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Comparison of the Josephson Voltage Standards of NMi VSL and the BIPM

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

S. Solve and R. Chayramy
Bureau International des Poids et Mesures
F- 92312 Sèvres Cedex, France

H.E. van den Brom and E. Houtzager
NMi Van Swindenlaboratorium
Thijsseweg 11 - 2629 JA Delft
PO Box 654, The Netherlands

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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 NMi Van Swindenlaboratorium (NMi VSL), The Netherlands, in October 2006. The results are in very good agreement and the measured overall standard relative uncertainty is 1.8 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 NMi Van Swindenlaboratorium (NMi VSL), The Netherlands, carried out at NMi VSL in October 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 300 nV, which is typically four times higher than in the BIPM's laboratory. 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 NMi VSL JAVS

The NMi VSL JAVS is routinely used to calibrate Zener diode based voltage standards. It is designed to run in a fully automatic manner once the operator has adjusted the array parameters (microwave frequency and power level). The NMi VSL working standards and some customer standards are directly measured against the JAVS. The array is biased with a modified commercial bias source (JVS-1002 from Vmetrix). The bias source is modified such that the array is floating from ground, such that the measurement ground can be chosen arbitrarily. The NISTVolt software biases the step, monitories the array using an HP 34420A, selects the Zener via a Dataproof 320B scanner, records the data using the same HP 34420A and computes the results. Some further details of the NMi VSL setup are:

- Type of array: 10 V SIS, manufactured by Hypres (s/n 2546H9);
- Detector: HP 34420A, used on the 10 mV range without any filter;
- Bias source: JVS-1002 from Vmetrix;
- Oscilloscope: A Tektronix 7603 oscilloscope is used to visualise the steps and adjust the RF power level at the beginning of a series;
- Software: modified version of NISTVolt;
- Frequency source stabilizer: Counter EIP 578B with locking of the frequency to the external 10 MHz reference and a stability better than ±4 Hz during the period

of the comparison. The NMi VSL array is irradiated at a frequency around 76 GHz;

- Thermal EMF (including array connections): approximately 700 – 900 nV, varies with liquid He level in reservoir;
- Total impedance of the two array measurement leads: 3.4 Ω;
- Leakage resistance of measurement leads: > 2.5×10^{11} Ω.

3. Comparison procedures

During the preliminary measurements carried out from 19 to 22 October, some significant defects coming from bad grounding connections, ground loops and leakage resistance were identified. Many different experiments (carried out on the four initial days) were required to isolate all their components and solve the correspondent defects. These test measurements are described in Appendix A. Measurements performed under the so-called "normal conditions comparison" were carried out on 23 and 24 October.

During the measurements, the NMi VSL array remained connected to its bias source which was battery operated and floating from 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 reference ground was chosen to be on the NMi VSL side. The two arrays were connected in series-opposition via the BIPM low thermal-EMF switch, which was always used in the same position (i.e., “forward” or “positive” position). In this comparison scheme (option “B”), the NMi VSL 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 NMi VSL to obtain a single measurement of the voltage of the BIPM array. For the comparison, the scanner and the JVS-1002 internal switching relays in the NMi VSL setup were not used. Instead, the JVS-1002 was used manually, whereas an HP 34401 was used to manually monitor the array voltage. In order to be more flexible and to have more control over the measurements, the NISTVolt software was replaced by a homebuilt program developed in Labview© to control the nanovoltmeter. Four sets of 30 readings 10 powerline cycles each (NPLC=10) are taken, two sets in the positive polarity of the bias of the two arrays, and two in the negative polarity. These measurements follow the scheme: +, -, -, +. For each set, the program acquires 30 readings of voltage difference measured by the detector. Those data are transferred from the internal memory of the nanovoltmeter to the computer at the end of the acquisition. The complete series of measurements takes about five minutes when there is no array instability. The readings are stored in an ASCII datafile which is then imported into an Excel spreadsheet where the value attributed to the BIPM standard is calculated. The nanovoltmeter gain correction factor and linearity correction are included into the calculations. The spreadsheet displays the residual of each reading allowing outliers to be manually removed from the calculation.

The differences between the values measured by the NMi VSL and the theoretical value of the BIPM array voltage during the comparison are plotted in Fig. 1.

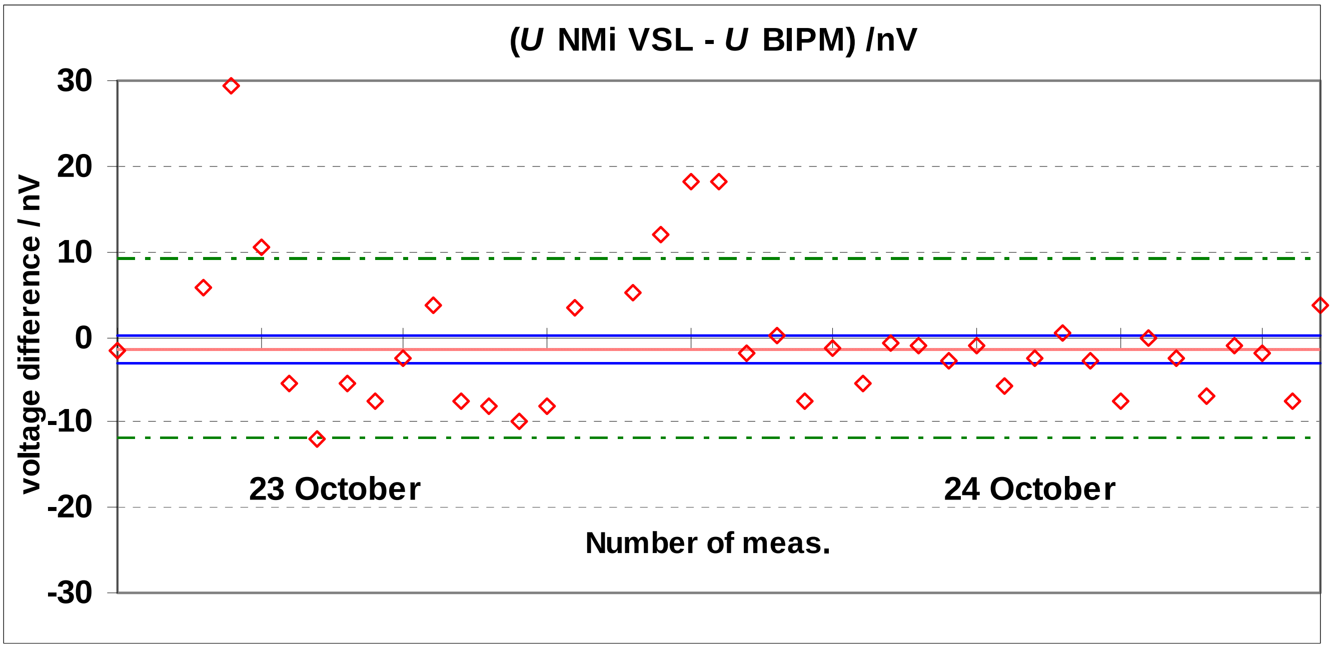

Fig. 1. Differences between the measured values and the theoretical value of the BIPM array voltage. The solid lines (––––) are the standard deviation of the mean, and the dotted lines (– – –) are the standard deviation of the single measurements.

5. Uncertainties and results

The sources of Type B uncertainty (Table 1) are: the absolute value of the frequency measured by the EIP counter (i.e., frequency offset), the measurement leakage resistance, 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 effect of the residual thermal EMFs (i.e., non-linear drift) is also already contained in the Type A uncertainty of the measurements.

Before and after each set of 30 readings, the frequency indicated by the NMi VSL counter was read. The deviation from the nominal value of 76.07 GHz, which was 1.3 Hz, was corrected for in the calculations. The standard deviation of the mean was taken as Type B uncertainty.

The uncertainty due to the leakage is the measurement lead resistance divided by the leak resistance.

The detector non-linearity was determined just before the comparison using the NMi VSL binary Josephson system. The 10 mV range was calibrated by applying a binary Josephson voltage varying from –10 mV to +10 mV with a step resolution of 144.7 μV (resulting in 139 calibration values), and repeating this sequence 100 times. A ninth order polynomial fit was used to correct for the deviation from linearity, which results in a Type B uncertainty of 1 nV taken as a rectangular distribution.

The standard Type A uncertainty of the mean was 1.6 nV.

	Type	Uncertainty/nV	
		BIPM	NMi VSL
Frequency (*)	B	0.2	0.03
Leakage resistance	B	0.4	0.10
Detector (**)	B	-	0.58
Total (RSS)	B	0.4	0.6

Table 1. Estimated Type B standard uncertainty components.

(*) As both systems were referred to the same 10 MHz frequency reference, only a Type A uncertainty of the EIP frequency is included.
(**) As the NMi VSL array was biased on different steps or at a voltage equal to that of the BIPM array, and as the detector gain and linearity were taken into account, 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 result, expressed as the relative difference between the values that would be attributed to the 10 V Josephson array standard by the NMi VSL ($U_{\text{NMi VSL}}$) and its theoretical value (U_{BIPM}) is:

$$(U_{\text{NMi VSL}} - U_{\text{BIPM}}) / U_{\text{BIPM}} = -1.5 \times 10^{-10} \text{ and } u_c / U_{\text{BIPM}} = 1.8 \times 10^{-10}$$

where u_c is the combined standard uncertainty.

6. Discussion and conclusion

This comparison is the ninth of a new series (started in September 2004) 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 on the very day of arrival. The preliminary measurements showed some discrepancies due to a heavy leakage effect to ground. These effects were not critical for Zeners diode standards calibration but were unacceptable for a comparison of two quantum standards. During the next four days many modifications were intentionally made to various parts of the whole system (assemblage of the BIPM standard and the NMi VSL measurement set-up) to find out the issues and correct for their influence on the measurements. The results of the comparison demonstrate the ability of NMi VSL in 10 V measurements. This comparison allowed the laboratory to characterise more accurately and improve the robustness of its measurement chain.

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.

Appendix A

This appendix describes the measurements in a chronological manner.

19 to 22 October 2006

After having assembled the BIPM equipment, we managed to obtain without major difficulties a satisfactory stability for the steps on both standards. The ground reference was decided to be set on the NMi VSL side. A DVM was added across the NMi VSL array to monitor its voltage. The first seven series of preliminary measurements gave a voltage difference between the two systems of 3 µV! The problem was identified as coming from a leakage effect between the ground (chassis of the measurement bay) and the NMi VSL bias source. Even if the JVS was operating on batteries (floating from the ground), the DAC (Digital-to-Analog Converter) of the source still seemed to be referred to the main ground. From that situation many experiments were carried out:

1- Grounding the systems on the BIPM side;

2- Grounding the low of the detector;

3- Changing the connections box that linked the two Josephson systems;

4- Shifting the grounding point from the shielding of the connecting box to a point inside it;

5- Building some new connecting wires (array biasing leads, connection leads).

None of these experiments improved the final result: the voltage difference was still found to be to the order of 3 µV with a repeatability of a few tens of nanovolts !

We finally decided to remove the JVS 1002 bias source and bias the NMi VSL by the BIPM array. In that configuration, both arrays are biased by the BIPM bias source which was referred to ground. This experiment was already carried by B. Wood (NRC), Y. Tang (NIST) and C.A. Hamilton (Vmetrix) during a similar exercise [1].

We found that a leakage still existed between the ground (chassis of the bay) and the grounding point in the connection box when the BIPM bias source was grounded. The leakage current disappeared each time the source was switched to batteries (within a capacitor loading effect) .

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[1] "Direct Josephson Voltage Array Comparison between NRC and NIST" CPEM 2006 conference digest pp 14-15.

We decided to warm up both systems to check the leakage resistance between the measurement wires (R_1) and between each of them and the ground (R_2).

We found $R_1 = 0.5 \times 10^{12}\ \Omega$ and $R_2 = 0.25 \times 10^{12}\ \Omega$ on the NMi VSL probe, and the expected values on the BIPM probe.

The NMi VSL array was then mounted on the BIPM probe in order to analyse its behaviour when operated by the BIPM system. It was found to be very stable over an interval of different RF frequencies.

From that situation, it was demonstrated that the leakage problem wasn't coming neither from the array itself nor its connection to the probe.

In order to determine if this repeatable difference of 3 µV was coming either from a ground loop or a leakage resistance, we decided to perform some measurements at 0 V and at 5 V. The measured difference was found to be 1.7 µV at 5 V and null at 0 V. The results showed that we were facing a real leakage resistance problem as the measured difference was proportional to the voltage nominal value.

It should be noticed that the 0 V comparison was carried out both on the zero step and on the critical current to check that there were thus no RF power rectified on the array.

On 23rd of October, we finally found two major issues in the NMi VSL setup:

- A resistance of 100 ohms was found between the metrological ground (measurement bay) and the earth plug of the mains! Furthermore, the computer was not powered on the same 220 V power line.
- The 10 MHz reference is distributed to several other experiments in the shielded laboratory. A metallic pipe fixed on the ceiling permits the distribution of the coaxial cables to the different sites. We noticed that the metallic outer part of each BNC extension cables was touching the pipe. This situation could create a ground loop and introduce some noise into the system.

To improve the ground connection :

- The measurement bay was powered through an isolation transformer, the metrological ground was maintained on the bay.

- All the instruments located in the bay that were not required were unplugged from the mains (for instance the charging module for the Zeners) and their IEEE bus plugs were also removed.

- The BIPM EIP internal 10 MHz oscillator was chosen to be the reference for both counters.

Furthermore, the measurement chain was simplified. For instance, the nanovoltmeter input was shorted during the adjustment period of the two systems in such a way that the scale of the nanovoltmeter was maintained on the 10 mV range without getting into overload. To perform this operation, NMi VSL uses a MI-4020A scanner for which the selected output (controlled by a IEEE bus) was shorted. We decided to replace this sophisticated system by a manual two positions switch. One of the positions was equipped with a short.

All these modifications lead to a noticeable improvement . A residual leakage was found between the chassis of the nanovoltmeter and the measurement bay. The HP34420A chassis was then isolated from the bay.

24 to 26 October 2006

Following this significant improvement, we decided to rebuilt the NMi VSL measurement chain point by point.

Biasing source

At this stage, the NMi VSL array was still biased by the BIPM array. We set up a JBS-500 biasing source to bias NMi VSL array. Compared to the JVS 1002, the JBS-500 allows to add a pulse (+12 V) on the biasing circuit and also to open the biasing circuitry once the adjustment is satisfactory. It is important to note that we kept the Gunn diode biasing source from the JVS 1002 module. After some measurements we successfully switched back to the "official" biasing source (JVS 1002).

10 MHz reference signal

The calibration of the nanovoltmeter was carried out with an binary Josephson setup using a Gunn diode stabilized with an EIP counter referred the external 10 MHz signal. As corrections were applied for gain and linearity on the comparison results, we had to refer the RF signals again to the external 10 MHz signal. We successfully used an isolation amplifier to isolate the reference signal.

Filtering connection between the two systems.

The additional BIPM filter in between the two systems was removed. We were then back to an operationally independent Josephson Voltage Standard measurement system. The details of the grounding connections between the two systems are shown in Fig. 2.

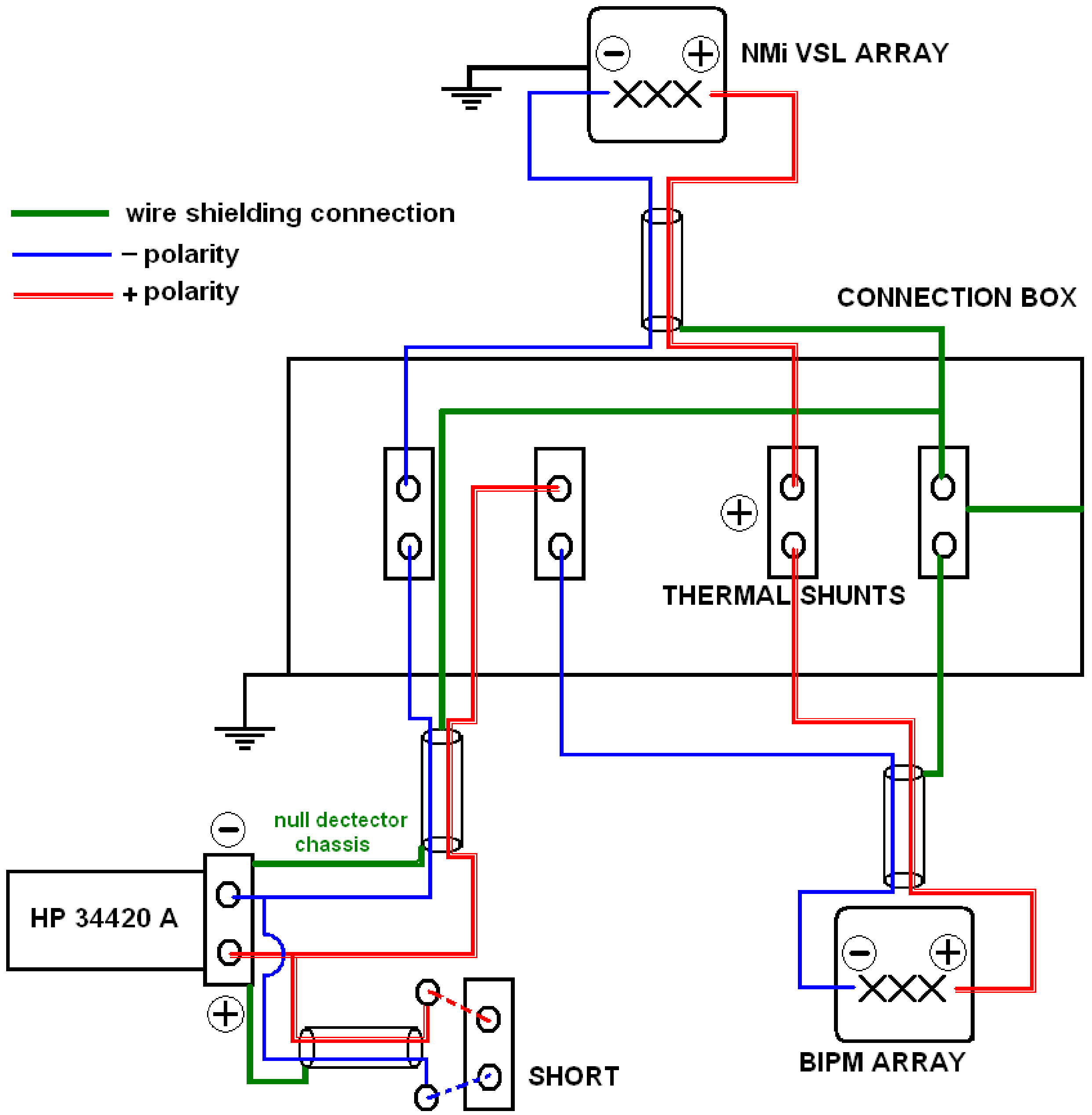

Fig 2: details of the connection box between the two JVS systems and grounding connections.

From this situation all the measurements carried out were very satisfactory and lead to the final result mentioned in the report.

Furthermore, the stability of the steps on the BIPM Josephson array was extended to a larger range of frequencies in such a way that it was possible to carry out the comparison using an identical frequency on both systems.