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APPLICATION OF NIST COMPACT JOSEPHSON VOLTAGE STANDARD FOR INTERCOMPARISON[*]

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Abstract

A compact Josephson voltage standard (CJVS) was constructed using a fixed microwave frequency at 76.76 GHz. The transportability of the CJVS enables the accomplishment of an *in-situ* JVS intercomparison. The uncertainty of a traditional JVS intercomparison using the Measurement Assurance Program (MAP) protocol is in the range of a few parts in 10^8 at 10 V; limited by Zener non-linear drift, environmental effects and shipping impact. The uncertainty of a JVS intercomparison can be improved by approximately an order of magnitude by using the CJVS to eliminate the uncertainty factors associated with Zener behavior and shipping. This paper describes the construction of the CJVS, the protocol of a JVS intercomparison using the CJVS, and CJVS application examples.

Index terms

Compact Josephson voltage standard, intercomparison, Josephson voltage standard, microwave, Zener standard, uncertainty

I. Introduction

The Josephson voltage standard (JVS) has been widely used in many national measurement institutes (NMIs) around the world as a primary voltage standard to maintain and disseminate the volt to the end user, such as calibration labs, instrument manufacturers and scientific researchers. 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

$$V_n = nhf/2e \qquad (1)$$

where n, the step number, is an exact integer, e is the electron charge, and h is Planck constant. For the purposes of voltage metrology, $2e/h$ is assigned the value K_{J-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 electronics, and frequency counter. A more detailed explanation of the construction and operation of the JVS system can be found in NCSLI RISP-1 [2]. Any malfunction of these instruments and components can cause an error in the measurement. For example, a 8×10^{-6} 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 common method to verify JVS performance is to carry out JVS intercomparisons between JVS laboratories. There are several protocols used to perform a JVS intercomparison. The Measurement Assurance Program (MAP) is a protocol that is commonly used because of its simplicity and low maintenance cost. The uncertainty of the

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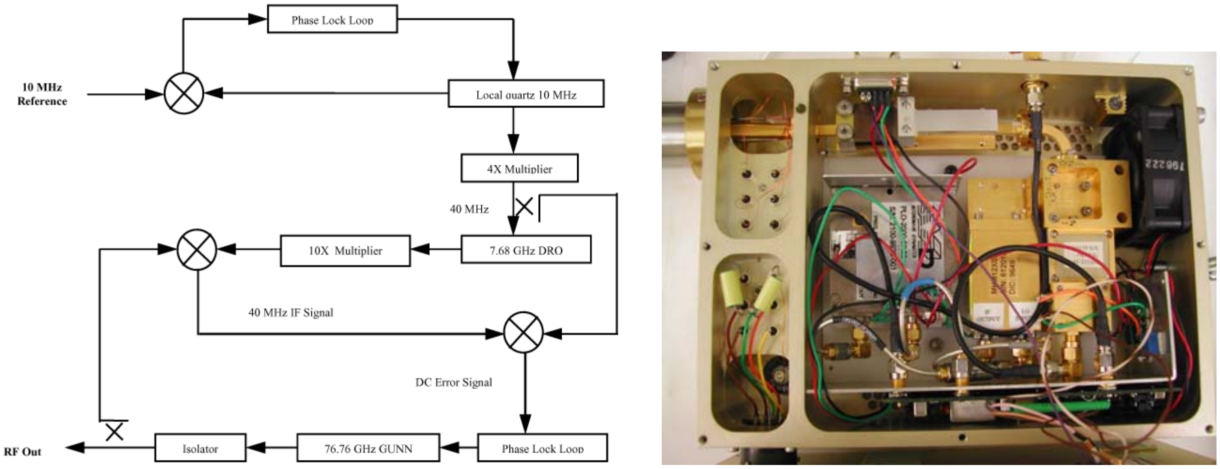
JVS intercomparison using the Zener MAP is limited to a few parts in 10^8 due to the characteristics exhibited by transported Zener standards, Some of these characteristics include environmental effects, the non-linear drift during the comparison period, and shipping effects. The uncertainty budget of a JVS is usually in a range of a few parts in 10^9 or better. It is difficult to detect errors of less than a few parts in 10^8 by relying on the measurements of Zener standards because the errors can be smaller than the short-term variation of the Zener standards. In order to improve the uncertainty of the JVS intercomparison using the Zener MAP, NIST has developed a compact JVS which can be conveniently transported. A protocol for using the NIST CJVS in the JVS intercomparison has been developed and used in several JVS intercomparisons conducted with the National Conference of Standard Laboratories International (NCSLI) and Sistema Interamericano de Metrologia (SIM). The uncertainty of the JVS intercomparison using the NIST CJVS is in the range of a few parts in 10^9, about an order of magnitude of improvement compared to the uncertainty using the Zener MAP protocol. The CJVS is capable of detecting small system errors of a few parts in 10^9, that otherwise would have not been detected in the Zener MAP.

II. Construction of the CJVS

The conventional laboratory JVS is built by integrating several instruments (such as digital voltmeter (DVM), bias electronics, frequency counter and scanner etc.), microwave components and cryogenic components together. It is difficult to ship the JVS to another location for an intercomparison. The CJVS includes four major components: cryoprobe, bias electronics, low noise DVM and a laptop computer to control the measurement. The system weighs approximate 20 kg. It can be easily shipped in two cases and set up in a remote location within an hour.

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 frequency counter, thereby reducing the weight of the system. This makes the system compact and transportable. Fig.1 shows the 76.76 GHz microwave assembly. A local 10 MHz quartz oscillator is phase-locked to a 10 MHz frequency reference from a Global Positioning System (GPS) or Cesium clock. A quadrupler generates a 40 MHz frequency from the 10 MHz signal. Inside the cryoprobe, the 40 MHz



(a) (b)

Fig.1 (a) Block diagram of a 76.76 GHz source for Josephson array operation;
(b) 76.76 GHz microwave assembly built-in cryoprobe.

signal is supplied as a reference to a Dielectric Resonance Oscillator (DRO) with an internal phase-lock loop (PLL) circuit. The DRO operates at 7.68 GHz. Its tenth harmonic 76.8 GHz is mixed with the 76.76 GUNN Oscillator, creating a 40 MHz intermediate frequency (IF). This 40 MHZ IF output is appropriately amplified and mixed with the original 40 MHz quartz signal to provide a dc error signal. The error signal is provided to the GUNN tuning to generate a phase-locked stable microwave frequency at 76.76 GHz for the Josephson array operation. The uncertainty of the fixed frequency 76.76 GHz is determined by the 10 MHz frequency reference in the range of a few parts in 10^{12} or better. Commercial bias electronics and software developed at NIST controls the measurement process.

III. CJVS Intercomparison Protocol

In the JVS intercomparison using the MAP protocol, a set of Zener standards is shipped between two JVS laboratories. The Zeners are measured by the JVS system in the laboratory. The process of making a bilateral comparison usually takes 3 to 4 weeks. When a JVS intercomparison is carried out using the NIST CJVS, the CJVS is shipped to the customer's laboratory, a set of Zener standards are measured *in situ* by the JVS and CJVS systems at the customer's laboratory. The process takes one or two days. Fig. 2 is the set up for a JVS intercomparison using the NIST CJVS.

In preparation for comparisons using the CJVS, a low thermal emf switch box was designed and built for switching between the JVS and CJVS systems. The low thermal emf switch box selects the different transfer Zener standards and polarities without introducing excessive uncertainty due to contact thermal emf and other thermal voltages. The difference between the short measurements from switching the JVS systems is less than 5 nV. The variation and repeatability of the short measurements among all the channels and polarities is less than 10 nV. The settling time for the transient thermal voltages to diminish to a negligible level is approximately 10 s to 15 s when switching channels or polarities.

The protocol for a comparison sequence is as follows: For Zener Z1, the measurement sequence was NIST (Z1+), LAB (Z1+), LAB (Z1-), NIST (Z1-). Utilizing JVS system measurement procedure, the leads connecting the JVS to the Zener standard are reversed at the Zener standard after each measurement to minimize offsets due to thermal voltages in the leads. The Z1+ and Z1- symbols indicate normal and reversed lead connections respectively. This protocol was selected to minimize the effect of Zener drift during the comparison sequence. The time for a comparison sequence was 15 min to 20 minutes and produced two pairs of plus and minus measurements, one pair for each system. The absolute values of each pair of plus and minus measurements were averaged to eliminate the effect of constant thermals emfs. These averages were then subtracted resulting in one voltage difference between the two systems. For the next measurement sequence, which could utilize the same, or a different Zener, the position of the NIST CJVS and LAB JVS in the sequence is interchanged as shown in Table 1. For these comparisons, the environmental conditions of the Zener standards were essentially identical for the CJVS and laboratory JVS systems. Since no significant changes in pressure, temperature, and humidity would occur in such a short time, no corrections for these environmental effects were required. Use of the CJVS in the JVS intercomparison resulted in a significant reduction in the uncertainty of the comparison [3].

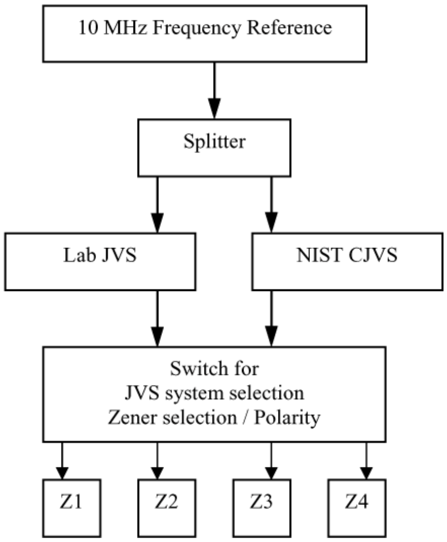


Fig. 2 A set up for JVS intercomparison using NIST CJVS.

Table 1 Measurement sequence for each Zener (selected using the switch box), the JVS (NIST or customer laboratory), and polarities (+ or -).

NIST (Z1+)	Lab (Z1+)	Lab (Z1-)	NIST (Z1-)
Lab (Z1+)	NIST (Z1+)	NIST (Z1-)	Lab (Z1-)

The difference D between a customer laboratory and the NIST CJVS is computed as the mean of the N differences of the paired measurements:

$$D = \frac{1}{N}\sum_{i=1}^{N}(V_{ith\ paired}^{Lab} - V_{ith\ paired}^{NIST-CJVS}) \qquad (2)$$

where $V_{ith\ paired}^{Lab}$ is the average of a normal and reverse measurement of a Zener standard by the customer laboratory. The expanded uncertainty U_c of the comparison at 95 % confidence can be calculated as

$$U_{\mathrm{c}} = t_{95}(\nu)\sqrt{\frac{1}{(N-1)}\sum_{i=1}^{N}\{(V_{ith\ paired}^{Lab} - V_{ith\ paired}^{NIST-CJVS}) - D\}^2} \qquad (3)$$

where $t_{95}(\nu)$ is the t-distribution factor for degrees of freedom ν at 95 % confidence.

IV. Results of CJVS Intercomparison

The NIST CJVS has been used in the NCSLI JVS Intercomparison (ILC) 2005. Table 2 lists the results of the comparisons between the CJVS and the five sub-pivot laboratories in the ILC 2005 and the corresponding results of ILC 2002 [4, 5]. For all of the five NIST CJVS – sub-pivot laboratory comparisons, four transfer Zener standards were used with 16 pairs of measurements from each JVS system. The same four Zener standards were used as transfer standards in the NCSL JVS ILC 2002 using the Zener MAP protocol. The differences between the CJVS and the sub-pivot laboratories 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 ILC 2002 varies from 7.6 to 10.8.

The initial comparison between the sub-pivot laboratory 1 and the NIST CJVS 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 laboratory 1 had a misplaced decimal point. This resulted in a computation error of −54 nV. After correcting the leakage adjustment, the difference between sub-pivot laboratory 1 and the NIST CJVS was 5 nV with an unchanged uncertainty of 27 nV. This small error of 5 parts in 10^9 would not have been detected without the improved uncertainty accomplished with the use of the CJVS.

In March 2006, Centro Nacional de Metrología (CENAM) of Mexico and NIST conducted a bilateral JVS comparison using the NIST CJVS. The uncertainty of the 24 pairs of Zener measurements was 42 nV at the 95 % level of confidence or a relative uncertainty of 4.2 X 10^{-9}. Fig. 3 shows that the differences between the NIST and CENAM measurements were all less than 300 nV. This is a factor of 9.7 improvement compared to the uncertainty that CENAM achieved in the NCSLI JVS ILC 1999, the last intercomparison that CENAM had participated in.

Table 2 Results of the *in-situ* comparison between the CJVS and the sub-pivot laboratories and the improvement compared to the 2002 JVS intercomparison using the Zener MAP.

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

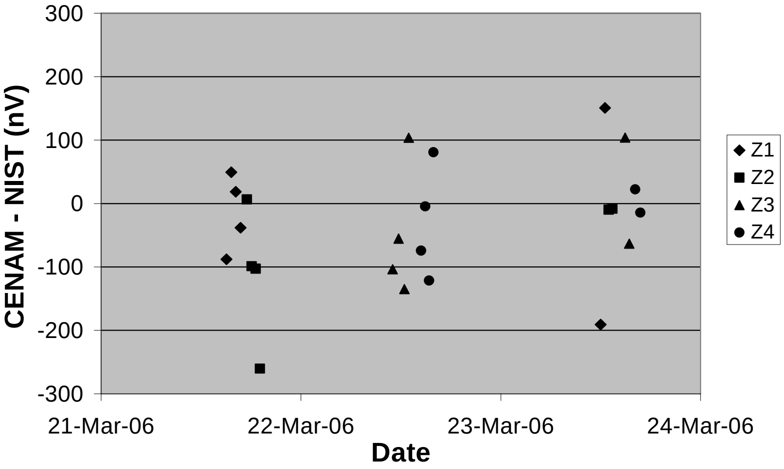


Fig. 3 Differences between the NIST and CENAM measurements for the four Zeners: Z1, Z2, Z3, and Z4.

V. Summary

The use of the CJVS for the JVS intercomparison has improved the uncertainty by about an order of magnitude to a few parts in 10^9 compared to the uncertainty of the JVS intercomparison using the Zener MAP protocol. Because the comparison is made *in-situ*, uncertainty from transportation effects, non-linear drift, and environmental effects is largely eliminated. Small system errors of a few parts in 10^9 can be detected and corrected with the use of a CJVS in an intercomparison.

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