Bilateral Comparison of 1.018 V and 10 V Standards between the NMISA (South Africa) and the BIPM April to June 2017

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

by S. Solve+, R. Chayramy+, A. M. Matlejoane*, L. Magagula*, and M. Stock+

+ Bureau International des Poids et Mesures, Sèvres, France

*NMISA, National Metrology Institute of South Africa
CSIR Campus, Building 5, Meiring Naude Road,
Brummeria Pretoria 0182
Private Bag X34, Lynnwood Ridge 0040, South Africa

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 Metrology Institute of South Africa, NMISA (South Africa), was carried out from April to June 2017. Two BIPM Zener diode-based travelling standards (Fluke 732B), BIPM_A (ZA) and BIPM_B (ZB), were transported by freight to NMISA and back to BIPM. In order to keep the Zeners powered during their transportation phase, a voltage stabiliser developed by BIPM was connected in parallel to the internal battery. It consists of a set of two batteries, electrically protected from surcharge-discharge, easy to recharge and is designed to power two transfer standards for 10 consecutive days. At NMISA, the reference standard for DC voltage is a Josephson Voltage Standard. The output EMF (Electromotive Force) of each travelling standard was measured by direct comparison with the primary standard.
At the BIPM, the travelling standards were calibrated, before and after the measurements at NMISA, with the Josephson Voltage Standard. Results of all measurements were corrected for the dependence of the output voltages of the Zener standards on internal temperature and atmospheric pressure.

Outline of the measuring method

NMISA 1.018 Vand 10 V measurements

The objective for NMISA in participating in the BIPM.EM-K11.a and b comparison of 1.018 V and 10 V DC voltage references was to prove international equivalence of NMISA DC voltage measurement results and support claimed measurement capabilities published in the KCDB (Key Comparison Database of the BIPM).

On receipt, the comparison standards were immediately connected to mains power supply until the internal batteries were fully charged before measurements were performed.
The following standards and equipment were used:

Agilent 5071A, Cesium beam oscillator, serial number US39301821.
MMWS-75a, 66 – 78 GHz source, serial number 6.
MMWS-75, Frequency synthesizer.
JVS 1002, Josephson system controller, serial number 56.
HP 3458A, Digital multimeter, serial number 2823A08754.
PTB, 10 V Josephson array chip, serial number ME-106/5.
Fluke 8842A, Digital multimeter, serial number 4427058.
Rotronic Hygroclip-S and Hygrolog-D Humidity/Temperature recorder, serial numbers 17131017 and 17932008.
PDI 142 Pressure indicator, serial number 1422505057

The DC voltage measurements were performed using a Josephson Voltage System made up of an MMWS-75a 66-78 GHz source, an MMWS-75 frequency synthesizer, a JVS 1002 Josephson system controller, an HP 3458A Digital multimeter and 10 V Josephson array chip.

During the measurements, the system oscillator frequency was locked to a 10 MHz reference obtained from a Cesium beam oscillator maintained by the NMISA Time and Frequency laboratory. The system DUT (Device Under Test) terminals were alternately reversed connected on DUT output posts on completion of each measurement sequence to cancel out system offset errors.

The JVS system temperature, relative humidity and pressure sensors were calibrated against Humidity/Temperature recorder and Pressure indicators respectively before measurements were performed and monitored during the measurement period.

The reported output voltage for each comparison standard was assigned by calculating an average of sequential measurement results.

Measurement uncertainty contributors for each reported output voltage were identified, quantified and evaluated as per reported uncertainty calculations.

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 - Hypres 10 V SIS array (S/N: 2538F-3), through a low thermal Electromotive Forces (EMF) switch. The binding post terminals “GUARD” and “CHASSIS” of the Zener standard are connected together to a single point which is the grounding reference point of the measurement setup.

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

The BIPM detector consists of an EM model N1a analog nanovoltmeter whose output is connected, via an optically-coupled isolation amplifier, to a digital voltmeter (DVM) which is connected to a computer.

This computer is used to monitor measurements, acquire data and calculate results. Low thermal electromotive force switches are used for critical switching, such as polarity reversal of the detector input.

The BIPM array biasing frequency has been adjusted to a value where the voltage difference between the primary and the secondary voltage standards is below 1.5 µV for both nominal voltages. The nanovoltmeter is set to its 3 µV range for the measurements performed at the level of 1.018 V and on its 10 µV range for those carried out at the level of 10 V. The measurement sequence can then be carried out. One individual measurement point is acquired according to the following procedure:

1- Positive array polarity and reverse position of the detector;
2- Data acquisition;
3- Positive array polarity and normal position of the detector;
4- Data acquisition;
5- Negative array polarity and reverse position of the detector;
6- Data acquisition;
7- Negative array polarity and normal position of the detector;
8- Data acquisition;
9- Negative array polarity and reverse position of the detector;
10- Data acquisition;
11- Negative array polarity and normal position of the detector;
12- Data acquisition;
13- Positive array polarity and reverse position of the detector;
14- Data acquisition;
15- Positive array polarity and normal position of the detector;
16- Data acquisition.

The reversal of the array polarity (by inversing the bias current) is always accompanied by a reversal of the Zener voltage standard using a switch. The reversal of the detector polarity is done to cancel out any detector internal thermo-electromotive forces with linear time-dependence and to check that there is no AC voltage noise rectified at the input of the detector (this is the case if the reading is different in the positive and negative polarity of the analog detector by up to a few hundred microvolts).

Each “Data Acquisition” step consists of 30 preliminary points followed by 500 measurement points. Each of these should not differ from the mean of the preliminary points by more than twice their standard deviation, if so the software warns the operator with a beep. If too many beeps occur, the operator can reject the “Data Acquisition” sequence and start it again. The “Data Acquisition” sequence lasts 25 s and the array must remain on its quantum voltage step during this period of time. The total measurement time (including polarity reversals and data acquisition) is approximately 5 minutes.

This procedure is repeated three times and the mean value corresponds to one result on the graph (Cf. Fig. 1).

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 the results of the BIPM to obtain the results for both standards and their uncertainties at the mean date of the NMISA measurements (2017/05/18).

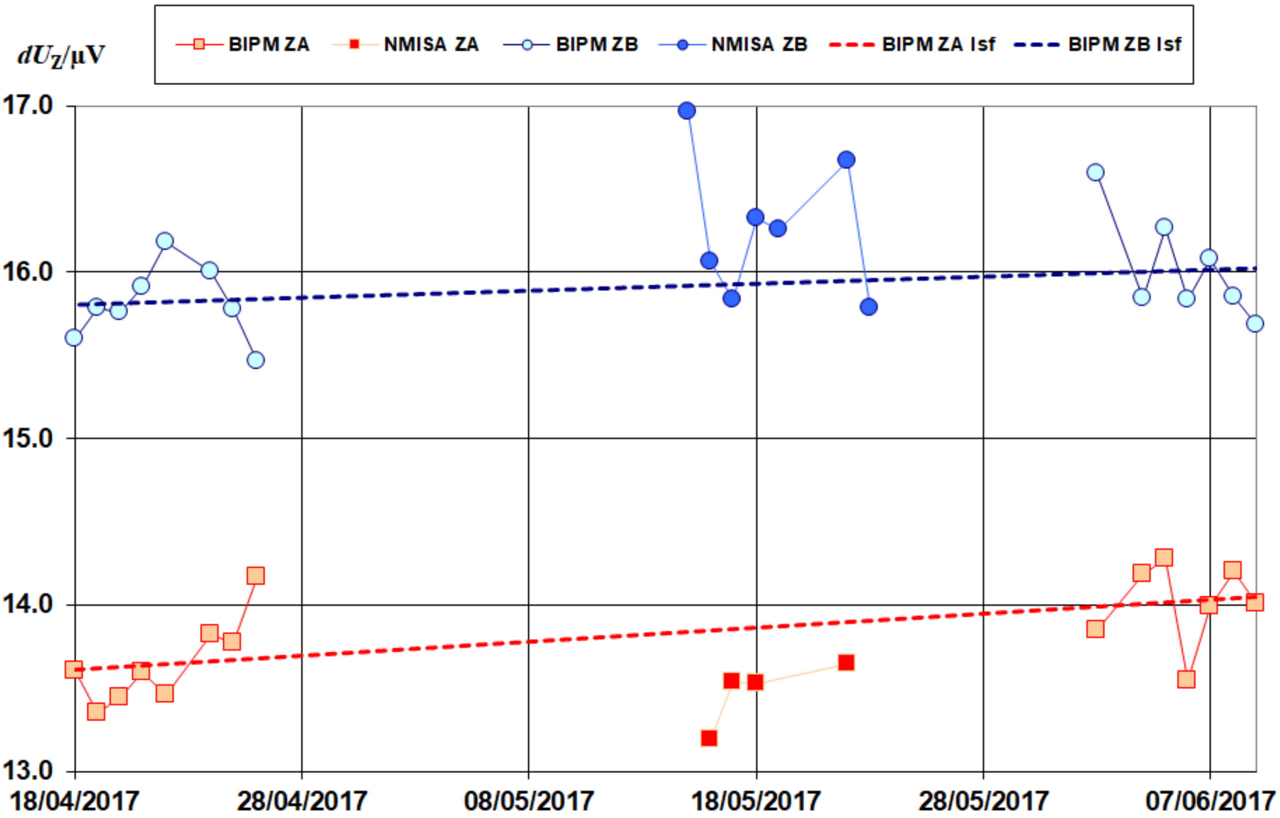

Figure 1. Voltage of ZA (filled squares) and ZB (disks) at 10 V measured at both institutes (light markers for BIPM and dark markers for NMISA), referred to an arbitrary origin as a function of time with a linear least-squares fit (lsf) to the BIPM measurements.

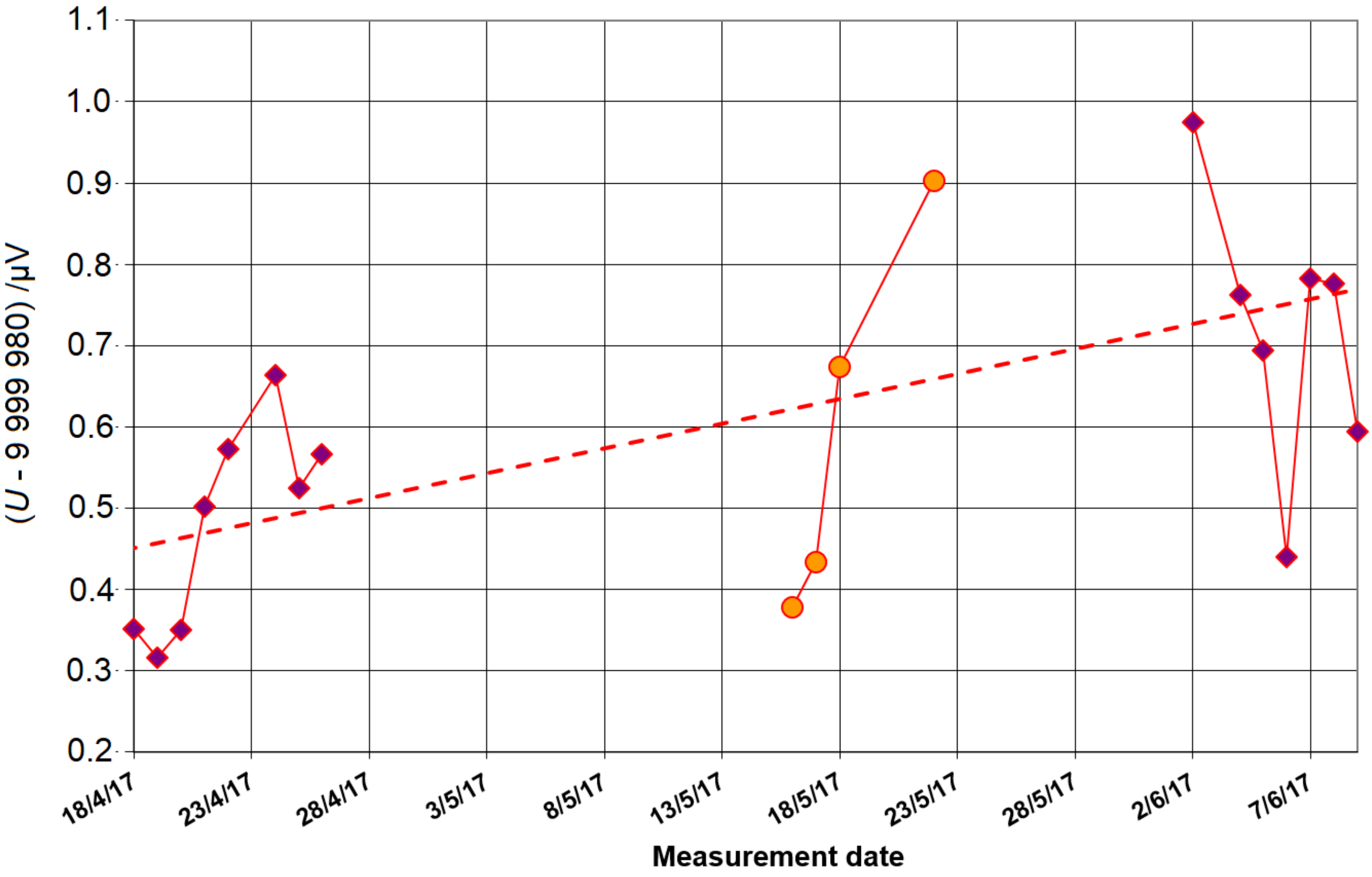

Figure 2. Voltage evolution of the simple mean of the two standards at 10 V. NMISA measurements are represented by disks and BIPM measurements by filled diamonds. Since the number of measurements is different for ZA and ZB at NMISA, the circles represent the mean drift of all the NMISA measurements.

Note on Figure 2: Since NMISA didn't carry out the same number of measurements for the two transfer standards, Figure 2 exhibits only the mean values of both standards for those days when both were measured. However, the calculation of the NMISA result at the mean date of NMISA measurements is basedon the mean of all the results. Therefore the comparison final result is calculated from all the data provided by the NMISA.

Table 1 lists the results and the uncertainty contributions for the comparison NMISA/BIPM at 10 V. At BIPM, we consider that the relative value of the voltage noise floor due to flicker noise of the Zeners is about 1 part in 10^8 and that this represents the ultimate limit of the stability of Zener voltage standards [1].

Table 1. Results and uncertainties of the NMISA (South Africa)/BIPM bilateral comparison of 10 V standards using two Zener traveling standards: reference date 18 May 2017. Uncertainties are 1 σ estimates.

		BIPM_A	BIPM_B
1	*NMISA (South Africa)* (U_Z – 10 V)/µV	-32.53	-6.23
2	Type A uncertainty/µV	0.03	0.04
3	correlated (Type B) unc. /µV	0.0015	
4	*BIPM* (U_Z – 10 V)/µV	-32.19	-6.57
5	Type A uncertainty/µV	0.1	0.1
6	correlated (Type B) unc./µV	0.001	
7	pressure and temperature correction uncertainty/µV	0.12	0.1
8	(U_{NMISA} – U_{BIPM})/µV	-0.33	0.34
9	uncorrelated uncertainty/µV	0.18	0.22
10	< U_{NMISA} – U_{BIPM} >/µV	0.001	
11	*a priori* uncertainty/µV	0.14	
12	*a posteriori* uncertainty/µV	0.34	
13	correlated uncertainty/µV	0.002	
14	comparison total uncertainty/µV	0.34	

In Table 1, the following elements are listed:

(1) the value attributed by NMISA to each Zener U_{NMISA}, computed as the simple mean of all data from NMISA;

(2) the NMISA Type A uncertainty (Cf. Tables 3a and 3b),

The experimental standard deviation of the mean of the measurements are:

0.1 µV and 0.16 µV for ZA and ZB respectively at NMISA, 0.07 µV for ZA and ZB at BIPM, once corrected for atmospheric pressure and internal temperature variations;

(3) the uncertainty component arising from the realization and maintenance of the volt at NMISA: this uncertainty is completely correlated between the different Zeners used for a comparison;

(5) Type A uncertainty which is the larger component between the standard deviation of the mean of the results and the 1/*f* noise floor of 10 nV which, according to the experience of the BIPM, in general, limits the accuracy of Zener voltage standards [1];

(4-6) the corresponding quantities for the BIPM referenced to the mean date of NMISA measurements;

Note: at BIPM, the Type A uncertainty is considered as the larger of the experimental standard deviation of the mean of the measurements performed at BIPM, and the 1/*f* Zener noise floor which, according to the experience of the BIPM, in general limits the accuracy of Zener voltage standards and is equal in 10^{-8} in relative parts [1];

(7) the uncertainty due to the combined effects of the uncertainties of the pressure and temperature coefficients[*] and to the differences of the mean pressures and temperatures in the participating laboratories is calculated using the following assumption:

The uncertainty on 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 temperature coefficient of this Zener standard:

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

where $U = 10$ V, $u(c_{\mathrm{T,ZA}}) = 0.39\times10^{-7}$ / kΩ, $u(c_{\mathrm{T,ZB}}) = 0.63\times10^{-7}$ / kΩ and $\Delta R_{\mathrm{ZA}} = 0.098$ kΩ and $\Delta R_{\mathrm{ZB}} = 0.047$ kΩ.

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

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

where $U = 10$ V, $u(c_{\mathrm{P,ZA}}) = 0.082\times10^{-9}$ / hPa, $u(c_{\mathrm{P,ZB}}) = 0.067\times10^{-9}$ / hPa, $\Delta P_{\mathrm{ZA}} = 141.7$ hPa and $\Delta P_{\mathrm{ZB}} = 142.3$ hPa.

The significant difference in the mean value of the pressure between both laboratories is mostly due to the difference in elevation between the location of the 2 laboratories.

The uncertainty on the measurement of the temperature and pressure is negligible.

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

(10) the result of the comparison is the simple mean of the differences of the calibration results for the different standards;

(11 and 12) the uncertainty related to the transfer, estimated by the following two methods:

---

[*] The evaluation of the correction coefficients was performed in 2000. A new determination of the temperature sensitivity coefficients has been carried out at BIPM in 2016. The final results are not yet available.

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

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

(13) the correlated part of the uncertainty, calculated as the quadratic sum of lines 3 and 6, and

(14) the total uncertainty of the comparison, which is the root sum square of the correlated part of the uncertainty and of the larger of (11) and (12).

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*. 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, and we use the larger of these two estimates in calculating the final uncertainty. In the present comparison, the "*a posteriori*" uncertainty is larger than the "*a priori*" uncertainty and is equal to 335 nV.

The comparison result is presented as the difference between the value assigned to a 10 V standard by NMISA, at NMISA, U_{NMISA}, and that assigned by the BIPM, at the BIPM, U_{BIPM}, which for the reference date is

$$\boldsymbol{U_{\mathrm{NMISA}} - U_{\mathrm{BIPM}} = 0.001\ \mu\mathrm{V};\ \ u_{\mathrm{c}} = 0.34\ \mu\mathrm{V}}\quad \textbf{on 2017/05/18},$$

where u_{c} is the combined standard uncertainty associated with the measured difference, including the uncertainty of the representation of the volt at NMISA, at the BIPM (based on $K_{\mathrm{J-90}}$), and the uncertainty related to the comparison.

---

* 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.

Table 2 summarizes the uncertainties related to the calibration of a Zener diode against the Josephson array voltage standard at the BIPM.

Tables 3a and 3b list the uncertainties related to the calibration of the Zeners at the NMISA for ZA and ZB respectively. Note that the uncertainty of the temperature and pressure corrections (last line in Italic) are given as an indication only and do not appear in the final uncertainty budget as they are included separately in the comparison uncertainty budget (Table 1).

Uncertainty Budgets

Table 2. The following table presents the estimated standard uncertainties arising from the JVS and the measurement setup for Zener calibrations with the BIPM equipment at the level of 10 V.

Note: the uncertainty of the temperature, pressure corrections and the contribution of the Zener noise (in italic in the tables) are given for completeness only and are not included in the total uncertainty as they are included separately in the comparison uncertainty budget (table 1).

JVS & detector uncertainty components	Uncertainty/nV
Noise of the measurement loop that includes the residual thermal electromotive forces including the residual EMF of the reversing switch	0.86
Zener noise (Type A)	*Not lower than the 1/f noise estimated to 100 nV*
Detector gain	0.11
Leakage resistance	3×10^{-2}
Frequency	3×10^{-2}
Pressure and temperature correction	*included in the Zener uncertainty budget*
Total	0.87

Table 3a and 3b. Estimated standard uncertainties for a Zener calibration with the NMISA equipment at the level of 10 V.

The standard deviation of the mean of the NMISA measurement results are 100 nV and 160 nV for BIPM_A and BIPM_B respectively (once corrected for the dependence of the standards to temperature and pressure variations).

Zener A

Quantity	Uncertainty (ppm)	Type	Distribution	Standard uncertainty (ppm)	Sensitivity	Uncertainty contribution (ppm)
Null voltage variability	0.002	A	Normal	0.002	1	0.002
Zero offset voltage	0.0008	A	Normal	0.0008	1	0.0008
Reference frequency accuracy	0.00000015	B	Rectangular	0.000000075	1	0.000000075
Leakage error	0.000087	A	Normal	0.000087	1	0.000087
Standard deviation	0.028	A	Normal	0.028	1	0.028
					Combined uncertainty (k=1)	0.028
					Expanded uncertainty (k=2)	0.056

Zener B

Quantity	Uncertainty (ppm)	Type	Distribution	Standard uncertainty (ppm)	Sensitivity	Uncertainty contribution (ppm)
Null voltage variability	0.0029	A	Normal	0.0029	1	0.0029
Zero offset voltage	0.0008	A	Normal	0.0008	1	0.0008
Reference frequency accuracy	0.00000015	B	Rectangular	0.000000075	1	0.000000075
Leakage error	0.000087	A	Normal	0.000087	1	0.000087
Standard deviation	0.0377	A	Normal	0.0377	1	0.0377
					Combined uncertainty (k=1)	0.038
					Expanded uncertainty (k=2)	0.076

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 to obtain the results for both standards and their uncertainties at a common reference date corresponding to the mean date of the NMISA measurements (2017/05/19).

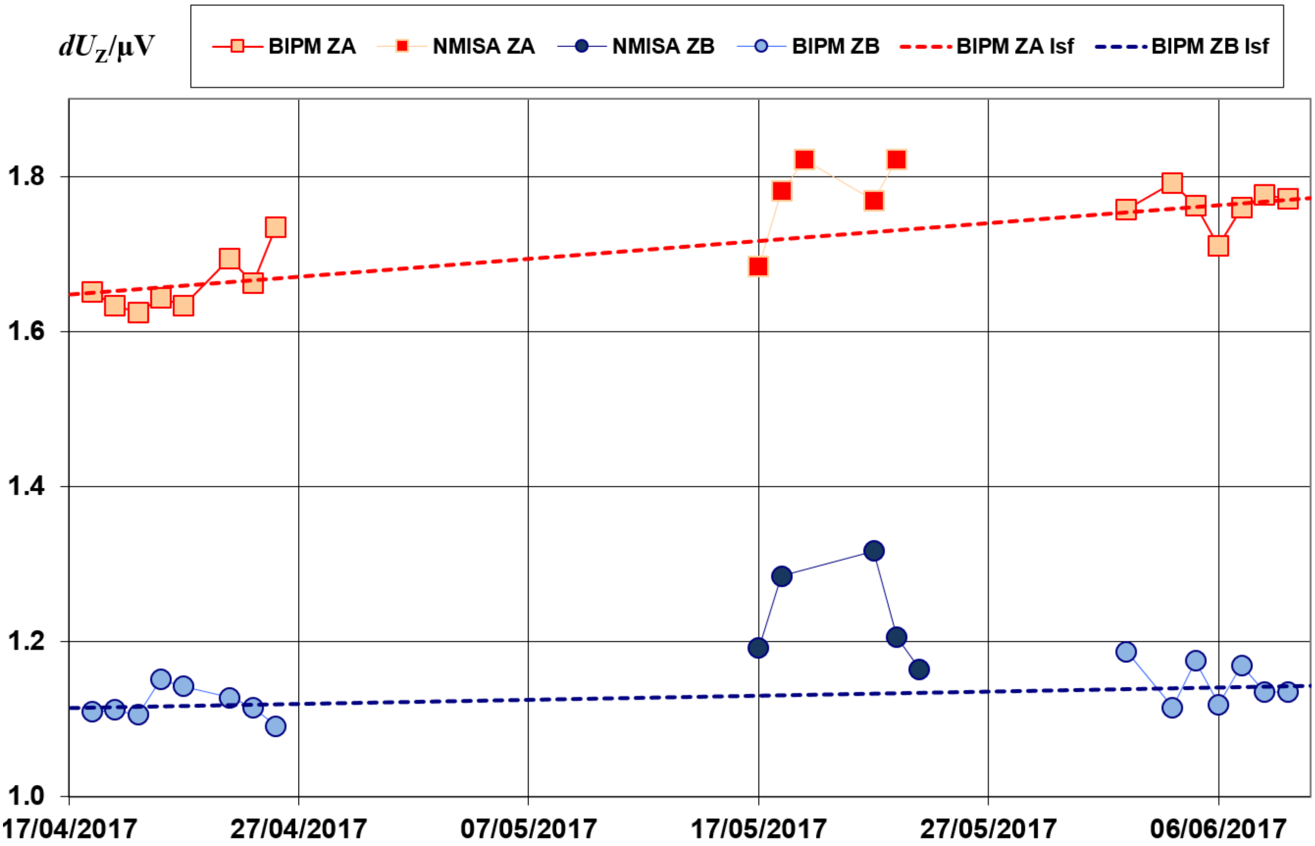

Figure 3. Voltage of BIPM_A (filled squares) and BIPM_B (disks) at 1.018 V measured at both institutes (light markers for BIPM and dark ones for NMISA), referred to an arbitrary origin, as a function of time, with a linear least-squares fit to the measurements of the BIPM.

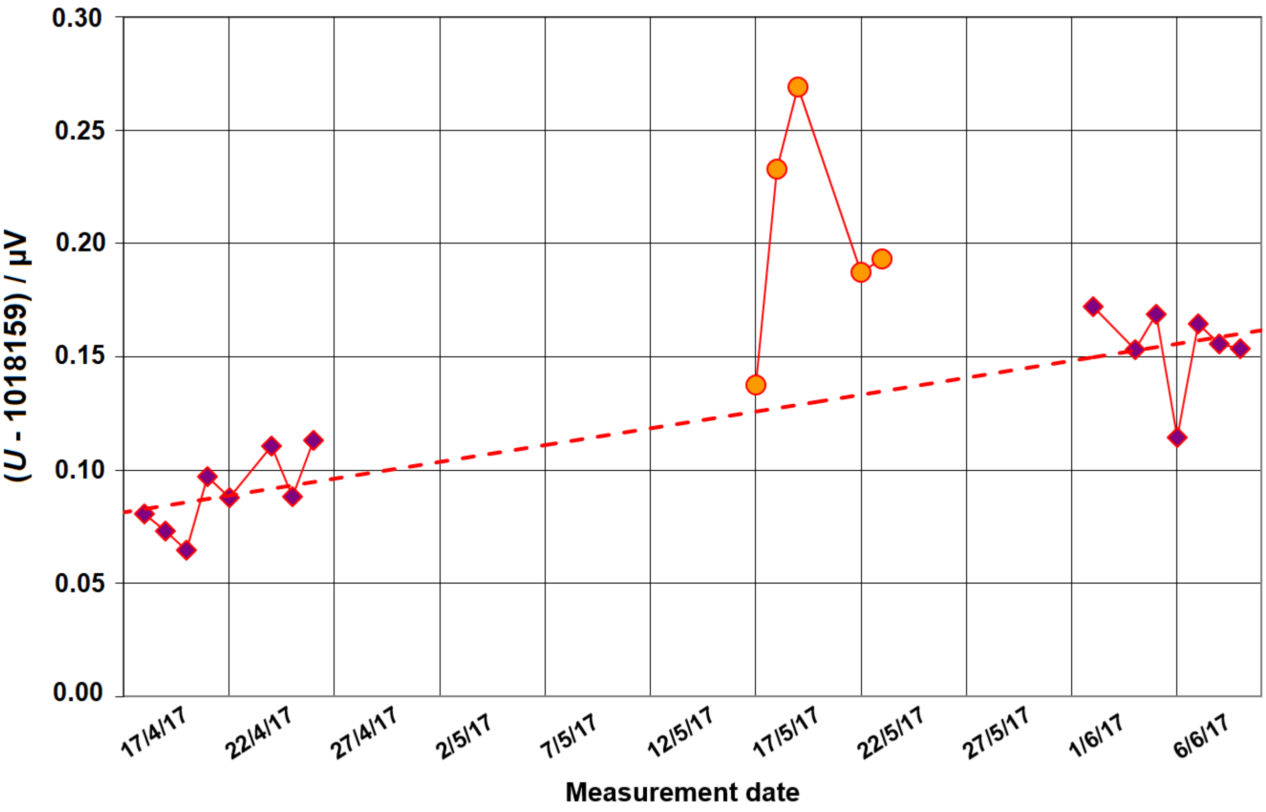

Figure 4. Voltage evolution of the simple mean of the two standards at 1.018 V. NMISA measurements are represented by disks and BIPM measurements by filled diamonds.

Table 4 lists the results of the comparison and the uncertainty contributions for the comparison NMISA/BIPM at 1.018 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 part in 10^8.

In estimating the uncertainty related to the stability of the standards during transportation, we have calculated the "*a priori*" uncertainty of the mean of the results and the "*a posteriori*" uncertainty as described for the measurements at 10 V.

Table 5 summarizes the uncertainties related to the calibration of a Zener diode against the Josephson array voltage standard at the BIPM and Table 6a and 6b list the uncertainties related to the calibration of ZA and ZB respectively against the Josephson array voltage standard at the NMISA.

Table 4. Results and uncertainties of the NMISA (South Africa)/BIPM bilateral comparison of 1.018 V standards using two Zener traveling standards: reference date 19 May 2017. Uncertainties are 1 σ estimates.

		BIPM_A	BIPM_B
1	*NMISA (South Africa)* (U_Z – 1.018 V)/µV	191.78	126.63
2	Type A uncertainty/µV	0.07	0.05
3	correlated unc. /µV	0.0015	
4	*BIPM* (U_Z – 1.018 V)/µV	191.72	126.54
5	Type A uncertainty/µV	0.01	0.01
6	correlated unc./µV	0.001	
7	pressure and temperature correction uncertainty/µV	0.009	0.010
8	(U_{NMISA} – U_{BIPM})/µV	0.05	0.09
9	uncorrelated uncertainty/µV	0.03	0.04
10	< U_{NMISA} – U_{BIPM} >/µV	0.07	
11	*a priori* uncertainty/µV	0.023	
12	*a posteriori* uncertainty/µV	0.024	
13	correlated uncertainty/µV	0.002	
14	comparison total uncertainty/µV	0.02	

In Table 4, the following elements are listed:

(1) the value attributed by NMISA to each Zener U_{NMISA}, computed as the simple mean of all data from NMISA;

(2) the Type A uncertainty claimed by NMISA (Cf. Tables 6.a and 6.b),

(3) the uncertainty component arising from the realization and maintenance of the volt at NMISA: this uncertainty is completely correlated between the different Zeners used for a comparison;

(5) see text of Table 1. The standard deviation of the mean of the BIPM measurement results, at the mean date of NMISA measurements is in the interval from 8 nV to 7 nV for ZA and ZB respectively, once corrected for the dependence of the standards to temperature and pressure variations

(4-6) the corresponding quantities for the BIPM referenced to the mean date of the NMISA measurements;

(7) the uncertainty due to the combined effects of the uncertainties of the pressure and temperature coefficients[*] and to the differences of the mean pressures and temperatures in the participating laboratories is calculated using the following assumption:

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

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

where U = 1.018 V, $u(c_{\mathrm{T,ZA}}) = 0.7\times10^{-7}$ / kΩ, $u(c_{\mathrm{T,ZB}}) = 0.52\times10^{-7}$ / kΩ and ΔR_{ZA} = 0.095 kΩ and ΔR_{ZB} = 0.063 kΩ.

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

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

where U = 1.018 V, $u(c_{\mathrm{P,ZA}}) = 0.043\times10^{-9}$ / hPa, $u(c_{\mathrm{P,ZB}}) = 0.063\times10^{-9}$ / hPa, ΔP_{ZA} = 142.1 hPa and ΔP_{ZB} = 143.7 hPa.

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

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

(10) the result of the comparison is the simple mean of the differences of the calibration results for the different standards;

(11 and 12) the uncertainty related to the transfer, estimated by the following two methods:

(11) the *a priori* uncertainty,

(12) the *a posteriori* uncertainty;

(13) the correlated part of the uncertainty, calculated as the quadratic sum of lines 3 and 6, and

(14) the total uncertainty of the comparison, which is the root sum square of the correlated part of the uncertainty and of the larger of (11) and (12).

As in this case the *a posteriori* uncertainty is not larger as the *a priori* uncertainty we conclude that there is no significant effect of the transport.

---

[*] The evaluation of the correction coefficients was performed in 2000. A new determination of the temperature sensitivity coefficients has been carried out at BIPM in 2016 but the results are not yet published.

The result of the comparison is presented as the difference between the value assigned to a 1.018 V standard by NMISA, at NMISA, U_{NMISA}, and that assigned by the BIPM, at the BIPM, U_{BIPM}, which for the reference date is:

$$\boldsymbol{U_{\mathrm{NMISA}} - U_{\mathrm{BIPM}} = 0.07\ \mu\mathrm{V}; \quad u_{\mathrm{c}} = 0.02\ \mu\mathrm{V}} \quad \textbf{on 2017/05/19},$$

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 $K_{\mathrm{J\text{-}90}}$) and at NMISA and the uncertainty related to the comparison.

Table 5. Estimated standard uncertainties for Zener calibrations with the BIPM equipment at the level of 1.018 V.

Note: the uncertainty of the temperature, pressure corrections and the contribution of the Zener noise (in italic in the tables) are given for completeness only and are not included in the total uncertainty as they are included separately in the comparison uncertainty budget (table 4).

JVS & detector uncertainty components	Uncertainty/nV
Residual thermal electromotive forces	included in the Type A uncertainty
Noise of the measurement loop that includes the residual thermal electromotive forces including the residual EMF of the reversing switch	0.34
Zener noise (Type A)	*Not lower than the 1/f noise estimated to 10 nV*
Detector gain	0.11
Leakage resistance	3×10^{-3}
Frequency	3×10^{-3}
Pressure and temperature correction	*included in the Zener unc. budget*
Total	0.36

Table 6a and 6b. Estimated standard uncertainties for Zener calibrations with the NMISA equipement at the level of 1.018 V.

The standard deviation of the mean of the NMISA measurement results is in the interval from 25 nV to 29 nV for BIPM_A and BIPM_B respectively (once corrected for the dependence of the standards to temperature and pressure variations).

Zener A

Quantity	Uncertainty (ppm)	Type	Distribution	Standard uncertainty (ppm)	Sensitivity	Uncertainty contribution (ppm)
Null voltage variability	0.015	A	Normal	0.015	1	0.015
Zero offset voltage	0.0008	A	Normal	0.0008	1	0.0008
Reference frequency accuracy	0.00000015	B	Rectangular	0.000000075	1	0.000000075
Leakage error	0.000087	A	Normal	0.000087	1	0.000087
Standard deviation	0.065	A	Normal	0.065	1	0.065
					Combined uncertainty (k=1)	0.067
					Expanded uncertainty (k=2)	0.133

Zener B

Quantity	Uncertainty (ppm)	Type	Distribution	Standard uncertainty (ppm)	Sensitivity	Uncertainty contribution (ppm)
Null voltage variability	0.016	A	Normal	0.016	1	0.016
Zero offset voltage	0.0008	A	Normal	0.0008	1	0.0008
Reference frequency accuracy	0.00000015	B	Rectangular	0.000000075	1	0.000000075
Leakage error	0.000087	A	Normal	0.000087	1	0.000087
Standard deviation	0.048	A	Normal	0.048	1	0.048
					Combined uncertainty (k=1)	0.051
					Expanded uncertainty (k=2)	0.101

Conclusion

The final result of the comparison is presented as the difference between the values assigned to DC voltage standards by NMISA, at the level of 1.018 V and 10 V, at NMISA, U_{NMISA}, and those assigned by the BIPM, at the BIPM, U_{BIPM}, at the reference dates of the 19th and 18th of May 2017, respectively.

$$U_{\mathrm{NMISA}} - U_{\mathrm{BIPM}} = +\,0.07\ \mu\mathrm{V};\ u_{\mathrm{c}} = 0.02\ \mu\mathrm{V},\ \text{at } 1.018\ \mathrm{V}$$

$$U_{\mathrm{NMISA}} - U_{\mathrm{BIPM}} = +\,0.001\ \mu\mathrm{V};\ u_{\mathrm{c}} = 0.34\ \mu\mathrm{V},\ \text{at } 10\ \mathrm{V}$$

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 NMISA, based on $K_{\mathrm{J-90}}$, and the uncertainty related to the comparison.

These are satisfactory results for both nominal voltages. The comparison results show that the voltage standards maintained by NMISA and the BIPM were equivalent, within their stated standard uncertainties at 10 V, on the mean date of the comparison. At 1 V, the uncertainty at the 3σ level still doesn't cover the difference. Furthermore, we noticed that the standard deviation of the mean of the NMISA results at 10 V is twice larger once the corrections related to the environmental parameters are applied. This is very unusual as one would expect exactly the contrary.

We also would like to underline that the difference in altitude of the location of the two laboratories where the transfer standards were measured leads to a significant atmospheric pressure difference for which the mean value is 140 hPa. In order to investigate on the reliability of the pressure sensitivity of the Zeners involved, we compared the results obtained to those that would have been obtained without applying any correction for pressure changes. The results are reported in Figure 5a and b.

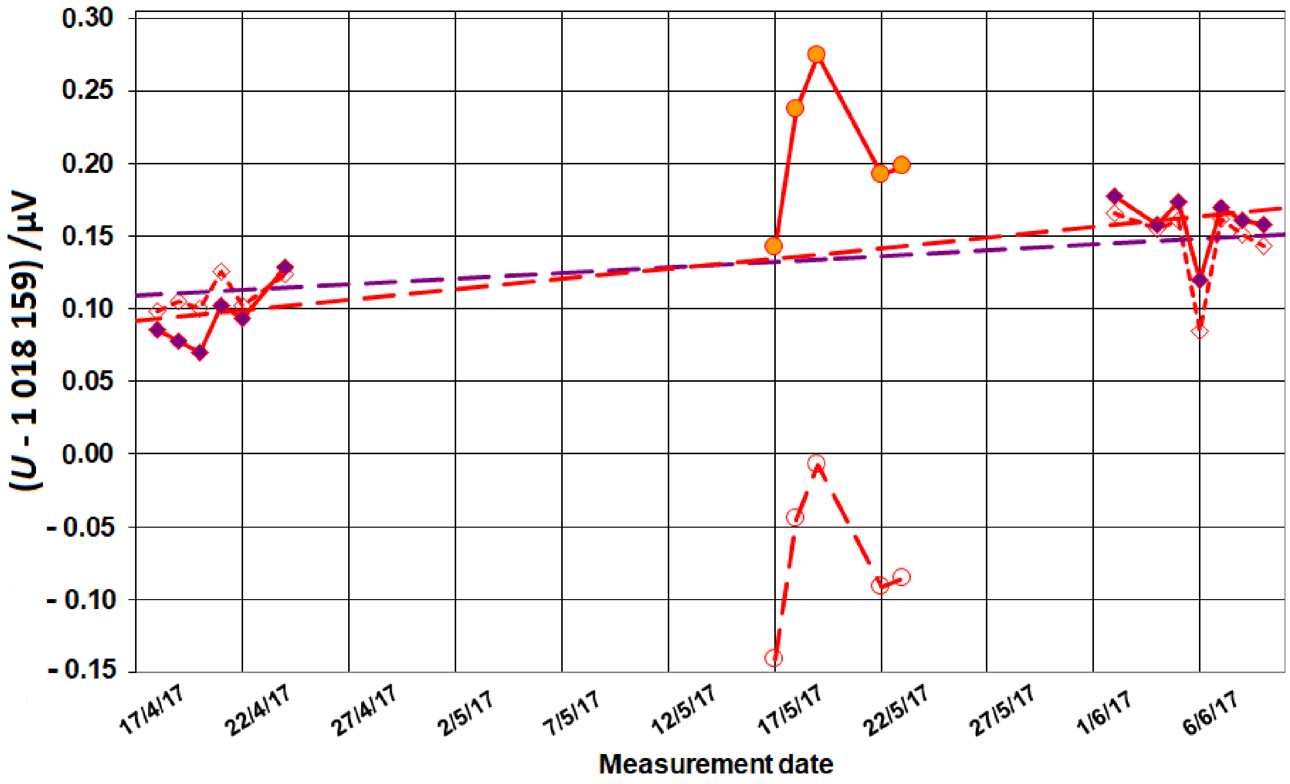

Figure 5a. Voltage evolution of the simple mean of the two standards at 1.018 V with and without corrections applied to the transfer standards for atmospheric pressure.

NMISA measurements are represented by disks and circles (no pressure correction applied) and BIPM measurements by filled diamonds (correction applied) and diamonds (no pressure correction applied).

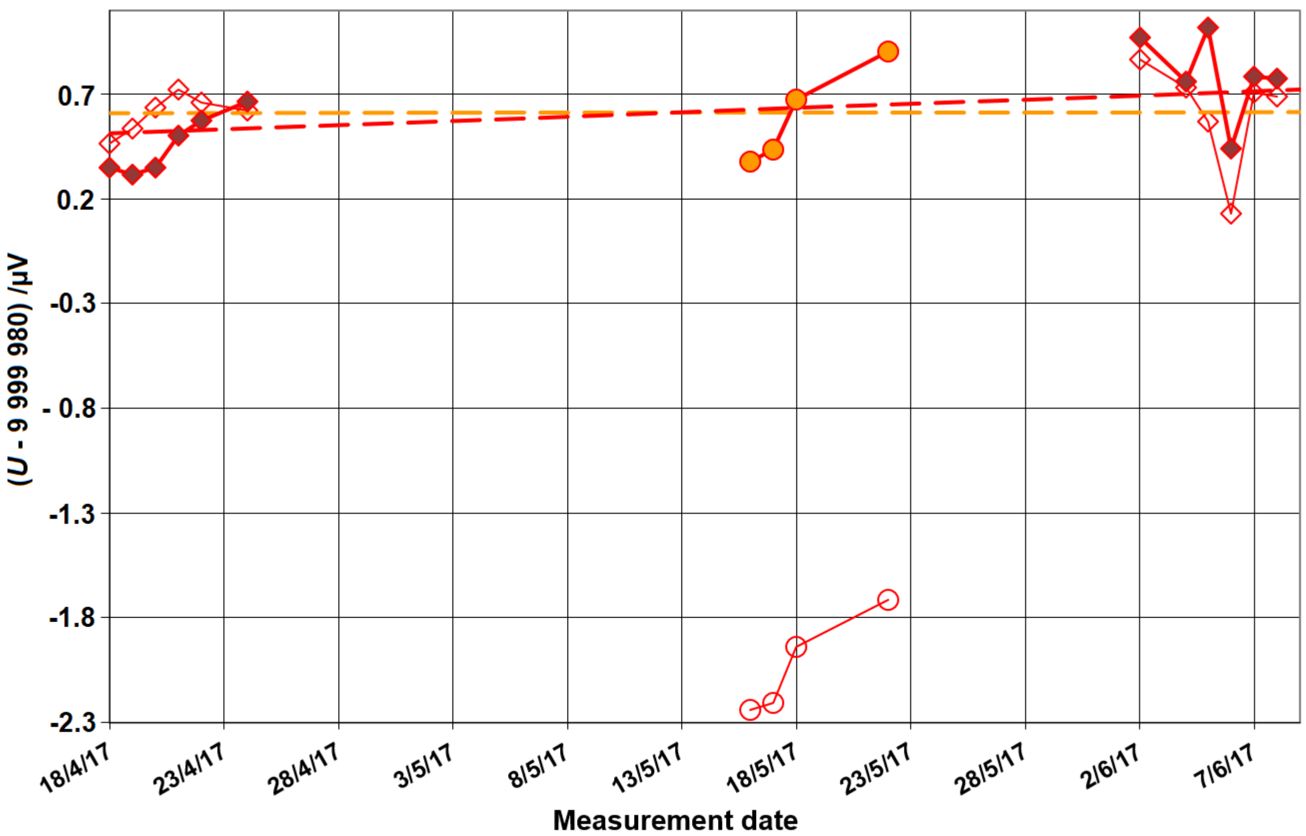

Figure 5b. Voltage evolution of the simple mean of the two standards at 10 V with and without corrections applied to the transfer standards for atmospheric pressure.

NMISA measurements are represented by disks and circles (no pressure correction applied) and BIPM measurements by filled diamonds (correction applied) and diamonds (no pressure correction applied).

If no pressure correction is applied, the relative error would reach 2×10^{-7} which is 20 times the 1/*f* noise voltage level considered at BIPM. The pressure sensitivity coefficients of the BIPM traveling secondary voltage standards are currently being measured again in order to evaluate a possible drift in their value since their initial determination 15 years ago. However, from these results, it is foreseeable that they have not changed by a large amplitude for the two zeners selected for this bilateral comparison.

References

[1] Witt, T.J., Maintenance and dissemination of voltage standards by Zener-diode-based instruments, IEE Proc. Sci. Meas. Technol., 149(6), pp 305-312, November 2002.