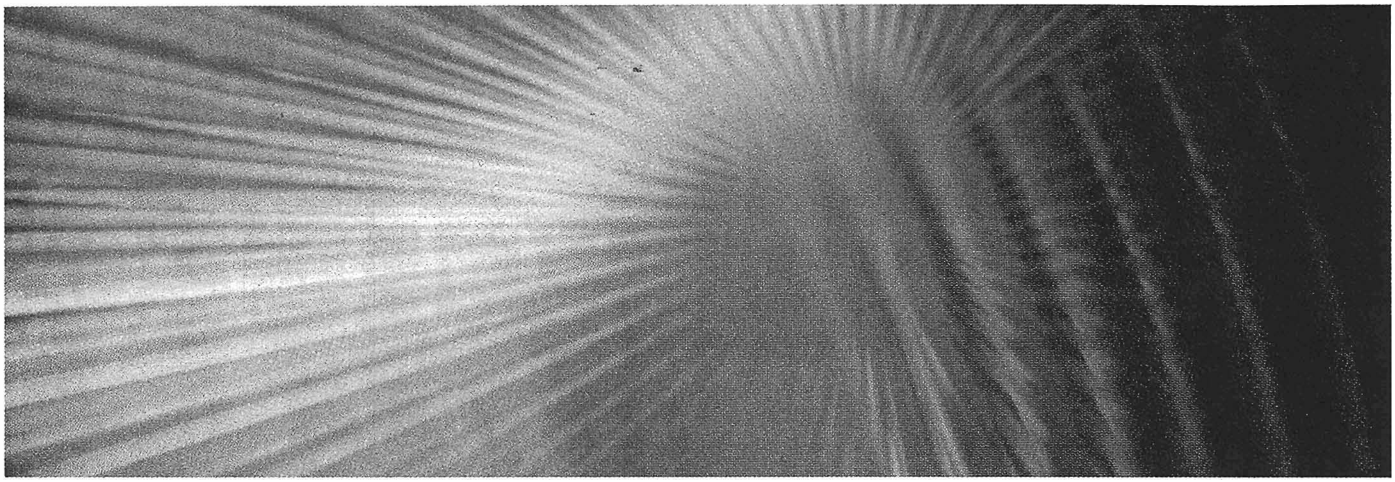

Experimental Design of NCSLI 2005 Josephson Voltage Standard Interlaboratory Comparison

Yi-hua Tang[1], Clark Hamilton, Harold Parks[2], David Deaver, and Barry Wood

The National Conference of Standards Laboratories International[3] (NCSLI) 2005 Josephson voltage standard (JVS) Interlaboratory Comparison (ILC) provides participating laboratories with a means of comparing dc voltage measurements in order to meet accreditation or contractual requirements, and to establish reliability, confidence, and improved system operation. Several changes in procedures are implemented in the 2005 JVS ILC. The National Institute of Standards and Technology (NIST), as the main pivot lab, will make comparisons with a set of 4 subset pivot labs using the NIST compact Josephson voltage standard (CJVS). This will be accomplished by shipping the CJVS to a subset pivot lab and making a comparison with the subset pivot lab's JVS *in situ* using a set of four Fluke 732B Zener standards as transfer standards. Each subset pivot lab is responsible for making comparison measurements with 3 participants using the same protocol as in the NCSLI JVS ILC organized in 2002 [1]. In order to monitor the condition of the transfer Zener standards, they will be shipped back to the subset pivot lab for a second set of measurements. This "daisy" pattern will be repeated with 4 comparisons between NIST and the subset pivot labs, and comparisons with about 12 additional participant labs using the transfer Zener standards. It is anticipated that this comparison method will greatly reduce the uncertainties corresponding to the non-linear drift characteristics associated with the environmental and transportability effects of the transfer Zener standards.

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[3] National Conference of Standards Laboratories (NCSL) was renamed as NCSL International (NCSLI) in 2000.

1. Introduction

The Josephson voltage standard (JVS) has been widely used in many national measurement institutes around the world to maintain and disseminate voltage to the end user, such as calibration labs, instrument manufacturers and scientific researchers. In North America, especially in the United States, the JVS is also used in many industrial, military and government laboratories. The JVS is based on the physical law that an ac current of frequency f applied to a Josephson junction generates a dc voltage V_n at the quantized values

$$V_n = nh\,f/2e \tag{1}$$

where n, the step number, is an exact integer, e is the electron charge, and h is Planck's constant. For the purposes of voltage metrology, $2e/h$ is assigned the value $K_{J\text{-}90}$ = 483 597.9 GHz/V which is the conventional value of the Josephson constant adopted worldwide on January 1, 1990 [1].

A JVS system using the Josephson junction array is a complex electronic system that includes a null voltage detector, switches, cryoprobe, bias source, frequency counter, etc. A more detailed explanation of the construction and operation of the JVS system can be found in National Conference of Standards Laboratories International (NCSLI) RISP-1 [2]. Any malfunction of these instruments and components can cause an unacceptable error in the measurement. For example, 8×10^{-6} in gain error of a digital voltmeter can cause a miscalculation of the step number n and an error of 155 µV in a voltage measurement at 10 V using a frequency of 75 GHz. A majority of the JVS labs operate only one system. It is difficult to detect errors of less than a few parts in 10^8 by relying on measurements of Zener reference check standards because such errors can be smaller than the short-term variation of a Zener reference. In the 1999 intercomparison, results of two laboratories were found to deviate approximately 9 σ from those of the other participants. Though much larger than the deviations of other laboratories in this intercomparison, both deviations were within the laboratories' claimed uncertainties and were unknown to them before participating in the intercomparison. Subsequent corrective actions were successful in determining the root cause of the deviations [3]. Therefore, it is essential to make periodic comparisons between JVS systems to verify their system operations.

This paper describes a brief history of the North American JVS interlaboratory comparisons since 1991 and summarizes the improvements made over the last decade. It also describes a new protocol using the National Institute of Standards and Technology (NIST) compact JVS as a transfer standard.

2. History of NCSLI JVS ILC

2.1 Beginning of the JVS ILC

The big breakthrough of a practical JVS came in 1985, when NIST demonstrated the first array of Josephson junctions at the 1-volt level [4]. Two years later, a 10 V standard was developed. With almost 20 000 junctions, it is believed to have been the largest practical superconducting circuit in the world at that time. In the next few years, the 10 V JVS was rapidly implemented in many US industrial, military and government labs. In 1991, NIST implemented the first 10 V JVS ILC with seven other participants, using 3 Zener references as transfer standards. It took about a year to circulate the transfer Zener references among the participating labs. NIST, as the pivot lab, took measurements three times: at the beginning, middle and the end of the experiment. The typical agreement among the participants was within 5 parts in 10^8.

The 2nd and 3rd JVS ILCs were sponsored by the NCSL and were carried out in 1993 [5] and 1995 with Fluke Corporation as the pivot lab. Four transfer Zener standards were circulated in a "daisy" pattern to minimize the time difference between the pivot lab and participant laboratories, thus minimizing the effects of long-term transfer standards noise. All of the laboratories were in agreement to within 2.5 parts in 10^8 (1993) and 3.5 parts in 10^8 (1995) at 10 V.

2.2 JVS ILC without pivot lab – the 4th ILC

In 1997, there were 15 laboratories participating in the 4th NCSL JVS ILC. The same four transfer Zener standards used in the 2nd and 3rd ILCs were circulated among the participants, but without a pivot lab to monitor the changes of the transfer standards. Figure 1 shows the path of the transfer standards. The advantage of this method is to eliminate the pivot lab's extra workload. On the other hand, if the transfer standards experience an unexpected change in their values, no corresponding measurement can be quickly taken to correct the problem. It took 5 months for all of the participants to finish the measurements. During this period, relative humidity change of the environment could significantly increase the uncertainty of the comparisons. Comparison measurements were based on a linear regression fit of time and atmospheric pressure. The peak-to-peak variation of all participants fell within the estimated 2σ uncertainty of 1.7 parts in 10^8, indicating that no significant difference was detected among them [6].

2.3 JVS ILC with pivot lab – 5th and 6th ILC

It was recognized by several research groups that Zener standards are affected by environmental conditions of atmospheric pressure, temperature and relative humidity [7, 8]. These effects on Zener standards can be pre-determined and the corresponding corrections can be applied. The pressure coefficients of a Zener reference Fluke 732B[4] fall into two categories. 732B's using the Linear Technology reference/amplifiers (Type L) have a pressure coefficient of about 20 nV/hPa. 732B's using the Motorola reference/amplifiers (Type M) have a pressure coefficient of about –2 nV/hPa.

The 5th NCSL JVS ILC in 1999 amended the protocol to implement measured pressure corrections for the transfer Zener references [3, 9]. Lockheed Martin Astronautics (LMA) took the

[4] Commercial equipment and materials are identified in order to adequately specify certain procedures. In no case does such identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

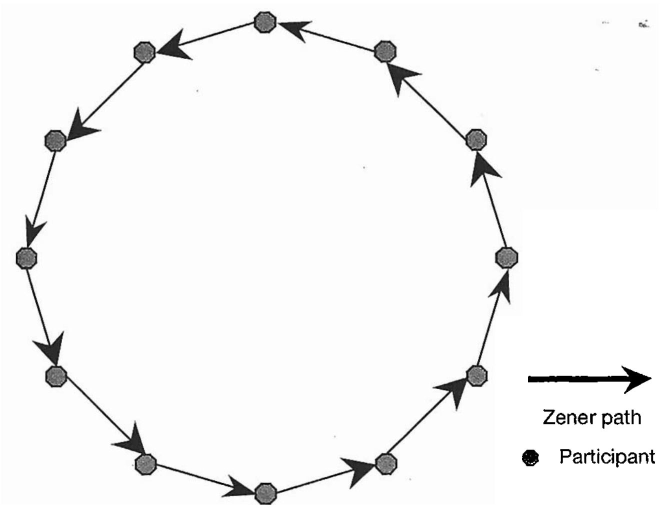

Figure 1. Traveling path of transfer standards in NSCL JVS ILC in 1997 (4th ILC). There was no pivot lab to monitor the traveling Zener standards.

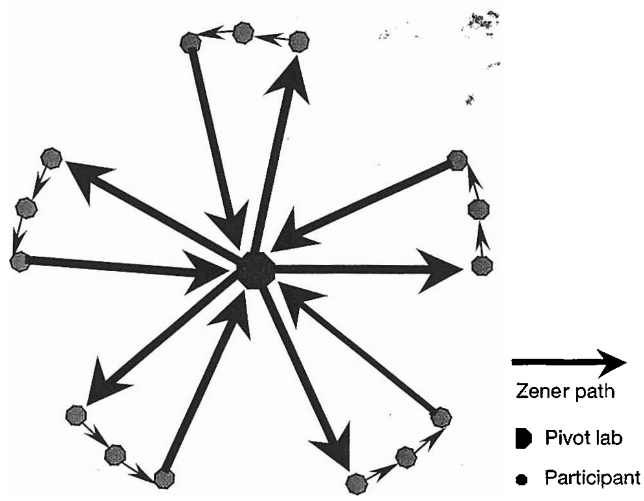

Figure 2. Traveling path of transfer standards in JVS ILC in 1999 (5th ILC) and 2002 (6th ILC).

leading role as the pivot lab. Four Zener references (Type M) were used as the transfer standards. The pressure difference among the participants can be as high as 200 hPa, resulting in a voltage difference of 0.4 μV or 4 parts in 10^8 at 10 V. The measurement data received from the participants were first adjusted to 1013.25 hPa and then used in the analysis. It is critical to make pressure correction for Zener references, especially if the transfer Zener is Type L, which has a pressure coefficient about 10 times higher than that of the Type M Zeners. It is now common practice in a JVS comparison to make a correction for the Zener pressure effect. In the 1999 ILC, all but two of the differences between pivot and participant labs fell within 2 parts in 10^8.

Based on the history of 5 successful intercomparisons and the tremendous effort required to conduct them, it was decided in 2000 to decrease the frequency of the NCSLI sponsored intercomparison from 2-year intervals to 3-year intervals. In 2002, Sandia National Laboratories (SNL) was the pivot lab in the NCSLI JVS ILC [10]. Sixteen national, industrial and military standard laboratories participated in the ILC. The protocol, shown in Figure 2, was similar to the one implemented in the NCSL JVS ILC in 1999. The pivot lab made measurements at the beginning, at the end, and at four other times during the comparison. The ILC 2002 procedure was modified to reduce the number of measurements by each participant from 64 to 32 (8 measurements for each of the four Zener references). In order to improve the link between the pivot laboratory and NIST, a portable JVS system was used as a transfer standard to make an on site comparison between the NIST and SNL JVS systems [11]. The measured differences and their uncertainties quantified the equivalence between each participant and the pivot lab, as well as between each participant and NIST. All of the differences fell within 2 parts in 10^8.

Table 1 shows the main features of the seven NCSLI 10 V JVS ILCs since 1991. All of the JVS ILCs use Zener references

ILC No.	Year	Pivot	Partici-pants	Agreement (Parts in 10^8)	Notes
1st	1991	NIST	8	5	First JVS ILC in North America
2nd	1993	Fluke	10	2.5	Daisy pattern implemented
3rd	1995	Fluke	12	3.5	Same protocol as JVS ILC 1993 implemented
4th	1997	None	15	1.7[5]	No pivot lab
5th	1999	LMA	17	2	Pressure effect correction for transfer standards
6th	2002	SNL	16	2	CJVS introduced to improve link between pivot lab and NIST
7th	2005	NIST	17		CJVS used as transfer standard between subset pivot lab and NIST

Table 1. List of NCSLI 10 V JVS ILC.

[5] The listed uncertainty excluded two participants.

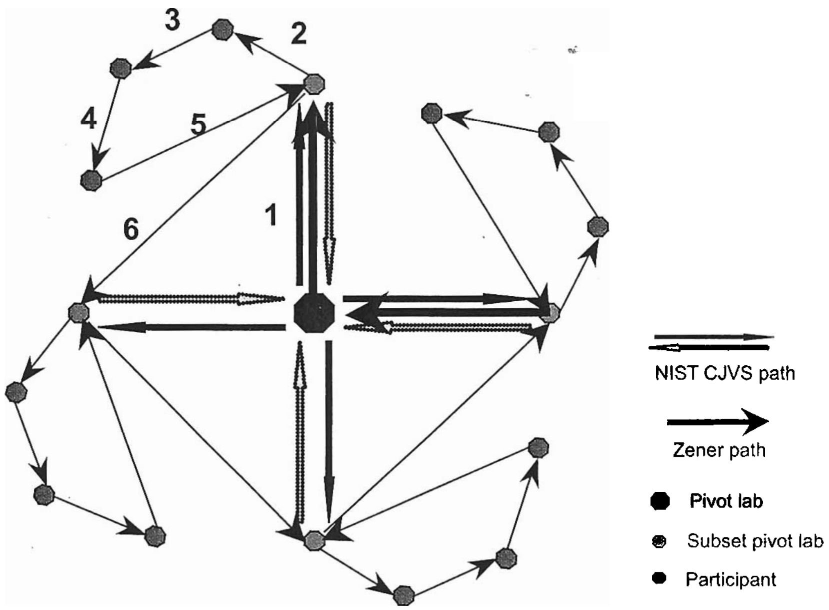

Figure 3. Path diagram of transport Zeners and CJVS for the 7th ILC.

as the transfer standard. Over the years, several process changes have been suggested and implemented to improve the ILC process. With all of these improvements, the limiting factor for such comparisons is still the imperfection of the Zener standard due to its response to environmental conditions and shipping. The consistency among JVS ILC participants is usually a few parts in 10^8.

3. Experimental Design for the NCSLI JVS ILC 2005

Humidity dependence has been observed on some, but not all Zeners, and corrections to Zeners at 1.018 V for humidity change have been reported in an international comparison [12]. Due to the hysteretic behavior of the humidity effect and the long time scale of the response, the correction is difficult to apply and often has considerable uncertainty. Additional Zener characteristics, such as non-ideal transportability and non-linear drift during the shipping and comparison, can also affect the results of the comparison. Non–ideal transportability is often the largest component of uncertainty. These issues are the motivation for the development of an alternative method of JVS comparison capable of achieving reduced uncertainty.

In the NCSLI JVS ILC 2002 (6th ILC), a portable JVS system was used to make an on site JVS comparison between the SNL and NIST laboratory systems. At about the same time, the two laboratory systems were compared using Zener standards traveling between the two labs. The difference between the NIST and SNL laboratory JVS at 10 V using the portable JVS as a transfer standard was 10 nV with an expanded uncertainty of 2 nV at 95 % confidence. This is a factor of 13 improvement over the traveling Zener comparison method.

The 2005 JVS ILC (7th ILC) is intended to provide participating laboratories with a means of comparing dc voltage measurements in order to meet accreditation or contractual requirements, and to establish reliability, confidence, and improved system operation. Several changes in the procedures will be implemented in the 2005 JVS ILC. NIST, as the pivot lab, will make four comparisons with selected subset pivot labs using the NIST compact Josephson voltage standard (CJVS) as the transfer standard. NIST will ship the CJVS, along with its accessories, to a subset pivot lab and NIST personnel will perform a comparison with the subset pivot lab's JVS in situ by measuring a set of four Fluke 732B Zener standards. After this comparison is performed, the subset pivot lab is responsible for making a set of measurements using a protocol similar to the one used in the ILC 2002. The Zener standards are then shipped to the next three labs for measurements. In order to monitor shipment effects, the Zener standards will be shipped back to the subset pivot lab for a second set of measurements. This "daisy" pattern will be repeated four times. Figure 3 shows the travel path of the transfer Zener references, as well as the path of the CJVS.

The Figure 3 shows the "modified daisy" pattern design for the NCSLI JVS ILC 2005. Color-coded arrows indicate the path of the Zener transfer standards and NIST CJVS transfer standard. The numbers indicate the sequence of comparisons.

The uncertainty of the comparison between the pivot lab and a subset pivot lab is expected to improve by an order of magnitude to a few parts in 10^9. Because the comparison is made in situ at the subset pivot lab, the problems associated with non-ideal Zener transportability, environmental dependence, and non-linear drift can largely be eliminated. The ultimate uncertainty for the comparison between the pivot lab and a subset pivot lab is determined by the noise of the Zener references used in the comparison.

Component	Uncertainty
Time base (nV)	0.1
Leakage (nV)	0.8
Thermals (nV)	6.0
DVM Gain (nV)	2.0
Uc (nV)	6.4

Table 2. Uncertainty of NIST CJVS at 10 V.

4. Preparation of the NCSLI JVS ILC 2005

The NIST CJVS consists of a cryoprobe, bias electronics, a digital voltmeter and a laptop computer for controlling the measurement. An integrated microwave package in the head of the cryoprobe produces a fixed microwave frequency of 76.76 GHz. The system can be shipped to another lab and assembled there for operation. Table 2 summarizes the uncertainty components of the NIST CJVS system. The estimated uncertainty of the CJVS is 6.4 nV for a 10 V measurement. The biggest contributions are due to the thermal voltages in the switch module and uncertainty caused by DVM gain error.

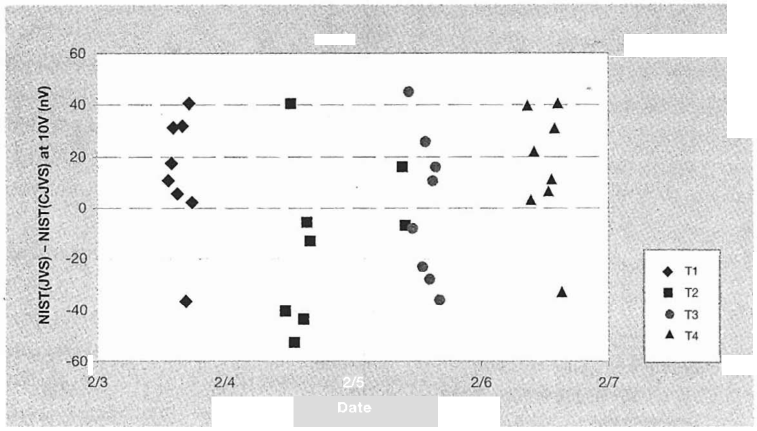

Figure 4. Difference between NIST JVS 10V system and NIST CJVS using the four Zener references used in NCSLI JVS ILC as transfer standards.

In the NIST Volt lab, the NIST CJVS has been compared against the NIST lab 10V JVS system several times using the same set of Zener references that are used in the NCSLI JVS ILC as transfer standards. Figure 4 shows the measurement results in a typical comparison of the two JVS systems. A total of 32 measurements by each JVS system for the four transfer Zener standards (T1, T2, T3 and T4) have been performed. The mean difference of these 32 pairs of measurements between the two JVS systems at 10 V was determined to be 4 nV. With 31 degrees of freedom (DOF) the expanded uncertainty of the difference between the two JVS systems at 95 % confidence was 10 nV or 1 part in 10^9.

The NIST CJVS has also been compared directly to a programmable JVS (PJVS) system at NIST. The comparison was carried out at 1.018 V by connecting the two arrays directly against each other. A low noise DVM was used to measure the difference between the two array voltages. The results of the comparison are shown in Figure 5. Using the mean value of 20 measurements, the difference in this comparison was 2 nV with a standard deviation of the mean of 2.6 nV. The expanded uncertainty at 95 % confidence with 19 DOF was therefore 5.5 nV or 5.4 parts in 10^9.

Other critical components used in the comparison such as the polarity switches have also been evaluated. The thermal voltages of the shorted switches in a stable temperature environment are generally a few nanovolts.

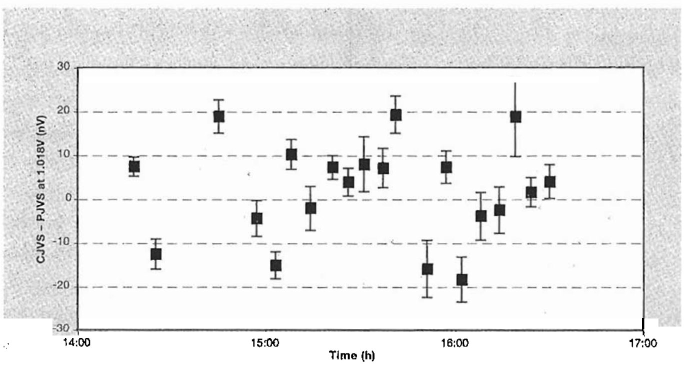

Figure 5. Difference between NIST PJVS system and NIST CJVS direct array comparison at 1.018 V.

5. Summary

The JVS intercomparison has become an important tool to evaluate JVS operation. Since 1991, NCSLI has conducted voluntary intercomparisons among JVS labs every two or three years. A majority of these comparisons have been made using a set of transport Zener standards. The protocol of the JVS ILC has been improved over the years in order to compensate for both non-ideal environmental dependence and non-linear drift of the Zener transfer standards. In the NCSLI JVS ILC 2005, NIST will implement its compact JVS as a transfer standard to make in situ comparisons with four subset pivot labs and improve the process by reducing the uncertainty of the comparisons with the subset pivot labs by an order of magnitude to a few parts in 10^9.

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