Bilateral Comparison of 1.018 V and 10 V Standards
between the SMD (Belgium) and the BIPM,
October to December 2021
(part of the ongoing BIPM key comparison BIPM.EM-K11.a and b)

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Final Report – February 2022

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 Service Métrologie – Metrologische Dienst (SMD)**,** Brussels, Belgium, was carried out from October to December 2021. Two BIPM Zener diode-based travelling standards (Fluke 732B), BIPM_B (ZB) and BIPM_6 (Z6), were transported to SMD and back to BIPM by road. At SMD, the reference standard for DC voltage is a Josephson Voltage Standard (JVS). The output EMF (Electromotive Force) 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 SMD, against the Josephson Voltage Standard (JVS) developed at the BIPM. Results of all measurements were corrected for the dependence of the output voltages of the Zener standards on internal temperature and ambient atmospheric pressure.

Outline of the measuring method

SMD 1.018 V and 10 V measurements

At SMD, the reference standard for DC voltage is a fully automated, commercial Josephson Voltage Standard (Supracon AG 10 V SIS array *s.n.* 05, that has been subject to a comparison with the BIPM travelling JVS in 2009 as part of the ongoing BIPM key comparison BIPM.EM-K10.b [1]). The output electromotive force (EMF) of each travelling standard was measured by direct comparison with the primary standard.

Each output terminal of the travelling standards was connected in series opposition to the JVS using a low thermal EMF polarity reversal switch with three different channels. The channels were randomly chosen every day, with the same two channels being used for all measurements performed within the same day (that is, four outputs in total).

The EMF differences are measured using a digital nanovoltmeter - 8 data points taken consecutively - with the simple mean value being considered as the result of the day. Each individual data point represents the mean of 40 measurements (20 in positive and 20 in negative polarity), that are automatically collected by the computer [2, 3].

The standards are disconnected from the mains about two and a half hours before and remain disconnected throughout the entire measurement session (that lasts approximatively 5 hours). The GUARD and CHASSIS binding posts are jointly connected to the common ground point of the setup. The internal thermistor resistance is measured at 10 µA and recorded prior to the start of the measurements.

BIPM Measurements for 1.018 V and 10 V

The output voltage of the Zener standard to be measured is 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]. This measurement setup built around a programmable array (SNS-based Josephson junctions) is fully independent from, and replaces, the former measurement setup built around a traditional SIS-based array of Josephson junctions. The agreement between both setups can be found in the literature [6]. The binding post terminals “GUARD” and “CHASSIS” of the Zener standard are connected together and connected to a single point which is the grounding reference point of the measurement setup.

The measurements start after at least two hours after the mains plug at the rear of the Zeners has 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 is used to monitor and record the measurements, acquire the data, correct for temperature and pressure dependence and calculate results.

The BIPM array biasing frequency is 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 Zener and the BIPM array are set in their positive polarity again and the reading sequence restarts (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 Zener and the BIPM array are set in their negative polarity again and the reading sequence restarts (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, 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 the BIPM results, of 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 SMD measurements (2021/11/17) and the mean value of SMD measurements and related uncertainties.

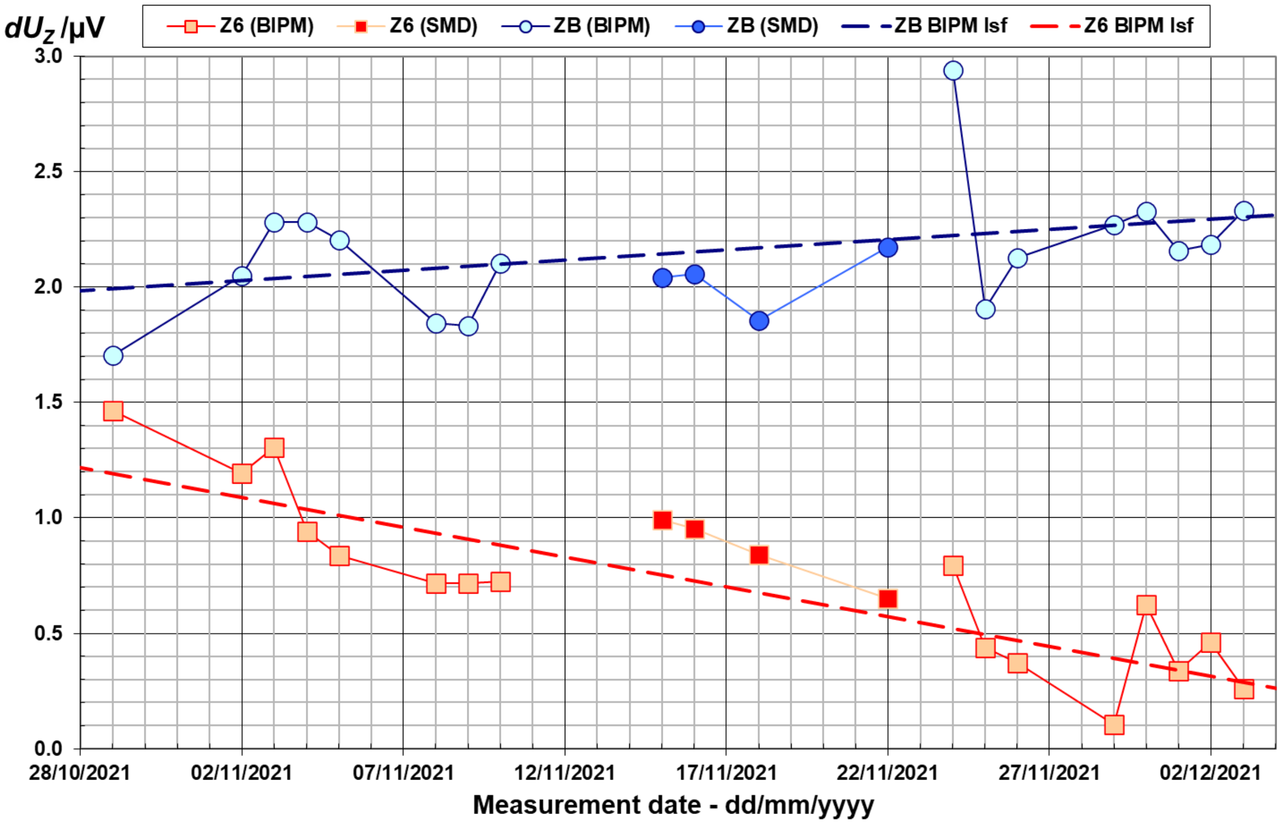

Figure 1: Voltage of Z6 (squares) and ZB (disks) at 10 V measured at both institutes (light markers for BIPM and dark markers for SMD), referred to an arbitrary offset, as a function of the measurement date with a linear least-squares fit (lsf) to the BIPM measurements**.**

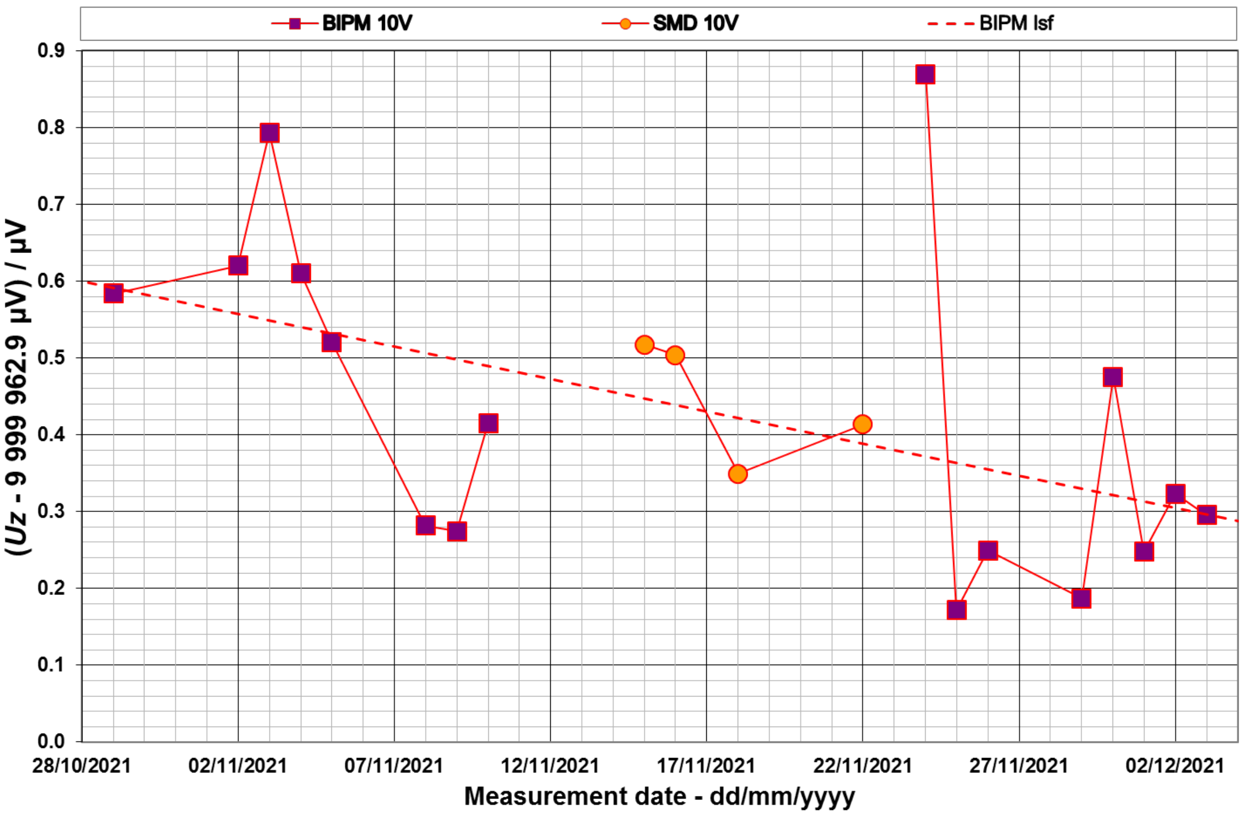

Figure 2: Voltage evolution of the arithmetic mean of the two standards at 10 V. SMD measurements are represented by disks and BIPM measurements by squares. A least-squares fit is applied to the BIPM measurements.

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.

SMD uncertainty budget at 10 V

Table 2a and 2b lists the uncertainties related to the calibration of the Zeners at the SMD for Z6 and ZB, respectively.

Note that the uncertainty of the temperature and pressure corrections (in italic) are given as an indication only and do not contribute to the final uncertainty budget used for this comparison as they are applied by the BIPM and included in the comparison uncertainty budget (Table 3).

Quantity	Type	Dist.	Standard uncertainty	Sensitivity	Uncertainty contribution
Measured thermistor resistance	A	Norm.	3 Ω	0.1 nV/Ω	0.30 nV
Measured air pressure	A	Norm.	0.8 hPa	0.1 nV/hPa	0.08 nV
Thermal coefficient of the Zener	*B*	*Rect.*	*0.29 nV/Ω*	*3 Ω*	*0.87 nV*
Pressure coefficient of the Zener	*B*	*Rect.*	*0.12 nV/hPa*	*120 hPa*	*14.4 nV*
Voltage due to gain error of the nanovoltmeter	B	Norm.	115 nV	1	115 nV
Measured output voltage from the terminal	A	Norm.	74.1 nV	1	74.1 nV
Reference frequency accuracy	B	Rect.	0.35 nV	1	0.35 nV
Voltage due to leakage current	B	Rect.	0.13 nV	1	0.13 nV
Voltage due to residual thermal EMF	B	Rect.	2.9 nV	1	2.9 nV
Residual voltage in the polarity switch	B	Norm.	200 nV	1	200 nV
			Combined uncertainty		243 nV
			Expanded uncertainty (*k*=2)		486 nV

Table 2a: Estimated standard uncertainties for a Zener calibration with the SMD equipment at the level of 10 V for Zener Z6.

Quantity	Type	Dist.	Standard uncertainty	Sensitivity	Uncertainty contribution
Measured thermistor resistance	A	Norm.	3.03 Ω	0.1 nV/Ω	0.30 nV
Measured air pressure	A	Norm.	0.8 hPa	0.1 nV/hPa	0.08 nV
Thermal coefficient of the Zener	*B*	*Rect.*	*0.29 nV/Ω*	*3.03 Ω*	*0.88 nV*
Pressure coefficient of the Zener	*B*	*Rect.*	*0.12 nV/hPa*	*120 hPa*	*14.4 nV*
Voltage due to gain error of the nanovoltmeter	B	Norm.	115 nV	1	115 nV
Measured output voltage from the terminal	A	Norm.	66.2 nV	1	66.2 nV
Reference frequency accuracy	B	Rect.	0.35 nV	1	0.35 nV
Voltage due to leakage current	B	Rect.	0.13 nV	1	0.13 nV
Voltage due to residual thermal EMF	B	Rect.	2.9 nV	1	2.9 nV
Residual voltage in the polarity switch	B	Norm.	200 nV	1	200 nV
			Combined uncertainty		240 nV
			Expanded uncertainty (*k*=2)		480 nV

Table 2b: Estimated standard uncertainties for a Zener calibration with the SMD equipment at the level of 10 V for Zener ZB.

Uncertainty contributions for the comparison SMD/BIPM at 10 V

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

		Results/µV		Uncertainty/µV	
		Z6	**ZB**	**Z6**	**ZB**
1	SMD (U_{SMD} – 10 V)	-63.94	-9.37		
2	Type A uncertainty			0.074	0.066
3	correlated (Type B) unc.			0.231	
4	BIPM (U_{BIPM} – 10 V)	-64.12	-9.23		
5	Type A uncertainty			0.15	0.15
6	correlated (Type B) unc.			<0.005	
7	pressure and temperature correction uncertainty			0.012	0.016
8	($U_{SMD} - U_{BIPM}$)	0.18	-0.14		
9	Total uncorrelated uncertainty			0.168	0.165
10	Total correlated uncertainty			0.231	
11	$< U_{SMD} - U_{BIPM} >$	**0.02**			
12	*a priori* uncertainty			0.117	
13	*a posteriori* uncertainty			0.157	
14	**comparison total standard uncertainty/µV**			**0.28**	

Table 3: Results and uncertainties of the SMD (Belgium)/BIPM bilateral comparison of 10 V standards using two Zener travelling standards: reference date 17 November 2021. Standard uncertainties are used throughout.

In Table 3, the following elements are listed:

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

(2) the SMD Type A uncertainty (cf. Tables 2a and 2b).

(3) the uncertainty component arising from the realization and maintenance of the volt at SMD: it is the quadratic combination of the Type B components of the participant 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 SMD 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:

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

where U = 10 V, $u(c_{T,Z6})$ = 0.196 × 10^{-7} / kΩ, $u(c_{T,ZB})$ = 0.409 × 10^{-7} / kΩ, ΔR_{Z6} = 0.019 kΩ and ΔR_{ZB} = 0.023 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:

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

where U = 10 V, $u(c_{P,Z6})$ = 0.059 × 10^{-9} / hPa, $u(c_{P,ZB})$ = 0.068 × 10^{-9} / hPa, ΔP_{Z6} = 18.6 hPa and ΔP_{ZB} = 18.6 hPa.

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

(8) the difference (U_{SMD} – 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 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. 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 SMD, at SMD, U_{SMD}, and that assigned by the BIPM, at the BIPM, U_{BIPM}, on the reference date of the 17th of November 2021:

$$\boldsymbol{U_{\mathrm{SMD}} - U_{\mathrm{BIPM}} = 0.02\ \mu\mathrm{V}; \qquad u_{\mathrm{c}} = 0.28\ \mu\mathrm{V}}$$

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

[1] 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 the SMD, to obtain the results for both standards and their uncertainties at the mean date of the SMD measurements (2021/11/17).

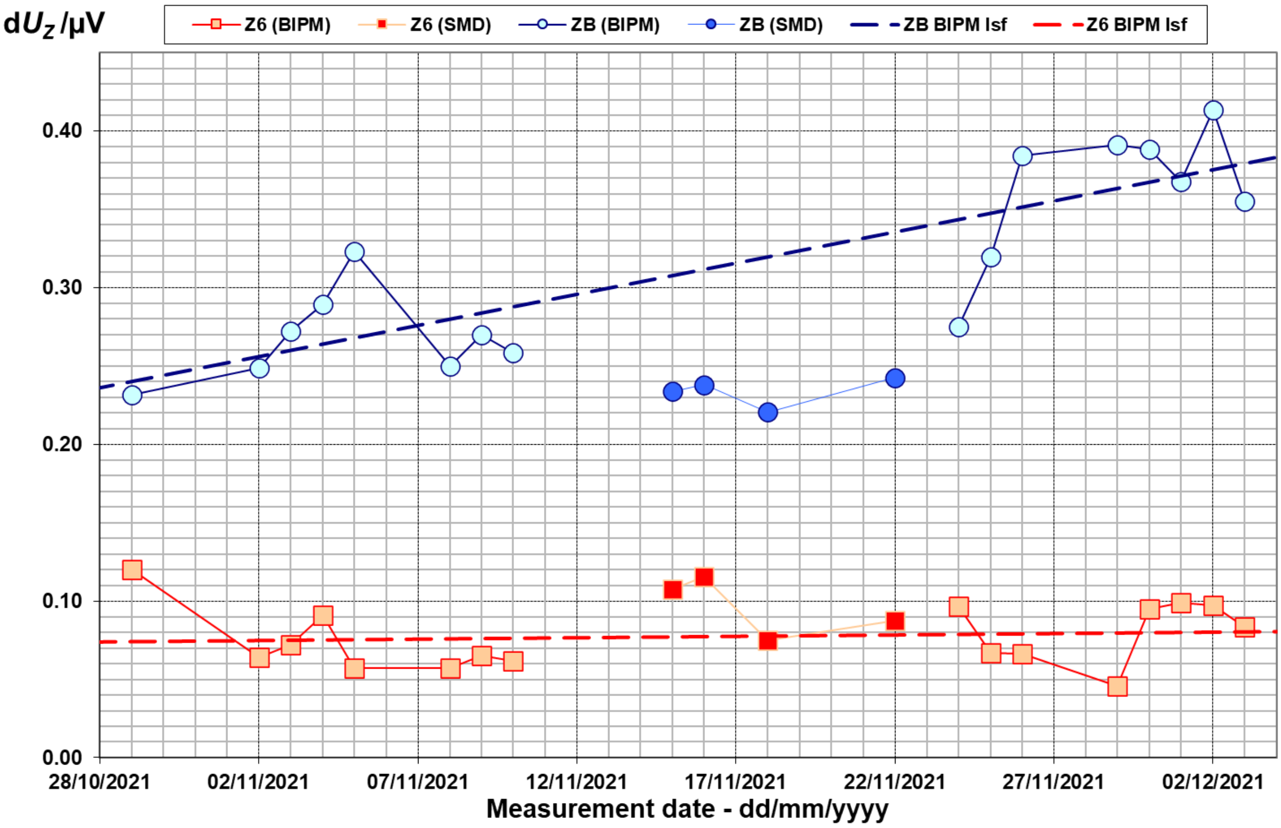

Figure 3: Voltage of Z6 (squares) and ZB (disks) at 1.018 V measured at both institutes (light markers for BIPM and dark markers for SMD), referred to an arbitrary offset, as a function of the measurement date with a linear least-squares fit (lsf) to the BIPM measurements**.**

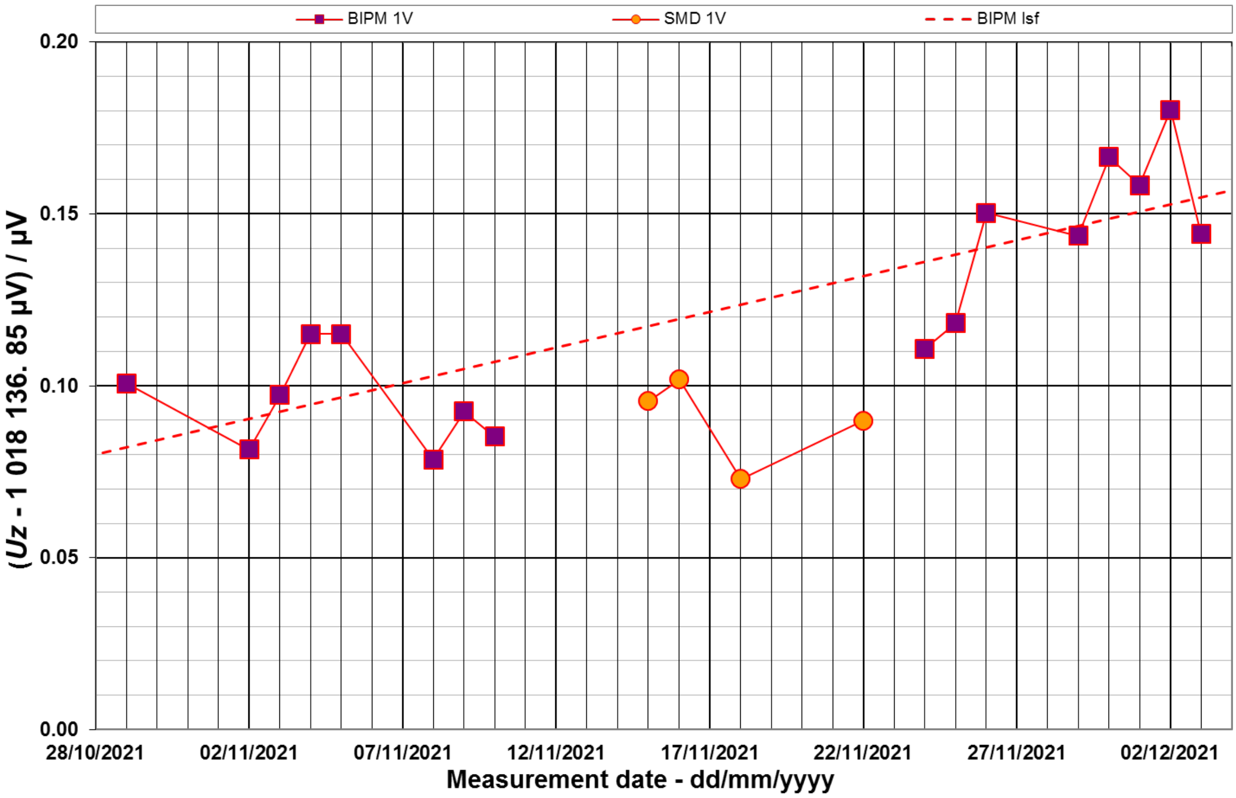

Figure 4: Voltage evolution of the arithmetic mean of the two standards at 1.018 V. SMD measurements are represented by disks and BIPM measurements by squares. A least-squares fit is applied to the BIPM measurements.

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)	0.1
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.

SMD uncertainty budget at 1.018 V

Table 5a and 5b list the uncertainties related to the calibration of the Zeners at the SMD for Z6 and ZB, respectively.

Note that the uncertainty of the temperature and pressure corrections (in italic) are given as an indication only and do not contribute to the final uncertainty budget used for this comparison as they are applied by the BIPM and included in the comparison uncertainty budget (Table 6).

Quantity	Type	Dist.	Standard uncertainty	Sensitivity	Uncertainty contribution
Measured thermistor resistance	A	Norm.	3 Ω	0.01 nV/Ω	0.03 nV
Measured air pressure	A	Norm.	0.8 hPa	0.01 nV/hPa	0.01 nV
Thermal coefficient of the Zener	*B*	*Rect.*	*0.06 nV/Ω*	*0.3 Ω*	*0.02 nV*
Pressure coefficient of the Zener	*B*	*Rect.*	*0.03 nV/hPa*	*12 hPa*	*0.36 nV*
Voltage due to gain error of the nanovoltmeter	B	Norm.	115 nV	1	115 nV
Measured output voltage from the terminal	A	Norm.	7.1 nV	1	7.1 nV
Reference frequency accuracy	B	Rect.	0.03 nV	1	0.03 nV
Voltage due to leakage current	B	Rect.	0.01 nV	1	0.01 nV
Voltage due to residual thermal EMF	B	Rect.	2.9 nV	1	2.9 nV
Residual voltage in the polarity switch	B	Norm.	20 nV	1	20 nV
			Combined uncertainty		117 nV
			Expanded uncertainty (*k*=2)		234 nV

Table 5a: Estimated standard uncertainties for a Zener calibration with the SMD equipment at the level of 1.018 V for Zener Z6.

Quantity	Type	Dist.	Standard uncertainty	Sensitivity	Uncertainty contribution
Measured thermistor resistance	A	Norm.	3.03 Ω	0.1 nV/Ω	0.30 nV
Measured air pressure	A	Norm.	0.8 hPa	0.1 nV/hPa	0.08 nV
Thermal coefficient of the Zener	*B*	*Rect.*	*0.06 nV/Ω*	*0.3 Ω*	*0.02 nV*
Pressure coefficient of the Zener	*B*	*Rect.*	*0.03 nV/hPa*	*12 hPa*	*0.36 nV*
Voltage due to gain error of the nanovoltmeter	B	Norm.	115 nV	1	115 nV
Measured output voltage from the terminal	A	Norm.	7.8 nV	1	7.8 nV
Reference frequency accuracy	B	Rect.	0.03 nV	1	0.03 nV
Voltage due to leakage current	B	Rect.	0.01 nV	1	0.01 nV
Voltage due to residual thermal EMF	B	Rect.	2.9 nV	1	2.9 nV
Residual voltage in the polarity switch	B	Norm.	20 nV	1	20 nV
			Combined uncertainty		117 nV
			Expanded uncertainty (*k*=2)		234 nV

Table 5b: Estimated standard uncertainties for a Zener calibration with the SMD equipment at the level of 1.018 V for Zener ZB.

Uncertainty contributions for the comparison SMD/BIPM at 1.018 V

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

		Results/µV		Uncertainty/µV	
		Z6	ZB	Z6	ZB
1	SMD (U_{SMD} – 1.018 V)	145.65	128.23		
2	Type A uncertainty			0.007	0.008
3	correlated (Type B) unc.			0.117	
4	BIPM (U_{BIPM} – 1.018 V)	145.63	128.32		
5	Type A uncertainty			0.015	0.015
6	correlated (Type B) unc.			<0.003	
7	pressure and temperature correction uncertainty			0.001	0.001
8	(U_{SMD} – U_{BIPM})	0.02	-0.08		
9	Total uncorrelated uncertainty			0.017	0.017
10	Total correlated uncertainty			0.117	
11	< U_{SMD} – U_{BIPM} >	**-0.03**			
12	*a priori* uncertainty			0.012	
13	*a posteriori* uncertainty			0.052	
14	**comparison total standard uncertainty/µV**			**0.13**	

Table 6: Results and uncertainties of the SMD (Belgium)/BIPM bilateral comparison of 1.018 V standards using two Zener travelling standards: reference date 17 November 2021. Standard uncertainties are used throughout.

In Table 6, the following elements are listed:

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

(2) the SMD Type A uncertainty (cf. Tables 5a and 5b).

(3) the uncertainty component arising from the realization and maintenance of the volt at SMD: it is the quadratic combination of the Type B components of the participant uncertainty budget listed in Tables 5a and 5b. 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 SMD 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 [6, 7] 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, $u(c_{T,Z6})$ = 0.232 × 10^{-7} / kΩ, $u(c_{T,ZB})$ = 0.415 × 10^{-7} / kΩ, ΔR_{Z6} = 0.028 kΩ and ΔR_{ZB} = 0.001 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:

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

where U = 1.018 V, $u(c_{P,Z6})$ = 0.052 × 10^{-9} / hPa, $u(c_{P,ZB})$ = 0.063 × 10^{-9} / hPa, ΔP_{Z6} = 19.0 hPa and ΔP_{ZB} = 19.1 hPa.

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

(8) the difference (U_{SMD} – 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 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).

As the *a priori* uncertainty and the *a posteriori* uncertainty are different, the larger component is considered as the transfer uncertainty and is therefore equal to 52 nV. However, comparing the results obtained at BIPM before the shipment of the Zeners before and after their return, it seems not obvious to conclude that the metrological quality of the standards was affected by their shipment.

The result of the comparison is presented as the difference between the value assigned to a 1.018 V standard by SMD, at SMD, U_{SMD}, and that assigned by the BIPM, at the BIPM, on the reference date of the 17th of November 2021:

$$U_{\mathrm{SMD}} - U_{\mathrm{BIPM}} = -0.03\ \mu\mathrm{V}; \qquad u_{\mathrm{c}} = 0.13\ \mu\mathrm{V}$$

where u_{c} is the combined standard uncertainty associated with the measured difference, including the uncertainty of the representation of the volt at the BIPM, (based on K_{J}) and at SMD 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 SMD, at the level of 1.018 V and 10 V, at SMD, U_{SMD}, and those assigned by the BIPM, at the BIPM, U_{BIPM}, at the reference date of the 17th of November 2021.

$$U_{\mathrm{SMD}} - U_{\mathrm{BIPM}} = -0.03\ \mu\mathrm{V}; \qquad u_{\mathrm{c}} = 0.13\ \mu\mathrm{V}, \text{ at } 1.018\ \mathrm{V}$$

$$U_{\mathrm{SMD}} - U_{\mathrm{BIPM}} = 0.02\ \mu\mathrm{V}; \qquad u_{\mathrm{c}} = 0.28\ \mu\mathrm{V}, \text{ at } 10\ \mathrm{V}$$

where u_{c} is the combined standard uncertainty associated with the measured difference, including the uncertainty of the representation of the volt at the BIPM and at SMD, based on K_{J}, and the uncertainty related to the comparison.

These are excellent results for both nominal voltages. The comparison results show that the voltages standards maintained by SMD and the BIPM were equivalent, within their stated standard uncertainties. Since the last equivalent exercise in 2014, the uncertainty budget of SMD was successfully re-evaluated, especially at the 10 V level. Nevertheless, it seems that the uncertainty components on the detector gain error and on the residual voltage of the switch may still be overestimated.

References

[1] **S. Solve *et al***., Metrologia, 47, 01004 (2010).

[2] Josephson Voltage Standard SupraVOLTcontrol Manual, Supracon AG, Wildenbruchstr. 15, 07745 Jena, Germany, Mai 2015.

[3] **Starkloff M., Wende G., Anders S., Schubert M., Meyer M. and Meyer H.-G.**: Operation and Accuracy of an Automated Cryocooler-based 10 Volt Josephson Voltage Standard System, IEEE/CSC & ESAS EUROPEAN SUPERCONDUCTIVITY NEWS FORUM (ESNF), No. 16, April 2011.

[4] **F. Mueller et al.**, 1 V and 10 V SNS Programmable Voltage Standards for 70 GHz IEEE Trans. On Applied Superconductivity, VOL. 19, NO. 3, JUNE 2009 pp.981-86.

[5] **Chayramy R. and Solve S**., A very low thermal EMF computer-controlled scanner, Meas. Sci. Technol. 24 025008 (2013).

[6] **Chayramy R. et al.**, Metrology of Zener-based secondary voltage standards, Meas. Sci. Technol. 32 (2021) 105019 (18pp) https://doi.org/10.1088/1361-6501/ac055e

[7] **Witt T. J.**, Maintenance and dissemination of voltage standards by Zener-diode-based instruments, IEE Proc.-Sci. Meas. Technol., vol. 149, pp. 305-312, 2002.

[8] **Solve S., Chayramy R. and Power O.**, Temperature sensitivity coefficients of the BIPM secondary voltage standards, *CPEM 2016 Digest, Ottawa*, DOI: 10.1109/CPEM.2016.7540702.

[9] **Solve S., Chayramy R. and Yang S.**, Pressure Sensitivity Coefficients of the BIPM secondary voltage standards, *CPEM 2018 Digest, Paris*: **DOI:** 10.1109/CPEM.2018.8501074

[10] **Hoel P. G.**, Introduction to Mathematical Statistics *4th edn*, 1971, New York: Wiley.