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Comparison of the Josephson Voltage Standards of the INETI 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 Instituto Nacional de Engenharia, Tecnologia e Inovação (INETI), Lisbon, Portugal, in March 2006. The results are in excellent agreement and the overall uncertainty is about 2.6 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 Instituto Nacional de Engenharia, Tecnologia e Inovação (INETI), carried out at the INETI in March 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 10V SIS array, the microwave equipment and the bias source for the array. The Gunn diode frequency is stabilized using an EIP 578 counter and an ETL/Advantest stabilizer. 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; during the measurements, the array is disconnected from this instrument. To verify the step stability, a HP 34401 A digital voltmeter (DVM) is used to measure the voltage between the array voltage bias leads. The series resistance of the measurement leads is 4 Ω, and the value of the thermal electromotive forces (EMFs) is less than 50 nV. The leakage resistance between the measurement leads is larger than 10^{11} Ω.

2.2 The INETI JAVS

The INETI JAVS is routinely used to calibrate Zener diode based standards. The INETI's working standards and some customer standards are directly measured against the JAVS, thereby significantly reducing the traceability chain. The 10V SIS is assembled with the cryoprobe by IPHT and biased by an isolated programmable current source. The RF source is a Millitech Gunn Diode with a central frequency at 75 GHz, and the working frequency is locked by an EIP578B frequency counter. The system was assembled in 2005 and has been operational since then. Step biasing, array monitoring and the connection of the Zener under test are automatically operated by software. The array is floating with respect to ground. At the INETI, the command program is coupled with a measuring program (both developed in a Labview environment). The voltage from the detector (Agilent 34420A), the frequency from the EIP counter, the power distributed by the RF source (measured by a powermeter Agilent E4418B coupled with an Agilent V8486A power sensor) and the voltage across the array (Agilent 3458A) are monitored and stored in an electronic file. The GPIB interface for reading the measurement instruments is optically isolated from the computer. The 10 MHz reference signal for the EIP counter distributed by a GPS receiver is also electrically isolated. Some further details :

- Type of array: 10 V SIS, produced by IPHT s/n 11038;
- Detector: Agilent 34420A, scale used 100 mV;
- Bias source: IPBS-JJ-02 produced by the NPL;
- Array: disconnected from the bias source during measurements;
- Software used: JZComp, version 2.1, INETI-production measurement program based on Labview, modified on 10 March 2006;
- Frequency source stabilizer: counter EIP 578B, internal locking of the frequency, stability better than 2 Hz;

- Measurement reversing switch: dataproof scanner - this device was not used during the comparison; the output of the BIPM array was connected to the INETI device through a BIPM low thermal EMF switch;
- Thermal EMFs approximately 200 nV;
- Impedance of measurement leads approximately 3.9 Ω;
- Leakage resistance approximately 3×10^{10} Ω.

3. Comparison procedures

Preliminary and test measurements carried out on 9 March 2006 are described in Appendix A. Only those measurements carried out on March 10, 13 and 14 are taken into consideration for the comparison.

During the measurements, both arrays were disconnected from their bias sources. The two arrays were connected in series via the BIPM low thermal EMF switch, always used in the same position. In this new procedure (option “B”), the INETI’s JAVS is used to measure the BIPM array voltage as if it were a Zener voltage standard. Actually, in the INETI Zener measurements, the polarity of the reference output voltage is reversed using the bias source and the reversing of the Zener voltage reference is performed with the scanner. During the comparison, only the bias of the two arrays were reversed and no switch reversal was made. Both systems were floating from the ground during the measurements.

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

The following is a brief description of the procedure used by the INETI software to obtain a single measurement of the voltage of the BIPM array. A series of 6 measurements are carried out, 3 in the positive polarity of the bias of the two arrays and 3 in the negative polarity. These measurements can follow two different chronological schemes : +, -, -, +, +, - or -, +, +, -, -, +. For each measurement in one polarity, the program acquires points (voltage difference measured by the detector) according to a mobile mean. The acquisition stops when the standard deviation of N successive points is below a certain level L (N=10 and L=100 nV for the calibration of Zener voltage standards and N=15 and L=10 nV during the Josephson comparison exercise). To remain within this level, INETI's array has to stay on the same step otherwise the

acquisition process starts again. The complete series of measurements takes about five minutes when there is no array instability after the reversal of the polarity. The value attributed to the BIPM standard is the mean of the positive measurements and of the negative measurements.
When acquisition starts, the measurements on the detector are not filtered. After a few seconds, when an equilibrium is reached (capacitor charge effect in the system), the numeric filter is engaged to reduce the noise level. The readings are corrected by the software to take account of the errors in the DVM. The DVM is periodically calibrated by the JVS.
A detailed description of the measurement configuration is given in the Appendix A.

It should be pointed out that in most cases the reproducibility of the different measurements within a series is poor, as compared with the expected stability of the thermal electromotive forces (EMFs). For this reason, the mean value of the dispersion of these measurements in each polarity can be considered as an estimate of the Type A uncertainty of each series.
Individual data for the difference between the value measured by the INETI and the theoretical value of the BIPM array voltage are plotted in Fig. 1 together with their Type A uncertainties.

5. Uncertainties and results

The sources of Type B uncertainty (Table 1) are: the absolute value of the frequency measured by the EIP counter, the measurement leakage resistance and the detector gain and linearity. The leakage resistance of the measurement circuit is the main source of Type B uncertainty; most of the effects of non linearity and frequency stability being already contained in the Type A uncertainty. As both array polarities were reversed during the measurements, the effect of the residual thermal EMFs is also already contained in the Type A uncertainty of the measurements. (The standard Type A uncertainty was 22 nV.)

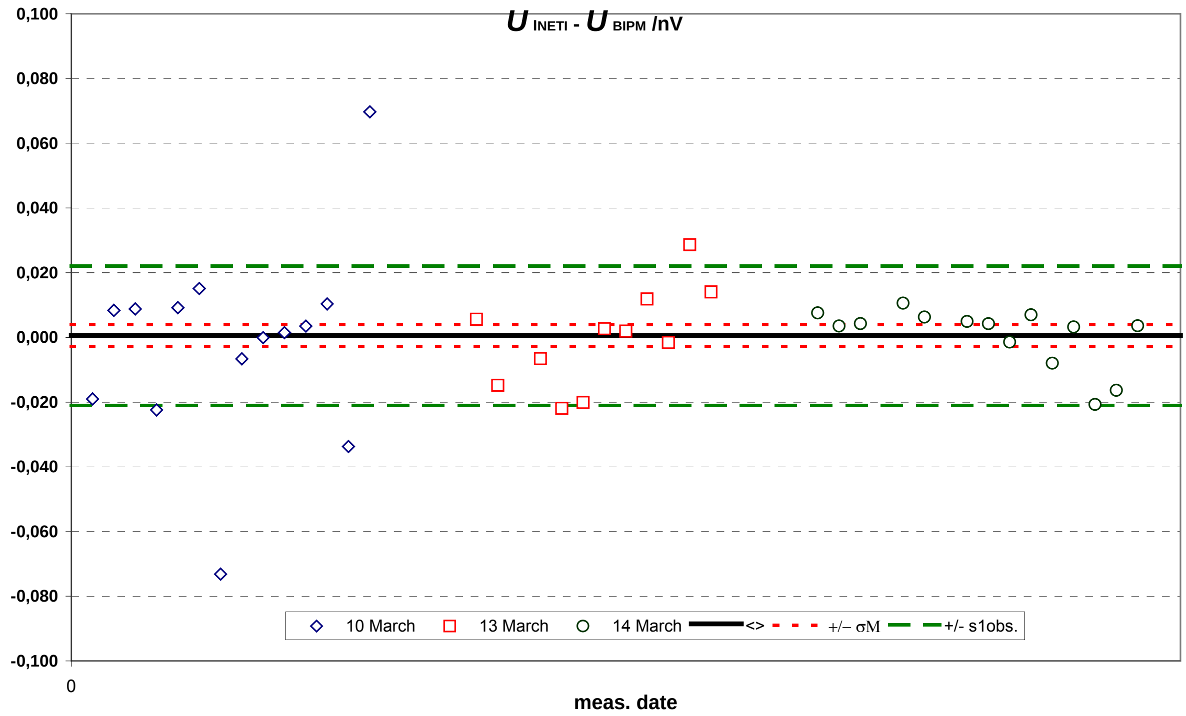

Fig. 1. Difference between the measured values and the theoretical value of the BIPM array voltage. The dashed lines (— — —) are the 1σ Type A uncertainties of a single measurement, and the dotted lines (- - -) are the 1σ Type A uncertainties of the mean.

	Type	Uncertainty/nV BIPM	INETI
Frequency	B	0.2	0.2
Leakage resistance	B	0.4	3.6
Detector (*)	B	-	2.9
Total (RSS)	B	0.4	4.6

Table 1. Estimated Type B standard uncertainty components.

(*) As the INETI array was biased on different steps and as the detector gain was taken into account, a large part of the detector uncertainty (linearity and gain) is already contained in the Type A uncertainty of the measurements. This component only express the resolution of the detector.

As both systems were refered to the same 10 MHz frequency reference, no additional uncertainty than the EIP frequency stability is included.

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

$$(U_{\mathrm{INETI}} - U_{\mathrm{BIPM}}) / U_{\mathrm{BIPM}} = 0.8 \times 10^{-10} \quad \text{and } u_{\mathrm{c}} / U_{\mathrm{BIPM}} = 4.6 \times 10^{-10}$$

where u_{c} is the combined standard uncertainty.

6. Discussion and conclusion

This comparison is the sixth 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 day after arrival. During the following days, adjustments were made to various parts of the INETI measurement set-up in order to improve the performance of the whole system (step stability, noise level of the detector, etc.). The comparison itself was then carried out with these improved conditions.

The results of the comparison demonstrate the ability of INETI in 10 V measurements. This comparison allowed the laboratory to study various problems, and to improve the measurement conditions. In particular :

1 By testing the array stability at frequencies other than the frequency suggested by the manufacturer.

2 By testing the software routine which calculates the correction for the readings of the DVM in respect of the linearity of the device's calibration.

3 By optimizing the use of the numerical filter of the DVM, it would be more satisfactory to use only an analog filter on the DVM readings and leave the appropriate calculation with an adequate computer routine, to the operator.

It should be pointed out that the INETI system, as it was at the beginning of the comparison, was already suitable for Zener measurements; as the observed deviations in these conditions were of only a few parts in 10^9, the limiting parameters could not have been determined without a direct Josephson comparison.

Appendix A

9th March: preliminary measurements

After having assembled the BIPM equipment, we had some difficulties in obtaining the expected stability for the steps on the BIPM standard whereas no difficulties were found with the normal working conditions for the INETI standard. This problem was finally solved by connecting the chassis of the EIP counter to the oscilloscope ground. No other difficulties observed on connecting the two systems together. The first series of measurements were carried out under the following conditions:

1 The frequency of the INETI Gunn diode was locked to the usual operational value: 75 GHz;

2 The numerical filter was activated on the nanovoltmeter;

3 As the INETI standard was floating from the ground, the BIPM bias source was maintained by the mains during adjustments phases. Both systems were completely floating during the measurements phases;

4 For each start of data acquisition, after a polarity reversal, an exponentially decreasing deviation of the signal was observed for the recorded voltage measured by the detector.

The results of the 5 first series lead to the following result:

U_{INETI} - U_{BIPM} = -59 nV, with a standard type A uncertainty of σ_{M} = 14 nV.

This result fulfils the CMCs for INETI.

Complementary measurements and improvements

Here we tried some improvements on the INETI Josephson Voltage Standard.

Detector within-a-run calibration

Here we mention some problems due to the way the final results were derived from the measured data. During the measurements, all the readings from the detector were corrected to take account of the detector's calibration values. Furthermore, at the end of the six series of measurements within a run, the intermediate results are used to re-calibrate the gain of the detector. When the series were made at very different values of the array voltage, this re-calculation had little effect on the final result. As most of the series were made on near values of the array voltage, the uncertainty of this re-calculation was large and the correction applied was not justified. For this reason, some improvements obtained in measurements during the following days could not been detected on real time, but only when computing the final result after the comparison.

10th March

In order to reduce the noise coupling between the two systems, an additional BIPM filter was installed in series with the BIPM array measurement leads. The immediate consequence was a decrease in the noise of the circuit; the extra leakage resistance introduced by this additional filter was taken into account for the calculation of the voltage delivered by the BIPM standard. In other words, the BIPM reference voltage has to be reduced by 0.5 nV, the voltage drop introduced by the leakage resistance of this filter. In addition, the voltage drop across the INETI measurement leads introduced by the 3×10^{10} Ω leakage resistance of a 1 μF capacitor, placed here to improve the steps stability, was taken into account.

13th March

The calibration software was modified to allow the operator to engage or disengage the numerical filter of the DVM. Thus a new procedure was set up to carry out the measurement to avoid the charge effect detected on the preliminary series. At the beginning of the measurements, during the time required for stabilization of the voltage, the filter was disengaged and then was engaged. The direct consequence was to eliminate the exponentially decreasing deviation of the recorded voltage at the beginning of the measurements.

As we observed that the stability of the steps was strongly sensitive to the RF power delivered by the Gunn diode, we tried to operate the array at other frequencies in the range 72 - 75 GHz, and found a better working condition of the array at 73.750 GHz.

In the afternoon, to increase the stability of the steps, a 6.8 μF capacitor was placed in parallel with the INETI voltage leads. The leakage resistor introduced by this new capacitor, measured by INETI, is also of the order of 3×10^{10} Ω.

The results of thirteen series of measurements undertaken this day, without using the “re-calculation process” gave the following result:

$U_{\mathrm{INETI}} - U_{\mathrm{BIPM}}$ = -7.1 nV, with a standard type A uncertainty of σ_{M} = 6.8 nV.

14th March

As explained in the paragraph “Detector within-a-run calibration”, possible improvements due to several modifications made on the INETI system could not be observed in the results.

The low input connector of the detector was connected to the ground after having set the BIPM standard in the battery operated mode. In this configuration, the stability of the INETI array was compromised and no measurements were possible.

At both the INETI and the BIPM, the mains voltage is about 230 V between a “neutral” and a “phase”. As the Portuguese mains plugs are symmetric, some instruments had been connected in the wrong position.

The voltmeter Agilent 3458A which allows the determination of the step number of the INETI array was suspected to introduce some electrical noise into the system. In order to verify this hypothesis, we connected an extra filter on the plugs of the DVM.

We saw that there was no dc-block between the upper part of the cryoprobe and the array. Unfortunately, after the installation of a dc-block we did not observe any decrease in the level of noise.

The results of fourteen series of measurements for this day, without using the "re-calculation process" gave the following result:

U_{INETI} - U_{BIPM} = 0.5 nV, with a standard type A uncertainty of σ_M = 2.6 nV.

Conclusion

The results represented on the Fig. 1 can be analyzed following these improvements. The noise level was not reduced during all the measurement series, nevertheless, there is no doubt that the stability of the INETI standard was improved. The repeatability of the measurement results was also clearly improved.

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.