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Comparison of the Josephson Voltage Standards of the NMIJ-AIST and the BIPM

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

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Abstract. 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 Metrology Institute of Japan, Tsukuba, Japan, in October 2005. The results are in excellent agreement and the overall uncertainty is about 1.3 parts in 10^{10}.

1. Introduction

In 2004, the BIPM sent a questionnaire to the national laboratories to propose, among different options, 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 using the routine measurement technique used for calibrations in the laboratories, requiring only the BIPM array, but not both arrays, to maintain a perfectly stable output throughout the measurements. This article describes the comparison of the BIPM 10V standard with that of the National Metrology Institute of Japan (NMIJ) that was carried out at the NMIJ in October 2005.

2. Comparison equipment

2.1 The BIPM JAVS

The part of the BIPM JAVS used in this comparison comprises the cryoprobe with a Hypres 10V SIS array, the microwave equipment and the bias source for the array. The Gunn diode frequency is stabilised using an EIP 578 counter and an ETL/Advantest stabiliser. To visualize the array characteristic, while keeping the array floating from the ground, an optical isolation amplifier is placed between the array and the oscilloscope; nevertheless, during the measurements the array is disconnected from this instrument.

To verify the step stability, a HP 34401 DVM is used to measure the voltage between the array voltage leads. The series resistance of the measurement leads is 4 Ω and the value of the thermal electromotive forces (EMFs) changes from 40 nV to 200 nV depending on the configuration (cf. Appendix A of the report). The leakage resistance between the measurement leads is larger than 10^{11} Ω.

2.2 The NMIJ JAVS

The NMIJ voltage calibration system is designed to run in a fully automated manner without the need for operator adjustments. The Zener-based voltage standards (Zeners) are directly measured against the primary standard, thereby significantly reducing the traceability chain. The array is biased with a manual bias source which adjusts the array voltage within 0.5 mV of the voltage of the Zener to be measured. A preliminary measurement of the voltage output of the device under calibration (DUC) allows the operator to bias the Josephson array to a closer value of this voltage.
Once the voltage difference between the NMIJ's reference and the DUC is measured the voltage of the Josephson standard is modified in order to reach a null difference on the DVM. This correction is made by changing the frequency of the time reference of the EIP using a synthesiser, referred to a 10 MHz frequency standard. The normal procedure has two steps in this correction: a coarse, then a fine adjustment. The main advantage of this method is that no correction for the linearity of the detector is required.

- Type of array: 10V SIS, produced by Hypres (this array was used for the measurements on 14/10/05, but then another 10V SIS, produced by Prema was used for the measurements on 17/10/05 and 19/10/05);
- Detector: Digital micro voltmeter Advantest R6561, scale used 10 mV;
- Measurements made by reversing both the array bias and the connections to the standard;
- Bias source: NMIJ home made bias source;
- Array disconnected from bias source during measurements;
- Software used: NMIJ home made software (developed under BASIC environment);
- Frequency source stabiliser: EIP 578B using an NMJ stabiliser, which guarantees a stability within a few Hz. The 10 MHz time reference of the EIP 578B is generated by an HP3325A synthesiser referred to a 10 MHz frequency standard;

- A Tektronics 5440 oscilloscope is used to visualise the I-V curves and the josephson voltage steps;
- Reversing switch: at the NMIJ, the Zeners are incorporated in a box that provides the necessary switches for measurements; therefore during the comparison, no reversing switch were used;
- Thermal EMFs (including array connections) approximately 500 nV for Hypres and approximately 600 nV for Prema;
- Impedance of measurement leads approximately 1 Ω;
- Impedance of LC filter approximately 4 Ω;
- Leakage resistance for both of the probe holder is larger than 10^{12} Ω;
- Hypres array and Prema array operates at 85 GHz and 76 GHz, respectively.

3. Comparison Procedures

Preliminary and complementary measurements carried out on 13 October 14 and on 18 and 19 October are described in Appendix A. Only those measurements carried out with the usual NMIJ equipment on 14, 17 and 19 October were taken into consideration for the final result of the comparison.

During the measurements, the BIPM array was disconnected from its bias source. The two arrays were connected in series opposition via the BIPM low thermal EMF-reversing switch. In this new procedure (protocol of the option “B” comparison), the NMIJ’s JAVS is used to measure the BIPM array voltage as if it were a Zener voltage standard. In fact, in NMIJ Zener measurements, the polarity of the output voltage is reversed using the integrated reversing switch of each standard whereas in the Josephson comparison, only the bias of the array was reversed.

4. Description of the measurements

The following is a brief description of the NMIJ’s procedure to obtain a single measurement of the voltage of the BIPM array. When the NMIJ array is biased on a given step, one set of 10 readings of the voltage difference between the two arrays is carried out, in the positive polarity of the bias of the two arrays; should this step change before the end of the set, the measurements restart from the beginning. Then two series of similar sets of 10 readings are carried out in the negative polarity and again one set of 10 readings in the positive polarity. The complete set of measurement takes about six minutes. The result is computed in two different ways, depending on how the drift between measurements in the same polarity is taken into account; no significant difference is observed between the results of the two methods.

5. Uncertainties and results

The sources of type-B uncertainty (Table 1) are frequency stability and leakage resistance (note : in the measurement method used by the NMIJ, the microvolt meter is used as a null detector; in consequence, the uncertainty of the detector is already contained in the type A uncertainty). As both array polarities were reversed during the measurements, the effect of the residual thermal EMFs is already contained in the type-A uncertainty of the measurements.

Table 1. Estimated type-B standard uncertainty components

		Uncertainty/nV	
	Type	BIPM	NMIJ
Frequency	B	0.2	0.4
Leakage resistance	B	0.4	0.1
Total (RSS)	B	0.4	0.4

After the measurements on 17 October, it was considered that no further measurements were necessary for the comparison, but that complementary measurements could help improve the accuracy of the NMIJ JAVS (*see* Appendix A). Nevertheless, the first series of measurements carried out in the “usual" conditions on 19 October showed an unexpected difference between the two arrays whereas this difference was not observed in the measurements carried out in the afternoon. It was then decided to include these measurements in the comparison. The result of the comparison is the mean of the results of the 10 series of measurements carried out in the NMIJ “usual” conditions; the type A uncertainty is then 1.2 nV.

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

$(U_{NMIJ} - U_{BIPM}) / U_{BIPM} = -1.2 \times 10^{-10}$ $\qquad$ $u_c / U_{BIPM} = 1.3 \times 10^{-10}$

where u_c is the combined overall uncertainty.

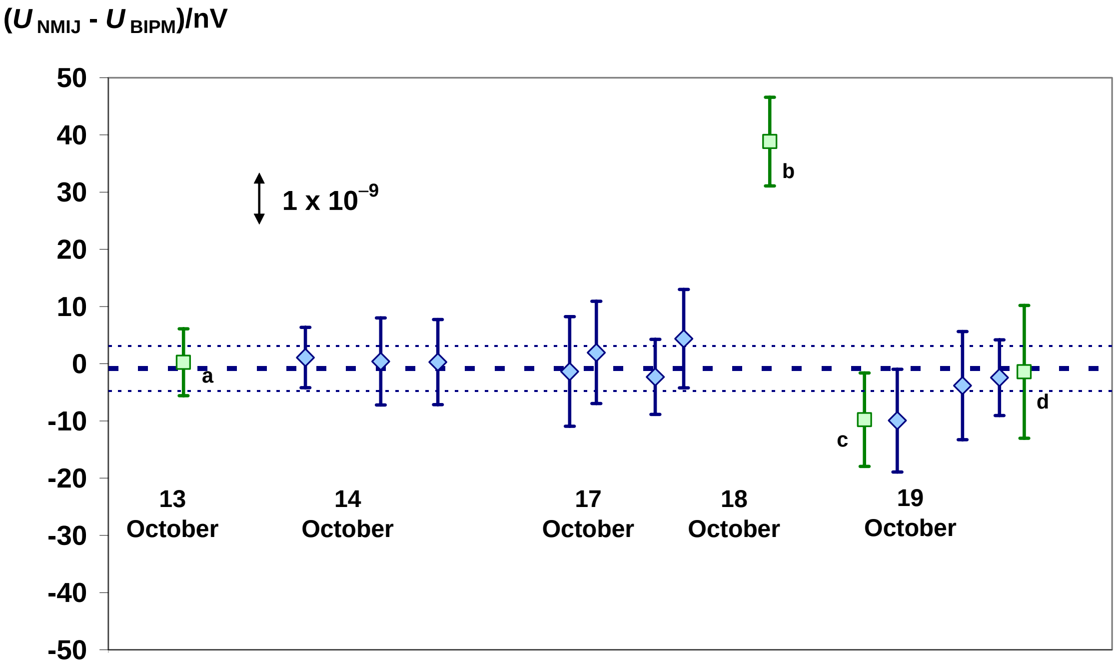

Fig. 1. Difference between the values measured by the NMIJ and the theoretical value of the BIPM array voltage. Diamonds: measurements taken into account in the comparison; squares: preliminary (a) and complementary measurements (b, c, d). The uncertainty bars represent the type A component (k=1).

6. Discussion and conclusion

This comparison is the fourth 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, but not both arrays, to maintain a perfectly stable and reproducible 10 V output throughout the measurements.

The BIPM equipment was installed and preliminary measurements were performed on the day after arrival; during the following days, adjustments were made to various parts of the NMIJ measurement system in order to improve the measurement conditions.

The results of the comparison demonstrate the ability of NMIJ in 10 V measurements. This comparison allowed the laboratory to study different problems, and improve the measurement conditions by using their new primary standard and guarantee the traceability from previous results.

Appendix A

Preliminary measurements.

Some difficulties had already been encountered when using different mains configurations during previous comparisons. At the NMIJ, the mains voltage is 100 V between a “neutral” and a “phase”. As the BIPM JAVS operates with a 220 V mains, a transformer was used whose output voltage was symmetric compared to the ground voltage. For this reason, preliminary measurements (“a” in Fig. 1) were carried out in order to verify that this would not disturb the BIPM JAVS stability.

NMIJ’s Josephson arrays.

Two different arrays are used by the NMIJ, each on a different probe holder.

In the past, the NMIJ encountered some problems with the Hypres array: spurious voltage offsets were observed during the measurements that were supposed to be due to RF rectifications at the positions of the electrical contacts. This was fixed by cleaning the contact board with acetone.

Measurements were carried out with this array on 14 October and then the other array, made by Prema was used on 17 October. The purpose of this part of the comparison was to ensure the traceability of the voltage primary standard of the NMIJ while changing the Hypres to the Prema 10V array. As no significant difference was observed between the results of those two arrays, this objective was achieved.

On 18 October, we proposed to mount the NMIJ’s Hypres array on the BIPM probe holder for further investigations. It appeared that in the range of 72 to 76 GHz the steps were either unstable (the microwave power was slightly too low) or sloped (at higher power, $R = 0.13\ \Omega$). As the BIPM JAVS is operated without bias current, it was expected to obtain satisfying results if the microwave power was sufficient to obtain stable steps, but the measured relative difference (“b” in Fig. 1) was 4 parts in 10^9.

NMIJ's null detectors.

The null detector used by the NMIJ in its measurement system is an Advantest R6561. This digital microvolt meter is relatively free of noise but has only a resolution of 10 nV. After having made in a very short time the necessary modification in the acquisition software, some measurements were carried out with an HP 34420A nanovoltmeter on 19 October.

The first series of measurements showed a relative difference of 1 part in 10^9 between the two arrays ("c" in Fig. 1). It was then decided to make another measurement with the original detector and an equivalent difference was observed. As subsequent measurements made in the afternoon without significant changes were in good agreement, no explanation could be given to the results obtained in the morning. A new series of measurement with the HP 34420A ("d" in Fig. 1) also gave satisfying results. Apparently, there is no noticeable difference between the results obtained with the two detectors.

Thermal EMFs

The total amount of thermal EMFs in the measurement circuit can be estimated by comparing the measurement values obtained when the arrays are biased in positive (+) and negative (–). It is to be noted that this also contains the input offset of the detector. As the measurements are carried out in a symmetric way (+, –, –, +), this quantity, as well as its linear drift, are eliminated in the measurement result. Only the non-linear part enters in the result. From Fig. 2, it appears that the short-term changes are more important than expected: this may be due to the detector environment.

The thermal EMFs in the BIPM JAVS were measured using both the BIPM reversing switch and array bias in "reverse" position. During the series on 14 and 17 October, a rather high value was measured (about 200 nV), but after the change of arrays on 18 and 19 October the usual value was obtained (less then 50 nV). We suppose that this difference was due to the position of the probeholder in the dewar (lower than usual in the first case) and/or to the pressure in the dewar (use of a helium gas recovering line in the first case).

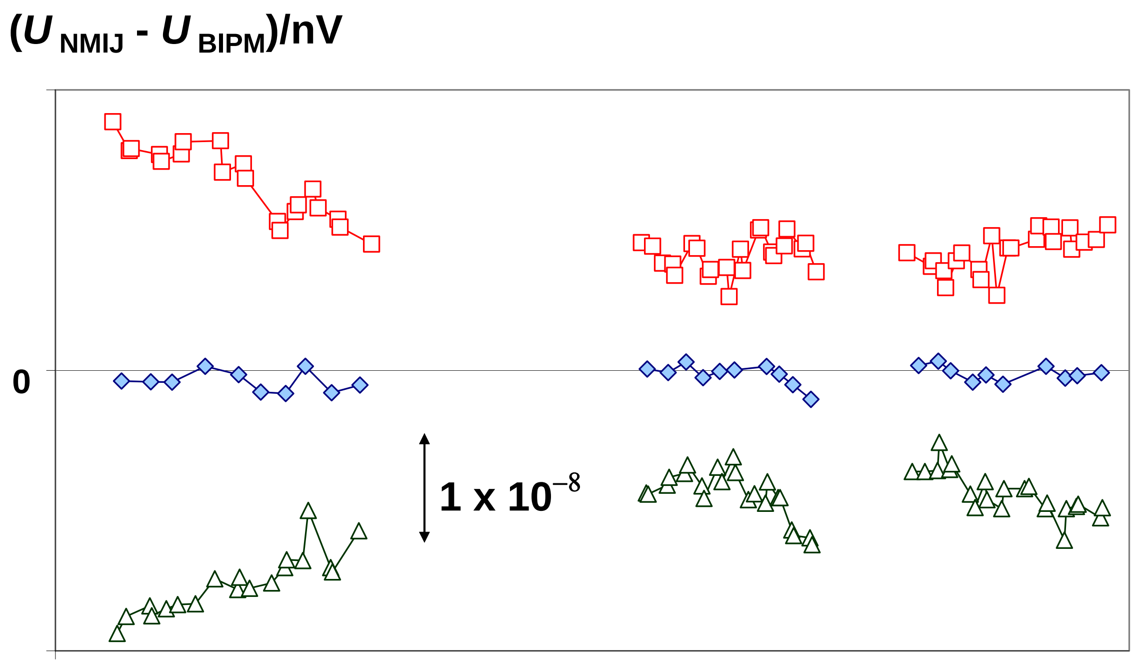

Fig. 2. Difference between the values measured by the NMIJ and the theoretical value of the BIPM array voltage on 19 October. Squares and triangles are for the values measured in (+) and in (–), respectively, with arbitrary origin (the mean value of the thermal EMFs is about 1 μV); diamonds are for the mean value of (+) and (–) measurements.

DISCLAIMER

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