BUREAU INTERNATIONAL
DES POIDS ET MESURES

Bilateral comparison of 1 Ω and 10 kΩ standards (ongoing BIPM key comparisons BIPM.EM-K13.a and 13.b) between the NMISA (South Africa) and the BIPM

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Final Report

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1 Introduction

A comparison of values assigned to 1 Ω and 10 kΩ resistance standards was carried out between the BIPM and the NMISA (South Africa) in the period January 2017 to July 2017.
Two 1 Ω and two 10 kΩ BIPM travelling standards were calibrated first at the BIPM, then at the NMISA and again at the BIPM after their return. The measurement periods are referred to as:

'Before' measurements at the BIPM: January 2017 – February 2017
NMISA measurements: March 2017 – May 2017
'After' measurements at the BIPM: June 2017 – July 2017

This report is organised as follows: details of the travelling standards used are listed in section 2. The results of the BIPM measurements are given in section 3, and the calibration reports provided by the NMISA are summarized in section 4; these two sections include the uncertainty budgets for each laboratory. Finally, the two sets of measurements are compared and analysed in section 5. The uncertainties arising from the transfer of the standards between the two laboratories are estimated and included at this point. The final results of the comparisons are given, in the form of the degrees of equivalence (deviations from the KCRV and associated uncertainties) between the NMISA and the BIPM for measurements of 1 Ω and 10 kΩ resistance standards.
This report covers the comparison of both 1 Ω standards (BIPM.EM-K13.a) and 10 kΩ standards (BIPM.EM-K13.b). The measurements of these two different resistance values are analysed separately, but are reported together here as the two comparisons were carried out simultaneously.

2 Travelling Standards

Four travelling standards provided by the BIPM were used for this comparison. The two 1 Ω standards are of CSIRO type, with working labels BIV193 (manufacturer's serial number S-64193) and BIV203 (manufacturer's serial number S-64203). The two 10 kΩ standards are TEGAM S104 type, and have the working labels B10k08 (manufacturer's serial number K201039730104) and B10k11 (serial number K205039730104). The standards were shipped by regular air freight between the laboratories.

All measurements are corrected to a reference temperature of 23.000 °C and reference pressure 1013.25 hPa using the known coefficients of the standards, given in table 1.
According to the protocol, the NMISA did not apply pressure and temperature corrections to its results, but supplied the raw values and the measured temperature and pressure. The corrections were applied in the analysis made by the BIPM.

	Relative temperature coefficients		Relative pressure coefficients
Standard #	α_{23} / (10^{-6}/K)	β / (10^{-6}/K²)	γ / (10^{-9}/hPa)
BIV193	− 0.0042	− 0.0012	− 0.170
BIV203	− 0.0096	− 0.0016	− 0.200
B10k08	− 0.0100	− 0.0230	− 0.162
B10k11	− 0.0700	− 0.0270	− 0.350

Table 1: Temperature and pressure coefficients of the travelling standards.

3 Measurements at the BIPM

The BIPM measurements are traceable to the quantum Hall resistance (QHR) standard via different measurement bridges and working standards for the two nominal values. In all cases, values are based on the conventional value of the von Klitzing constant, $R_{K\text{-}90} = 25812.807\ \Omega$. (The standard uncertainty associated with the use of $R_{K\text{-}90}$, which has a relative value of 1×10^{-7}, has not been included.)

The 1 Ω measurements were carried out by comparison with a 100 Ω reference resistor (identifier BI100-3) whose value is calibrated against the BIPM QHR standard regularly (at least once every 6 months). The comparison was performed using a DC cryogenic current comparator operating with 50 mA current in the 1 Ω resistors.

The 1 Ω travelling standards were kept in a temperature controlled oil bath at a temperature which is close (within a few mK) to the reference temperature of 23 °C. The oil temperature close to each standard was determined by means of a calibrated Standard Platinum Resistance Thermometer (SPRT), in conjunction with thermocouples. The air pressure in the laboratory was recorded using a calibrated manometer at the time of each measurement.

The travelling standards were measured 13 times during the period labelled 'before' (January 2017 – February 2017) and 12 times during the period labelled 'after' (June 2017 – July 2017). The individual BIPM measurement data are plotted in figures 2 and 3 of section 5 (after application of the temperature and pressure corrections). The mean results are summarized in Table 2 and the uncertainty budget in Table 3. The dispersion of each group of measurements is estimated by the standard deviation.

BIPM	**Relative difference from nominal 1 Ω value / 10^{-6}**					
Standard #	BEFORE	Std dev. u_{1B}	AFTER	Std dev. u_{1A}	INTERPOLATED ON 20-04-2017	Std dev.
BIV193	− 5.218	0.012	− 5.143	0.022	− 5.181	0.018
BIV203	+ 0.532	0.008	+ 0.522	0.011	+ 0.527	0.010

Table 2: Summary of BIPM calibrations of the 1 Ω standards.

Source of uncertainty	**relative standard uncertainty /10^{-9}**
Imperfect realisation of $R_{K\text{-}90}$	2
Calibration of the BIPM 100 Ω reference (BI100-3) against $R_{K\text{-}90}$	3
Interpolation / extrapolation of the value of BI100-3	13
Measurement of the (1Ω / BI100-3) ratio	8
Temperature correction for the 1 Ω standard	2
Pressure correction for the 1 Ω standard	3
Combined uncertainty u_2	**16**

Table 3: BIPM uncertainty budget for the calibration of the 1 Ω travelling standards.

The 10 kΩ measurements were carried out by comparison with a set of two 10 kΩ reference resistors (identifiers B10K1 and B10K2) which are calibrated regularly (at least once every 6 months) against the BIPM QHR standard. The comparison was performed using a Warshawsky bridge operating with a 0.1 mA DC current (i.e. at a measurement voltage of 1 V).

The 10 kΩ travelling standards were kept in a temperature-controlled air bath at a temperature which is close to the reference temperature of 23 °C (within 0.05 °C). The temperature of the standards was determined by means of a calibrated platinum resistance thermometer, in conjunction with thermocouples. The air pressure in the laboratory was recorded using a calibrated manometer at the time of each measurement. The relative humidity in the air bath was not monitored, but the laboratory air conditioning system controls the relative humidity to 50 % (± 10 %).

The travelling standards were measured 16 times during the period labelled 'before' (January 2017 – February 2017) and 9 times during the period labelled 'after' (June 2017 – July 2017). The individual BIPM measurement data are plotted in figures 4 and 5 of section 5 (after application of the temperature and pressure correction). The mean results are summarized in Table 4 and the uncertainty budget in Table 5. The dispersion of each group of measurements is estimated by the standard deviation.

BIPM	**Relative difference from nominal 1 Ω value / 10^{-6}**					
Standard #	BEFORE	Std dev. u_{1B}	AFTER	Std dev. u_{1A}	INTERPOLATED ON 20-04-2017	Std dev.
B10k08	+ 0.905	0.002	+ 0.918	0.003	+ 0.912	0.003
B10k11	+ 1.066	0.001	+ 1.083	0.003	+ 1.075	0.002

Table 4: Summary of BIPM calibrations of the 10 kΩ standards.

Source of uncertainty	**relative standard uncertainty / 10^{-9}**
Imperfect realization of R_{K-90}	2
Calibration of the BIPM 100 Ω reference (BI100-3) against R_{K-90}	3
Link 100 Ω / 10 000 Ω	5
Link 10 000 Ω / (mean reference B10K1-B10K2)	7
Extrapolation of mean value of 10 kΩ reference	8
Measurement of the voltage applied to the bridge	5
Measurements of the bridge unbalance voltage	5
Leakage resistances	1
Temperature correction for travelling standard	3
Pressure correction for travelling standard	2
Combined uncertainty u_2	**15**

Table 5: BIPM uncertainty budget for the calibration of the 10 kΩ travelling standards.

4 Measurements at the NMISA

4.1 Method of calibration:

The measurements were carried out by comparison with a 1 Ω (S/N 1132427) and 10 kΩ (S/N 4975043) reference resistor respectively, using a commercial direct current comparator resistance bridge (MIL 6010 C) at 50 mA and 100 µA respectively.

All resistors were allowed to stabilize before the measurement. The 1 Ω resistors were installed in a thermostatic oil bath, Guildline model 9732VTon 2017/03/27 and were measured 30 times from 2017/03/27 to 2017/05/17. The measurements were made at a mean temperature of (22.965 ± 0.05) °C and pressure of (869.4 ±5.0) hPa, monitored by a calibrated digital Pt resistance thermometer and barometer.
The BIPM travelling 10 kΩ standards were installed in a temperature-stabilized laboratory on 2017/03/27 and were measured 30 times from 2017/03/27 to 2017/05/17. The measurements were made at a mean temperature of (22.6 ± 0.5) °C in the air bath and pressure of (869.4 ±5.0) hPa monitored by a calibrated digital Pt resistance thermometer and barometer.
The operating current was 50 mA for the 1 Ω standards and 100 µA for the 10 kΩ standards.
The results reported here are the mean values calculated from the bridge readings.

The NMISA 1 Ω and 10 kΩ reference standards are maintained by means of periodic calibrations at the BIPM and other National Metrology Institutes; the last such calibration with the BIPM before this comparison was in February 2015. In between, their values are obtained from a model which includes the effects of temporal drift and temperature. Hence the uncertainty associated with each of the two reference resistors comprises the temperature correction coefficients, uncertainty of the historical data and the uncertainty due to the parameter fitting.
Figure 1 illustrates the drift of the 1 Ω standard. The temporal drift for 1 Ω standard was estimated using previous BIPM three calibrations data and for 10 kΩ using previous BIPM two calibrations data. The 10 kΩ standard was twice calibrated by BIPM, hence the drift analyse graph excluded.

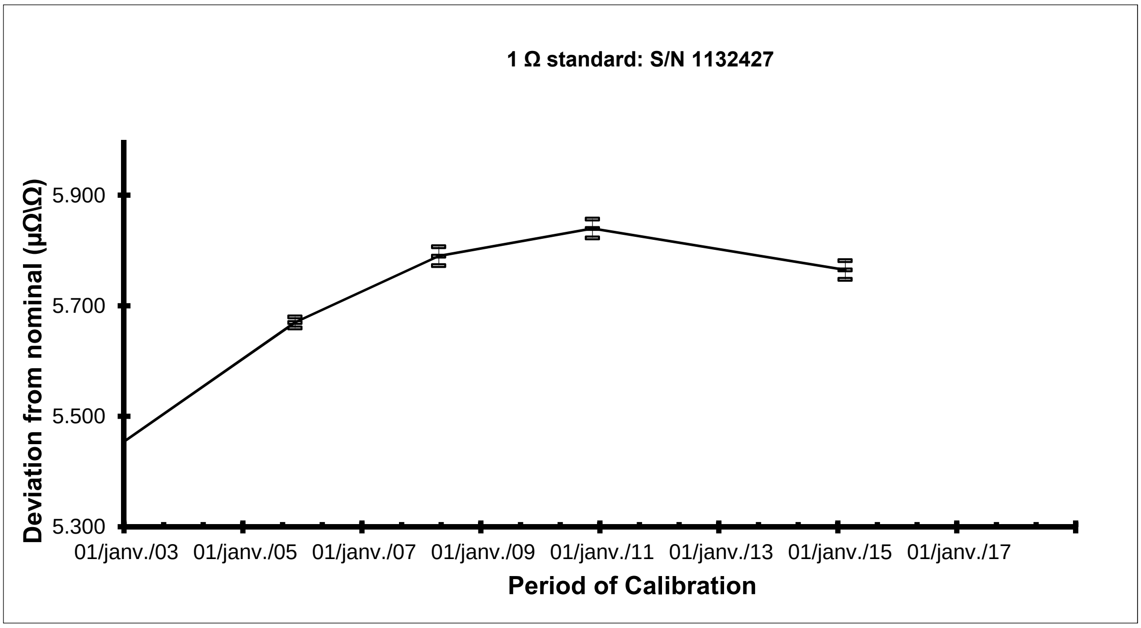

Figure 1: 1 Ω: S/N 1132427 temporal drift

4.2 <u>Operating conditions</u>:

The air pressure and the relative humidity in the laboratory were recorded at the time of each measurement set, using a calibrated manometer (DPI 142, S/N: DPI 1422505057) and a calibrated humidity data logger (Hygrolog-D, S/N: 17131017).

The temperatures of the 1 Ω standard resistors in the oil bath were measured with a single calibrated temperature probe (PT100). The temperatures of the 10 kΩ standard resistors in the temperature-stabilized laboratory were measured with individual calibrated temperature probes (PT100) inserted in the thermometer well.

4.3 NMISA results at 1 Ω:

The 1 Ω travelling standards were measured 30 times in the period March – May 2017. Table 6 gives the mean values at the mean date of 20 April 2017, before application of temperature and pressure corrections. The repeatability is estimated by the standard deviation of the series of measurements.

Standard #	Relative difference from nominal 1 Ω value /10^{-6}	Std dev. /10^{-6}	Mean temperature / °C	Mean atmospheric pressure / hPa
BIV193	− 5.277	0.024	22.965	869.44
BIV203	+ 0.431	0.014	22.965	869.44

Table 6: Summary of NMISA 1 Ω calibrations.

Corrections for temperature and pressure:

The value $R(23)$ of the resistance corrected for T_0 = 23 °C is:

$$R(23) = R(T) \times \left[1 - \alpha_{23}(T - T_0) - \beta(T - T_0)^2\right]$$

where $R(T)$ is the resistance of the standard at temperature T.

The value $R(1013.25)$ of the resistance corrected for P_0 = 1013.25 hPa is:

$$R(1013.25) = R(P) \times \left[1 - \gamma_{1013.25}(P - P_0)\right]$$

where $R(P)$ is the resistance of the standard at pressure P.

The NMISA results are corrected to the reference temperature and the reference pressure using the coefficients α_{23}, β and γ shown in Table 1.

Reference temperature = 23.000°C Reference pressure = 1013.25 hPa		
	Relative corrections /10^{-6}	
Standard #	For temperature	For pressure
BIV193	0.000	− 0.024
BIV203	0.000	− 0.029

Table 7: Corrections applied to the NMISA 1 Ω results.

The uncertainties on temperature and pressure measurements at the NMISA are 0.05 °C and 500 Pa respectively. Taking into account the differences from the reference temperature and reference pressure, and the uncertainties associated with the coefficients, the relative standard uncertainties u_{Temp} and u_{Press} associated with the temperature and pressure corrections applied by the BIPM are estimated to be $u_{\mathrm{Temp}} < 0.001 \times 10^{-6}$ and $u_{\mathrm{Press}} = 0.035 \times 10^{-6}$, leading to a combined relative standard uncertainty $u_3 = 0.035 \times 10^{-6}$.
The pressure coefficient can be assumed to be constant over the range 870 hPa to 1050 hPa [1], but taking into account that the pressure condition at NMISA implies an unusually large correction, the uncertainties of the pressure coefficients for BIV193 and BIV203 were multiplied by a factor of two.

Uncertainty Budget Provided by the NMISA

Input Quantity (Source of uncertainty) (Xi)	Estimated uncertainty	Unit	Probability distribution (N,R,T,U)	k=	Divisor factor	Standard uncertainty U(Xi)	Sensitivity coefficient (Ci)	Standard uncertainty contribution
								μΩ/Ω
Rstd calibration	0.017	μΩ/Ω	Normal	1	1.00	0.0170	1	0.0170
Rstd drift	0.006	μΩ/Ω	Rectangular	1.73	1.73	0.0035	1	0.0035
6010C Bridge accuracy	0.05	μΩ/Ω	Rectangular	1.73	1.73	0.0290	1	0.0290
6010C Bridge resolution	0.001	μΩ/Ω	Rectangular	3.46	3.46	0.0003	1	0.0003
6010C linearity	0.01	μΩ/Ω	Rectangular	1.73	1.73	0.0060	1	0.0060
6010C Ratio error	0.014	μΩ/Ω	Rectangular	1.73	1.73	0.0081	1	0.0081

Combined uncertainty u_2 = 0.035 × 10^{-6}

Table 8: Summary of the NMISA uncertainty budget for 1 Ω.

NMISA After corrections	**Relative difference from nominal value / 10^{-6}**	**Relative standard uncertainties**		
		Repeatability u_1 / 10^{-6}	Systematic u_2 / 10^{-6}	Corrections u_3 / 10^{-6}
BIV193	− 5.301	0.024	0.035	0.035
BIV203	+ 0.402	0.014	0.035	0.035

Table 9: Summary of the NMISA results at 1 Ω, after corrections.

Note: The distinction between 'systematic' and 'repeatability' is made in tables 9 and 13 because our model is that the latter can reasonably be reduced by taking an average across several transfer standards. The former cannot be reduced in this way. (This does not correspond exactly to the more usual division into Type A and Type B components).
For the 'repeatability' component (u_1) in the summary results, we use the standard deviation of the series of measurements, rather than the standard deviation of the mean. This is based on the assumption that the dispersion of measurements repeated over a period of several weeks is due as much to variations in the value of the standard as to the noise of the measurement system.

4.3 <u>NMISA results at 10 kΩ</u>:

The 10 kΩ travelling standards were measured 30 times in the period March – May 2017. Table 10 gives the mean values at the mean date of 20 April 2017, before application of temperature and pressure corrections. The repeatability is estimated by the standard deviation of the mean of the series of measurements.

Standard #	Relative difference from nominal 10 kΩ value /10^{-6}	Std dev. of the mean /10^{-6}	Mean temperature / °C	Mean atmospheric pressure / hPa
B10k08	+ 1.446	0.021	22.60	869.44
B10k11	+ 1.665	0.020	22.64	869.44

Table 10: Summary of NMISA 10 kΩ calibrations.

Corrections for temperature and pressure:

The value $R(23)$ of the resistance corrected for T_0 = 23 °C is:

$$R(23) = R(T) \times \left[1 - \alpha_{23}(T - T_0) - \beta(T - T_0)^2\right]$$

where $R(T)$ is the resistance of the standard at temperature T.

The value $R(1013.25)$ of the resistance corrected for P_0 = 1013.25 hPa is:

$$R(1013.25) = R(P) \times \left[1 - \gamma_{1013.25}(P - P_0)\right]$$

where $R(P)$ is the resistance of the standard at pressure P.

The NMISA results are corrected to the reference temperature and the reference pressure using the coefficients α_{23}, β and γ shown in Table 1.

Reference temperature = 23.000°C Reference pressure = 1013.25 hPa		
	Relative corrections /10^{-6}	
Standard #	For temperature	For pressure
B10k08	+ 0.000	− 0.023
B10k11	− 0.021	− 0.050

Table 11: Corrections applied to the NMISA 10 kΩ results.

The uncertainties on temperature and pressure measurements at the NMISA are 0.5 °C and 500 Pa respectively. Taking into account the differences from the reference temperature and reference pressure, and the uncertainties associated with the coefficients, the relative standard uncertainties u_{Temp} and u_{Press} associated with the temperature and pressure corrections applied by the BIPM are estimated to be $u_{\text{Temp}} = 0.005 \times 10^{-6}$ and $u_{\text{Press}} = 0.035 \times 10^{-6}$, leading to a combined relative standard uncertainty $u_3 = 0.035 \times 10^{-6}$ for B10k08 and, $u_{\text{Temp}} = 0.035 \times 10^{-6}$ and $u_{\text{Press}} = 0.035 \times 10^{-6}$, leading to a combined relative standard uncertainty $u_3 = 0.049 \times 10^{-6}$ for B10k11.

The pressure coefficient can be assumed to be constant over the range 870 hPa to 1050 hPa [1], but taking into account that the pressure condition at NMISA implies an unusually large correction, the uncertainties of the pressure coefficients for B10k08 and B10k11 were multiplied by a factor of two.

Uncertainty Budget Provided by the NMISA

Input Quantity (Source of uncertainty) (Xi)	Estimated uncertainty	Unit	Probability distribution (N,R,T,U)	k=	Divisor factor	Standard uncertainty U(Xi)	Sensitivity coefficient (Ci)	Standard uncertainty contribution
								μΩ/Ω
Rstd calibration	0.018	μΩ/Ω	Normal	1	1.00	0.0180	1	0.0180
Rstd drift	0.5008	μΩ/Ω	Rectangular	1.73	1.73	0.2891	1	0.2891
6010C Bridge accuracy	0.05	μΩ/Ω	Rectangular	1.73	1.73	0.0289	1	0.0289
6010C Bridge resolution	0.001	μΩ/Ω	Rectangular	3.46	3.46	0.0003	1	0.0003
6010C linearity	0.01	μΩ/Ω	Rectangular	1.73	1.73	0.0058	1	0.0058
6010C Ratio error	0.014	μΩ/Ω	Rectangular	1.73	1.73	0.0081	1	0.0081

Combined uncertainty u_2 = 0.291 × 10^{-6}

Table12: Summary of the NMISA uncertainty budget for 10 kΩ.

NMISA After corrections	Relative difference from nominal value / 10^{-6}	Relative standard uncertainties		
		Repeatability u_1 / 10^{-6}	Systematic u_2 / 10^{-6}	Corrections u_3 / 10^{-6}
B10k08	+ 1.423	0.021	0.291	0.035
B10k11	+ 1.594	0.020	0.291	0.049

Table 13: Summary of the NMISA results at 10 kΩ, after corrections.

Note: The distinction between 'systematic' and 'repeatability' is made in tables 9 and 13 because our model is that the latter can reasonably be reduced by taking an average across several transfer standards. The former cannot be reduced in this way. (This does not correspond exactly to the more usual division into Type A and Type B components).

Normally, for the 'repeatability' component (u_1) in the summary results, we use the standard deviation of the series of measurements, rather than the standard deviation of the mean. This is based on the assumption that the dispersion of measurements repeated over a period of several weeks is due as much to variations in the value of the standard as to the noise of the measurement system. In that case, the standard deviation of the mean probably underestimates the uncertainty on the value of the standard at any given point in time. In the case of the NMISA 10 kΩ measurements in this comparison, the bridge noise dominates and it is therefore reasonable to reduce this to the standard deviation of the mean.

5 Comparison NMISA – BIPM

The individual measurement results for each of the four standards are shown in figures 2 to 5 below. The plots also show the mean value of the NMISA measurements with the uncertainty bar corresponding to the expanded uncertainty (k = 2) of the comparison U_c provided below, and a linear fit to the BIPM before and after measurements. We assume that the value of each standard is subject to a simple linear drift during the period of the comparison. Inspection of figures 2 to 5 indicates that this is an appropriate model. Both 1 Ω standards and 10 kΩ standards fit this model well. We treat the 1 Ω and 10 kΩ results as two separate cases.

Within this model, the result of the comparison for a given standard is the difference between the mean of the NMISA measurements and the interpolated value of the linear fit to the BIPM measurements on the mean date of the NMISA measurements.

The difference between the NMISA and the BIPM calibrations of a given standard R_i can be written as:

$$\Delta_i = R_{\mathrm{NMISA},i} - R_{\mathrm{BIPM},i}$$

If two standards are used, the mean of the differences is:

$$\Delta_{\mathrm{NMISA-BIPM}} = \frac{1}{2}\sum_{i=1}^{2}\left(R_{\mathrm{NMISA},i} - R_{\mathrm{BIPM},i}\right)$$

For each standard, the uncertainty u_1 associated with the dispersion for the interpolated BIPM value is calculated from the linear fit; u_2 is the uncertainty arising from the combined contributions associated with the BIPM measurement facility and the traceability, as described in table 3 or 5. This component is assumed to be strongly correlated between calibrations performed in the same period.

For a single standard, the BIPM uncertainty $u_{\mathrm{BIPM},\,i}$ is obtained from: $u^2_{\mathrm{BIPM},\,i} = u^2_{1,\,i} + u^2_{2,\,i}$

When the mean (for two standards) of the NMISA − BIPM relative difference is calculated, the BIPM contribution to the uncertainty is:

$$u^2_{\mathrm{BIPM}} = \sum_{i=1}^{2}\frac{u^2_{1,i}}{2^2} + u^2_2$$

Similarly, for the NMISA measurements, we expect the uncertainty components u_2 and u_3 of tables 9 and 13 to be correlated between standards, and u_1 to be uncorrelated. We therefore calculate the total uncertainty as

$$u^2_{\mathrm{NMISA}} = \sum_{i=1}^{2}\frac{u^2_{1,i}}{2^2} + u^2_2 + u^2_3$$

Uncertainty associated with the transfer

Changes in the values of the standards due to the effects of transport can add an extra uncertainty component to a comparison. In this case, from inspection of the BIPM 'before' and 'after' measurements in figures 2 to 5, we can see that any such effects are negligible compared to the overall uncertainty of the comparison, and for simplicity we do not include any extra uncertainty components.

<u>Results at 1 Ω</u>

The differences between the values assigned by the NMISA, R_{NMISA}, and those assigned by the BIPM, R_{BIPM}, to each of the two travelling standards on the mean date of the NMISA measurements are shown in Table 14.

NMISA − BIPM	
Standard #	$10^6 \times (R_{\text{NMISA}} - R_{\text{BIPM}})$ / (1 Ω)
BIV193	− 0.120
BIV203	− 0.125
mean	**− 0.123**

Table 14: Differences for the two 1 Ω travelling standards.

The mean difference between the NMISA and the BIPM calibrations is:

$$(\boldsymbol{R}_{\text{NMISA}} - \boldsymbol{R}_{\text{BIPM}}) / (1\ \Omega) = -0.123 \times 10^{-6}$$

The relative combined standard uncertainty of the comparison, u_{C}, is:

$$u_c^2 = u_{BIPM}^2 + u_{\text{NMISA}}^2$$

where $u_{\text{BIPM}} = 0.021 \times 10^{-6}$,
$u_{\text{NMISA}} = 0.054 \times 10^{-6}$,

Giving: $\boldsymbol{u}_{\text{C}} = \mathbf{0.06 \times 10^{-6}}$

The final result of the comparison is presented as a degree of equivalence, composed of the deviation, D, between the NMISA and the BIPM for values assigned to 1 Ω resistance standards, and its expanded relative uncertainty (expansion factor $k = 2$, corresponding to a confidence level of 95 %) , U_{C}

$$\boldsymbol{D} = (\boldsymbol{R}_{\text{NIMSA}} - \boldsymbol{R}_{\text{BIPM}}) / 1\ \Omega = -0.123 \times 10^{-6}$$

$$\boldsymbol{U}_{\text{C}} = 0.12 \times 10^{-6}$$

The difference between the NMISA and the BIPM calibration results is 1.02 times larger than the expanded uncertainty.

Results at 10 kΩ

The differences between the values assigned by the NMISA, R_{NMISA}, and those assigned by the BIPM, R_{BIPM}, to each of the two travelling standards on the mean date of the NMISA measurements are shown in Table 15.

NMISA − BIPM	
Standard #	$10^6 \times (R_{\text{NMISA}} - R_{\text{BIPM}})$ / (10 kΩ)
B10k08	+ 0.511
B10k11	+ 0.519
mean	**+ 0.515**

Table 15: Differences for the two 10 kΩ travelling standards.

The mean difference between the NMISA and the BIPM calibrations is:

$$(R_{\text{NMISA}} - R_{\text{BIPM}}) / (10\ \text{k}\Omega) = +0.515 \times 10^{-6}$$

The relative combined standard uncertainty of the comparison, u_{C}, is:

$$u_c^2 = u_{BIPM}^2 + u_{\text{NMISA}}^2$$

where $u_{\text{BIPM}} = 0.015 \times 10^{-6}$,
$u_{\text{NMISA}} = 0.295 \times 10^{-6}$,

Giving: $\boldsymbol{u_{\text{C}} = 0.30 \times 10^{-6}}$

The final result of the comparison is presented as a degree of equivalence, composed of the deviation, D, between the NMISA and the BIPM for values assigned to 10 kΩ resistance standards, and its expanded relative uncertainty (expansion factor $k = 2$, corresponding to a confidence level of 95 %) , U_{C}

$$D = (R_{\text{NMISA}} - R_{\text{BIPM}}) / 10\ \text{k}\Omega = +0.515 \times 10^{-6}$$

$$U_{\text{C}} = 0.60 \times 10^{-6}$$

The difference between the NMISA and the BIPM calibration results is within the expanded uncertainty.

[1]: Jones, G. R., Pritchard, B. J., & Elmquist, R. E. (2009). Characteristics of precision 1 Ω standard resistors influencing transport behaviour and the uncertainty of key comparisons. *Metrologia, 46(5), 503–511. http://doi.org/10.1088/0026-1394/46/5/015*

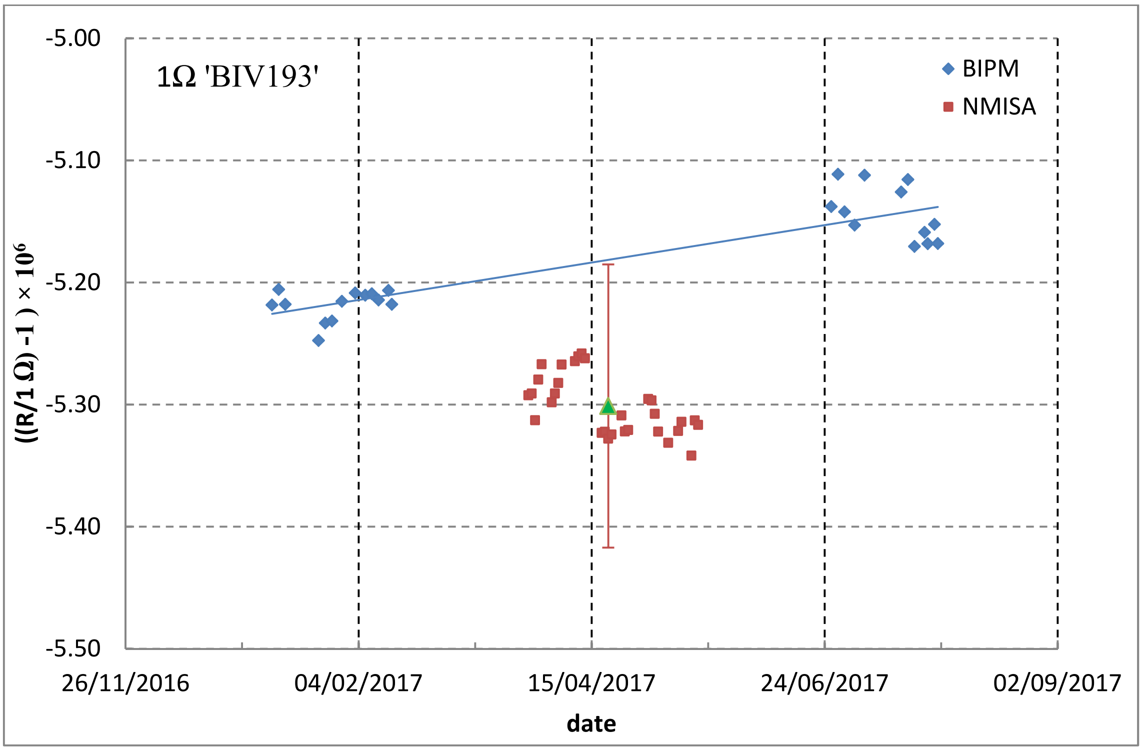

Figure 2: results for 1 Ω standard BIV193; uncertainty bar shows the combined expanded uncertainty (*k* = 2) on the mean NMISA results

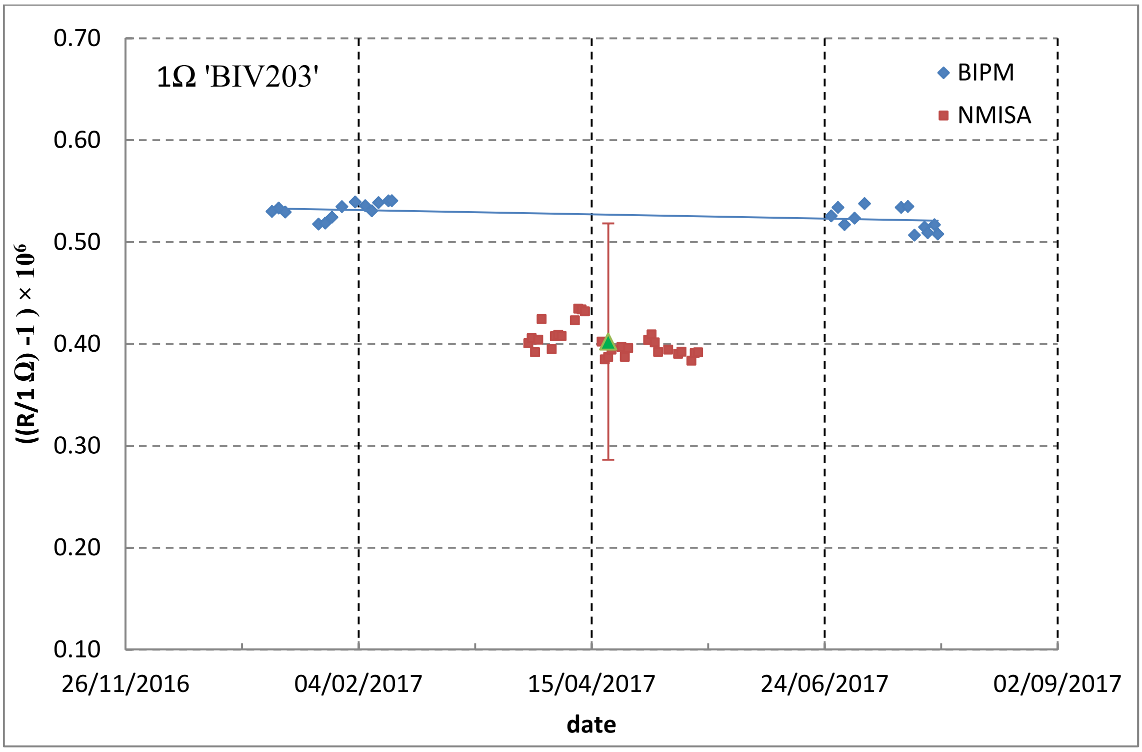

Figure 3: results for 1 Ω standard BIV203

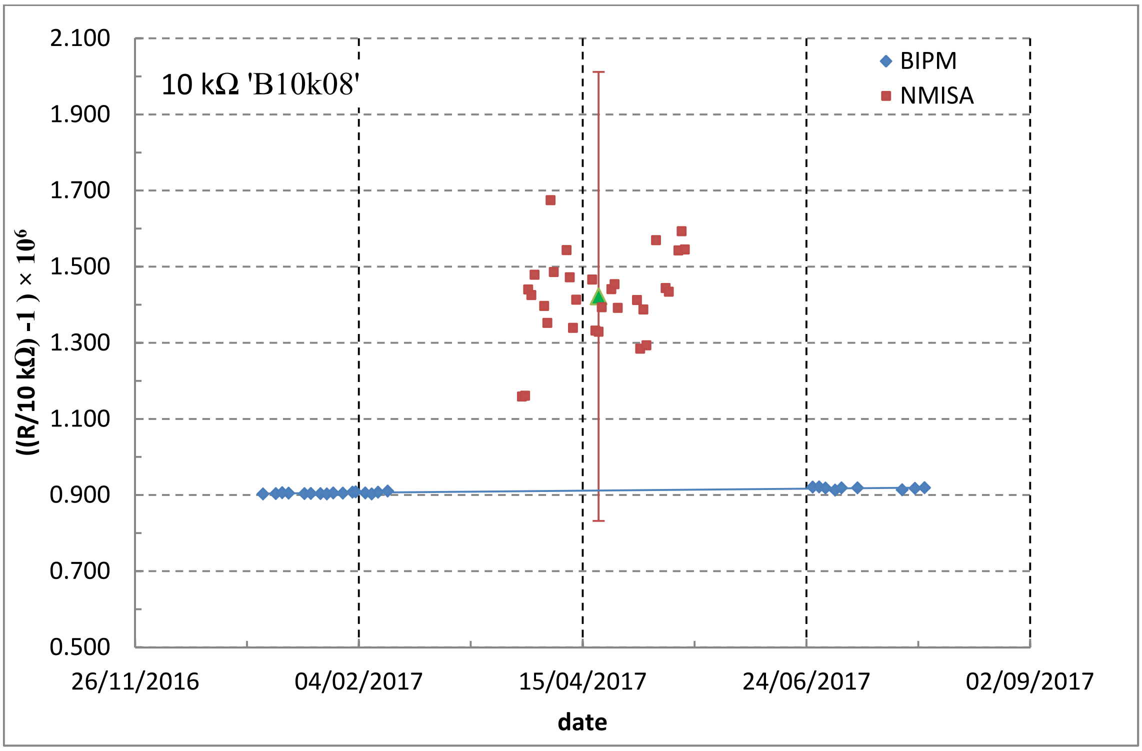

Figure 4: results for 10 kΩ standard B10k08
uncertainty bar shows the combined expanded uncertainty (*k* = 2) on the mean NMISA results

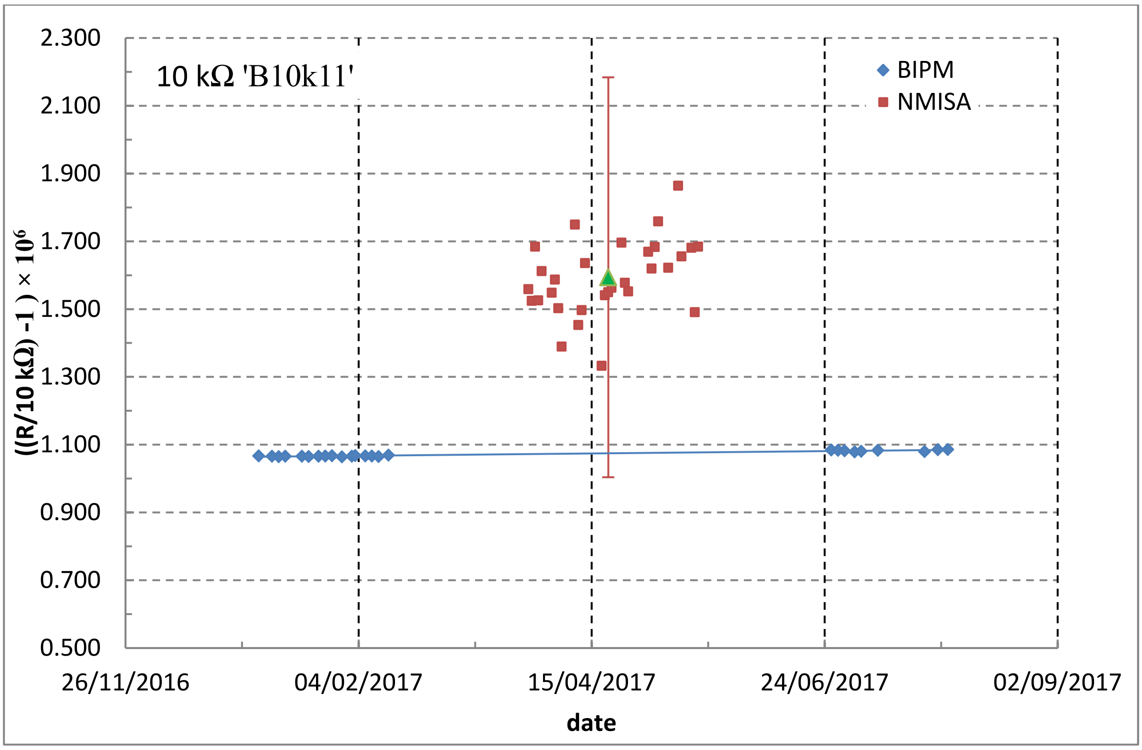

Figure 5: results for 10 kΩ standard B10k11