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Comparison of the Josephson Voltage Standards of the CEM 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 Centro Español de Metrología, Tres Cantos, Madrid, Spain, in September 2005. The results are in excellent agreement and the overall uncertainty is about 1.5 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 Centro Español de Metrología (CEM) that was carried out at the CEM in September 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 3458 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 EMFs is less than 50 nV. The leakage resistance between the measurement leads is larger than 10^{11} Ω.

2.2 The CEM JAVS

The CEM 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 computer driven bias source which adjusts the array voltage within 3 mV of the voltage of the Zener to be measured. A manual low thermal EMF switch is used to connect and reverse the polarity of the Zener.

- Type of array: 10V SIS, produced by Hypres
- Detector: Keithley 182, scale used 3 mV
- Measurements made by reversing both the array bias and the connections to the standard
- Bias source: JBS 500
- Array disconnected from bias source during measurements
- Software used: Nistvolt version 4.7 , modified by CEM in 1997
- Frequency source stabiliser: EIP 578B using JBS 500 internal locking, stability within a few Hz
- Reversing switch: Guildline Model 9145A5
- Thermal EMFs (including array connections) approximately 200 nV
- Impedance of measurement leads approximately 1.2 Ω

3. Comparison Procedures

Preliminary measurements carried out from September 15 to 19 are described in Appendix A. Only those carried out on September 20 and 21 are taken into consideration for the comparison.

During the measurements, the BIPM array was disconnected from its bias source. The two arrays were connected in series opposition via the CEM's reversing switch and a BIPM low thermal EMF-reversing switch. In this new procedure (option "B"), the CEM's JAVS is used to measure the BIPM array voltage as if it were a Zener voltage standard. In fact, in CEM Zener measurements, the polarity of the output voltage is reversed using the switch whereas in the main part of the Josephson comparison, only the bias of the array was reversed and no switch reversal were made. The "low" of the CEM detector was connected to ground via the bias source.

The CEM system uses the DVM readings to determine the step-number of the array. During the comparison, both CEM and BIPM millimetre-wave frequencies were identical, so that jumps in the CEM and BIPM array (seldom for the BIPM array) were compensated for by the CEM analysis system.

4. Description of the measurements

The following is a brief description of the procedure used by the CEM software to obtain a single measurement of the voltage of the BIPM array. Twelve sets of 40 readings of the voltage difference between the two arrays were carried out, in the positive polarity of the bias of the two arrays. Then twelve sets of 80 such readings were carried out, in the negative polarity and again twelve sets of 40 readings in the positive polarity. The complete measurement took about fifteen minutes. From each twelve sets of measurements, only the ten nearest to the mean were kept. The result is the mean of the positive measurements computed at the mean time of the measurements and of the negative measurements.

The readings were corrected by the software to take into account the value of the DVM gain. This value was measured by biasing the BIPM array on different steps while the CEM array was kept at 0 V on its critical current (without millimetre waves).

During the last two measurements on September 20, and all of the measurements on September 21, the numerical filter of the Keithley 182 was "on", whereas it was "off" during five previous measurements. As this resulted in no significant change, the results were computed using all of the 16 determinations.

Individual data for measurements in the different bias polarities and the mean value of the difference between the value measured by the CEM and the theoretical value of the BIPM array voltage are plotted in Fig. 1.

5. Uncertainties and results

The sources of type-B uncertainty (Table 1) are frequency stability, measurement leakage resistance and detector gain and linearity. The effect of the uncertainty of the gain on the comparison result is the main source of type-B uncertainty, most of the effect of non linearity 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 already contained in the type-A uncertainty of the measurements. (The type-A uncertainty is 1 nV)

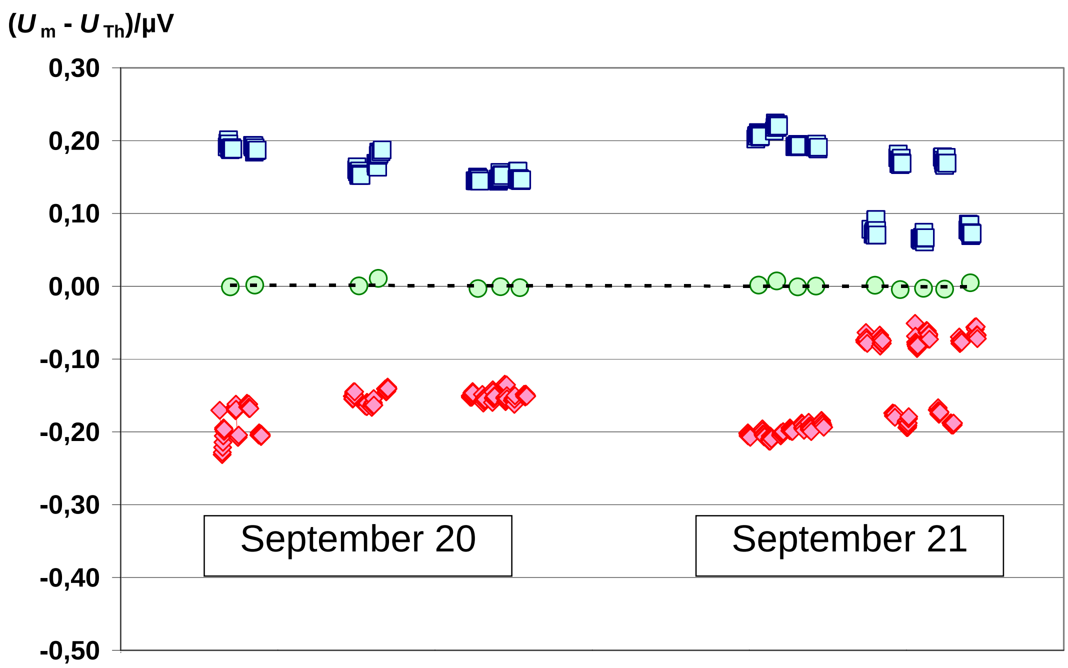

Fig. 1. Difference between the measured values and the theoretical value of the BIPM array voltage for both polarities of the bias and for the mean. Diamonds are for positive polarity, squares for negative polarity and circles for the mean. During the last five measurements both the BIPM array bias polarity and reversing switch, were changed from series to series to estimate the BIPM measurement leads thermal EMFs (typically 20 nV).

Table 1. Estimated type-B standard uncertainty components

TABLE 1

		Uncertainty/nV	
	Type	BIPM	CEM
Frequency	B	0.2	0.7
Leakage resistance	B	0.4	0.2
Detector			0.8
Total (RSS)	B	0.4	1.1

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

$(U_{CEM} - U_{BIPM}) / U_{BIPM} = 0.4 \times 10^{-10}$ $u_c / U_{BIPM} = 1.5 \times 10^{-10}$

where u_c is the combined overall uncertainty

6. Discussion and conclusion

This comparison is the third 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 next two days, adjustments were made to various parts of the CEM measurement operation. The comparison itself was then carried out with these improved conditions.

The results of the comparison demonstrate the ability of CEM in 10 V measurements. This comparison allowed the laboratory to study different problems, and improve the measurement conditions by applying DVM calibration corrections.

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

Appendix A

The BIPM equipment was first installed outside the CEM Josephson cabin, but no measurements could be made because of noise due to different ground connections. Thus, it was decided to move the BIPM equipment inside the cabin. The output of the BIPM array was connected trough a low thermal EMF-reversing switch to the measurement leads of the CEM. This reversing switch was used to provide an always positive signal to the CEM measurement device, when the BIPM array was biased in different polarities to remove the array leads thermal EMFs.

When measuring a Zener, twelve sets of 20 readings of the voltage difference between the two arrays were carried out, in the positive polarity of the bias of the two arrays. Then twelve sets of 40 such readings were carried out, in the negative polarity and again twelve sets of 20 readings in the positive polarity. The complete measurement took about ten minutes. From each twelve sets of measurements, only the ten nearest to the mean were kept. The result is the mean of the positive measurements computed at the mean time of the measurements and of the negative measurements.

Four measurements were made on September 15 with a rather large dispersion of the results partly due to the CEM array automatic bias supply that made both arrays unstable. The noise produced by the control cable that connects the computer to the bias source and the DVM is partly responsible for this instability. On September 16 and after, the bias of the CEM array was made manually, but the DVM connection to the bus was still a source of jumps of the CEM array.

The values computed by the Nistvolt programme from the readings of the DVM appeared to be correlated with the step difference between the CEM and the BIPM arrays. This resulted for the first seven measurements to a difference of 6 nV with a type-A uncertainty of 14 nV. Then an other DVM of the same type was used, but the results were not significantly different. This apparent correlation was due to the DVM calibration; and after having made a rough calibration using the BIPM array, a correction factor was incorporated in the programme. Afterwards, new more precise calibrations were made before and after the measurement series, that resulted in a correction of the DVM readings of 51.5 ppm. Applying this correction to the data of September 16 reduced the type-A uncertainty by a factor 10.

To apply this correction, it is necessary to know the DVM readings (or the CEM array step numbers), but this information is not kept by the programme. By chance, these step numbers were noted during most of the measurements by the BIPM staff. Nevertheless, on September 19, this was not made for the first two series.

Finally, it appeared that, probably due to possible thermal EMF drift just after having changed the position of the CEM reversing switch and also to the effect of the digital filter of the DVM, the DVM readings were drifting with time during typically one minute. It was thus decided to remove, for some series of measurements, the digital filter on the DVM, to keep the reversing switches always in the same position and to wait for the DVM stabilisation before starting the measurements. In order to reduce the effect of the DVM noise, it was also decided to increase by a factor of two the number of readings in each set of measurements.