Josephson Voltage Standard Comparison Automation

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***Abstract* - To ensure the uniformity of the representation of the volt based on K_{J-90}, a series of key comparisons have been carried out by the Bureau International des Poids et Mesures (BIPM) under the auspices of the Consultative Committee for Electricity and Magnetism (CCEM) using the BIPM.EM.K10 Technical Protocols Option A and Option B for the Josephson Voltage Standards (JVS) operated by National Metrology Institutes (NMI) around the world. These JVS comparisons are manually operated. Comparisons of this type can also be performed using the automatic protocol that was developed recently. The automatic protocol improves the comparison through the modification of the bias electronics and automation. This paper will present the principal for the automation and its practical realization. Examples detailing the actual usage of the automatic protocol by the Key Comparison, Regional Metrology Organization (RMO), and the National Conference of Standards Laboratories International (NCSLI) will also be presented. The uncertainty of the JVS comparison using the automatic protocol is comparable with that listed in the Key Comparison Data Base (KCDB).**

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I. INTRODUCTION

In the BIPM.EM-K10 Technical Protocol Option B, the BIPM provides a reference voltage that has to be measured by the "laboratory" using its Josephson standard with its own measuring device. Vice versa, in the BIPM.EM-K10 Technical Protocol Option A, the BIPM JVS measures a reference voltage that is generated by the laboratory's JVS. In either case, a step jump in a Josephson junction array can occur during the data acquisition process, and subsequently the reference voltage must be manually adjusted back to the original value by the operator in order to continue the measurement process [1].

The voltage generated by a JVS is based on the Josephson effect via the Josephson constant K_{J-90}. The critical quantity δ, that is used to examine the uniformity between the two JVSs, is the deviation of the measured difference between the two voltages generated by the JVSs V_{meas} from the theoretical difference V_{theo} [2].

$$\delta = V_{meas} - V_{theo} \qquad (1)$$

The automatic protocol allows both arrays to change steps during the comparison and uses a single bias source to generate the two JVSs' voltages within established criteria for the comparison. This paper describes the principle of the automatic protocol. Several examples using the automatic protocol in a JVS comparison are presented. The issue related to accumulation of a large amount of data points using the automatic protocol is also discussed. A similar approach was used in [3].

II. JVS COMPARISON AUTOMATION

The manual operation of the BIPM.EM-K10 protocols is necessary because of the strict requirement for a fixed reference voltage for a JVS comparison. In order to accomplish the comparison automation, we need to loosen this requirement by allowing both array voltages to change their voltages as long as the two voltages meet the following conditions:

$$|V_{a1} - V_{nom}| < 10\ mV \qquad (2)$$

$$|V_{DVM2}| = \ < 1\ mV \qquad (3)$$

where V_{a1} is the JVS1 array voltage, V_{nom}, with 10 V as the nominal voltage for the comparison and V_{DVM2} is the DVM2 reading of the voltage difference between V_{a1} and V_{a2}, the JVS2 array voltage, in addition to other components in the measurement loop, such as thermal voltages as shown in Fig.1. The automatic protocol uses a single bias source to generate the two arrays voltages that are close to the nominal voltage. Simultaneous biasing of both arrays is achieved by the insertion of a shorting switch in parallel with the null detector, a digital nanovoltmeter DVM2. A digital voltmeter DVM1 is always connected to the array1. Both DVM1 and DVM2 used by the NIST Compact JVS are Agilent 34420A*. The DVM1 monitors the voltage of array1 and determines if it meets the range condition defined in Eq. (2). With the DVM2 shorted by a shorting switch, the JVS1 bias system biases the JVS1 array and the JVS2 array voltages close to the nominal voltage. Once the conditions shown in Eq. (2) and Eq. (3) are met, the JVS1 bias source can then be disconnected from the two arrays and the shorting switch opened. The data acquisition then starts. If the voltage of the JVS1 array deviates by an amount that is beyond the

* 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.

defined nominal voltage range or the difference between the two arrays becomes larger than 1 mV, the two arrays will be rebiased and the process is repeated as described above. The voltage difference between the two arrays is always controlled within 1 mV so that the measurement can be performed with the 1 mV range of the nanovoltmeter to avoid any change in gain and linearity when the DVM2 range changes from 1 mV to 10 mV. The operation of the bias and shorting switch can now be controlled automatically by software.

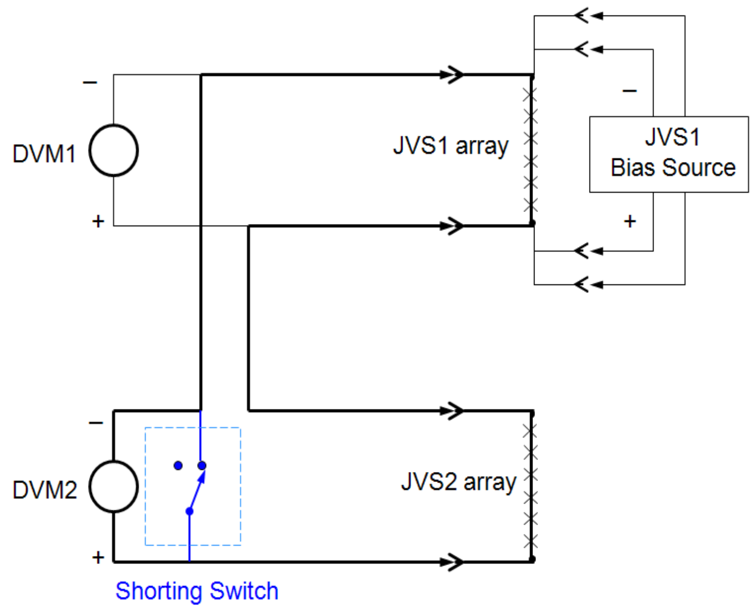

Fig.1. The setup using a single source to bias two arrays. A shorting switch for the DVM2 controlled by software makes the automatic process possible.

III. EXAMPLES OF AUTOMATIC PROTOCOL FOR JVS COMPARISONS

In March 2009, BIPM carried out a key comparison with NIST using both BIPM.EM-K10 Technical Protocols Option A and Option B. BIPM shipped its JVS system to NIST, Gaithersburg, MD, and it was compared to the NIST Compact JVS [4]. The NIST compct JVS used a fixed frequency either at 76.76 GHz or 76.84 GHz, while the BIPM JVS used several frequencies near the frequency used by the NIST Compact JVS. The automatic protocol was also tested during the week-long exercise that lasted from March 21 to March 25, 2009. Table 1 summarizes the comparison using the three protocols. The results do not show a statistically significant difference in the comparison uncertainties and demonstrate the validity of the automatic protocol for the JVS comparison. Another improvement accomplished by the automatic protocol involved the reduction of the total man-hours (defined by the number of operators multiplied by the hours necessary for the data acquisition and the hardware adjustments) from the time required by the BIPM Protocols Option A and Option B.

Table I. NIST-BIPM direct JVS comparison (BIPM.EM-K10.b) using three different protocols

	BIPM Option A Protocol	BIPM Option B Protocol	NIST Automatic Protocol
Difference (nV)	–1.53	–0.07	1.07
Type A (nV)	0.75	0.68	0.75
Type B (nV)	0.77	0.93	1.08
Combined uncertainty (nV)	1.07	1.15	1.31
Number of measurements	22	37	50
Total man-hours	5	12	0.5

Two comparisons between the NIST Compact JVS and the Instituto Nacional de Metrologia, Normalização e Qualidade Industrial (Inmetro) JVS, Brazil, were carried out in June 2009 as SIM.EM.BIPM-K10.b.1, first using the NIST Compact JVS to measure the 10 V against the Inmetro JVS and then using the Inmetro JVS to measure the 10 V against the NIST Compact JVS [5]. The automatic data acquisition used for the comparisons significantly improved the efficiency and reduced the intensive labor required by a manual operation. The results of the two comparisons were in agreement to within 1.1 nV and their mean indicated that the difference between the two JVSs at 10 V was 0.54 nV with a total combined standard uncertainty of 1.48 nV. A link between Inmetro and BIPM was established via an earlier key comparison between NIST and BIPM to be 0.26 nV with a standard uncertainty of 1.76 nV.

The automatic protocol was also used for a JVS comparison between NIST and Sandia National Laboratories (SNL), Albuquerque, NM, in December 2010. In this JVS comparison, the difference between the NIST Compact JVS and the SNL JVS was found to be -2.0 nV at 10 V with a standard uncertainty of 1.44 x 10^{-10}. More than one hundred data points were collected over a 12 hour time period. This large number of data points enabled the investigation and the evaluation of the impact of the filter network on the comparison measurements. It was found that the polarization of the dielectric material of the capacitor used in the SNL cryoprobe filter could affect the measurements. The difference between the two JVSs was reduced from -6 nV to -2 nV by extending the waiting period for the capacitor to recover from polarization to equilibrium. SNL is the pivot lab for the upcoming National Conference of Standard Laboratories International (NCSLI) 9th JVS Interlaboratory Comparison (ILC) that begins in March 2011. There will be a total of 13 labs from major US industries and national laboratories that will participate in the JVS ILC 2011. The results of the NCSLI JVS ILC will allow its participants to establish a voltage measurement link to NIST via the pivot lab SNL.

In the JVS comparison using the automatic protocol, a large number of data points can be collected in a relatively short time (several hours). This can provide the opportunity for research, such as the evaluation of the limit of the Type A uncertainty, the investigation of the DVM polarity offset, and the impact of the filter network on the comparison measurements. Some of the results of these investigations have been detailed in several publications [6-7].

IV. CONCLUSION

The automation protocol for the JVS comparison was developed using a single bias source to measure the difference between two JVSs voltages at a nominal value to determine the deviation from the theoretical difference. This procedure can be used for key or regional JVS comparisons to obtain the same level of uncertainty as those by the BIPM.EM-K10 Technical Protocol Option A or Option B. Because the automatic data acquisition feature of the automatic protocol is able to acquire a large number of data points in a relatively short time period, this protocol can be used to study issues that have been observed in JVS comparisons, such as the DVM polarity offset, the impact of 1/f noise floor on the Type A uncertainty limit, and the effect of the capacitor in the filter network on the comparison results.

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