Bilateral Comparison of 10 V Standards

between the NML (Ireland) and the BIPM,

March to May 2004

(part of the ongoing BIPM key comparison BIPM.EM-K11b)

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As a part of the ongoing BIPM key comparison BIPM.EM-K11b, a comparison of the 10 V voltage reference standards of the BIPM and the National Metrology Laboratory (NML), Dublin, Ireland, was carried out from March to May 2004. Two BIPM 732B Zener diode-based travelling standards, BIPM8 and BIPM9, were transported by freight. The NML measurements were carried out by comparison with the mean of the NML voltage standard. The BIPM measurements of the travelling standards were carried out by direct comparison with the Josephson effect standard. Results of all measurements were corrected for the dependence of the output voltages on ambient temperature and pressure.

Figure 1 shows the measured values obtained for the two standards by the two laboratories. The BIPM values and uncertainties, and those of the NML are calculated for the reference date from linear least-squares fits to all data from each laboratory.

Table 1 lists the results of the comparison and the component uncertainty contributions for the comparison NML/BIPM. Experience has shown that flicker or $1/f$ noise dominates 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 flicker floor voltage is about 1 part in 10^8.

In estimating the uncertainty we have calculated the *a priori* uncertainty based on all known uncorrelated sources except that associated with the stability of the standards when transported. We compare this with the *a posteriori* uncertainty estimated by the standard deviation of the mean of the results from the two travelling standards. 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. If the *a posteriori* uncertainty is significantly different from 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 predicted value U_{NML} of each Zener, computed using a linear least squares fit to all of the data from the NML and referenced to the mean date of the NML's measurements;

(2) the Type A uncertainty due to the instability of the Zener, computed as the standard uncertainty of the value predicted by the linear drift model, or as an estimate of the $1/f$ noise voltage level;

(3) the uncertainty component arising from the measuring equipment of the NML: this uncertainty is completely correlated between the different Zeners used for a comparison[1];

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

(7) the uncertainty due to the combined effects of the uncertainties of the pressure and temperature coefficients and to the difference of the mean pressures and temperatures in the participating laboratories; although the same equipment is used to measure the coefficients for all Zeners, the uncertainty is dominated by the Type A uncertainty of each Zener, so that the final uncertainty can be considered as uncorrelated among the different Zeners used in a comparison;

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

(10) the result of the comparison, which is the weighted mean of the differences of the calibration results for the different standards, using as weights the reciprocal of the square of the uncorrelated part of the uncertainty components for each travelling standard;

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

 (11) the *a priori* uncertainty, which is the standard deviation of the mean value of the results, from the different Zeners, counting only the uncorrelated uncertainties of the individual results;

 (12) the *a posteriori* uncertainty, which is the standard deviation of the mean of the different 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).

[1.] At 10 V, there is a high degree of correlation between these input quantities and we can assume a correlation coefficient of unity without significantly affecting the standard uncertainty of the result of this comparison.

Table 2 summarizes the uncertainties due to the BIPM measuring equipment.

Table 3 lists the uncertainties of maintenance and measuring equipment at the NML.

The final result of the comparison is presented as the difference between the values assigned by the two laboratories to a 10 V standard. The difference between the value assigned to a 10 V standard by the NML, at the NML, U_{NML}, and that assigned by the BIPM, at the BIPM, U_{BIPM}, for the reference date is

$$U_{\mathrm{NML}} - U_{\mathrm{BIPM}} = -1.86 \ \mu V; \qquad u_{\mathrm{c}} = 1.01 \ \mu V \text{ on } 2004/04/26,$$

where u_{c} is the combined Type A and Type B standard uncertainty from both laboratories, that is the standard uncertainty associated with the measured difference.

As can be observed in Figure 1 and in Table 1 (line 8), the results obtained for both Zeners are quite identical. This indicates a possible uncompensated change in the value of the as-maintained reference of the NML. The results obtained on the 1.018 V output of the same Zener travelling standards (*see* Appendix A) could be due to the same reason.
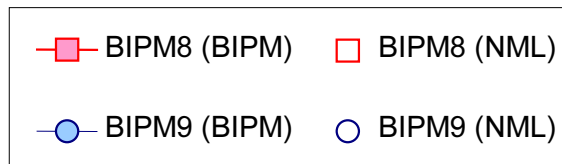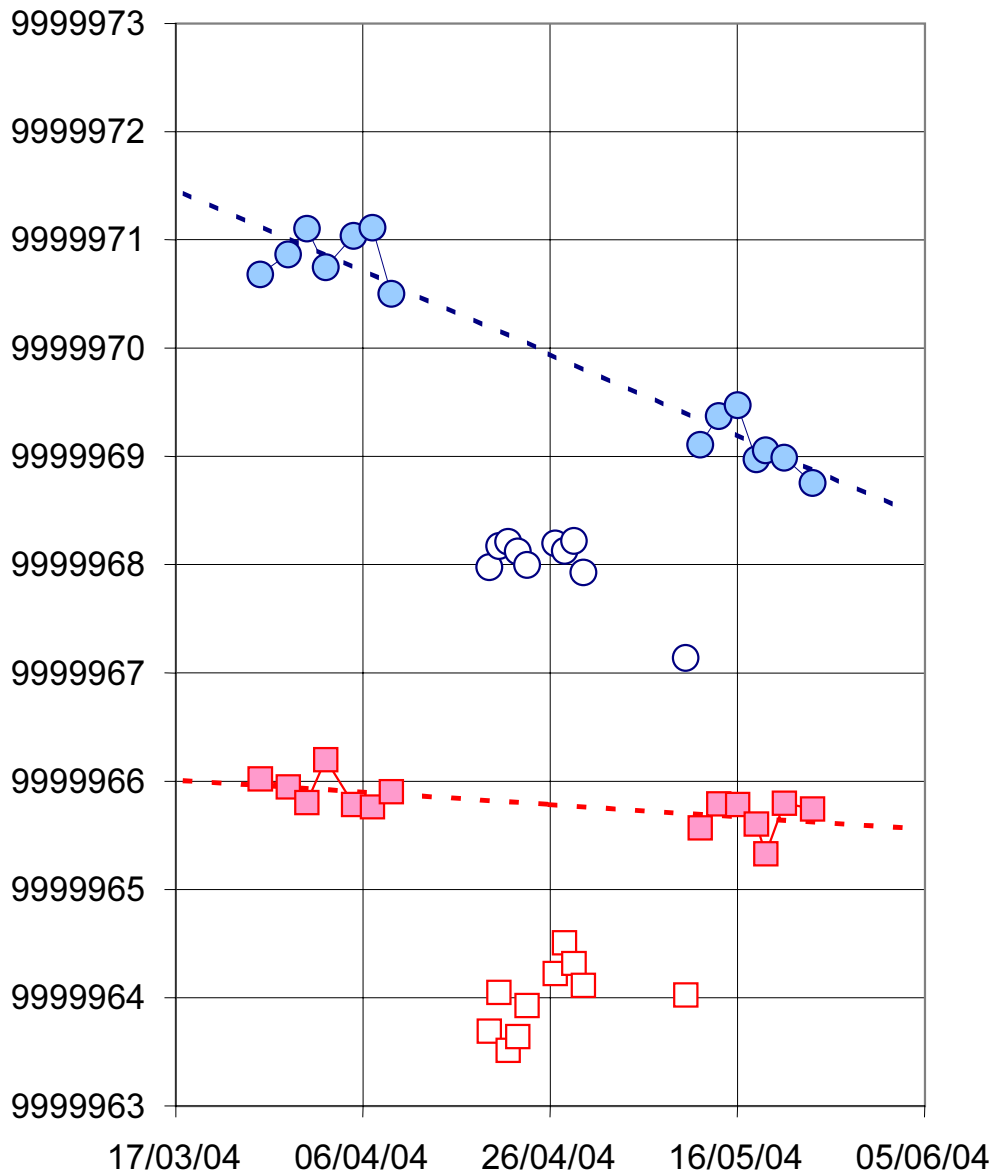
$U_Z/\mu V$

Figure A1. Voltage of BIPM8 and BIPM9 at 10 V as a function of time, with linear least-squares fit to the measurements of the BIPM.

Table 1. Results of the NML(Ireland)/BIPM bilateral comparison of 10 V standards using two Zener travelling standards: reference date 26 April 2004. Uncertainties are 1 σ estimates. The uncorrelated uncertainty is $w = [r^2 + t^2 + v^2]^{1/2}$, the expected transfer uncertainty is $x = [w_8^2 + w_9^2]^{1/2}/2$, and the correlated uncertainty is $y = [s^2 + u^2]^{1/2}$.

			BIPM8	BIPM9	
1	*NML (Ireland)*	$(U_Z - 10V)/\mu V$	−36.00	−31.99	
2		type-A uncertainty/μV	0.10	0.10	r
3	equipment uncertainty/μV		1.01		s
4	*BIPM*	$(U_Z - 10V)/\mu V$	−34.22	−30.05	
5		type-A uncertainty/μV	0.10	0.10	t
6	equipment uncertainty/μV		0.01		u
7	pressure and temperature corrections uncertainty/μV		0.08	0.08	v
8	$(U_{Z\_NML} - U_{Z\_BIPM})/\mu V$		−1.78	−1.94	
9	uncorrelated uncertainty/μV		0.16	0.16	w
10	$<U_{NML} - U_{BIPM}>/\mu V$		−1.86		
11	expected transfer uncertainty/μV		0.12		x
12	s_M of difference for two Zeners/μV		0.08		
13	correlated uncertainty/μV		1.01		y
14	comparison total uncertainty/μV		1.01		

Table 2. Estimated standard uncertainties for Zener calibrations with the BIPM equipment.

	Uncertainty/nV
thermal electromotive forces	3
detector / electromagnetic interference	3
leakage resistance	3
frequency	0.3
pressure correction	4
temperature correction	1
total	6.6

Table 3. Estimated standard uncertainties for Zener calibrations with the NML equipment.

	Uncertainty/μV
reference group stability	0.90
comparator	0.45
pressure correction	0.03
temperature correction	0.003
total	1.01

Appendix A

Bilateral Comparison of 1.018 V Standards
between the NML (Ireland) and the BIPM,
March to May 2004

At the same time as the formal, declared key comparison described in the first part of this report, an informal comparison of the 1.018 V voltage reference standards of the BIPM and the National Metrology Laboratory (NML), Dublin, Ireland, was also carried out, using the same two BIPM 732B Zener diode-based travelling standards, Z BIPM8 and Z BIPM9. The NML measurements were carried out by using a precision potentiometer to scale between 10 V and 1.018 V and hence to measure the 1.018 V outputs of the Zeners in terms of a 10 V reference standard. The BIPM measurements of the travelling standards were carried out by direct comparison with the Josephson effect standard. Results of all measurements were corrected for the dependence of the output voltages on ambient temperature and pressure.

Figure A1 shows the measured values obtained for the two standards by the two laboratories. The BIPM values and uncertainties, and those of the NML are calculated for the reference date from linear least-squares fits to all data from each laboratory.

Table A1 lists the results of the comparison and the component uncertainty contributions for the comparison NML/BIPM. Experience has shown that flicker or $1/f$ noise dominates 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 flicker floor voltage is about 1 part in 10^8.

In estimating the uncertainty we have calculated the *a priori* uncertainty based on all known uncorrelated sources except that associated with the stability of the standards when transported. We compare this with the *a posteriori* uncertainty estimated by the standard deviation of the weighted mean of the results from the two travelling standards. 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. If the *a posteriori* uncertainty is significantly different from 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 A1, the following elements are listed:

(1) the predicted value U_{NML} of each Zener, computed using a linear least squares fit to all of the data from the NML and referenced to the mean date of the NML's measurements;

(2) the Type A uncertainty due to the instability of the Zener, computed as the standard uncertainty of the value predicted by the linear drift model, or as an estimate of the $1/f$ noise voltage level;

(3) the uncertainty component arising from the measuring equipment of the NML: 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 NML's measurements;

(7) the uncertainty due to the combined effects of the uncertainties of the pressure and temperature coefficients and to the difference of the mean pressures and temperatures in the participating laboratories; although the same equipment is used to measure the coefficients for all Zeners, the uncertainty is dominated by the Type A uncertainty of each Zener, so that the final uncertainty can be considered as uncorrelated among the different Zeners used in a comparison;

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

(10) the result of the comparison, which is the weighted mean of the differences of the calibration results for the different standards, using as weights the reciprocal of the square of the uncorrelated part of the uncertainty components for each travelling standard;

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

(11) the *a priori* uncertainty, which is the standard deviation of the mean value of the results, from the different Zeners, counting only the uncorrelated uncertainties of the individual results;

(12) the *a posteriori* uncertainty, which is the standard deviation of the mean of the different 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).

Table A2 summarizes the uncertainties due to the BIPM measuring equipment.

Table A3 lists the uncertainties of maintenance and measuring equipment at the NML.

The final result of the comparison is presented as the difference between the values assigned by the two laboratories to a 1.018 V standard. The difference between the value assigned to a 1.018 V standard by the NML, at the NML, U_{NML}, and that assigned by the BIPM, at the BIPM, U_{BIPM}, for the reference date is

$$U_{\text{NML}} - U_{\text{BIPM}} = -0.174 \ \mu\text{V}; \quad u_{\text{c}} = 0.461 \ \mu\text{V on 2004/05/04,}$$

where u_{c} is the combined Type A and Type B standard uncertainty from both laboratories, that is the standard uncertainty associated with the measured difference.

This is a satisfactory result. The difference between the values assigned to the mean voltage of the travelling standards by the two laboratories is less than the standard uncertainty associated with the difference.
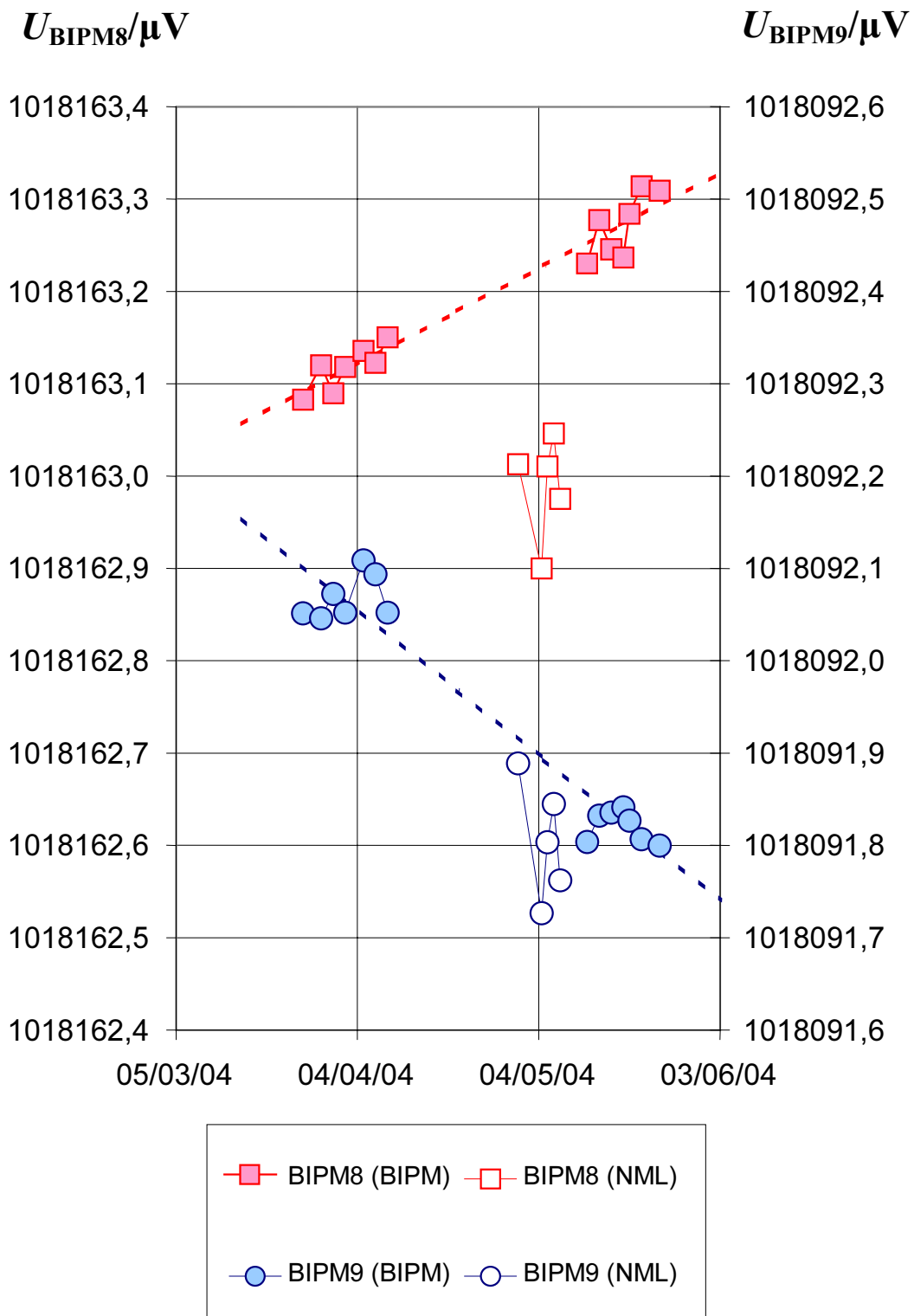
Figure A1. Voltage of BIPM8 and BIPM9 at 1.018 V as a function of time, with linear least-squares fit to the measurements of the BIPM.

Table A1. Results of the NML(Ireland)/BIPM bilateral comparison of 1.018 V standards using two Zener travelling standards: reference date 04 May 2004. Uncertainties are 1 σ estimates.

The uncorrelated uncertainty is $w = [r^2 + t^2 + v^2]^{1/2}$, the expected transfer uncertainty is $x = [w_8^2 + w_9^2]^{1/2}/2$, and the correlated uncertainty is $y = [s^2 + u^2]^{1/2}$.

		BIPM8	BIPM9	
1	*NML (Ireland)* $(U_Z - 1.018\text{V})/\mu\text{V}$	162.989	91.805	
2	type-A uncertainty/μV	0.029	0.028	*r*
3	equipment uncertainty/μV	0.455		*s*
4	*BIPM* $(U_Z - 1.018\text{V})/\mu\text{V}$	163.228	91.893	
5	type-A uncertainty/μV	0.010	0.010	*t*
6	equipment uncertainty/μV	0.005		*u*
7	pressure and temperature corrections uncertainty/μV	0.012	0.024	*v*
8	$(U_{Z\_\text{NML}} - U_{Z\_\text{BIPM}})/\mu\text{V}$	−0.239	−0.087	
9	uncorrelated uncertainty/μV	0.033	0.038	*w*
10	$<U_{\text{NML}} - U_{\text{BIPM}}>/\mu\text{V}$	−0.174		
11	expected transfer uncertainty/μV	0.025		*x*
12	s_{M} of difference for two Zeners/μV	0.075		
13	correlated uncertainty/μV	0.455		*y*
14	comparison total uncertainty/μV	0.461		

Table A2. Estimated standard uncertainties for 1.018 V Zener calibrations with the BIPM equipment.

	Uncertainty/nV
thermal electromotive forces	3.0
detector / electromagnetic interference	3.0
leakage resistance	3.0
frequency	0.03
pressure correction	0.4
temperature correction	1.6
total	5.5

Table A3. Estimated standard uncertainties for 1.018 V Zener calibrations with the NML equipment.

	Uncertainty/nV
10 V reference standard	0.25
comparator	0.38
pressure correction	0.004
temperature correction	0.005
total	0.455