BUREAU INTERNATIONAL
DES POIDS ET MESURES

ON-SITE COMPARISON OF QUANTUM HALL EFFECT RESISTANCE STANDARDS OF METAS AND THE BIPM

ONGOING KEY COMPARISON BIPM.EM-K12

Report on the December 2017 on-site comparison

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1. Introduction

The ongoing on-site comparison BIPM.EM-K12 is part of the BIPM programme implemented to verify the international coherence of the primary resistance standards. It allows National Metrology Institutes (NMIs) to validate their implementations of the Quantum Hall Effect (QHE) for dc resistance traceability by comparison to the reference maintained at the BIPM.

In this comparison, the realization of the ohm from the QHE-based standard of the NMIs at 100 Ω is compared with that realized by the BIPM from its own transportable quantum Hall resistance (QHR) standard. This comparison is normally completed by scaling measurements from 100 Ω to 1 Ω and 10 kΩ.

The comparison programme BIPM.EM-K12 started in 1993. A first series of five comparisons were carried out from this date until 1999. After a suspension period, the comparison was resumed in 2013. Since then two comparisons has been successfully completed whose results may be consulted on the webpage of the Key Comparison Data Base (KCDB), [1].

In December 2017 a new BIPM.EM-K12 comparison was carried out at the Federal Institute of Metrology of Switzerland (METAS). The first METAS measurement system implementing a QHR was developed in the early nineties and was validated by the second on-site comparison of the first round of BIPM.EM-K12 comparisons in 1994 [2]. After 20 years of regular calibration, this system needed to be updated and a complete new system was recently developed. The goal of the present comparison was to validate this new QHE measurement system.

In this comparison, due to some technical issues encountered during the implementation on site of the QHRs from both METAS and the BIPM, the comparison measurements could not be totally completed. In effect, the time dedicated to on-site comparisons is limited and any setbacks imply a reduction of the comparison program. We then gave priority to the 100 Ω calibration against the QHR and to the scaling from 100 Ω to 10 kΩ. Consequently, no comparison results regarding the scaling from 100 Ω to 1 Ω will be presented in this report.

2. Principle of the comparison measurements

The ohm can be reproduced from the QHE routinely with an accuracy of the order of 1 part in 10^9 or better. The present comparison is performed on-site in order to eliminate the limitation due to transporting transfer resistance standards between the BIPM and the participating institute, which would otherwise result in an increase of the comparison uncertainty by at least a factor of 10.
To this end, the BIPM has developed a complete transportable system that can be operated at the participant's facilities to transfer the ohm from a QHE reference to a 100 Ω standard and scale this value to 1 Ω and 10 kΩ (meaning that not only the QHE systems are covered in this comparison but also the scaling devices).

For the reason given in the above introduction, only the calibration of the 100 Ω standard and scaling to 10 kΩ have been addressed in the present comparison between METAS and the BIPM which then comprised the two following stages, also schematized in figure 1:

(i) The calibration of a 100 Ω standard resistor in terms of the QHE-based standard of each of the institutes (METAS and BIPM).
The conventional value $R_{\text{K-90}}$ is used to define the quantum Hall resistance value. The relative difference in the calibrated values of the standard resistor of nominal value R=100 Ω is expressed as $(R_{\text{METAS}} - R_{\text{BIPM}})/R_{\text{BIPM}}$ where R_{BIPM} and R_{METAS} are the values attributed by the BIPM and METAS, respectively.

(ii) The scaling from 100 Ω to 10 kΩ, through the measurement of the ratio $R_{10k\Omega}/R_{100\Omega}$ of the resistance of two standards of nominal value 10 kΩ and 100 Ω. The relative difference in the measurement of this ratio, hereinafter referred to as $K1$, is expressed as $(K1_{METAS} - K1_{BIPM})/K1_{BIPM}$ where $K1_{BIPM}$ and $K1_{METAS}$ are the values attributed by the BIPM and METAS respectively.

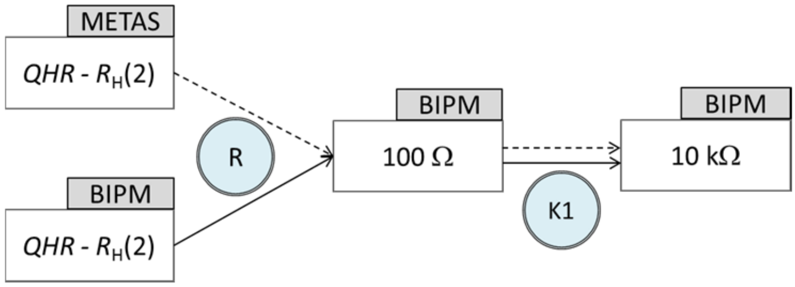

Figure 1: Schematic of the onsite comparison carried out at METAS in December 2017. Rectangles represent the resistances to be compared and circles correspond to the resistance R or the ratio $K1$ to be measured. Solid and dashed arrows stand for the measurements with the 1 Hz-bridge of the BIPM or with the CCC bridge of METAS, respectively.

The resistance value of each of the standard resistors used in this comparison is defined as its five-terminal dc-resistance value[1]. This means that it corresponds to the dc voltage to current ratio once any thermal emf across the resistor has reached a stable value.

3. The BIPM measurement system and the transfer standards

3.1. Implementation of the QHE

A complete transportable QHE reference [3] has been developed at the BIPM for the purpose of the BIPM.EM-K12 on-site comparison programme. It is composed of a compact liquid helium cryostat equipped with an 11 tesla magnet and a sample space that can be cooled to 1.3 K with the associated vacuum pump. The superconducting magnet has an additional support at the bottom of the dewar to allow safe transport.

The separate sample probe can support two TO-8 mounted quantum Hall devices simultaneously (side by side within the magnet), with guarded wiring for eight terminals on each device. The BIPM uses GaAs heterostructure devices fabricated in the LEP 1990 EUROMET batch [4]. They give an i=2 plateau centered around 10.5 T which is well quantized for currents of at least 100 μA at 1.3 K. The cryostat and the QHE devices are suitable for a representation of the ohm (Ω-90), meeting all the requirements of the CCEM guidelines [5] for a relative standard uncertainty of the order of 1×10^{-9} or below.

A transportable resistance bridge is used with the QHE system for the measurement of the different resistance ratios being the subject of the comparison. It is based on a room-temperature low-frequency current comparator (LFCC) operated at 1 Hz (sinusoidal signal), meaning that all resistance or ratio measurements are carried out at 1 Hz by the BIPM during the comparison. This procedure is preferable to the transport of the BIPM CCC bridge on-site since the 1Hz-bridge is a more rugged instrument, simple to operate, and much less sensitive to electromagnetic interference and temperature variations. Furthermore, it provides resolution and reproducibility that are comparable to those achievable with the BIPM CCC.

[1] Ratio of the voltage drop between the high and low potential terminals to the current flowing in the low current terminal, with the case - fifth terminal - maintained at the same potential as the low potential terminal

The 1 Hz-bridge is equipped with two separate LFCCs of ratio 129:1 and 100:1, having turns 2065/16 and 1500/15. The construction and performances of these devices are detailed in [6, 7].

3.2. Transfer standards

Two transfer resistance standards of nominal value 100 Ω and 10 kΩ are used during the comparison. The values assigned by the BIPM and METAS to the 100 Ω resistor in terms of R_{K-90} and to the ratio 10 kΩ/100 Ω are the measurands being compared in this comparison.

The transfer standards are provided by the BIPM. Both the 100 Ω and the 10 kΩ standards are Tegam resistors of type SR102 (s/n: A2030405) and SR104 (s/n: K204039730104), respectively. They are fitted in individual temperature-controlled enclosures held at 25°C. The temperature-regulation system can be powered either from the mains or from external batteries.

For each of these standards, the difference between resistance values measured at 1 Hz and at 'dc' is small but not negligible. These differences were determined at the BIPM prior to the comparison and checked after the comparison. The 'dc' value was measured with the BIPM cryogenic current comparator (CCC) whilst the 1 Hz value with the transportable 1Hz-bridge subsequently used onsite during the comparison. The differences are applied as corrections to the measurements performed at 1 Hz meaning that the 1 Hz-bridge is used as a transfer instrument referenced to the BIPM CCC.

The frequency corrections (1 Hz-'dc') are reported in Table 1 for the two transfer standards. The main possible error sources contributing to these corrections are the QHR, the 1 Hz-bridge and the transfer standard itself. Nevertheless, at 1 Hz, the frequency dependence of the QHR is negligible compared to the comparison uncertainty [8], and the characterization of the bridge evidenced that its error at 1 Hz is below 1 part in 10^9. Consequently, the frequency dependence observed is mainly attributed to the resistance standards themselves, without excluding a contribution of the 1 Hz-bridge.

Resistance or resitance ratio	1 Hz – 'dc' relative correction /10^{-9}	Standard Uncertainty /10^{-9}
$(R_{100\Omega}(1\text{Hz}) - R_{100\Omega}(\text{dc})) / 100$	-9.8	1.0
$(K1(1\text{Hz}) - K1(\text{dc})) / 100$	10.0	1.0

Table 1: Relative value of the 1 Hz to 'dc' corrections applied to the BIPM measurements carried out at 1 Hz. These values are specific to the standards used in the present comparison.

For the sake of completeness, it must be noticed that the 'dc' resistance value (or ratio) measured with the BIPM CCC-bridge results from a current signal passing through the resistors having polarity reversals with a waiting time between polarity inversions, cf. figure 2. The polarity reversal frequency is of the order of 3 mHz (340 s cycle period) and the measurements are sampled only during 100 s before the change of polarity.

Previous characterization measurements of the $R_H(2)$/100 Ω and 10 kΩ/100 Ω ratios have shown that if the polarity reversal frequency is kept below 0.1 Hz, any effects of settling or ac behaviour remain of the order of 1 part in 10^9 or less.

In order to ensure the best possible comparability of the measurements performed by the BIPM and the participating institute, the measuring system of the latter should be ideally configured to match the reference polarity reversal cycle of the BIPM CCC. As this is generally not possible, a correction may be applied if necessary on the participating institute's measurements based on additional characterization of the influence of the polarity reversal rate on the actual measured resistance ratio.

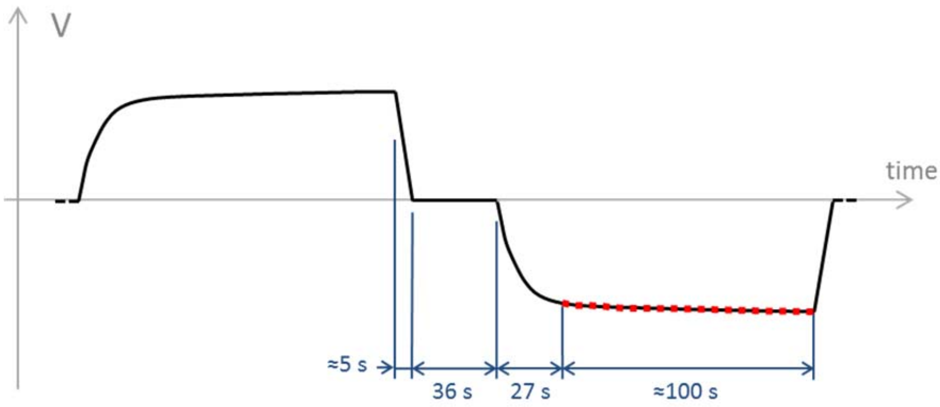

Figure 2: Schematic representation of the reference current signal with polarity reversals used in the BIPM CCC-bridge. The reversal cycle comprises a waiting time of about 36 s at zero current. The red dotted line corresponds to the sampling time period

3.3. Uncertainty budget

Table 2 summarizes the BIPM type B standard uncertainties for the measurement of the 'dc' value of the 100 Ω standard in terms of the recommended value of the von Klitzing constant R_{K-90}, as well as the uncertainties for the measurement of the 10 kΩ/100 Ω ratio.

Information about the imperfect realization of the ratio QHR/100 Ω could be found in the references [6] and [8]. Further details about the ac measurement of the QHE will be found in the review paper [9].

	Relative standard uncertainties / 10^{-9}	
Ratio / *Parameters*	$R_H(2)$/100 Ω	10 kΩ/100 Ω
Reference CCC bridge		
Imperfect CCC winding ratio	1.0	1.0
Resistive divider calibration	0.5	0.5
Leakage resistances	0.2	0.2
Noise rectification in CCC	1.0	1.0
Imperfect realization of the QHR/100 Ω ratio at 1 Hz	0.8	-
Correction of the 1 Hz-to-'dc' difference	1.0	1.0
Combined type B standard uncertainty, u_B=	**2.0**	**1.8**

Table 2: Contributions to the combined type B uncertainty (k=1) for the measurement of the two mentioned resistance ratios at the BIPM.

4. METAS measurement system

A new measurement system has been developed at METAS to replace and upgrade the original system used in the comparison of 1994 [2]. It is still based on a DC cryogenic current comparator (CCC). However, the hardware was completely upgraded with new equipment:

- A new dual current source was designed in order to facilitate the operation of the bridge.
- After repeated failures and repairs, the original RF SQUID was replaced by a DC SQUID.

- A new CCC torus, its windings and pick-up coil were designed and fabricated.

- A new cryogenic insert was designed and constructed for the CCC.

- A new ^{3}He cryostat was purchased, including a new cryoprobe and its custom wiring to the QHR sample.

Since the system has been almost completely modified, the present comparison and the comparison of 1994 can be considered as independent from one another.

Table 3 gives the estimation of the type-B contributions to the uncertainty budget for the bridge.

Parameters	Distribution	$R_H(2)/100\ \Omega$ parts in 10^9	$10\ k\Omega/100\ \Omega$ parts in 10^9
Winding ratio calibration CCC error	normal	0.1	0.1
Resistive-divider calibration error	normal	0.4	0.4
Gain voltage measurement at balance (Vm< 20 nV)	normal	0.3	0.3
Uncompensated zero offsets	rectangular	0.6	0.6
Direct shunt leakage (for the larger resistance)	normal	0.6	0.5
Leakage to ground	normal	0.0	0.0
Combined type B standard uncertainty, u_B=		1.0	0.9

Table 3: Type-B contributions (k=1) to the uncertainty budget for METAS measurements of the mentioned resistance ratios.

The measurement sequence is computer-controlled and is based on periodic reversal of the DC currents. It is depicted in figure 3.

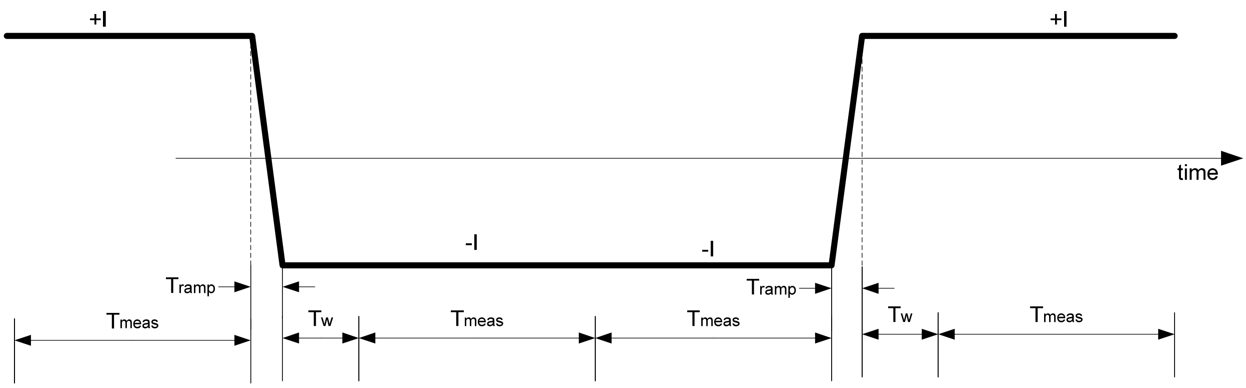

Figure 3: Current reversal sequence in METAS setup. T_{ramp} is the time required to reverse currents, T_w is the time during which no measurement is taken and T_{meas} is the interval were measurements are taken. One measurement is composed of 2 intervals at negative current separating two intervals at positive current.

5. Measurement of the 100 Ω transfer standard in terms of $R_H(2)$

5.1. BIPM measurements

5.1.1. Preliminary tests

The quantum Hall sample used during the present comparison was operated on the i=2 plateau at a temperature of 1.3 K and with a rms current of 40 μA. The magnetic flux density corresponding to the middle of the plateau was determined by recording the longitudinal voltage V_{xx} versus flux density and was found to be 10.5 T. The two-terminal Hall resistance of the four-terminal-pairs device was checked before and after each series of measurements, showing that the contact resistance was smaller than a few ohms (and in any case not larger than 5 Ω - measurements limited by the resolution of the DVM used).
The absence of significant longitudinal dissipation along both sides of the device was tested as described in [5] section 6.2, by combining the measurements obtained from four different configurations of the voltage contacts (two opposite pairs in the center and at the end of the sample, and two diagonal configurations). The absence of dissipation was demonstrated within 5×10^{-10} in relative terms with a standard deviation of the same order. Subsequent series of measurements were taken from the central pair of contacts only.

5.1.2. BIPM results

As mentioned above, the quantum Hall sample was used with a rms current of 40 μA. The current in the 100 Ω transfer standard was then 5.2 mA, corresponding to a Joule heating dissipation of 2.7 mW.

After a preliminary set of measurements on 4 December 2017, four measurements of the 100 Ω standard were interleaved with four measurements by METAS on 5 December 2017. The 1 Hz-measured and dc-corrected values of the 100 Ω standard are reported in Table 4. They are expressed as the relative difference from the 100 Ω nominal value: $(R_{BIPM}/100\ \Omega) - 1$.

Each measurement reported in the table below is the mean value of at least seven individual measurements corresponding to a minimum integration time of about 35 minutes.

Time	$(R_{BIPM}/100\ \Omega)$-1 /10^{-6}		Standard deviation of the mean /10^{-9}
	1 Hz measurements	'dc' corrected (1 Hz-'dc' correction)	
12 :15	-0.6140	-0.6042	0.7
13 :58	-0.6134	-0.6035	0.9
15 :40	-0.6140	-0.6042	0.8
17 :37	-0.6141	-0.6043	0.7
	Mean value =	**-0.6041**	
	Standard deviation, u_A =	**0.0003**	

Table 4 : BIPM measurements of the 100 Ω standard in terms of $R_H(2)$, on 5 December 2017. Results are expressed as the relative difference from the nominal 100 Ω value.

BIPM result : $\mathbf{R_{BIPM} = 100 \times (1 - 0.6041 \times 10^{-6})\ \Omega}$

Relative standard uncertainty : $\mathbf{u_{BIPM} = 2.0 \times 10^{-9}}$

where u_{BIPM} is calculated as the quadratic sum of $u_A = 0.3 \times 10^{-9}$ and, from Table 2, $u_B = 2.0 \times 10^{-9}$.

5.2. METAS measurements of $R_H(2)/100\ \Omega$

5.2.1. Preliminary tests

For this comparison, METAS used a GaAs heterostructure (identifier: EPF 277/5) fabricated by the Swiss Federal Institute of Technology in Lausanne (EPFL). The device has a mobility of 42 T^{-1} and a carrier concentration of $4{,}8 \cdot 10^{15}$ m^{-2}. The sample was operated on the i=2 plateau at a temperature of 0.3 K, with a current of 38.76 μA. The magnetic flux density at the center of the plateau was 9.9 T. A residual longitudinal resistivity of less than 16 μΩ was measured in these conditions on both side of the device. The resistance of the contacts was measured as outlined in [10] and found to be smaller than 1 Ω. Both the residual dissipation and the contact resistance attest the high quality of the device and its full compliance to the technical guideline for high accuracy measurement of the QHR [5].

5.2.2.Possible influence of the measurement cycle duration

The standard measurement times at METAS are T_w=13 s and T_{meas}=15 s, see figure 3. T_{ramp} is typically less than 5 s. These time intervals have been carefully chosen together with the measurement sequence, which is capable of compensating drifts of influence parameters such as offsets, provided these drifts have a constant slope over time. Such linearity of drifts is easier to achieve with short time intervals, and the typical times required to match the BIPM measurements at DC are too large for METAS equipment in this respect. Nevertheless, METAS has carried out one measurement with time parameters T_w=60 s and T_{meas}=50 s followed by a measurement using standard measurement times without noticing any significant difference.

5.2.3. METAS results for standard measurement cycle duration

Four measurements (interleaved with the four BIPM measurements of table 4) were taken on 5 December 2017, each consisting of 20 standard measurement cycles (integration time of 20 minutes). The current through the 100 Ω standard was 5 mA corresponding to a joule heating very similar to that dissipated in the 100 Ω resistor during measurements carried out by the BIPM . The turns ratio of cryogenic current comparator was 2065/16.

Table 5 presents the measurement results obtained under these conditions. No correction is applied.

Time	$(R_{METAS}/100\ \Omega)$-1 /10^6	Standard deviation of the mean /10^{-9}
10:50	-0.6046	0.5
13:27	-0.6031	0.8
14:43	-0.6031	0.7
16:10	-0.6034	0.4
Mean value =	**-0.6036**	
Standard deviation, u_A =	**0.0007**	

Table 5: METAS measurements of the 100 Ω standard in terms of $R_H(2)$ on 5 December 2017. Results are expressed as the relative difference from the nominal 100 Ω value.

METAS result: $\boldsymbol{R_{METAS} = 100 \times (1 - 0.6036 \times 10^{-6})\ \Omega}$

Relative standard uncertainty: $\boldsymbol{u_{METAS} = 1.2 \times 10^{-9}}$

where u_{METAS} is calculated as the quadratic sum of: $u_A = 0.7 \times 10^{-9}$ and, from Table 3, $u_B = 1.0 \times 10^{-9}$.

5.3. 100 Ω measurements comparison

Figure 4 presents the corrected interleaved measurements from METAS and BIPM on 5 December 2017 (from data in tables 4 and 5). Error bars correspond to the dispersion observed for each measurement.

Figure 4 suggests that, within the limit of the dispersion of the results, the stability of the 100 Ω transfer resistor is such that any uncertainty contribution from possible instabilities can be estimated as negligible.

The difference between METAS and the BIPM can then be calculated as the relative difference of the means of the series of measurements carried out by both institutes (mean values in tables 4 and 5):

Relative difference METAS-BIPM: $\mathbf{(R_{METAS} - R_{BIPM}) / R_{BIPM} = +0.5 \times 10^{-9}}$

Relative combined standard uncertainty: $\mathbf{u_{comp} = 2.3 \times 10^{-9}}$

where u_{comp} is calculated as the quadratic sum of $u_{BIPM} = 2.0 \times 10^{-9}$ and $u_{METAS} = 1.2 \times 10^{-9}$.

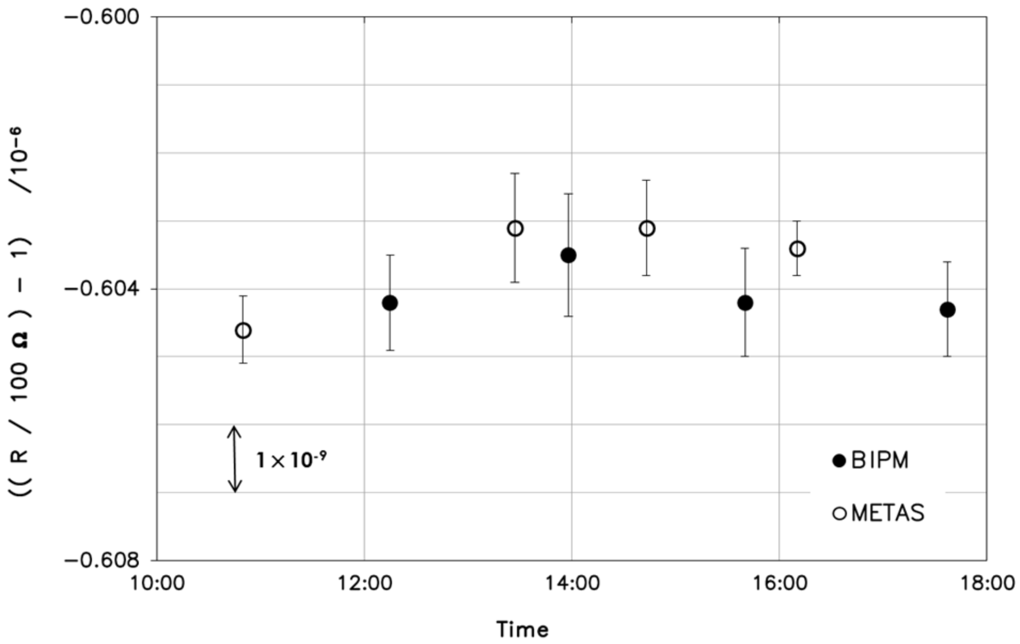

Figure 4: METAS (white circles) and BIPM (black dots) measurements of the 100 Ω resistance R in terms of $R_H(2)$ on 5 December 2017. The uncertainty bars correspond to the dispersion observed during each measurement.

6. Measurement of the (10 000 Ω / 100 Ω) ratio *K*1

6.1. BIPM measurements of *K*1

For the measurement of the $K1$ ratio the 129:1 LFCC equipping the BIPM's 1 Hz-bridge for $R_H(2)$/100 Ω ratio measurement was replaced by a 100:1 LFCC. The rms current in the 10 000 Ω standard was 50 µA corresponding to 5 mA in the 100 Ω standard. The two standards were connected alternately to the BIPM and METAS bridges. Measurements of $K1$ were carried out over two days: a first series of four BIPM measurements interleaved with three METAS measurements was performed on 7 December 2017, and a second series of four BIPM measurements interleaved with three METAS measurements was done on 8 December 2017.

As the two series are separated by a break of about 14 hours, they have been processed separately. The results of the measurements carried out on 7 and 8 December 2017 are reported in the Table 6.

Each of the measurement results reported in this table corresponds to the mean value of at least seven individual measurements corresponding to a minimum integration time of about 35 minutes. The associated dispersion corresponds to the standard deviation of the mean of the individual measurements.

Date	Time	($K1_{\mathrm{BIPM}}$/100)-1 /10^{-6}		Dispersion /10^{-9}
		1 Hz measurements	'dc' corrected (1 Hz-'dc' correction)	
07/12/2017	13:46	0.8170	0.8070	0.7
	15:15	0.8158	0.8058	1.0
	16:45	0.8189	0.8089	0.6
	18:05	0.8169	0.8069	0.8
		Mean value =	**0.8072**	
		Standard deviation, u_A =	**0.0013**	
08/12/2017	08:30	0.8207	0.8107	0.7
	09:59	0.8198	0.8098	1.3
	11:20	0.8182	0.8082	0.8
	12:42	0.8168	0.8068	0.7
		Mean value =	**0.8089**	
		Standard deviation, u_A =	**0.0017**	

Table 6: BIPM measurements of the (10 000 Ω/100 Ω) ratio $K1$ on 7 and 8 December 2017. Results are expressed as the relative difference from the nominal ratio value 100.

BIPM result on **7 December 2017**: $\boldsymbol{K1_{\mathrm{BIPM}} = 100 \times (1 + 0.8072 \times 10^{-6})}$

Relative standard uncertainty: $\boldsymbol{u_{\mathrm{BIPM}} = 2.2 \times 10^{-9}}$

where u_{BIPM} is calculated as the quadratic sum of $u_{\mathrm{A}} = 1.3 \times 10^{-9}$ and, from Table 2, $u_{\mathrm{B}} = 1.8 \times 10^{-9}$.

BIPM result on **8 December 2017**: $\boldsymbol{K1_{\mathrm{BIPM}} = 100 \times (1 + 0.8089 \times 10^{-6})}$

Relative standard uncertainty: $\boldsymbol{u_{\mathrm{BIPM}} = 2.5 \times 10^{-9}}$

where u_{BIPM} is calculated as the quadratic sum of $u_{\mathrm{A}} = 1.7 \times 10^{-9}$ and, from Table 2, $u_{\mathrm{B}} = 1.8 \times 10^{-9}$.

6.2. METAS measurements of *K*1

6.2.1. METAS results for standard cycle duration

The measurements carried out by the BIPM on 7 and 8 December 2017 were interleaved with three and four METAS measurements, respectively. Each of these measurements consisted of 20 standard measurement cycles corresponding to an integration time of 20 minutes. The measurement current through the 10 000 Ω standard was 50 µA, as for the BIPM. The turns ratio of the cryogenic current comparator was 2000/20. Results are given in Table 7.

Date	Time	$(K1_{\mathrm{METAS}}/100)$-1 parts in 10^6	Scattering parts in 10^9
07/12/2017	14:35	0.8073	1.1
	16:15	0.8086	0.8
	17:31	0.8082	0.5
Mean value =		**0.8080**	
Standard deviation, u_A =		**0.0007**	
08/12/2017	07:53	0.8089	1.1
	09:19	0.8085	1.3
	10:48	0.8071	1.0
	12:11	0.8086	0.6
Mean value =		**0.8083**	
Standard deviation, u_A =		**0.0008**	

Table 7: METAS measurements of the (10 000 Ω/100 Ω) ratio $K1$ on 7 and 8 December 2017. Results are expressed as the relative difference from the nominal ratio value 100.

METAS result on **7 December 2017**: $\boldsymbol{K1_{\mathrm{METAS}} = 100 \times (1 + 0.8080 \times 10^{-6})}$

Relative standard uncertainty: $\boldsymbol{u_{\mathrm{METAS}} = 1.1 \times 10^{-9}}$

where u_{METAS} is calculated as the quadratic sum of $u_{\mathrm{A}} = 0.7 \times 10^{-9}$ and, from Table 3, $u_{\mathrm{B}} = 0.9 \times 10^{-9}$.

METAS result on **8 December 2017**: $\boldsymbol{K1_{\mathrm{METAS}} = 100 \times (1 + 0.8083 \times 10^{-6})}$

Relative standard uncertainty: $\boldsymbol{u_{\mathrm{METAS}} = 1.2 \times 10^{-9}}$

where u_{METAS} is calculated as the quadratic sum of $u_{\mathrm{A}} = 0.8 \times 10^{-9}$ and, from Table 3, $u_{\mathrm{B}} = 0.9 \times 10^{-9}$.

6.2.2. Possible influence of the cycle duration

As for $R_{\mathrm{H}}(2)/100\ \Omega$ ratio, no effect of reversal cycle timing on the measurement of $K1$ ratio has been observed by METAS (see section 5.2.2).

6.3. Comparison of $K1$ measurements

Figures 5 and 6 present the interleaved measurements from METAS and BIPM on 7 and 8 December 2017 (data from tables 6 and 7). The error bars reported on the graphs correspond to the dispersion observed for each measurement.

Considering figure 6, it could be argued that there is a slight drift in the results for the measured ratio of the two standard resistors. This is more obvious for the BIPM measurements. Since the mean measurement times for the BIPM and METAS are very similar, a linear drift correction in place of a simple arithmetic mean would not significantly change the comparison result. A drift correction has therefore not been applied. It can be seen that this apparent drift remains within the uncertainty of the measurements (in 1σ).

Figures 6 and 7 suggest that, within the limit of the dispersion of the results, no significant instabilities of the standards can be evidenced and therefore no additional uncertainty component was included in the final result.

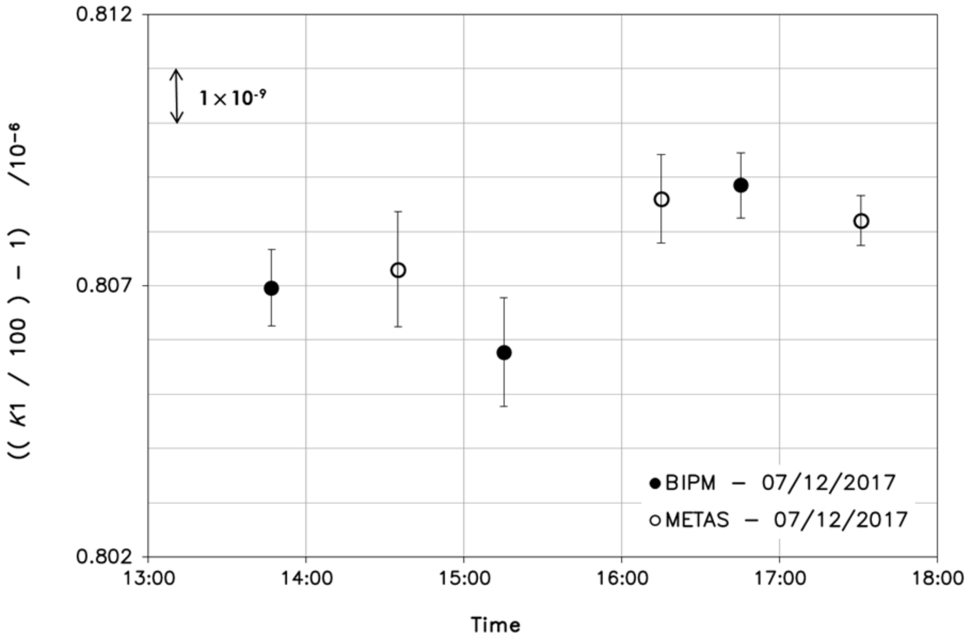

Figure 5: METAS (white circles) and BIPM (black dots) measurements of the ratio $K1$ (10 000 Ω/100 Ω) on **7 December 2017**. The uncertainty bars correspond to the dispersion observed during each measurement.

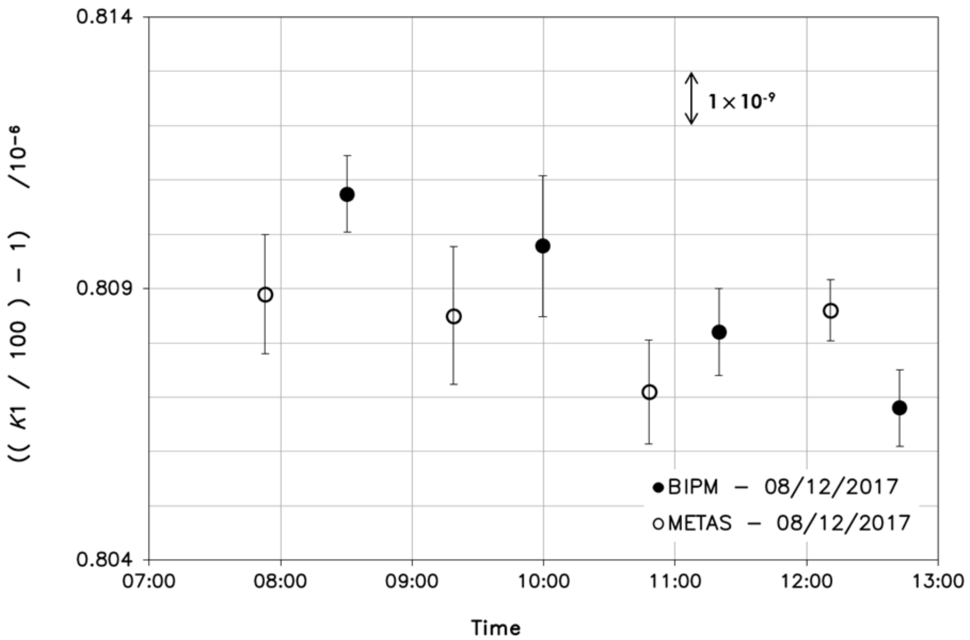

Figure 6: METAS (white circles) and BIPM (black dots) measurements of the ratio $K1$ (10 000 Ω/100 Ω) on **8 December 2017**. The uncertainty bars correspond to the dispersion observed during each measurement

The difference between METAS and the BIPM can then be calculated as the mean of the differences computed from measurements obtained on 7 and 8 December. The two differences and their mean as well as the associated relative combined uncertainties are reported in table 8.

Date	Relative difference METAS-BIPM $(\boldsymbol{K1_{\mathrm{METAS}} - K1_{\mathrm{BIPM}}}) / \boldsymbol{K1_{\mathrm{BIPM}}}$	u_{BIPM}	u_{METAS}	Relative combined standard uncertainty $(u_{BIPM}^2 + u_{METAS}^2)^{1/2}$
07/12/2017	**$+1.0 \times 10^{-9}$**	2.2×10^{-9}	1.1×10^{-9}	**2.5×10^{-9}**
08/12/2017	**-0.7×10^{-9}**	2.5×10^{-9}	1.2×10^{-9}	**2.8×10^{-9}**
Mean relative difference METAS-BIPM			$+0.2 \times 10^{-9}$	
Relative combined standard uncertainty of the mean			**1.9×10^{-9}**	

Table 8: Mean relative difference between METAS and the BIPM and its associated relative uncertainty calculated from the measurements carried out on 7 and 8 December.

7. Conclusion

The on-site key comparison BIPM.EM-K12 carried out in December 2017 between the BIPM and METAS showed a very good agreement in the measurements of a conventional 100 Ω resistor in terms of the quantized Hall resistance ($R_{\mathrm{H}}(2)$), as well as in the determination of the resistance ratio 10 000 Ω/100 Ω ($K1$).

The results of the comparison are summarized in table 9. The relative difference between the BIPM and METAS is less than 1 part in 10^9 for $R_{100\Omega}$ and $K1$, with relative uncertainties of the order of 2×10^{-9} (k=1).

In contrast with previous on-site BIPM.EM-K12 comparisons, no specific influence of the cycle time has been evidenced from METAS measurements (see section 5.2.2). However, on the two measured ratios $R_{\mathrm{H}}(2)$/100 Ω and 10 000 Ω/100 Ω, this influence, when detected in the past, was on the order of the measurement uncertainties or lower.

$R_{100\Omega}$ in terms of $R_{\mathrm{H}}(2)$	$(R_{\mathrm{METAS}} - R_{\mathrm{BIPM}}) / R_{\mathrm{BIPM}}$ = **$+0.5\times10^{-9}$**	u_{comp} = **2.3×10^{-9}**
$K1 = R_{10\mathrm{k}\Omega}/R_{100\Omega}$	$(K1_{\mathrm{METAS}} - K1_{\mathrm{BIPM}}) / K2_{\mathrm{BIPM}}$ = **$+0.2\times10^{-9}$**	u_{comp} = **1.9×10^{-9}**

Table 9: Summary of the results and the associated relative standard uncertainties of the BIPM-METAS onsite comparison BIPM.EM-K12.

The above results will also appear as Degree of Equivalence (DoE) in the BIPM Key Comparison Database (KCDB). The DoE of the participating institute with respect to the reference value is given by a pair of terms: the difference D from the reference value and its expanded uncertainty for k=2, i.e. U=2u. The reference value of the on-going comparison BIPM.EM-K12 was chosen to be the BIPM value. The comparison results expressed as DoEs are summarized in table 10.

	Degree of equivalence D /10^{-9}	Expanded uncertainty U /10^{-9}
$R_{100\Omega}$ in terms of $R_{\mathrm{H}}(2)$	**+0.5**	**4.6**
$K1 = R_{10\mathrm{k}\Omega}/R_{100\Omega}$	**+0.2**	**3.8**

Table 10: Summary of the comparison results expressed as degrees of equivalence (DoEs): difference from the BIPM reference value and expanded uncertainty U (k=2).

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