JOSEPHSON VOLTAGE STANDARD INTERCOMPARISON

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Abstract*: The majority of Josephson Voltage Standard (JVS) intercomparisons have been performed by using Zener voltage transfer standards and a protocol based on the Measurement Assurance Program (MAP) with uncertainties in the range of a few parts in 10^8 at 10 V that are limited by the Zener characteristics. In order to improve the uncertainty of the comparison, protocols using a compact Josephson voltage standard (CJVS) as the transfer standard have been developed. The uncertainty using the CJVS in the comparison can be in the range of a few parts in 10^9 at 10 V. The array-to-array direct comparison using the conventional JVS or programmable JVS (PJVS) can further improve the uncertainty of the comparison to a few parts in 10^{10}.

Keywords: intercomparison, Josephson voltage standard, Measurement Assurance Program (MAP), programmable Josephson junction array, uncertainty

1. INTRODUCTION

The Josephson Voltage Standard (JVS) system is widely used as the primary voltage standard in many national metrology institutes (NMIs). A traditional "traceability path" of an unbroken chain of comparisons with stated references does not apply to the case of the JVS operating in different locations. However, the equivalence of the JVS used by different laboratories must be demonstrated through comparisons.

This paper discusses the JVS intercomparison protocols that were developed in the last decade. The majority of the JVS intercomparisons use a set of Zener voltage standards as transfer standards that are measured by participating laboratories. The uncertainty of such a comparison is in the range of a few parts in 10^8 at 10 V and is limited by the Zener characteristics. To improve the uncertainty in a JVS comparison, a protocol using a transportable compact Josephson voltage standard (CJVS) to measure a set of Zener voltage standards *in situ* by two JVS systems has been developed. The non-ideal responses of the Zener standards to environmental and shipping conditions can be eliminated or reduced with this protocol. The uncertainty using the CJVS for an intercomparison can be in the range of a few parts in 10^9 at 10 V and enables JVS system errors at the level of a few parts in 10^9 to be detected and corrected. An array-to-array direct comparison can further improve the uncertainty of a JVS comparison. This is the ultimate comparison with an uncertainty of a few parts in 10^{10} at the 10 V level and is limited by the noise of the null detector used in the comparison. Due to the instability of the voltage steps of the conventional Josephson junction array developed during the 1980s, direct comparisons using this type of array are difficult to carry out. In 1997, the programmable Josephson junction array using non-zero current bias voltage steps was developed. An array-to-array direct comparison is much quicker and easier to perform when using this device and the uncertainties can be improved by two orders of magnitude when compared to the JVS comparison using the Zener Measurement Assurance Program (MAP).

This paper will use examples to illustrate the various protocols of JVS comparisons. The uncertainty results using actual JVS comparison data will be demonstrated. New developments and the future perspective concerning the JVS comparison will also be discussed.

2. JVS INTERCOMPARISON USING VARIOUS PROTOCOLS

2.1. Measurement Assurance Program

A Measurement Assurance Program (MAP) is commonly used to establish the difference between the measurement units realized at different laboratories. For

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example, a set of transfer Zener standards is measured at NIST and then sent to a customer for measurement in a voltage MAP. After a specified number of measurements have been taken, the transfer Zener standards are returned to NIST for further measurements. The data are then analyzed to determine the difference between NIST and the customer measurements and the total uncertainty that includes all known uncertainty contributions. In the case of the JVS systems, when the offset between the NIST and customer measurements can not be explained by the uncertainty analysis, a further investigation should be conducted to determine the source of the difference.

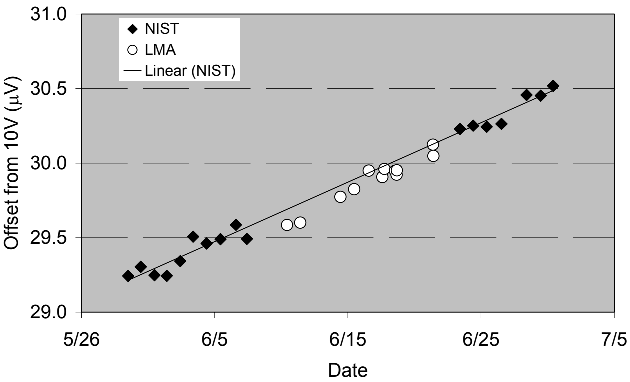

Fig. 1 Measurements of a transfer Zener standard at NIST and LMA.

Fig. 1 shows an example of a JVS comparison between NIST and Lockheed Martin Astronautics (LMA) [1]. The data have been adjusted to the standard atmospheric pressure of 1013.25 hPa. A least squares fit line is obtained using NIST data only. It was assumed that the transfer Zener standards' drift rates are the same at LMA and NIST. An offset between LMA and NIST for a Zener standard was calculated based on LMA's measurements and on the drift rate from the NIST data. The difference between the LMA and NIST measurements can be obtained by averaging the differences of the four transfer Zener standards. A corresponding uncertainty can also be calculated based on the *Guide to the Expression of Uncertainty in Measurement* [2].

The MAP protocol and its variation have been widely used in JVS Interlaboratory comparisons (ILC) that are sponsored by the National Conference of Standards Laboratories International (NCSLI) every 2 or 3 years since 1991. A pivot lab is selected for the NCSLI JVS ILC. Four transfer Zener standards were circulated in a "daisy" pattern to minimize the time difference between the pivot lab and the participant laboratories, thus minimizing the effects of long-term Zener standard noise. There were several NCSLI JVS intercomparisons in which the transfer Zeners returned to the pivot lab after measurements by 2 or 3 participating labs in order to reduce the workload of the pivot lab and the operational cost. Most key comparisons conducted by the Bureau International des Poids et Mesures (BIPM) with other NMIs also use Zener standards as the transfer standards. The uncertainty of this type of comparison is also in the range of a few parts in 10^8 at 10 V. Table 1 lists the results from a NCSLI JVS ILC. Table 2 lists several examples from the BIPM Key Comparison Data Base (KCDB). The expanded uncertainty (k = 2) is used in the tables.

Table 1. Results of the NCSLI JVS comparisons at 10 V using MAP protocol.

Year	Pivot	Lab	Uncertainty $k = 2$ (Parts in 10^8)
1991	NIST	8	5
1993	Fluke	10	2.5
1995	Fluke	12	3.5
1997	None	15	1.7
1999	LMA	17	2.3
2002	SNL	16	2.4
2005	NIST	17	0.2 – 3.3

Table 2. Selected results of JVS comparisons at 10 V using transfer Zeners in BIPM Key Comparison Data Base (see Appendix for NMI list).

Year	NMI	Uncertainty $k = 2$ (Parts in 10^8)	Country
1998	SPRING	2.2	Singapore
1998	SMU	6.4	Slovakia Republic
1998	NIST	2.8	USA
1999	METAS	2.8	Switzerland
2001	BEV	2.0	Austria
2001	GUM	2.6	Poland
2003	CSIR-NML	6.6	South Africa
2003	NMIA	2.8	Australia

The advantage of using the MAP protocol is that the cost to the participants is minimal, usually just the shipping expense. The drawback of such a comparison is that the uncertainty is in the range of a few parts in 10^8 at 10 V, limited by the characteristics of the transfer Zener standards. The type B uncertainty of a JVS system is normally a few parts in 10^{10} at 10 V. A small system error may not be detected in the comparison using the MAP protocol.

It is a presumption that transfer Zener standards drift linearly during the comparison. The time period of the comparison varies from a few weeks to a few months, depending on how the pivot lab controls the process. The non-linear drift of transfer Zener standards can increase the uncertainty of the comparison. Non-ideal responses of Zener standards to environmental conditions can also affect the results of the comparison. Non-ideal transportability is often the largest component of the uncertainty of the comparison using the MAP protocol.

2.2. JVS Comparison Using Compact JVS

To reduce the uncertainty contribution from the non-ideal behavior of transfer Zener standards, the use of a compact JVS (CJVS) as a transfer standard was introduced in the NCSLI JVS ILC 2002 to link the pivot lab, Sandia National Laboratories (SNL) and NIST [3].

As a further development, NIST implemented its CJVS for comparisons with 5 sub-pivot labs in the NCSLI JVS ILC 2005. The same set of four Zener standards were used as transfer standards during the comparison between each sub-pivot lab's JVS and the CJVS. A low thermal switch system was implemented to change the Zener polarity.

Because the comparison was carried out by measuring the same Zener set in a sub-pivot lab, the environmental effects due to atmospheric pressure, temperature and relative humidity, and the possible shipping impact on the Zeners were largely eliminated. The measurements performed by the two JVS systems were made in an interlaced pattern within a few hours so that the Zener drift during the measurement period was insignificant. The uncertainty of such a comparison is mostly determined by the *1/f* noise floor of the transfer Zeners used in the comparison [4]. Lower *1/f* noise floor corresponds to better comparison uncertainty. Fig. 2 shows the comparison results from the NIST CJVS and a sub-pivot lab JVS during the NCSLI JVS ILC 2005.

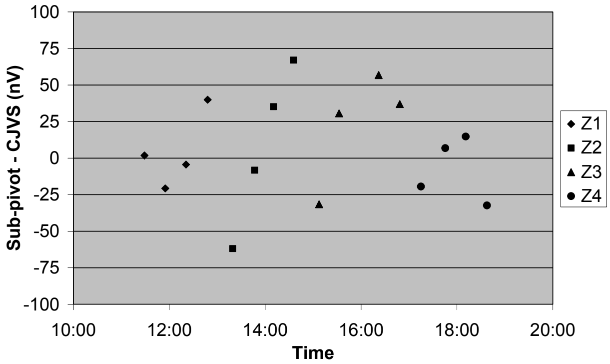

Fig. 2 The differences between a sub-pivot lab JVS and the NIST CJVS for a set of 4 transfer Zeners over a time period of 7 hours.

Table 3 lists the results of the comparisons between the CJVS and the five sub-pivot labs in ILC 2005 compared to the results of ILC 2002. The differences between the CJVS and the sub-pivot labs varied from 3.5 nV to 15 nV with a 95 % confidence uncertainty of 19 nV to 27 nV at 10 V. The uncertainty improvement factor relative to the ILC 2002 varies from 7.6 to 10.8 [5]. The cost of performing a comparison using the CJVS is higher than a comparison using the MAP protocol. Normally, NIST sends the CJVS with staff personnel to perform the measurements at the customer's site. Training the customer to make measurements using the CJVS can reduce the cost of such a comparison in the future.

Table 3. Results of the *in situ* comparison between the CJVS and the sub-pivot labs and the improvement compared to the 2002 JVS intercomparison.

Lab	Date	Lab-CJVS (nV)	Uc (95%) (nV)	Lab-NIST (nV) in 2002	Uc (95%) (nV) in 2002	Factor 2002 / 2005
Sub-1	4/5/2005	4.7	26.8	30.0	206.0	7.7
Sub-2	5/10/2005	7.0	19.0	-41.0	206.0	10.8
Sub-3	6/7/2005	-3.5	26.8	-6.0	205.0	7.6
Sub-4	7/12/2005	-2.4	25.0	-59.0	215.0	8.6
Sub-5	8/16/2005	-15.0	24.5	0.0	205.0	8.4

The initial CJVS comparison with sub-pivot 1 showed a difference of 49 nV with a 95 % uncertainty of 27 nV. This apparent discrepancy was resolved when it was discovered that a leakage correction factor that was previously entered into the software of sub-pivot 1 had a misplaced decimal point. This small error of 5 parts in 10^9 would not have been detected without the improved uncertainty of the CJVS comparison.

2.3. Direct Array Comparison

While the ILC results are a significant improvement, direct comparisons between two Josephson array systems can yield even smaller uncertainties by eliminating any contribution associated with the Zener reference standards. Direct array comparisons using similar nanovolt detectors have achieved uncertainties in the order of 3 nV [6], a ten fold improvement over the indirect comparison using Zener intermediate standards.

In a direct array comparison, two arrays are connected in series opposition polarity through a null detector. The sources of uncertainty in a direct array comparison are frequency stability, frequency measurement, leakage error from the cryoprobe and the null detector. If both arrays are operated correctly, the uncertainty of such a comparison is mainly limited by the noise performance of the null detector. A digital nanovoltmeter is often used in a direct array comparison. The uncertainty of such a comparison is usually a few nanovolts which is equivalent to an uncertainty of a few parts in 10^{10} for a 10 V JVS comparison. An ultra low noise analog null detector can also be used to measure the difference between the two array voltages. The uncertainty using an analog null detector can be lower.

BIPM has pioneered the array-to-array direct comparisons since the early 1990s. The successful development of the Josephson junction array delivering up to 10 V in the mid 1980s was based on the technology of the zero bias current Josephson junction with high intrinsic capacitance shown in Fig. 3. Since all the voltage steps are biased at zero current, the array is intrinsically non-stable. A voltage step can jump to nearby voltage steps during the measurement due to electromagnetic interference in the measurement circuit. The step transition makes a direct array comparison difficult to perform. Only a small portion of the JVS comparisons are carried out directly. Table 4 lists some direct array comparison performed by BIPM in the Key Comparison Data Base BIPM.EM-K10.b.

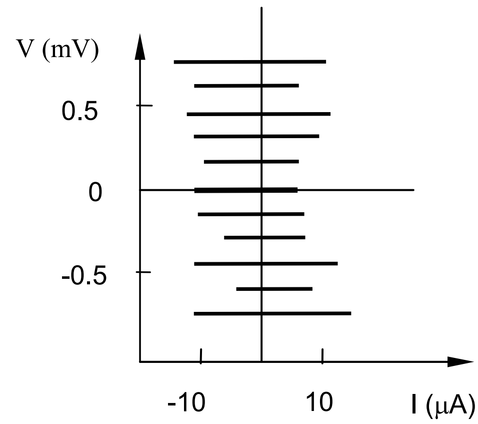

Fig. 3 Voltage steps of zero bias current Josephson junction array.

Fig. 4 shows an example of the bias and measurement circuit for a direct JVS comparison between NRC and NIST [7]. Simultaneous biasing of both arrays is achieved by including a shorting switch in parallel with the nanovoltmeter Agilent 34420A[1] and keeping the array

Table 4. Direct array comparison at 10 V carried out by BIPM (see Appendix for NMI list).

Year	NMI	NMI – BIPM (nV)	Uncertainty $k = 2$ (Parts in 10^{10})	Country
1994	LNE	1.2	2.4	France
1998	PTB	-0.3	1.0	Germany
1998	SP	1.4	2.4	Sweden
1999	SMU	14	22	Slovakia
2004	NPL	-1.5	4.4	United Kingdom
2004	NRC	2.8	6.2	Canada
2005	CEM	0.4	3.0	Spain
2005	NMIJ	-1.2	2.6	Japan
2005	BEV	1.1	7.0	Austria

with its measurement system disconnected from its bias circuitry. With the nanovoltmeter shorted, the NRC JVS system biases both the NRC array and the CJVS array to the same voltage. Open circuiting the NRC bias caused both arrays to jump several steps from the bias voltage (typically ~2 mV) but both arrays remained within one step of each other. Opening the nanovoltmeter switch usually resulted in a jump between the two arrays of one or two steps. A simple manual toggle switch is used as the nanovoltmeter switch but it can be easily automated by either system.

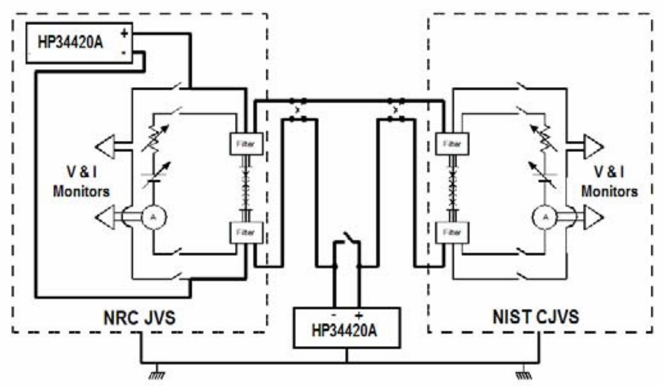

Fig. 4: A simplified schematic of the direct comparison circuit linking the NRC JVS measurement system and the NIST CJVS array.

Note that the nanovoltmeter switch has no thermal emf contributions to the measurements since it is an open circuit and not in the potential measurement loop.

It is important to recognize 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. Unlike Zeners, the polarity of each array can be reversed without using a reversing switch. Reversing switch offset and repeatability is embedded in an indirect comparison using Zeners and can also be evaluated by short circuit measurements.

2.4. Direct Array Comparison using Programmable JVS

A new type array, the Programmable Josephson voltage standard (PJVS), was developed in 1997 at NIST [8]. The PJVS, biased at non-zero current, has distinct voltage values depending on the bias current, as shown in Fig. 5. Unless the bias current changes, the voltage output of a junction is programmed to be stable for an infinitely long time. The programmable array has a superior stability due to its higher current step amplitude (i.e. current margin), as much as 100 times compared to that of the conventional array with zero bias current. This property makes it convenient to perform a direct array comparison between a PJVS and a conventional JVS.

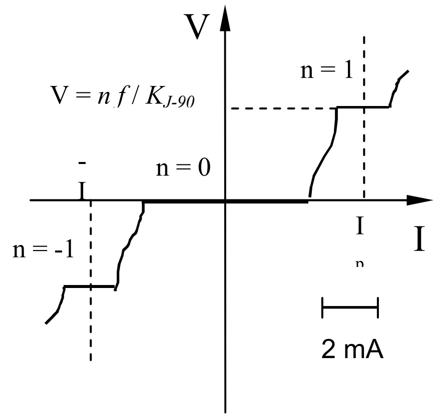

Fig. 5 Programmable Josephson junction array. K_{J-90} is the Josephson constant adopted by the Consultative Committee for Electricity and Magnetism (CCEM) since January 1, 1990.

Two types of programmable arrays were developed in recent years by NIST and PTB. NIST has developed a programmable array based on the Superconductor-Normal metal-Superconductor (SNS) junction working at 16 GHz while PTB has designed a programmable array based on the Superconductor - Insulator - Normal metal – Insulator - Superconductor (SINIS) working at 75 GHz, similar to the frequency used by a conventional array. The voltage generated by the NIST PJVS has been reported to reach 2.6 V [9]. A continuous effort to raise the voltage output to 10 V is in progress.

Fig. 6 shows an example of a direct comparison between NIST10, a conventional 10 V JVS system, and the PJVS at 1.018 V over a 3 week period to monitor the long-term performance of the NIST10 JVS system. The difference between the two systems was found to be 0.5 nV with an expanded uncertainty of 0.58 nV at the 95 % confidence level or a relative uncertainty of 5.6 x 10^{-10}. Fig. 7 is the histogram of all the data points collected during the 3 weeks. The NIST PJVS was also used for making direct comparisons with the CJVS during the NCSLI JVS ILC 2005 before the CJVS was shipped to a sub-pivot lab. The comparisons were carried out at the highest PJVS voltage output of 2.5 V. The typical uncertainty of such a

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

comparison was in the vicinity of 1 x 10^{-9} based on about a dozen measurements.

EUROMET carried out a regional JVS intercomparison at a nominal voltage of 1.09 V using a PJVS designed by PTB [10]. Twelve NMIs and BIPM participated in the intercomparison from September 2003 to May 2004. The uncertainty of the direct comparisons between the PJVS and the participating NMIs was in the range from 5.2 x 10^{-10} to 1.2 x 10^{-8} at the 95 % confidence level.

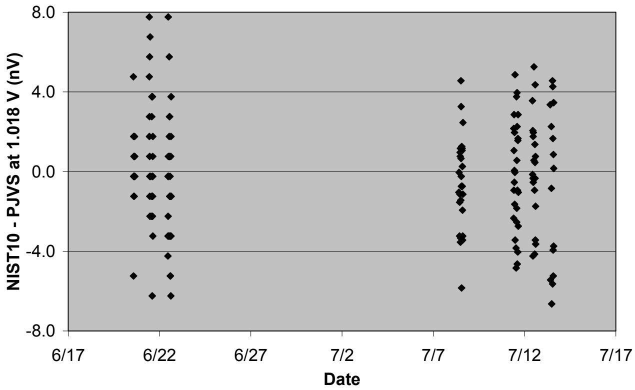

Fig. 6 Results of direct comparison between NIST10, a conventional JVS system, and PJVS at 1.018 V

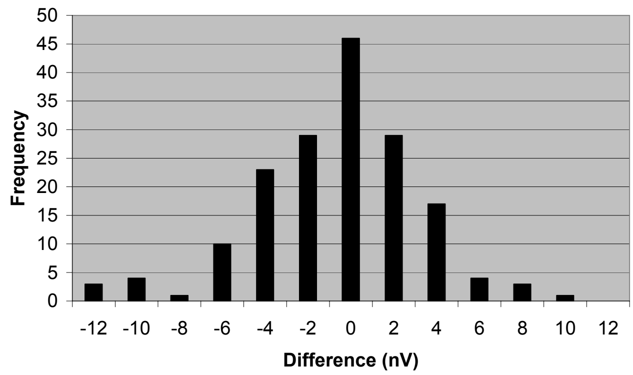

Fig. 7 Histogram based on the data from the direct comparison between NIST10 and PJVS at 1.018 V in Fig. 6.

3. SUMMARY

Since the JVS was established as the primary voltage standard in the late 1980s, different protocols have been developed to make comparisons between JVS systems. The uncertainty of a JVS comparison has been improved over the last two decades. By implementing a CJVS or PJVS, the uncertainty of a JVS comparison can be reduced by an order of magnitude or better compared to a comparison using the MAP protocol as shown in Table 5. The effort to develop a 10 V PJVS is in progress. Using a PJVS working at a higher voltage up to 10 V will enable future JVS comparisons more efficient, convenient, and with lower uncertainties.

Table 5 Summary of different protocols for JVS comparison.

	MAP	CJVS	JVS vs. JVS	JVS vs. PJVS
Voltage range	Up to 10 V	Up to 10 V	Up to 10 V	Up to 2.5 V
Uncertainty	2 x 10^{-8}	2 x 10^{-9}	1 - 7 x 10^{-10}	5 x 10^{-10}
Time needed	Weeks	Days	Hours	Hours
Expense	Low	High	High	Potentially low

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Appendix: List of selected NMIs

	Name	Country
BEV	Bundesamt für Eich-und Vermessungswesen	Austria
CEM	Centro Español de Metrologia	Spain
CSIR-NML	The Council for Scientific and Industrial Research – National Metrology Laboratory	South Africa
GUM	Central Office of Measures	Poland
LNE	Laboratoire National de Métrologie et d'Essais	France
METAS	Swiss Federal Office of Metrology and Accreditation	Switzerland
NIST	National Institute of Standards and Technology	USA
NMIA	National Measurement Institute of Australia	Australia
NMIJ	National Metrology Institute of Japan	Japan
NPL	National Physical Laboratory	United Kingdom
NRC	National Research Council	Canada
PTB	Physikalisch-Technische Bundesanstalt	Germany
SMU	Slovakia Institute of Metrology	Slovakia
SP	Swedish National Testing and Research Institute	Sweden
SPRING	Standards, Productivity and Innovation Board	Singapore