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 NSAI-NML (Ireland) 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 NSAI-NML (Ireland) in the period January 2018 to May 2018.
Two 1 Ω and two 10 kΩ BIPM travelling standards were calibrated first at the BIPM, then at the NSAI-NML and again at the BIPM after their return. The measurement periods are referred to as:

'Before' measurements at the BIPM: January 2018 – February 2018
NSAI-NML measurements: February 2018 – March 2018
'After' measurements at the BIPM: March 2018 – May 2018

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 NSAI-NML 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 NSAI-NML 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 BIV203 (manufacturer's serial number S-64203) and BIV207 (manufacturer's serial number S-64207). The two 10 kΩ standards are TEGAM S104 type, and have the working labels B10k08 (manufacturer's serial number K201039730104) and B10k09 (serial number K203039730104). 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 NSAI-NML 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)
BIV203	− 0.0096	− 0.0016	− 0.200
BIV207	− 0.0094	− 0.0001	− 0.250
B10k08	− 0.0100	− 0.0230	− 0.162
B10k09	− 0.0400	− 0.0220	− 0.164

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-90} = 25812.807 Ω. (The standard uncertainty associated with the use of R_{K-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 2018 – February 2018) and 14 times during the period labelled 'after' (March 2018 – May 2018).

The individual BIPM measurement data are plotted in figures 1 and 2 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 28-02-2018	Std dev.
BIV203	+ 0.493	0.009	+ 0.495	0.009	+ 0.494	0.009
BIV207	− 0.461	0.008	− 0.497	0.007	− 0.478	0.008

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

Source of uncertainty	**relative standard uncertainty /10^{-9}**
Imperfect realisation of R_{K-90}	2
Calibration of the BIPM 100 Ω reference (BI100-3) against R_{K-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 12 times during the period labelled 'before' (January 2018 – February 2018) and 13 times during the period labelled 'after' (March 2018 – May 2018).
The individual BIPM measurement data are plotted in figures 3 and 4 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 10 kΩ value / 10^{-6}**					
Standard #	BEFORE	Std dev. u_{1B}	AFTER	Std dev. u_{1A}	INTERPOLATED ON 01-03-2018	Std dev.
B10k08	+ 0.935	0.002	+ 0.952	0.001	+ 0.943	0.002
B10k09	− 0.144	0.001	− 0.052	0.005	− 0.102	0.005

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

Source of uncertainty	**relative standard uncertainty / 10^{-9}**
Imperfect realization of $R_{K\text{-}90}$	2
Calibration of the BIPM 100 Ω reference (BI100-3) against $R_{K\text{-}90}$	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 NSAI-NML

4.1 Method of calibration:

The resistance of each travelling standard was measured by comparison with the NSAI-NML 1 Ω reference standard, comprised of a group of seven 1 Ω standard resistors, maintained in a temperature controlled oil bath at 20 °C. The value assigned to each resistor of the group is obtained from a secular drift model which, in turn, is based on the results of previous comparisons with the BIPM, obtained over a fifteen year period.
The comparison of the travelling standards (R_x) with the reference group was carried out using a direct current comparator resistance bridge (MIL Model 6010C).
Two measurements procedures were used.
In the first measurement procedure a substitution method was used. The ratios of the BIPM standards and each NML standard were measured in turn against a buffer 1 Ω resistor. In this way the ratio of each BIPM standard to each NML standard was evaluated.
In the second measurement procedure, the ratio of each BIPM standard was measured directly against each NML standard. For each ratio measurement the resistors were interchanged to correct for the bridge ratio error.

The 10 kΩ measurements were performed using a MIL 6000B bridge which operates on the binary divider principle. Actually, a substitution measurement technique was used against the 10 kΩ reference standard maintained at NSAI-NML; the value of this standard is also maintained with reference to R_{K-90} by periodic comparisons with the BIPM and by extrapolation of the behaviour over time.

4.2 Operating conditions:

Upon receipt the 1 Ω standards were placed in a stirred temperature controlled oil bath (Fluke 5140) at a nominal temperature of 23 °C. The terminals of the BIPM standards were approximately 150 mm below the surface of the oil (oil density 850 kg.m-3).The oil temperature was monitored using a standard Platinum resistance thermometer. The measured oil temperature did not vary by more than ±2 mK during the entire period of the resistance measurements.
The BIPM resistors were connected to the measuring system via a low thermal matrix scanner (MIL Model 4220). A test current of 50 mA and a current reversal time of 32 seconds was used for all measurements.

Upon receipt the 10 kΩ standards were placed in a temperature controlled air bath (Kambic TK-190) at a nominal temperature of 23 °C. The air bath temperature varied by less than ±0.05 K during the entire period of the resistance measurements. The temperature, pressure and humidity were reported for each measurement. The measurement current was 0.5 mA.

4.3 NSAI-NML results at 1 Ω:

The 1 Ω travelling standards were measured 23 times in the period February – March 2018. Table 6 gives the mean values at the mean date of 28 February 2018, 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
BIV203	+ 0.502	0.023	23.00	1002.7
BIV207	− 0.434	0.018	23.00	1002.7

Table 6: Summary of NSAI-NML 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 relative pressure height correction in the oil bath is estimated to be **+12 hPa** on the mean atmospheric pressure.

The NSAI-NML 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
BIV203	+ 0.000	+ 0.000
BIV207	+ 0.000	+ 0.000

Table 7: Corrections applied to the NSAI-NML 1 Ω results.

The uncertainties on temperature and pressure measurements at the NSAI-NML are 0.01 °C and 2 hPa 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 $u_{\mathrm{Press}} = 0.001 \times 10^{-6}$, leading to a combined relative standard uncertainty $u_3 = 0.001 \times 10^{-6}$.

Uncertainty Budget Provided by the NSAI-NML:

Measurement Model:
Note: The following is a simplified model of the measurement.
In practice, a least squares reduction of the data is used to calculate the best estimate of the unknown resistor.
The simplified model is sufficient for the purposes of uncertainty evaluation.

$R\mathrm{x} = R_s \times r_x + d_X + d_{Rev}$
where R_x is the value of the unknown resistance
R_s is the value assigned to the weighted mean of the NML 1ohm group reference standard (seven resistors)
r_x is the measured ratio of R_x to R_s
d_X is a correction, with nominal value zero, which represents the non-repeatability of the measurement
d_{Rev} is a correction, with nominal value zero, which represents the effect of the stabilisation time.

Uncertainty budget:

Quantity	**Value**	**Standard Uncertainty**	**Sensitivity coefficient**	**Uncertainty Contribution / µΩ**
R_s	1 Ω	0.070 µΩ	1	0.07
r_x	1	0.00000003	1 Ω	0.030
d_X	0 Ω	0.02 µΩ	1	0.02
d_{Rev}	0 Ω	0.02 µΩ	1	0.02
Rx				**0.081**

Combined relative uncertainty u_2 = 0.081 × 10^{-6}

Table 8: Summary of the NSAI-NML uncertainty budget for 1 Ω.

NSAI-NML 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}
BIV203	+ 0.502	0.023	0.081	0.001
BIV207	− 0.434	0.018	0.081	0.001

Table 9: Summary of the NSAI-NML 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).

4.3 <u>NSAI-NML results at 10 kΩ</u>:

The 10 kΩ travelling standards were measured 23 times in the period February – March 2018. Table 10 gives the mean values at the mean date of 1 March 2018, 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 10 kΩ value /10^{-6}**	**Std dev. /10^{-6}**	**Mean temperature / °C**	**Mean atmospheric pressure / hPa**
B10k08	+ 1.005	0.017	22.99	1003.7
B10k09	− 0.026	0.034	22.95	1003.7

Table 10: Summary of NSAI-NML 10 kΩ calibrations.

Corrections for temperature and pressure:

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

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

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:

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

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

The NSAI-NML 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	− 0.002
B10k09	− 0.002	− 0.002

Table 11: Corrections applied to the NSAI-NML 10 kΩ results.

The uncertainties on temperature and pressure measurements at the NSAI-NML are 0.025 °C and 2 hPa 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 $u_{\text{Temp}} = 0.001 \times 10^{-6}$ and $u_{\text{Press}} = 0.001 \times 10^{-6}$, leading to a combined relative standard uncertainty $u_3 = 0.001 \times 10^{-6}$.

Uncertainty Budget Provided by NSAI-NML

Measurement Model:

$R_x = R_{10k} \times r_x + dR_T + dR_L$

R_{10k} is the value assigned to the NSAI-NML 10kohm reference standard

r_x is the measured ratio of R_x to R_s

dR_T is the correction to R_x due to temperature

dR_L is the correction to R_x due to leakage effects

Uncertainty budget:

Quantity	**Value**	**Standard Uncertainty**	**Sensitivity Coefficient**	**Uncertainty contribution / mΩ**
R_{10k}	10 kΩ	1.4 mΩ	1	1.4
r_X	0.99999968	0.00000014	10 kΩ	1.4
dR_T	0 Ω	0.1 mΩ	1	0.1
dR_L	0 Ω	0.7 mΩ	1	0.7
$\boldsymbol{R_x}$	**10000.0077 Ω**			**2.1**

Combined relative uncertainty $u2$ = 0.210 × 10^{-6}

Table12: Summary of the NSAI-NML uncertainty budget for 10 kΩ.

NSAI-NML 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	+ 1.003	0.017	0.210	0.001
B10k09	− 0.030	0.034	0.210	0.001

Table 13: Summary of the NSAI-NML 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).

5 Comparison NSAI-NML – BIPM

The individual measurement results for each of the four standards are shown in figures 1 to 4 below. The plots also show the mean value of the NSAI-NML 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 1 to 4 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 NSAI-NML measurements and the interpolated value of the linear fit to the BIPM measurements on the mean date of the NSAI-NML measurements.

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

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

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

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

For each standard, the uncertainty u_1 associated with 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 NSAI-NML − 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 NSAI-NML 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

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

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 1 to 4, 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.

Results at 1 Ω

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

NSAI-NML − BIPM	
Standard #	$10^6 \times (R_{\text{NSAI-NML}} - R_{\text{BIPM}})$ / (1 Ω)
BIV203	+ 0.008
BIV207	+ 0.044
mean	+ **0.026**

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

The mean difference between the NSAI-NML and the BIPM calibrations is:

$$\boldsymbol{(R_{\text{NSAI-NML}} - R_{\text{BIPM}}) / (1\ \Omega) = +\ 0.026 \times 10^{-6}}$$

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

$$u_c^2 = u_{BIPM}^2 + u_{\text{NSAI-NML}}^2$$

where $u_{\text{BIPM}} = 0.018 \times 10^{-6}$,
$u_{\text{NSAI-NML}} = 0.084 \times 10^{-6}$,

Giving: $\boldsymbol{u_{\text{C}} = 0.086 \times 10^{-6}}$

The final result of the comparison is presented as a degree of equivalence, composed of the deviation, D, between the NSAI-NML 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}

$$\boldsymbol{D = (R_{\text{NSAI-NML}} - R_{\text{BIPM}}) / 1\ \Omega = +\ 0.026 \times 10^{-6}}$$

$$\boldsymbol{U_{\text{C}} = 0.17 \times 10^{-6}}$$

The difference between the NSAI-NML and the BIPM calibration results is within the expanded uncertainty.

Results at 10 kΩ

The differences between the values assigned by the NSAI-NML, $R_{\mathrm{NSAI\text{-}NML}}$, and those assigned by the BIPM, R_{BIPM}, to each of the two travelling standards on the mean date of the NSAI-NML measurements are shown in Table 15.

NSAI-NML − BIPM	
Standard #	$10^6 \times (R_{\mathrm{NSAI\text{-}NML}} - R_{\mathrm{BIPM}})$ / (10 kΩ)
B10k08	+ 0.060
B10k09	+ 0.072
mean	**+ 0.066**

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

The mean difference between the NSAI-NML and the BIPM calibrations is:

$$(R_{\mathrm{NSAI\text{-}NML}} - R_{\mathrm{BIPM}}) / (10\ \mathrm{k\Omega}) = +\,0.066 \times 10^{-6}$$

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

$$u_c^2 = u_{BIPM}^2 + u_{\mathrm{NSAI-NML}}^2$$

where $u_{\mathrm{BIPM}} = 0.016 \times 10^{-6}$,
$u_{\mathrm{NSAI\text{-}NML}} = 0.213 \times 10^{-6}$,

Giving: $\boldsymbol{u_{\mathrm{C}} = 0.214 \times 10^{-6}}$

The final result of the comparison is presented as a degree of equivalence, composed of the deviation, D, between the NSAI-NML 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}

$$D = (R_{\mathrm{NSAI\text{-}NML}} - R_{\mathrm{BIPM}}) / 10\ \mathrm{k\Omega} = +\,0.066 \times 10^{-6} \quad \dagger$$

$$U_{\mathrm{C}} = 0.43 \times 10^{-6}$$

The difference between the NSAI-NML and the BIPM calibration results is within the expanded uncertainty.

† *Misprinted value, corrected on 26th November 2018*

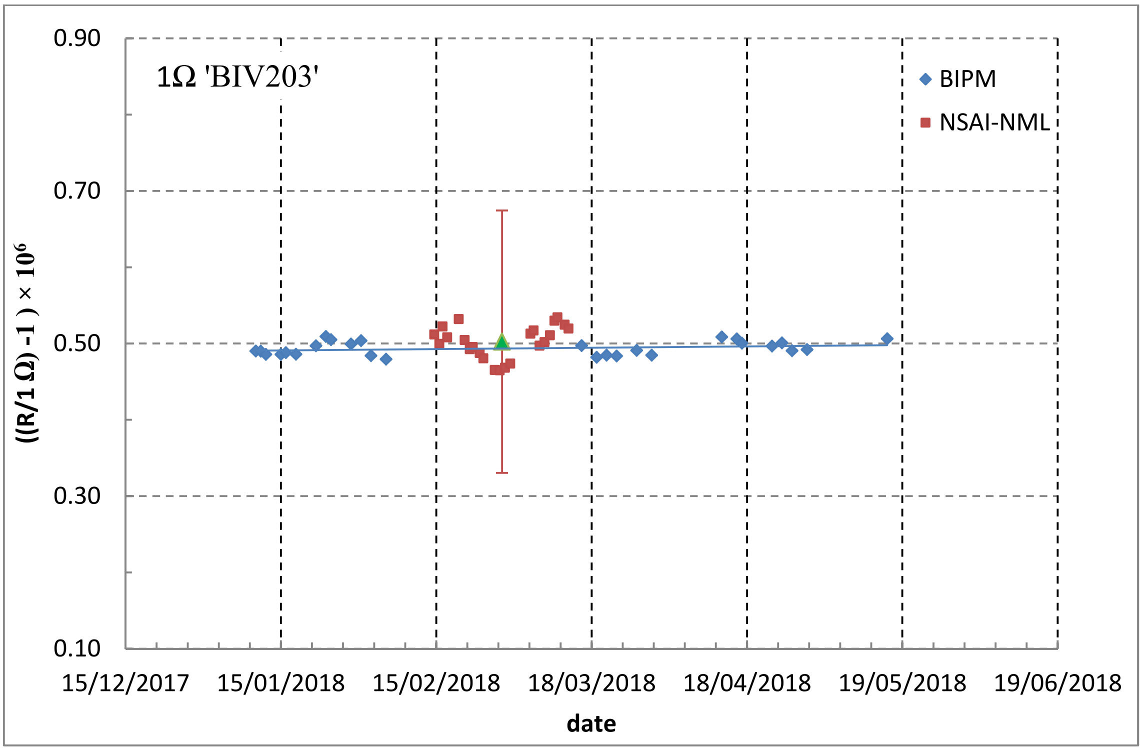

Figure 1: results for 1 Ω standard BIV203;
uncertainty bar shows the combined expanded uncertainty on the mean NSAI-NML results

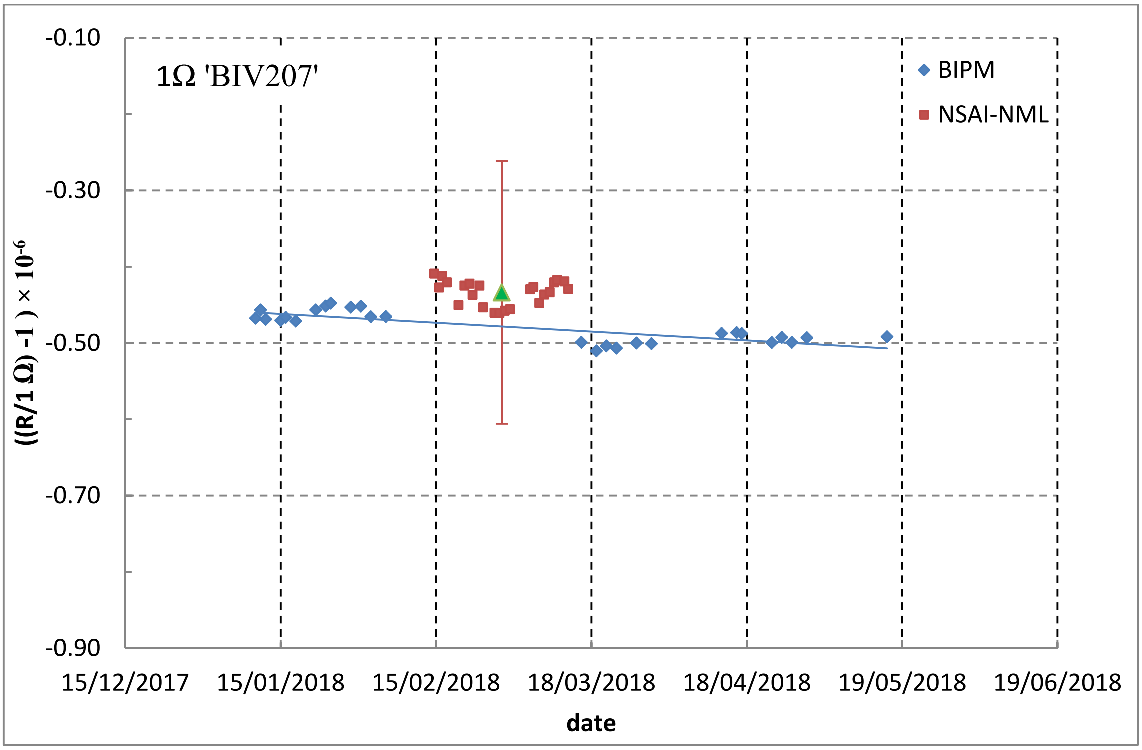

Figure 2: results for 1 Ω standard BIV207

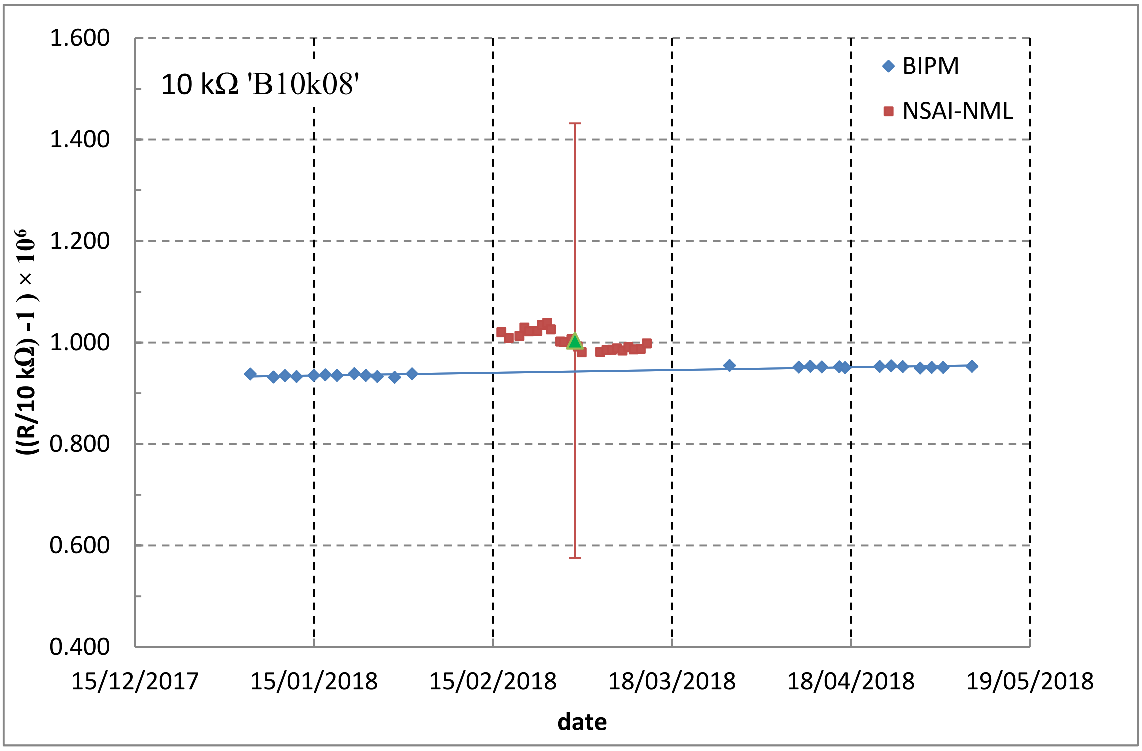

Figure 3: results for 10 kΩ standard B10k08
uncertainty bar shows the combined expanded uncertainty on the mean NSAI-NML results

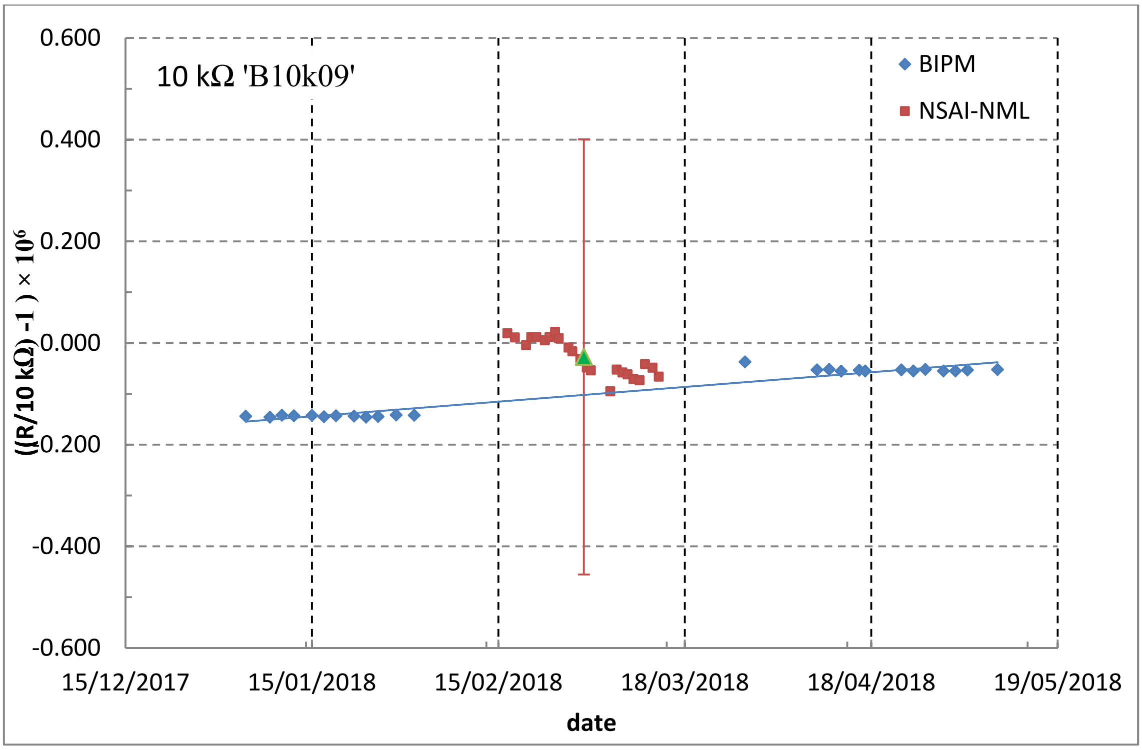

Figure 4: results for 10 kΩ standard B10k09