

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

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

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Abstract. A comparison of the 10 V Josephson array voltage standard of the Bureau International des Poids et Mesures (BIPM) was made with that of the Hellenic Institute of Metrology (EIM), Greece, in March 2010. For this exercise, the option B of the BIPM.EM-K10.b comparison protocol was applied, in which the BIPM only provides a reference voltage that has to be measured by the EIM using its Josephson voltage standard and its own measuring device. The results of both participants are in very good agreement and the overall relative standard uncertainty is 2.0 parts in 10^{10} .

1. Introduction

In the framework of CIPM-MRA key comparisons, the BIPM performed a direct Josephson voltage standard (JVS) comparison with the National Metrology Institute of Greece (EIM), Thessaloniki, Greece, in March 2010. The transportable BIPM JVS was shipped to EIM and the comparison was carried out on-site.

This comparison followed the technical protocol for BIPM.EM-K10.b comparisons and was carried out for option B of the protocol where the participating laboratory operates its own measurement setup that usually includes a digital voltmeter as a detector.

This article describes the technical details of the experiments which were carried out to achieve the final result of the comparison.

2. Comparison equipment

2.1 The BIPM JVS

The BIPM JVS used in this comparison comprises the cryoprobe, the microwave equipment and the bias source for the Hypres 10 V SIS array (S/N: 2538F-3). The Gunn diode frequency was stabilized using an EIP 578B counter, and an ETL/Advantest stabiliser. To visualize the array *I-V* characteristics, while keeping the array floating from ground, an optical isolation amplifier was placed between the array and the oscilloscope; during the measurements, the array was disconnected from this instrument. Initially, an HP 34420A digital voltmeter (DVM) was inserted between the array voltage bias leads to measure the voltage in order to verify the step stability. As reported below, we had to remove this instrument which was responsible for bringing some noise in the measurement loop. However, the measurement was possible without monitoring the voltage across the BIPM JVS as it was stable enough for remaining on the selected step during the time required for the measurement.

The series resistance of the measurement leads was less than 3Ω in total (both measurement leads), and the value of the thermal electromotive forces (EMFs) due to both JVS was found to range between 250 nV and 350 nV (Cf. **Fig. 1**). The insulation resistance between the measurement leads was of the order of $1 \times 10^{11} \Omega$.

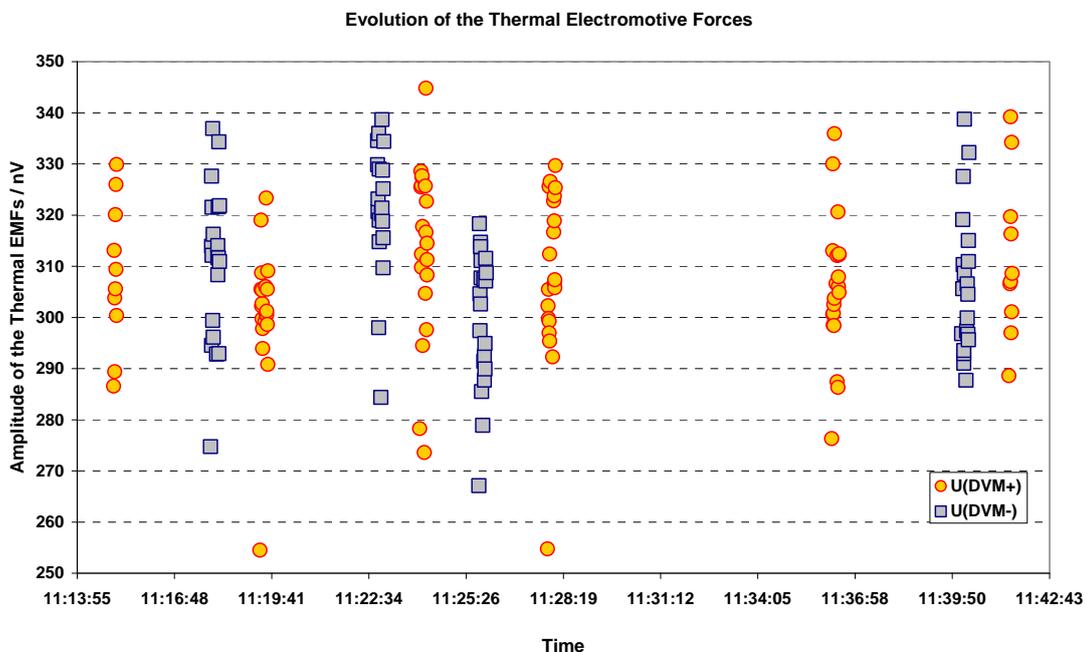


Fig.1. Example of the short term evolution of the thermal EMFs for the complete measurement loop during the comparison. $U(\text{DVM})+$ is the reading of the detector once its positive polarity is on the EIM JVS side and $U(\text{DVM})-$ is the opposite direction. The readings are presented in terms of their absolute value.

2.2 The EIM JVS

- The EIM JVS was manufactured by Hypres Inc. and was installed in 2000. It is composed of the following parts:
 1. A Hypres model CP525 cryoprobe with the chip carrier for the JVS circuit with about 20 208 SIS Josephson junctions;
 2. A liquid helium dewar;
 3. The JVS electronics unit;
 4. The microwave unit which includes a Gunn oscillator, an isolator, a directional coupler, a mixer and a manual attenuator;
 5. An EIP 578B source locking microwave counter;
 6. A HP34420A nanovoltmeter;
 7. A remote channel polarity reversal switch;
 8. Sensors for recording the temperature and the relative humidity of the air as well as the atmospheric pressure;
 9. An USB/IEEE 488 interface;
 10. A parallel port to drive the biasing source and the switch;
 11. A portable PC with the suitable *NISTVolt for Windows* software for driving the nanovoltmeter and the EIP frequency counter.

Other details of the EIM JVS are as follows:

- Resistance of both precision measurement leads : 2.0 Ω ;
- Leakage resistance between the precision measurement leads: $1.7 \times 10^{11} \Omega$;
- 10 V Hypres Josephson junction array – sn: KL-1032-37;
- Null detector: Keithley 2182A – sn: 1127509 - range: 10 mV;
- Bias source :JBS 2001– sn: 01 ;
- Software : *Nistvolt for Windows* (ver 2.2.7) and a Labview based software.

3. Comparison procedures - Option B

Under the option B, considered here, the BIPM only provides a reference voltage that has to be measured by the EIM using its JVS with its own measuring device. The BIPM array is floating from ground.

3.1 Preliminary measurements

Within the week allotted to the comparison, different experiments were carried out in order to achieve the lowest voltage difference between the two JVS.

On the very first attempt to measure the voltage difference between the two JVS, the level of noise on the apparatuses connected together was so high that it was impossible to carry out a measurement. An investigation was performed and we found many imperfections in the measurement loop, contributing all to the instability of both JVS. All the details of this investigation and its solution are described in Appendix A.

Before trying to improve the results, a preliminary measurement was made in the configuration routinely used by EIM. The results of the experiments made to improve the situation are described in the next section.

Depending on the measurement configuration, the EIM JVS array was either connected (biasing current adjustment phase) or disconnected from its bias source (data acquisition phase).

The BIPM bias source was operated on batteries during the step adjustment sequence, and was then disconnected from the array during the data acquisition process. The reference ground was connected to the EIM JVS. The two arrays were connected in series-opposition via the switch controlled by the EIM JVS measurement setup. In this comparison scheme (option “B”), the EIM JVS measurement setup was used to measure the BIPM array voltage as if it were a Zener voltage standard, but without using the polarity reversal switch. During the comparison, only the biases of the two arrays were reversed (no mechanical switch reversal). This operation was done manually on both JVS. The polarity reversal could typically be achieved within 30 s depending on the time needed to adjust the EIM JVS in order to measure a voltage difference between the two arrays lower than 1 mV.

Once sufficiently stable conditions were found (Cf. Appendix A), the JVS were connected together and 13 measurement points were acquired following the procedure applied by the software which controls the EIM JVS.

The result was $(U_{\text{EIM}} - U_{\text{BIPM}}) / U_{\text{BIPM}} = + 1.1 \times 10^{-9}$.

The experimental standard deviation of the mean was 17 nV on these 13 measurements points, that is 1.7×10^{-9} in relative terms.

This comparison result shows the reliability of the EIM Josephson Voltage Standard and validates the CMCs of the laboratory. Following the preliminary measurements, a larger series of measurements was carried out where we tried to vary the measurement conditions.

3.2 Description of the additional measurements (See also Appendix A)

Both JVS were connected to the same 230 V and 50 Hz uninterruptible power supply. The operating conditions in the underground room were as usual, that is $23\text{ }^{\circ}\text{C} \pm 0.5\text{ }^{\circ}\text{C}$ for the air temperature and $45\% \pm 10\%$ for the relative humidity.

3.2.1 Operating setup for the first measurements

The following is a brief description of the procedure used at EIM to obtain a single measurement of the voltage of the BIPM array. During the comparison, the BIPM current bias source was manually adjusted to select the same step after each polarity reversal. The *NISTvolt for Windows* software was used to disconnect the bias source and a dedicated Labview program was run to control the detector and to record the data. The detector was a digital nanovoltmeter (Keithley 2182A set on its 10 mV range). Four sets of 10 readings taken at an integration time of 10 powerline cycles (NPLC = 10) were taken, one set in the positive polarity of the bias of the two arrays, two sets in the negative polarity, a fourth set in the positive polarity of the bias of the two arrays. The measurements followed the scheme: +, -, -, + and lead to the calculation of two successive measurement results. The recorded data were transferred to the computer through a GPIB interface. The complete series of measurements (+, -, -, +), took from 1 to 4 minutes depending on the adjustability of the EIM JVS. A delay of 10 s was applied after each polarity reversal. The readings were stored in an ASCII data file and the values attributed to the BIPM standard were calculated.

Both JVS were always at the same value of the frequency, and within 6 Shapiro steps away from each other, which correspond to a voltage difference below 1 mV. Each reading was corrected for the gain correction of the nanovoltmeter which was measured twice during the comparison (Cf. Appendix A).

During the subsequent days, experiments were carried out on various parts of the whole system to achieve the lowest difference and uncertainty.

3.2.2 Operating setup for the best measurements

To achieve the best measurements, significant changes were made to the EIM JVS and the measurement loop as described in the Appendix A. The measurement loop was arranged in such a way that both positive potential sides of the arrays were connected together and the nanovoltmeter was placed in between the two negative polarities of the arrays. The “High” of the nanovoltmeter was always connected to the BIPM array.

Both measurement setups were grounded from one unique point on the EIM side. The cases of the BIPM equipment as well as the He dewar were grounded using the shielding of the cable connecting both JVS in series-opposition.

Three improvements had a significant impact on the amelioration of the stability of the Shapiro step on both arrays which lead to the best results:

- Electrical insulation of the RF source from the EIM probe;
- Grounding of the BIPM dewar;
- Removal of the DVM that monitored the voltage across the BIPM array (through the voltage bias leads).

The 35 individual points used for the computation of the final result have been performed on the 8th of March in different configurations: a range of RF frequencies of both JVS, different internal DVM filter settings and different RF sources.

Note: each frequency change on the EIM JVS was followed by an adjustment of the BIPM JVS to the same frequency.

- 9 points obtained at $f = 74.46$ GHz;
- 6 points obtained at $f = 74.5$ GHz;
- 5 points obtained $f = 74.5$ GHz with the internal filter of the nanovoltmeter on;
- 5 points obtained at $f = 74.02$ GHz;
- 2 points obtained at $f = 73.88$ GHz;

- 2 points obtained at $f = 74.212$ GHz;
- 6 points obtained at $f = 74.2$ GHz with a different RF source on the EIM JVS.

3.2.3 Individual comparison measurements

The differences between the values measured by the EIM JVS and the theoretical value of the BIPM array voltage during the comparison are plotted on Fig. 2.

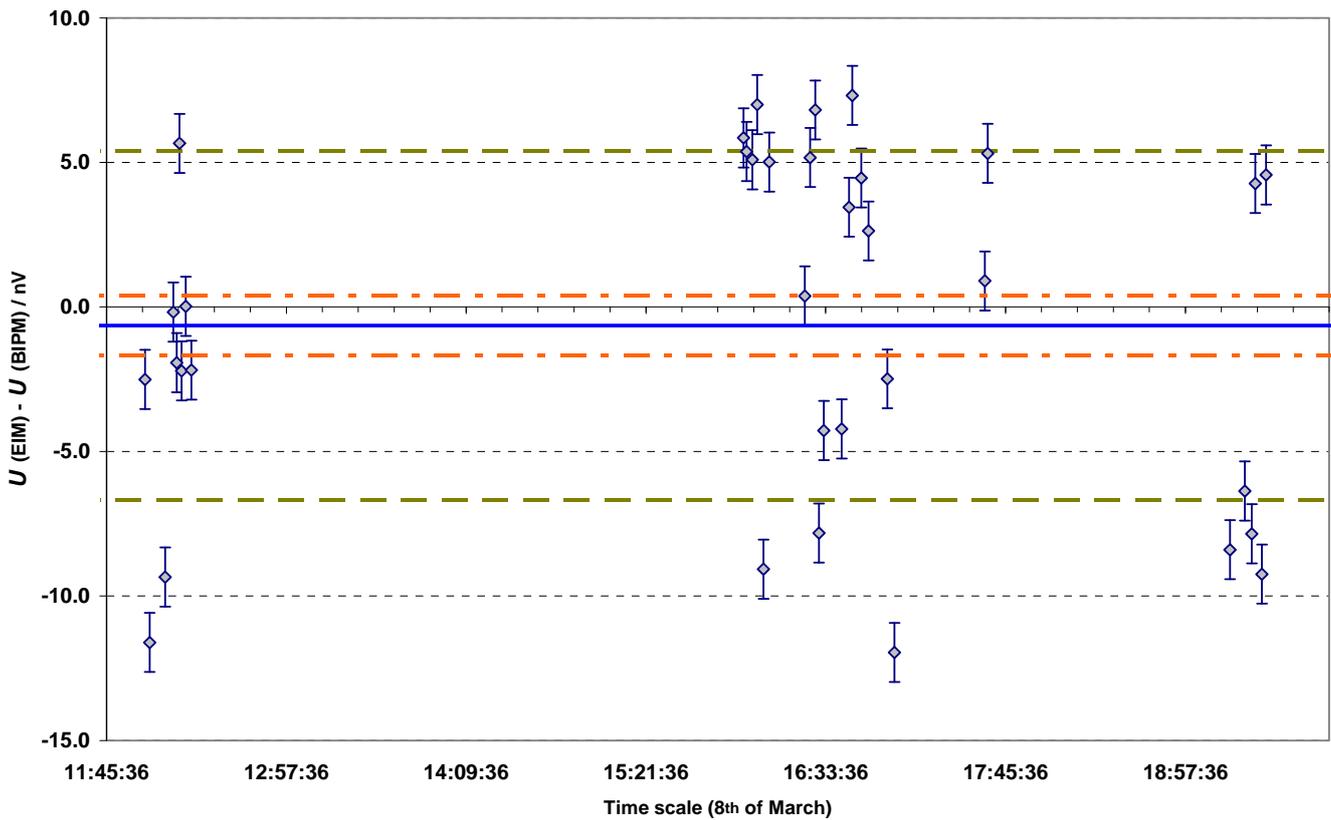


Fig. 2. Voltage difference between the values measured by the EIM and the theoretical value of the BIPM array voltage. The solid line represents the mean value, the dashed lines (---) represent the experimental standard deviation, and the dotted-dashed lines (- - -) are the experimental standard deviation of the mean.

3.2.4 Considerations on the Type A uncertainty

All the 35 points have been considered as **not strongly correlated** as there were carried out at different frequencies. The number of measurements isn't large enough to perform a statistical test of this assumption (Allan Deviation for instance). However, we have calculated the Birge ratio in order to see if the 35 points can be considered as belonging to the same statistical population.

We have calculated the standard deviation of the mean based on internal consistency for the 7 series of measurements (also called *a priori* uncertainty) which is given by: $\sigma_I^{-1} = \sum_j w_j$ where $w_j = \sigma_j^{-1}$ is the weight of the j^{th} series, estimated by the reciprocal of the series' sample variance. This result was compared to the standard deviation based on external consistency (also called *a posteriori* uncertainty) calculated from $\sigma_E = \left[\sum_j w_j \times (x_j - m_w)^2 \right] / \left[(N-1) \sum_j w_j \right]$, where N is the total number of series of measurements (7 in this case) and m_w is the weighted mean [1]. The Birge ratio is then given by $R_B = \sigma_E / \sigma_I$ and is equal to one if the consistency is perfect. In our case, $R_B = 0.71$ ($\sigma_E = 0.513$ nV and $\sigma_I = 0.724$ nV). This result infers that all the seven series of measurement values do belong to the same statistical population. The Type A uncertainty can be calculated from the standard deviation of the mean of the 35 individual results and is equal to 1.02 nV.

3.3 Uncertainties and results

The sources of Type B uncertainty (Table 1) are: the frequency accuracy of the EIM frequency counters, the leakage currents and the detector gain and linearity. Most of the effects of detector gain and frequency stability are already contained in the Type A uncertainty. As both array polarities were reversed during the measurements, the effects of linear drifts of thermal EMFs are corrected, and effects of the residual non-linear drift and electromagnetic interferences are also contained in the Type A uncertainty of the measurements. Uncertainty components related to RF power rectification and sloped Shapiro voltage steps are considered negligible.

	Type	Uncertainty / nV	
		BIPM	EIM
Frequency	B	0.02 ¹	1.2 ²
Leakage resistance	B	0.20	0.12
Detector linearity and gain	B		1.20 ³
Uncompensated thermal EMFs or drifts	B	incl. in type A	incl. in type A
Total (RSS)	B	0.20	1.7

Table 1. Estimated Type B standard uncertainty components.

(¹) As both systems are referred to the same 10 MHz frequency reference, its uncertainty does not contribute to the uncertainty of the voltage difference. Only a Type B uncertainty from the frequency measured by the EIP is included [2].

(²) For the EIM counter the Type B uncertainty of the EIP counter is ± 15 Hz [3], thus $(\pm 15 \text{ Hz}/75 \text{ GHz}) = \pm 0.2 \times 10^{-9}$. For the 10 measurements, this is $0.2 \times 10^{-9} \times 10 \text{ V} / \sqrt{3} = 1.2 \text{ nV}$.

The 10 MHz frequency reference used in the comparison is issued directly by a system of three Cesium clocks that comprises the time and frequency standard of EIM.

(³) A large part of the detector uncertainty is already contained in the Type A uncertainty of the measurements. This component only expresses the effect of the uncertainty of the detector non-linearity correction. The uncertainty due to DVM gain and linearity errors was estimated by 1.2 nV due to the fact that the maximum voltage differences taken into account by the nanovoltmeter were fixed to six steps and the uncertainty on the short term gain linearity was evaluated as 1.3 ppm.

The Type A uncertainty is 1.02 nV as described in section 3.2.4

The final Option B result, expressed as the relative difference between the values that would be attributed to the 10 V Josephson array standard by EIM (U_{EIM}) and its theoretical value (U_{BIPM}) is:

$$(U_{\text{EIM}} - U_{\text{BIPM}}) / U_{\text{BIPM}} = -6.4 \times 10^{-11} \quad \text{and} \quad u_c / U_{\text{BIPM}} = 2.0 \times 10^{-10}$$

where u_c is the combined standard uncertainty.

It is important to note that the uncertainty budget is applicable to this comparison only.

6. Conclusion

The preliminary measurements demonstrated EIM's ability to perform accurate and precise automatic 10 V measurements.

The EIM JVS is a commercial automatic system which has shown a good reliability which was improved by the work realised over the week dedicated to the comparison exercise. This setup is dedicated to routine measurements like Zener calibrations.

The final result shows that both JVS are in very good agreement within the stated uncertainties.

References

- [1] R. T. Birge, Phys. Rev. 40 (207) 1932.
- [2] Djordjevic S., Séron O., Solve S., Chayramy R, Direct comparison between a programmable and a conventional Josephson voltage standard at the level of 10 V, [Metrologia, 2008, 45, n°4, 429-435](#)
- [3] Field Note 5, Rev 02/90, EIP Microwave Inc.

DISCLAIMER

Certain adequate equipment, instruments or materials are identified in this paper in order to specify the environmental and experimental procedures. Such identification does not imply recommendation or endorsement by the BIPM or the EIM, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

Appendix A

This appendix describes the comparison measurements in a chronological manner.

04 March 2010

After having assembled the BIPM equipment, we cooled down a BIPM array (PTB-JK 50/11) and obtained a suitable critical current of 230 μA on the first cooling process. However, we didn't manage to get usable Shapiro steps over the frequency range available from the BIPM RF sources. We decided to switch to a second JVS chip (Hypres S/N 2538F-3) for which the critical current amplitude was 85 μA . We successfully checked for the proper height of the Shapiro steps ($\cong 20 \mu\text{A}$) at the level of 10 V and their stability ($f = 74.46 \text{ GHz}$).

Connection operations

The EIM JVS system is grounded through its DC biasing source. By the use of the NISTVolt program, the array is connected to the biasing source during its adjustment sequence, but it is disconnected from the ground and it is completely floating during the measurement process. The EIM Helium Dewar is always referred to the earth ground of the laboratory through the cryoprobe.

The BIPM JVS DC biasing source was operated on batteries during the adjustment phase and was then disconnected from the array biasing leads. It was found that the level of noise in the measurement loop decreased significantly if the BIPM dewar was referred to the earth ground of the laboratory.

The positive poles of the two quantum standards were connected together and the detector was inserted in between the negative poles, with the high side of the detector connected to the EIM

JVS side. The JVS were connected through a manual switch in such a way that each polarity reversal of the standards could be done after the opening of the measurement loop.

Improvement of the initial setup

Stable Shapiro steps were found on the EIM array at 73.88 GHz and the biasing frequency of the BIPM array was adjusted to the same value.

Under these conditions, the *NISTvolt* software was run to carry out a first measurement point but during the biasing operation of the EIM array, a lot of noise was sent to the measurement loop and both arrays jumped constantly from their initial position. The software interpreted the voltage difference measurements as the presence of $\frac{1}{2}$ step on the EIM array and therefore constantly tried to re-bias it.

At this point we added a BIPM Π filter in between the two JVS. The direct consequence was a significant amelioration of the stability on the EIM JVS but it was still impossible to carry out a measurement point in this configuration.

It was thus decided to bias the EIM array manually and to run a software written in Labview© to record the data from the nanovoltmeter. Within this configuration it is no more possible to disconnect the EIM array from the ground but this isn't a key issue as the BIPM array is completely floating from the ground.

05 March 2010

In the morning of this day, it was impossible to recover stable conditions on the EIM array over the working range of the RF sources available (70 GHz to 78 GHz). The steps were tiny and highly instable.

The EIM EIP counter was known to have an intermittent failure (freezing of the display on the front panel) for some days. The search for stable operating parameters (i.e. frequency) was then performed with the BIPM EIP counter but was also unsuccessful. The presence of ice in the waveguide was then suspected and it was decided to warm up both measurement probes and to test the EIM array on the BIPM probe.

On the first cooling process, an expected critical current $I_c = 105 \mu\text{A}$ was measured and the chip (Hypres KL-1032-37) was tested from 70 GHz to 76.5 GHz. The results are presented in figure A1:

f (GHz)	stability
70.2	red
70.5	red
71.1	red
71.2	orange
71.425	orange
71.57	orange
71.788	orange
72.12	orange
72.245	orange
72.345	orange
72.45	orange
72.55	orange
72.65	orange
72.75	red
72.85	red
73.087	green
73.36	green
73.345	green
73.37	green
73.8	green
74.06	green
74.24	green
74.325	green
74.47	green
74.53	green
74.62	green
74.88	green
74.94	green
75.04	green
75.08	green
75.2	green
75.5	red
75.8	red
76.07	red
76.28	red
76.365	red

Fig. A1: Results of the frequency test performed on the EIM array with the BIPM equipment: the first column presents the tested frequency in GHz and the second column shows the corresponding non quantitative result in terms of the quality of the stability of the steps (green: > 10 s, orange: <10 s, red: no step).

Following the test, the array was successfully mounted on the EIM probe again and both arrays were biased at 74.78 GHz. Even if both systems were stable on their own it was impossible to carry out a single point because of the noise level in the measurement loop once both JVS connected together.

The following two changes resulted in important improvements:

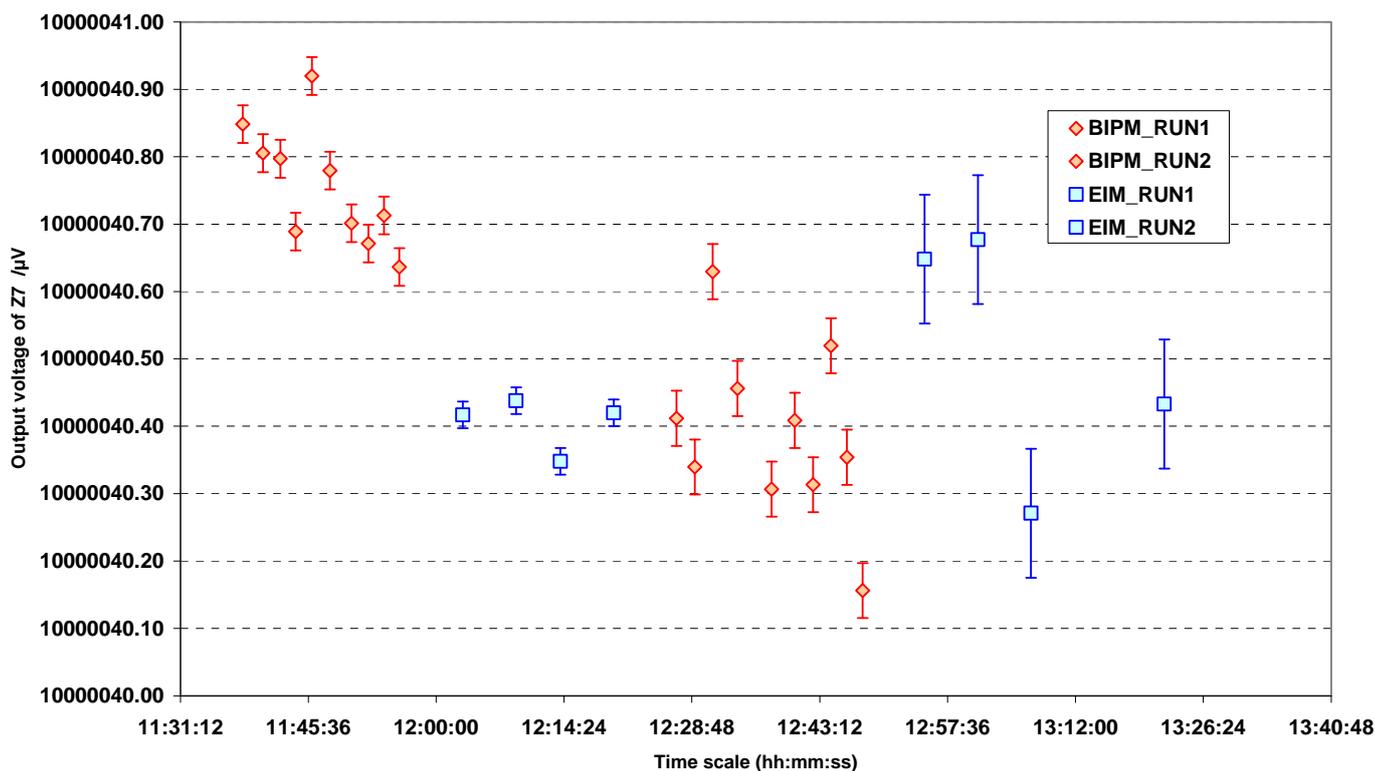


Fig A2b: Comparison results of the Zener Z7. EIM measurement results appear in blue and BIPM measurement results in red. The uncertainty bars represent the standard deviation of the mean of each individual series.

The results show that the voltage difference between the standards is quite large compared to what can be expected from an on-site Zener comparison:

$$U_{\text{BIPM}}(Z6) - U_{\text{EIM}}(Z6) = -0.411 \mu\text{V} \text{ and } U_{\text{BIPM}}(Z7) - U_{\text{EIM}}(Z7) = +0.167 \mu\text{V}$$

In particular, the BIPM measurements on Graph A2b show a drift of the Zener output voltage of 350 nV in about 1 hour. Investigating the possible reasons, we found out that the wire connecting the Zener to the BIPM reversing switch was damaged introducing an intermittent poor quality in the connection between the standards.

07 March 2010

The damaged leads were replaced and a quick check of the JVS was successfully performed. An additional improvement was done by removing the voltmeter that monitors the voltage across the BIPM JVS. This device was responsible for bringing too much noise in the measurement loop. The BIPM JVS had already shown a high level of stability and even if a jump could occur during

the measurement process, it will be interpreted by the software as a jump of the EIM JVS as both quantum standards were biased at the same frequency.

Within this configuration we managed to complete a set of preliminary measurements.

08 March 2010

Concerning the noise level in the measurement loop, an amelioration was achieved by grounding the BIPM Helium Dewar to the same potential of the EIM JVS through the shielding of the cables that connected both JVS and the quality of the connection between the two JVS, through the EIM electronic switch was improved (gold plated pins).

The *Windows* version of *Nistvolt* was implemented. This version of the software allows to control independently each module under remote control (EIP counter, biasing source, DVM, switch). The objective was to be able to disconnect the biasing source once the EIM array was manually adjusted on a selected step.

A nanovoltmeter Keithley 2182A was installed to measure the voltage difference between the two JVS. This instrument was controlled through a dedicated Labview© software.

The shielding of the IEEE bus that controls the nanovoltmeter was disconnected on one side in order to prevent from a ground loop.

Gain correction of the nanovoltmeter

The linearity of the nanovoltmeter was measured with the BIPM JVS leading to the determination of the gain correction to be applied to each measurement. Fig A3 presents the linearity of the detector.

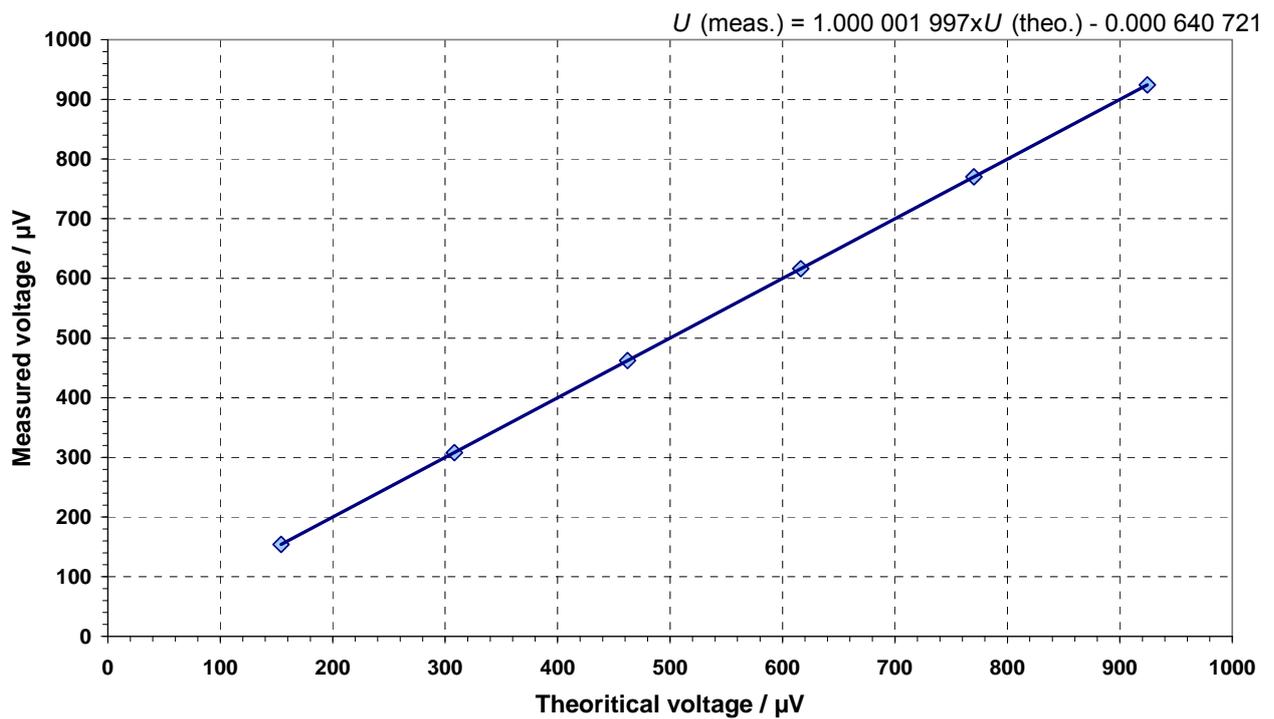


Fig. A3: Linearity of the nanovoltmeter used to measure the voltage difference of the two JVS.

Resistance of the measurement leads and uncertainty due to the leakage resistance

From the measurements of the resistance of each lead connected to the array (Cf. Fig. A4), it is possible to determine the resistance of the measurement leads ($R_E + R_F$) for each of the two arrays (Cf. Table A1):

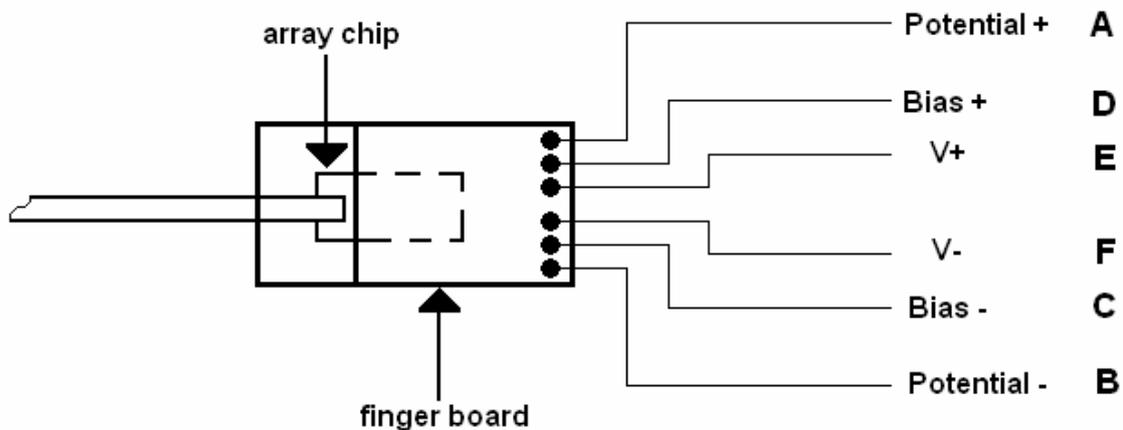


Fig. A4 : Detail of the finger board of an SIS Josephson array.

BIPM JVS	EIM JVS
$(R_E + R_A) = 2.5 \Omega ; (R_C + R_B) = 1.9 \Omega$	$(R_E + R_A) = 1.5 \Omega ; (R_C + R_B) = 0.9 \Omega$
$(R_D + R_A) = 1.8 \Omega ; (R_C + R_F) = 2.7 \Omega$	$(R_D + R_A) = 0.9 \Omega ; (R_C + R_F) = 1.5 \Omega$
$(R_E + R_D) = 2.6 \Omega ; (R_B + R_F) = 2.9 \Omega$	$(R_E + R_D) = 1.4 \Omega ; (R_B + R_F) = 1.4 \Omega$

Table A1: Details of the series resistance measurement.

$$(R_E + R_F)(\text{BIPM}) = 2.7 \Omega \text{ and } (R_E + R_F)(\text{EIM}) = 2.0 \Omega$$

Therefore, the uncertainty u_L on the voltage provided by the JVS due the leakage resistance R_L , will be expressed by the following equation if we assume a rectangular statistical distribution:

$$u_L = \Delta V / \sqrt{3} = ((R_E + R_F) / R_L) \times 10 \text{ V} / \sqrt{3}$$

$$u_L (\text{BIPM}) = 0.2 \text{ nV}$$

$$u_L (\text{EIM}) = 0.07 \text{ nV}$$