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

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

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BIPM

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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 National Measurement Institute (NMIA), Australia, in May 2006. The results are in very good agreement and the overall standard uncertainty is 1.7 parts in 10^{10}.

1. Introduction

In 2004, the BIPM sent a questionnaire to the national laboratories to propose a new type of comparison, where a stable reference voltage produced across the BIPM Josephson array is measured using the laboratories' Josephson array voltage standards (JAVS). This would allow direct comparison with the routine measurement technique used for calibrations in the laboratories, requiring only the BIPM array (not both arrays) to maintain a perfectly stable output during the measurements. This article describes the comparison of the BIPM 10 V standard with that of the National Measurement Institute (NMIA), Australia, carried out at the NMIA in May 2006.

2. Comparison equipment

2.1 The BIPM JAVS

The part of the BIPM JAVS used in this comparison comprises the cryoprobe with a Hypres 10 V SIS array, the microwave equipment and the bias source for the array. The Gunn diode frequency was stabilized using an EIP 578 counter and an ETL/Advantest stabiliser. To visualize the array characteristic, 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. To verify the step stability, an HP 34401A digital voltmeter (DVM) was used to measure the voltage between the array voltage bias leads. The series resistance of the measurement leads was 4 Ω, and the value of the thermal electromotive forces (EMFs) was found to be less than 50 nV. The leakage resistance between the measurement leads was greater than 10^{11} Ω. It should be noted that this value does not take into account the leakage due to the DVM and the external filter used during this comparison.

2.2 The NMIA JAVS

The NMIA voltage calibration system is a fully manual setup, except for automated data acquisition from the detector. All clients' standards are measured directly against the array, thereby significantly simplifying the traceability chain.

The cryoprobe is NMIA-designed and manufactured, and incorporates 3-stage low-pass filters on all lines. The array is equipped with a single mu-metal screen and a DC-block is not used. The array is biased with an NMIA-designed and built bias source which is powered by batteries and remains connected to the array during measurements. The step selection is manual. A characteristic feature of the NMIA bias source is that one side of the array is held as a virtual earth, which means that the standard being measured must be floating.

The Gunn diode supply has been designed and built by NMIA. The frequency is stabilised with an EIP 578B counter which is externally locked to the 10 MHz reference obtained directly from the NMIA-maintained primary frequency standard. The detector is a Keithley 182 nanovoltmeter connected to a pc via a GPIB/optic-fibre interface. Readings are stored in an ASCII data file which is imported into a spreadsheet for computations. The nanovoltmeter is periodically directly calibrated against the JJA (Josephson Junctions Array).

During normal calibrations, the Zener standard is disconnected from mains power and is connected to the array in series-opposition. The array is reversed using the bias source, and the Zener is reversed using a special NMIA designed and manufactured low-thermal emf reversing switch.

Some further details of the NMIA setup are:

- Type of array: 10 V SIS, manufactured by IPHT (s/n 1154/4);
- Detector: Keithley 182, used on the 3 mV range with analogue filter;
- Bias source: Designed and built by the NMIA, manually operated, with one side of the array held as a virtual earth. The array remains connected and is permanently biased during measurements;
- Oscilloscope: An HP 130C oscilloscope is used to visualise the steps;
- Software: a program developed in MODULA2 interfaces the nanovoltmeter, allowing the acquisition and electronic storage of the readings;
- Frequency source stabilizer: Counter EIP 578B with locking of the frequency to the external 10 MHz reference and a stability better than ±2 Hz during the period of the comparison. The NMIA array was irradiated at a frequency around 73 GHz;
- Measurement reversing switch: NMIA low thermal EMF switch;
- Thermal EMF (including array connections): approximately 400 – 600 nV, varies with liquid He level in reservoir;
- Impedance of array measurement leads: 6.5 Ω;
- Leakage resistance of measurement leads: > 3×10^{10} Ω.

3. Comparison procedures

The three preliminary measurements carried out on 11 May were satisfactory, and were included in the comparison results. During the week, some tests were performed to evaluate the robustness of the NMIA system, and to quantify different components; for example, the estimate of the thermal electromotive forces, the detector voltage offset and linearity tests, etc. The test measurements are described in Appendix B. Some measurements were also performed under the so-called "normal conditions comparison".

During the measurements, the NMIA array remained connected to its bias source referred to a virtual ground. The BIPM array was operated on batteries and was thus floating from ground during the step adjustment sequence, and was then disconnected from its bias source during the data acquisition process. The two arrays were connected in series-opposition via the NMIA low thermal-EMF switch, which was always used in the same position (ie., “forward” or “positive” position). In this comparison scheme (option “B”), the NMIA’s JAVS was used to measure the BIPM array voltage as if it were a Zener voltage standard. During the comparison, only the biases of the two arrays were reversed and no switch reversal was made.

4. Description of the measurements (also See Appendix A)

The following is a brief description of the procedure used by the NMIA to obtain a single measurement of the voltage of the BIPM array. Eight sets of 50 readings were taken, four sets in the positive polarity of the bias of the two arrays, and four in the negative polarity. These measurements followed the scheme: +, -, -, +, +, -, -, +. For each set, the program acquired 50 readings of voltage difference measured by the detector in about 12 seconds. The complete series of measurements took about five minutes when there was no array instability. The readings were stored in an ASCII datafile which was then imported into an Excel spreadsheet where the value attributed to the BIPM standard was calculated. The nanovoltmeter gain correction factor was included in the calculations. The spreadsheet displayed the residual of each reading allowing outliers to be manually removed from the calculation.

The differences between the values measured by the NMIA and the theoretical value of the BIPM array voltage during the comparison are plotted in Fig. 1, together with their Type A uncertainties. It is important to note that these values have been corrected for the 0.5 nV voltage drop due to the leakage in the BIPM filter added between the two systems.

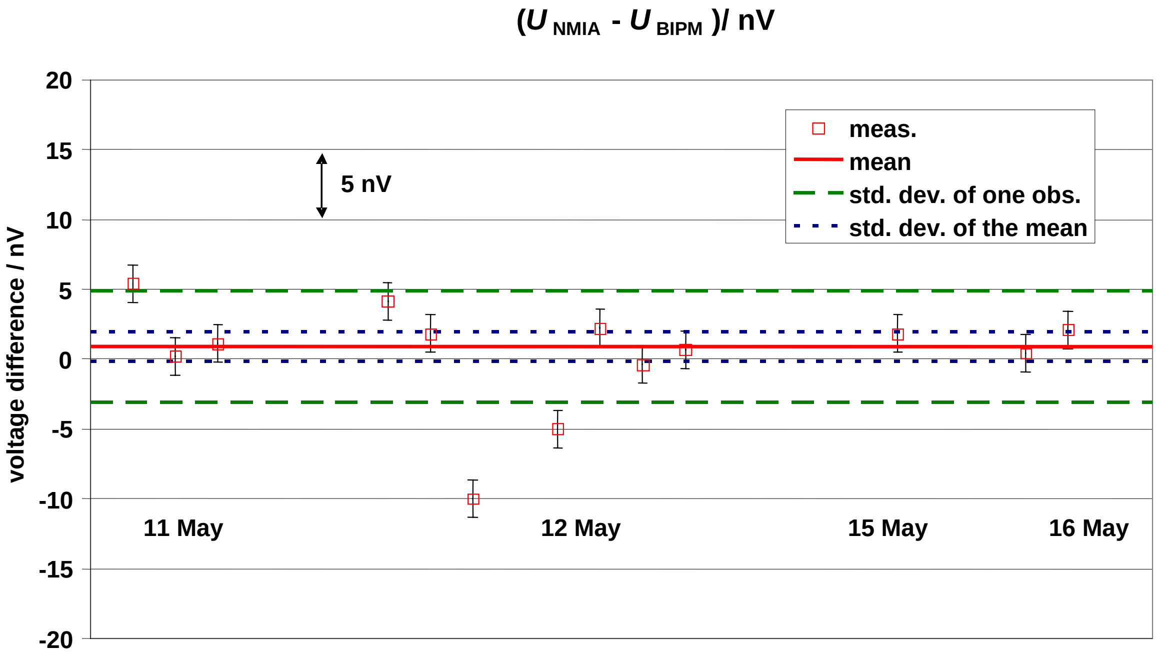

Fig. 1. Differences between the measured values and the theoretical value of the BIPM array voltage. Vertical bars are the mean value of the 1σ Type A uncertainties of the measurements (due only to the spread of detector readings during a measurement) and have a value of 1.35nV. The solid lines (––––) are the 1σ Type A uncertainty of the mean, and the dotted lines (– – –) are the 1σ Type A uncertainty of single measurements.

5. Uncertainties and results

The sources of Type B uncertainty (Table 1) are: the absolute value of the frequency measured by the EIP counter (ie., frequency offset), the measurement leakage resistance, and the detector gain and linearity. The frequency offset of the EIP counter is the main source of Type B uncertainty. Most of the effects of detector non-linearity and frequency stability are already contained in the Type A uncertainty. As both array polarities were reversed during the measurements, the effect of the residual thermal

EMFs (ie., non-linear drift) is also already contained in the Type A uncertainty of the measurements. (The standard Type A uncertainty of the mean was 1.1 nV.)

	Type	Uncertainty/nV	
		BIPM	NMIA
Frequency (*)	B	0.2	1.0
Leakage resistance	B	0.4	0.7
Detector (**)	B	-	0.1
Total (RSS)	B	0.4	1.2

Table 1. Estimated Type B standard uncertainty components.

(*) As both systems were referred to the same 10 MHz frequency reference, no uncertainty other than the EIP frequency offset is included.
(**) As the NMIA array was biased on different steps or at a voltage equal to that of the BIPM array, and as the detector gain was taken into account, a large part of the detector uncertainty (linearity) is already contained in the Type A uncertainty of the measurements. This component only expresses the effect of the uncertainty of the detector gain correction factor.

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

$$(U_{\mathrm{NMIA}} - U_{\mathrm{BIPM}}) / U_{\mathrm{BIPM}} = +0.9 \times 10^{-10} \quad \text{and} \quad u_{\mathrm{c}} / U_{\mathrm{BIPM}} = 1.7 \times 10^{-10}$$

where u_{c} is the combined standard uncertainty.

6. Discussion and conclusion

This comparison is the eighth of a new series where the host laboratory uses its own Josephson equipment to measure the voltage of the BIPM array, considered as the transfer instrument. The main feature of this new measurement technique is that it requires only the BIPM array, not both arrays, to maintain a perfectly stable and reproducible 10 V output during the measurements.

The BIPM equipment was installed and preliminary measurements were performed on the very day of arrival. During the following days, some modifications were intentionally made to various parts of the whole system (assemblage of the BIPM standard and the NMIA's measurement set-up) to check their influence on the measurements (step stability, noise level of the detector, etc.).

The results of the comparison demonstrate the ability of NMIA in 10 V measurements. This comparison allowed the laboratory to study the robustness of its measurement chain under different operating conditions.

It should be pointed out that no major improvements were carried out on the NMIA system, as a satisfactory level of accuracy (limited by the spread of the detector readings) was already attained at the stage of the preliminary measurements.

Appendix A

This appendix describes the measurements in a chronological manner.

11 May 2006

After having assembled the BIPM equipment, we had some difficulties in obtaining the expected stability for the steps on both standards. This problem was finally resolved by removing a capacitor (which is present in the usual operating conditions) between the bias leads of the BIPM array and by adding a filter at the output of the BIPM array measurement leads. This reduced the level of the noise introduced into the NMIA system when connecting it to the BIPM standard. With this new configuration, both systems demonstrated stability and three series of measurements were carried out.

12 May 2006

The stability of the NMIA standard was so satisfactory that, after the measurements carried out on 11 May, the BIPM and NMIA microwave frequencies were set in such a way that the voltages across the two arrays were adjusted to within a few microvolts.

Three series of measurements were carried out under the same conditions as 11 May. During the third series, the polarity of the detector was reversed without a significant change in the measured value to test for possible effects related to the side where the virtual ground of the NMIA bias source was connected to the detector.

After the test points described in Appendix B, four further series of measurements were carried out. In the first and second of these, the detector remained reversed. In the second and third series (and in the last series on 11 May), the DVM that monitored the BIPM array voltage was disconnected from the measurement leads. No significant change was observed.

15 May 2006

One series of measurements was carried out before the test measurements.

16 May 2006

Two series of measurements were carried out before the test measurements.

Appendix B

This appendix describes different test measurements carried out on the NMIA JAVS.

Thermal EMFs

During the preliminary measurements carried out on 11 May, the voltage of the thermal EMFs in the circuit appeared to be higher than expected. Since these spurious voltages, or at least their mean value and linear drift, were eliminated by the measurement procedure, they did not induce errors in the measurements. Nevertheless, on 13 May, five series of measurements were carried out to quantify the thermal EMFs in the leads that connect the arrays and the detector.

Measurements were carried out with both arrays biased on step #0 or on the critical current and with different polarities of the detector.

Considering the connections of the two Josephson standards shown in Fig. 2, and assuming the thermal EMFs to be constant, the following equations were derived:

$$D_N^{\,n} = -\,\varepsilon_A + \varepsilon_B - \varepsilon_D \quad (1);$$

$$D_R^{\,n} = +\,\varepsilon_A - \varepsilon_B - \varepsilon_D \quad (2);$$

$$D_N^{\,r} = -\,\varepsilon_A - \varepsilon_B - \varepsilon_D \quad (3);$$

$$D_R^{\,r} = +\,\varepsilon_A + \varepsilon_B - \varepsilon_D \quad (4).$$

D is the voltage measured by the detector with the subscript N when the detector is in the normal position, and with the subscript R when it is in the reverse position; ε_A is the sum of the thermal EMFs in series with Array A (BIPM), ε_B is the sum of the thermal EMFs in series with Array B (NMIA), ε_D is the thermal EMFs in series with the detector D (includes the detector bias); and the superscripts n and r denote the normal and reverse connections of array A.

ε_D can be found by combining equations 1 and 2 or 3 and 4. ε_A can be found by combining equations 1 and 3 or 2 and 4, and using the value of ε_D. ε_B can also be found by combining equations 1 and 4 or 2 and 3, and using the value of ε_D.

The values found for the thermal EMFs in the BIPM array measurement leads are consistent with those measured on 11 May by reversing the lead connections and biasing the BIPM array in the reverse polarity. (The same value was found within 1 nV.)

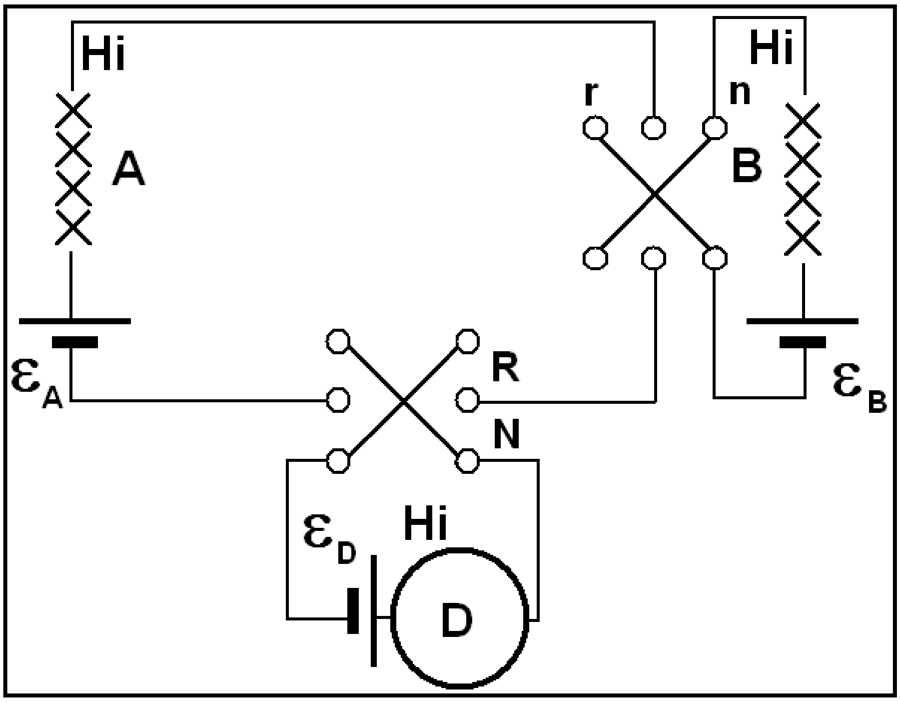

Fig. 2. Schematic diagram of the connections with the detector in normal (N) or reverse (R) position, and with the NMIA array in normal (n) or reverse (r) position. During the Josephson comparison, the NMIA array was always connected in the normal position.

Source	Thermal EMFs/nV
BIPM array (ε_A)	55
NMIA array (ε_B)	601
Detector (ε_D)	267

Table 2. Measured values of the thermal EMFs.

To check the stability of the thermal EMFs of the NMIA system, the vent valve of the liquid Helium vessel containing the array was left closed while measuring the voltage in the circuit. No significant drift was observed.

Detector noise

Five measurements were carried out on 15 May to test the parameters influencing the DVM noise. The NMIA JAVS measured zero voltage in different conditions without significant change:

a) the leads to the BIPM array were shorted at the top of the probe holder and the BIPM instruments were ON;
b) same as a) but with the BIPM instruments OFF;
c) the leads to the BIPM array were shorted on an external thermal shunt;
d) the leads to the detector were removed from the NMIA reversing switch and shorted;
e) same as d) but with detector set to analogue filter OFF (normally ON) and digital filter set to MEDIUM (normally OFF).

Test of other detectors

An EM-A10 amplifier was added to the input of the nanovoltmeter connected either with or without a home-made filter; measurements were then carried out with the filter (τ = 1 sec) to measure the gain of the amplifier with the two arrays biased at different voltages corresponding to 10 steps in both directions.

Three series of measurements were carried out to compare the two Josephson standards at 10 V, using the amplifier and filter connected at the input of the nanovoltmeter. Under these conditions, the steps of the NMIA array were less stable. Furthermore, though the noise level of the measurement was lower by a factor of 10, a longer time was needed to perform the measurements since the capacitor in the amplifier filter needed longer to charge. No significant improvement was thus obtained.

As it was possible under the usual measurement conditions to bias the two arrays at quite identical voltages, it should have been possible to carry out the measurements with an analogue null detector. An EM-N11 was thus connected in place of the Keithley 182. Nevertheless, it was not possible to obtain stable steps on the NMIA array under these conditions.

Leakage resistance test

A series of measurements at 10 V was carried out with a 1 kΩ resistor inserted in series between the two arrays, to measure the effects due to the leakage to ground. The observed difference would not be noticeable under normal conditions where the overall series resistance is typically 100 times lower. So no spurious voltages due to leakages were detected.