

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

(part of the ongoing BIPM key comparison BIPM.EM-K10b)

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

C. H. Porter, T.J.B.M. Jansen and J.M. Williams, National Physical Laboratory
Teddington, Middlesex TW11 0LW, United Kingdom



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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 National Physical Laboratory (NPL), Teddington, United Kingdom, in September 2004. The results are in very good agreement and the overall uncertainty is about 2 parts in 10^{10} .

1. Introduction

In 2004, the BIPM proposed to the national laboratories a new type of voltage comparison referred to as “option B”, where a stable reference voltage produced across the BIPM Josephson array is measured using the laboratories’ Josephson array voltage standards (JAVS). This allows direct comparisons using the routine measurement technique used for calibration in the laboratories, requiring only the BIPM array, but not both arrays, to maintain a perfectly stable output (i.e. stay on the right step) throughout the measurements. This article describes the comparison of the BIPM 10 V standard with that of the NPL that was carried out at the NPL in September 2004.

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 observe the array characteristic while keeping the array isolated from the mains 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 34420A digital voltmeter (DVM) is used to measure the voltage between the array bias leads. The series

resistance of the measurement leads is 4Ω and the thermal electromotive forces (EMFs) are typically about 50 nV. The leakage resistance between the measurement leads is more than $10^{11} \Omega$.

2.2 The NPL JAVS

The NPL voltage calibration system is designed to run in a fully automated manner without the need for operator adjustments. All customer standards are directly measured against the primary standard, thereby significantly reducing the traceability chain. The main compromise made is that the Gunn diode frequency is not adjusted to minimize the null detector reading. The array is biased with an NPL-designed and built bias source which features an optically isolated interface link with the measurement computer and high performance isolated power supplies which allow the bias source to be permanently powered from the mains supply. Also the GPIB interface for the measurement instruments and 10 MHz reference for the frequency counter are optically isolated. The bias source is fully automated and controlled via a LabVIEW™ executable program which contains features for observing current-voltage curves, step selection, relay switching and array monitoring. The bias source and array are floating from the measurement shield which means that the measurement shield reference point can be chosen arbitrarily. In the NPL system the customer standards are continuously powered from the mains supply and the standards are measured with both the guard and low voltage terminal connected to the shield of the measurement system. This means that the standard always has the same potential relative to mains ground independent of a forward or reverse measurement.

- Type of array: 10 V SIS, PTB-produced s/n ME37-9
- Detector: HP34420A, scale used 10 mV
- Measurements made by reversing both the array bias and the connections to the standard
- Bias source: IPBS-JJ-02, NPL-produced bias source
- Array disconnected from bias source during measurements
- Software used: Measurements made with MacroLIP Version 7.0.6, NPL-produced measurement program based on LabVIEW. Analysis made with AGJD Version 5.0.1, NPL Josephson analysis program based on LabVIEW.
- Frequency source stabilizer: EIP 578B using internal locking, stability a few Hz
- Thermal EMFs (including array connections) approximately 400 nV
- Impedance of measurement leads approximately 8Ω
- Datron 1281 for array step number determination

3. Comparison procedures

During the measurements, both the BIPM and the NPL arrays were disconnected from their bias sources. The two arrays were connected in series opposition and their common point was connected to the measurement shield (note: this is different from the usual conditions at the BIPM where the whole measurement circuit is floating from ground). Using this new procedure, the NPL's JAVS was used to measure the BIPM array voltage as if it were a Zener voltage standard, except that in Zener measurements the polarity of the output voltage is reversed using a low thermal EMF switch, whereas in the Josephson comparison it is the bias of the array that is reversed and no reversing switch is used.

4. Description of the measurements

The following is a brief description of the procedure used by the NPL software to obtain a single measurement of the voltage of the BIPM array. Twelve sets of eight samples of the difference between the voltages of the two arrays are taken, six in each polarity of the bias of the two arrays in turn. During the first ten sets of these measurements, the voltage across the NPL array is automatically adjusted close to that of the BIPM array. During the last two series of measurements the NPL array voltage is deliberately adjusted to be about +10 mV from that of the BIPM array, which allows the analysis routine to obtain a calibration for the null detector. The complete measurement takes about eight minutes. A least squares fit is applied to the complete data set (i.e. all twelve sets) with the unknown voltage, detector gain, thermal drift and offset as fit parameters. Each single determination is provided with the Type A uncertainty of the fit. Six such determinations are usually necessary to calibrate a reference standard. For the present comparison, this procedure was repeated 24 times on 21 September 2004.

As no significant change was made during all these measurements, the results were computed using all of the 24 determinations. Both the simple mean and the weighted mean (using the square of the reciprocal of the fit uncertainty as a weight) were computed. The difference between the two methods was not significant and the results are given as the weighted mean.

5. Complementary measurements

In order to investigate possible sources of errors due to leakage currents to the measurement shield, some additional measurements were carried out with a 1 k Ω resistor placed in series with

the arrays in two different positions. Details of measurements configuration, results and possible interpretations are given in Appendix A.

6. Uncertainties and results

The main sources of Type B uncertainty (Table 1) are frequency stability, measurement leakage resistance, gain and linearity of the detector. (Details about some components of the uncertainty budget are given in Appendices A and B.) 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 standard uncertainty was 0.9 nV.

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

$$(U_{\text{NPL}} - U_{\text{BIPM}}) / U_{\text{BIPM}} = -1.5 \times 10^{-10}, \quad u_c / U_{\text{BIPM}} = 2.2 \times 10^{-10}$$

where u_c is the combined overall standard uncertainty.

7. Discussion and conclusion

This comparison is the first 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 of arrival; only one further day was required for the comparison itself.

The results of the comparison demonstrate the ability of the NPL in 10 V measurements. The main difference with Zener calibrations, apart from the stability of the Zener itself, is that the thermal EMFs were cancelled out by reversing the array bias polarity. The uncertainty attributed to the thermal EMFs in the reversing switch and scanner used by the NPL for Zener measurements is about 60 nV, comparable with the limiting $1/f$ noise of the Zener which of the order of 70 nV in the best case.

Table 1. Estimated Type B standard uncertainty components.

TABLE 1

	Type	Uncertainty/nV	
		BIPM	NPL
Frequency	B	0.2	1.2
Leakage resistance	B	0.4 (*)	1.5
Detector (**)			0.4
Total (RSS)	B	0.4	2.0

(*) This value was derived from the measured leakage resistance. In the experimental configuration used here, where the common point of the two arrays is grounded, this may be underestimated (see Appendix A).

(**) As the NPL array was biased on different steps and as the detector gain was measured during the measurements, a large part of the detector uncertainty is already contained in the Type A uncertainty of the measurements.

Appendix A. Effect of leakage resistance to ground

During the measurements, the BIPM and NPL arrays were connected in direct series opposition and their common point was connected to the measurement shield (note: this is different from the usual conditions at the BIPM where all the measurement circuit is floating from ground). The detector was placed between the “Hi” terminals of the arrays (see Fig. 1).

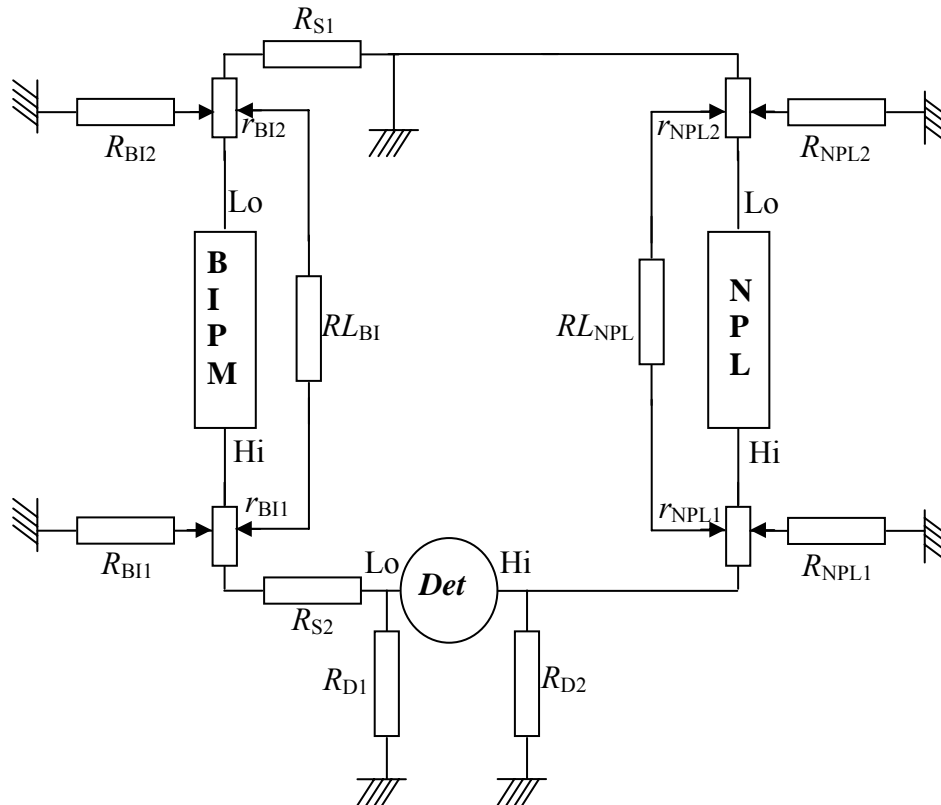


Fig. 1. In this simplified schematic, the bias leads are not shown; **BIPM** and **NPL** represent the two arrays, and **Det** is the NPL detector (HP 34420A nanovoltmeter). r_{BI} and r_{NPL} are the measurement lead resistances; R_{BI} , R_{NPL} and R_D are the leakage resistances to the shield; R_{LBI} and R_{LNPL} are the leakage resistances between the measurement leads. R_{S1} and R_{S2} represent the 1 k Ω resistance when connected in series in the measurement. Lo and Hi are for the low and high connections of the array and nanovoltmeter. The Lo of the arrays are connected to the measurement shield and therefore the Hi of the arrays are either +10V or –10V depending on the direction of the bias.

During the “normal” comparison measurements (series 1 to 4) $R_{S1} = R_{S2} = 0 \Omega$; in the supplementary series (5a) $R_{S1} = 1 \text{ k}\Omega$ and $R_{S2} = 0 \Omega$; in the supplementary series (5b) $R_{S1} = 0 \Omega$ and $R_{S2} = 1 \text{ k}\Omega$. Results of series 5a indicate that the value of the BIPM array voltage measured

by the NPL device is about 300 nV lower than the theoretical value. Compared to the previous conditions, this could be explained by a current flowing through R_{S1} that would circulate through leakage resistors R_{B11} and R_{D1} ; this could be explained by an effective leakage resistance equal to $3.3 \times 10^{10} \Omega$ ($R_{B11} // R_{D1}$). Results of series 5b indicate that the value of the BIPM array voltage measured by the NPL device is about 30 nV lower than the theoretical value. Compared to the original conditions, this could be explained by a current flowing through R_{S2} that would circulate through leakage resistors R_{D1} ; this could be explained by an effective leakage resistance equal to $3.3 \times 10^{11} \Omega$ (R_{D1}).

Comparing the results of series 5a and 5b, we found that R_{B11} should be $3.7 \times 10^{10} \Omega$. The value measured at the NPL for the overall leakage resistance of the BIPM array ($R_{B11} // R_{B12}$) was $5 \times 10^{10} \Omega$, so we would expect that R_{B11} would be equal to $1 \times 10^{11} \Omega$. When measuring the leakage resistance, it appears that some time delay is necessary to reach the final value, due to the capacitors in the filters, particularly those of the bias leads. In the measurement process, there are only 10 seconds or less between the time when the polarity of the array is reversed and the time the measurement starts: it is possible that the observed leakage current be due to this charging of the capacitors.

From the detailed data of series 5a, for each set of eight measurements the difference between each individual point and their mean value indicates a mean drift of about 0.2 μ V between the first and the last point (see Fig. 2). Complementary measurements were carried out at the BIPM to evaluate this effect (see Fig. 3).

The leakage resistance can be derived from the final deviation of the detector. The final leakage current is

$$i_L = \delta V / R_{S1} = 50 \text{ pA}.$$

This leakage current is due to the bias voltage ($U_B = 10 \text{ V}$) across the leakage resistance R_{B11} and hence $R_{B11} = U_B / i_L = 2 \times 10^{11} \Omega$.

Nevertheless, as the mean time of each measurement was about 20 s after reversing the bias polarity, the “actual” leakage resistance is probably not larger than $5 \times 10^{10} \Omega$, which agrees with that measured at the NPL.

During measurement series 1 to 4, i.e. those that form the basis of the comparison results, the lead resistance was 4 Ω rather than 1 k Ω , therefore this effect was approximately 200 times smaller.

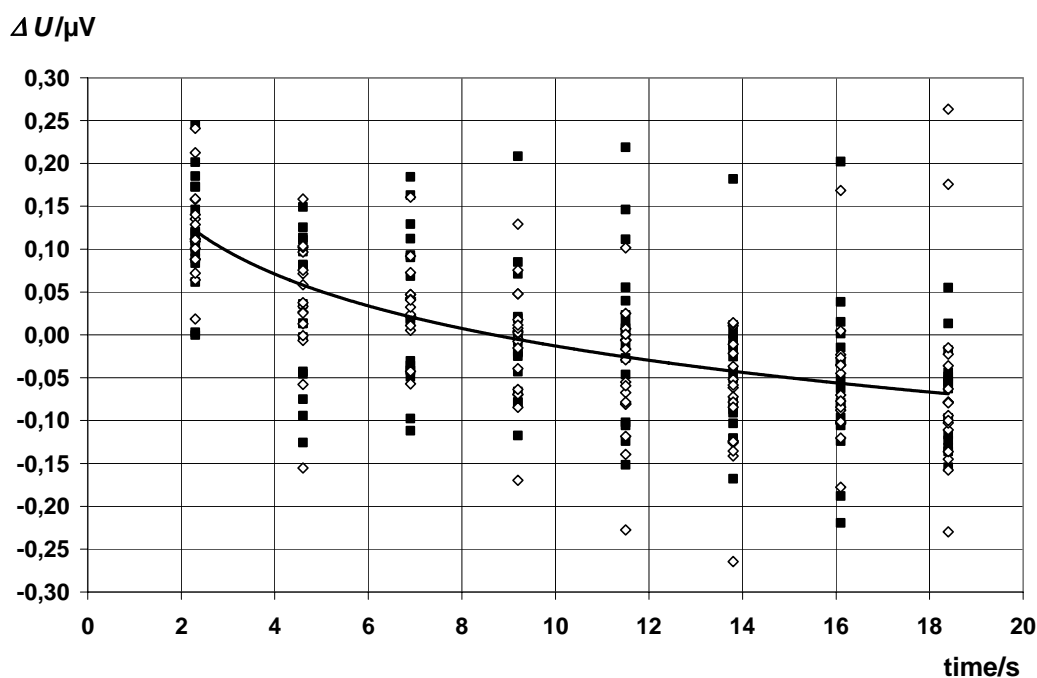


Fig. 2. Filter capacitors loading effect. Solid squares: polarity measurements; open diamonds: negative polarity measurements; the curve is the “Excel logarithm estimate” computed on the median of all the data.

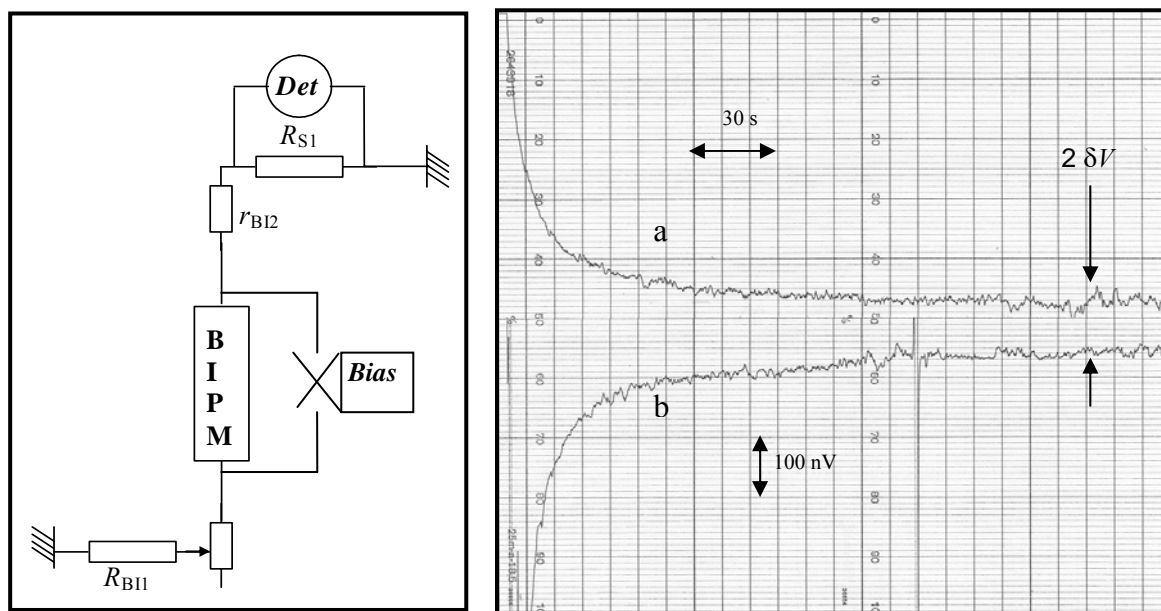


Fig. 3. Measurement of the loading effect of the filter capacitors at the BIPM. Left: the measurement scheme, the detector being placed across the $1\text{k}\Omega$ resistor. Right: two sets of chart-recorder traces: a) biasing the array with $+10\text{V}$ and b) biasing the array with -10V . At 30s after polarity reversal, the leakage current is typically twice the asymptotic value, corresponding to an apparent insulation resistance of half the long-term value.

Appendix B. Effect of the non-linearity of the null detector

In order to assess the effect of the non-linearity of the null detector in the measurement system, a separate calibration of this detector was performed. For this measurement, the null detector was connected directly across the array which was biased at a number of voltages spanning the 10 mV range of the detector. Using the known array step number, the gain of the detector can be determined by fitting a straight line to the detector readings. The residuals of this fit are a measure of the non-linearity of the detector. Figure 4 shows the result of ten such detector calibrations. From this it is clear that the detector has a non-linearity with outer limits of approximately ± 25 nV over a ± 10 mV span. During routine measurements of a Zener standard, the array is biased randomly at step voltages close to the Zener voltage and normally the difference between the array and the Zener changes throughout the series. All the null detector readings during the present comparison were analysed to assess their randomness. The mean reading for all 24 determinations for the measurements carried out in the positive polarity was not significantly different from zero (mean value 0.35 mV with a 1σ dispersion 3.5 times larger), however, a noticeable bias was observed for those in negative polarity (mean value 1.13 mV with a 1σ dispersion 3.5 times lower). To evaluate the effect of this bias, a 6th order polynomial was fitted to the data in Fig. 4 and used to correct all the null detector readings. This new analysis of all the measurements resulted in a change of 4 nV of the weighted mean of all the measurement (-1.5 nV instead of $+2.6$ nV for the uncorrected readings) whereas the weighted uncertainty remained the same. The uncertainty due to the DVM correction procedure is estimated to be 0.4 nV. The value of -1.5 nV is the result adopted for the comparison result.

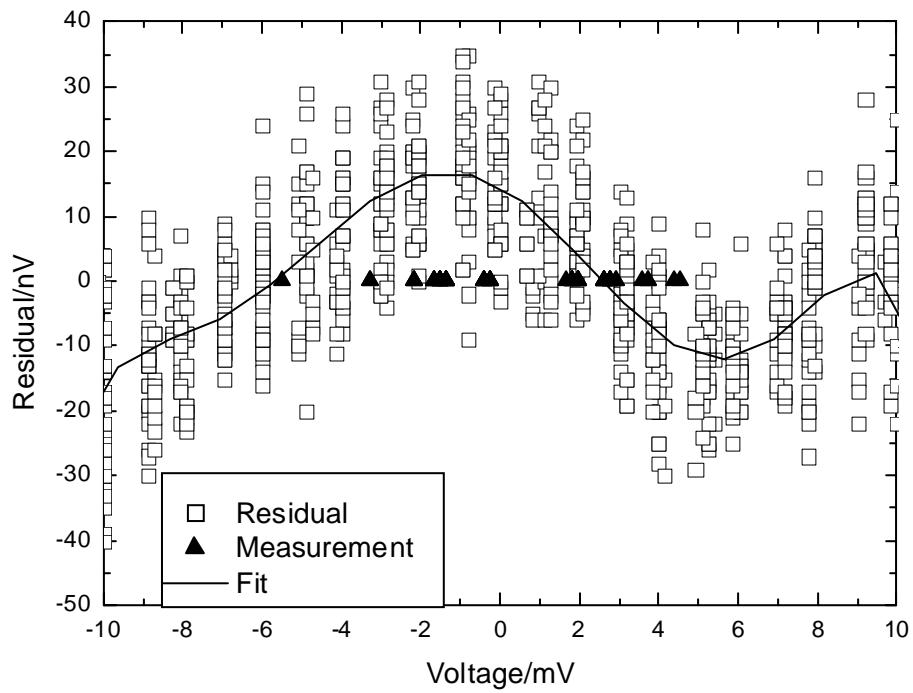


Fig. 4. Residual of gain calibration of null detector (\square) and array voltages used during measurement (\blacktriangle). Solid line: 6th order polynomial fit to the residuals.