Bilateral Comparison of 1.018 V and 10 V Standards

between the NSAI (Ireland) and the BIPM,

May to June 2024

(part of the ongoing BIPM key comparison BIPM.EM-K11.a and b)

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Introduction

As part of the ongoing BIPM key comparison BIPM.EM-K11.a and b, a comparison of the 1.018 V and 10 V voltage reference standards of the BIPM and the *National Standards Authority of Ireland, National Metrology Laboratory* (NSAI-NML), Dublin, Ireland, was carried out from May to June 2024. Two BIPM Zener diode-based travelling standards (Fluke 732B), BIPM_B (ZB) and BIPM_C (ZC), were transported by freight to NSAI-NML and back to BIPM. In order to keep the Zeners powered during their transportation phase, an additional battery was connected in parallel to the internal battery.

At the NSAI-NML, the reference standard for DC voltage is a Programmable Josephson Voltage Standard (PJVS). The output electromotive force (EMF) of each travelling standard was measured by direct comparison with the primary standard.

At the BIPM, the output EMF of each travelling standard was calibrated before and after the measurements at the NSAI-NML against the PJVS developed at the BIPM around a PTB programmable SNS Josephson junctions (Superconductor/Normal Metal/Superconductor) array.

Results of all measurements were corrected by the BIPM for the dependence of the output voltages of the Zener standards on internal temperature and ambient atmospheric pressure.

Outline of the measuring method

NSAI-NML 1.018 V and 10 V measurements

At the NSAI-NML, the core element of the standard is a Josephson array of 265 000 Superconductor/Normal Metal/ Superconductor (SNS) junctions divided into 23 segments. The smallest segment comprises 6 junctions corresponding to a voltage of exactly 228.29 µV at 18.4 GHz. The array is mounted on a cryoprobe and immersed in liquid helium. It can be programmed by a novel, compact bias source which sits on top of the cryoprobe and is connected to a controlling computer via an optical fibre interface. The junctions of the array are uniformly irradiated by a microwave signal with a frequency of approximately 18.4 GHz supplied by a National Instruments model FSW-0020 synthesizer and associated amplifier. The synthesizer is locked to NSAI-NML's reference frequency standard (BIPM Code IE-10049). A *Keysight*[*] model 34420A is used as a null detector to measure the voltage difference between the array voltage and the voltage under test. The measuring system is controlled by proprietary software using the LabView platform. The Josephson array was supplied by the National Institute for Standards and Technology (USA) [1] and the bias source, cryoprobe, optical fiber interface, and software were developed and supplied by the National Physical Laboratory (UK) [2].

The measuring sequence used was as follows:

1. The voltage standard under test was disconnected from the mains supply and allowed to stabilize under battery power for a period of more than 2 hours before any measurements are made.
2. The PJVS was programmed to a step near to the nominal output voltage of the voltage standard.
3. The output of the voltage standard was connected in series opposition to the PJVS output via the null detector and a reversing switch.
4. With the array biased in the forward direction and the reversing switch in the forward position the bias current was swept along the step during the readings in order to ensure the array remains on quantized state (the slope of the step was evaluated from the null meter readings with typical values of 5×10^{-8} V/s)
5. 61 readings of the null detector reading were recorded at a rate of one sample per second.

[*] Certain commercial instruments are identified in this paper to facilitate understanding. Such identification does not imply recommendation or endorsement by BIPM, or NSAI-NML, nor does it imply that the materials or equipment that are identified are necessarily the best available for the purpose.

6. The mean [(D_1 = U(Zener) - U(PJVS)].and standard deviation of the null detector readings were evaluated.
7. The array was isolated and reversed.
8. The Zener reversing switch was reversed and the Zener was reconnected in series opposition to the array. The time between reversals was typically 150 seconds
9. With the array biased in the reverse direction and the reversing switch in the reverse position the bias current was swept along the step
10. 61 readings of the null detector reading were recorded at a rate of one sample per second.
11. The mean (D_2) and standard deviation of the null detector readings were evaluated.
12. The internal thermistor resistance and the ambient pressure were recorded.
13. The measured value of the voltage standard's output was evaluated:

$$V_X = V_{PJAVS} + \left(\frac{D_1 - D_2}{2}\right) \quad (1)$$

14. The magnitude of offset voltages due to thermal EMFs and other effects is:

$$V_{Thermal} = \left(\frac{D_1 + D_2}{2}\right) \quad (2)$$

15. The measuring sequence was repeated at least five times on each day.

BIPM Measurements for 1.018 V and 10 V

The output voltage of the Zener standard to be measured was connected in series opposition to the BIPM Josephson Voltage Standard - PTB 10 V SNS array (S/N: 2013-02/4a) [3], through a low thermal EMF multiplexer [4-5]. The binding post terminals "GUARD" and "CHASSIS" of the Zener standard were connected together and connected to a single point which is the grounding reference point of the measurement setup.

The measurements started at least two hours after the mains plug at the rear of the Zeners had been disconnected in order for the Zener internal temperature to stabilize.

In this comparison, the BIPM detector was a digital nanovoltmeter *Keithley 2182A*[*] operated on its 10 mV range. A computer was used to monitor, record the measurements, acquire the data, correct for temperature and pressure dependence, and calculate results.

The BIPM array biasing frequency was adjusted in such a way that the voltage difference between the primary and the secondary voltage standards was always below 1 µV for both nominal voltages.

[*] Certain commercial instruments are identified in this paper to facilitate understanding. Such identification does not imply recommendation or endorsement by BIPM, or NSAI-NML, nor does it imply that the materials or equipment that are identified are necessarily the best available for the purpose.

One individual measurement point was acquired according to the following:

1- The Zener and the BIPM array are set in their positive polarity, connected in series opposition and the detector data reading sequence starts;
2- The polarity of the detector is reversed (this operation lasts 20 s) and a reading sequence is carried out.. The number of measurements is twice the number acquired in step 1;
3- The polarity of the detector is reversed again to match the conditions of step 1 and the reading sequence restarts;
4- The Zener and the BIPM array are set in their negative polarity, connected in series opposition and the detector is set in its positive polarity (this operation lasts 25 s). The data reading sequence starts;
5- The polarity of the detector is reversed and a reading sequence is carried out. The number of measurements is twice the number acquired in step 4;
6- The polarity of the detector is reversed again to match the conditions of step 4 and the reading sequence restarts.

The reversal of the array polarity (by reversing the bias current) is always accompanied by a reversal of the Zener voltage standard using the multiplexer. The reversal of the detector polarity is done to cancel out any internal detector thermal EMF with a constant drift rate.

Each data acquisition step consists of 50 preliminary measurements followed by 100 measurements. Each of these should not differ from the mean of the preliminary measurements by more than four times their standard deviation. If so, the software warns the operator with a beep. If too many beeps occur, the operator can restart the “Data Acquisition” step in progress. The procedure to acquire one individual measurement point is repeated five times in a row and the mean value corresponds to one result on the graph (cf. Fig. 1, 2, 3, and 4).

Results at 10 V

Figure 1 shows the measured values obtained for the two standards by the two laboratories at 10 V. Figure 2 presents the voltage evolution of the simple mean of the two standards which is used to compute the final result at 10 V. A linear least squares fit is applied to all of the individual BIPM results, and to the mean value of both transfer standards. The comparison result is the voltage difference between the BIPM fitted value at the mean date of the NSAI-NML measurements (28/05/2024) and the mean value of the NSAI-NML measurements, and the related uncertainties.

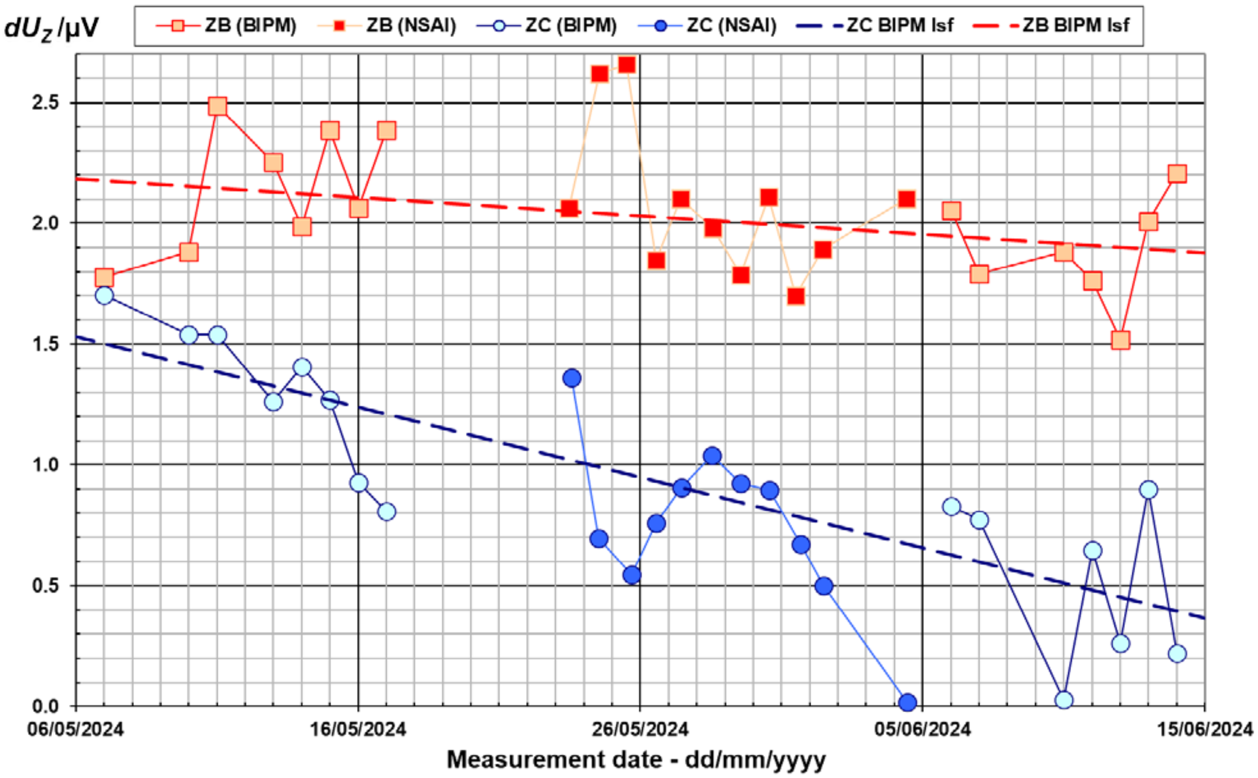

Figure 1: Voltage of ZB (squares) and ZC (disks) at 10 V measured at both institutes (light markers for BIPM and dark markers for NSAI-NML), referred to an arbitrary offset, as a function of the measurement date with a linear least-squares fit (lsf) to the BIPM measurements**.**

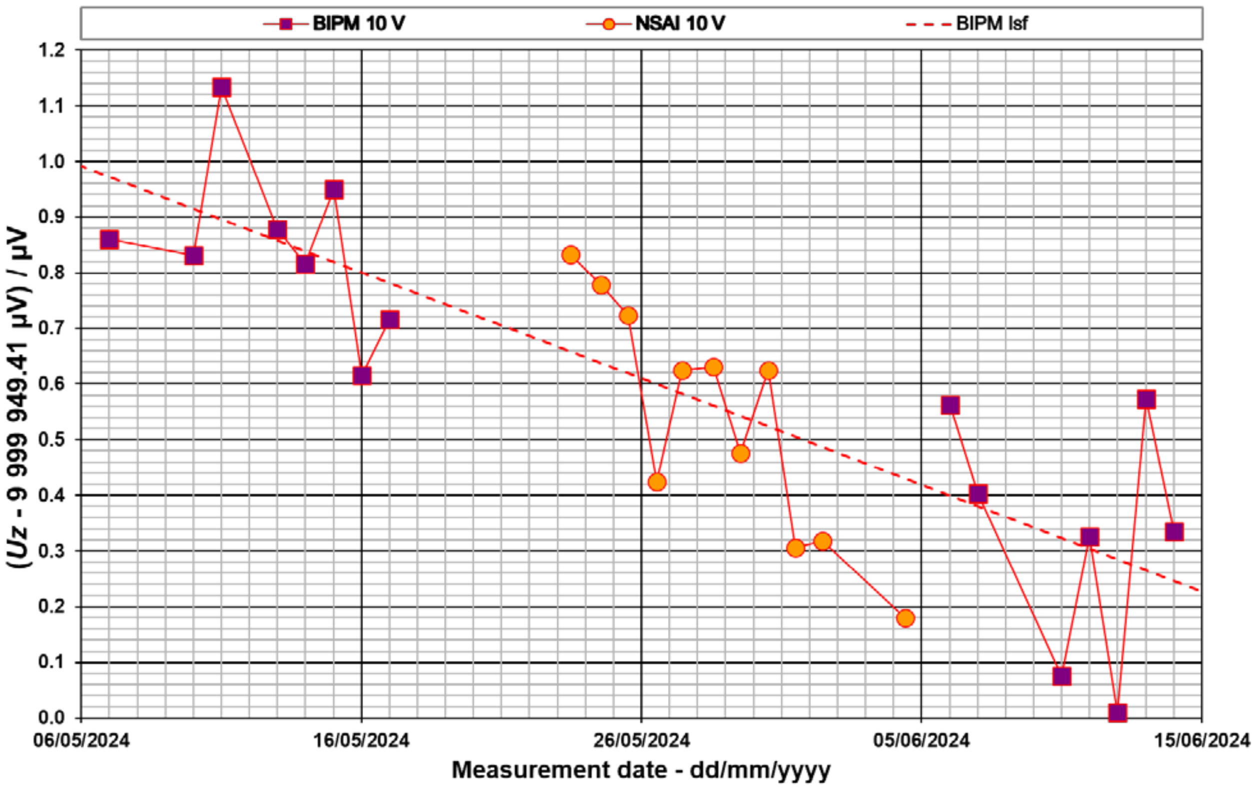

Figure 2: Voltage evolution of the arithmetic mean of the two standards at 10 V. NSAI-NML measurements are represented by disks and BIPM measurements by squares. A least-squares fit is applied to the BIPM measurements.

Uncertainty Budgets at 10 V

BIPM uncertainty budget at 10 V

Table 1 summarizes the uncertainties related to the calibration of a Zener diode against the Josephson array voltage standard at the BIPM at the level of 10 V.

Experience has shown that flicker or 1/*f* noise ultimately limits the stability characteristics of Zener diode standards and it is not appropriate to use the standard deviation divided by the square root of the number of observations to characterize the dispersion of measured values. For the present standards, the relative value of the voltage noise floor due to flicker noise is about 1.5 parts in 10^8 [6]. The Type A standard uncertainty in the Table 1 therefore has a lower limit of 150 nV. However, if the standard deviation of the measurements at the mean date of the participant is larger than the flicker noise floor, it is this standard deviation which is considered to be the Type A standard uncertainty.

JVS & detector uncertainty components	**Uncertainty (nV)**
Noise of the measurement loop that includes the residual thermal EMF including the residual EMF of the reversing switch (Type A)	2
Detector gain (Type B)	negligible
Leakage resistance (Type B)	4
Frequency (Type B)	0.1
Zener noise (Type A)	Not lower than the 1/*f* noise estimated as 150 nV, included in the comparison uncertainty budget (Table 3)
Zener pressure and temperature correction	Included in the comparison uncertainty budget (Table 3)

Table 1: Estimated standard uncertainties arising from the JVS and the measurement setup for Zener calibrations with the BIPM equipment at the level of 10 V.

NSAI-NML uncertainty budget at 10 V

Tables 2 lists the uncertainties related to the calibration of the Zeners at NSAI-NML.

The corrections for internal temperature and ambient pressure were not included as these corrections are dealt in the BIPM analysis of the measurement data. The standard uncertainties of the measured thermistor resistance and ambient pressure are as follows:

Measured Quantity	Standard Uncertainty
Thermistor Resistance	2 Ω
Ambient Pressure	0.2 kPa

Quantity	Estimate	Standard uncertainty	Sensitivity Coefficient	Uncertainty contribution
Mean difference voltage measured by the null detector	277.16 µV	85 nV	1	85 nV
Microwave Reference frequency	18.39 GHz	1.8 Hz	0.54 nV/Hz	1 nV
Voltage due to leakage current	0 V	5 nV	1	5 nV
Voltage due to gain error of the nanovoltmeter	0 V	24 nV	1	24 nV
Non-compensated offset of the measurement circuit	0 V	52 nV	1	52 nV
	Total combined standard uncertainty			**103 nV**

Table 2: Estimated standard uncertainties for a Zener calibration with the NSAI-NML equipment at the level of 10 V for Zener ZB and ZC.

Uncertainty contributions for the comparison NSAI-NML/BIPM at 10 V

Table 3 lists the results and the uncertainty contributions for the comparison NSAI-NML/BIPM at 10 V.

		Results/µV		Uncertainty/µV	
		ZB	ZC	ZB	ZC
1	NSAI-NML ($U_{\mathrm{NSAI\text{-}NML}}$ – 10 V)	-8.32	-91.78		
2	Type A uncertainty			0.085	0.085
3	correlated (Type B) unc.			0.057	
4	BIPM (U_{BIPM} – 10 V)	-8.39	-91.67		
5	Type A uncertainty			0.15	0.15
6	correlated (Type B) unc.			<0.005	
7	pressure and temperature correction uncertainty			0.042	0.041
8	($U_{\mathrm{NSAI\text{-}NML}}$ – U_{BIPM})	0.07	-0.11		
9	Total uncorrelated uncertainty			0.177	0.177
10	Total correlated uncertainty			0.057	
11	< $U_{\mathrm{NSAI\text{-}NML}}$ – U_{BIPM} >	**-0.02**			
12	*a priori* uncertainty			0.122	
13	*a posteriori* uncertainty			0.090	
14	**Comparison total combined standard uncertainty**			**0.13**	

Table 3: Results and uncertainties of NSAI-NML (Ireland)/BIPM bilateral comparison of 10 V standards using two Zener travelling standards: reference date 28 May 2024. Standard uncertainties are used throughout.

In Table 3, the following elements are listed:

(1) the value attributed by NSAI-NML/BIPM to each Zener, $U_{\mathrm{NSAI\text{-}NML}}$, computed as the simple mean of all data from NSAI-NML/BIPM and corrected for temperature and pressure differences between both laboratories by the BIPM.

(2)/(5) the (NSAI-NML)/(BIPM) combined Type A uncertainty (cf. Table 2).

(3) the uncertainty component arising from the realization and maintenance of the volt at NSAI-NML/BIPM: it is the quadratic combination of the Type B components of the participant uncertainty budget listed in Table 2. This uncertainty is completely correlated between the different Zeners used for the comparison.

(4-6) the corresponding quantities for the BIPM referenced to the mean date of the NSAI-NML measurements. In this case, the Type A uncertainty is limited by the flicker noise level of 150 nV.

(7) the uncertainty due to the combined effects of the pressure and temperature coefficients [7,8] and to the differences of the mean pressures and temperatures in the participating laboratories is calculated as follows:

The uncertainty of the temperature correction $u_{T,i}$ of Zener i is determined for the difference ΔR_i between the mean values of the thermistor resistances measured at both institutes which is then multiplied by the uncertainty $u(c_{T,i})$ of the relative temperature coefficients of each Zener standard:

$$u_{T,i} = U \times u(c_{T,i}) \times \Delta R_i$$

where U = 10 V, $u(c_{T,ZB})$ = 0.409 × 10^{-7} / kΩ, $u(c_{T,ZC})$ = 0.213 × 10^{-7} / kΩ, ΔR_{ZB} = 0.032 kΩ and ΔR_{ZC} = 0.067 kΩ.

The same procedure is applied for the uncertainty $u_{P,i}$ of the pressure correction for the difference ΔP_i between the mean values of the pressure measured at both institutes:

$$u1_{P,i} = U \times u(c_{P,i}) \times \Delta P_i$$

where U = 10 V, $u(c_{P,ZB})$ = 0.068 × 10^{-9} / hPa, $u(c_{P,ZC})$ = 0.050 × 10^{-9} / hPa, ΔP_{ZB} = 5.0 hPa and ΔP_{ZC} = 3.4 hPa.

However, since the NSAI-NML uncertainty is 2 hPa, the dominant contribution becomes:

$$u2_{P,i} = U \times c_{P,i} \times uP_i$$

where U = 10 V, $c_{P,ZB}$ = 19.53 × 10^{-9} V/ hPa, $c_{P,ZC}$ = 18.91 × 10^{-9} V/ hPa, uP_{ZB} = uP_{ZC} = 2 hPa.The total uncertainty on pression correction is therefore the quadratic combination of $u_{1,P,\mathrm{i}}$ and $u_{2,P,\mathrm{i}}$.

(8) the difference ($U_{\mathrm{NSAI\text{-}NML}}$ – U_{BIPM}) for each Zener, and (9) the uncorrelated part of the uncertainty, calculated as the quadratic sum of lines 2, 5 and 7.

(10) the correlated part of the uncertainty, calculated as the quadratic sum of lines 3 and 6, for each travelling standard.

(11) the result of the comparison is the simple mean of the differences of the calibration results for the different standards.

(12 and 13) the uncertainty related to the transfer, estimated by comparing the following uncertainties:

(12) the *a priori* uncertainty, determined as the standard uncertainty of the mean, obtained by propagating the uncorrelated uncertainties for both Zeners;

(13) the *a posteriori* uncertainty, which is the standard deviation of the mean of the two results.

(14) the total uncertainty of the comparison, which is the root sum square of the correlated part of the uncertainty (10) and of the larger of (12) and (13).

To estimate the uncertainty related to the stability of the standards during transportation, we have calculated the "*a priori*" uncertainty of the mean of the results obtained for the two standards (also called statistical internal consistency). It consists of the quadratic combination of the uncorrelated uncertainties of each result. We compared this component to the "*a posteriori*" uncertainty (also called statistical external consistency) which consists of the experimental standard deviation of the mean of the results from the two travelling standards*.

If the "*a posteriori*" uncertainty is significantly larger than the "*a priori*" uncertainty, we assume that a standard has changed in an unusual way, probably during its transportation. This is not the case. We use the larger of these two estimates in calculating the final uncertainty.

The comparison result is presented as the difference between the value assigned to a 10 V standard by NSAI-NML, at NSAI-NML, $U_{\text{NSAI-NML}}$, and that assigned by the BIPM, at the BIPM, U_{BIPM}, on the reference date of the 28th of May 2024:

$$\boldsymbol{U_{\text{NSAI-NML}} - U_{\text{BIPM}} = -0.02\ \mu\text{V}; \qquad u_{\text{c}} = 0.13\ \mu\text{V}}$$

where u_{c} is the combined standard uncertainty associated with the measured difference, including the uncertainty of the realization of the volt at NSAI-NML, at the BIPM, and the uncertainty related to the comparison.

* With only two travelling standards, the uncertainty of the standard deviation of the mean is comparable to the value of the standard deviation of the mean itself.

Results at 1.018 V

Figure 3 shows the measured values obtained for the two standards by the two laboratories at 1.018 V and Figure 4 presents the voltage evolution of the simple mean of the two standards which is used to compute the final result at 1.018 V.

A linear least squares fit is applied to the results of the BIPM, before and after the measurements at NSAI-NML, to obtain the results for both standards and their uncertainties at the mean date of the NSAI-NML measurements (28/05/2024).

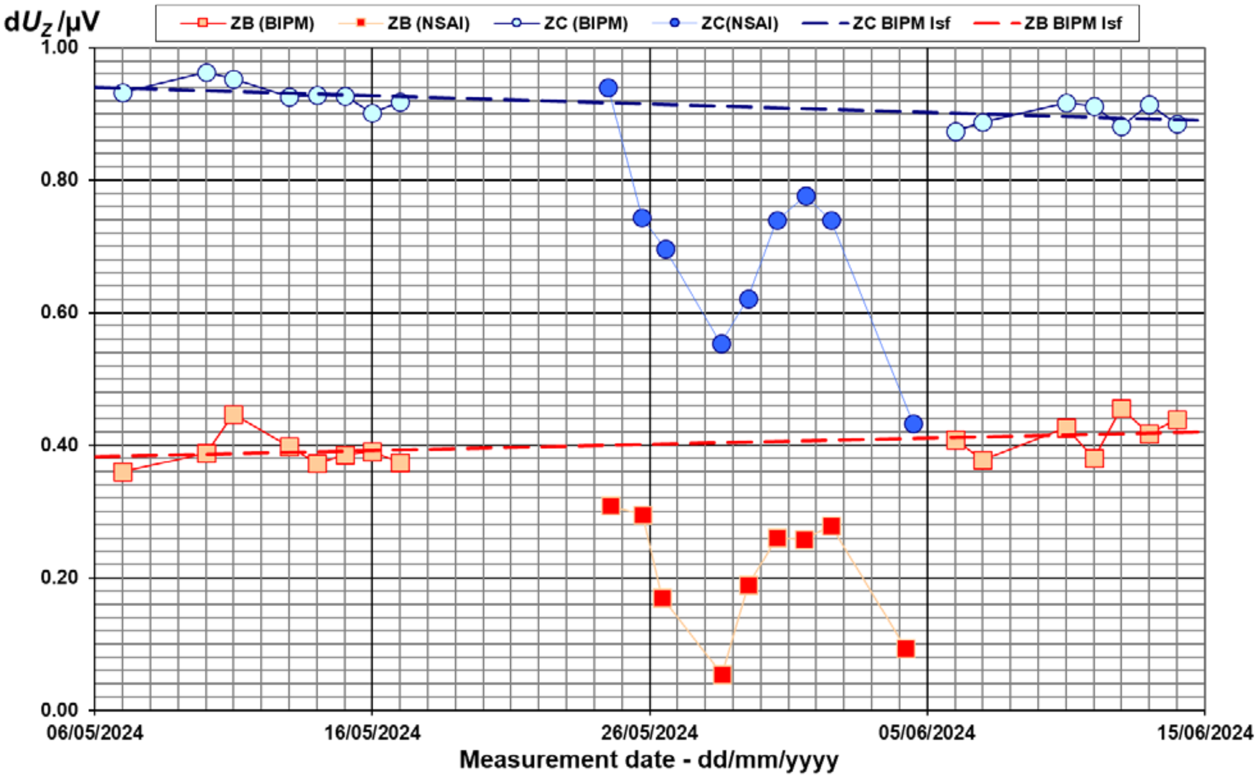

Figure 3: Voltage of ZB (squares) and ZC (disks) at 1.018 V measured at both institutes (light markers for BIPM and dark markers for NSAI-NML), referred to an arbitrary offset, as a function of the measurement date with a linear least-squares fit (lsf) to the BIPM measurements**.**

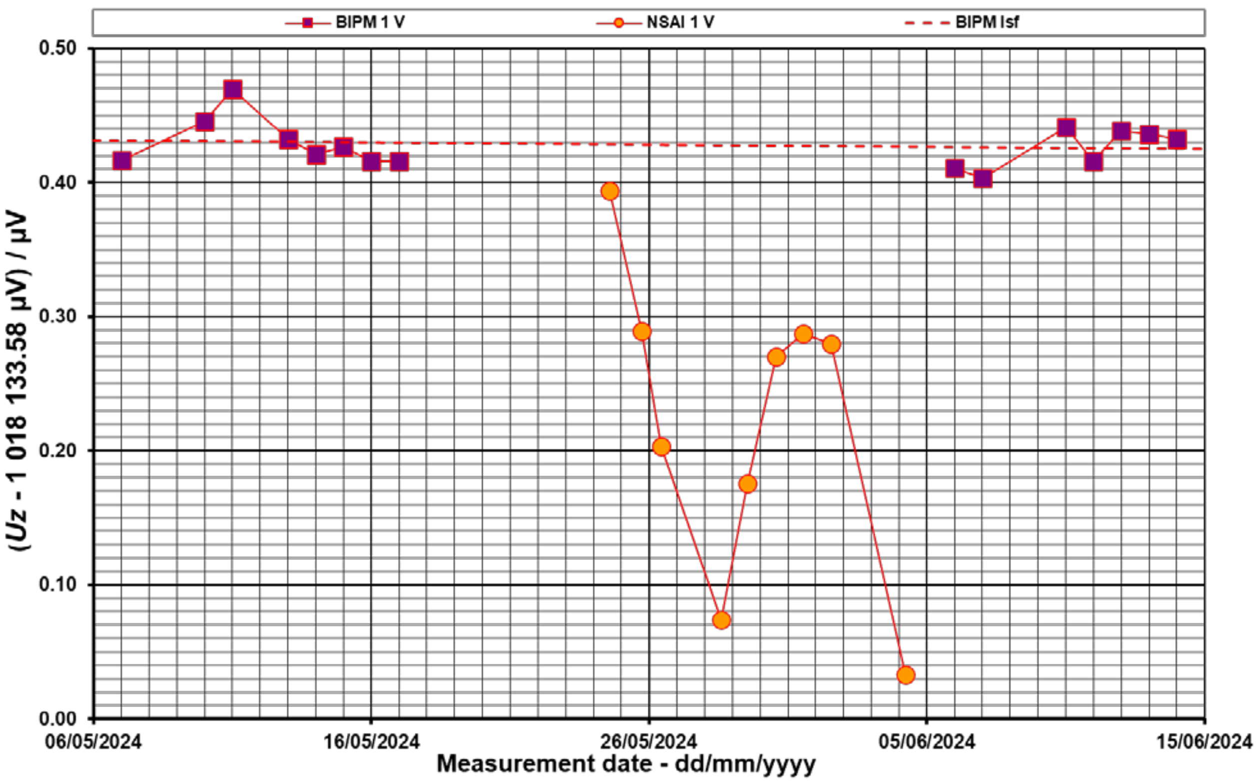

Figure 4: Voltage evolution of the arithmetic mean of the two standards at 1.018 V. NSAI-NML measurements are represented by disks and BIPM measurements by squares. A least-squares fit is applied to the BIPM measurements.

Uncertainty Budgets at 1.018 V

BIPM uncertainty budget at 1.018 V

Table 4 summarizes the uncertainties related to the calibration of a Zener diode against the Josephson array voltage standard at the BIPM at the level of 1.018 V.

JVS & detector uncertainty components	Uncertainty (nV)
Noise of the measurement loop that includes the residual thermal EMF including the residual EMF of the reversing switch (Type A)	2
Detector gain (Type B)	negligible
Leakage resistance (Type B)	0.4
Frequency (Type B)	0.01
Zener noise (Type A)	Not lower than the 1/*f* noise estimated as 15 nV, included in the comparison uncertainty budget (Table 6)
Zener pressure and temperature correction	Included in the comparison uncertainty budget (Table 6)

Table 4: Estimated standard uncertainties arising from the JVS and the measurement setup for Zener calibrations with the BIPM equipment at the level of 1.018 V.

NSAI-NML uncertainty budget at 1.018 V

Tables 5 list the uncertainties related to the calibration of the Zeners at NSAI-NML.

The corrections for internal temperature and ambient pressure were not included as these corrections are dealt in the BIPM analysis of the measurement data. The standard uncertainties of the measured thermistor resistance and ambient pressure are as follows:

Measured Quantity	Standard Uncertainty
Thermistor Resistance	2 Ω
Ambient Pressure	0.2 kPa

Quantity	Estimate	Standard uncertainty	Sensitivity Coefficient	Uncertainty contribution
Mean difference voltage measured by the null detector	29.457 µV	32 nV	1	32 nV
Microwave Reference frequency	18.40 GHz	1.8 Hz	0.055 nV/Hz	0.1 nV
Voltage due to leakage current	0 V	5 nV	1	5 nV
Voltage due to gain error of the nanovoltmeter	0 V	39 nV	1	39 nV
Non-compensated offset of the measurement circuit	0 V	59 nV	1	59 nV
	Total combined standard uncertainty			**78 nV**

Table 5: Estimated standard uncertainties for a Zener calibration with the NSAI-NML equipment at the level of 1.018 V for Zener ZB and ZC.

Uncertainty contributions for the comparison NSAI-NML/BIPM at 1.018 V

Table 6 lists the results and the uncertainty contributions for the comparison NSAI-NML/BIPM at 1.018 V.

		Results/µV		Uncertainty/µV	
		ZB	**ZC**	**ZB**	**ZC**
1	NSAI ($U_{\text{NSAI-NML}}$ – 1.018 V)	128.61	138.99		
2	Type A uncertainty			0.032	0.032
3	correlated (Type B) unc.			0.078	
4	BIPM (U_{BIPM} – 1.018 V)	128.80	139.21		
5	Type A uncertainty			0.015	0.015
6	correlated (Type B) unc.			<0.005	
7	pressure and temperature correction uncertainty			0.005	0.004
8	($U_{\text{NSAI-NML}}$ – U_{BIPM})	-0.19	-0.22		
9	Total uncorrelated uncertainty			0.036	0.036
10	Total correlated uncertainty			0.078	
11	< $U_{\text{NSAI-NML}}$ – U_{BIPM} >	**-0.20**			
12	*a priori* uncertainty			0.024	
13	*a posteriori* uncertainty			0.015	
14	**Comparison total combined standard uncertainty**			**0.082**	

Table 6: Results and uncertainties of NSAI-NML (Ireland)/BIPM bilateral comparison of 1.018 V standards using two Zener travelling standards: reference date 28 May 2024. Standard uncertainties are used throughout.

In Table 6, the following elements are listed:

(1) the value attributed by NSAI-NML to each Zener $U_{\text{NSAI-NML}}$, computed as the simple mean of all data from NSAI-NML and corrected for temperature and pressure differences between both laboratories by the BIPM.

(2)/(5) the NSAI-NML/BIPM combined Type A uncertainty (cf. Table 5).

(3) the uncertainty component arising from the realization and maintenance of the volt at NSAI-NML: it is the quadratic combination of the Type B components of the participant uncertainty budget listed in Table 5. This uncertainty is completely correlated between the different Zeners used for the comparison.

(4-6) the corresponding quantities for the BIPM referenced to the mean date of NSAI-NML measurements. In this case, the Type A uncertainty is limited by the flicker noise level of 15 nV.
(7) the uncertainty due to the combined effects of the pressure and temperature coefficients [5, 6] and to the differences of the mean pressures and temperatures in the participating laboratories is calculated as follows:

The uncertainty of the temperature correction $u_{T,i}$ of Zener i is determined for the difference ΔR_i between the mean values of the thermistor resistances measured at both institutes which is then multiplied by the uncertainty $u(c_{T,i})$ of the relative temperature coefficients of each Zener standard:

$$u_{T,i} = U \times u(c_{T,i}) \times \Delta R_i$$

where U = 1.018 V, $u(c_{T,ZB})$ = 0.415 × 10^{-7} / kΩ, $u(c_{T,ZC})$ = 0.272 × 10^{-7} / kΩ, ΔR_{ZB} = 0.067 kΩ and ΔR_{ZC} = 0.052 kΩ.
The uncertainties of the measurement of the temperature are negligible.
The same procedure is applied for the uncertainty $u_{P,i}$ of the pressure correction for the difference ΔP_i between the mean values of the pressure measured at both institutes:

$$u_{P,i} = U \times u(c_{P,i}) \times \Delta P_i$$

where U = 1.018 V, $u(c_{P,ZB})$ = 0.062 × 10^{-9} / hPa, $u(c_{P,ZC})$ = 0.058 × 10^{-9} / hPa, ΔP_{ZB} = 6.2 hPa and ΔP_{ZC} = 5.8 hPa.
However, since the NSAI-NML uncertainty is 2 hPa, the dominant contribution becomes:

$$u2_{P,i} = U \times c_{P,i} \times uP_i$$

where U = 1.018 V, $c_{P,ZB}$ = 1.96 × 10^{-9} V/ hPa, $c_{P,ZC}$ = 1.99 × 10^{-9} V/ hPa, $uP_{ZB} = uP_{ZC}$ = 2 hPa.The total uncertainty on pression correction is therefore the quadratic combination of $u_{1,P,\mathrm{i}}$ and $u_{2,P,\mathrm{i}}$.

(8) the difference ($U_{\mathrm{NSAI\text{-}NML}} - U_{\mathrm{BIPM}}$) for each Zener, and (9) the uncorrelated part of the uncertainty, calculated as the quadratic sum of lines 2, 5 and 7.
(10) the correlated part of the uncertainty, calculated as the quadratic sum of lines 3 and 6, for each travelling standard.
(11) the result of the comparison is the simple mean of the differences of the calibration results for the different standards.

(12 and 13) the uncertainty related to the transfer, estimated by comparing the following uncertainties:

(12) the *a priori* uncertainty, determined as the standard uncertainty of the mean, obtained by propagating the uncorrelated uncertainties for both Zeners;

(13) the *a posteriori* uncertainty, which is the standard deviation of the mean of the two results.

(14) the total uncertainty of the comparison, which is the root sum square of the correlated part of the uncertainty (10) and of the larger of (12) and (13).

In this case the *a priori* uncertainty is comparable to the *a posteriori* uncertainty. We therefore confirm the assumption made for the 10 V measurements: the metrological behavior of the travelling standards was not affected by the transportation phases.

The result of the comparison is presented as the difference between the value assigned to a 1.018 V standard by NSAI-NML, at NSAI-NML, $U_{\text{NSAI-NML}}$, and that assigned by the BIPM, at the BIPM, on the reference date of the 28th of May 2024:

$$\boldsymbol{U_{\text{NSAI-NML}} - U_{\text{BIPM}} = -0.20\ \mu\text{V}; \qquad u_{\text{c}} = 0.08\ \mu\text{V}}$$

where u_{c} is the combined standard uncertainty associated with the measured difference, including the uncertainty of the realization of the volt at the BIPM, (based on K_{J}) and at NSAI-NML and the uncertainty related to the comparison.

Conclusion

The final result of the comparison is presented as the difference between the values assigned to DC voltage standards by NSAI-NML, at the level of 1.018 V and 10 V, at NSAI-NML, $U_{\text{NSAI-NML}}$, and those assigned by the BIPM, at the BIPM, U_{BIPM}, at the reference date of the 28th of May 2024.

$$U_{\text{NSAI-NML}} - U_{\text{BIPM}} = -0.20\ \mu\text{V}; \quad u_c = 0.08\ \mu\text{V, at 1.018 V}$$

$$U_{\text{NSAI-NML}} - U_{\text{BIPM}} = -0.02\ \mu\text{V}; \quad u_c = 0.13\ \mu\text{V, at 10 V}$$

where u_c is the combined standard uncertainty associated with the measured difference, including the uncertainty of the realization of the volt at the BIPM and at NSAI-NML, based on K_J, and the uncertainty related to the comparison.

The 10 V comparison results show that the voltages standards maintained by NSAI-NML and the BIPM were equivalent, within their stated standard uncertainties at 10 V. At 1.018 V, the uncertainty at the 2σ level doesn't cover the difference.

The NSAI-NML results at 1.018 V show a similar behavior of the two standards in day-to-day measurement. The standard deviation of the mean of the NSAI-NML results is 30 nV and 50 nV for ZB and ZC, respectively; the difference between day-to-day measurement could reach 190 nV for ZB and 310 nV for ZC.

In the case of the BIPM, the standard deviation of the mean of the results is 8 nV and 7nV for ZB and ZC, respectively, and the maximum deviation from day to day measurement is 80 nV and 30 nV for ZB and ZC, respectively. This allows us to conclude that the discrepant results are independent of the metrological quality of the two standards and that the issue is caused by the NSAI-NML measurement setup and electromagnetic environment.

To our knowledge, there are four hypotheses which could explain this behavior:

1. Considerable electrical noise was interfering with the measurement setup;
2. A considerable ground loop was present in the measurement setup;
3. The quality of contacts of the reversing switch was not reliable and led to spurious voltages in the measurement line.
4. PJVS voltage step widths were such that the selected biasing current was outside the quantization locked range because of some electric noise brought to them.

This would need to be investigated.

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