BUREAU INTERNATIONAL
DES POIDS ET MESURES

On-site comparison of Quantum Hall Effect resistance standards of the NIM and the BIPM

⬩⬩⬥ Ongoing key comparison BIPM.EM-K12 ⬥⬩⬩

Report on the September 2019 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 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 standard. This comparison is 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, six comparisons have been successfully completed whose results may be consulted on the webpage of the Key Comparison Data Base (KCDB) [1].

In September 2019 a new BIPM.EM-K12 comparison was carried out at the National Institute of Metrology (NIM), China. It was the first time the NIM participated in this comparison program. This report presents the measurement results obtained during this exercise.

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 of 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 reproduce the ohm from a QHE reference at 100 Ω 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).

Practically, the comparison comprises three stages 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 (NIM and BIPM). The SI value of the von Klitzing constant R_K is used to define the quantum Hall resistance value of both institutes. The relative difference in the calibrated values of the standard resistor of nominal value 100 Ω is expressed as $(R_{NIM} - R_{BIPM})/R_{BIPM}$ where R_{BIPM} and R_{NIM} are the values attributed to $R_{100\Omega}$ by the BIPM and NIM, 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 $(K1_{NIM} - K1_{BIPM})/K1_{BIPM}$ where $K1_{BIPM}$ and $K1_{NIM}$ are the values attributed by the BIPM and the NIM, respectively.

(iii) The scaling from 100 Ω to 1 Ω, through the measurement of the ratio $R_{100\Omega}/R_{1\Omega}$ of the resistance of two standards of nominal value 100 Ω and 1 Ω. The relative difference in the measurement of this ratio, hereinafter referred to as $K2$, is expressed as $(K2_{\mathrm{NIM}} - K2_{\mathrm{BIPM}})/K2_{\mathrm{BIPM}}$ where $K2_{\mathrm{BIPM}}$ and $K2_{\mathrm{NIM}}$ are the values attributed by the BIPM and the NIM, respectively.

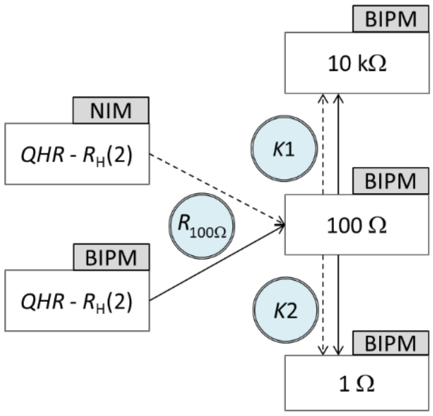

Figure 1: Schematic of the on-site comparison carried out at the NIM in September 2019. Rectangles represent the resistances to be compared and circles correspond to the resistance R or the ratios $K1$ and $K2$ to be measured. Solid and dashed arrows stand for the measurements with the 1 Hz bridge of the BIPM or with the CCC bridge of the NIM, 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, unless otherwise specified, that it corresponds to the dc voltage to current ratio once any thermal emf across the resistor, particularly those induced by the Peltier effect, has reached a stable value. The influence of the Peltier effect on precision resistance measurements has already been discussed in several papers [2-6], in which an extended description of the observed phenomena is provided (in particular regarding 1 Ω resistance measurement).

3. The BIPM measurement system and the transfer standards

3.1. Implementation of the QHE

A complete transportable QHE reference [7] 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 included 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 [8]. They give an i=2 plateau centered around 10.5 T which is well quantized for currents of at least 100 μA at 1.5 K. The cryostat and the QHE devices are suitable for a realization of the ohm meeting all the requirements of the CCEM guidelines [9] for a relative standard uncertainty of the order of 1×10^{-9}.

A transportable resistance bridge is used with the QHE cryostat 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

[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

measurements are carried out at 1 Hz by the BIPM during the comparison. That way to proceed is preferable to the transport of the BIPM Cryogenic Current Comparator (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 bridge.

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 performance of these devices are detailed in [10,11].

3.2. Transfer standards

Three transfer resistance standards of value 1 Ω, 100 Ω and 10 kΩ are used during the comparison. The values assigned by the BIPM and the NIM to the 100 Ω resistor in terms of R_K and to the two ratios 100 Ω/1 Ω and 10 kΩ/100 Ω are the measurands being compared in this comparison.

The transfer standards were provided by the BIPM. The 1 Ω standard was a 9331R series resistor from Measurement International (s/n: 1103856), the 100 Ω was a SR102 type resistor from IET Labs (s/n: J2-1425644) and the 10 kΩ was a SR104 type resistor from Tegam (s/n: K 201119630104). All three resistors were 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. It is therefore the same for ratios of standards such as $K1$ and $K2$. The differences 1 Hz-'dc' for $R_{100\Omega}$, $K1$ and $K2$ were determined at the BIPM prior to the comparison and checked afterwards. The 'dc' value was measured with the BIPM CCC whilst the 1 Hz value with the transportable 1 Hz bridge (the same as that used for on-site measurements). 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 $R_{100\Omega}$, $K1$ and $K2$. The main possible sources contributing to these corrections are the quantum Hall resistance (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 [12], and the characterization of the bridge provides evidence 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.

Resistance or resistance ratio	1 Hz-'dc' correction /10^{-9}	Standard uncertainty /10^{-9}
($R_{100\Omega}$(1 Hz) - $R_{100\Omega}$(dc)) / 100	-3.83	1.10
($K1$(1 Hz) - $K1$(dc)) / 100	-4.70	1.00
($K2$(1 Hz) - $K2$(dc)) / 100	9.99	1.50

Table 1: Value of the 1 Hz to 'dc' corrections applied to the BIPM measurements carried out at 1 Hz (with, Value('dc') = Value(1 Hz) – Correction). 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 to zero between polarity inversions, cf. Figure 2. The polarity reversal frequency is of the order of 3 mHz (about 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, then any effects of settling or ac behaviour remain of the order of 1 part in 10^9 or less. Regarding the 100 Ω/1 Ω ratio this is most often not the case due to unavoidable Peltier effects in the 1 Ω standard.

Consequently, 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 configured to match as closely as possible the reference polarity reversal cycle of the BIPM CCC. In case this is not feasible, a correction must be estimated and applied to the participating NMI's measurements based either on additional characterization of the influence of the polarity reversal rate on the actual measured resistance ratio, or by any other means using the most relevant and reliable information available.

Notice that in case different reversal current cycles would be used by the BIPM and the NMI, an estimation of the difference of the effective powers dissipated in the resistance standards measured should be done and, if necessary, a correction applied taking into account the power coefficients of those standards.

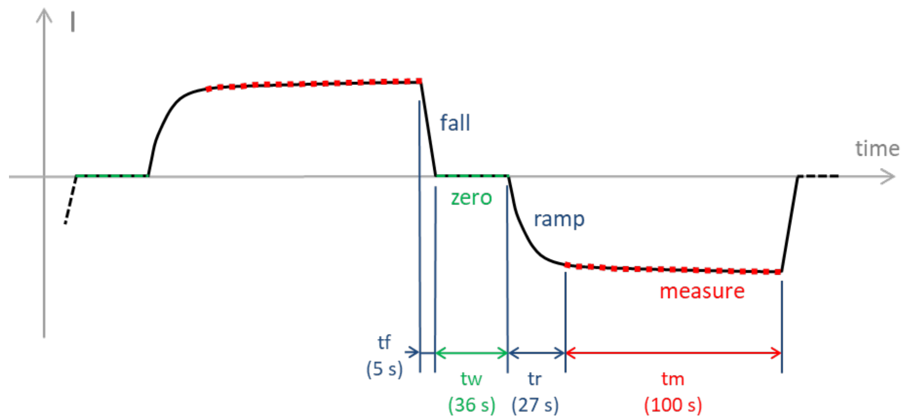

Figure 2: Schematic representation of the reference current cycle with polarity reversals used in the BIPM CCC-bridge. Each half-cycle comprises a waiting time at zero current of 36 s, a ramp time of 27 s, a measuring (sampling) time of 100 s and a fall time of 5 s. The complete reversal cycle time is 336 s.

3.3. Uncertainty budget

Table 2 summarizes the BIPM standard uncertainties for the measurement of the 'dc' value of the 100 Ω standard in terms of the SI value of the von Klitzing constant R_K, as well as the measurement uncertainties for both the 10 kΩ/100 Ω and 100 Ω/1 Ω ratios (K1 and K2, respectively).

Parameters	Measurement Setup		
Resistance ratio	$R_H(2)$/100 Ω	10 kΩ/100 Ω	100 Ω/1 Ω
LFCC ratio	129/1	100/1	100/1
Current	40 µA/5.16 mA	50 µA/5 mA	0.5 mA/50 mA
Source of Uncertainty (type B)	Relative standard uncertainties / 10^{-9}		
Reference CCC bridge			
Imperfect CCC winding ratio	1.0	1.0	1.0
Resistive divider calibration	0.5	0.5	0.5
Leakage resistances	0.2	0.2	-
Noise rectification in CCC	1.0	1.0	1.0
Imperfect realization of the QHR	0.8	-	-
Correction of the 1 Hz-to 'dc' difference	1.1	1.0	1.5
Combined type B uncertainty, u_B=	**2.0**	**1.8**	**2.1**

Table 2: Contributions to the combined type B standard uncertainty for the 'dc' measurement of the three mentioned resistance ratios at the BIPM.

4. The NIM measurement system

4.1. Implementation of the QHE

There are two independent QHE systems at NIM located on two different campuses. The QHE system which was used during the present comparison was the more recent one. It is located on the Changping campus and is in operation since 2017.

The cryogenic setup consisted of a cryostat comprising a 14 T magnet and a pumped helium-4 insert in which the temperature was reduced to below 1.5 K. The sample probe was equipped with two quantum Hall devices mounted on TO-8 sockets. These devices were both GaAs heterostructures fabricated by LEP. Test measurements were performed prior to the comparison in order to confirm the equivalence of the LEP devices used with other devices fabricated by NIM.

4.2. Resistance bridge

The NIM resistance bridge used during the comparison includes a CCC and a DC SQUID as null detector. The CCC electronics is a commercial one, purchased from Magnicon GmbH.

The CCC has 18 windings with turn numbers ranging from 1 to 4096, including 3923 and 78. When measuring the ratio $R_H(2)/100\,\Omega$, the turns ratio can be set either to 10067/78 or 4001/31. For the present comparison, the turns ratio was set 4001/31.

Regarding the measurement of the ratios $K1$ (10 kΩ/ 100 Ω) and $K2$ (100 Ω/ 1 Ω), the turns ratios were set to 3200/32 and 400/4, respectively.

The shape of a typical current reversal cycle provided by the bridge electronics is schematized in Figure 3. The default or standard configuration of a full cycle current reversal cycle was established to 100 s (see section 5.2.1). The reversal ramp time between the positive and negative current cycle is about 0.4 s and the measurement time *tm* is about 29.6 s preceded by a settle time *ts* of 20 s.

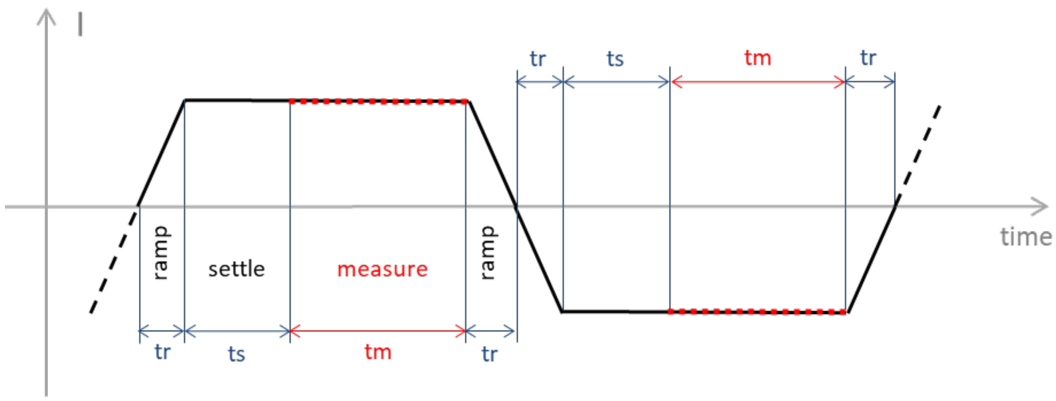

Figure 3: Standard current waveform and reversal cycle timing of the NIM CCC-bridge. The ramp time (t_r), the settle time (t_s) and the measuring time (t_m) of the standard cycle used for measurements were 0.2 s, 20 s and 29.6 s, respectively, for a total cycle period of 100 s.

4.3. Measuring environmental conditions

During the whole period of the comparison, the laboratory maintained an ambient temperature at (20.4±0.1) °C and relative humidity at (44±5) %. The atmospheric pressure during the comparison period from 10 to 14 September 2019 was in the range of 998.9 hPa to 1008.8 hPa with a mean of 1003.9 hPa.

4.4. Uncertainty budget

The uncertainty budget for the measurement of the 100 Ω resistance standard, the 10 kΩ/100 Ω ratio and the 100 Ω/1 Ω ratio are shown in Table 3. The 100 Ω measurements are based on the SI value of the von Klitzing constant, R_K (25 812.807 459 Ω).

Parameters	Measurement Setup		
Resistance ratio	$R_H(2)$/100 Ω	10 kΩ/100 Ω	100 Ω/1 Ω
Number of turns N1/N2	4001/31	3200/32	400/4
Voltage drop (I_1R_1) (V)	0.5	0.5	0.05
Source of Uncertainty (type B)	Relative standard uncertainties / 10^{-9}		
CCC windings ratio	0.19	0.19	0.19
Compensation ratio	0.036	0.010	0.016
Correction of $R_H(2)$ for finite dissipation	0.1	-	-
Leakage resistances	0.1	0.1	<0.01
Bridge voltage ΔU measurement	0.20	0.15	0.62
Combined type B uncertainty	**0.31**	**0.26**	**0.65**

Table 3: Contributions to the combined type B standard uncertainty for the NIM measurement of the three mentioned resistance ratios.

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 device (LEP 514) 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 *Vxx* versus flux density and was found to be 10.2 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 [9] 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, an rms current of 40 µA was applied to the quantum Hall device. The current in the 100 Ω transfer standard was then 5.16 mA, corresponding to a Joule heating dissipation of about 2.66 mW.

After preliminary measurement tests on September 9, 2019, four BIPM measurements of the 100 Ω standard were interleaved with four measurements by NIM on September 10, 2019. A difference of about -8.5×10^{-9} between NIM and BIPM was measured. This difference being higher than expected, the cause of the discrepancy was sought by verifying both the BIPM and the NIM QHR systems, cable connections and grounding paths. After those investigations, including a couple of series of testing measurements, it was found that the connection to ground of the case of the 100 Ω standard was not properly done on the NIM measuring system and was inducing a grounding loop.

The transportable 100 Ω transfer standard was specifically designed for on-site comparisons. It is enclosed in a rack mount case in which are assembled both, the resistor in its own commercial shielding case mounted in two nested thermo-regulated enclosures, and the temperature regulation electronics.

Considering that the grounding and guarding of the standard resistor can be specific to the CCC-bridge used by the host NMI, the inner rack case enclosures (shielding case of the resistor and the thermo-regulated enclosures) and the rack case itself, all have their own insulated connection terminals available from the rack case front panel. Thus, all the inner enclosures and the rack case can be grounded or guarded separately, either from the measuring cable or by any other means, as required for a proper functioning the CCC-bridge.

On September 10, after the difference between the BIPM and the NIM has been recorded, both systems have been re-checked and a few different grounding schemes of the resistor have been tested with the NIM system, it was finally realized that the initial grounding scheme that had been chosen by NIM was inadequate and was leading to the formation of a grounding loop. This was the result of a simple misunderstanding between the BIPM and the NIM about how the wiring of the different enclosures of the 100 Ω standard was made inside the rack case.

Then, after having performed the required modification of the grounding path between the 100 Ω case and the CCC-bridge of the NIM, a new series of five BIPM measurements interleaved with five NIM measurements was performed on September 11 and 12, 2019. This second series showed significantly better results even if a small linear drift of approximately 4 parts in 10^9 was observed on the whole measurement duration (about 8 hours, as shown on see Figure 7, section 5.3). This drift must be attributed to the temperature change of the 100 Ω transfer standard which remains, despite being temperature-controlled, slightly dependent on the temperature changes in the lab and to self-heating due to repeated series of measurements. As both the BIPM and NIM series of measurements experienced the same linear drift, they were both corrected from this drift before comparison of measurements for which difference has been reduced to a few parts in 1×10^{-10}.

The 1 Hz measured and dc-corrected values of the 100 Ω standard for the two series of measurements performed by the BIPM on September 10 and 11 are reported in Table 4. These measurement results are not drift-corrected. However, as the standard deviation (u_A) is meaningful only for drift-corrected measurements, the value of u_A on September 11 has been computed from drift-corrected measurements.

The reported results are expressed as the relative difference from the 100 Ω nominal value: (R_{BIPM}/100 Ω) - 1. Each measurement reported in Table 4 is the mean value of a set of eight individual measurements corresponding to a total integration time of about 27 minutes.

The resistance values $\boldsymbol{R_{BIPM}}$ reported below correspond to the mean of the measurements carried out by the BIPM on September 10 and 11, 2019:

September 10, 2019: Mean value: $\boldsymbol{R_{BIPM} = 100 \times (1 + 2.492\ 54 \times 10^{-6})\ \Omega}$

Relative standard uncertainty: $\boldsymbol{u_{BIPM} = 2.3 \times 10^{-9}}$

where u_{BIPM} is calculated as the quadratic sum of $u_A = 1.2 \times 10^{-9}$ and, from Table 2, $u_B = 2.0 \times 10^{-9}$.

September 11-12, 2019: Mean value: $\boldsymbol{R_{BIPM} = 100 \times (1 + 2.492\ 79 \times 10^{-6})\ \Omega}$

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

where u_{BIPM} is calculated as the quadratic sum of $u_A = 0.9 \times 10^{-9}$ and, from Table 2, $u_B = 2.0 \times 10^{-9}$.

Date and Time	$(R_{\mathrm{BIPM}}/100\ \Omega)-1$ /10^{-6}		Dispersion /10^{-6}
	1 Hz measurements	'dc' corrected (1 Hz-'dc' correction)	
10/9/19 17:39	2.489 62	2.493 45	0.000 9
10/9/19 19:41	2.490 53	2.494 36	0.000 7
10/9/19 21:28	2.488 34	2.492 17	0.000 2
10/9/19 23:16	2.486 37	2.490 20	0.000 4
	Mean value =	**2.492 54**	
	Standard deviation, u_A =	**0.001 21**	
11/9/19 17:08	2.487 97	2.491 80	0.000 4
11/9/19 18:59	2.486 90	2.490 73	0.000 4
11/9/19 20:55	2.489 66	2.493 49	0.000 5
11/9/19 22:55	2.488 93	2.492 76	0.000 5
12/9/19 0:58	2.491 31	2.495 14	0.000 6
	Mean value =	**2.492 79**	
	Standard deviation, u_A =	**0.000 94**	

Table 4: BIPM measurements of the 100 Ω standard in terms of $R_H(2)$, on September 10, 11 and 12, 2019. Each measurement corresponds to an integration time of about 27 minutes. Results are expressed as the relative difference from the nominal 100 Ω value. Date and time correspond to the mean time of measurement and the dispersion to the standard deviation of the mean of the considered series of measurements. The standard deviation u_A for the measurement series performed on September 11 has been computed after having corrected the measurement results for drift.

5.2. NIM measurements of $R_H(2)$/100 Ω

5.2.1. Preliminary tests

The LEP QHE device used by the NIM was cooled down to less than 1.5 K and biased at the center of the $i = 2$ plateau, $B = 10.5$ T. With an applied current of 38.7 μA, the longitudinal voltage V_{xx} was measured to be less than (5 ± 2) nV on both side of the device. All the contact resistances were measured to be less than 20 Ω. The turns ratio of the NIM CCC bridge was set to 4001/31.

Before starting the comparison measurements, the NIM studied the possible influence of the selected current reversal cycling period as well as the influence of the settling time of the current before measurements (*ts*, see Figure 3). It was shown that, in the NIM system, the settling time has to be carefully chosen, Figure 4. Indeed, it can be seen on that figure that settle times lower than 12 s can lead to measurement errors. However, it seems that the cycle period as no influence on the measurement of the 100 Ω as long as the settle time is larger than 12 s - at least for cycle times between 50 and 150 s (measuring time *tm* between 7 s and 57 s, Figure 5).

Following those measurements, NIM decided to set the parameters of the measurement cycle (shown on Figure 3) as follows: ramp/fall time $t_r = 0.2$s, settle time t_s =20 s and the measuring time t_m = 29.6 s, for a total cycle period of 100 s. This was the standard cycle for these measurements.

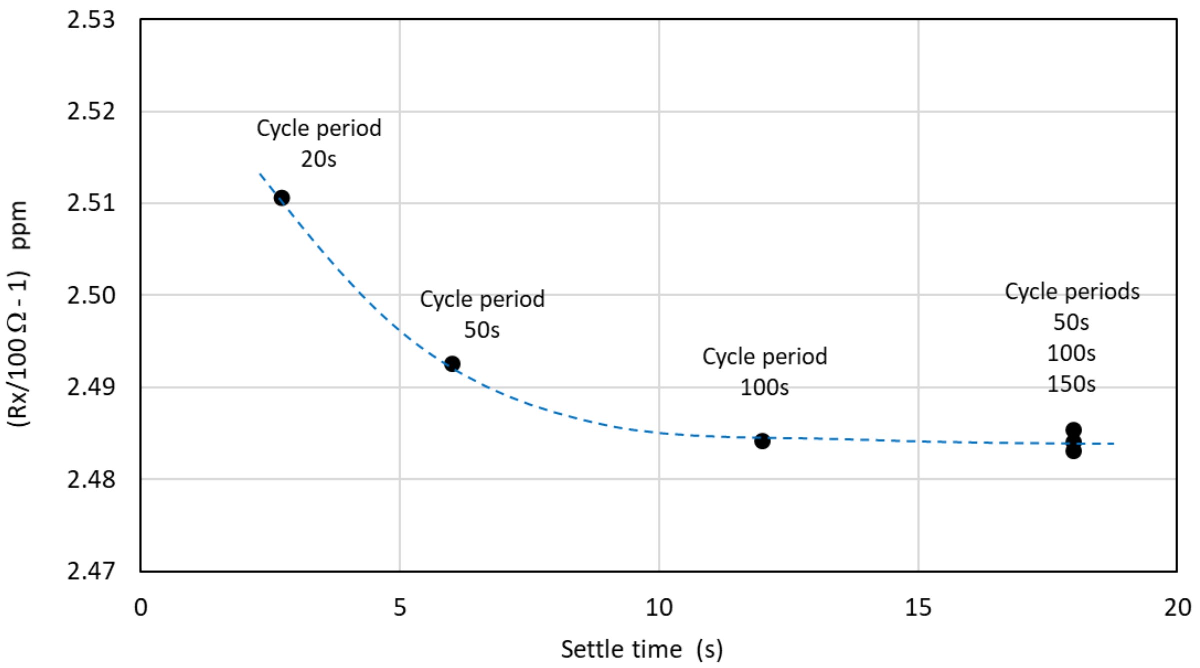

Figure 4: Preliminary measurements with NIM QHE system: influence of the settle time on measurements of the 100 Ω transfer standard carried out for different cycle times (dashed line is just a guide for eyes).

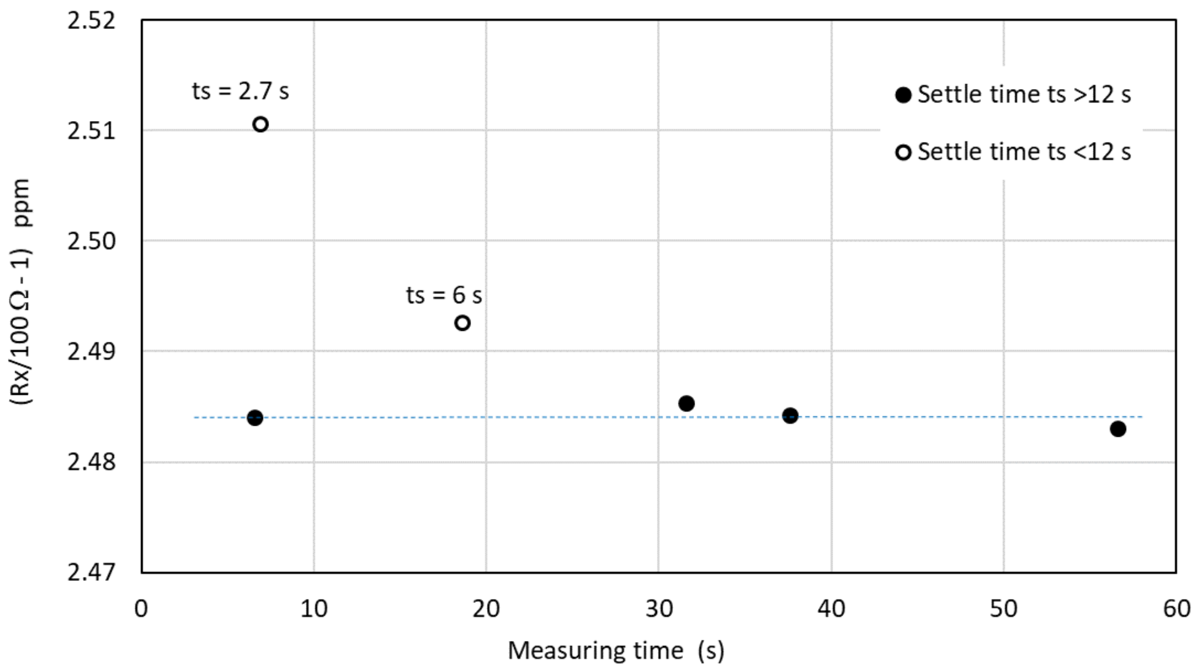

Figure 5: Preliminary measurements with NIM QHE system: independence of the measurements of the 100 Ω transfer standard from measuring time (tm) for settle times larger than 12 s (dashed line is just a guide for eyes).

5.2.2. NIM results for standard measurement cycle duration

The 100 Ω resistance standard was measured with a current of 5 mA (38.74 μA in the QHR). The standard current reversal cycle defined above was used.

On September 10, 2019 four measurements by NIM, interleaved with four BIPM measurements were conducted. Each of the NIM measurements consisted of a set of 26 consecutive cycles corresponding to an effective time of measurement of about 26 minutes.

As explained in section 5.1.2, due to the observed discrepancy between the NIM and the BIPM measurement results for this first series, a second series of measurements was performed on September 11, 2019 after the identified cause of the discrepancy was corrected (improper grounding path between the 100 Ω standard and the NIM CCC bridge). Five NIM measurements interleaved with five BIPM measurements were carried out in the same experimental conditions as the first series except for the corrected grounding of the 100 Ω.

As also mentioned in section 5.1.2, a slight linear drift was observed on the second NIM series of measurements. This drift, which is attributable to the drift of 100 Ω transfer standard, is also visible on the BIPM results with the same magnitude (approximately 4 parts in 10^9 on a time period of about 8 hours, see Figure 7).

The raw and 'power' corrected measurement results obtained on September 10 and 11 are shown in Table 5 along with the mean time of measurement and dispersion (standard deviation of the mean). The estimation of the power correction applied on NIM measurements is detailed in section 5.2.3 below. The measurement results of September 11 are not drift-corrected but the corresponding standard deviation u_A has been computed from the drift corrected measurements.

Date and Time	$(R_{NIM}/100\ \Omega)-1\quad /10^{-6}$		Dispersion $/10^{-6}$
	Raw measurements	'power' corrected measurements	
10/9/19 18:40	2.484 15	2.484 50	0.000 7
10/9/19 20:39	2.482 49	2.482 84	0.001 0
10/9/19 22:22	2.484 29	2.484 64	0.001 4
11/9/19 0:30	2.482 93	2.483 28	0.000 8
	Mean value =	**2.483 82**	
	Standard deviation, u_A =	**0.002 00**	
11/9/19 18:04	2.490 28	2.490 63	0.000 8
11/9/19 19:28	2.491 37	2.491 72	0.001 0
11/9/19 21:54	2.490 73	2.491 08	0.001 0
11/9/19 23:53	2.492 87	2.493 22	0.001 1
12/9/19 2:24	2.495 20	2.495 55	0.001 1
	Mean value =	**2.492 44**	
	Standard deviation, u_A =	**0.000 89**	

Table 5: NIM measurements of the 100 Ω standard in terms of $R_H(2)$, on September 10, 11 and 12, 2019. Each measurement corresponds to an integration time of 26 minutes. Results are expressed as the relative difference from the nominal 100 Ω value. Date and time correspond to the mean time of measurement and the dispersion to the standard deviation of the mean of the considered measurements. The standard deviation u_A for the measurement series performed on September 11 has been computed after having corrected the measurement results for drift.

The resistance values $\boldsymbol{R}_{\mathbf{NIM}}$ reported below correspond to the mean of 100 Ω measurements carried out by the NIM, corrected from the difference of powers dissipated in the resistor, on both days: September 10 and 11, 2019.

September 10, 2019: Mean value: $\boldsymbol{R}_{\mathbf{NIM}} = \mathbf{100 \times (1 + 2.483\,82 \times 10^{-6})\ \Omega}$

Relative standard uncertainty: $\boldsymbol{u}_{\mathbf{NIM}} = \mathbf{2.2 \times 10^{-9}}$

where u_{NIM} is calculated as the quadratic sum of: $u_{\mathrm{A}} = 2.0 \times 10^{-9}$, $u_{power} = 0.9 \times 10^{-9}$ the standard uncertainty on power correction and, from Table 3, $u_{\mathrm{B}} = 0.31 \times 10^{-9}$.

September 11, 2019: Mean value: $\boldsymbol{R}_{\mathbf{NIM}} = \mathbf{100 \times (1 + 2.492\,44 \times 10^{-6})\ \Omega}$

Relative standard uncertainty: $\boldsymbol{u}_{\mathbf{NIM}} = \mathbf{1.3 \times 10^{-9}}$

where u_{NIM} is calculated as the quadratic sum of: $u_{\mathrm{A}} = 0.9 \times 10^{-9}$, $u_{power} = 0.9 \times 10^{-9}$ the standard uncertainty on power correction and, from Table 3, $u_{\mathrm{B}} = 0.31 \times 10^{-9}$.

5.2.3. Estimation of the power correction of NIM measurements

Although the measurements performed by both the NIM and the BIPM were made for approximately the same rms current driven in the 100 Ω, the non-zero power coefficient of the 100 Ω resistor had nevertheless a small influence. This is due to the fact that not only the current magnitude has an influence on the dissipated power in the resistor, but also the shape and timing of the current reversal cycle.

From the current magnitudes and reversal cycle shapes used by the BIPM and NIM CCC bridges (see Figures 2 and 3 for BIPM and NIM, respectively), it was estimated that the effective power dissipated in 100 Ω by NIM was 0.59 mW higher than that dissipated by BIPM. Considering the power coefficient of the 100 Ω measured by the BIPM during the comparison, estimated to (-0.59 ± 0.84) parts in 10^9 per mW, a power correction was computed and applied to the NIM measurement results (Table 5). This correction was estimated to be (0.35 ± 0.90) parts in 10^9.

5.3. 100 Ω measurements comparison

For the sake of completeness, Figures 6 and 7 present the corrected interleaved measurements from NIM and BIPM on September 10, 11 and 12, 2019, respectively (from data in Tables 4 and 5). As explained in section 5.1.2, the measurement discrepancy observed in Figure 6 was due to an inappropriate grounding connection. Since this connection was corrected before carrying out the second series of measurements, only results obtained on September 11 and 12, 2019 were considered for the comparison, Figure 7.

During the second series of measurements, the 100 Ω standard experienced a slight linear drift but no significant instabilities of the 100 Ω transfer resistor were observed within the limit of the dispersion of the results. Therefore, no additional uncertainty component was included in the final comparison results. The standard deviation values (u_{A}) which were used for the computation of the comparison uncertainty (reported in Tables 4 and 5) were computed after correction for the drift.

The difference between NIM and BIPM was then calculated as the difference of the mean of the series of measurements carried out by both institutes on September 11 and 12, 2019 (mean values reported in Tables 4 and 5):

Relative difference NIM-BIPM: $\mathbf{(\boldsymbol{R}_{NIM} - \boldsymbol{R}_{BIPM}) / \boldsymbol{R}_{BIPM} = -0.4 \times 10^{-9}}$

Relative combined standard uncertainty: $\boldsymbol{u}_{\mathbf{comp}} = \mathbf{2.6 \times 10^{-9}}$

where u_{comp} is calculated as the quadratic sum of $u_{\mathrm{BIPM}} = 2.2 \times 10^{-9}$ and $u_{\mathrm{NIM}} = 1.3 \times 10^{-9}$.

Notice that the above value of u_{NIM} includes the power correction uncertainty resulting from the difference in the powers dissipated in the 100 Ω standard between NIM and BIPM. In case it wouldn't be necessary to apply this correction, u_{NIM} would be reduced to 1.0×10^{-9}.

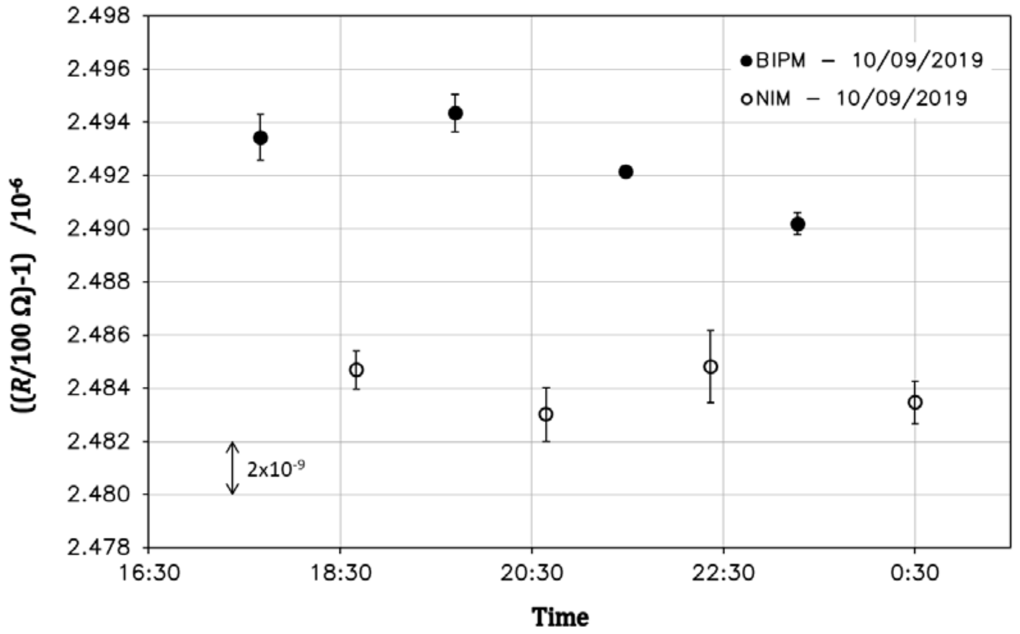

Figure 6: NIM (open circles) and BIPM (black dots) corrected measurements of the 100 Ω resistance R in terms of $R_H(2)$ on **September 10, 2019**. The recorded difference of about 8.5 parts in 10^9 is the result of a grounding loop caused by an improper grounding of the resistor during NIM measurements (see details section 5.1.2). The error bars correspond to the dispersion observed during each measurement.

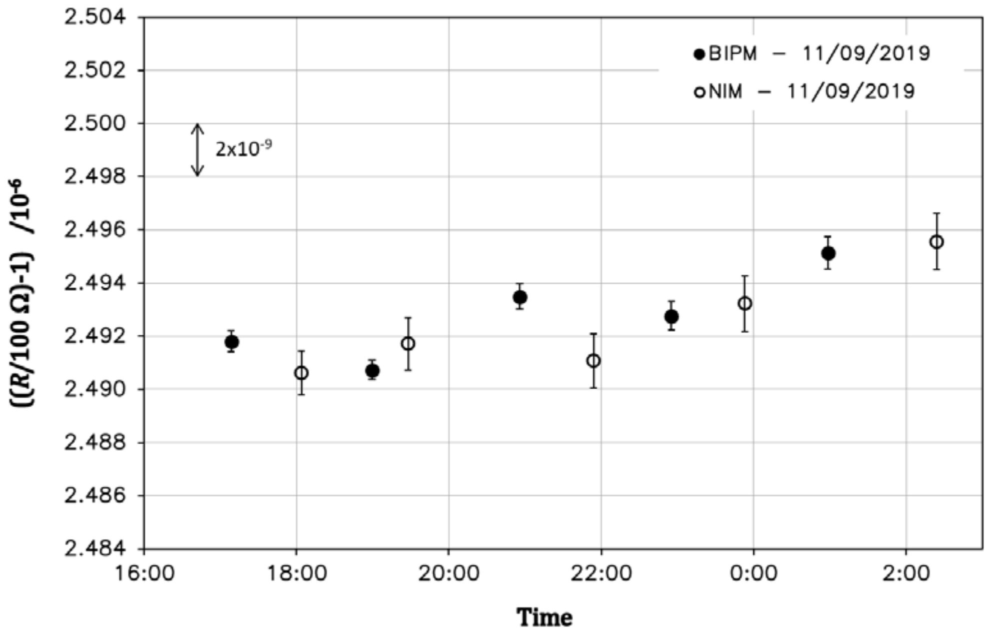

Figure 7: NIM (open circles) and BIPM (black dots) corrected measurements of the 100 Ω resistance R in terms of $R_H(2)$ on **September 11-12, 2019**. The error bars correspond to the dispersion observed during each measurement.

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

6.1. BIPM measurements of *K*1

For the measurement of the *K*1 ratio the 129:1 LFCC equipping the BIPM 1 Hz bridge for the $R_H(2)/100\ \Omega$ ratio measurement was replaced by a 100:1 LFCC. The rms current in the 10 kΩ standard was 50 µA corresponding to 5 mA in the 100 Ω standard. On September 12, 2019, these two standards were connected alternately to the BIPM and NIM bridges and seven BIPM measurements at 1 Hz were interleaved with six NIM measurements.

Each of the seven BIPM measurements, reported in Table 6, corresponds to the mean value of nine individual measurements corresponding to a total integration time of about 30 minutes. The 1 Hz - dc correction applied to the raw measurements is given in Table 1 (section 3.2). The dispersion corresponds to the standard deviation of the mean of the nine individual measurements.

It must be noticed that the fourth measurement of the series (mean time 17:56) has not been taken into account for the calculation of the mean value. Indeed, the tuning of the frequency resonance of the detection winding of the LFCC of the BIPM bridge was improperly carried out during this series, inducing a measurement error related to a loss of the sensitivity of the balance detection. This improper tuning was only detected after the series was finished and, as it was not possible to apply a correction, it was decided to exclude it from the comparison.

Date and Time	$(K1_{BIPM}/100)-1$ /10^{-6}		Dispersion /10^{-6}
	1 Hz measurements	'dc' corrected (1 Hz-'dc' correction)	
12/9/19 11:38	-1.170 9	-1.166 2	0.000 4
12/9/19 13:51	-1.169 0	-1.164 3	0.000 7
12/9/19 15:54	-1.171 4	-1.166 7	0.000 5
12/9/19 17:56	*-1.173 0*	*-1.168 3*	*0.000 5*
12/9/19 19:56	-1.170 3	-1.165 6	0.000 4
12/9/19 21:56	-1.170 2	-1.165 5	0.000 6
12/9/19 23:55	-1.169 6	-1.164 9	0.000 4
	Mean value =	**-1.165 5**	
	Standard deviation, u_A =	**0.000 9**	

Table 6: BIPM measurements of the ratio *K*1 (10 kΩ/100 Ω) on September 12, 2019. Each measurement corresponds to an integration time of about 30 minutes. Results are expressed as the relative difference from the nominal ratio value 100. Date and time correspond to the mean time of measurement and the dispersion to the standard deviation of the mean of the considered series of measurements.

The *K*1 ratio value reported below correspond to the mean of the ratio measurements carried out by the BIPM on September 12, 2019.

Mean value: $\boldsymbol{K1_{BIPM} = 100 \times (1 - 1.165\,5 \times 10^{-6})}$

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

where u_{BIPM} is calculated as the quadratic sum of $u_A = 0.9 \times 10^{-9}$ and, from Table 2, $u_B = 1.8 \times 10^{-9}$.

6.2. NIM measurements of *K*1

For the measurement of the *K*1 ratio, the currents through the 100 Ω and 10 kΩ resistance standards were, as for the BIPM, 5 mA and 50 µA, respectively. The current reversal cycle used was the 100 s standard one with t_r = 0.2 s, t_s =20 s and time t_m = 29.6 s (see Figure 3 for the definition of the time parameters). The turns ratio of the NIM CCC resistance bridge was set to 3200/32.

As mentioned earlier, six NIM measurements interleaved with seven BIPM measurements were carried out on September 12, 2019. Each NIM measurement consisted of a set of 26 consecutive current reversal cycles corresponding to an effective time of measurement of about 26 minutes.

Although both NIM and BIPM drove the same currents in the 100 Ω and 10 kΩ standards, a power correction was still applied on NIM results because of the difference of the effective powers dissipated in those resistors between NIM and BIPM (due to the difference in the current reversal cycle shapes used).

The difference of dissipated powers was evaluated from the cycle timing parameters and considering that power was only dissipated in the 100 Ω standard (negligible dissipation in the 10 kΩ standard). It was then estimated that the power dissipated by NIM in 100 Ω was 0.71 mW higher than that dissipated by BIPM. Then, using the power coefficient of the 100 Ω standard given in section 5.2.3, the power correction of the *K*1 ratio was estimated in turn to (-0.42 ± 0.90) × 10^{-9}.

The raw and 'power' corrected measurement results of NIM are reported in Table 7. They are expressed as the relative difference from the nominal ratio value 100 with a dispersion corresponding to the standard deviation of the mean of the 6 individual measurements.

Date and Time	$(K1_{NIM}/100)$-1 /10^{-6}		Dispersion /10^{-6}
	Raw measurements	'power' corrected measurements	
12/9/19 12:51	-1.160 7	-1.161 2	0.001 0
12/9/19 14:56	-1.161 2	-1.161 6	0.000 7
12/9/19 16:56	-1.159 9	-1.160 3	0.000 7
12/9/19 18:58	-1.160 5	-1.161 0	0.000 6
12/9/19 20:59	-1.159 8	-1.160 2	0.000 6
12/9/19 23:02	-1.15 84	-1.158 8	0.000 8
	Mean value =	**-1.160 5**	
	Standard deviation, u_A =	**0.001 0**	

Table 7: NIM measurements of the ratio *K*1 (10 kΩ/100 Ω) on September 12, 2019. Each measurement corresponds to an integration time of about 26 minutes. Results are expressed as the relative difference from the nominal ratio value 100. Date and time correspond to the mean time of measurement and the dispersion to the standard deviation of the mean of the considered set of measurements.

The *K*1 ratio value reported below correspond to the mean of the ratio measurements carried out by the NIM on September 12, 2019.

Mean value: $\mathbf{K1_{NIM} = 100 \times (1 - 1.160\,5 \times 10^{-6})}$

Relative standard uncertainty: $\mathbf{u_{NIM} = 1.4 \times 10^{-9}}$

where u_{NIM} is calculated as the quadratic sum of u_A =1.0 × 10^{-9} , u_{power} = 0.90 × 10^{-9} the standard uncertainty on power correction and, from Table 3, u_B = 0.26 × 10^{-9}.

6.3. Comparison of *K*1 measurements

Figure 8 presents the corrected measurements from NIM and BIPM on September 12, 2019 (data from Tables 6 and 7). Error bars correspond to the dispersion observed for each measurement.

Except for the fourth measurement of the BIPM for which the balance detection circuit was de-tuned (see section 6.1), no significant instabilities of the measured ratio *K*1 were observed within the limit of the measurement uncertainties. Therefore, no specific additional uncertainty component was included in the final comparison results.

In contrast, the NIM and the BIPM results are clearly shifted by about 5×10^{-9}. In spite of the different test measurements performed subsequently to the first series of September 12, no explanation to this offset could be found. During those tests, all the critical elements of the bridges were checked as well as connections and grounding. The limited time duration of the comparison didn't allow these investigations to be continued.

Consequently, the series of measurements of September 12, 2019 were kept as the final results of the comparison for the *K*1 ratio and the difference between NIM and BIPM was then calculated as the difference of the means of the series of measurements carried out by both institutes on that day (mean values reported in Tables 6 and 7):

Relative difference NIM-BIPM: $\mathbf{(K1_{NIM} - K1_{BIPM}) / K1_{BIPM} = 5.0 \times 10^{-9}}$

Relative combined standard uncertainty: $\mathbf{u_{comp} = 2.4 \times 10^{-9}}$

where u_{comp} is calculated as the quadratic sum of $u_{BIPM} = 2.0 \times 10^{-9}$ and $u_{NIM} = 1.4 \times 10^{-9}$.

Notice that the above value of u_{NIM} includes the power correction uncertainty resulting from the different powers dissipated in the 100 Ω standard between NIM and BIPM. In standard NIM conditions, u_{NIM} would have been reduced to 1.0×10^{-9}.

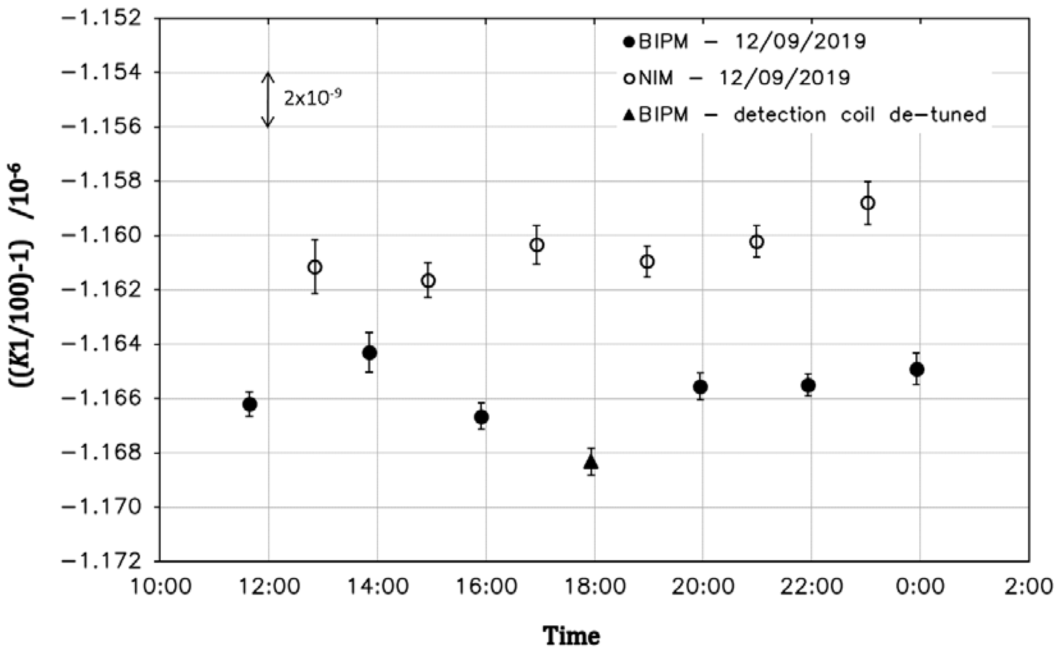

Figure 8: NIM (open circles) and BIPM (black dots) corrected measurements of the ratio *K*1 (10 kΩ/100 Ω) on September 12, 2019. The BIPM measurements made with the LFCC detection coil de-tuned is also reported (black triangle). The error bars correspond to the dispersion observed during each measurement.

7. Measurement of the (100 Ω/1 Ω) ratio *K*2

7.1. Preliminary measurements: influence of the current reversal cycle time

Previous studies [2-6] have shown that close attention must be paid to the Peltier effect in the 1 Ω standard when measuring the ratio *K*2. In particular, it has been shown in [2,4,5] that,

- the Peltier effect doesn't allow a true 'dc' value of this ratio to be reached when increasing the current reversal cycle duration (at least up to a duration of 340 s or more),
- there exists a threshold cycle time duration (typically of the order of 10 s or less) below which *K*2 measurements remain stable within the uncertainty of measurements.

In such a case, it seems preferable to perform the comparison of *K*2 measurements for short cycle times, for which the error due to Peltier effect is limited or null. It is the choice that was made during the previous BIPM-EM.K12 comparisons because the measurements performed by the participating NMI using a short cycle time, defined from preliminary measurements, could be directly compared to the 1 s current reversal cycle measurements made by the BIPM with its 1 Hz bridge.

So, a first series of preliminary measurements were carried out by NIM in order to determine the influence of the cycle time on *K*2 when the latter time was varied from 15 s to 300 s. The 15 s cycle period was the shortest possible with the NIM system that allowed an acceptable dispersion of the results, and the 300 s cycle time corresponds approximately to the BIPM CCC standard cycle time. The current in the 100 Ω and 1 Ω standards was 0.5 mA and 50 mA, respectively, and all the other experimental conditions were the same as those used for the measurement of *K*1 ratio.

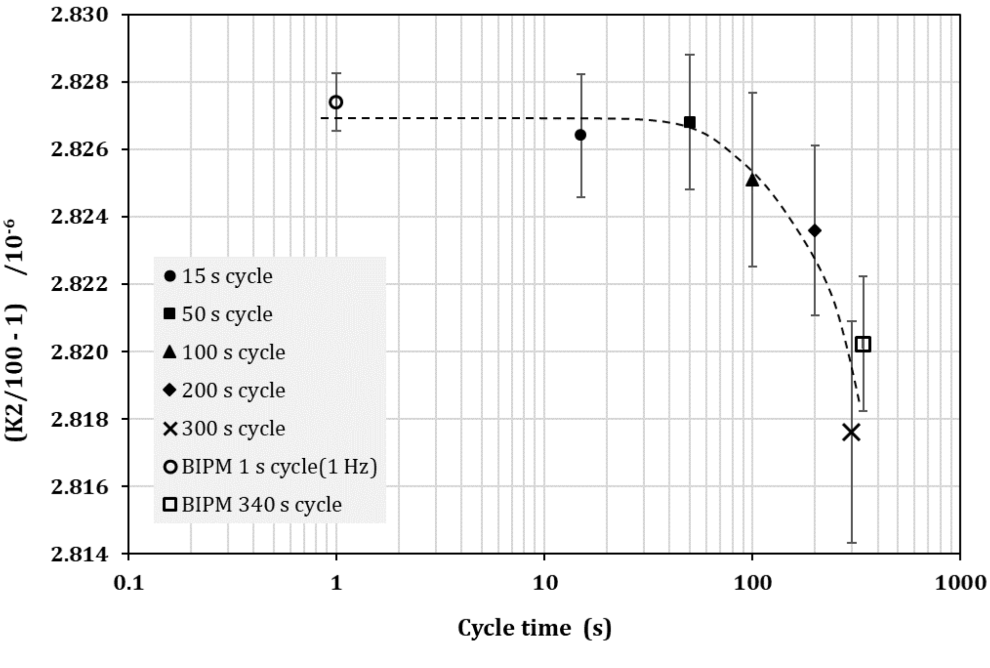

Figure 9: Preliminary measurements of the ratio *K*2 when the current reversal cycle time is varied from 15 s to 300 s. The dotted line is just a guide for the eye.

The results of the preliminary NIM measurements are reported on Figure 9, as well as the BIPM results for 1 Hz and for a 340 s cycle time. These measurements are not direct measurements but have been deduced from the measured difference between NIM and BIPM for the ratio *K*2 at short cycle times (15 s, see section 7.6), and from the 1 Hz-'dc' difference measured at the BIPM and reported in Table 1 (difference of the measurements performed with the 1 Hz bridge and with the CCC bridge for a 340 s cycle time). It should also be noted that, because the waveform of the 300 s reversal cycle of the NIM is different from that a 340 s cycle of the BIPM would have been, the BIPM estimated measurement at 340 s of Figure 9 is also corrected for the induced residual difference of the powers dissipated in the 1 Ω standard (power dissipated in the 100 Ω is negligible).

The results of Figure 9 are broadly similar to that obtained in [2-5]. As can be seen, the measured value of $K2$ remains unchanged (within the dispersion of measurement) for 15 s and 50 s cycle times and then, start to decrease for longer cycles from a threshold cycle time around 50 s.

It is interesting to note that the threshold time for which $K2$ starts to decrease is higher than those observed in references [2-5]. This could be due to the fact that the resistors used for this comparison were not the same, in particular the 1 Ω resistor, which was of different technology.

Finally, it can be remarked that the difference between $K2$ values measured by NIM and BIPM for the 340 s cycle are within about 2×10^{-9}.

7.2. Comparison measurements of *K*2

Although it would have been, a priori, possible to perform the comparison with either short or long cycle times, it was decided to carry it out as it was done during the previous BIPM.EM-K12 comparisons (since 2013), that is to say by comparing directly the 1 Hz BIPM measurements of $K2$ to the NIM measurements performed with the shortest cycle time (15 s in the present case). The main reason of this choice was to keep a better comparability with the previous comparisons (uniformity in the analysis of $K2$ measurements).

7.3. Influence of comparing measurements at 1 Hz on the BIPM uncertainty budget

When the 1 Hz bridge of the BIPM is no longer used as a transfer instrument referenced to its CCC bridge, one has to take into account the uncertainty associated with the accuracy of its room temperature current comparator and resistive divider [10]. The uncertainty budget for the use of the BIPM 1 Hz bridge for the measurement of the ratio $K2$ is reported in Table 8.

Furthermore, in order to cover for the assumption that the plot of $K2$ versus cycle time (Figure 9) shows a plateau corresponding to a negligible Peltier effect below the threshold cycle time of about 50 s (including the fact that this plateau actually begins for the same cycle time for square and sinusoidal cycle shapes), a relative standard uncertainty of $u_{\text{Peltier}} = 1.5 \times 10^{-9}$ was estimated.

Resistance ratio $K2$ (100 Ω/1 Ω)	
Relative standard uncertainties	$/10^{-9}$
Ratio error of the room temperature current comparator	1.0
Resistive divider calibration of the secondary current source	0.5
Finite gain of servo of the bridge balance	0.5
Combined type B uncertainty, u_B=	**1.2**

Table 8: Uncertainty budget for the measurement at 1 Hz of the ratio $K2$ using the BIPM 1 Hz bridge (the 1 Hz bridge being no longer used as a transfer instrument referenced to the BIPM CCC bridge).

7.4. BIPM measurements of *K*2

Five successive measurements of $K2$, interleaved with four NIM measurements, were carried out on September 14 and 15, 2019. For these measurements, the 100 Ω and 1 Ω standards were fed by 0.5 mA and 50 mA nominal rms currents, respectively. All the other experimental conditions were the same as for the measurement of ratio $K1$.

The raw 1 Hz BIPM measurements are summarized in Table 9 below. Each of the measurements corresponds to the mean value of eight individual measurements corresponding to a total integration time of about 27 minutes. The dispersion corresponds to the standard deviation of the mean of the eight measurement sets.

Date and Time	$(K2_{\mathrm{BIPM}}/100)-1$ /10^{-6}	Dispersion /10^{-6}
	1 Hz measurements	
14/9/19 17:06	2.833 4	0.000 5
14/9/19 19:00	2.833 1	0.000 3
14/9/19 20:44	2.833 2	0.000 6
14/9/19 22:35	2.832 6	0.000 6
15/9/19 0:17	2.833 5	0.000 4
Mean value =	**2.833 2**	
Standard deviation, u_A =	**0.000 4**	

Table 9: BIPM measurements of the ratio $K2$ (100 Ω/1 Ω) carried out on September 14, 2019. Each measurement corresponds to an integration time of about 27 minutes. Results are expressed as the relative difference from the nominal ratio value 100. Date and time corresponds to the mean time of measurement and the dispersion to the standard deviation of the mean of the considered series of measurements.

The $K2$ ratio value reported below correspond to the mean of the 1 Hz ratio measurements carried out by the BIPM on September 14 and 15, 2019.

Mean value: $\mathbf{K2_{BIPM} = 100 \times (1 + 2.833\,2 \times 10^{-6})}$

Relative standard uncertainty: $\mathbf{u_{BIPM} = 1.3 \times 10^{-9}}$

where u_{BIPM} is calculated as the quadratic sum of u_{A} =0.4 × 10^{-9} and, from Table 8, u_{B} = 1.2 × 10^{-9}.

7.5. NIM measurements of *K*2

As mentioned above, on the same day, September 14, 2019, the NIM carried out four measurements interleaved with the five BIPM measurements. They were conducted using a 15 s current reversal cycle (time parameters were t_{r} = 0.2s, t_{s} =2.6 s and t_{m} = 4.5 s). Each of the NIM measurement consisted of a set 160 consecutive cycles corresponding to an effective time of measurement of 24 minutes.

The raw measurement results from NIM are summarized in Table 10. These values correspond to the means of each of the four 24 minutes sets of measurements. The estimation of a 'power' correction was made on the same basis as for the $K1$ ratio but not applied for the reason given in section 7.5.1. Date and time correspond to the time of measurement and the dispersion to the standard deviation of the mean.

The $K2$ ratio value reported below corresponds to the mean of the ratio measurements carried out by the NIM on September 14, 2019.

Mean value: $\mathbf{K2_{NIM} = 100 \times (1 + 2.832\,2 \times 10^{-6})}$

Relative standard uncertainty: $\mathbf{u_{NIM} = 0.9 \times 10^{-9}}$

where u_{NIM} is calculated as the quadratic sum of u_{A} =0.6 × 10^{-9} and, from Table 3, u_{B} = 0.65 × 10^{-9}.

Date and Time	$(K2_{NIM}/100)$-1 /10^{-6}	Dispersion /10^{-6}
	Raw measurements	
14/9/19 18:06	2.831 7	0.002 0
14/9/19 19:49	2.832 6	0.001 8
14/9/19 21:37	2.832 8	0.001 6
14/9/19 23:24	2.831 7	0.001 6
Mean value =	**2.832 2**	
Standard deviation, u_A =	**0.000 6**	

Table 10: NIM measurements of the ratio *K*2 (100 Ω/1 Ω) carried out on September 14, 2019. Results are expressed as the relative difference from the nominal ratio value 100. Date and time corresponds to the mean time of measurement and the dispersion to the standard deviation of the mean of the concerned series of measurements.

7.5.1. Power correction of the *K*2 ratio

The currents driven in the 1 Ω and 100 Ω standards by the BIPM and the NIM were the same (50 mA and 0.5 mA, respectively) but the current reversal cycles shapes were different (1 Hz measurement for the BIPM and 15 s cycle time measurement for the NIM). As a consequence, there was a difference in the effective powers dissipated in the resistance standards during the measurements performed by the BIPM and the NIM.

A 'power' correction was then estimated and applied to the raw measurements of Table 10. This correction was computed from the difference of the effective powers dissipated in the 1 Ω standard between the NIM and the BIPM, and from the power coefficient of the ratio *K*2 (the power dissipated in the 100 Ω is considered negligible). The power coefficient was measured by the BIPM before the comparison and checked after.

The difference of the effective powers and the power coefficient of *K*2, having been evaluated to 17 µW and (3.93 ± 0.75) parts in 10^9 per mW, respectively, the 'power' correction was estimated to be equal to (-0.07 ± 0.80) part in 10^9. As this correction is quite small compared to its uncertainty, it was decided to use the uncorrected raw measurements for the comparison and add to the uncertainty budget an uncertainty component u_{power} of 0.8 part in 10^9 to account for the small effective power difference.

7.6. Comparison of *K*2 measurements

For the reasons detailed in the previous sections 7.1 and 7.2, the comparison between BIPM and NIM measurements of *K*2 ratio was performed using the 1 Hz measurements of the BIPM and the 15 s cycle time measurements of the NIM.

The four *K*2 BIPM measurements made on September 14 and 15, 2019 at 1 Hz (Table 9) were then compared to the four interleaved 15 s cycle time NIM measurements made on September 14, 2019 (Table 10).

Figure 10 presents the series of interleaved measurements with error bars corresponding to the dispersion observed for each measurement. It appears from the dispersion observed on the BIPM results that there are no significant instabilities of the measurements. Therefore, no specific additional uncertainty component was included in the final comparison results.

The difference between the NIM and the BIPM was computed as the difference of the means of the measurement values of Tables 9 and 10:

$$(K2_{NIM} - K2_{BIPM}) / K2_{BIPM} = -1.0 \times 10^{-9}$$

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

where u_{comp} is calculated as the quadratic sum of $u_{BIPM} = 1.3 \times 10^{-9}$, $u_{NIM} = 0.9 \times 10^{-9}$, $u_{Peltier} = 1.5 \times 10^{-9}$ (defined in section 7.3) and $u_{power} = 0.8 \times 10^{-9}$ (defined in section 7.5.1).

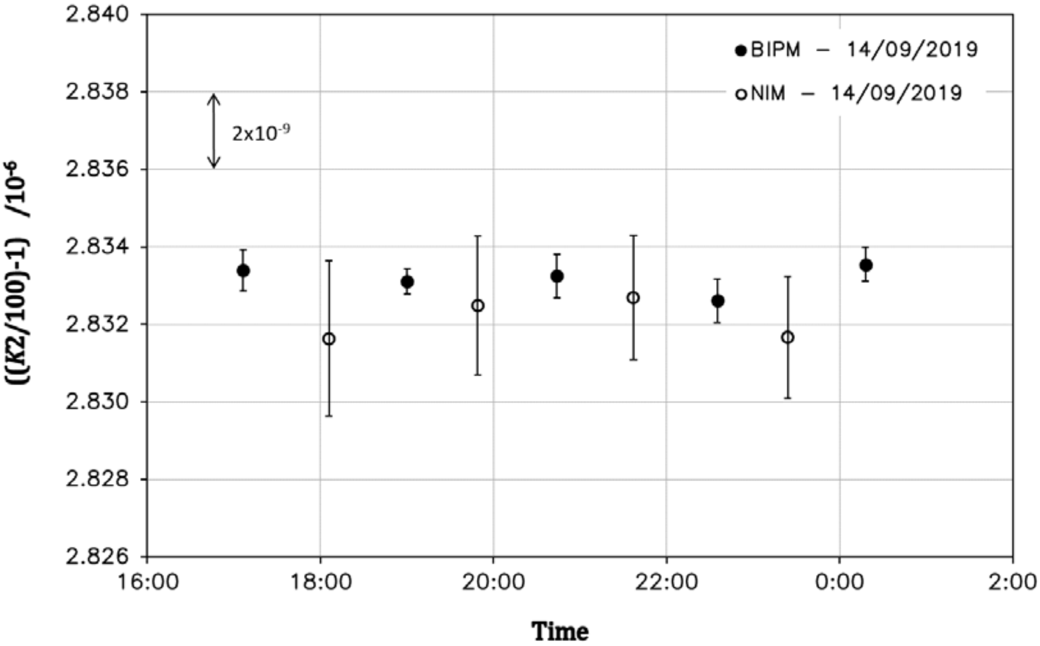

Figure 10: Measurement results for the ratio $K2$ on September 14, 2019: BIPM at 1 Hz (black dots) and NIM for a 15 s cycle time (open circles). Error bars correspond to the dispersion observed for each measurement.

8. Conclusion

The on-site key comparison BIPM.EM-K12 carried out in September 2019 between the BIPM and the NIM showed a good agreement in the measurements of a conventional 100 Ω resistor in terms of the quantized Hall resistance ($R_H(2)$), and in the determination of the resistance ratio $K2$ (100 Ω/1 Ω). A larger deviation was measured for the measurement of the ratio $K1$ (10 kΩ/100 Ω), which couldn't be explained during the limited time of the comparison despite several attempts to do so.

The comparison results for the measurement of $R_{100\Omega}$ in terms of $R_H(2)$ and of $K1$ and $K2$ ratios are summarized in Table 11.

$R_{100\Omega}$ in terms of $R_H(2)$	$(R_{NIM} - R_{BIPM}) / R_{BIPM}$ = **-0.4×10^{-9}**	u_{comp} = **2.6×10^{-9}**
$K1 = R_{10k\Omega}/R_{100\Omega}$	$(K1_{NIM} - K1_{BIPM}) / K1_{BIPM}$ = **5.0×10^{-9}**	u_{comp} = **2.4×10^{-9}**
$K2 = R_{100\Omega}/R_{1\Omega}$	$(K2_{NIM} - K2_{BIPM}) / K2_{BIPM}$ = **-1.0×10^{-9}**	u_{comp} = **2.3×10^{-9}**

Table 11: Summary of the results of the NIM-BIPM on-site comparison BIPM.EM-K12 and associated relative standard uncertainties. The measurement of $K2$ ratio was carried out at 1 Hz without 'dc' correction by the BIPM and with a cycle time of 15 s by the NIM.

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 12.

	Degree of equivalence D /10^{-9}	Expanded uncertainty U /10^{-9}
$R_{100\Omega}$ in terms of $R_H(2)$	**-0.4**	**5.2**
$K1 = R_{10k\Omega}/R_{100\Omega}$	**5.0**	**4.8**
$K2 = R_{100\Omega}/R_{1\Omega}$	**-1.0**	**4.6**

Table 12: 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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[1] http://kcdb.bipm.org/appendixb/KCDB_ApB_search.asp.

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