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

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Abstract. Comparisons of the 10 V Josephson array voltage standard of the Bureau International des Poids et Mesures (BIPM) were made with that of the Slovak Institute of Metrology (SMU), Bratislava, Slovakia, in May 1999. The results are in good agreement and the overall uncertainty is about 1 part in 10^9.

1. Introduction

International comparisons of Josephson array voltage standards (JAVS) are of great interest since they demonstrate the accuracy of practical realisations of these standards. This article describes the comparison of the BIPM 10V standard with a commercially made JAVS belonging to the Slovak Institute of Metrology (SMU) that was carried out at the SMU in May 1999.

2. Comparison equipment

2.1 The BIPM JAVS

The BIPM equipment is that used in previous comparisons [1]. This system is routinely used to measure 10V Zener-diode based standards (Zeners) with a combined type-A and type-B standard uncertainty, u_c, of the order of 100 nV, mainly limited by the stability of the Zeners.

2.2 The SMU JAVS

The SMU JAVS is a commercial system made by RMC. It uses a 10V array made by the National Institute of Standards and Technology (NIST). The microwave source is a Gunn diode stabilised in frequency by a EIP 578B counter. Voltages are measured with a HP 3458 voltmeter. Step selection is made manually with a JBS 106 bias source. Critical switching for reversing the output leads of the array and selecting the standard to be calibrated is made by a Guildline push-

button switch. Data acquisition and analysis are carried out automatically using the NISTVolt software. The SMU JAVS is routinely used to measure Zener diode standards with a type-B standard uncertainty of 0.02 µV and a combined type-A and type-B standard uncertainty, u_c, of 0.10 µV.

3. Comparison Procedures

During the measurements, both the BIPM and the SMU arrays are disconnected from their bias source and floated from ground.

In both type of measurements during the comparison, the SMU system occasionally produced spurious readings clearly inconsistent, by several microvolts, with the anticipated values. These readings were rejected from the calculation of the comparison results but their origin was not elucidated. Such spurious readings could possibly go undetected in routine Zener calibrations or in bilateral comparisons via travelling Zeners.

3.1 Direct comparison

For the direct comparison, the two arrays are connected in series opposition and the voltage difference is measured with a detector. To achieve the highest precision in such direct comparisons, a sensitive nanovoltmeter must be used as a null detector. For a 10 V comparison, this requires that the output voltages of the two arrays be kept equal to within a few microvolts throughout the measurements. This mode of operation is not programmed into the commercial JAVS used by the SMU. We cannot carry out the best on-site comparisons with a JAVS unless it can repeatedly reproduce the same absolute value of voltage in both polarities throughout the measurements. Since the SMU JAVS is not programmed to do this, we could not carry out the usual direct comparison. Instead, the SMU's JAVS was used to measure the BIPM array voltage as if it were a Zener voltage standard. The precision was then limited to that available from the SMU's digital nanovoltmeter when measuring voltages of up to about 5 mV.

3.2 Comparison via Zener diode measurements

The procedure for comparison of calibrations of standards was simply to calibrate a Zener diode based electronic standard (Zener) with each JAVS following as closely as possible the established routine for each laboratory. These calibration results were then compared.

4. Description of the measurements

The follow is a brief description of the procedure used by the NISTVOLT software to obtain a single precise value of the voltage of a Zener being calibrated. First, the Zener voltage is measured directly with the DVM. This serves to determine the voltage step number. The array output voltage is then connected in series opposition with the Zener voltage and the resulting voltage difference is read with the DVM. The array output voltage is adjusted to be within a few millivolts of the Zener voltage. There are three phases to the measurements. In the first phase, the array is biased in the positive polarity and the Zener polarity switch is put to (+). In the second phase, the array is biased in negative polarity and the Zener polarity switched to (−). The third phase is identical to the first with the array and Zener in (+). In the first and third phases, successive measurements are divided onto twelve groups of n DVM readings while the second phase consists of twelve groups of $2n$ measurements. In each phase, the results from only ten of the twelve groups are retained for further analysis. In the version of NISTVOLT used by the SMU, it appears that the two groups yielding the lowest values are rejected. The mean voltages from the two (+) phases are averaged. This is averaged with the mean of the voltages measured in the (−) phase to yield a single final value for the Zener voltage. The effects of possible jumps of the array voltage are eliminated by comparing successive individual DVM readings and rejecting readings that differ by more than some maximum acceptable value. The step number is deduced by comparing the result of the preliminary direct measurement of the Zener voltage with the precise value measured as just described.

Occasionally during that part of the comparison in which the SMU array was used to directly measure the output voltage of the BIPM array (Fig. 1), the latter voltage changed abruptly when the BIPM array jumped from the required step. Such jumps were easily detected by a DVM connected in parallel with the bias voltage leads of the BIPM array. In such a case, the array could be re-biased quickly enough to avoid having to re-start the measurement. If the jump resulted in an incorrect DVM reading because the software could not distinguish a jump of the BIPM array from a jump of the SMU array, the DVM reading was eliminated manually. On 12 May, only six of a total of 570 readings had to be eliminated. On 13 May, two readings of a total of 600 had to be eliminated. Thus, no significant error can be attributed to spontaneous jumps in the output voltage of the BIPM array. Nevertheless, on two occasions on 13 May we observed stable DVM readings differing by 1 µV or more from the expected values. These results were

rejected and no explanation was found for their occurrence. In addition, three outlying results, believed to be due to unexplained large thermal emfs, were rejected.

The results of the Zener measurements are plotted in Fig. 2. A single measurement series consists of two measurements of the Zener voltage made using the BIPM JAVS followed by a measurement made with the SMU JAVS and completed with two more measurements made with the BIPM JAVS. A linear fit of the BIPM results as a function of time is used to interpolate the BIPM value to the mean time of the SMU measurement. Nine series of measurements were made both on 11 May and 13 May. On 13 May, two series were rejected because of what appears to be unexplained large thermal emfs in the values measured by the SMU.

5. Uncertainties and results

The sources of type-B uncertainty (Table 1 and 2) are frequency stability and measurement, leakage resistance, effects arising in the detectors, and, for Zener measurements, thermal emfs.

As usual, the results are expressed as the difference between the values that would be attributed to a 10 V standard by the two laboratories.

A. Direct comparison.

| May 12 (18 points out of 19) | $\Delta U = + 0{,}019 \ \mu V$ | ; | $u = 0{,}008 \ \mu V$ |
| May 13 (18 points out of 20) | $\Delta U = + 0{,}011 \ \mu V$ | ; | $u = 0{,}006 \ \mu V$ |

where $\Delta U = U_{SMU} - U_{BIPM}$ and u is the type-A standard uncertainty.

Those results are weighted using the reciprocal of the square of the type-A standard uncertainty. The weighted mean and the combined type-A and type-B standard uncertainty, u_c, are:

$$U_{SMU} - U_{BIPM} = + 0{,}014 \ \mu V \quad ; \quad u_c = 0{,}011 \ \mu V.$$

B. Zener diode-based standard.

| May 11 (9 points out of 9) | $\Delta U = + 0{,}065 \ \mu V$ | ; | $u = 0{,}041 \ \mu V$ |
| May 13 (7 points out of 9) | $\Delta U = + 0{,}058 \ \mu V$ | ; | $u = 0{,}044 \ \mu V$ |

where $\Delta U = U_{SMU} - U_{BIPM}$ and u is the type-A standard uncertainty.

Those results are weighted using the reciprocal of the square of the type-A standard uncertainty. The weighted mean and the combined type-A and type-B standard uncertainty, u_c, are:

$$U_{\text{SMU}} - U_{\text{BIPM}} = + 0,062 \ \mu V \quad ; \quad u_c = 0,036 \ \mu V.$$

6. Discussion and conclusion

We believe that the problems encountered in operating the SMU system show that implementations of Josephson array standards are not intrinsically accurate and that it is necessary to compare them with other JAVS. This is best done by direct on-site comparisons, such as those carried out by the BIPM.

It is worth noting that the random uncertainty of the on-site comparison of the Zener calibrations is about one order of magnitude smaller than that of the bilateral comparisons carried out with Zeners as travelling standards [2]. The on-site comparison has lower uncertainty because measurements were made alternately by each array in such a way as to track the medium-term variations of the Zener over periods of several minutes. Furthermore, the on-site comparisons provided a sensitive way to identify and reject spurious readings when they occurred.

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References

1   J. P. Lo-Hive, D. Reymann and G. Genevès, "Comparisons of 10-V Josephson Array Voltage Standards Between the BNM/LCIE and the BIPM", *IEEE Trans. Instrum. Meas.*, vol. 44, No. 2, pp. 230-233, Apr. 1995.

2   Avrons D., Reymann D., Vrabček P., Witt T.J., Bilateral comparison of 10 V and 1.018 V standards between the SMU and the BIPM, May through October 1998, *Rapport BIPM-99/1*, 1999, 7p.

Table 1. Estimated type-B standard uncertainty components for the direct comparison.

TABLE 1

	Type	Uncertainty/nV Direct
Frequency	B	2
Leakage resistance	B	1
Detector	B	10
Total (RSS)	B	10

Table 2. Estimated type-B standard uncertainty components for the Zener measurements.

TABLE 2

	Type	Uncertainty/nV	
		BIPM	SMU
Frequency	B	0.3	2
Leakage resistance	B	0.1	1
Detector	B	0.5	10
Thermal emfs	B	0.5	17
Total (RSS)	B	0.8	20

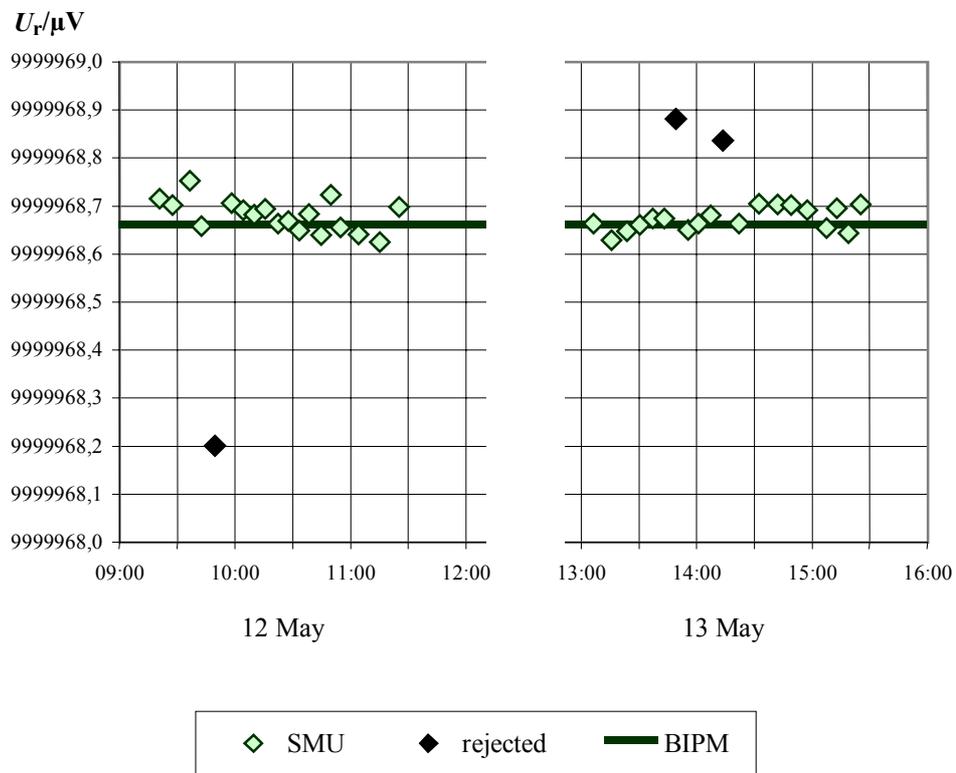Fig.1 : Measurements of the BIPM array voltage by the SMU JAVS.

Fig.2 : Measurements of a 732B Fluke Zener by the BIPM and the SMU JAVS