Bilateral Comparison of 1.018 V and 10 V Standards between SASO-NMCC (Saudi Arabia) and the BIPM, September to November 2023

(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 Saudi Arabia Standards Metrology and Quality Organisation, National Measurement and Calibration Center (SASO-NMCC), Riyadh (Saudi Arabia), was carried out from September to November 2023. Two BIPM Zener diode-based traveling standards (Fluke 732B), BIPM_E (ZE) and BIPM_F (ZF), were transported by freight to the SASO-NMCC and back to the BIPM. In order to keep the Zeners powered during the transportation, a voltage stabiliser developed by the BIPM was connected in parallel to the internal battery. The voltage stabiliser consists of a set of two batteries, electrically protected against overcurrent surges, and easy to recharge. This device is designed to power two Fluke 732B transfer standards for at least 10 consecutive days. Unfortunately, ZF was delivered cold when it arrived at the SASO-NMCC. Investigations at the SASO-NMCC showed that the power shortage of the Zener was due to a defective soldering joint in the cable connecting the Zener and the voltage stabiliser. Fortunately, upon examination of the first set of measurements, ZF seemed not to have suffered from the power shortage. Regrettably, ZE and ZF were delivered cold when they were shipped back to the BIPM for the return measurements. It was observed that the voltage stabiliser was not connected to the traveling standards. The internal thermistors of ZE and ZF were recorded respectively as 95 kΩ and 117 kΩ indicating that the standards had remained cold for a long period (cf. Annex 1).

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

At the BIPM, the output EMF of each traveling standard was calibrated before and after the measurements at the SASO-NMCC against a PJVS and associated measurement system developed at the BIPM.

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

SASO-NMCC 1.018 V and 10 V measurements

On receipt, the traveling standards ZE and ZF were connected to the mains power supply and left in the laboratory at a temperature of (23 ± 2) °C and relative humidity of (45 ± 15) % to stabilize for several days before performing the measurements.

At the SASO-NMCC, the output voltages of each traveling standard were measured with a fully automated, commercial PJVS: AC Quantum Voltmeter operated with SupraVOLT^{TM} control system [1, 2, 3], equipped with a 10 V array of Josephson junctions inside a cryocooler. The output electromotive force (EMF) of each traveling standard was measured by direct comparison with the PJVS.

Each pair of output terminals of the traveling standards was connected in series opposition to the PJVS using a low thermal EMF polarity reversal switch with three different channels.

The EMF differences were measured using a digital nanovoltmeter *Keithley 2182A* (serial number: 4312247) operated on its 10 mV range. Before a Zener standard measurement, the calibration of the gain was carried out using the PJVS in order to correct for the nanovoltmeter gain error.

The standards were disconnected from the mains at least two hours before and remained disconnected throughout the entire measurement session. The GUARD and CHASSIS binding posts were jointly connected.

The critical current amplitude of the array was verified prior to starting the daily measurements.

At the operating frequency of 70 GHz the PJVS array temperature was close to 3.6 K.

The 70 GHz signal was phase-locked to a 10 MHz external reference frequency with a relative uncertainty of 1×10^{-14} provided by the SASO-NMCC's Time and Frequency laboratory.

The internal thermistor resistance of each Zener was measured using an ohmmeter on its 300 kΩ range using a measuring current of 1.5 μA.

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) [4], through a low thermal EMF multiplexer [5, 6]. 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* (SN: 4330344) operated on its 10 mV range. A dedicated computer and associated software were used to monitor and 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 is below 1 μV for both nominal voltages.

One individual measurement point is 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 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 and a reading sequence is carried out with the same configuration described in step 1;
4- The Zener and the BIPM array are set in their negative polarity, connected in series opposition and the detector 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 and a reading sequence is carried out with the same configuration described in step 4.

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, and 3).

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 SASO-NMCC measurements (30/09/2023) and the mean value of the SASO-NMCC measurements, and the related uncertainties.

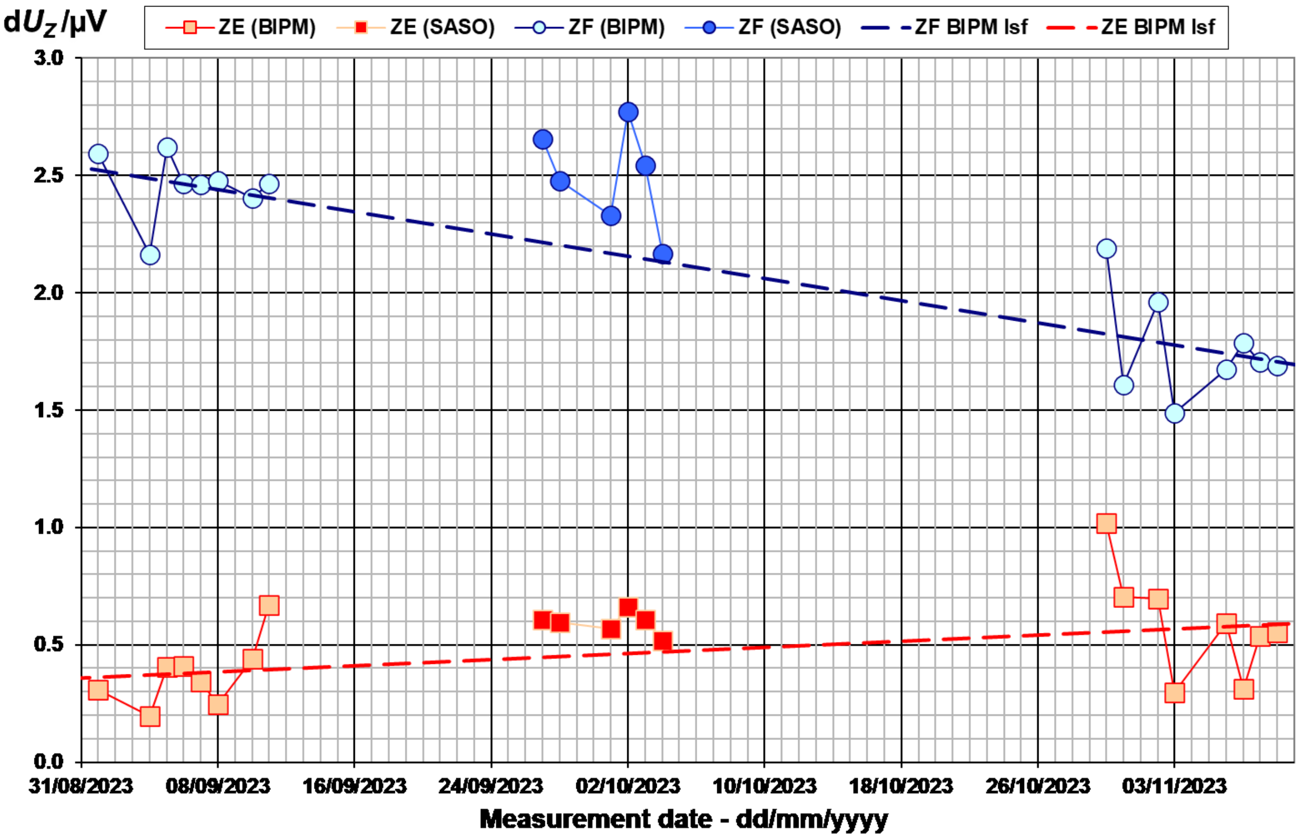

Figure 1: Voltage of ZE (squares) and ZF (disks) at 10 V measured at both institutes (light markers for BIPM and dark markers for SASO-NMCC), referred to an arbitrary offset, as a function of the measurement date with a linear least-squares fit (lsf) to the BIPM measurements.

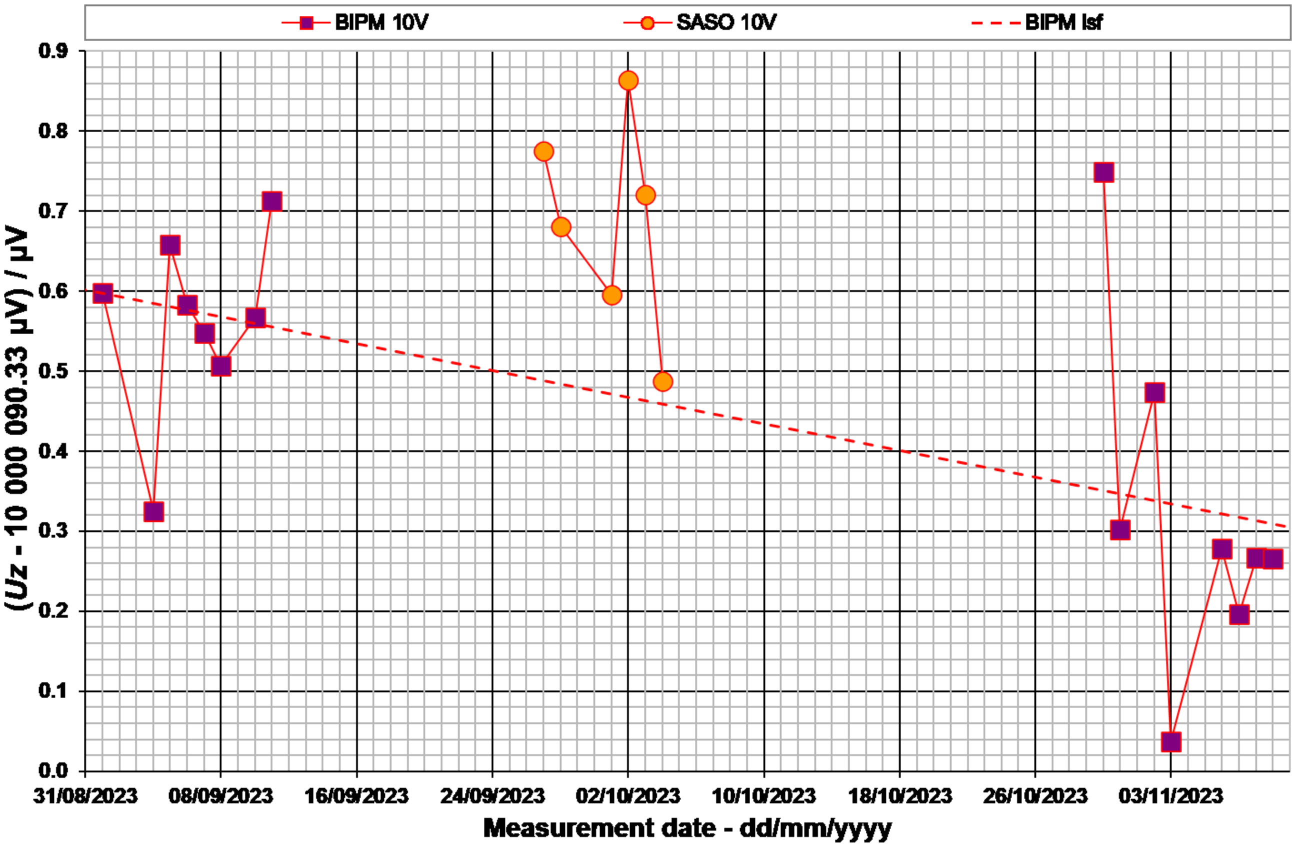

Figure 2: Voltage evolution of the arithmetic mean of the two standards at 10 V. SASO-NMCC measurements are represented by disks and BIPM measurements by squares. A least-squares fit is applied to the BIPM measurements.

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 [7]. 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
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.

SASO-NMCC uncertainty budget at 10 V

Table 2a and 2b lists the uncertainties related to the calibration of the Zeners at SASO-NMCC for ZE and ZF, respectively.

Source of uncertainty	Type	Dist.	Standard uncertainty	Sensitivity	Uncertainty contribution
Standard deviation	A	Norm.	20 nV	1	20 nV
Josephson system	B	Norm.	0.5 nV	1	0.5 nV
Frequency	B	Norm.	0.5 nV	1	0.5 nV
Nanovoltmeter gain error	B	Rect.	0.58 nV	1	0.58 nV
Leakage current	B	Rect.	0.17 nV	1	0.17 nV
Thermal EMF	B	Rect.	2.9 nV	1	2.9 nV
Environmental parameters	B	Rect.	58 nV	1	58 nV
			Combined uncertainty		61.4 nV
			Expanded uncertainty (*k* = 2)		123 nV

Table 2a: Estimated standard uncertainties for a Zener calibration with the SASO-NMCC equipment at the level of 10 V for Zener ZE.

Source of uncertainty	Type	Dist.	Standard uncertainty	Sensitivity	Uncertainty contribution
Standard deviation	A	Norm.	98 nV	1	98 nV
Josephson system	B	Norm.	0.5 nV	1	0.5 nV
Frequency	B	Norm.	0.5 nV	1	0.5 nV
Nanovoltmeter gain error	B	Rect.	0.58 nV	1	0.58 nV
Leakage current	B	Rect.	0.17 nV	1	0.17 nV
Thermal EMF	B	Rect.	2.9 nV	1	2.9 nV
Environmental parameters	B	Rect.	58 nV	1	58 nV
			Combined uncertainty		113.9 nV
			Expanded uncertainty (*k* = 2)		228 nV

Table 2b: Estimated standard uncertainties for a Zener calibration with the SASO-NMCC equipment at the level of 10 V for Zener ZF.

Uncertainty contributions for the comparison SASO-NMCC/BIPM at 10 V

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

		Results/µV		Uncertainty/µV	
		ZE	ZF	ZE	ZF
1	SASO-NMCC ($U_{\text{SASO-NMCC}}$ – 10 V)	95.09	86.94		
2	Type A uncertainty			0.020	0.098
3	correlated (Type B) unc.			0.003	
4	BIPM (U_{BIPM} – 10 V)	94.96	86.62		
5	Type A uncertainty			0.15	0.15
6	correlated (Type B) unc.			<0.005	
7	pressure and temperature correction uncertainty			0.042	0.054
8	($U_{\text{SASO-NMCC}} – U_{\text{BIPM}}$)	0.13	0.32		
9	Total uncorrelated uncertainty			0.157	0.187
10	Total correlated uncertainty			0.058	
11	< $U_{\text{SASO-NMCC}} – U_{\text{BIPM}}$ >	**0.22**			
12	*a priori* uncertainty			0.122	
13	*a posteriori* uncertainty			0.095	
14	**comparison total standard uncertainty/µV**			**0.12**	

Table 3: Results and uncertainties of SASO-NMCC (Saudi Arabia)/BIPM bilateral comparison of 10 V standards using two Zener traveling standards: reference date 30 September 2023. Standard uncertainties are used throughout.

In Table 3, the following elements are listed:

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

(2) SASO-NMCC combined Type A uncertainty (cf. Tables 2a and 2b).

(3) the uncertainty component arising from the realization and maintenance of the volt at SASO-NMCC: it is the quadratic combination of the Type B components of the participant’s uncertainty budget listed in Tables 2a and 2b. 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 SASO-NMCC 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 [8, 9] 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:

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

where U = 10 V, $u(c_{T,ZE})$ = 0.311 × 10^{-7} / kΩ, $u(c_{T,ZF})$ = 0.297 × 10^{-7} / kΩ, ΔR_{ZE} = 0.108 kΩ and ΔR_{ZF} = 0.084 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:

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

where U = 10 V, $u\left(c_{P,ZE}\right)$= 0.042 × 10^{-9} / hPa, $u(c_{P,ZF})$ = 0.080 × 10^{-9} / hPa, ΔP_{ZE} = 59.1 hPa and ΔP_{ZF} = 59.1 hPa.
The uncertainties of the measurement of the temperature and the pressure are negligible.

(8) the difference ($U_{\text{SASO-NMCC}} - U_{\text{BIPM}}$) 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 traveling 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 traveling standards[1].

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 their transportation. This is not the case at the 10 V output despite the fact that the Zeners were delivered cold after their return journey. 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 SASO-NMCC, at SASO-NMCC, $U_{\text{SASO-NMCC}}$, and that assigned by the BIPM, at the BIPM, U_{BIPM}, on the reference date of the 30th of September 2023:

$$\boldsymbol{U_{\text{SASO-NMCC}} - U_{\text{BIPM}} = 0.22\ \mu\text{V}; \qquad u_{\text{c}} = 0.12\ \mu\text{V}}$$

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

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[1] With only two traveling 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

At the BIPM, both traveling standards were calibrated before and after the measurements at SASO-NMCC. On its return to the BIPM, the traveling standard ZE exhibited a large drift of 150 nV on its 1.018 V output compared to the previous measurements (cf. Annex1). This large shift is due to the fact that the Zener internal voltage divider was affected by being unpowered for a while during the return to the BIPM since the voltage stabilizer was not connected to the Zeners. Fortunately, the measurements of ZF did not indicate such a significant change in its 1.018 V output. As a consequence, the measurements of ZE at 1.018 V are excluded from the comparison.

Figure 3 shows the measured values obtained for ZF by the two laboratories at 1.018 V. A linear least squares fit is applied to all of the individual BIPM results. The comparison result is the voltage difference between the BIPM fitted value at the mean date of the SASO-NMCC measurements (30/09/2023) and the mean value of SASO-NMCC measurements, and the associated uncertainty.

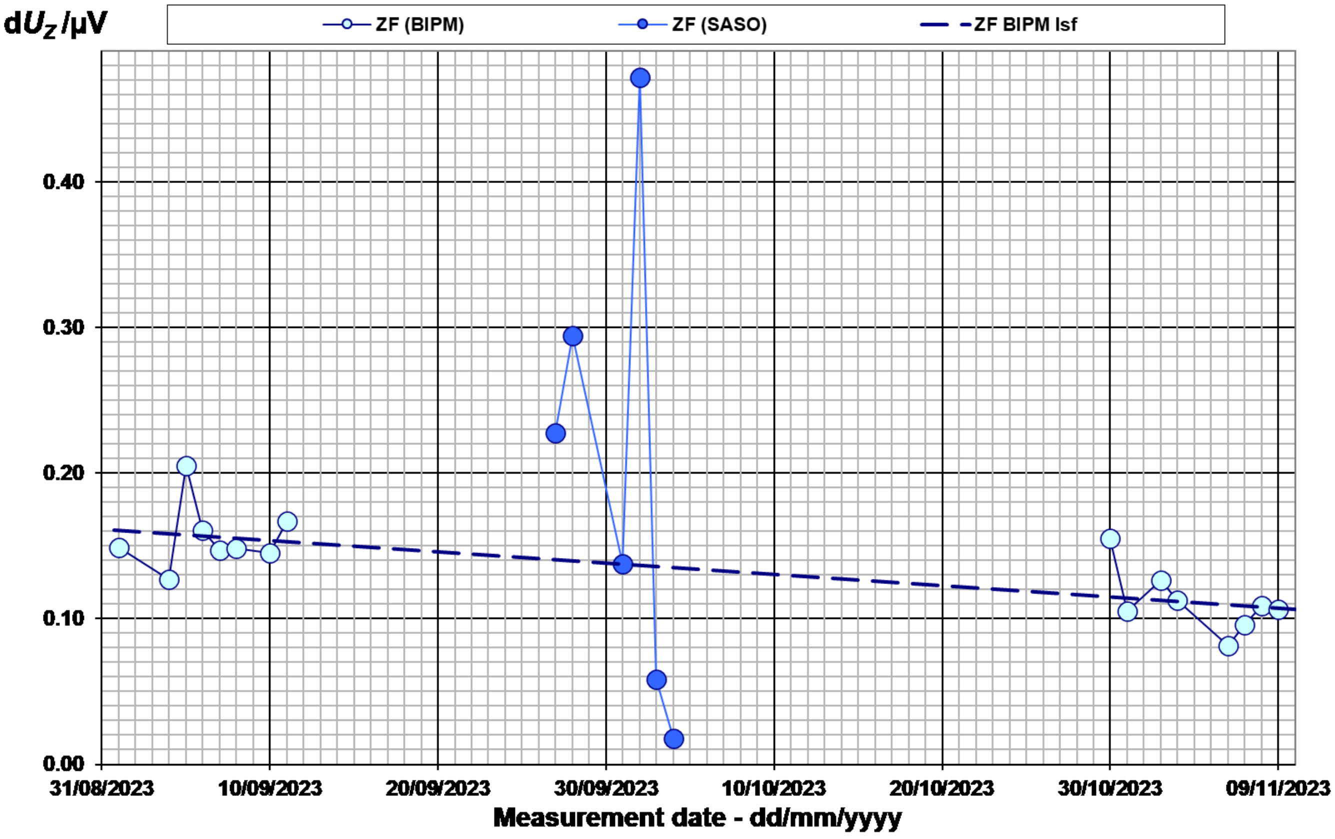

Figure 3: Voltage of ZF at 1.018 V measured at both institutes (light markers for BIPM and dark markers for SASO-NMCC), referred to an arbitrary offset, as a function of the measurement date with a linear least-squares fit (lsf) to the BIPM measurements.

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
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.

SASO-NMCC uncertainty budget at 1.018 V

Table 5 lists the uncertainties related to the calibration for ZF at the SASO-NMCC.

Source of uncertainty	Type	Dist.	Standard uncertainty	Sensitivity	Uncertainty contribution
Standard deviation	A	Norm.	44 nV	1	44 nV
Josephson system	B	Rect.	2.9 nV	1	2.9 nV
Frequency	B	Rect.	2.9 nV	1	2.9 nV
Nanovoltmeter gain error	B	Rect.	1.7 nV	1	1.7 nV
Leakage current	B	Rect.	5.8 nV	1	5.8 nV
Thermal EMF	B	Rect.	12 nV	1	12 nV
Environmental parameters	B	Rect.	58 nV	1	58 nV
			Combined uncertainty		74 nV
			Expanded uncertainty (*k* = 2)		148 nV

Table 5: Estimated standard uncertainties for a Zener calibration with the SASO-NMCC equipment at the level of 1.018 V for Zener ZF.

Uncertainty contributions for the comparison SASO-NMCC at 1.018 V

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

		Results/μV	Uncertainty/μV
		ZF	
1	SASO-NMCC ($U_{\text{SASO-NMCC}}$ – 1.018 V)	161.58	
2	Type A uncertainty		0.044
3	SASO-NMCC Type B) unc.		0.014
4	BIPM (U_{BIPM} – 1.018 V)	161.52	
5	Type A uncertainty		0.015
6	BIPM Type B unc.		<0.003
7	pressure and temperature correction uncertainty		0.005
8	Total uncertainty		0.049
9	($U_{\text{SASO-NMCC}}$ – U_{BIPM})	**0.06**	
10	transfer uncertainty		negligible
11	**comparison total standard uncertainty/μV**		**0.05**

Table 6: Results and uncertainties of the SASO-NMCC (Saudi Arabia)/BIPM bilateral comparison of 1.018 V standard using one Zener traveling standard: reference date 30 September 2023. Standard uncertainties are used throughout.

In Table 6, the following elements are listed:

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

(2) the SASO-NMCC Type A uncertainty (cf. Table 5).

(3) the uncertainty component arising from the realization and maintenance of the volt at SASO-NMCC: it is the quadratic combination of the Type B components of the participant uncertainty budget listed in Table 5.

(4-6) the corresponding quantities for the BIPM referenced to the mean date of SASO-NMCC 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 [8, 9] and to the differences of the mean pressures and temperatures in the participating laboratories is calculated as follows:

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

$$u_{T,ZF} = U \times u(c_{T,ZF}) \times \Delta R_{ZF}$$

where U = 1.018 V, $u(c_{T,ZF})$ = 0.329 × 10^{-7} / kΩ and ΔR_{ZF} = 0.079 kΩ.

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

$$u_{P,ZF} = U \times u(c_{P,ZF}) \times \Delta P_{ZF}$$

where U = 1.018 V, $u(c_{P,ZF})$ = 0.074 × 10^{-9} / hPa and ΔP_{ZF} = 59.1 hPa.

The uncertainties of the measurement of the temperature and the pressure are negligible.

(8) the total uncertainty, calculated as the quadratic sum of lines 2, 3, 5 ,6 and 7.

(9) the result of the comparison is the simple mean of the differences of the calibration results for the Zener standard.

(10) The estimate of the drift of ZF between the initial and the final measurements at the BIPM shows that the standard didn’t exhibit any abnormal behaviour from its shipment between BIPM and the participant. Therefore, we consider that the uncertainty related to the transfer of the standard can be neglected in comparison to the difference between the SASO-NMCC and the BIPM (cf. Annex 2 and Figure A2).

(11) the total uncertainty of the comparison, calculated as the quadratic sum of lines 8 and 10.

The result of the comparison is presented as the difference between the value assigned to a 1.018 V standard by SASO-NMCC, at SASO-NMCC, $U_{\text{SASO-NMCC}}$, and that assigned by the BIPM, at the BIPM, on the reference date of the 30th of September 2023:

$$\boldsymbol{U_{\text{SASO-NMCC}} - U_{\text{BIPM}} = 0.06\ \mu\text{V}; \qquad u_{\text{c}} = 0.05\ \mu\text{V}}$$

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 SASO-NMCC 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 SASO-NMCC, at the level of 1.018 V and 10 V, at SASO-NMCC, $U_{\mathrm{SASO\text{-}NMCC}}$, and those assigned by the BIPM, at the BIPM, U_{BIPM}, at the reference date of the 30th of September 2023.

$$U_{\mathrm{SASO\text{-}NMCC}} - U_{\mathrm{BIPM}} = 0.06\ \mu\mathrm{V};\ u_{\mathrm{c}} = 0.05\ \mu\mathrm{V},\ \text{at } 1.018\ \mathrm{V}$$

$$U_{\mathrm{SASO\text{-}NMCC}} - U_{\mathrm{BIPM}} = 0.22\ \mu\mathrm{V};\ u_{\mathrm{c}} = 0.12\ \mu\mathrm{V},\ \text{at } 10\ \mathrm{V}$$

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 SASO-NMCC, based on K_{J}, and the uncertainty related to the comparison.

These are satisfactory results. At 1.018 V the comparison results show that the voltage standards maintained by SASO-NMCC and the BIPM were equivalent, within their stated standard uncertainties. Nonetheless, the dispersion of SASO-NMCC is very large, indicating a possible issue with the earthing of the measurement setup. Furthermore, since one of the traveling standards suffered from not being powered during the shipment phase between Saudi Arabia and the BIPM, the result relies only on the results obtained with one standard.

The results at the 10 V level are covered by the uncertainties with a coverage factor of 2, on the mean date of the comparison.

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ANNEX 1

Two BIPM Zener diode-based traveling standards (Fluke 732B) were shipped to Riyadh (Saudi Arabia) in September 2023 after being measured for 8 days at BIPM against the BIPM primary standard. In October 2023 the traveling standards were delivered cold to the BIPM laboratory. The return measurements performed at the BIPM exhibited a very significant change on the 1.018 V output for one of the two traveling standards (ZE) reaching 150 nV which is 10 times the 1/*f* noise floor. Figure A1 shows the monitoring of the 1.018 V output value of the standard ZE. Our experience of using Fluke 732B as transfer standards in the BIPM.EM-K11 comparison program is different from that of the manufacturer [10-11]: the resistors of the voltage divider of the standards can change if the Zener furnace temperature hasn't been maintained for a long time after internal power interruption. In the present case, only one of the four voltage dividers (two Zeners with two voltage outputs each) was affected by the internal power interruption. To investigate on the shift effect on the voltage output value, we looked at the BIPM results obtained with ZE in a previous bilateral comparison and plotted a linear fit of all available measurements (Cf. Fig. A1).

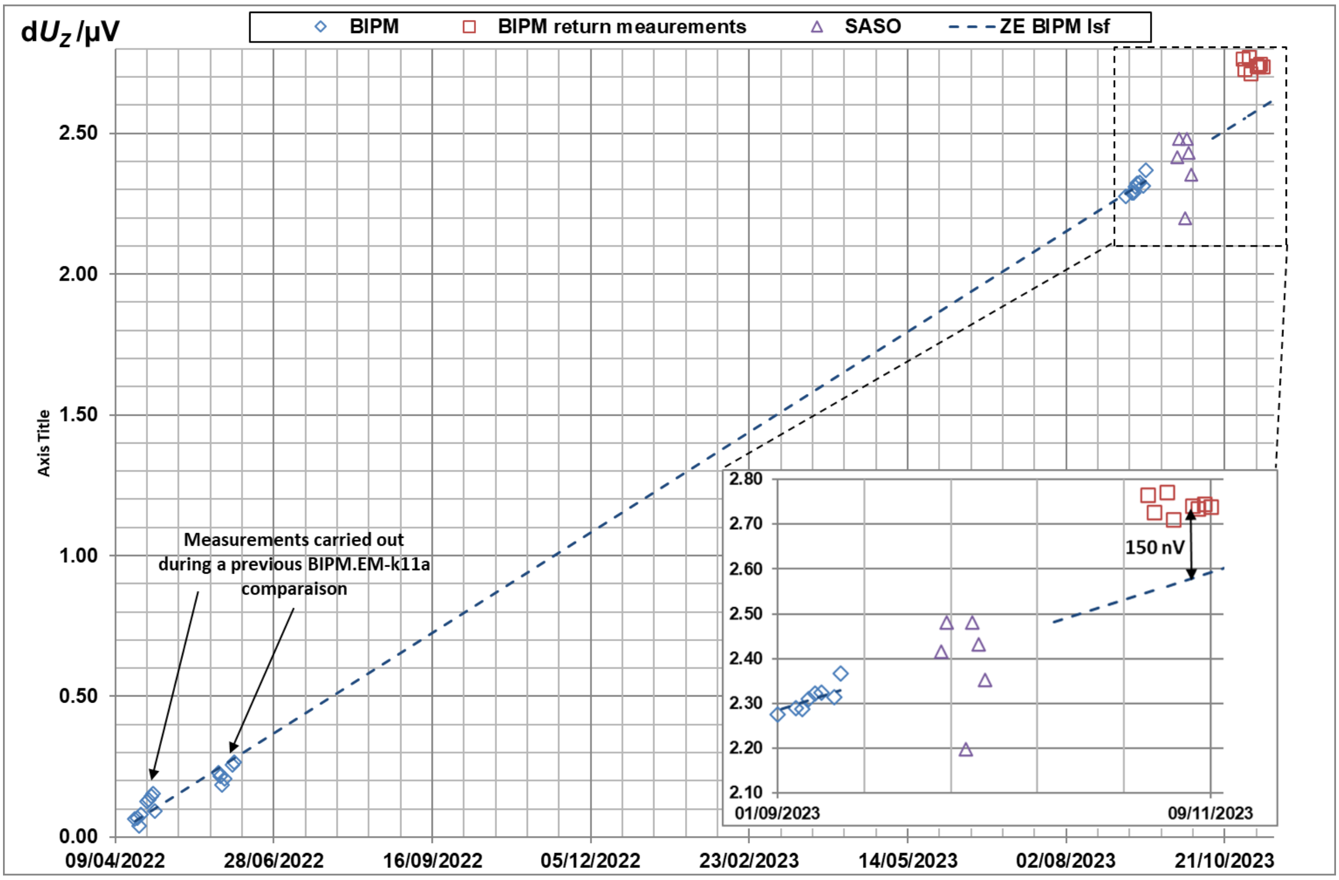

Figure A1: Voltage of ZE at 1.018 V (diamonds and squares markers for BIPM and triangles markers for SASO NMCC), referred to an arbitrary offset, as a function of the measurement date with a linear least-squares fit (lsf) to the BIPM measurements represented with diamonds markers.

ANNEX 2

This annex describes in detail the process followed to derive a proper uncertainty component to take into account any change of the standard due to the transportation phases.

Experience showed that a linear model can be used to give an approximate description of the behaviour of the voltage output of the Zener U as a function of time t:

$$U = \beta_0 + \beta_1 \times t$$

where β_0 and β_1 are constants.

We can estimate a regression model:

$$\widehat{U} = \widehat{\beta_0} + \widehat{\beta_1} \times t$$

Using the formula for the variance of the sum of two random variables:

$$V(\widehat{U}) = V\left(\widehat{\beta_0}\right) + t^2 \times V\left(\widehat{\beta_1}\right) + 2 \times t \times Cov(\widehat{\beta_0}, \widehat{\beta_1})$$

An unbiased estimate of σ^2 is obtained from the sum of squares of the residuals r_i [12] and we get:

$$\widehat{\sigma}^{\,2} = \frac{1}{\mathrm{n} - 2} \times \sum_{i=1}^{n} {r_i}^2$$

Replacing $V\left(\widehat{\beta_0}\right), V\left(\widehat{\beta_1}\right)$ and $Cov(\widehat{\beta_0}, \widehat{\beta_1})$ with their expressions [12], we find that,

$$V(\widehat{U}) = \sigma^2 \times \left[\frac{1}{n} + \frac{(t - \bar{t}\,)^2}{\sum_{i=1}^{n}(t_i - \bar{t}\,)^2}\right]$$

We notice that $V(\widehat{U})$ is minimum when $t = \bar{t}$.

Using the initial and the final measurements data at the BIPM on the reference date t_{Ref} of the 30th of September we computed $\sqrt{V(\widehat{U} \middle| t_{Ref}\,)}$ in order to derive the transfer uncertainty of ZF at 1.018 V. Hence, we obtain a transfer uncertainty of 0.006 µV.

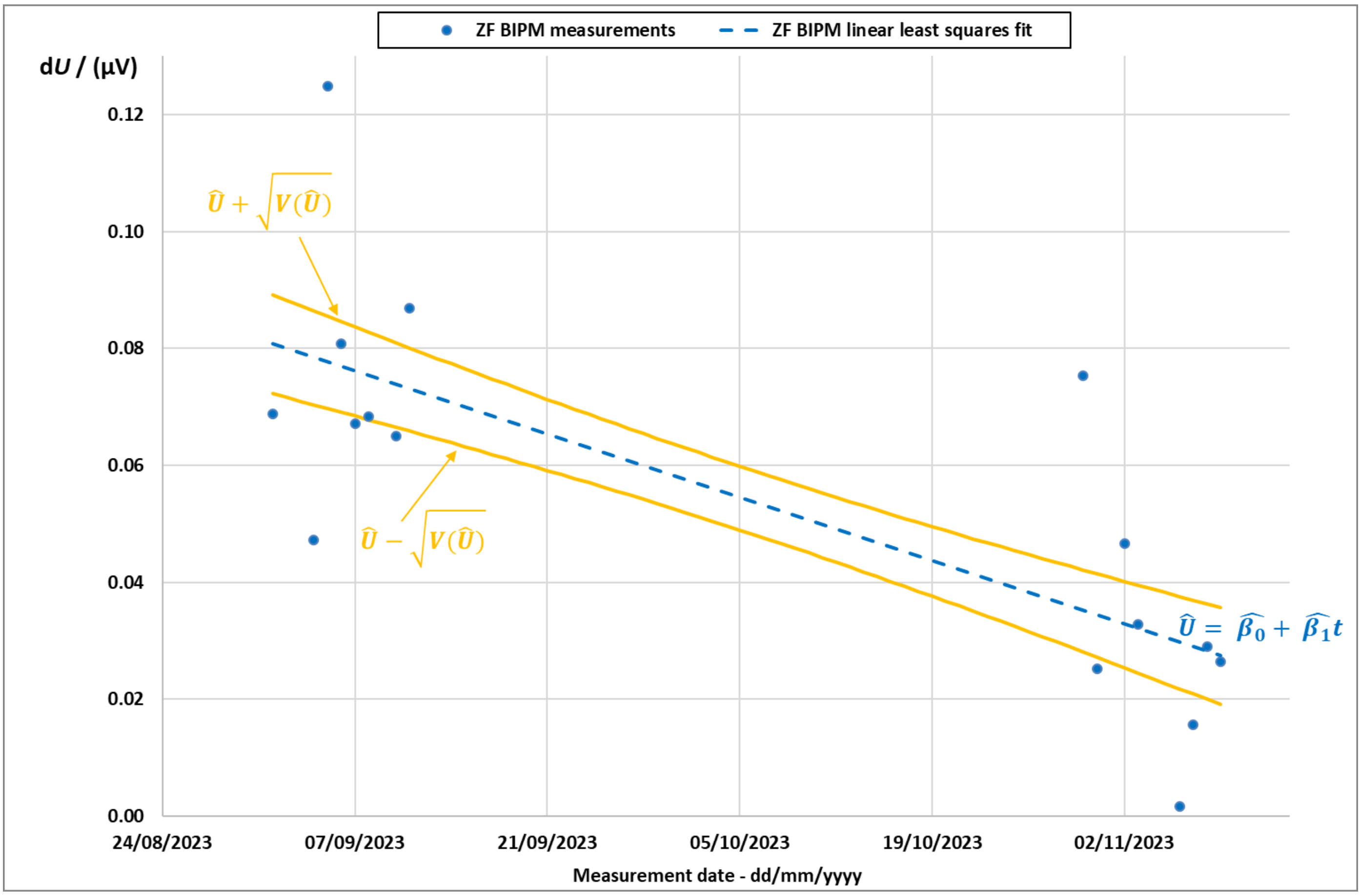

Figure A2: BIPM ZF Voltage measurements at 1.018 V, referred to an arbitrary offset, as a function of the measurement date together with a linear least-squares fit (lsf) applied to the measurements. The confidence interval for the forecasted values of $\widehat{U}$ is also represented by the space between the two orange curves.