# 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 NIMT (Thailand) and the BIPM

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## Final Report

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## 1 Introduction

A comparison of values assigned to1 Ω and 10 kΩ resistance standards was carried out between the BIPM and the NIMT (Thailand) in the period January to August 2015.
Two 1 Ω and two 10 kΩ BIPM travelling standards were calibrated first at the BIPM, then at the NIMT and again at the BIPM after their return. The measurement periods are referred to as:

'Before' measurements at the BIPM: January - February 2015
NIMT measurements: April - June 2015
'After' measurements at the BIPM: July - August 2015

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 NIMT 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 NIMT 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 S64193) and BIV200 (manufacturer’s serial number S64200). The two 10 kΩ standards are TEGAM S104 type, and have the working labels B10k09 (manufacturer’s serial number K203039730104) 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 NIMT 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 #** | $\alpha_{23}$ / ($10^{-6}$/K) | $\beta$ / ($10^{-6}$/K²) | γ / ($10^{-9}$/hPa) |
| BIV193 | − 0.004 | − 0.001 | − 0.17 |
| BIV200 | − 0.007 | + 0.000 | − 0.10 |
| B10k09 | − 0.040 | − 0.022 | − 0.16 |
| B10k11 | − 0.070 | − 0.027 | − 0.35 |

**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 $1\times10^{-7}$, 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 14 times during the period labelled 'before' (January - February 2015) and 8 times during the period labelled 'after' (August 2015).
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. $u_{1A}$ |
| **BIV193** | − 5.206 | 0.010 | − 5.146 | 0.013 |
| **BIV200** | − 0.776 | 0.006 | − 0.666 | 0.018 |

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

| **Source of uncertainty** | **relative standard uncertainty /$10^{-9}$** |
|---|---|
| Imperfect realisation of $R_H$ | 2 |
| Calibration of the BIPM 100 Ω reference (BI100-3) against $R_H$ | 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 two10 kΩ reference resistors (identifiersB10K1 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 10kΩtravelling 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 - February 2015) and 10 times during the period labelled 'after' (July - August 2015)
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. $u_{1A}$ |
| **B10k09** | −0.101 | 0.028 | −0.188 | 0.007 |
| **B10k11** | + 0.963 | 0.013 | + 1.003 | 0.011 |

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

| **Source of uncertainty** | **relative standard uncertainty / $10^{-9}$** |
|---|---|
| Imperfect realization of $R_H(2)$ | 2 |
| Link $R_H(2)$ / 100 Ω | 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 |
| Leakage resistances | 5 |
| 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 NIMT

### 4.1 Method of calibration:

The resistance values of the group of 1 Ω standards and the group 10 kΩ standards in the National Institute of Metrology Thailand (NIMT) are traceable to reference resistors calibrated at the BIPM. The last such calibration previous to this comparison was in January 2013.
The BIPM travelling standards in this comparison were compared with NIMT reference group of 1 Ω Standard and 10 kΩ standards which are maintained by the Resistance Laboratory in NIMT. The measurement calibrations were performed by using a Direct Current Comparator (DCC) Bridge system. Twenty measurements were made on each standard over a period of 6 weeks, which were used to determine the average value for the NIMT measurement results.

### 4.2 Operating conditions:

The two 1 Ω BIPM resistance standards were measured in a mineral oil bath. The NIMT reference group standards were also controlled at 23.00°C in an oil bath. The temperature of the mineral oil bath was measured with a calibrated SPRT.
The operating conditions for 1 Ω travelling resistors were 50 mA measurement current and average 1011.12 hPa atmospheric pressure.
The air type 10 kΩ BIPM standards were kept in 23.0°C controlled room temperature. The room temperature was measure by RH520 humidity and temperature recorder.
The operating conditions for 10 kΩ travelling resistors were 100 µA measurement current and average 50 % relative humidity and 1011.12 hPa atmospheric pressure.

### 4.3 <u>NIMT results at 1 Ω</u>:

The 1 Ω travelling standards were measured 20 times in the period April– June 2015.Table 6 gives the mean values at the mean date of 18May 2015, 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** | −5.246 | 0.021 | 23.005 | 1011.12 |
| **BIV200** | −0.784 | 0.020 | 23.005 | 1011.12 |

**Table 6: Summary of NIMT1 Ω calibrations.**

## Corrections for temperature and pressure:

| Reference temperature = 23.000°C<br>Reference pressure = 1013.25 hPa | | |
|---|---|---|
| | Relative corrections /10$^{-6}$ | |
| Standard # | For temperature | For pressure |
| BIV193 | 0.000 | 0.000 |
| BIV200 | 0.000 | 0.000 |

**Table 7: Corrections applied to the NIMT 1 Ω results.**

The uncertainties on temperature and pressure measurements at the NIMT are 0.02 °C and 0.03 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 $u_{\text{Temp}}$ and $u_{\text{Press}}$ 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 the NIMT**

| Description | Quantity | Estimate | Rel. Std Uncert. /$10^{-6}$ | Prob. distr. | Eff. Deg. Freed. | Sens. Coeff. | Relative uncertainty Contribution / $10^{-6}$ |
|---|---|---|---|---|---|---|---|
| Measured resistance ratio | $K$ | 1 | 0.0207 | Norm | 9 | 1 | -* |
| Value of reference standard | $R_s$ | 1 Ω | 0.0085 | Nom | ∞ | 1 | 0.0085 |
| Drift of reference standard | $\delta R_{sd}$ | 0 | 0.06 | Rect | ∞ | 1 | 0.06 |
| Bridge ratio error | $\delta_{Ratio}$ | 0 | 0.06 | Rect | ∞ | 1 | 0.06 |
| Error due to scanner | $\delta_{sc}$ | 0 | 0.02 | Rect | ∞ | 1 | 0.02 |
| Temperature correction of reference | $\delta_{Rst}$ | 0 | 0.03 | Rect | ∞ | 1 | 0.03 |
| **Combined uncertainty ,$u_2$** | | | | | ∞ | | **0.093** |

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

*Note the type A uncertainty is not counted here as it is included separately as $u_1$ in the comparison analysis.

| **NIMT 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** | − 5.246 | 0.02 | 0.093 | 0.000 |
| **BIV200** | − 0.784 | 0.02 | 0.093 | 0.000 |

**Table 9: Summary of the NIMT 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 NIMTresults at 10 kΩ:

The 10 kΩ travelling standards were measured 20 times in the period April – June 2015. Table 10 gives the mean values at the mean date of 18 May 2015, 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 |
|---|---|---|---|---|
| **B10k09** | − 0.37 | 0.24 | 22.96 | 1011.12 |
| **B10k11** | + 0.59 | 0.25 | 22.96 | 1011.12 |

**Table 10: Summary of NIMT10 kΩ calibrations.**

## Corrections for temperature and pressure:

| Reference temperature = 23.000°C<br>Reference pressure = 1013.25 hPa | | |
|---|---|---|
| | Relative corrections /$10^{-6}$ | |
| Standard # | For temperature | For pressure |
| B10kxx | −0.002 | 0.000 |
| B10kxx | −0.003 | 0.000 |

**Table 11: Corrections applied to the NIMT10 kΩ results.**

The uncertainties on temperature and pressure measurements at the NIMT are 0.5 °C and 0.03 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 $u_{\mathrm{Temp}}$ and $u_{\mathrm{Press}}$ associated with the temperature and pressure corrections applied by the BIPM are estimated to be $u_{\mathrm{Temp}} = 0.03 \times 10^{-6}$ and $u_{\mathrm{Press}} < 0.001 \times 10^{-6}$, leading to a combined relative standard uncertainty $u_3 = 0.03 \times 10^{-6}$.

**Uncertainty Budget Provided by NIMT**

| Description | Quantity | Estimate | Rel. Std Uncert. /$10^{-6}$ | Prob. distr. | Eff. Deg. Freed. | Sens. Coeff. | Relative uncertainty Contribution / $10^{-6}$ |
|---|---|---|---|---|---|---|---|
| Measured resistance ratio | $K$ | 1 | 0.25 | Norm | 9 | 1 | - * |
| Value of reference standard | $R_s$ | 10 kΩ | 0.009 | Nom | ∞ | 1 | 0.009 |
| Drift of reference standard | $\delta R_{sd}$ | 0 | 0.30 | Rect | ∞ | 1 | 0.30 |
| Bridge ratio error | $\delta_{Ratio}$ | 0 | 0.10 | Rect | ∞ | 1 | 0.10 |
| Error due to scanner | $\delta_{sc}$ | 0 | 0.02 | Rect | ∞ | 1 | 0.02 |
| Temperature correction of reference | $\delta_{Rst}$ | 0 | 0.03 | Rect | ∞ | 1 | 0.03 |
| **Combined uncertainty ,$u_2$** | | | | | ∞ | | **0.32** |

**Table12: Summary of the NIMT uncertainty budget for 10 kΩ.**

*Note the type A uncertainty is not counted here as it is included separately as $u_1$ in the comparison analysis.

| NIMT After corrections | Relative difference from nominal value / $10^{-6}$ | Relative standard uncertainties | | |
|---|---|---|---|---|
| | | Repeatability $u_1$ / $10^{-6}$ | Systematic $u_2$ / $10^{-6}$ | Corrections $u_3$ / $10^{-6}$ |
| **B10k09** | − 0.37 | 0.25 | 0.32 | 0.03 |
| **B10k11** | + 0.59 | 0.25 | 0.32 | 0.03 |

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

## 5 Comparison NIMT– BIPM

The individual measurements results for each of the four standards are shown in figures 1 to 4 below. The plots also show the mean value of the NIMT measurements with an uncertainty bar corresponding to the combined standard uncertainty provided in tables 8 and 12, 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 the 1 Ω and 10 kΩ standards and the fit this model well. Any non-linear drift or non-ideal transport effects are not significant relative to the NIMT uncertainty. 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 NIMT measurements and the interpolated value of the linear fit to the BIPM measurements on the mean date of the NIMT measurements.

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

$$\Delta_i = R_{NIMT,i} - R_{BIPM,i}$$

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

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

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 NIMT-BIPM relative difference is calculated, the BIPM contribution to the uncertainty is:

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

Similarly, for the NIMTmeasurements, 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

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

**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 bythe NIMT, $R_{\mathrm{NIMT}}$, and those assigned by the BIPM, $R_{\mathrm{BIPM}}$, to each of the two travelling standards on the mean date of the NIMT measurements are shown in Table 14.

| NIMT- BIPM | |
|---|---|
| Standard # | $10^6 \times (R_{\mathrm{NIMT}} - R_{\mathrm{BIPM}}) / (1\ \Omega)$ |
| BIV193 | − 0.073 |
| BIV200 | −0.069 |
| **mean** | **−0.071** |

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

The mean difference between the NIMTand the BIPM calibrations is:

$$(\boldsymbol{R}_{\mathbf{NIMT}} - \boldsymbol{R}_{\mathbf{BIPM}}) / (1\ \Omega) = -0.07 \times 10^{-6}$$

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

$$u_c^2 = u_{BIPM}^2 + u_{\mathrm{NIMT}}^2$$

where $u_{\mathrm{BIPM}} = 0.017 \times 10^{-6}$,
$u_{\mathrm{NIMT}} = 0.094 \times 10^{-6}$,

Giving: $\boldsymbol{u}_{\mathbf{C}} = \mathbf{0.10 \times 10^{-6}}$

The final result of the comparison is presented as a degree of equivalence, composed of the deviation, $D$, between the NIMT 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 %), $U_{\mathrm{C}}$

$$\boldsymbol{D} = (\boldsymbol{R}_{\mathbf{NIMT}} - \boldsymbol{R}_{\mathbf{BIPM}}) / 1\ \Omega = -0.07 \times 10^{-6}$$

$$\boldsymbol{U}_{\mathbf{C}} = 0.20 \times 10^{-6}$$

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

**Results at 10 kΩ**

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

| **NIMT- BIPM** | |
|---|---|
| Standard # | $10^6 \times (R_{\text{NIMT}} - R_{\text{BIPM}}) / (10\ \text{k}\Omega)$ |
| B10k09 | − 0.22 |
| B10k11 | − 0.39 |
| **mean** | **−0.31** |

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

The mean difference between the NIMTand the BIPM calibrations is:

$$(R_{\text{NIMT}} - R_{\text{BIPM}}) / (10\ \text{k}\Omega) = -0.31 \times 10^{-6}$$

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

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

where $u_{\text{BIPM}} = 0.021 \times 10^{-6}$,
$u_{\text{NIMT}} = 0.37 \times 10^{-6}$,

Giving: $\boldsymbol{u_{\text{C}} = 0.37 \times 10^{-6}}$

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

$$D = (R_{\text{NIMT}} - R_{\text{BIPM}}) / 10\ \text{k}\Omega = -0.31 \times 10^{-6}$$

$$U_{\text{C}} = 0.74 \times 10^{-6}$$

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

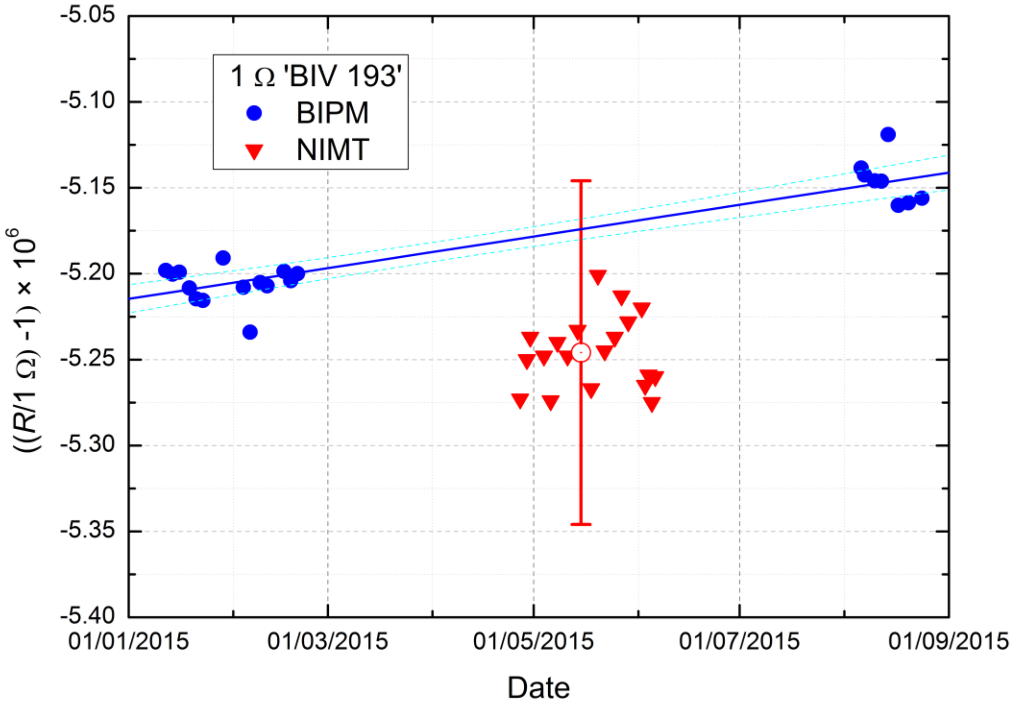


**Figure 1: results for 1 Ω standard BIV193;**
**uncertainty bar shows the combined standard uncertainty on the mean NIMTresults**

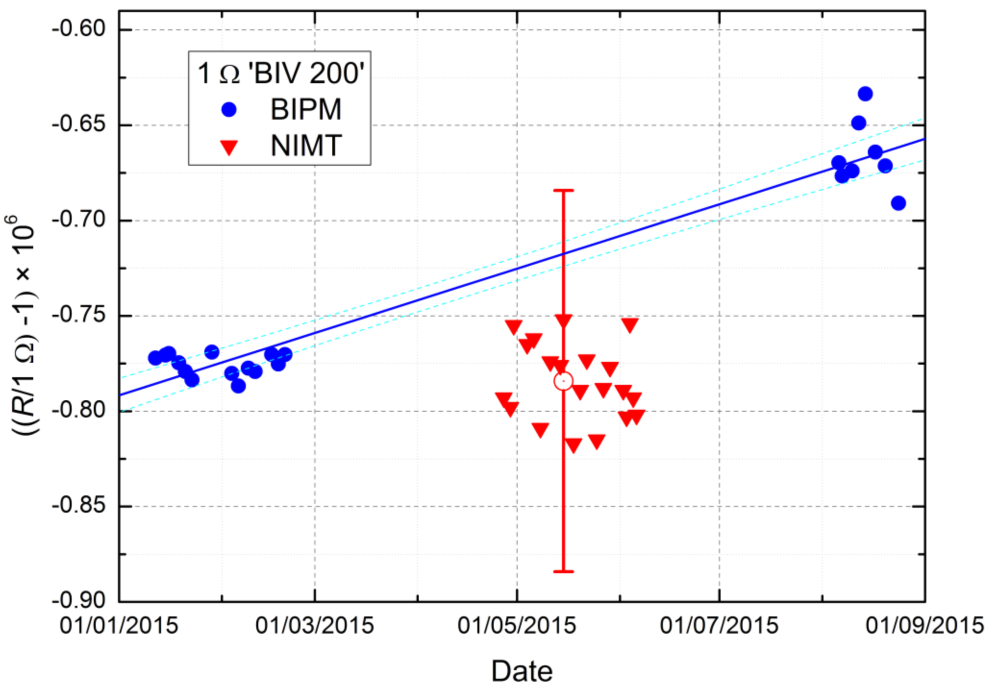


**Figure 2: results for 1 Ω standard BIV200**

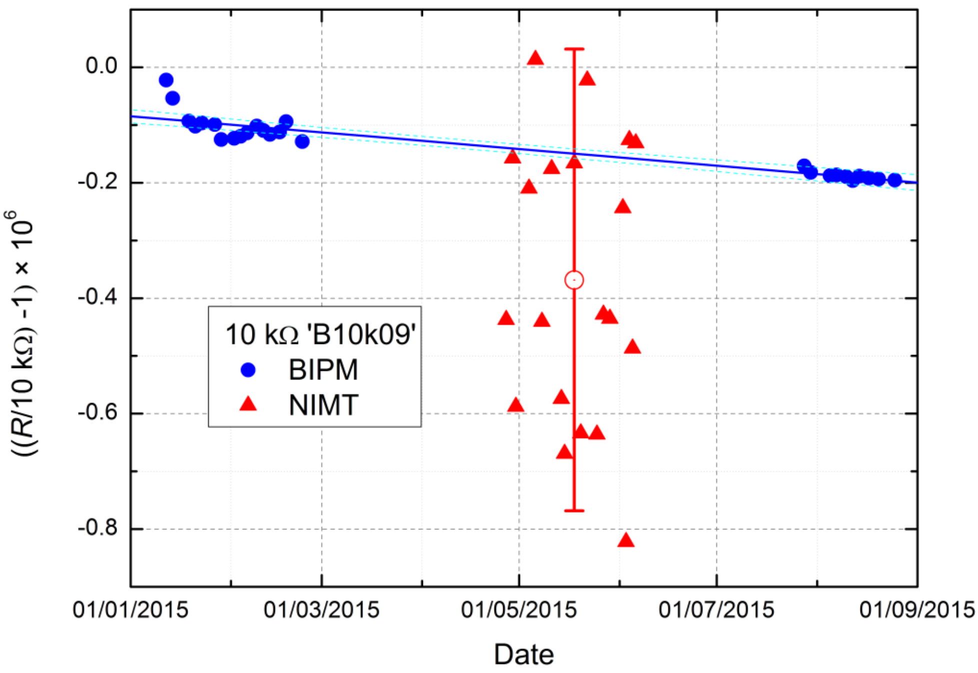


**Figure 3: results for 10 kΩstandard B10k09**
**uncertainty bar shows the combined standard uncertainty on the mean NIMTresults**

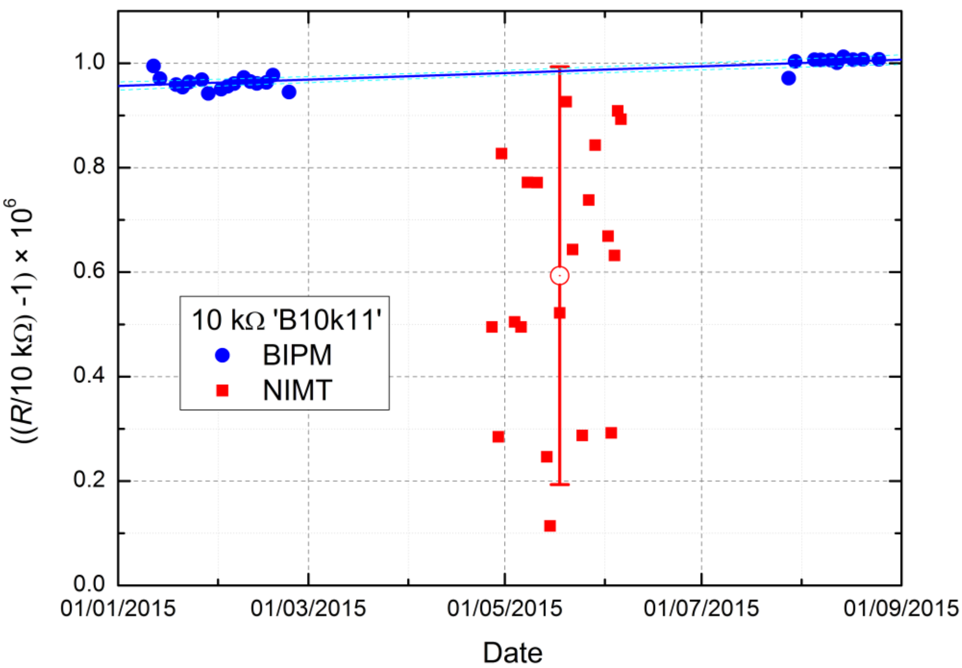


**Figure 4: results for 10 kΩ standard B10k11**