A 10 V Josephson Voltage Standard Comparison Between NIST and INMETRO as a Link to BIPM

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***Abstract*—This paper describes a 10 V Josephson Voltage Standard (JVS) direct comparison between the National Institute of Standards and Technology (NIST) and the Instituto Nacional de Metrologia, Normalização e Qualidade Industrial (INMETRO) using automatic data acquisition. The results were in agreement to within 1.1 nV and the mean difference between the two JVSs at 10 V is 0.54 nV with a pooled combined standard uncertainty of 1.48 nV. Considering a recent JVS comparison between NIST and the Bureau International des Poids et Mesures (BIPM), the difference between INMETRO and the BIPM thus was found to be -0.26 nV with a standard uncertainty of 1.76 nV. INMETRO JVS improvements since the 2006 INMETRO-BIPM comparison are also described.**

***Index Terms*—Automation, interlaboratory comparison, Josephson arrays, Josephson Voltage Standard (JVS), uncertainty.**

I. INTRODUCTION

THE Instituto Nacional de Metrologia Normalização e Qualidade Industrial (INMETRO) and the Bureau International des Poids et Mesures (BIPM) Josephson voltage standards (JVSs) were directly compared at 10 V in 2006 [1]. The difference between the two systems was found to be 19 nV with a standard uncertainty of 16 nV. Although the INMETRO JVS system was suitable for Zener measurements, the accuracy was not satisfactory for a JVS system. After some improvements in the INMETRO JVS system, a comparison between the INMETRO JVS and the National Institute of Standards and Technology (NIST) Compact JVS (CJVS) was performed in June 2009 [2]. In addition to checking the INMETRO JVS, this comparison allowed the establishment of a link between INMETRO and the BIPM, due to a previous comparison between NIST and the BIPM JVSs [3]. The process consisted of two comparisons, the first using the NIST CJVS to measure the 10 V reference provided by the INMETRO JVS and the second using the INMETRO JVS to measure the 10 V reference voltage provided by the NIST CJVS. Both comparisons used the NISTVolt software for data acquisition. A few topics related to this comparison were discussed in the 2010 Conference on Precision Electromagnetic Measurements (CPEM) paper [4]. This paper describes the INMETRO JVS improvements, the protocol used for the comparisons, and the results of the two comparisons.

II. INMETRO JVS IMPROVEMENTS[1]

A. 10 MHz Reference

Up until 2008, the INMETRO JVS 10 MHz reference was provided by a HP 58503A GPS. When it was locked on one or more satellites, the frequency accuracy was better than 1×10^{-12} Hz/Hz for a 1-day average, with an Allan deviation of 5×10^{-11} for 100 s averaging. A typical 75 GHz microwave frequency subsystem of a JVS requires a frequency accuracy of at least 1.3×10^{-10} Hz/Hz.

In June 2009, INMETRO started using a 10 MHz reference (1 V RMS @ 50 Ω) from a Symmetricom 5071A cesium atomic clock (high-performance option) with frequency accuracy of $\pm 2 \times 10^{-13}$ Hz/Hz and an Allan deviation of less than 8.5×10^{-13} for 100 s averaging. The cesium atomic clock and the JVS are located in different labs. A 70 m low-loss 50 Ω coax cable (4.9 dB/100 m attenuation @ 10 MHz) was used to connect the cesium clock to the JVS. Since the cable can be an antenna, a passive choke was used to filter the undesirable signals. The JVS counter is an EIP 578B, which requires a 1 V peak-to-peak (minimum, @ 300 Ω) 10 MHz reference signal. For this reason, a 50–300 Ω impedance matching transformer was used. The 10 MHz signal measured at the counter input is a 3 V peak-to-peak sinusoid.

In order to check the effect of the coax cable on the 10 MHz signal accuracy, we compared the cesium atomic clock signal to a Symmetricom 8040CLN rubidium clock using an Agilent 53132A counter. The rubidium clock was disciplined to the cesium clock and their 10 MHz signals were directly compared to each other. After that, the rubidium clock and the 10 MHz signal provided by the cesium clock through the coax cable were compared to each other. Finally, the rubidium clock and the cesium clock 10 MHz signals were directly compared to each other again (just in case there is any drift effect). The error between those two situations was found to be of $(-40 \pm 86) \times 10^{-13}$ Hz/Hz $(k = 2)$, which is negligible for our purposes. This constant negative frequency error seems to

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

be related to the counter limitations rather than a physical effect. The uncertainty analysis was done according to [5]–[7].

B. Microwave Source

The microwave source is a Millitech Gunn oscillator. The microwave frequency of the Gunn oscillator is measured by a counter (EIP 578B). This counter generates a signal used by the Gunn oscillator bias source (VMetrix GS1002) to modulate the Gunn oscillator bias voltage, composing a phase-lock feedback loop for the frequency stabilization. The frequency is locked around 75 GHz and the fluctuations should be less than 10 Hz (it typically fluctuates less than ±1 Hz in a 1 s averaging time) [8]. When there is any problem in this loop control, the frequency can change beyond ±10 Hz. At the beginning of 2006, the INMETRO JVS experienced a sporadic instability in the microwave frequency when the frequency changed more than ±10 Hz. Unfortunately, the frequency instability became more frequent, showing an increasing degradation in the frequency control loop. After several tests and adjustments in every component of the frequency control loop (counter, Gunn oscillator, and its bias source), the problem was concluded to be caused by the Gunn oscillator, which was replaced in September 2008.

It is recommended that the Gunn oscillator bias voltage be adjusted 1 V lower than the specified voltage [8]. The bias voltage of INMETRO's old Gunn oscillator was set previously at its specified value (9.7 V). This limited the frequency control loop excursion, since there was no room for the modulation input to increase the Gunn oscillator bias voltage without reaching the voltage limit. In addition, the temperature condition of the old Gunn oscillator when it was running was slightly warm, and this condition may have reduced its life time. The bias voltage of the new Gunn oscillator was adjusted correctly, according to [8].

C. Josephson Junction Array (Chip)

After cooling down the Josephson junction array, one can check if it is working properly by analyzing its I–V curve. With the microwaves turned off, it is possible to check if the array minimum critical current is normal. With the microwaves on, it is possible to check if the voltage steps are stable [8]. The INMETRO JVS array sometimes exhibited low critical current. After a few warm-up and cool-down cycles, the array minimum critical current reached its normal value (around 95 μA). The INMETRO JVS array also sometimes produced unstable voltage steps which lead to an abnormal amount of step jumps (more than 20) during a Zener calibration. This problem was solved by adjusting the microwave power (sometimes by choosing another locking frequency). This is a common situation observed during normal JVS operation.

The occurrences of the problems described above, however, became more frequent, until the I–V curve (with the microwave on) showed no voltage steps. After a visual inspection of the array surface, it was noticed that the surface was dirty with water marks. Normal annual operation cycle of the INMETRO JVS is from February to November. Many cool-down and warm-up cycles are necessary, not only during the JVS start-up, but also during the Dewar exchanges. Water may have condensed onto the chip surface when the chip was exposed to air during the warm-up process, and after the water had evaporated, water marks were left on the surface. If those dirty spots are located on the chip contacts, a resistive effect can be established in any of the chip circuits (microwave, bias, voltage monitoring, or voltage generation) and cause a chip malfunction.

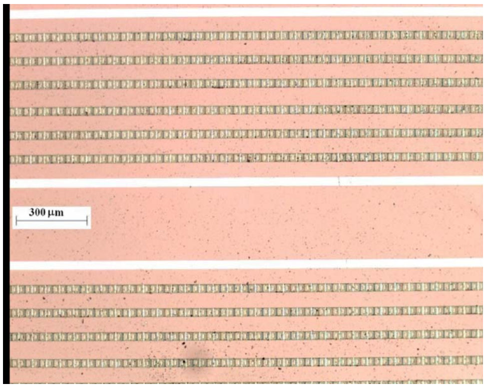

Fig. 1. Chip surface after cleaning (50× magnification).

The array chip can be cleaned inside or outside the chip holder. Although cleaning it inside the holder is safer (there is less risk of damaging the chip), some areas can be difficult to reach. Since the chip surface is not protected, the cleaning process must be done very carefully to avoid damaging any junctions (or the chip). The preference is to clean it outside the chip holder, following these steps:

1) Blow the chip surface with helium gas (to remove the largest dust particles);
2) Stream dehydrated alcohol (95% alcohol at the minimum) onto the chip surface;
3) Clean carefully the chip surface using a Q-TIP cotton swab (saturated with dehydrated alcohol);
4) Blow the chip surface with helium gas;
5) Make a visual inspection. If the array chip's condition is still dirty, repeat steps 1 to 4.

It is recommended that the chip be cleaned with its position slightly inclined, to avoid the dust remaining on the chip surface.

The chip holder spring finger contacts were also cleaned. Fig. 1 shows the chip surface and Fig. 2 shows the array I–V curve (with the microwave on @ 75 GHz) after cleaning the chip. 5 μA/div vertical shows about 30 μA steps, spanning in 70 mV, at least (Fig. 2). On the other hand, about 20 μA steps spanning in 10 mV (at most) was got before cleaning the chip.

III. COMPARISON EQUIPMENT

A. INMETRO JVS

The INMETRO JVS is routinely used to calibrate Zener diode-based standards, and it is designed to run in a fully automatic manner once the operator has adjusted the array parameters (microwave frequency and power level). INMETRO's

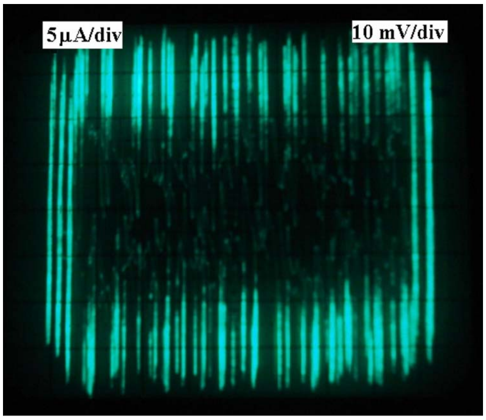

Fig. 2. Voltage steps after cleaning the chip. Expanded set of steps near 10 V. 10 mV/div horizontal, ac coupled. Origin at 10 V. 5 μA/div vertical, dc coupled.

working standards and some customer standards are directly measured against the primary standard, thereby significantly simplifying the traceability chain. A Hypres 10 V Josephson chip (superconductor–insulator–superconductor junction array) is mounted onto the lower WR-12 flange of a tube waveguide, inside a magnetic shield at the bottom of the cryoprobe (model CP-525, made by High Precision Devices).

Each of the six lines that connect to the Josephson chip passes through a low-pass filter network in the box at the top of the cryoprobe. This multiple-stage radio frequency interference (RFI) filter is built to intercept frequencies below 100 MHz and to block higher frequencies. The filter uses three stages of discrete components with successive cutoff frequencies of 1.6 MHz, 160 kHz, and 0.5 kHz. Frequencies above 100 MHz are blocked by lossy transmission lines created by pressing conductive foam against a meander line on the printed circuit board. The foam also attenuates RFI that may be transmitted through the air between the input and output sides of the box enclosing the filter.

The array is biased by a programmable current source. The RF source is a Millitech Gunn oscillator with a central frequency at 75 GHz and a ±1 GHz mechanical tuning range. The microwave frequency is locked by an EIP-578B frequency counter. This JVS system was assembled in 2007 and has been operational since its deployment. Only the 10 V array and the cryoprobe have been retained from the previous INMETRO JVS DOS-based system (which was used in the BIPM.EM-K10.b [1]). Step biasing, array monitoring, and the connection of the Zener under test are operated automatically by software. The bias source is disconnected during the measurements and the array is floating with respect to ground, which means that the measurement ground reference point can be chosen arbitrarily. The voltage from the detector (HP 3458A) and the frequency from the EIP counter are monitored and stored in an electronic file. The GPIB interface for reading/controlling the measurement instruments is optically isolated from the computer, which is 5 m away from the JVS (greatly reducing any conducted or radiated electromagnetic interference from the computer). The 10 MHz reference signal for the EIP counter, distributed by a Symmetricon 5071A cesium atomic clock, is also electrically isolated. During the comparison, the cesium atomic clock was located in the same room where the comparison was performed (since at that time, we did not know the effect of the coax cable on the 10 MHz signal accuracy). An analog oscilloscope is used to visualize the array I–V characteristics and adjust the RF power level at the beginning of the operation (during the measurements, the array is disconnected from this instrument). The laboratory temperature was regulated to better than $\pm 0.8\ ^{\circ}$C over the week when the measurements were conducted. This minimizes the thermal voltages and ensures good voltage stability during the measurements. The room temperature and humidity are measured and recorded during the measurements by the software through external sensors. The system is powered by a dedicated uninterrupted power supply through an isolation transformer.

B. NIST CJVS

The CJVS, constructed at NIST, uses a fixed microwave frequency of either 76.76 GHz or 76.84 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. More details about the NIST CJVS are presented in [2] and [9]. The 10 MHz reference signal for 76.76 GHz or 76.84 GHz generation was supplied by the same Symmetricon 5071A cesium atomic clock used by the INMETRO JVS.

IV. MEASUREMENT PROTOCOL AND COMPARISON SETUP

The protocol for this comparison was first used in a JVS comparison between the NIST and the National Research Council, Canada that is described in [9] and is briefly summarized here. A JVS direct comparison is made by connecting two arrays in series opposition and measuring the difference voltage V_d with a sensitive digital voltmeter (DVM) such that

$$V_d = V_{a1} - V_{a2} = \frac{N_1.f_1 - N_2.f_2}{K_{J-90}} \tag{1}$$

where V_{a1} is the voltage, N_1 is the step number, and f_1 is the microwave frequency related to the JVS1 array, K_{J-90} is the Josephson constant, and the remaining variables are related to the JVS2 array.

The purpose of a direct JVS comparison is to measure the quantity δ, by which the measured difference voltage V_m deviates from its theoretical value V_d. Considering that: $V_o + mt$ 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 for effects such as DVM nonlinearity and nonlinear thermal emf drift); and E_g is the gain error of the voltmeter, one can get:

$$\delta = V_d - \frac{V_m}{1 + E_g} - V_o - m.t - V_n. \tag{2}$$

The unknowns in (2) are V_o, m, and δ. Their best estimates can be computed by taking sets of measurements with two or

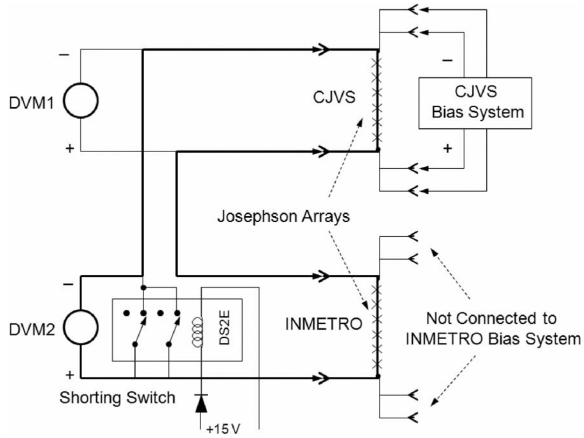

Fig. 3. Setup using the NIST CJVS to bias both JVS arrays.

more polarity reversals using a three-parameter least square fit that minimizes the root sum square (RSS) of the residuals $R(i)$ in (2) where:

$$R(i) = V_d(i) - \frac{V_m(i)}{1+E_g} - V_o - m.t(i) - \delta. \tag{3}$$

This comparison involved both JVSs systems, using the INMETRO JVS to measure the voltage reference provided by the traveling NIST CJVS and using the NIST CJVS to measure the voltage reference provided by the INMETRO JVS.

Simultaneous biasing of both arrays was achieved by the insertion of a shorting switch in parallel with the nanovoltmeter. The data acquisition consists of three steps as shown in Fig. 3. First, the DVM2 shorting switch is closed and the CJVS bias source is connected to both arrays at the nominal voltage of 10 V. Second, the bias is disconnected from the arrays. The third step opens the shorting switch of DVM2 so that the difference between the two arrays can be measured by the DVM2. All operations for the DVM2 shorting switch and bias source are controlled by the automatic measurement software. The data acquisition starts when the following two conditions are met:

1) The CJVS array is within 5 mV of the nominal target voltage;
2) The voltage difference between the two arrays is within 7 voltage steps.

The data acquisition follows the $+ - + -$ measurement sequence where $+$ represents both arrays biased positively (normal), and $-$ represents both arrays biased negatively (reversed). There are no mechanical switches in the measurement loop, thereby avoiding switch thermal voltages. The polarity change of the arrays was accomplished electronically by the bias source.

V. MEASUREMENT RESULTS AND UNCERTAINTY

A. *Measurement Information*

The NISTVolt software was used for the data acquisition and calculation of the difference between the two JVS systems. The difference between the two arrays was always controlled within seven steps so that the DVM was always on the 1 mV range.

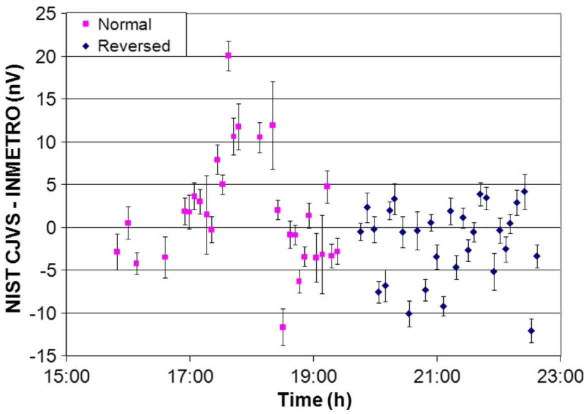

Fig. 4. Differences between the measured value and the theoretical value of the NIST CJVS—INMETRO JVS. The bars show the Type-A standard uncertainty only.

The frequency of the CJVS was fixed at 76.76 GHz and the frequency of the INMETRO JVS was 75.991 GHz. 58 points were taken using the NIST CJVS to measure the INMETRO JVS and 40 points were taken using the INMETRO JVS to measure the NIST CJVS. Half of those points were taken using the DVM in the normal polarity mode and the other half using the DVM in the reversed polarity mode. Each point was calculated from four sets of DVM measurements with array polarity $+ - + -$. Each set consisted of 15 DVM readings. The average time to finish a comparison measurement point was from 6 to 9 min. There were no corrections made to compensate for the cryoprobe leakage; rather, the leakage errors were taken into account as a Type-B uncertainty.

The difference between the two JVSs made by either JVS is the mean of the two data sets with normal DVM polarity and reversed DVM polarity modes:

$$D_{LAB} = \frac{\dfrac{\sum\limits_i D_i^{LAB+}}{N_{LAB+}} + \dfrac{\sum\limits_i D_i^{LAB-}}{N_{LAB-}}}{2} \tag{4}$$

where $\mathrm{D}_\mathrm{i}^{\mathrm{LAB+}}$ is the ith measurement and N_{LAB+} is the number of measurements taken by the LAB JVS with DVM normal polarity mode, $\mathrm{D}_\mathrm{i}^{\mathrm{LAB-}}$ is the ith measurement and N_{LAB-} is the number of measurements taken by LAB JVS with DVM reversed polarity mode. In the comparison, an equal number of DVM normal polarity and reversed polarity mode measurements were taken.

Fig. 4 shows the measurements made by the NIST CJVS. The error bar shows the Type-A uncertainty of each measurement. The measurements made by the INMETRO JVS and other results can be seen in [2].

It has been reported that the difference between the two JVSs is dependent on the polarity of the null detector when an external filter network is used to improve step stability during the comparison [10]. For this comparison, no filter for the DVM was used, and the comparison was made with normal and reversed DVM polarity.

During the data acquisition for the comparisons, the laboratory temperature and its relative humidity were controlled at 22.0 °C ± 0.2 °C and at 53% ± 4%, respectively.

TABLE I
DIFFERENCES BETWEEN THE TWO JVSs AND ASSOCIATED TYPE-A UNCERTAINTIES

	Made by NIST	Made by INMETRO
INMETRO - NIST (nV)	-0.03	1.11
Number of measurements (each polarity)	29	20
Standard deviation (nV)	4.00	3.54
Type A uncertainty (nV)	0.74	0.79

TABLE II
TYPE-B UNCERTAINTY COMPONENTS OF EACH JVS SYSTEM WHEN THE NIST CJVS MEASURED THE INMETRO JVS

Uncertainty component	NIST (nV)	INMETRO (nV)
Frequency reference (correlated)	0.01	0.01
Frequency counter (correlated)		1.08
Leakage (correlated)	0.70	0.21
Detector gain and linearity (uncorrelated)	0.88	
Combined Type B uncertainty u_B^{NIST} (nV)	1.57	

TABLE III
TYPE-B UNCERTAINTY COMPONENTS OF EACH JVS SYSTEM WHEN THE INMETRO JVS MEASURED THE NIST CJVS

Uncertainty component	NIST (nV)	INMETRO (nV)
Frequency reference (correlated)	0.01	0.01
Frequency counter (correlated)		1.08
Leakage (correlated)	0.70	0.21
Detector gain and linearity (uncorrelated)		0.26
Combined Type B uncertainty $u_B^{INMETRO}$ (nV)	1.33	

B. Uncertainty

Type-A uncertainty of the LAB JVS measurements is the pooled standard deviation of the mean of all the measurements:

$$u_A^{LAB} = \sqrt{\left(u_A^{LAB+}/2\right)^2 + \left(u_A^{LAB-}/2\right)^2} \tag{5}$$

where u_A^{LAB+} and u_A^{LAB-} is the standard deviation of the mean for data sets with normal and reversed DVM polarity modes, respectively. Table I summarizes the differences between the two JVS systems along with the associated Type-A uncertainties.

The sources of Type-B uncertainty are the frequency stability of the Gunn oscillators, the cryoprobe leakage currents, and the detector gain and linearity. Only the uncertainty related to the detector is considered uncorrelated since the INMETRO JVS and NIST CJVS detectors are used in different comparisons (INMETRO JVS measuring the NIST CJVS and the NIST CJVS measuring the INMETRO JVS). The other Type-B uncertainties are considered correlated because they appear in both comparisons. The Type-B uncertainty components of each JVS system can be seen in Tables II and III.

Most of the effects of the detector gain and frequency stability are already contained in the Type-A uncertainty. Since both arrays had their polarities reversed during the measurements, the effect of the residual thermal emfs (i.e., nonlinear drift) and electromagnetic interferences are also contained in the Type-A uncertainty of the measurements. Uncertainty component related to sloped Shapiro voltage steps is considered negligible; since we made the measurement with bias source disconnected from the arrays, there should not be a step slope problem because the step is always biased at zero current.

TABLE IV
DIFFERENCES BETWEEN BOTH JVS

INMETRO - NIST (nV)	0.54
Pooled Type A uncertainty u_A (nV)	0.54
Pooled Type B uncertainty u_B (nV)	1.38
Combined standard uncertainty u_c (nV)	1.48

TABLE V
LINK BETWEEN INMETRO AND BIPM VIA THE NIST-BIPM DIRECT JVS COMPARISON LISTED IN KCDB BIPM.EM-K10.B

	Difference (nV)	Uncertainty (nV)
INMETRO - NIST	0.54	1.48
NIST – BIPM	-0.80	0.95
INMETRO - BIPM	-0.26	1.76

The combined Type-B uncertainty, for each lab, is the RSS of all the components:

$$u_B^{LAB} = \sqrt{u_B^2(correlated) + \left(u_B^{LAB}\right)^2 (uncorrelated)}. \tag{6}$$

The pooled Type-A uncertainty of the final result (mean value of the two results) is then:

$$u_A^2 = \frac{\left(u_A^{NIST}\right)^2 + \left(u_A^{INMETRO}\right)^2}{4}. \tag{7}$$

The pooled Type-B uncertainty of the final result (mean value of the two results) is then:

$$u_B^2 = u_B^2(correlated) + \frac{\left(u_B^{NIST}\right)^2(uncorrelated) + \left(u_B^{INMETRO}\right)^2(uncorrelated)}{4}. \tag{8}$$

The final reported difference between the INMETRO JVS and the NIST CJVS shown in Table IV is the mean difference of the measurements made by the NIST CJVS and the INMETRO JVS. The combined uncertainty associated with the difference is the RSS of the pooled Type-A and pooled Type-B uncertainties.

A link between INMETRO and BIPM can be established via the NIST-BIPM direct JVS comparison BIPM.EM-K10.b performed in March 2009 [3]. The same NIST CJVS, including all its hardware and software, was used in the NIST-BIPM direct JVS comparison. The degree of equivalence of INMETRO with respect to BIPM is given in Table V by the following relations, both expressed in nV:

$$d_{INMETRO-BIPM} = d_{INMETRO-NIST} + d_{NIST-BIPM} \tag{9}$$

$$u^2_{INMETRO-BIPM} = u^2_{INMETRO-NIST} + u^2_{NIST-BIPM}. \tag{10}$$

VI. CONCLUSION

Two comparisons between the NIST CJVS and the INMETRO JVS were carried out in June 2009 as SIM.EM.BIPM-K10.b.1, first using the NIST CJVS to measure 10 V against the INMETRO JVS and then using the INMETRO JVS to measure 10 V against the NIST CJVS. The automatic data acquisition used for the comparisons greatly improved the efficiency and reduced the intensive labor required for 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 that was established via an earlier key comparison between NIST and BIPM was determined to be −0.26 nV with a standard uncertainty of 1.76 nV.

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