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

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

D. Reymann and S. Solve, Bureau International des Poids et Mesures
F- 92312 Sèvres Cedex, France
E. Afonso, V. Ferreira and R. P Landim
Instituto Nacional de Metrologia, Norm. e Qual. Industrial
Rio de Janeiro, Brazil

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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 National Institute of Metrology, Standardization and Industrial Quality (INMETRO), Rio de Janeiro, Brazil, in April 2006. The results are in fairly good agreement and the overall relative uncertainty is less than 2.0 parts in 10^9.

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 ensemble of 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 National Institute of Metrology, Standardization and Industrial Quality (INMETRO), carried out at INMETRO in April 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 is stabilized using an EIP 578 counter and an ETL/Advantest stabilizer. To visualize the array characteristic, while keeping the array floating from 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, an HP 34401 A digital voltmeter (DVM) is used to measure the voltage between the array voltage measurement 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 greater than 10^{11} Ω.

2.2 The INMETRO JAVS

The INMETRO JAVS is routinely used to calibrate Zener diode-based standards. The INMETRO’s working standards and some customer’s standards are directly measured against the JAVS, thereby significantly reducing the traceability chain. The 10 V SIS array (Hypres) is mounted on an HPD CP-525 cryoprobe and biased by a 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 operated automatically by software. The array is floating with respect to ground. The voltage from the detector (HP 3458) and the frequency from the EIP counter 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, manufactured by Hypres, s/n KL164B-5;
- Detector: HP 3458, scale used for the measurement sequence 100 mV;
- Bias source: Vmetrix JBS-500;
- Array: disconnected from the bias source during measurements;
- Software used: Nistvolt, version 6.0 (June 1999);
- Frequency source stabilizer: counter EIP 578B;
- Measurement reversing switch: Dataproof scanner - this device was not used during the comparison; the output of the BIPM array was connected to the INMETRO device through a BIPM low thermal EMF switch;
- Thermal EMFs: *see* Appendix C;
- Impedance of measurement leads approximately 20 Ω;
- Leakage resistance approximately 2 × 10^{11} Ω.

3. Comparison procedures

In the normal comparison procedure, the DVM used to verify the step stability of the BIPM array is placed across the voltage bias leads. For the INMETRO comparison, this resulted in poor stability of the steps, probably due to electromagnetic interference (EMI). This problem was resolved by connecting the DVM across the voltage measurement leads where the filter is more efficient. During the preparatory measurements carried out on 6 April 2006 the input resistance of the DVM was left in the “default” position (10 MΩ). This created a shunting effect which resulted in output voltage errors that were only understood on 9 April. The DVM was then set to the “high input resistance” position.

Measurements carried out from 10 to 12 April 2006 are described in detail in Appendix A.

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 the option “B” procedure, the INMETRO’s JAVS was used to measure the BIPM array voltage as if it were a Zener voltage standard. In the INMETRO’s Zener measurements procedure, the polarity of the array voltage is reversed by reversing the bias current polarity; and polarity reversal of the Zener voltage reference is performed with the scanner. During the present comparison, only the biases of the two arrays were reversed and no switch reversal was made. Both systems were floating from ground during the measurements.

4. Description of the measurements

The following is a brief description of the procedure used by the Nistvolt program to obtain a single measurement of the voltage of a Zener.

A) The Zener and the array are connected in series with the detector. The microwave source is off and the bias source is not connected to the array. The detector, on the 10 V scale, measures the Zener voltage in order to compute the bias voltage and the step number for the next part of the measurements. The microwave source is then turned on and the free running frequency is measured; the microwave source frequency is locked at a value near this free running frequency.

B) The bias voltage is applied to the array and the voltage difference between the array and the Zener is measured by the detector on the 1 V scale. When the step is sufficiently stable and the voltage difference is below 5 mV, the first part of the measurement starts. The initial measurement set consists of 12 samples each of 10 detector readings. If a step jump occurs during a sample, the program automatically corrects the subsequent readings to the correct step number. The mean value of the 12 samples is computed and if one or two samples appear as “outliers”, they are removed from the data set; otherwise the first two samples are removed: in all cases 10 samples of 10 detector readings are used.

C) For the second part of the measurement procedure, both the Zener and the array voltages are reversed and the difference is measured by the detector on the 1 V scale. The same process as in B) is then followed.

The procedures in B and C are then repeated a second time, so that a series of 4 sets each of 10 data blocks are recorded in total.

The program applies a fit to those 40 data blocks assuming a linear drift of the thermal EMFs during the measurement. The results are the best estimate of the Zener voltage and the Type A uncertainty. The complete series of measurements takes about six minutes when the array steps are stable.

The same procedure was used in the present comparison, except that whereas the Zener voltage was reversed using a scanner, the BIPM array voltage was reversed using the bias source in such a way that no extra source of thermal EMFs was introduced.

It should be pointed out that in most cases, the reproducibility of the different measurements within a series was poor, as compared with the expected stability of the thermal EMFs. A detailed analysis of the data within a series (*see* Appendix B) indicated that each time the detector range was changed a new value of the offset voltage was obtained which appeared to have a “short-term” drift. This value depended on the different changes of scales and was reproducible from one set of a series to the same set of the next one.

Individual data for the difference between the value measured by INMETRO 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 leakage resistance, and the detector gain and its linearity. In the INMETRO uncertainty budget for Zener measurements, a “zero offset uncertainty” refers to the reproducibility of the thermal EMFs of the scanner. This uncertainty is estimated from routine measurements where the Zeners are replaced by short-circuits. This source of uncertainty was not present for the Josephson comparison. The BIPM team nevertheless considers that a “zero offset uncertainty” value has to be taken into account for the uncertainty due to the offset input change of the detector. This value was estimated using the standard deviation of the measured thermal EMFs within the measurements carried out on 11 April 2006 (*see* Appendix C), and is the main source of Type B uncertainty as most of the effects of non linearity and frequency stability are already included 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 6.8 nV).

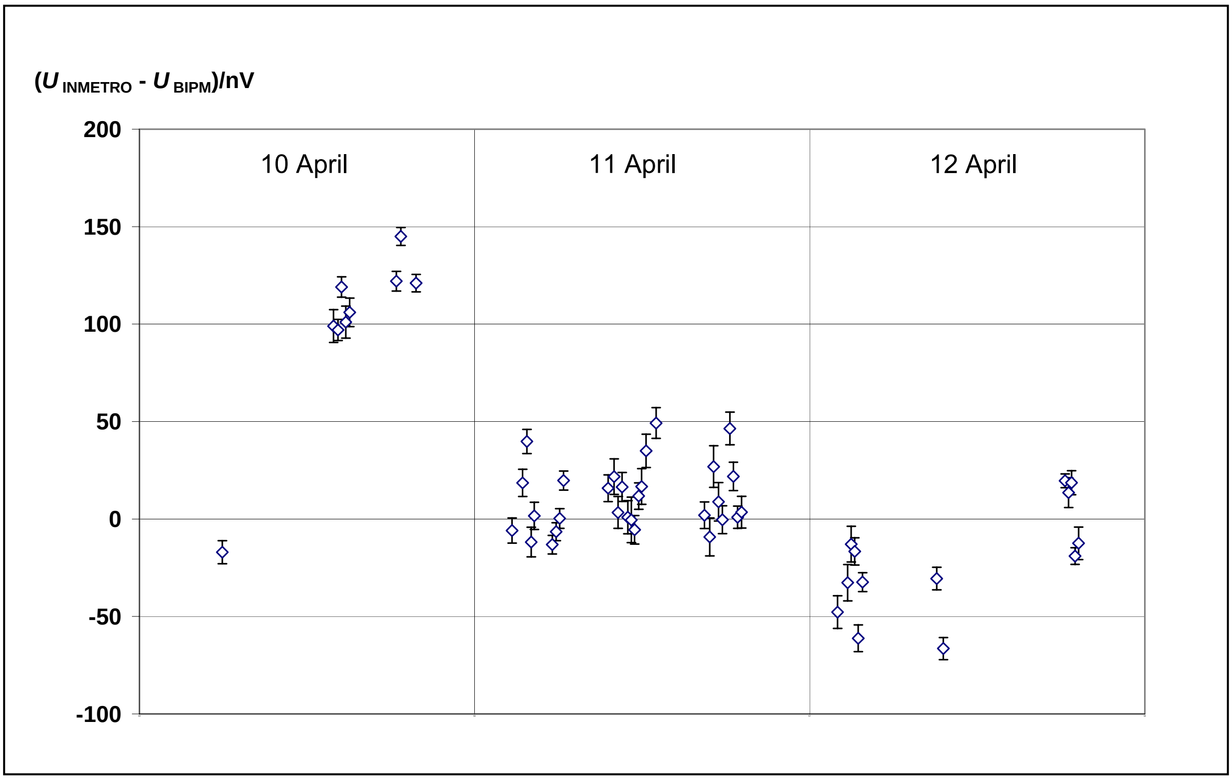

Fig. 1. Difference between the voltage values measured by INMETRO and the corresponding theoretical values of the BIPM array voltage. The error bars are the 1σ Type A uncertainties, as computed by the Nistvolt program.

	Type	Uncertainty/nV BIPM	INMETRO
Frequency (*)	B	0.2	1.2
Leakage resistance	B	0.4	1.2
Detector input offset (**)	B	-	14.5
Total (RSS)	B	0.4	14.6

Table 1. Estimated Type B standard uncertainty components.

(*) Both systems were referred to the same 10 MHz frequency reference, so no additional uncertainty other than the EIP frequency stability is included.
(**) The INMETRO array was biased on different steps throughout the comparison and the detector gain was taken into account in the computation of the results, so the detector linearity and gain uncertainty are considered to be already included in the Type A uncertainty of the measurements. This component only refers to the observed input offset changes of the detector.

The result, computed from all 50 series of measurements, is expressed as the relative difference between the values that would be attributed to the 10 V Josephson array standard by the INMETRO (U_{INMETRO}) and its theoretical value (U_{BIPM}). The Type A relative standard uncertainty is 0.68×10^{-9}.

$$(U_{\mathrm{INMETRO}} - U_{\mathrm{BIPM}}) / U_{\mathrm{BIPM}} = 1.9 \times 10^{-9} \quad \text{and } u_{\mathrm{c}} / U_{\mathrm{BIPM}} = 1.6 \times 10^{-9}$$

where u_{c} is the combined overall standard uncertainty.

6. Discussion and conclusion

This comparison is the seventh 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 that only the BIPM array (not both arrays) maintains 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 INMETRO measurement set-up to improve the performance of the whole system (step stability, noise level of the detector, etc.).

The results of the comparison demonstrate the ability of INMETRO in 10 V measurements. This comparison allowed the laboratory to study various problems, and to begin improving the measurement conditions. It appears that some significant modifications of equipment and/or measurement procedure are necessary to reach the accuracy that should be attainable with a Josephson array voltage standard. Nevertheless, it should be pointed out that the present INMETRO system is suitable for Zener measurements, as the observed deviations, under “normal functioning conditions”, are of the order of few parts in 10^9, and in the “worst case” were no more than one part in 10^8.

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

General remarks

Since the mains voltage at INMETRO is 120 ACV, a transformer was used to power part of the BIPM equipment. As is often the case, this introduced noise sources so that grounding connections had to be carefully chosen to obtain stable steps on the BIPM array.

During most of the measurements the microwave frequency of the INMETRO standard was around 74.5 GHz. This microwave frequency was sometimes not as stable as it should be, which could have been due to EMIs between the two systems that occur under non reproducible conditions from day to day, and could explain part of the discrepancy observed during the different series of measurements.

10 April 2006

The first problem encountered was an unexpected lack of stability of the INMETRO microwave frequency. After resolving this problem, a preliminary point was obtained and the observed difference between the measured voltage of the BIPM array and its theoretical value (ΔU) was 17 nV.

On this day, different modifications were made to improve the stability of the INMETRO array steps. They included modifying the ground connections, using an external capacitor across the INMETRO array bias leads and removing the BIPM DVM monitor during the measurements.

Despite all these modifications, the results of 8 series of measurements were fairly reproducible; the mean difference ΔU was 114 nV with a Type A standard uncertainty of 6 nV.

It is possible that the parameters needed to improve the step stability are not the most appropriate to limit the EMIs between the two systems.

11 April 2006

To test for possible leakage resistance in the INMETRO system, which might have explained the difference observed on 10 April 2006, all the leads to the array were disconnected before starting the measurements; nothing abnormal was detected.

Two Zener measurements were carried out with the INMETRO JAVS, and the result was about the expected Zener value.

In the morning, 11 series of measurements were carried out, but 2 series had to be rejected because a jump of the BIPM array step was corrected by the Nistvolt program as if it had been a jump of the INMETRO array, leading to a wrong value.

In the beginning of the afternoon, 12 series of measurements were carried out, but 1 series had to be rejected for the same reason.

At the end of the afternoon, 11 series of measurements were carried out, but 2 series had to be rejected for the same reason.

For the 9 series of measurements carried out in the morning, the mean difference ΔU was +4.7 nV with a relative Type A standard uncertainty of 5.9 nV.

For the 11 series of measurements carried out at the beginning of the afternoon, the mean difference ΔU was +15.0 nV with a relative Type A standard uncertainty of 4.9 nV.

For the 9 series of measurements carried out at the end of the afternoon, the mean difference ΔU was +11.2 nV with a relative Type A standard uncertainty of 5.8 nV.

For these 29 series of measurements all together, the mean difference ΔU was 10.6 nV with a Type A standard uncertainty of 3.2 nV.

At the end of this day, three measurements were carried out in similar conditions with the leads short-circuited at the output connector of the BIPM array. The measured mean value was 12 nV with a Type A standard uncertainty of 21 nV.

12 April 2006

Three measurements were carried out with the INMETRO Josephson system under conditions similar to those at the end of April 11, except that the leads were short-circuited at the output connector of a Zener reference. Then 3 measurements were carried out on the Zener itself. The mean value of the short circuit EMFs was –3 nV with a Type A standard uncertainty of 2 nV. The result for the Zener was about 100 nV lower than that measured on 11 April with a Type A standard uncertainty of 70 nV.

In the morning, 7 series of measurements were carried out, but 1 series had to be rejected because of a jump of the BIPM array.

In the afternoon, 14 series were carried out, but only 2 gave the expected results. At the time it was supposed that instabilities in the systems resulted in unexpected jumps of the BIPM array, though later it appeared that this was not the only reason. Two measurements of the Zener gave a value 700 nV higher than in the morning; this difference may have been partly due to a change of the Zener voltage as the instrument was disconnected from the mains since the morning.

At the end of this day, it was proposed to change the microwave frequency of the INMETRO system to try to find stabler steps. This resulted in an improved reproducibility of the measurements and values closer to those expected. This was obtained after many changes to the measurement configuration, so that it is possible that the same cause could have produced the frequency instability, step instability, and non reproducible results.

For the 9 series of measurements carried out in the morning and the beginning of the afternoon, the mean difference ΔU was –37.6 nV with a relative Type A standard uncertainty of 6.9 nV.

For the 5 series of measurements carried out at the end of the afternoon, the mean difference ΔU was +4.1 nV with a relative Type A standard uncertainty of 8.2 nV.

13 April 2006

Eight measurements of thermal EMFs were carried out with the INMETRO Josephson system under similar conditions to those of April 12 with the leads short-circuited at the output connector of a Zener reference.

The mean value of the short circuit was –6 nV with a Type A standard uncertainty of 4 nV.

Discussion

One characteristic of these measurements is the coherent stability of the dispersion of the results between the different groups of series: for the 8 series on 10 April, the three groups of 9, 11 and 9 series on 11 April, the first 9 series on 12 April and the last 5 series on 12 April, the standard deviation of a single observation is typically between 15 nV and 20 nV.

Because various modifications were made to the INMETRO JAVS on 10 April to improve the stability of the INMETRO array steps, our INMETRO colleagues consider that the series of April 10 should be considered as preliminary measurements, and only the series carried out on 11 and 12 April should be taken into consideration for the final comparison result. However, the BIPM team feel that all series should be taken into account because their dispersion is evidence of the true day-to-day reproducibility of the INMETRO system in its present condition.

It remains possible that the reproducibility problem is due to EMIs between the two systems, and this would signify a lack of “robustness” of the measurement system.

Appendix B

This appendix elaborates the discussion in section 4. The reproducibility of the different measurement sets within a series has to be compared with their reproducibility from one series to the next series. Each series comprises four sets of measurements in different polarities (1+), (1–), (2+) and (2–). If the observed drift of the measured voltage between (1+) and (2+) and between (1–) and (2–) within a series were due to the thermal EMFs in the measurement leads, the measured voltages of the same sets in the next series would be at about the extrapolated values from the previous sets. Figure 2a represents the measured data of three series on 11 April.

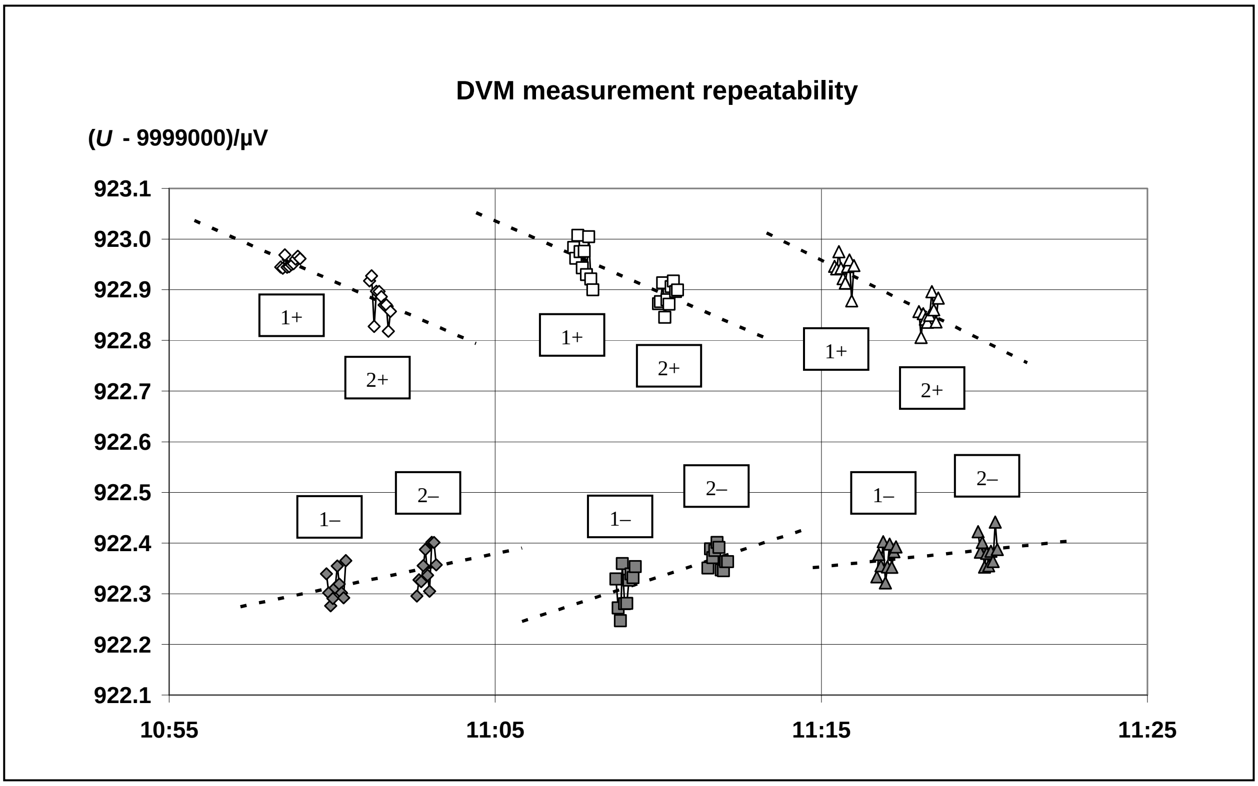

Fig. 2a. Measured values of the BIPM array with the INMETRO system. The open symbols represent the measurements in polarity (+) of three series carried out between 10:58 and 11:20 on 11 April; the filled symbols represent the measurements in polarity (–). The dotted lines show the mean drift of the measured values of the two sets in the same polarity during each series.

To visualize the repeatability of the measured values of the same set in the different series, the data of Figure 2a have been referred to a common time origin corresponding to the beginning of each series.

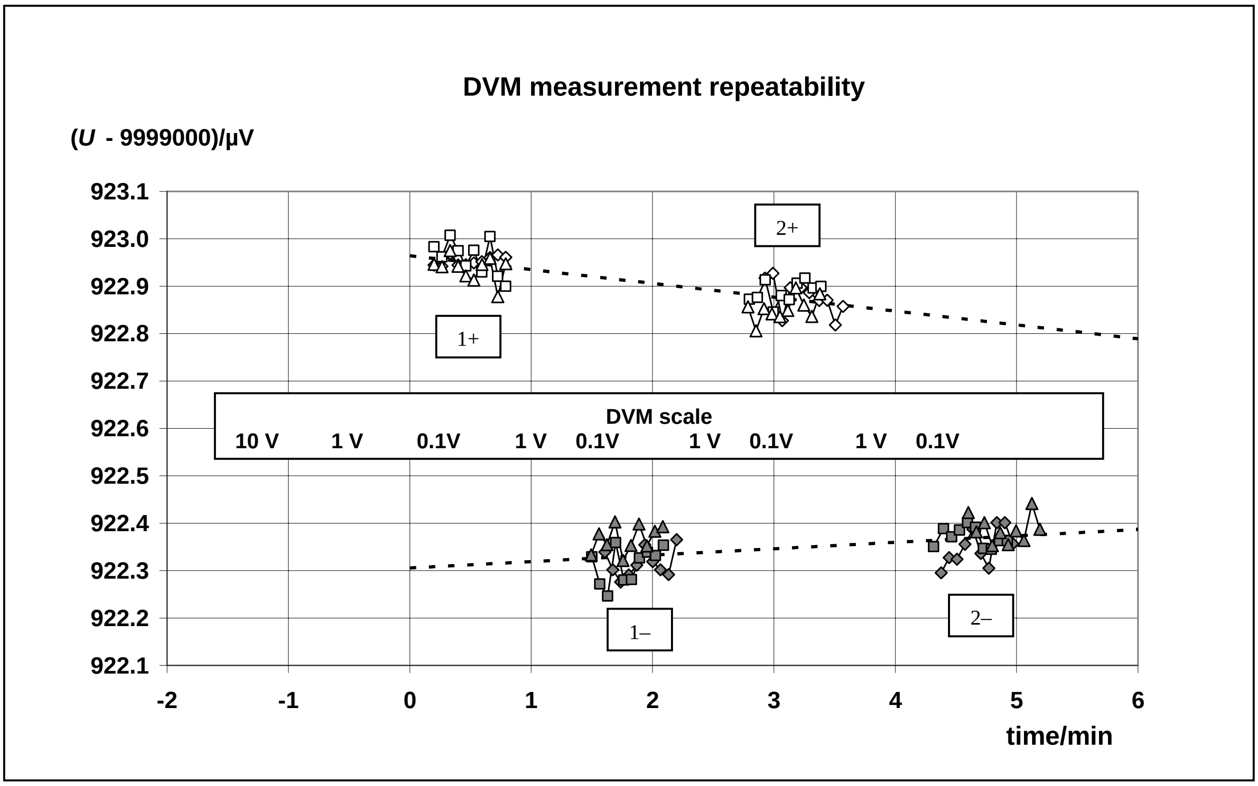

Fig. 2a. Measured values of the BIPM array with the INMETRO system. The open diamonds, squares and triangles are for the measurements in polarity (+) of three series carried out between 10:58 and 11:20 on 11 April; The dark diamonds, squares and triangles are for the measurements in polarity (–). The data are referred to a common time origin corresponding to the beginning of each series.

This seems to indicate that the largest source of drift in the measured values is due to a change of the input offset of the DVM each time it changes scale. Furthermore, as it is only in the first part of the series that the DVM scale is set to 10 V, this makes an asymmetry in the measurement sequence, with the consequence that the drift rate between (1+) and (2+) is more than a factor two greater than that in the opposite direction, between (1–) and (2–).

This effect could possibly be reduced by introducing a time lag, or by using the "autozero" mode of the detector at the beginning of each set of measurements.

Appendix C

This appendix elaborates the discussion in section 5. In the INMETRO uncertainty budget for Zener measurements, a "zero offset uncertainty" refers to the reproducibility of the thermal EMFs of the scanner. This uncertainty is estimated from routine measurements where the Zeners are replaced by short-circuits. This source of uncertainty was not present for the Josephson comparison. Nevertheless, as explained in Appendix B, the hypothesis of linear behaviour of the thermal EMFs used in the Nistvolt program is not justified. What are considered as "thermal EMFs" are rather a combination of the real thermal EMFs and of the detector input offset due to scale changes. The Nistvolt program computes from the same set of data both the voltage of the device under test and the mean value of the "thermal EMFs". For this reason, the dispersion of the "thermal EMFs" can be used as an estimator of uncertainty due to the input offset voltage of the detector. Figure 3 represents the values of the "thermal EMFs" in the measurements carried out on 11 April. This shows a long term drift of about 40 nV/hour. The standard deviation of the data around this mean drift is 14.5 nV.

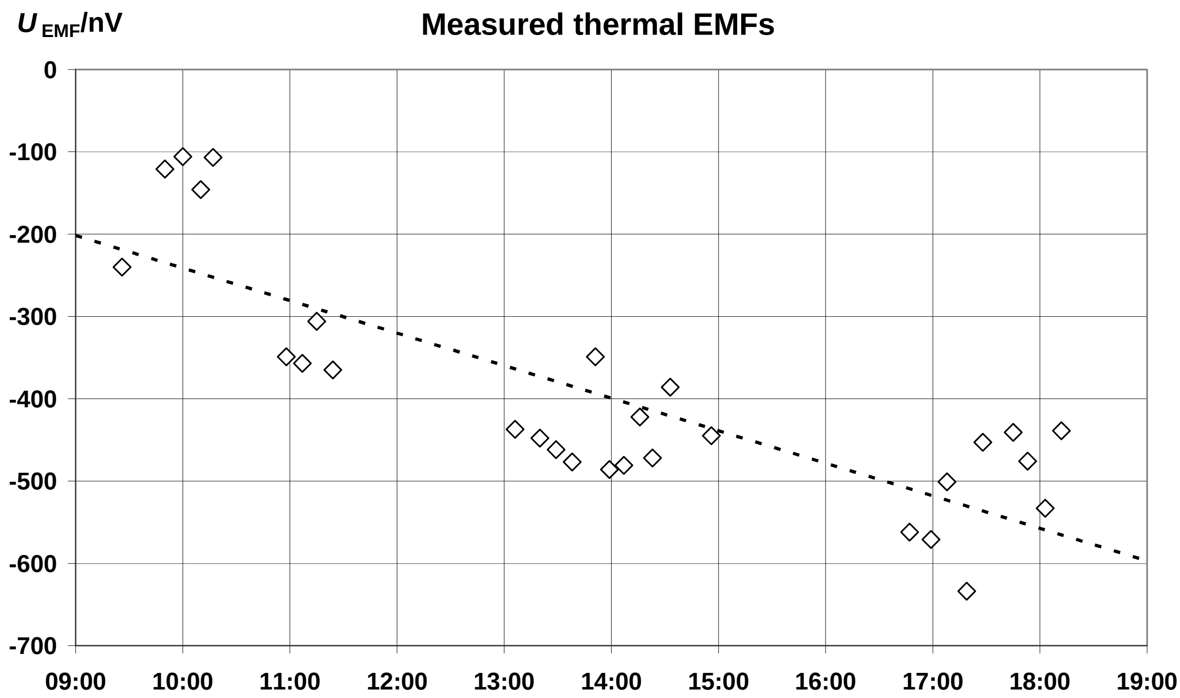

Fig. 3. Measured values of the thermal EMFs during the series of measurements of the BIPM array with the INMETRO system on 11 April. The open diamonds are the thermal EMFs and the dotted line represents the long-term drift.