Bilateral Comparison of 1 V and 10 V Standards between the INM (Romania) and the BIPM, August to October 2013 (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 V and 10 V voltage reference standards of the BIPM and the Institut National de Metrologie (INM)**,** Bucharest, Romania, was carried out from August to October 2013. Two BIPM Zener diode-based travelling standards (Fluke 732B), BIPM_7 (Z7) and BIPM_8 (Z8), were transported by freight to INM. At INM, 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 INM, 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 ambient atmospheric pressure.

Outline of the measuring method

INM 1 V and 10 V measurements

The EMF at each output terminal of the travelling standard is connected in series opposition to a commercial Josephson Voltage Standard that includes a low thermal EMF scanner with three different channels. The same two channels were used for the 10 V and 1 V outputs of the Zeners. The EMF differences are measured 8 times every day using a digital nanovoltmeter and the simple mean value is considered as the result of the day. The travelling standard is disconnected from the mains supply during the measurements. The “GUARD” and “CHASSIS” terminals are jointly connected to a common ground point. The internal thermistor resistance is monitored during the measurements.

BIPM Measurements for both 1 V and 10 V

The output voltage of the Zener standard to be measured is connected to the BIPM Josephson Voltage Standard (in series opposition with the BIPM array of Josephson junctions) through a low thermal EMF switch. 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 since the mains plug at the rear of the Zeners has been disconnected.

The BIPM detector consists of an EM model N1a analog nanovoltmeter whose output is connected, via an optically-coupled isolation amplifier, to a pen recorder and 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 0.5 µV. for both nominal voltages. The nanovoltmeter is set to its 3 µV range for the measurements performed at the level of 1 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 offset error and internal linear thermo-electromotive forces.

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 this occurs, the “Data Acquisition” sequence starts again. The “Data Acquisition” sequence lasts 25 s. 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 INM measurements (2013/09/06). The discrepancy observed on the 10 V measurements on Z7 is discussed in the conclusion of the report.

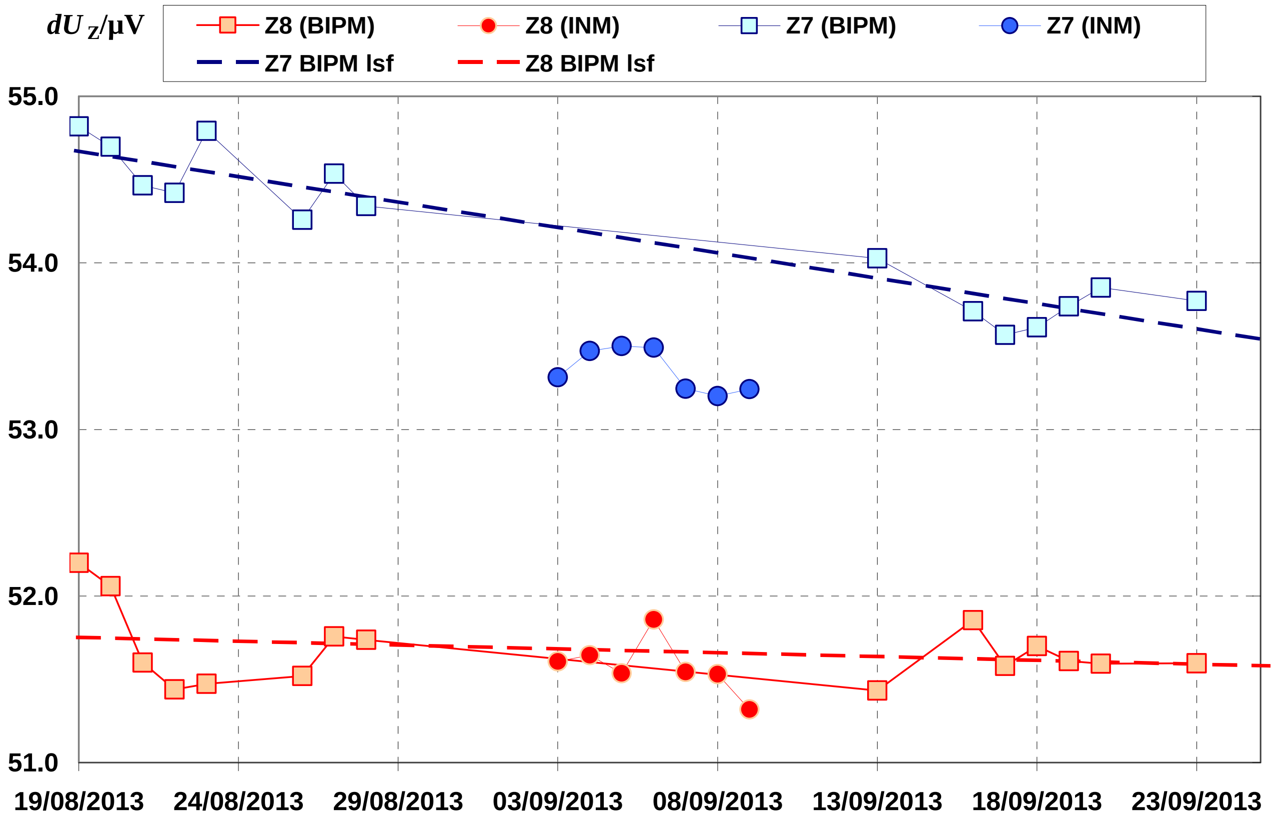

Figure 1a: Voltage of Z7 (top) and Z8 (bottom) at 10 V measured at both institutes (squares for BIPM and disks for INM) referred to an arbitrary origin as a function of time, with a linear least-squares fit adjustment to the BIPM measurements.

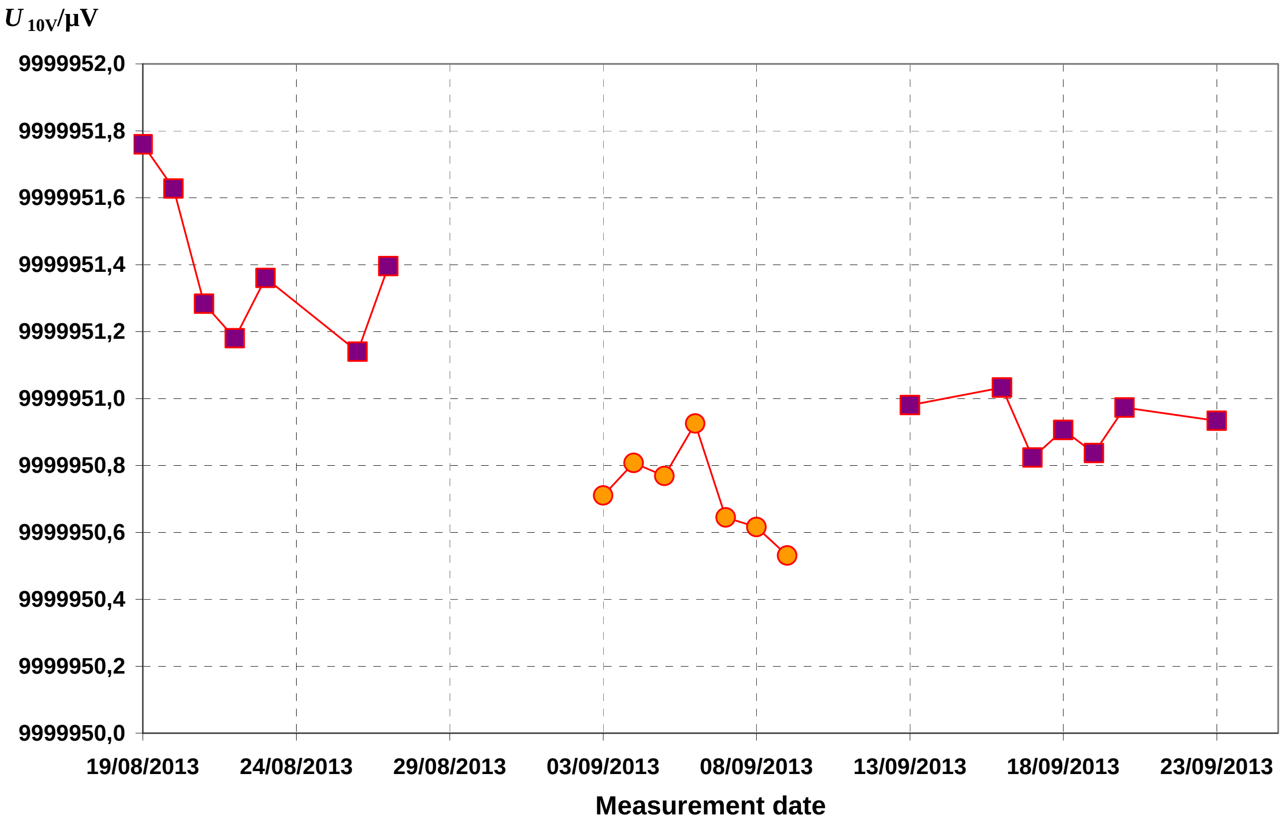

Figure 2: Voltage evolution of the simple mean of the two standards at 10 V. INM measurements are represented by circles and BIPM measurements by squares.

Table 1 lists the results of the comparison and the uncertainty contributions for the comparison INM/BIPM at 10 V. The relative value of the voltage noise floor due to flicker noise is about 1 part in 10^8 and represents the ultimate limit of the stability of Zener voltage standards.

Table 1. Results of the INM (Romania)/BIPM bilateral comparison of 10 V standards using two Zener traveling standards: reference date 06 September 2013. Uncertainties are 1 σ estimates.

		BIPM_7	BIPM_8	
1	*INM (Romania)* (U_Z – 10 V)/µV	-37.85	-60.72	
2	Type A uncertainty/µV	0.116	0.121	r
3	correlated (Type B) unc. /µV	0.0165		s
4	*BIPM* (U_Z – 10 V)/µV	-37.08	-60.63	
5	Type A uncertainty/µV	0.1	0.1	t
6	correlated (Type B) unc./µV	0.001		u
7	pressure and temperature correction uncertainty/µV	0.19	0.01	v
8	(U_{INM} – U_{BIPM})/µV	-0.77	-0.09	
9	uncorrelated uncertainty/µV	0.24	0.16	w
10	< U_{INM} – U_{BIPM} >/µV	-0.43		
11	*a priori* uncertainty/µV	0.15		x
12	*a posteriori* uncertainty/µV	0.34		
13	correlated uncertainty/µV	0.0165		y
14	comparison total uncertainty/µV	0.34		

The uncorrelated uncertainty is $w = [r^2 + t^2 + v^2]^{1/2}$.

The correlated uncertainty is $y = [s^2 + u^2]^{1/2}$.

As the *a priori* uncertainty and the *a posteriori* uncertainty are significantly different, we consider the largest component (*a posteriori* uncertainty $x = ½\,[w_{Z7}^2 + w_{Z8}^2]^{1/2}$) as the transfer uncertainty.

r is the INM Type A uncertainty (2);
s is the INM Type B uncertainty, which is assumed to be correlated for both transfer standards (3);
t is the BIPM Type A uncertainty (5); The standard deviation of the mean of the BIPM daily measurement results is equal to 77 nV but we consider that the Type A uncertainty can’t be lower than the 1/f noise floor estimated to 100 nV.

u is the BIPM Type B uncertainty, which is assumed to be correlated for both transfer standards (6);
v is the pressure and temperature coefficient correction uncertainty (7);
w_i is the quadratic combination of the uncorrelated uncertainties for the Zener (9);
x is the uncertainty of the mean based on internal consistency (11) *ie* quadratic combination of theType A uncertainty of both laboratories;
y is the quadratic combination of the correlated uncertainties (13).

Note: The *a posteriori* uncertainty is the standard deviation of the mean of the voltage difference of each individual transfer standard.

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 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 and we use the larger of these two estimates in calculating the final uncertainty.

In Table 1, the following elements are listed:

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

(2) the Type A uncertainty which is the experimental standard deviation of the measurements performed at INM;

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

(4-6) the corresponding quantities for the BIPM referenced to the mean date of INM 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 the thermistor resistances measured at both institutes which is then multiplied by the uncertainties $u(c_{T,i})$ of the temperature coefficients of each Zener standard:

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

where $U = 10$ V, $u(c_{\mathrm{T,Z7}}) = 1.07\times10^{-7}$ / kΩ, $u(c_{\mathrm{T,Z8}}) = -0.95\times10^{-7}$ / kΩ and $\Delta R_{Z7} = 0.175$ kΩ and $\Delta R_{Z8} = 0.013$ 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:

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[*] 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.

[*] The evaluation of the correction coefficients was performed in 1997.

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

where U = 10 V, $u(c_{\mathrm{P,Z7}})$= 0.046×10^{-9} / hPa, $u(c_{\mathrm{P\text{-}Z8}})$ = 0.051×10^{-9} / hPa, $\Delta P_{Z7} = \Delta P_{Z8}$ = 1 hPa.
Note: the uncertainty on the measurement of the temperature and the pressure are negligible.

(8) the difference ($U_{\mathrm{INM}} - U_{\mathrm{BIPM}}$) for each Zener, and (9) the uncorrelated part of the uncertainty;

(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, determined as described on page 6;

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

(13) the correlated part of the uncertainty 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).

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

$$\boldsymbol{U_{\mathrm{INM}} - U_{\mathrm{BIPM}} = -\,0.43\ \mu\mathrm{V}; \quad u_{\mathrm{c}} = 0.34\ \mu\mathrm{V} \quad \text{on 2013/09/06}},$$

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

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 a Zener at the INM. Note that the uncertainty of the temperature (3) and pressure (4) corrections are given as an indication and do not appear in the final uncertainty budget as they are included separately in the comparison uncertainty budget (Table 1).

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Uncertainty Budgets

Table 2. For information, 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 without the contribution of the Zener noise.

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
detector gain	0.11
leakage resistance	3×10^{-2}
frequency	3×10^{-2}
pressure and temperature correction	included in the Zener unc. budget
total	0.87

Table 3. Estimated standard uncertainties for Zener calibrations with the INM equipment at the level of 10 V for each Zener.

Table 3a

Uncertainty budget BIPM 7_10 V

Quantity	**Uncertainty**	**Type**	**Dist..**	**Std. Unc.**	**Sensitivity**	**Uncertainty contribution**
Frequency	10 Hz	B	Rect.	5.8 Hz	0.13 nV/Hz	0.8 nV
Null detector	6.0 nV	B	Rect.	3.5 nV	1	3.5 nV
Leakage error	1.0 nV	B	Norm.	1.0 nV	1	1.0 nV
Thermal emf	16.4 nV	A	Norm.	16.4 nV	1	16.4 nV
Electromagnetic interference						
Thermistor resistence	10 Ω	B	Norm.	10 Ω	110 nV/kΩ	1.1 nV
Ambient pressure	0.5 hPa	B	Norm.	0.5 hPa	19 nV/hPa	9.5 nV
Standard deviation	115.7 nV	A	Norm.	115.7 nV	1	115.7 nV

Combined standard uncertainty	117.3 nV
Expanded uncertainty (k=2)	235 nV

Table 3b

Table 3bUncertainty budget BIPM 8_10 V

Quantity	**Uncertainty**	**Type**	**Dist.**	**Std. Unc.**	**Sensitivity**	**Unc.**
Frequency	10 Hz	B	Rect.	5.8 Hz	0.13 nV/Hz	0.8 nV
Null detector	6.0 nV	B	Rect.	3.5 nV	1	3.5 nV
Leakage error	1.0 nV	B	Norm.	1.0 nV	1	1.0 nV
Thermal emf	15.7 nV	A	Norm.	15.7 nV	1	15.7 nV
Electromagnetic interference						
Thermistor resistence	10 Ω	B	Norm.	10 Ω	780 nV/kΩ	7.8 nV
Ambient pressure	0.5 hPa	B	Norm.	0.5 hPa	21 nV/hPa	10.5 nV
Standard deviation	120.8 nV	A	Norm.	120.8 nV	1	120.8 nV

Combined standard uncertainty	122.6 nV
Expanded uncertainty (k=2)	245 nV

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 INM measurements (2013/09/06).

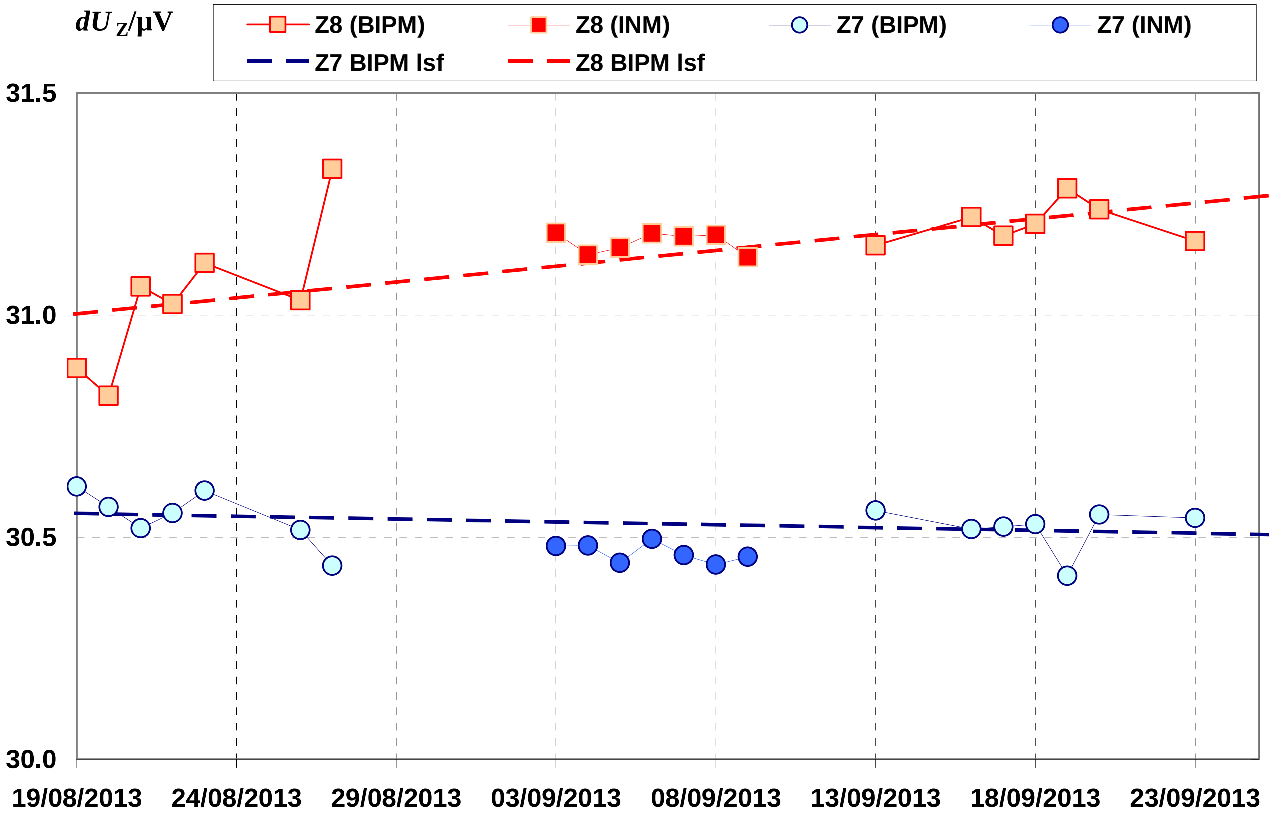

Figure 3: Voltage of BIPM_7 (on top) and BIPM_8 (on bottom) at 1.018 V measured at both institutes, referred to an arbitrary origin, as a function of time, with a linear least-squares fit to the measurements of the BIPM.

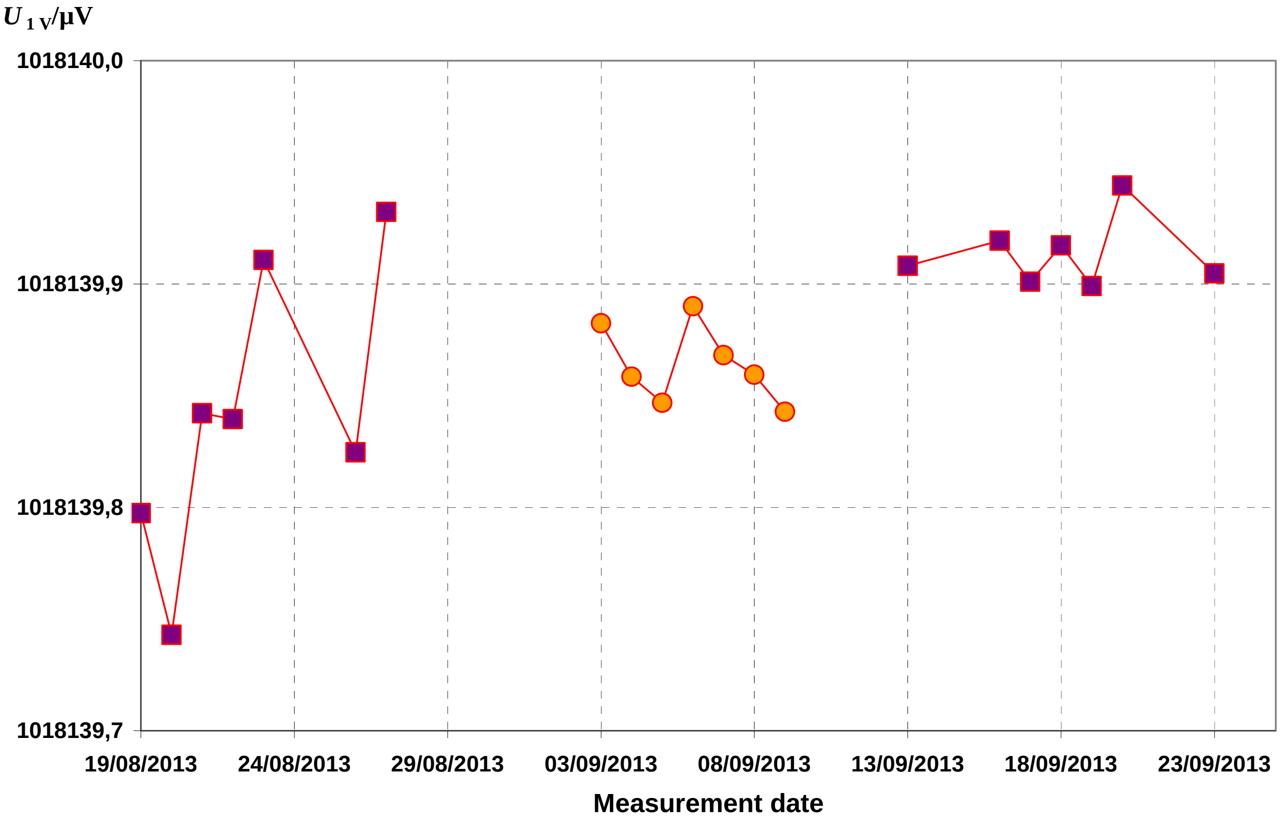

Figure 4: Voltage evolution of the simple mean of the two standards at 1.018 V.

Table 4 lists the results of the comparison and the uncertainty contributions for the comparison INM/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 which consists of the experimental standard deviation of the mean of the results from the two traveling standards. Then we applied the same methodology as described in the measurements at 10 V.

In Table 4, the following elements are listed:

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

(2) the Type A uncertainty due to the instability of the Zener at INM;

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

(4-6) the corresponding quantities for the BIPM referenced to the mean date of the INM 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 uncertainties $u(c_{T,i})$ of the temperature coefficients of each Zener standard:

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

where $U = 1.018$ V, $u(c_{\mathrm{T,Z7}}) = 1.62\times10^{-7}$ / kΩ, $u(c_{\mathrm{T,Z8}}) = 1.10\times10^{-7}$ / kΩ and $\Delta R_{\mathrm{Z7}} = -0.159$ kΩ and $\Delta R_{\mathrm{Z8}} = -0.008$ 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($c_{\mathrm{P,Z7}}$) = 0.02×10^{-9} / hPa, u($c_{\mathrm{P,Z8}}$) = 0.05×10^{-9} / hPa, $\Delta P_{\mathrm{Z7}} = 0.9$ hPa and $\Delta P_{\mathrm{Z8}} = 1.2$ hPa.

Note that the uncertainty on the measurement of the temperature and the pressure were neglected as being negligible.

(8) the difference ($U_{\mathrm{INM}} - U_{\mathrm{BIPM}}$) for each Zener, and (9) the uncorrelated part of the uncertainty;

(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, determined as described on page 12;

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

(13) the correlated part of the uncertainty 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).

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[*] The evaluation of the correction coefficients was performed in 1997.

Table 5 summarizes the uncertainties related to the calibration of a Zener diode against the Josephson array voltage standard at the BIPM and Table 6 lists the uncertainties related to the calibration of a Zener diode against the Josephson array voltage standard at the INM.

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

$$\boldsymbol{U_{\mathrm{INM}} - U_{\mathrm{BIPM}} = -0.014\ \mu\mathrm{V};\ u_{\mathrm{c}} = 0.051\ \mu\mathrm{V}} \quad \textbf{on 2013/09/06},$$

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

(U_{Z} – 1.018 V)

Table 4. Results of the INM (Romania)/BIPM bilateral comparison of 1.018 V standards using two Zener traveling standards: reference date 06 September 2013. Uncertainties are 1 σ estimates.

		BIPM_7	BIPM_8	
1	*INM (Romania)* (U_{Z} – 1.018 V)/µV	108.46	171.16	
2	Type A uncertainty/µV	0.010	0.010	r
3	correlated unc. /µV	0.006		s
4	*BIPM* (U_{Z} – 1.018 V)/µV	108.53	171.13	
5	Type A uncertainty/µV	0.016	0.01	t
6	correlated unc./µV	0.014		u
7	pressure and temperature correction uncertainty/µV	0.026	0.001	v
8	($U_{\mathrm{INM}} - U_{\mathrm{BIPM}}$)/µV	-0.07	0.03	
9	uncorrelated uncertainty/µV	0.032	0.014	w
10	< $U_{\mathrm{INM}} - U_{\mathrm{BIPM}}$ >/µV	-0.014		
11	*a priori* uncertainty/µV	0.018		x
12	*a posteriori* uncertainty/µV	0.049		
13	correlated uncertainty/µV	0.015		y
14	comparison total uncertainty/µV	0.051		

The uncorrelated uncertainty is $w = [r^2 + t^2 + v^2]^{1/2}$, the expected transfer uncertainty (*a posteriori* uncertainty) is $x = ½\ [w_{\mathrm{Z7}}{}^2 + w_{\mathrm{Z8}}{}^2]^{1/2}$, and the correlated uncertainty is $y = [s^2 + u^2]^{1/2}$, where:

Note: The *a posteriori* uncertainty is the standard deviation of the mean of the voltage difference of each individual transfer standard.

r is the INM Type A uncertainty (2);
s is the INM Type B uncertainty, which is assumed to be correlated for both transfer standards (3);
t is the BIPM Type A uncertainty (5); the standard deviation of the mean of the BIPM daily measurement results is equal to 16 nV. We consider that the Type A uncertainty can't be lower than the 1/f noise floor estimated at 10 nV
u is the BIPM Type B uncertainty, which is assumed to be correlated for both transfer standards (6);
v is the pressure and temperature coefficient correction uncertainty (7);
w_i is the quadratic combination of the uncorrelated uncertainties for the Zener (9);
x is the expected uncertainty of the mean, based on internal consistency (11);
y is the quadratic combination of the correlated uncertainties (13).

Table 5. Estimated standard uncertainties for Zener calibrations with the BIPM equipment at the level of 1.018 V without the contribution of the Zener noise.

JVS & detector uncertainty components	Uncertainty/nV
Residual thermal electromotive forces	included in the Type A uncertainty
Type A uncertainty	0.34
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 INM for BIPM_7 and BIPM_8 respectively at the level of 1.018 V. The standard deviation of the mean of the INM daily measurement results is equal to 7 nV.

Table6a

Uncertainty budget BIPM 7_1.018 V

Quantity	**Uncertainty**	**Type**	**Dist..**	**Std. Unc.**	**Sensitivity**	**Uncertainty contribution**
Frequency	10 Hz	B	Rect.	5.8 Hz	0.013 nV/Hz	0.1 n V
Null detector	6.0 nV	B	Rect.	3.5 nV	1	3.5 nV
Leakage error	0.1 nV	B	Norm.	0.1 nV	1	0.1 nV
Thermal emf	5.9 nV	A	Norm.	5.9 nV	1	5.9 nV
Electromagnetic interference						
Thermistor resistence	10 Ω	B	Norm.	10 Ω	499 nV/kΩ	5 nV
Ambient pressure	0.5 hPa	B	Norm.	0.5 hPa	2 nV/hPa	1 nV
Standard deviation	18.1 nV	A	Norm.	18.11 nV	1	18.1 nV
				Combined standard uncertainty		20.0 nV
				Expanded uncertainty (k=2)		40 nV

Table 6b

Uncertainty budget BIPM 8_1.018 V

Quantity	**Uncertainty**	**Type**	**Dist.**	**Std Unc.**	**Sens.**	**Uncertainty contribution**
Frequency	10 Hz	B	Rect.	5.8 Hz	0.013 nV/Hz	0.1 n V
Null detector	6.0 nV	B	Rect.	3.5 nV	1	3.5 nV
Leakage error	0.1 nV	B	Norm.	0.1 nV	1	0.1 nV
Thermal emf	4.4 nV	A	Norm.	4.4 nV	1	4.4 nV
Electromagnetic interference						
Thermistor resistence	10 Ω	B	Norm.	10 Ω	234 nV/kΩ	2.3 nV
Ambient pressure	0.5 hPa	B	Norm.	0.5 hPa	2,1 nV/hPa	1.1 nV
Standard deviation	22.5 nV	A	Norm.	22.5 nV	1	22.5 nV
				Combined standard uncertainty		23.3 nV
				Expanded uncertainty (k=2)		47 nV

Conclusion

The final result of the comparison is presented as the difference between the values assigned to DC voltage standards by INM, at the level of 1.018 V and 10 V, at INM, U_{INM}, and those assigned by the BIPM, at the BIPM, U_{BIPM}, at the reference date of the 06th of September 2013.

$\boldsymbol{U_{\mathrm{INM}} - U_{\mathrm{BIPM}} = -0.014\ \mu\mathrm{V};\ u_{\mathrm{c}} = 0.051\ \mu\mathrm{V}}$**, at 1 V**

$\boldsymbol{U_{\mathrm{INM}} - U_{\mathrm{BIPM}} = -0.43\ \mu\mathrm{V};\quad u_{\mathrm{c}} = 0.34\ \mu\mathrm{V}}$**, at 10 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 INM, based on $K_{\mathrm{J-90}}$, and the uncertainty related to the comparison.

These are satisfactory results. The comparison results show that the voltage standards maintained by INM and the BIPM were equivalent, within the comparison uncertainty, on the mean date of the comparison.

It is however important to point out the significant difference of about 500 nV between the 10 V measurements of Z7 at BIPM and at INM. We discuss different hypothesis in the next paragraph.

Consistency of the results with the behavior of the standards at BIPM.

The comparison result at 10 V is affected by the significant weight of the INM measurements of BIPM_7 which are almost 500 nV below BIPM measurements, a deviation which is 4 times higher than the Type A uncertainty of the INM measurements. This difference can also be seen on the 1 V measurements, but with at a much lower amplitude.

To explain this discrepancy, we firstly thought of a possible leakage resistance effect in the scanner operated by INM. But the same channel of the scanner was operated for the 10 V of each of the two transfer standards and the discrepancy doesn’t appear on the measurements of BIPM_8.

The fact that the handle of this particular Zener was damaged during its shipment and that it’s internal battery, replaced in July 2013, was found unreliable in October 2013 can’t either explain by themselves the discrepancy, especially because the return measurements at BIPM were in agreement with the measurements carried out before the shipment.

We noticed that the internal temperature of the Zener was also significantly different between INM and BIPM (difference of 150 Ω while a typical value would be one order of magnitude lower). The mean value of the thermistor measurements at BIPM was 38.47 kΩ while the mean value of the measured temperature at INM was 38.30 kΩ. The thermistor reference value for this Zener is 38.30 kΩ. The corresponding voltage correction difference between the two laboratories is of the order of 400 nV to 600 nV.

As the temperature correction coefficients of the two transfer standards haven’t been checked since 2004 and as it can be assumed that they have changed over 9 years, we investigated on a possible new value for the temperature coefficient. A coefficient of 4.59×10^{-7} / kΩ (40 times higher than the present correction coefficient) would explain the observed difference (Cf. Fig 5).

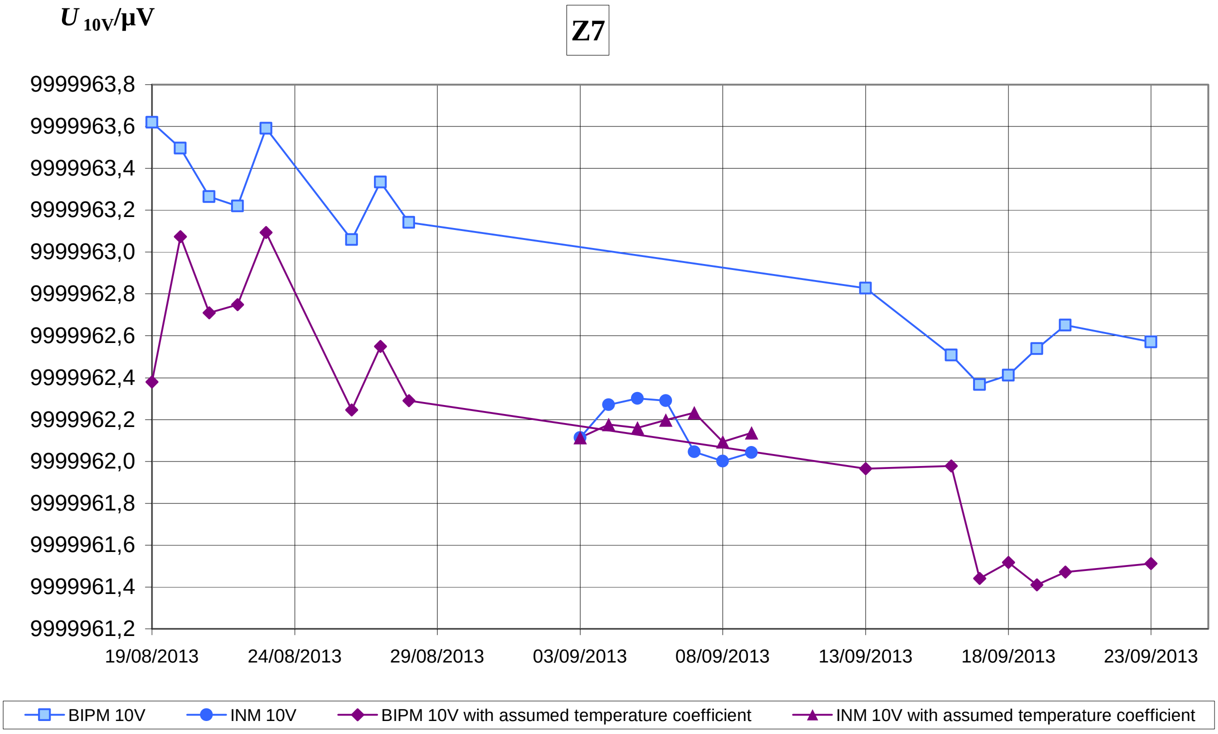

Figure 5: Voltage of Z7 at 10 V measured with the applied temperature coefficient (squares for BIPM and disks for INM) and the calculated one (losanges for BIPM and triangles for INM).

This coefficient value is consistent with the whole correction coefficients measured on the 28 zeners investigated at BIPM for their sensitivity coefficients in the period 1997-2002 [1]. The impact on the BIPM measurements is more significant as the measurements were carried out at different temperature: the standard deviation of the mean of all the BIPM measurements changed from 115 nV to 155 nV (increase of nearly 40%).

From the 1 V measurements, if the temperature correction coefficient is increased with the same amplitude, the results are no longer coherent as the voltage difference at the mean date of the INM measurement reach -0.7 µV while it is only -0.07 µV with the present coefficient.

The measurements of the correction coefficients carried out in 2002 also show that the correlation between the Zener temperature coefficient at 1 V and 10 V is very low,and therefore it is possible that the sensitivity to temperature of one voltage divider (10 V output) would change while the other one would remain unchanged (1 V).

Finally, the following point is probably the better one to explain the descrepency on the 10 V measurements of Z7 at INM: the temperature measurements carried out at INM show a higher value then the one measured when the Zener is connected to the mains.

This is a surprising result, we couldn’t reproduce in our laboratory. Effectively, when the Zener diode is disconnected from the mains, its internal temperature will decrease over the following two hours before reaching an equilibrium temperature. This anomaly might also explain the discrepancy in the final result.

In conclusion, it can be assumed that an error in the thermistance measurement of Z7 at INM together with a change of the temperature correction coefficient of BIPM_7 transfer, standard for the 10 V output, over 11 years and might be the major causes for the observed discrepancy.

References

[1] Witt T.J., *Maintenance and dissemination of voltage standards by Zener-diode-based instruments*, IEE Proceedings 6(149), p305-312, Nov. 2002