Comparison of the Josephson Voltage Standards of the NIM and the BIPM

(part of the ongoing BIPM key comparison BIPM.EM-K10.b)

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Abstract. A comparison of the Josephson array voltage standards of the *Bureau International des Poids et Mesures* (BIPM) and the *National Metrology Institute* (NIM), Beijing, P.R China, was carried out in November 2013 at the level of 10 V. For this exercise, options A and B of the BIPM.EM-K10.b comparison protocol were applied. Option B required the BIPM to provide a reference voltage for measurement by NIM using its Josephson standard with its own measuring device. Option A required NIM to provide a reference voltage for measurement by the BIPM using its analogue detector and associated measurement loop. In both cases the BIPM array was kept floating from ground.

The final results were in good agreement within the combined relative standard uncertainty of 9.2 parts in 10^{11} for the nominal voltage of 10 V.

1. Introduction

Within the framework of CIPM MRA key comparisons, the BIPM performed a direct Josephson voltage standard (JVS) comparison with the NIM, P.R. China, in November 2013.

The BIPM JVS was shipped to NIM, Beijing, P.R. China, where an on-site direct comparison was carried out from 6 November to 14 November 2013. The comparison followed the technical protocols for the options A and B of the BIPM.EM-K10 comparisons. The comparisons involved the BIPM measuring the voltage of the NIM programmable JVS using its measurement loop where an analogue voltmeter was used as a detector for option A and NIM measured the voltage of the BIPM transportable JVS using its own measurement chain for option B.

For both protocol options, the BIPM array was kept floating from ground and was biased on the same Shapiro constant voltage step for each polarity, which was necessary to maintain stability during the timeframe required for the data acquisition.

This article describes the technical details of the experiments carried out during the comparison.

2. Comparison equipment

2.1 The BIPM JVS

In this comparison the BIPM JVS comprised a cryoprobe with a Hypres 10 V SIS array (S/N: 2538E-7), the microwave equipment and the bias source for the array. The Gunn diode frequency was stabilized using an EIP 578B counter and an ETL/Advantest stabilizer [1]. An optical isolation amplifier was placed between the array and the oscilloscope to enable the array *I*-*V* characteristics to be visualized, while the array was kept floating from ground. During the measurements, the array was disconnected from this instrument. The measurements were carried out without monitoring the voltage across the BIPM JVS. The RF biasing frequency was adjusted to minimize the theoretical voltage difference between the two JVS to zero.

The series resistance of the measurement leads was less than 4 Ω in total and the value of the thermal electromotive forces (EMFs) was found to be in the order of 30 nV. Their influence was eliminated by polarity reversal of the arrays. The leakage resistance between the measurement leads was greater than 5×10^{11} Ω for the BIPM JVS.

2.2 The NIM JVS

2.1 Primary standard operated for the Option A comparison

The NIM JVS against which the BIPM standard was firstly connected is a NIST 10 V PJVS system. Although a complete description of this system is available here [2], we present a short overview of the PJVS equipment. The current bias source for the array comprises a National Instruments[1] PXI chassis equipped with 6 multifunction cards providing a total of 24 digital-to-analog converter (DAC) voltages (4 per card). Each card is electrically isolated from the PXI chassis and powered by on-card dc-to-dc converters. In order to generate the bias current for each node of the array,

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

the DAC voltages are individually in line with a buffer amplifier and a 110 Ω resistor. The microwave biasing source is an Agilent 8257D synthesizer capable of 1 mHz resolution and amplified with Agilent an 36020A amplifier in such a way that the microwave power distributed to the arrays could reach +25 dBm at the cryoprobe head.

The bias source is controlled via *NIST-Core* software installed on an embedded controller which allows setting an accurate voltage out of the PJVS with a resolution of 1 nanovolt. The software also allows performing the required tests to check the quantization of the array voltage. For the comparison, the PJVS was “manually” controlled to reverse its voltage polarity. More details are presented in paragraph 3.

2.2 Primary standard operated for the Option B comparison

In this comparison, a 10 V SIS array was operated. The microwave irradiation applied to the array came from a miniature millimeter wave synthesizer, with the external frequency reference of 10 MHz. The array was biased with a NIM-designed and built bias source which was powered by batteries. The cryoprobe used was fabricated by High Precision Devices, Inc. The measurement leads in the cryoprobe were filtered and presented the series resistance of less than 12 Ω in total. Additional two pairs of leads are used to bias the array and to visualize the I-V characteristics of the array. These leads are disconnected from the instruments during the measurements. The leakage resistance between the measurement leads was 1.5×10^{11} Ω. The NIM 10 V JAVS is routinely used to calibrate Zener diode voltage references. In order to carry out calibration, an automatic switch with very low thermal emf of less than 3 nV is used to change the polarity of the custom voltage references.

Other details of the NIM 10V JAVS are as follows:

Microwave RF source: compact synthesizer made by Jülicher SQUID GmbH

Josephson junction array: IPHT 10 V SIS array (IPHT-N°1947-5)

Null detector: Agilent 34420A SN US36003059, range used 100 mV without filter.

Bias source : NIM designed bias source, powered supplied by two 15 V batteries in series

Software: In-house software based on *Visual Basic*

3. Comparison procedures - Option A at the 10 V level

3.1 First series of measurements using a digital nanovoltmeter

After the BIPM JVS was set-up and checked for trapped flux, it was decided to start the exercise by comparing the 10 V NIM primary standard based on a programmable array and associated electronics as the traditional SIS system needed some adjustments to be completed before being ready to be involved in the direct comparison.

The NIM programmable Josephson standard has a RF bias source with a 1 mHz resolution which allows to reduce the theoretical voltage difference between the two arrays to better than 1 picovolt. The BIPM array was biased to f = 75.480 GHz while the NIM PJVS was set to f = 19.331 958 651 799 GHz for the 250 152 selected Josephson junctions.

In the BIPM measurement setup, the two standards are connected in series opposition using a thermal shunt on which the detector (K2182A) is also connected, with its positive polarity to the NIM PJVS low potential. A very low thermal emf switch is used to open the measurement circuit during the polarity reversal of the arrays which is performed manually.

The first series of measurements suffered from a such significant level of electrical noise that no result could be derived. The sensitivity of the measurement setup to electromagnetic interferences was significantly reduced by:

1- Powering all the equipment involved with plugs equipped with a earth connection;

2- Switching the 10 MHz reference signal shared by the two primary voltage standards from the NIM 10 MHz distribution rack to the internal 10 MHz reference of the BIPM EIP 578B frequency counter;

3- grounding the dewar of the NIM PJVS and bringing this reference potential to the BIPM dewar through the shield of the cables connecting the two voltage standards.

Two series of 10 measurement points were carried out and one point clearly identified as an outlier was discarded. The mean value of the 19 remaining points gives the preliminary result:

$(U_{NIM} - U_{BIPM}) / U_{BIPM} = 0.89 \times 10^{-10}$ with a relative experimental standard deviation of the mean, of $u_A / U_{BIPM} = 3.25 \times 10^{-10}$.

3.2 Improvements of the measurement setup and second series of measurements

The measurement setup was again investigated and the following improvements were brought to the measurement setup:

1- The BIPM JVS was surprisingly perturbed if the potential of the probe was brought to the chassis of the bias source through the shield of the biasing cable. Therefore we installed a biasing cable with no shield.

2- It appears that the level of noise was much lower if the dewars were not connected to the ground potential, however the dewars still had to be kept to the same potential.

3- The metallic He gas recovery line was removed from the NIM Dewar

4- A HP 34420A nanovoltmeter was operated on its 1 mV range in replacement of the K2182A.

20 measurements points were performed (Cf. Fig. 1) and the Option A comparison result using a digital nanovoltmeter was calculated to be:

$(U_{NIM} - U_{BIPM}) / U_{BIPM} = -0.91 \times 10^{-10}$ with a relative experimental standard deviation of the mean of $u_A / U_{BIPM} = 0.69 \times 10^{-10}$.

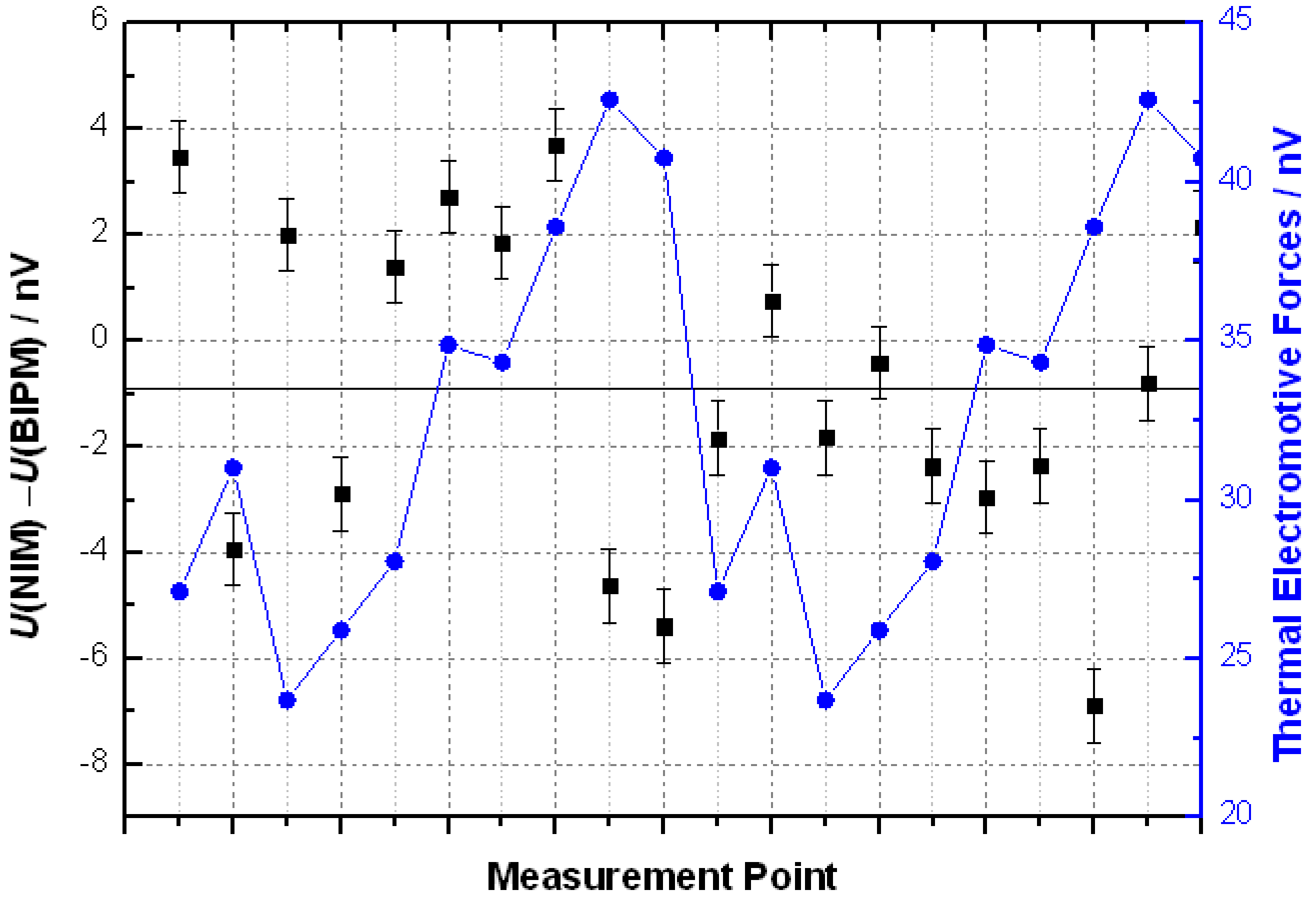

Fig. 1: Individual measurement points (black squares) obtained to calculate the preliminary result of the option A comparison scheme at the level of 10 V using a digital nanovoltmeter (left scale). The solid line represents the mean value and the uncertainty bars represent the experimental standard deviation of the mean of the series. The blue disks represent the evolution of the Thermal Electromotive Forces between the two JVS (right scale).

This second comparison result showed that the two standards were in excellent agreement. The stability achieved on the BIPM JVS was excellent and the quantization of the PJVS voltage was checked on frequent occasions by carrying out a DC flatspot. Therefore, during the remaining period dedicated to the comparison, many experiments and measurement configurations were tested to achieve the lowest voltage difference between the two JVS and the lowest Type A uncertainty. Details of the experiments are described in Appendix A.

3.3 Third series of measurements using an analog detector EM-N11

From the previous measurements, the stability and electrical noise level (interferences between the two primary standards and corresponding grounding configuration) were found adequate to change the digital nanovoltmeter for an analogue detector for which the internal noise floor is expected to be of the order of 0.3 nV on its 3 µV range.

The BIPM RF source was set to f = 74.875 GHz and 250 152 junctions of the NIM PJVS were irradiated at f = 19.332 052 612 011 GHz.

The zero adjustment of the N11 was performed and several series of measurements for a total of 22 individual points were carried out. Some adjustments were done in between each series so that there isn't a strong correlation between each individual points:

1- The 3 µV range of the nanovoltmeter was changed to the 1 µV range; This was possible as the residual thermal electromotive forces between the 2 JVS remained small (80 nV);

2- The shielded room door was closed making the environment fully protected from external fields;

3- The neon lights inside the shielded room were switched off;

4- The filter position at the input of the detector was set to 2 (1 is the lower value and 6 the highest);

22 measurements points were performed (Cf. Fig. 2) and the Option A comparison result using a analog nanovoltmeter was calculated to be:

$(U_{\mathrm{NIM}} - U_{\mathrm{BIPM}}) / U_{\mathrm{BIPM}} = -0.21 \times 10^{-10}$ with a relative experimental standard deviation of the mean $u_{\mathrm{A}} = 0.79 \times 10^{-10}$.

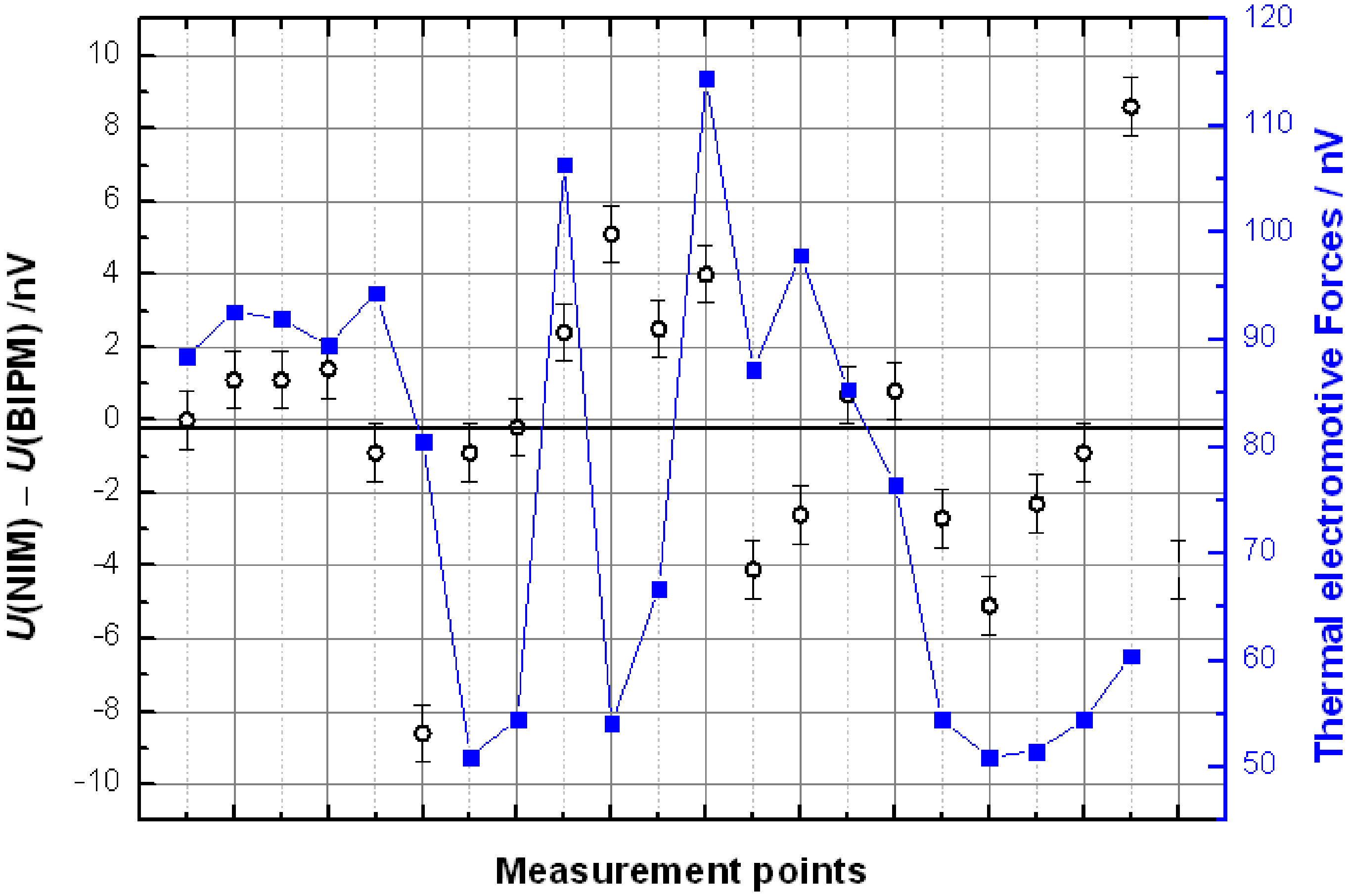

Fig. 2: Individual measurement points (black circles) obtained to calculate the final result of the option A comparison scheme at the level of 10 V using an **analog** nanovoltmeter (left scale). The solid line represents the mean value and the uncertainty bars represent the experimental standard deviation. The blue open squatres represent the evolution of the Thermal Electromotive Forces between the two JVSs (right scale).

4. Comparison procedures - Option B

The option B comparison took place after the option A comparison as the conventional NIM SIS array unit needed some adjustments before being involved in a direct comparison. During the adjustment process during which different arrays, RF bias sources operating at different frequencies and providing different levels of power were tried. The related experiments are fully described in a chronological manner in the Appendix A.

4.1 Measurement set-up

The measurement loop operated for the option B comparison is the following:

1- A HP34420A nanovoltmeter was measuring the voltage difference between the two arrays on its 100 mV range: The gain of the range was calibrated and the correction was found to be +0.2 ppm, therefore no correction was applied to the readings.

2- NIM could not precisely adjust the voltage on a precise step but could proceed to an adjustment and set the voltage difference within 3 mV accordingly to the requirement of the measurement software. The measurement software, written in *Visual Basic* was following the process presented here:

1- Positive polarity of both arrays;
2- 10 data readings acquisition on NPLC 10;
3- Negative polarity of the arrays;
4- 20 data readings acquisition on NPLC 10;
5- Positive polarity of both arrays;
6- 10 data readings acquisition on NPLC 10;

During the measurement process, the BIPM bias source was adjusted manually to the same step after each polarity reversal. After each polarity reversal 10 seconds elapsed before beginning the data acquisition in order to limit the amplitude of the effects of filter capacitor discharge and dielectric absorbtion effects.

4.2 Results of the option B, at the 10 V level

A total of 19 individual measurement points were performed at the 10 V level within different experimental conditions (see Appendix A). The final result, calculated as the mean value is: $(U_{\mathrm{NIM}} - U_{\mathrm{BIPM}}) = 0.09$ nV with a standard deviation of the mean of 1.43 nV (Fig. 3). This result confirms that the traditional NIM SIS primary voltage standard offer a very satisfactory metrological reliability.

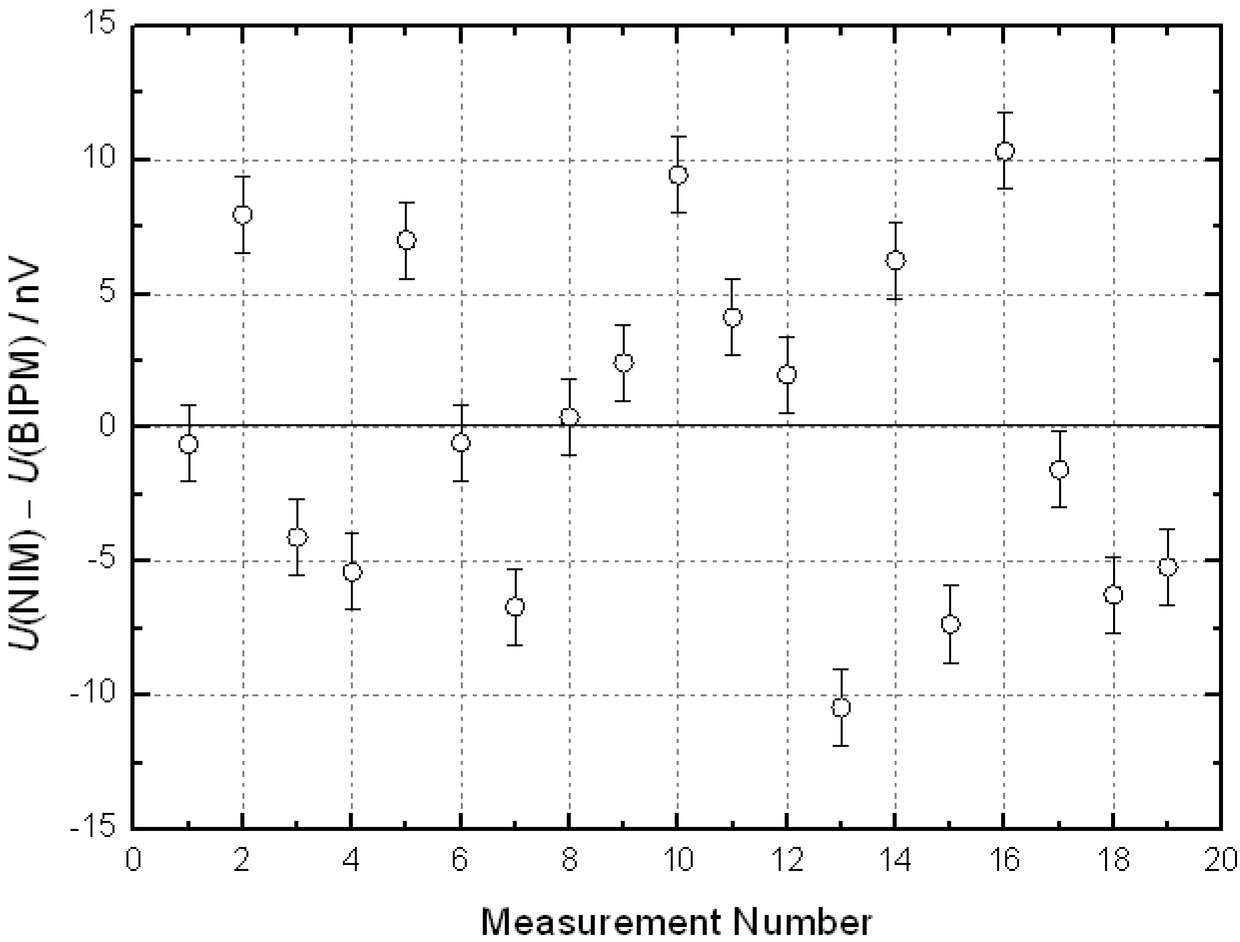

Fig. 3: Individual results obtained with the Option B comparison protocol at the 10 V level. The uncertainty bars represent the standard deviation of the mean of the complete series. The line slightly above zero represents the mean value of the 19 individual measurements (+0.09 nV).

5. Uncertainties and results

5.1 Option B - 10 V final result

5.1.1 Type B uncertainty components (option B protocol)

The sources of Type B uncertainty (Table 1) are: the frequency accuracy of the BIPM Gunn diode and the NIM compact synthetiser, the leakage currents, and the detector gain and linearity. Most of the effects of detector noise and frequency stability are already contained in the Type A uncertainty. The effect of residual thermal EMFs (i.e. non-linear drift) and electromagnetic interferences are already contained in the Type A uncertainty of the measurements because both array polarities were reversed during the measurements. Uncertainty components related to RF power rectification and sloped Shapiro voltage steps are considered negligible because no such behaviour was observed and the bias sources were disconnected on both arrays and therefore the sloped steps effects were eliminated if they ever existed.

	Type	Relative uncertainty	
		BIPM	**NIM**
Frequency offset [(A)]	B	8.0×10^{-12}	8.0×10^{-12}
Leakage resistance [(B)]	B	5.0×10^{-12}	4.5×10^{-11}
Detector [(C)]	B		2.0×10^{-11}
Total (RSS)	B	9.4×10^{-12}	5.0×10^{-11}

Table 1: Estimated Type B relative standard uncertainty components (Option B).

[(A)] As both systems referred to the same 10 MHz frequency reference, only a Type B uncertainty from the frequency measured by the EIP is included. The 10 MHz signal used as the frequency reference for the comparison was produced by the internal reference of the BIPM frequency counter EIP 578B.

BIPM JVS has demonstrated on many occasions that the EIP-578B has a good frequency locking performance and that the accuracy of the frequency can reach 0.1 Hz [3]. However, in the particular case of using the internal EIP frequency reference, we consider a frequency offset of 1 Hz to which we apply a rectangular distribution. The relative uncertainty for the offset of the frequency can be calculated from the formula: $u_f = (1/\sqrt{3}) \times (1/75) \times 10^{-9} = 8 \times 10^{-12}$.

According to the performance of the NIM compact synthesizer, its frequency accuracy is similar to that of the input 10 MHz reference, can reach 1 Hz. If a rectangular distribution is assumed then the relative uncertainty for the offset of the frequency can be calculated from the formula:

$u_f = (1/\sqrt{3}) \times (1/75) \times 10^{-9} = 8 \times 10^{-12}$.

[(B)] If a rectangular statistical distribution is assumed then the relative uncertainty contribution of the leakage resistance R_L can be calculated as: $u_f = (1/\sqrt{3}) \times (r / R_L)$. For NIM, the related variables were measured to $r = 11.6\ \Omega$ and $R_L = 1.5 \times 10^{11}\ \Omega$. The isolation resistance value includes all the cables from the JVS to the DVM. For BIPM, those parameters are measured to $r = 4\ \Omega$ and $R_L = 5 \times 10^{11}\ \Omega$.

(C) For NIM JVS, an Agilent 34420 served as the null detector, with the correction of +0.2 ppm on its 100 mV range. As the voltage difference was adjusted with the maximum of 3 mV, when a normal distribution is assumed and the confidence coefficient is taken as 1, the relative uncertainty on the detector can be calculated as $u_d = 2.0 \times 10^{-11}$.

5.1.2 Result at 10 V (option B)

The result using option B, is expressed as the relative difference between the values attributed to the 10 V BIPM JVS (U_{BIPM}) by the NIM JVS measurement set-up (U_{NIM}):

$$(U_{\mathrm{NIM}} - U_{\mathrm{BIPM}}) / U_{\mathrm{BIPM}} = 0.09 \times 10^{-10} \quad \text{and } u_{\mathrm{c}} / U_{\mathrm{BIPM}} = 1.52 \times 10^{-10}$$

where u_{c} is the total combined standard uncertainty and the relative Type A is
$u_{\mathrm{A}} / U_{\mathrm{BIPM}} = 1.43 \times 10^{-10}$.

This result supports the CMCs (Calibration and Measurement Capabilities) of the NIM.

5.2 Option A - 10 V final result

5.2.1 Type B uncertainty components (option A protocol)

	Type	Relative uncertainty	
		BIPM	**NIM**
Frequency offset	B	8.0×10^{-12}	4.0×10^{-12}
Leakage resistance	B	5.0×10^{-12}	4.0×10^{-11}
Detector (D)	B	depending of the detector	
Total (RSS)	B	2.67×10^{-11}	4.0×10^{-11}

Table 2: Estimated Type B relative standard uncertainty components (Option A).

(D) The uncertainty on the accuracy of the nanovoltmeter is calculated from the difference between the nominal calibration factor and the measured one. The difference is applied to the maximum voltage difference measured by the N11 on the 3 µV range which leads to: $u_{\mathrm{D}} = 0.25$ nV.

The preliminary measurement was obtained using a Keithley 2182A nanovoltmeter on its 10 mV range with a gain error of 5 ppm applied on voltages lower than 1 µV. If we apply a rectangular distribution to this measurement we end with a relative uncertainty $u_{\mathrm{D}} = 2.9 \times 10^{-13}$

5.2.2 Final result at 10 V (option A)

The preliminary result was obtained using the option A protocol with a numeric detector. It is expressed as the relative difference between the values attributed to the 10 V NIM JVS (U_{NIM}) by the BIPM JVS measurement set-up (U_{BIPM}) is:

$$(U_{NIM} - U_{BIPM}) / U_{BIPM} = 0.89 \times 10^{-10} \quad \text{and } u_c / U_{BIPM} = 3.25 \times 10^{-10} \quad ,$$

where u_c is the total relative combined uncertainty. The relative Type A uncertainty, calculated as the standard deviation of the mean of 19 individual measurements is $u_A / U_{BIPM} = 3.25 \times 10^{-10}$.

The best result obtained using the option A comparison protocol, expressed as the relative difference between the values attributed to the 10 V NIM PJVS (U_{NIM}) by the BIPM JVS measurement set-up based on an analog nanvolmeter (U_{BIPM}) is:

$$(U_{NIM} - U_{BIPM}) / U_{BIPM} = -0.21 \times 10^{-10} \quad \text{and } u_c / U_{BIPM} = 0.92 \times 10^{-10} \quad ,$$

where u_c is the total relative combined uncertainty. The relative Type A uncertainty, calculated as the standard deviation of the mean of 22 individual measurements is $u_A / U_{BIPM} = 0.79 \times 10^{-10}$.

6. Discussion and conclusion

The comparison was carried out in the NIM Electricity Laboratories where the environmental conditions were adequate. However, a better control of the ambient parameters, the quality of the isolation of the 10 MHz reference signal distribution if some improvements in the filtering of the mains powering the shielded room could bring a better electromagnetic compatibility between the measurement environment and the measurement setup .

Two different NIM 10 V primary voltage standards were successfully involved in the direct comparison with the BIPM Josephson Voltage Standard and the NIM measurement loop for secondary standards was as well investigated.

The results fully support the NIM CMCs in the field of DC voltage Metrology.

References

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[4] Tang Y., Solve S., Witt T.J., Allan variance analysis of Josephson voltage standard comparison for data taken at unequal time intervals, *IEEE Trans. Instrum. Meas.,* 2011, **60**(7), 2248-2254

DISCLAIMER

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Appendix A

This appendix describes the measurements performed in chronological order.

06 November 2013:

The BIPM JVS was assembled and tested during the afternoon of that day. The proper power distribution to the BIPM equipment was achieved once a plug equipped with an Earth male connector was used.

The NIM SIS JVS unit equipped with an Hypres array (SN: 2518-B3) was found unstable probably because of the presence of magnetic trapped flux in a junction. It was also known that one contact was missing on the array connection board.

07 November 2013:

It was decided to investigate on the NIM Hypres array using the BIPM JVS equipment. The lowest critical current was measured to 90 µA while the other junctions were at the level of 160 µA to 170 µA.

The array was then irradiated at f = 74.920 GHz and exhibited stable voltage steps for both polarities at the level of 10 V. However, the steps were found considerably sloped (10 Ω to 20 Ω) and a power adjustment was required at every polarity reversal.

Such a resistance value can't be explained by a default on the microscopic structure of the array and we suspected the bad macroscopic contact on the board to explain it. The array protection cover was removed and the electrical contacts were successfully cleaned up.

On the second cool-down attempt, while the weakest Josephson junction was still showing 90 µA of critical current, the resistance issue fully disappeared and the array behaved properly at the 10 V level with no identified sloped steps and no more power adjustments required.

After the array was warmed up, it was decided to test an IPHT SIS array (JA-145/10), on the BIPM equipment. The array showed the same critical current value (100 µA) for all the junctions and exhibitednice stable steps at 10 V for f =75.49 GHz. As an intrinsic characteristic of IPHT SIS array, it was found required to shut down the microwave power and to set it back up again after each polarity reversal in order to find the steps again.

In the meantime the NIM 10 V PJVS was checked and confirmed to be operational.

The BIPM Hypres array was cooled down and connected in series opposition with the PJVS. The first measurement couldn't be completed because of the noise level in the measurement setup. This noise was considerably reduced with the use of the 10 MHz internal reference of the EIP 578B as the reference signal for each JVS.

The first series of measurement were successfully carried out using a Keithley 2182A nanovoltmeter on its 10 mV range, NPLC 5, with the analog filter ON.

The preliminary comparison result, using a digital nanovoltmeter was achieved on that day from 19 individual measurements to: $(U_{\mathrm{NIM}} - U_{\mathrm{BIPM}}) / U_{\mathrm{BIPM}} = -0.89 \times 10^{-10}$ with a relative Type A uncertainty $u_{\mathrm{A}} / U_{\mathrm{BIPM}} = 3.25 \times 10^{-10}$.

08 November 2013:

The RF source of the NIM SIS array is a Jülicher SQUID GmbH compact synthetiser (MMWS) which is at its limits, in terms of power level, to produce the steps from the SIS array.

We decided to draw a response map in terms of frequency using a BIPM 74 GHz-76 GHz, 21 dBm output power Gunn oscillator. The array was found to require slightly less power around a frequency of f= 75.4 GHz. Unfortunately, this frequency was also the one where the MMWS was producing less power.

In the meantime, the direct comparison with the NIM PJVS was conducted with a HP 34420A nanovoltmeter in replacement of the K2182A and we spent more time to investigate the grounding configuration of the measurement setup:

1- The NIM dewar was grounded and the reference potential brought to the BIPM dewar through the shield of the measurements cables;
2- However, the shield of the BIPM biasing cable needed to be cut between the bias chassis and the probe to guarantee the stability of the BIPM quantum voltage;
3- The configuration where both dewars were grounded separately was too noisy to achieve satisfactory results;
4- The He gas recovery line which is a metallic tube connected itself to a tubular metallic structure was removed as it was responsible for a ground loop.
5- The configuration where both dewars were connected to the same reference potential (different from the ground potential) appeared to be the best one.
6- Two different devices HP 34420A were tested on the measurement setup and the best one gave a simple standard deviation of 10 consecutive readings of 8 nV to 12 nV where the

second one gave 20 nV to 30 nV. Both nanovoltmeter were operated on their 1 mV range, without any filter engaged for an NPLC of 10.

The result applying the option A comparison protocol and using a digital nanovoltmeter was achieved from 22 individual measurements to: $(U_{NIM} - U_{BIPM}) / U_{BIPM} = -0.91 \times 10^{-10}$ with a relative Type A uncertainty $u_A / U_{BIPM} = 0.69 \times 10^{-10}$.

11 November 2013:

As the electrical noise conditions of the measurement setup were satisfactory and as the preliminary measurement was affected by the 1/f noise floor of the detector [4] as the limiting factor, we decided to replace the digital nanovoltmeter with an analog EM N11 nanovoltmeter.

The Type A uncertainty of the first 5 consecutive points was 9 nV. A coupling interference between the BIPM Gunn frequency stabilizer and the Gunn amplifier power supply was identified when the BIPM frequency changed by several tens of Hertz from the locked frequency. The position of the two devices was changed and a stability within 1 Hz on the counter display was recovered.

We also observed a slight deviation of the nanovoltmeter needdle from its equilibrium position at the time the IEEE488 commands were sent to the DVM used to digitilize the N11 readings. The deviation amplitude was reduced when decoupling the potential of the IEEE 488 plug between the computer board and the instrument. In the future and in order to solve this issue, the DVM will need to be updated to a more recent version equipped with an internal memory to be used to store the readings with no IEEE bus activity during the reading process.

In the meantime, some more experiments were carried out on the traditional system in order to produce stable voltages. A third array (IPHT-N°1947-5) was cooled down and tested with the MMWS from the calibration laboratory (Beijing) as this device is equipped with an amplifier and might provide more RF energy to the array. The stability on the voltage steps was not satisfactory therefore it was suspected that the spectral content coming out of the MMWS was not pure enough to produce the Shapiro steps.

The RF source was changed and replaced with the MMWS of the lab. In order to gain a little bit of power at the input of the microwave guide (top of the probe) the magnetic isolator together with a tapered filter (bandwidth 69 GHz – 81 GHz) were removed.

The gain of the 1 mV, 10 mV, 100 mV, 1 V and 10 V of the HP 34420A operated on the NIM SIS system were calibrated over night, using the NIM PJVS.

12 November 2013:

A BIPM gunn with 21 dBm output power over the interval 74 GHz – 76 GHz was tried on the NIM system in order to identify the frequency that would require less power. It was almost impossible to get stable steps confirming that the power was not the only issue in the production of the steps.
The RF source was switched again to the NIM MMWS equipped with the RF filter but the magnetic isolator was removed. Different irradiating frequencies around 75 GHz were tried on the IPHT array. Some nice 15 µA stable steps were finally found at 10 V at *f* =74.750 GHz which is a frequency recommended by the manufacturer as requiring less power than the others.
Furthermore, it was found that the µwave power didn't have to be shut down and put back up again to get the steps at each polarity reversal.

At this point, the option B comparison was started using a HP 34420A nanovoltmeter on its 100 mV range (with no correction for the gain) with a +, - , + polarity configuration and 10 readings for the positive polarity of the arrays and a 20 readings for the negative polarity of the arrays, all readings at a NPLC = 20. A software written under *Visual Basic* was operated from a laptop computer powered from its internal battery.

Different grounding configurations were tried and the best one was exactly the same found for the option A comparison described in the paragraph dedicated to the experiments carried out on the 8th of November.
The leakage resistance between the two precision measurement leads of the NIM probe was measured using the BIPM portable equipment (Keithley 500) to a value of $1.5 \times 10^{11}\ \Omega$.
We noticed that the noise of the measurements was found significantly lower at the end of the day, at the time when all other laboratory activities around were stopped. .
The result of the option B comparison is calculated from 19 individual points:

$(U_{\mathrm{NIM}} - U_{\mathrm{BIPM}}) / U_{\mathrm{BIPM}} = 0.09 \times 10^{-10}$ with a relative Type A uncertainty $u_{\mathrm{A}} / U_{\mathrm{BIPM}} = 1.43 \times 10^{-10}$.