BUREAU INTERNATIONAL DES POIDS ET MESURES

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

Ongoing key comparison BIPM.EM-K12

Report on the June 2018 on-site comparison

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P. Gournay*, B. Rolland* and C. Sanchez**

* Bureau International des Poids et Mesures (BIPM)
** National Research Council Canada (NRC-CNRC), Canada

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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 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 three comparisons have been successfully completed whose results may be consulted on the webpage of the Key Comparison Data Base (KCDB) [1].

In June 2018 a new BIPM.EM-K12 comparison was carried out at the National Research Council Canada (NRC-CNRC), Canada. It was the first time the NRC 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 by at least a factor of 10 of the comparison uncertainty.
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 (NRC 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 $(R_{\text{NRC}} - R_{\text{BIPM}})/R_{\text{BIPM}}$ where R_{BIPM} and R_{NRC} are the values attributed by the BIPM and NRC, respectively.

(ii) The scaling from 100 Ω to 10 kΩ, through the measurement of the ratio $R_{10\text{k}\Omega}/R_{100\Omega}$ 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 $(K1_{\text{NRC}} - K1_{\text{BIPM}})/K1_{\text{BIPM}}$ where $K1_{\text{BIPM}}$ and $K1_{\text{NRC}}$ are the values attributed by the BIPM and the NRC, 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 $(K2_{\mathrm{NRC}} - K2_{\mathrm{BIPM}})/K2_{\mathrm{BIPM}}$ where $K2_{\mathrm{BIPM}}$ and $K2_{\mathrm{NRC}}$ are the values attributed by the BIPM and the NRC, respectively.

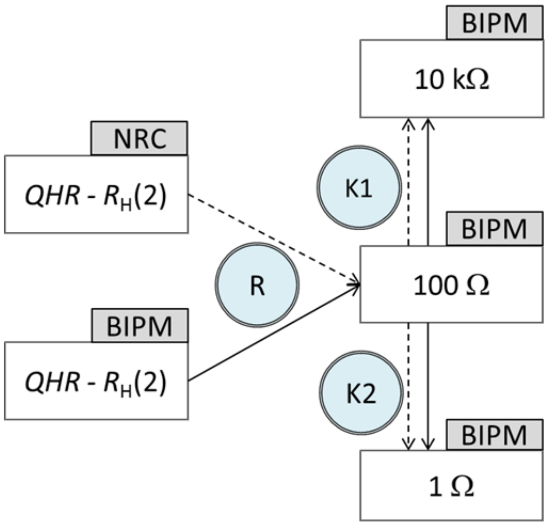

Figure 1: Schematic of the onsite comparison carried out at the NRC in June 2018. Rectangles represent the resistances to be compared and circles correspond to the resistance R or the ratios $K1$ and $K2$ to be measured. Solid and dashed arrows stand for the measurements with the 1 Hz-bridge of the BIPM or with the CCC bridge of the NRC, 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, particularly those induced by Peltier effect, has reached a stable value. As will be seen later on in this report the estimation of the dc-resistance value of a resistor, or a ratio of resistors, may be vitiated by a significant measurement error especially for the 1 Ω standard. This issue has already been discussed in several papers [2-5] in which an extended description of the observed phenomena is provided.

3. The BIPM measurement system and the transfer standards

3.1. Implementation of the QHE

A complete transportable QHE reference [6] 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 [7]. 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

[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

devices are suitable for a realization of the ohm (Ω-90) meeting all the requirements of the CCEM guidelines [8] for a relative standard uncertainty down to 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 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 performances of these devices are detailed in [9,10].

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 NRC to the 100 Ω resistor in terms of R_{K-90} 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 of CSIRO-type (s/n: S-64202) and the 100 Ω and the 10 kΩ standards were Tegam resistors of type SR102 (s/n: A2030405) and SR104 (s/n: K204039730104), respectively. All three resistors were fitted in individual temperature-controlled enclosures held at 25°C. The temperature-regulation system might 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 'dc' value was measured with the BIPM CCC whilst the 1 Hz value with the transportable 1Hz-bridge subsequently used on-site during the comparison. The differences are applied as corrections to the measurements performed at 1 Hz meaning that the 1Hz-bridge is used as a transfer instrument referenced to the BIPM CCC.

The frequency corrections (1 Hz-'dc') are reported in table 1 for each of the three transfer standards. The main possible error 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 [11], 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.

Resistance or Resistance ratio	1 Hz – 'dc' Correction $/10^{-9}$	Standard Uncertainty $/10^{-9}$
$(R_{100\Omega}(1\text{ Hz}) - R_{100\Omega}(\text{dc}))\ /\ 100$	-9.88	1.2
$(K1(1\text{ Hz}) - K1(\text{dc}))\ /\ 100$	9.46	1.2
$(K2(1\text{ Hz}) - K2(\text{dc}))\ /\ 100$	27.31	2.0

Table 1: Value of the 1 Hz to 'dc' corrections (in relative) 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 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 $R_{H}(2)/100\ \Omega$ 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 ideally configured to match the reference polarity reversal cycle of the BIPM CCC. In case this is not feasible, a correction must be applied on the participating institute's measurements based on additional characterization of the influence of the polarity reversal rate on the actual measured resistance ratio.

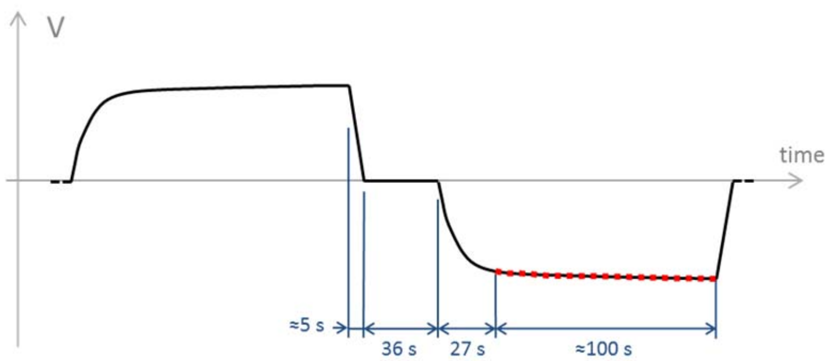

Figure 2: Schematic representation of the reference current signal with polarity reversals used in the BIPM CCC-bridge. The reversal cycle comprises a waiting time of about 36 s at zero current. The red dotted line corresponds to the sampling time period.

3.3. Uncertainty budget

Table 2 summarizes the BIPM 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 $R_{K\text{-}90}$, as well as the measurement uncertainties for both the 10 kΩ/100 Ω and 100 Ω/1 Ω ratios ($K1$ and $K2$, respectively).

	Relative standard uncertainties / 10^{-9}		
Parameters \ *Ratio*	$R_{H}(2)/100\ \Omega$	10 kΩ/100 Ω	100 Ω/1 Ω
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
QHE device dissipation	0.5	-	-
Correction of the 1 Hz-to 'dc' difference	1.2	1.2	2.0
Combined type B uncertainty, u_{B}=	**2.0**	**1.9**	**2.5**

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

4. The NRC measurement system

4.1. Implementation of the QHE

The QHE system presently at use at NRC has been in operation since 2008. The cryogenic system consists of a 9 T magnet and a pumped helium-4 insert with a base temperature of 1.3 K. The samples are GaAs heterostructures fabricated at NRC and engineered to have i=2 plateau centers at magnetic field densities between 6 and 8 T [12]. Under these conditions, suitable samples typically have a longitudinal resistance $R_{xx} \approx 10^{-9}\ R_K$ for currents up to 78 µA.

4.2. Resistance bridge

The NRC resistance bridge uses a CCC and a DC SQUID as a null detector for magnetic flux [13]. The CCC has 15 windings with turn numbers ranging from 1 to 1000 and scaled in a way that allows self-checking of the ratio errors of all windings. The voltage drop across the resistors is sensed with an EM N11 nanovolt meter. In operation, two feedback loops run simultaneously to keep zero magnetic flux in the CCC and zero voltage at the input of the nanovolt meter. The ratio of the resistors is obtained by measuring the ratio of a small current (injected into a winding of the CCC) to the primary current, using a precision digital multimeter and a calibrated resistor.

The bridge is routinely used at NRC for resistance measurements between 1 Ω and 100 kΩ including direct measurements of 10 kΩ, 1 kΩ, 100 Ω and 50 Ω directly against the QHE (R_K/2).

4.3. Uncertainty budget

The NRC uncertainty budget is summarized in table 3.

	Relative standard uncertainties / 10^{-9}		
	$R_H(2)$/100 Ω	10 kΩ/100 Ω	100 Ω/1 Ω
CCC ratio errors	0.07	0.07	0.07
Feedback loop errors	0.1	0.1	2.6
Readout calibration	0.1	0.1	0.1
Noise induced SQUID offset	0.2	0.2	0.2
Leakage	0.2	0.1	0.1
QHE sample dissipation	0.3	-	-
Power coefficient of resistors	0.2	0.2	-
Current reversal timing	0.6	0.5	-
Combined type B uncertainty (k=1), u_B=	**0.8**	**0.6**	**2.6**

Table 3: Contributions to the combined type B uncertainty (k=1) for the NRC measurement of the three mentioned resistance ratios.

The last two components in table 3 are specific to this comparison as they arise from differences in current reversal timing and waveform of the two systems. These effects are discussed in sections 5.2.2. and 5.2.3. The higher feedback-loop error for the 100 Ω/1 Ω measurements (2.6 parts in 10^9) is due to the fast reversal rate used in this comparison. Increasing the settle time by a few extra seconds would significantly decrease the integrator error but, unfortunately, this would increase the uncertainty of the comparison due to the Peltier effect, as explained in section 7.1.

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 [8] 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 (6×10^{-10}). Subsequent series of measurements were taken from the central pair of contacts only.

5.1.2. BIPM results

As mentioned above, a rms current of 40 µA was drawn in the quantum Hall device. The current in the 100 Ω transfer standard was then a bit less than 5.2 mA, corresponding to a Joule heating dissipation of about 2.7 mW.

After a preliminary set of measurements on June 26, 2018, five measurements of the 100 Ω standard were interleaved with four measurements by NRC on June 27, 2018. 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: $(R_{\mathrm{BIPM}}/100\ \Omega) - 1$.

Each measurement reported in the table below is the mean value of seven individual measurements corresponding to a total integration time of about 23 minutes.

Time	$(R_{\mathrm{BIPM}}/100\ \Omega)-1$ /10^{-6}		Dispersion /10^{-6}
	1 Hz measurements	'dc' corrected (1 Hz-'dc' correction)	
11 :06	-0.619 8	-0.609 9	0.001 0
12 :28	-0.619 1	-0.609 3	0.000 6
13:49	-0.618 6	-0.608 7	0.001 0
15:05	-0.618 4	-0.608 5	0.000 4
16 :26	-0.618 9	-0.609 0	0.000 8
	Mean value =	**-0.609 1**	
	Standard deviation, u_A =	**0.5×10^{-9}**	

Table 4: BIPM measurements of the 100 Ω standard in terms of $R_H(2)$, on June 27, 2018. Results are expressed as the relative difference from the nominal 100 Ω value.

BIPM result: $\boldsymbol{R_{\mathrm{BIPM}} = 100 \times (1 - 0.609\,1 \times 10^{-6})\ \Omega}$

Relative standard uncertainty: $\boldsymbol{u_{\mathrm{BIPM}} = 2.1 \times 10^{-9}}$

where u_{BIPM} is calculated as the quadratic sum of $u_A = 0.5 \times 10^{-9}$ and, from table 2, $u_B = 2.0 \times 10^{-9}$.

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

5.2.1. Preliminary tests

The NRC QHR sample, serial number V0053-10-28, was cooled down to 1.3 K and biased at the center of the i = 2 plateau, B = 6.8 T. All contact resistances were measured to be less than 1 Ω. With an applied current of 38.74 µA, the longitudinal voltage V_{xx} was measured to be (-0.02 ± 0.13) nV on one side of the sample and (0.13 ± 0.08) nV on the other side.

5.2.2. Power coefficient of the 100 Ω resistor

Even though both BIPM and NRC measurements were made with approximately the same rms current, the power coefficient of the 100 Ω resistor had a small effect on the measurements because the BIPM CCC measurement cycle has a plateau at zero, resulting in a smaller average power. NRC determined a power coefficient of (-0.8 ± 0.3) parts in 10^9 per mW for the 100 Ω resistor. It was also estimated that the average power dissipation was 27 % lower for the measurements with the BIPM CCC (i.e. an average power of 1.8 mW). A correction of (0.4 ± 0.2) parts in 10^9 was applied to the NRC measured ratios to compare with the BIPM measured ratios.

5.2.3.Influence of the measurement cycle duration

The current waveform and cycle timing of the NRC CCC is shown in figure 3. A typical measurement uses a ramp time (t_r) of 3 s, a settle time (t_s) of 15 s and a measurement time (t_m) of 35 s, for a total cycle period of 106 s. The NRC measurements were made using this standard cycle. An additional measurement was made with a cycle period of 340 s (t_r = 10 s, t_s = 53 s, t_m = 107 s), comparable to the BIPM CCC measurement cycle, to determine the difference in the results obtained with each configuration. For this ratio ($R_H(2)/100\ \Omega$), the difference was within the type A uncertainty of the measurement and no correction was applied.

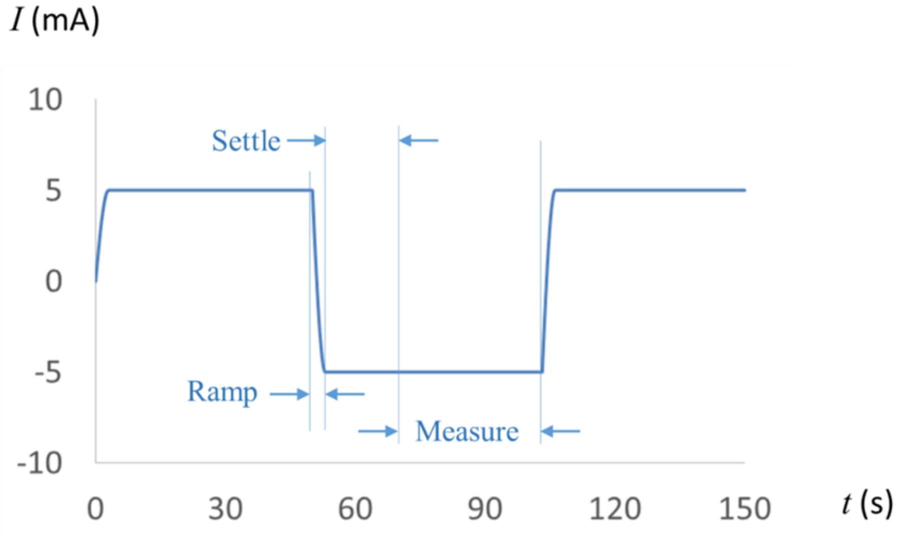

Figure 3: Typical current waveform and reversal cycle timing of the NRC CCC. The ramp time (t_r), settle time (t_s) and measurement time (t_m) of the standard cycle used for measurements were 3 s, 15 s and 35 s, respectively, for a total cycle period of 106 s.

5.2.4. NRC results for standard measurement cycle duration

Four measurements, interleaved with the BIPM measurements shown on table 4, were made on June 27, 2018. Each NRC measurement consisted of 12 independent points and a total measurement time of 21 minutes. The results are summarized in table 5.

Time	(R_{NRC}/100 Ω)-1 /10^{-6}		Dispersion /10^{-6}
	Raw measurements	'Power' corrected	
11:58	-0.610 1	-0.609 7	0.000 3
13:08	-0.610 4	-0.601 0	0.000 7
14:32	-0.609 9	-0.609 5	0.000 4
15:48	-0.609 4	-0.609 0	0.000 4
	Mean value =	**-0.609 6**	
	Standard deviation, u_A =	**0.4×10^{-9}**	

Table 5: NRC measurements of the 100 Ω standard in terms of $R_H(2)$ on June 27, 2018. Results are expressed as the relative difference from the nominal 100 Ω value.

NRC result: $\boldsymbol{R_{NRC} = 100 \times (1 - 0.609\,6 \times 10^{-6})\ \Omega}$

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

where u_{NRC} is calculated as the quadratic sum of: $u_A = 0.4 \times 10^{-9}$, and from table3, $u_B = 0.8 \times 10^{-9}$.

5.3. 100 Ω measurements comparison

Figure 4 presents the corrected interleaved measurements from NRC and BIPM on June 27, 2018 (from data in tables 4 and 5). Error bars correspond to the dispersion observed for each measurement.

No significant instabilities of the 100 Ω transfer resistor were observed within the limit of the dispersion of the results and therefore no additional uncertainty component was included in the final comparison results.

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

Relative difference NRC-BIPM: $\boldsymbol{(R_{NRC} - R_{BIPM}) / R_{BIPM} = -0.5 \times 10^{-9}}$

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

where u_{comp} is calculated as the quadratic sum of $u_{BIPM} = 2.1 \times 10^{-9}$ and $u_{NRC} = 0.9 \times 10^{-9}$.

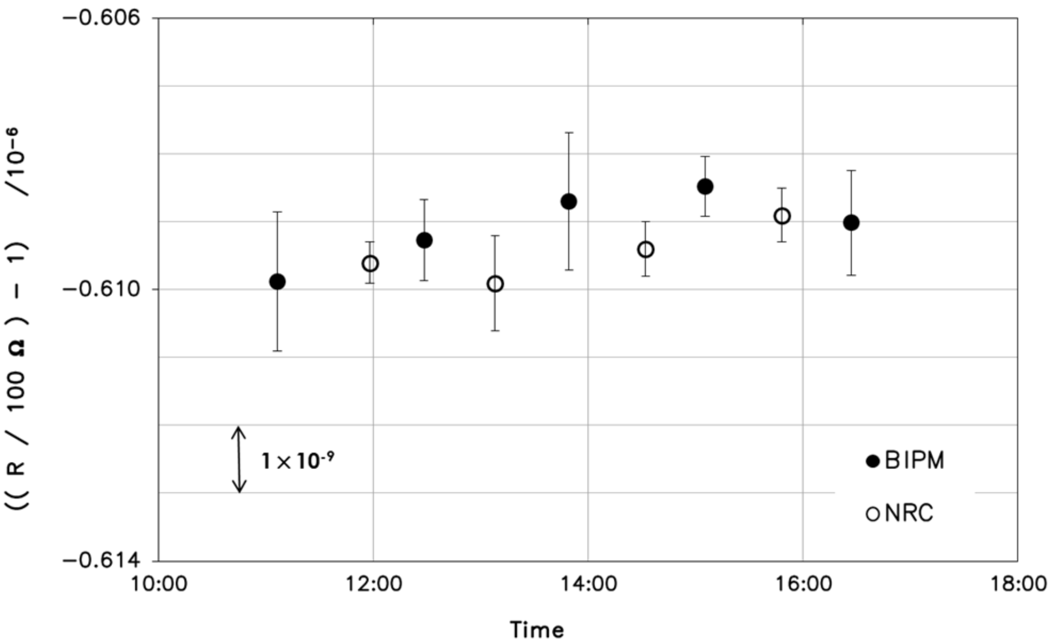

Figure 4: NRC (white circles) and BIPM (black dots) corrected measurements of the 100 Ω resistance R in terms of $R_H(2)$ on June 27, 2018. The uncertainty bars correspond to the dispersion observed during each measurement.

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

6.1. BIPM measurements of *K*1

For the measurement of the $K1$ ratio the 129:1 LFCC equipping the BIPM 1 Hz-bridge for $R_H(2)$ / 100 Ω ratio measurement was replaced by a 100:1 current comparator. 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 NRC bridges. Three series of interleaved measurements of ratio $K1$ were performed on three days - June 28, June 29 and July 2 - for the reasons explained in section 6.2.3.

All the BIPM measurements carried out during this period are reported in the table 6. Each of the measurement results corresponds to the mean value of eight individual measurements corresponding to a total integration time of about 27 minutes. The associated dispersion corresponds to the standard deviation of the eight measurements.

The $K1$ ratio values reported below correspond to the mean of the ratio measurements carried out by the BIPM on each of the three days: June 28, June 29 and July 2, 2018.

BIPM result on **June 28, 2018**: $\boldsymbol{K1_{\mathrm{BIPM}} = 100 \times (1 + 0.816\,2 \times 10^{-6})}$

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

where u_{BIPM} is calculated as the quadratic sum of $u_A = 1.1 \times 10^{-9}$ and, from table 2, $u_B = 1.9 \times 10^{-9}$.

BIPM result on **June 29, 2018**: $\boldsymbol{K1_{\mathrm{BIPM}} = 100 \times (1 + 0.815\ 2 \times 10^{-6})}$

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

where u_{BIPM} is calculated as the quadratic sum of $u_{\mathrm{A}} = 0.5 \times 10^{-9}$ and, from table 2, $u_{\mathrm{B}} = 1.9 \times 10^{-9}$.

BIPM result on **July 2, 2018**: $\boldsymbol{K1_{\mathrm{BIPM}} = 100 \times (1 + 0.816\ 6 \times 10^{-6})}$

Relative standard uncertainty: $\boldsymbol{u_{\mathrm{BIPM}} = 1.9 \times 10^{-9}}$

where u_{BIPM} is calculated as the quadratic sum of $u_{\mathrm{A}} = 0.1 \times 10^{-9}$ and, from table 2, $u_{\mathrm{B}} = 1.9 \times 10^{-9}$.

Date	Time	$(K1_{\mathrm{BIPM}}/100)$-1 /10^{-6}		Dispersion /10^{-6}
		1 Hz measurements	'dc' corrected (1 Hz-'dc' correction)	
28/06/2018	10:07	0.825 7	0.816 2	0.000 6
	11:36	0.826 1	0.816 7	0.000 8
	13:32	0.825 4	0.815 9	0.000 3
	17:15	0.824 1	0.814 6	0.000 6
	18:51	0.827 1	0.817 7	0.000 7
		Mean value =	**0.816 2**	
		Standard deviation, u_A =	**0.001 1**	
29/06/2018	09:54	0.824 9	0.815 5	0.000 4
	11:25	0.824 1	0.814 6	0.000 5
	12:44	0.824 8	0.815 4	0.000 5
	13:58	0.824 3	0.814 8	0.000 8
	15:26	0.825 3	0.815 9	0.000 8
		Mean value =	**0.815 2**	
		Standard deviation, u_A =	**0.000 5**	
02/07/2018	14:23	0.827 5	0.818 0	0.000 8
	18:03	0.825 5	0.816 0	0.001 0
	20:00	0.824 9	0.815 4	0.000 9
	21:41	0.824 0	0.814 5	0.000 6
		Interpolated value at mean time =	**0.816 6**	
		Standard deviation (drift corrected), u_A =	**0.000 1**	

Table 6: BIPM measurements of the ratio $K1$ (10 000 Ω/100 Ω) on June 28, June 29 and July 2, 2018. Results are expressed as the relative difference from the nominal ratio value 100. Standard deviation u_A for the measurement series on July 2 is calculated with the reported measurement values but corrected from drift.

6.2. NRC measurements of $K1$

6.2.1. Power coefficient of the 100 Ω resistor

NRC measured the ratio $K1$ with the same rms current values as those used by the BIPM, i.e. 50 µA and 5 mA in the 10 000 Ω and 100 Ω standards, respectively.

As discussed in section 5.2.2, a correction of (0.5 ± 0.2) parts in 10^9 was applied to the NRC measured ratios.

6.2.2. Influence of the measurement cycle duration

The NRC measurements were made with the standard cycle period of 106 s (t_r = 3 s, t_s = 15 s, t_m = 35 s) specified in section 5.2.3. One additional measurement was made with a cycle period of 340 s (t_r = 10 s, t_s = 53 s, t_m = 107 s) to determine the difference between the two configurations. The observed difference was $(\mathrm{Ratio}_{106} - \mathrm{Ratio}_{340})/\mathrm{Ratio}_{106} = (1.4 \pm 0.5) \times 10^{-9}$ and a correction was applied to the NRC measurements accordingly.

6.2.3. NRC results for standard measurement cycle duration

The standard NRC CCC bridge was configured with a N_1/N_2 = 100 ratio with N_1 = 1000, N_2 = 10. Measurements were made on three days: June 28, 29 and July 2, 2018.

The June 28 measurements are shown in table 7. After two measurements had been completed, a small but clear difference was observed between the BIPM and NRC measurements. Part of the difference was eventually found to be due to the difference between the standard NRC cycle (106 s) and the slow, 340 s cycle, as discussed in section 6.2.2. However, an accurate measurement of this difference was not made until July 2 and so, on June 28, several changes were made in the measurement configuration, as indicated in the comments, to try to discover any possible systematic errors. Other shorter tests were made, such as changing various cables and changing the grounding point of the bridge from the low of the current source to the low of the nanovoltmeter. None of these changes made any significant difference in the measured ratio.

On June 29 four standard measurements were made which were interleaved with the BIPM measurements (table 6). These measurements are shown in table 7.

Finally, a last set of measurements was made on July 2 (also reported table 7). The first measurement shown on the table was an indirect measurement, via the QHE, which was meant to be a consistency check and a test for systematic errors. In this case, the 10 kΩ/100 Ω ratio was determined by first measuring the ratio of $R_\mathrm{H}(2)$/100 Ω and then measuring the ratio of $R_\mathrm{H}(2)$/10 kΩ. The rest of the measurements on this day were direct measurements made with the standard configuration.

Additionally, two more measurements were made on July 2. The first one, at 15:28, was a long measurement with a 340 s cycle with the uncorrected result of:

$$(K1_{340}/100) - 1 = (0.818\,5 \pm 0.000\,4) \times 10^{-9}.$$

The second one, made at 18:28 with a 10 s measurement cycle, yielded the following result (again, without corrections):

$$(K1_{10}/100) - 1 = (0.826\,4 \pm 0.001\,7) \times 10^{-9}.$$

This last measurement was made with the ground connection at the low of the nanovoltmeter, for the reasons explained in section 7.2.2.

Date	Time	$(K1_{NRC}/100)-1$ $/10^{-6}$			Dispersion $/10^{-6}$	Comments
		Raw measurement	Power corrected	Cycle corrected		
June 28, 2018	11:02	0.821 0	0.820 5	0.819 1	0.000 6	Standard measurement
	13:02	0.818 9	0.818 4	0.817 0	0.000 5	Standard measurement
	14:14	0.819 3	0.818 8	-	0.001 1	Slow cycle 340 s
	14:58	0.817 9	0.817 4	0.816 0	0.000 6	Case of 100 Ω resistor grounded
	15:21	0.818 5	0.818 0	0.816 6	0.001 1	Additional filtering on primary source
	15:40	0.819 7	0.819 2	0.817 8	0.001 1	SQUID on high bandwith mode
	16:14	0.817 4	0.816 9	0.815 5	0.001 1	$N_1 = 500$, $N_2 = 5$
	16:42	0.818 7	0.818 2	0.816 8	0.000 8	$N_1 = 1600$, $N_2 = 16$
	17:51	0.819 1	0.818 6	0.817 2	0.001 8	$N_1 = 200$, $N_2 = 2$
	19:36	0.819 2	0.818 7	0.817 3	0.001 0	Standard measurement
Mean value =				**0.817 2**		
Standard deviation, u_A =				**0.001 1**		
June 29, 2018	10:40	0.819 2	0.818 7	0.817 3	0.000 8	Standard measurement
	12:10	0.818 9	0.818 4	0.817 0	0.000 6	Standard measurement
	13:21	0.819 3	0.818 8	0.817 4	0.000 5	Standard measurement
	14:44	0.819 4	0.818 9	0.817 5	0.000 5	Standard measurement
Mean value =				**0.817 3**		
Standard deviation, u_A =				**0.000 2**		
July 2, 2018	11:29	0.821 6	0.821 1	0.819 7	0.001 0	Standard meas., two steps via the QHE
	12:35	0.821 5	0.821 0	0.819 6	0.001 0	Standard measurement
	16:48	0.819 0	0.818 5	0.817 1	0.000 6	Standard measurement
	18:58	0.818 6	0.818 1	0.816 7	0.000 8	Standard measurement
	20:53	0.817 5	0.817 0	0.815 6	0.000 7	Standard measurement
Interpolated value at mean time =				**0.817 3**		
Standard deviation (drift corrected), u_A =				**0.000 3**		

Table 7: NRC measurements of the (10 000 Ω/100 Ω) ratio $K1$ on June 28, June 29 and July 2, 2017. Results are expressed as the relative difference from the nominal ratio value 100. The mean value and standard deviation on July 2 doesn't include the first measurement of the day ("Standard meas., two steps via the QHE"). Standard deviation u_A for the measurement series on July 2 is calculated with the reported measurement values but corrected from drift.

The $K1$ ratio values reported below correspond to the mean of the ratio measurements carried out by the NRC on each of the three days: June 28, June 29 and July 2, 2018.

NRC result on **June 28, 2018**: $\boldsymbol{K1_{NRC} = 100 \times (1 + 0.817\,2 \times 10^{-6})}$

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

where u_{NRC} is calculated as the quadratic sum of $u_A = 1.1 \times 10^{-9}$ and, from table 3, $u_B = 0.6 \times 10^{-9}$.

NRC result on **June 29, 2018**: $\boldsymbol{K1_{\mathrm{NRC}} = 100 \times (1 + 0.817\,3 \times 10^{-6})}$

Relative standard uncertainty: $\boldsymbol{u_{\mathrm{NRC}} = 0.6 \times 10^{-9}}$

where u_{NRC} is calculated as the quadratic sum of $u_{\mathrm{A}} = 0.2 \times 10^{-9}$ and, from table 3, $u_{\mathrm{B}} = 0.6 \times 10^{-9}$.

NRC result on **July 2, 2018**: $\boldsymbol{K1_{\mathrm{NRC}} = 100 \times (1 + 0.817\,3 \times 10^{-6})}$

Relative standard uncertainty: $\boldsymbol{u_{\mathrm{NRC}} = 0.7 \times 10^{-9}}$

where u_{NRC} is calculated as the quadratic sum of $u_{\mathrm{A}} = 0.3 \times 10^{-9}$ and, from table 3, $u_{\mathrm{B}} = 0.6 \times 10^{-9}$.

6.3. Comparison of *K*1 measurements

Figures 5, 6 and 7 present the corrected measurements from NRC and BIPM on June 28, June 29 and July 2, 2018, respectively (data from tables 6 and 7). Error bars correspond to the dispersion observed for each measurement.

All the measurements carried out by NRC on June 28 for the different settings of their measuring system - as mentioned in section 6.2.3 and table 7 - are reported in figure 5. Some of these measurements were performed one after the other in order to shorten the time between tests. As a consequence, the measurements in this series are not strictly interleaved. However, as no nonlinear drift can be detected on this complete day of measurements, the means of the BIPM and NRC series of measurements at the mean time can be compared.

Measurements made by NRC on June 29 and July 2 using only the standard cycle specified in section 5.2.3 were all interleaved with a BIPM measurement, figures 6 and 7. As can be remarked on these figures, no drift was experienced by the standard resistors on June 29 while the measurements on July 2 show a clear drift of one or both of those standards. However, the drift being clearly linear, the means interpolated at the mean time of measurement can be compared. Notice that the first data point of figure 7 (triangle) corresponds to the indirect measurement, via the QHE, of the ratio *K1* (determined by first measuring the ratio of $R_{\mathrm{H}}(2)/100\ \Omega$ and then measuring the ratio of $R_{\mathrm{H}}(2)/10\ \mathrm{k}\Omega$). This measurement has not been included in the measurement set used for the interpolation at the mean time.

Furthermore, as can be seen on figures 6, 7 and 8, no significant instabilities of the standards can be evidenced within the limit of the dispersion of the results and, therefore, no additional uncertainty component was included in the final results.

The difference between NRC and BIPM can then be calculated as the mean of the differences computed from measurements obtained on June 28, June 29 and July 2, 2018. The three differences and their mean as well as the associated relative combined uncertainties are reported in table 8.

<table>
<tr><th rowspan="2">Date</th><th rowspan="2">Relative difference NRC-BIPM
$(\boldsymbol{K1_{\mathrm{NRC}} - K1_{\mathrm{BIPM}}})/\boldsymbol{K1_{\mathrm{BIPM}}}$</th><th colspan="2">NRC</th><th colspan="2">BIPM</th><th rowspan="2">RSS of the u_A</th></tr>
<tr><th>u_A</th><th>u_B</th><th>u_A</th><th>u_B</th></tr>
<tr><td>June 28</td><td>$+1.0 \times 10^{-9}$</td><td>1.1×10^{-9}</td><td rowspan="3">0.6×10^{-9}</td><td>1.1×10^{-9}</td><td rowspan="3">1.9×10^{-9}</td><td>1.6×10^{-9}</td></tr>
<tr><td>June 29</td><td>$+2.1 \times 10^{-9}$</td><td>0.2×10^{-9}</td><td>0.5×10^{-9}</td><td>0.5×10^{-9}</td></tr>
<tr><td>July 2</td><td>$+0.7 \times 10^{-9}$</td><td>0.3×10^{-9}</td><td>0.1×10^{-9}</td><td>0.3×10^{-9}</td></tr>
<tr><td colspan="4">**Mean relative difference NRC-BIPM**</td><td colspan="3">$\boldsymbol{+1.3 \times 10^{-9}}$</td></tr>
<tr><td colspan="4">**Relative combined standard uncertainty of the mean, u_{comp}**</td><td colspan="3">$\boldsymbol{2.1 \times 10^{-9}}$</td></tr>
</table>

Table 8: Mean relative difference between NRC and BIPM and its associated relative uncertainty calculated from the measurements carried out on June 28, June 29 and July 2, 2018. The combined uncertainty u_{comp} is calculated as the root sum squared (RSS) of the type B uncertainties and of the mean of the RSS of the u_A.

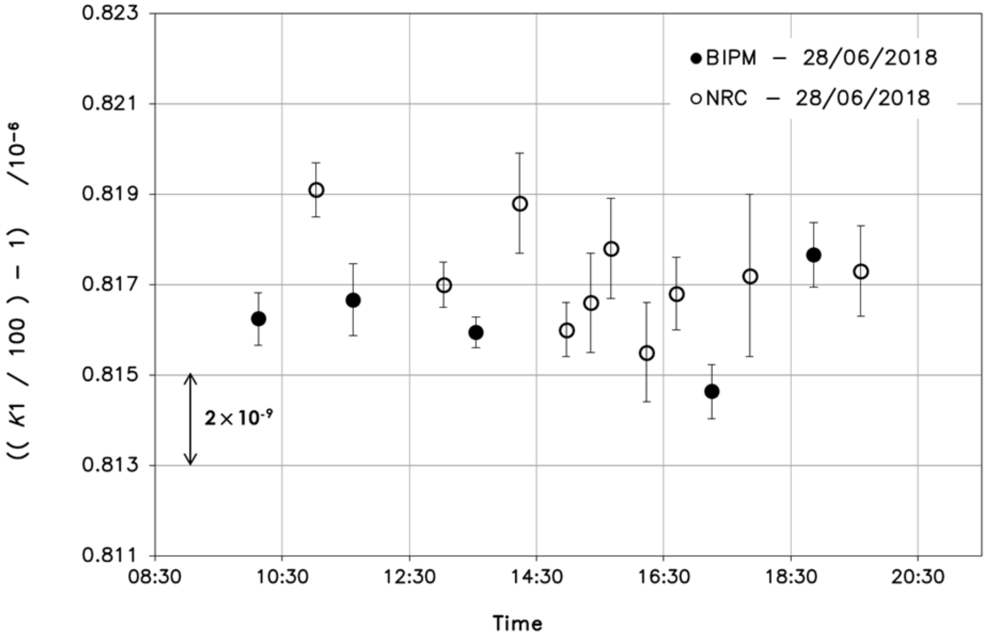

Figure 5: NRC (white circles) and BIPM (black dots) corrected measurements of the ratio $K1$ (10 000 Ω/100 Ω) on June 28, 2018. The uncertainty bars correspond to the dispersion observed during each measurement

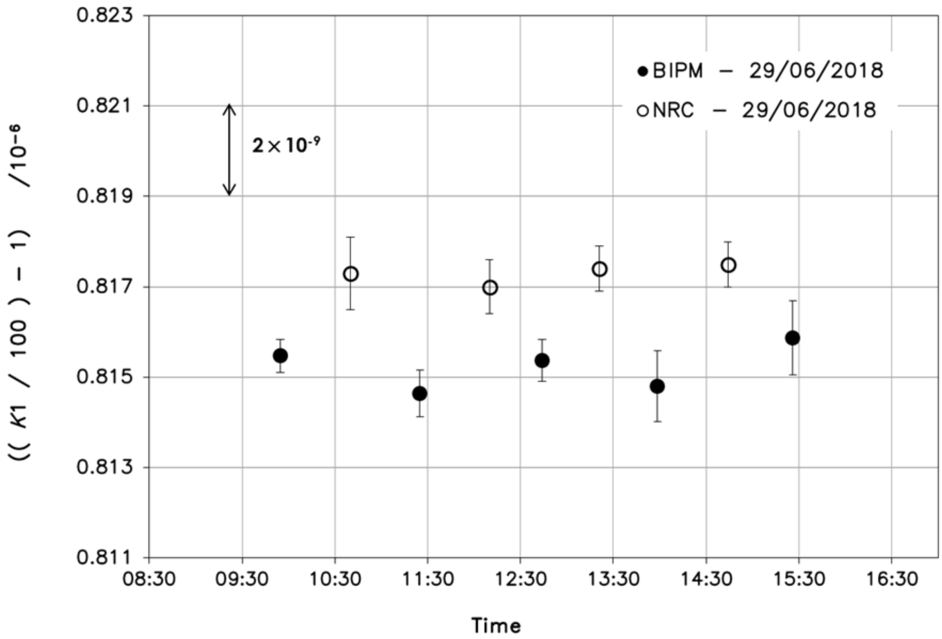

Figure 6: NRC (white circles) and BIPM (black dots) corrected measurements of the ratio $K1$ (10 000 Ω/100 Ω) on June 29, 2018. The uncertainty bars correspond to the dispersion observed during each measurement

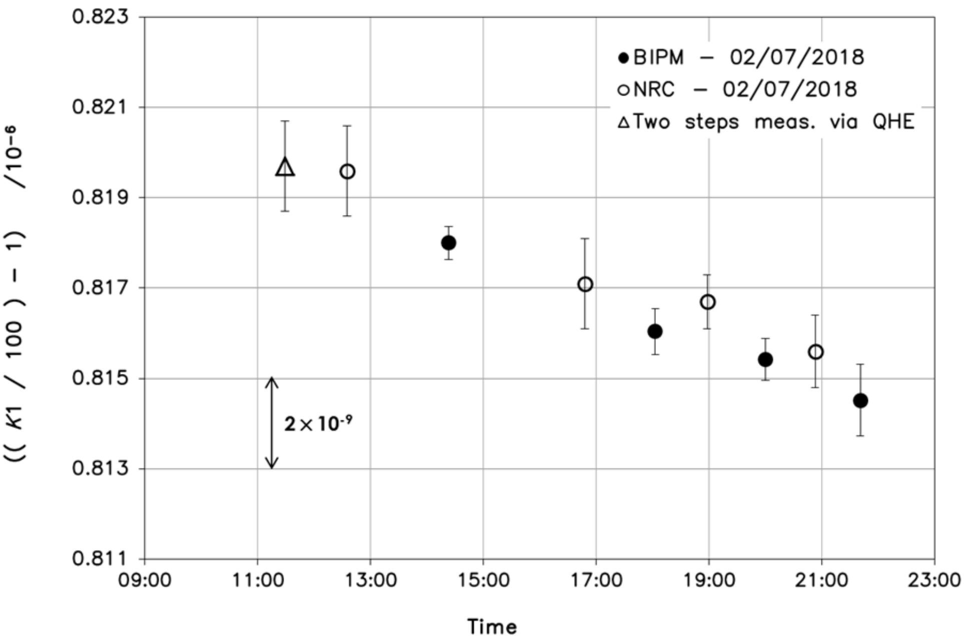

Figure 7: NRC (white circles) and BIPM (black dots) corrected measurements of the ratio $K1$ (10 000 Ω/100 Ω) on July 2, 2018 (correction from drift not applied). The uncertainty bars correspond to the dispersion observed during each measurement

7. Measurement of the (100 Ω / 1 Ω) ratio $K2$

7.1. Influence of the cycle time duration

As already pointed out in previous comparisons [2,3,4,14], the Peltier effect in the 1 Ω resistor generates a non-negligible voltage drop across its voltage terminals which depends on the current cycle duration and, additionally, on the delay before measurement after reversing the current [14]. When the cycle duration is varied from typically 5 s to 350 s, the error this voltage drop induces on the value of the 1 Ω standard is of the order of several parts in 10^8 (for the CSIRO-type 1 Ω resistor used during this comparison). This error is almost entirely transferred to the *K2* ratio value as the Peltier effect remains negligible in the 100 Ω resistor (typically 1 to few parts in 10^9, depending on the type of resistor).

The dependence of the ratio *K2* on cycle time duration has been clearly evidenced and quantified in [2, 4]. The main conclusions that have been drawn from these works is that the conditions of dc measurement of the ratio *K2* were not sufficiently well-defined in regard to the resolution of the two measurement systems in comparison and that a better comparability of the *K2* ratio could be obtained for the shortest cycle times investigated during the comparison (1 Hz for the BIPM and about 0.2 Hz for the compared NMIs).

On the basis of these previous observations, a study of the influence of the cycle timing on the *K2* value has been carried out in this comparison, similarly to what had been done in [2, 14]. Measurements have been performed on July 1, 2018 using the NRC CCC-bridge for cycle times ranging from 6.6 s to 340 s, all other conditions of measurement being the same as those used for the measurement of the $K1$ ratio but with a nominal current of 50 mA in the 1 Ω standard (0.5 mA in the 100 Ω).

The results are summarized in table 9. Measurements with cycle times between 6.6 s and 19.3 s were made by taking a direct reading with the nanovoltmeter, in order to minimize the error due to insufficient settling of the feedback loop. To account for the gain of the nanovoltmeter, a correction was calculated by comparing the 9.8 s measurement in table 9 with the measurement results presented in table 11, section 7.4.

Those results are also shown on figure 8 below together with the measurements of *K2* of the BIPM at 1 Hz (sinusoidal signal). An additional measurement at 0.5 Hz has been made by modifying slightly the BIPM 1 Hz-bridge. It is reported as well on figure 8.

Date	Time	Cycle time (s)	Ramp time (s)	Settle time (s)	Measuring time (s)	$(K2/100) - 1$ /10^{-6}		U_A / 10^{-9}
						Raw measurement	corrected	
July 1, 2018	17:43	6.6	0.1	2.5	0.7	-0.680 1	-0.685 1	0.001 4
	17:51	9.8	0.5	3	1.4	-0.681 8	-0.686 7	0.001 5
	18:05	13	0.1	5	1.4	-0.683 3	-0.688 2	0.001 5
	18:20	15.9	0.1	5	2.8	-0.684 1	-0.689 0	0.001 3
	18:32	19.3	0.1	6	3.5	-0.686 2	-0.691 2	0.001 2
	19:54	100	5	15	30	-0.695 3	-0.695 3	0.000 8
	19:23	340	10	53	107	-0.702 8	-0.702 8	0.000 6

Table 9: Effect of the measurement cycle duration on the measured ratio *K2*. Measurement were carried out on July 1, 2018 using the CCC-bridge from NRC. Ramp time, settle time and measuring time refer to the definition of figure 3.

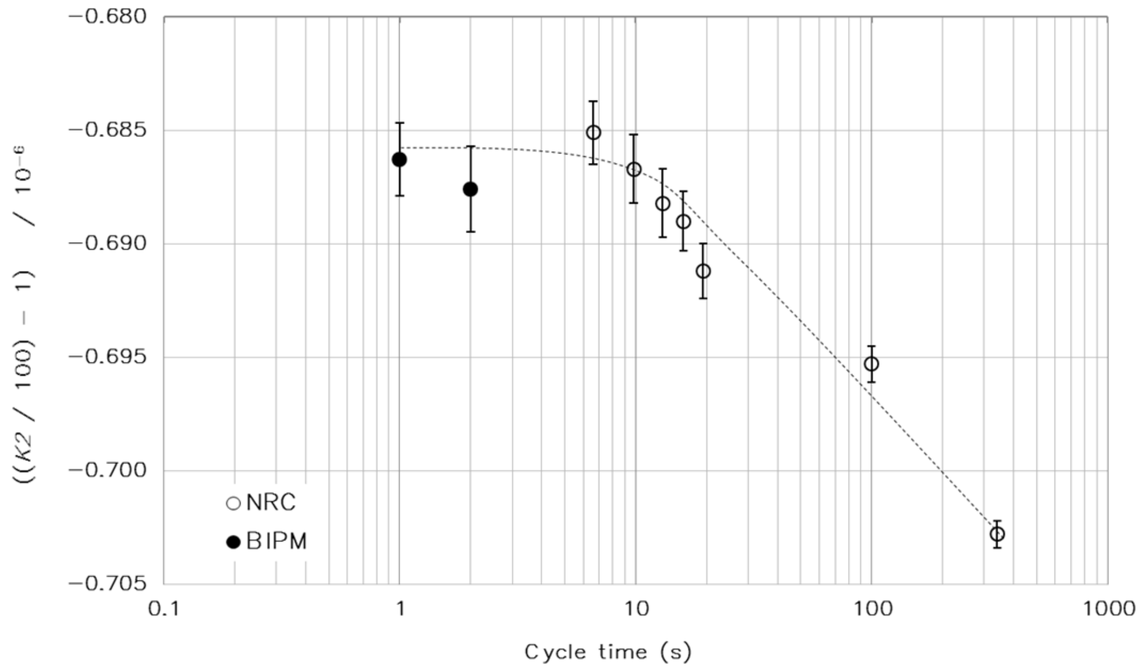

Figure 8: Differences from nominal value of $K2$ ratio measured by the BIPM and by the NRC for several current reversal frequencies. The $K2$ values of the BIPM presented in this graph were obtained with sinusoidal current reversal having frequencies of 0.5 Hz and 1 Hz. The *K2* values of NRC were obtained with the current reversal cycle represented in figure 3 and for cycle times ranging from 6.6 s to 340 s. Error bars correspond to measurement dispersion (type A). The dotted line is just a guide for the eyes.

The “shape” of the variation of *K2* versus cycle time is very similar to that previously observed during the on-site comparison carried out at PTB [2] and CMI [4]. Hence, the same observation can be made:

- no ‘dc’ value of the ratio *K2* can be extrapolated when the cycle time is increased up to at least 340 s (no convergence towards a stable ratio value);
- the difference between BIPM and NRC measurements for long cycles (340 s) has a value clearly higher than the resolution of both measuring systems; a comparison of long cycle measurements on July 1, 2018 has shown a relative difference equal to $(K2_{\mathrm{NRC}}\text{-}K2_{\mathrm{BIPM}})/K2_{\mathrm{BIPM}} = -15.7\times10^{-9}$;
- a kind of plateau can be observed for short cycle times which could be explained by the fact that below a given value, the cycle time becomes smaller than the time constant of the thermal emf induced by the Peltier effect [3]. This plateau is found to range at least from 1 s to 10 s cycle times.

Finally, it is worthwhile to notice that in the present comparison the CCC-bridge used by NRC is different from that which has been used during the comparison at PTB and CMI, those two NMIs using the same CCC-bridge type. Also, the 1 Ω standard used at NRC was the same one used at CMI but not at PTB.

7.2. Comparability of BIPM and NRC measurements of *K*2

As it has been concluded for the previous comparisons at PTB and CMI, it would not be satisfactory to compare the supposed ‘dc’ values of ratio *K*2 determined by NRC and BIPM for a 340 s cycle time. Indeed, even if the reason is not well understood and would require further investigation, a ‘true dc value’ cannot be estimated with a reasonable uncertainty in regard to the resolution of the measuring systems.

However, the apparent existence of a plateau for cycle times below 10 s suggests that the equivalence of the measuring systems of NRC and BIPM can still be demonstrated if we only consider the measurements of *K*2 ratio made on this plateau. Consequently, it was decided to compare *K*2 measurements carried out at 1 Hz for the BIPM and at 9.8 s cycle time for NRC.

7.3. Influence on the *K*2 comparison 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 [9]. The uncertainty budget for the use of the BIPM 1 Hz-bridge for the measurement of the ratio *K*2 is reported in table 10.

Furthermore, in order to cover the assumptions that the plateau corresponding to a negligible Peltier effect is reached at a cycle time of 9.8 s and that the plateau begins for the same cycle time when using square or sinusoidal cycle shapes, a relative standard uncertainty component of $u_{\mathrm{Peltier}} = 2\times10^{-9}$ was estimated.

Resistance ratio *K*2 (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 uncertainty, u_B=	**1.2**

Table 10: Uncertainty budget associated with 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 measurements of *K2* ratio at 1 Hz, interleaved with five NRC measurements at 9.8 s cycle time, were carried out on July 1, 2018. The current was 50 mA in the 1 Ω standard and 0.5 mA in the 100 Ω standard (the same 100:1 LFCC as for *K1* measurements was used).

BIPM measurements are summarized in table 11. Each of the measurements corresponds to the mean value of eight individual measurements corresponding to a total integration time of about 27 minutes. The associated dispersion corresponds to the standard deviation of the eight measurements.

Time	$(K2_{\mathrm{BIPM}}/100)$ - 1 /10^{-6}	Dispersion /10^{-6}
	1 Hz measurements	
09:39	-0.679 4	0.000 7
10:44	-0.678 5	0.000 6
11:41	-0.680 0	0.000 8
12:47	-0.683 9	0.000 7
13:47	-0.684 2	0.000 5
Interpolated value at mean time =	**-0.681 5**	
Standard deviation (drift corrected), u_A =	**1.2 × 10^{-9}**	

Table 11 : BIPM measurements of *K2*, on July 1, 2018. Results are expressed as the relative difference from the nominal ratio value 100. Standard deviation u_A is calculated with the reported measurement values but corrected from drift.

BIPM result: $\boldsymbol{K2_{\mathrm{BIPM}} = 100 \times (1 - 0.681\,5 \times 10^{-6})\ \Omega}$

Relative standard uncertainty: $\boldsymbol{u_{\mathrm{BIPM}} = 1.7 \times 10^{-9}}$

where u_{BIPM} is calculated as the quadratic sum of $u_{\mathrm{A}} = 1.2 \times 10^{-9}$ and, from table 10, $u_{\mathrm{B}} = 1.2 \times 10^{-9}$.

7.5. NRC measurements of *K2*

NRC performed *K2* measurements not only for a cycle time of 9.8 s but also for a cycle timing reproducing as accurately as possible the current waveform characteristics of the BIPM CCC. For this, the NRC CCC was programmed as shown in figure 9, with t_{r} = 5 s, t_{s} = 22 s, t_{m} = 100 s and a time at zero current (t_{z}) of 36 s (total cycle time of 337 s).

For the measurements at 9.8 s cycle time, the normal CCC reversal waveform was used (figure 3), with t_{r} = 0.5 s, t_{s} = 3 s, t_{m} = 1.4 s.

A first set of measurements with those two cycle times was made June 30, 2018. These measurements were made with the NRC CCC grounded at the low of the secondary source, which is the standard grounding configuration. For a standard measurement with a settle time of 15 s and a ratio N_1/N_2 = 100, this scheme has a leakage error of about 0.1 parts in 10^9, independent of the value of the resistors and therefore, it is advantageous when the resistor on the secondary side is of high value (e.g. R_2 = 10 kΩ).

However, the measurements with a fast measurement cycle (9.8 s) which were made for this comparison are not made routinely at NRC and it was realized only at the end of the day that the standard grounding scheme could introduce a significant leakage error with such fast reversal rates. This was confirmed by moving the ground connection to the low of the nanovoltmeter, which caused a change in the measured ratio of about 6 parts in 10^9 (9.8 s cycle).

A second set of measurement was then made on July 1, 2018, with the low of the nanovoltmeter grounded. The measurements performed for a cycle time of 9.8 s are summarized in table 12. The error due to insufficient settling of the feedback loop of the nanovoltmeter was estimated and a correction was applied.

The additional measurements made using a time cycle similar to that of the BIPM-CCC will be presented in section 7.7.

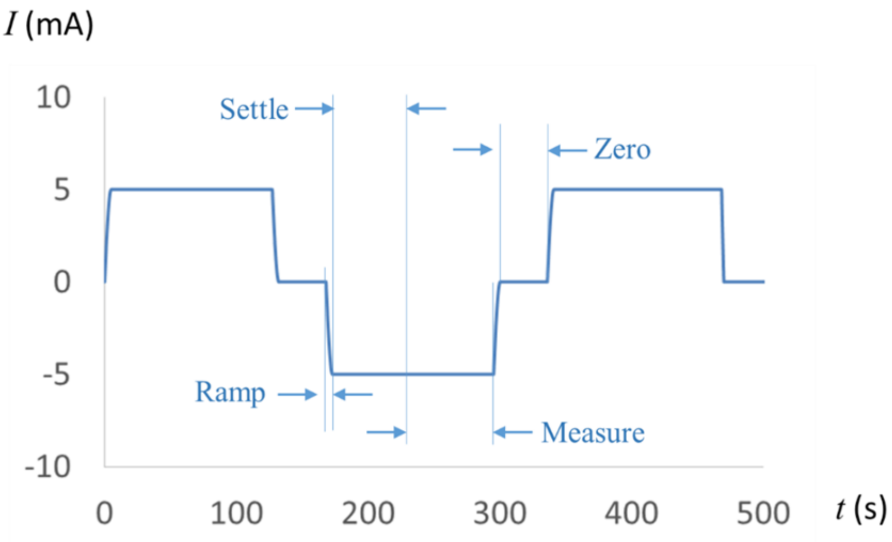

Figure 9: Cycle time programmed on NRC CCC to reproduce as accurately as possible the current waveform characteristics of the BIPM CCC. The timing of the cycle was: ramp time t_r = 5 s, settle time t_s = 22 s, measuring time t_m = 100 s and a time at zero current (t_z) of 36 s (total cycle time of 337 s).

Time	Measurement Cycle (s)	$(K2_{NRC} / 100) - 1$ /10^{-6}		Dispersion /10^{-6}
		Raw measurements	Corrected measurements	
10:16	9.8	-0.676 6	-0.679 2	0.001 5
11:13	9.8	-0.679 8	-0.682 4	0.002 2
12:08	9.8	-0.677 0	-0.679 6	0.002 4
13:23	9.8	-0.680 7	-0.683 3	0.002 3
14:13	9.8	-0.681 7	-0.684 3	0.002 1
Interpolated value at mean time =			**-0.681 4**	
Standard deviation (drift corrected), u_A =			**1.4×10^{-9}**	

Table 12: NRC measurements of $K2$, for a standard cycle time of 9.8 s, performed on July 1, 2018. Results are expressed as the relative difference from the nominal ratio value 100. The dispersion corresponds to the standard deviation of each individual measurement. Standard deviation u_A is calculated with the reported measurement values but corrected from drift.

NRC result : **$K2_{NRC} = 100 \times (1 - 0.681\,4 \times 10^{-6})\ \Omega$**

Relative standard uncertainty : **$u_{NRC} = 3.0 \times 10^{-9}$**

where u_{NRC} is calculated as the quadratic sum of $u_A = 1.4 \times 10^{-9}$ and, from table 3, $u_B = 2.6 \times 10^{-9}$.

7.6. Comparison of $K2$ measurements

As stated in section 7.2, the best operating conditions of comparability of $K2$ measurements consist in comparing the 1 Hz measurement of BIPM to the 9.8 s cycle time measurement of NRC.

Figure 10 presents the series of interleaved measurements of BIPM and NRC (from data of tables 11 and 12) with error bars corresponding to the dispersion observed for each measurement. As it can be seen, one or both of the resistors experienced a slight drift that can be considered in first approximation as linear. It appears also that, within the limit of the dispersion of the results, there are no significant instabilities of the measurements. Therefore, no additional uncertainty component was included in the final comparison results.

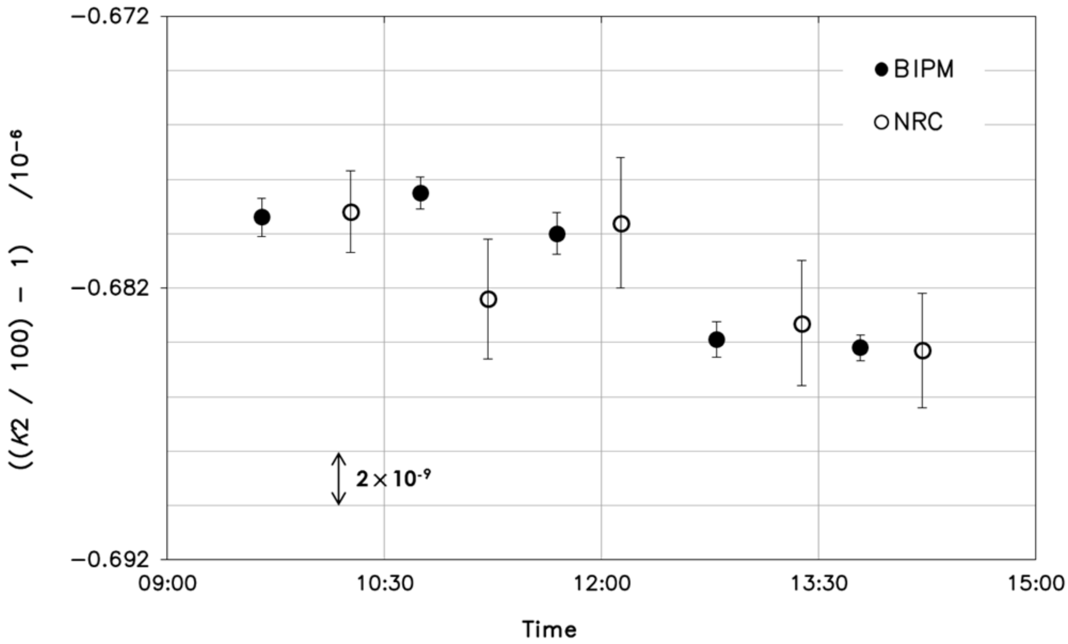

Figure 10: BIPM measurements at 1 Hz (black dots) and NRC corrected measurements at 9.8 s cycle time (white circles) of $K2$ ratio (correction from drift not applied). Measurements were carried out on July 1, 2018. Error bars correspond to the dispersion observed for each measurement.

The relative difference NRC - BIPM in the measurement of $K2$ ratio was found to be:

$$(K2_{\mathrm{NRC}} - K2_{\mathrm{BIPM}}) / K2_{\mathrm{BIPM}} = +0.1 \times 10^{-9}$$

Relative combined standard uncertainty: $\boldsymbol{u_{\mathrm{comp}} = 4.0 \times 10^{-9}}$

where u_{comp} is calculated as the quadratic sum of $u_{\mathrm{BIPM}} = 1.7 \times 10^{-9}$, $u_{\mathrm{NRC}} = 3.0 \times 10^{-9}$ and $u_{\mathrm{Peltier}} = 2.0 \times 10^{-9}$ (see sections 7.1 and 7.3).

7.7. Additional investigations

As mentioned in section 7.5, in addition to the measurements of *K2* for 9.8 s cycle time, NRC also performed additional measurements for a cycle timing reproducing as accurately as possible the current waveform characteristics of the BIPM CCC (see figures 2 and 9). As a reminder, the NRC CCC was programmed with t_r = 5 s, t_s = 22 s, t_m = 100 s and a time at zero current (t_z) of 36 s (total cycle time of 337 s). These measurements were made on July 1, 2018 following the interleaved measurements at 9.8 s cycle time presented in the previous section.

In order to be able to make a direct comparison between long and short cycle times, two measurements at 337 s and 9.8 s cycle times were interleaved. The BIPM also carried out two measurements, one before the interleaved series of NRC measurements, and one after. Results are summarized in table 13 and shown on figure 11.

Time	Institute	Measurement Cycle	$(K2/100) - 1$ /10^{-6}		Dispersion /10^{-6}
			Raw or 1 Hz measurement	Corrected measurement	
13:47	BIPM	340 s	-0.684 2	-0.711 5	0.000 5
14:13	NRC	9.8 s	-0.681 7	-0.684 3	0.002 1
14:40	NRC	337 s	-0.700 6	-0.700 6	0.001 8
15:09	NRC	9.8 s	-0.679 1	-0.681 7	0.002 2
15:36	NRC	337 s	-0.701 8	-0.701 8	0.000 8
16:02	NRC	9.8 s	-0.683 8	-0.686 4	0.001 8
16:27	BIPM	340 s	-0.685 9	-0.713 2	0.000 5

Table 13: Additional NRC measurements of *K2* including measurements at long cycle time reproducing the BIPM CCC cycle timing. Measurements were carried out on July 1, 2018. Results are expressed as the relative difference from the nominal ratio value 100. The dispersion corresponds to the standard deviation of each individual measurement.

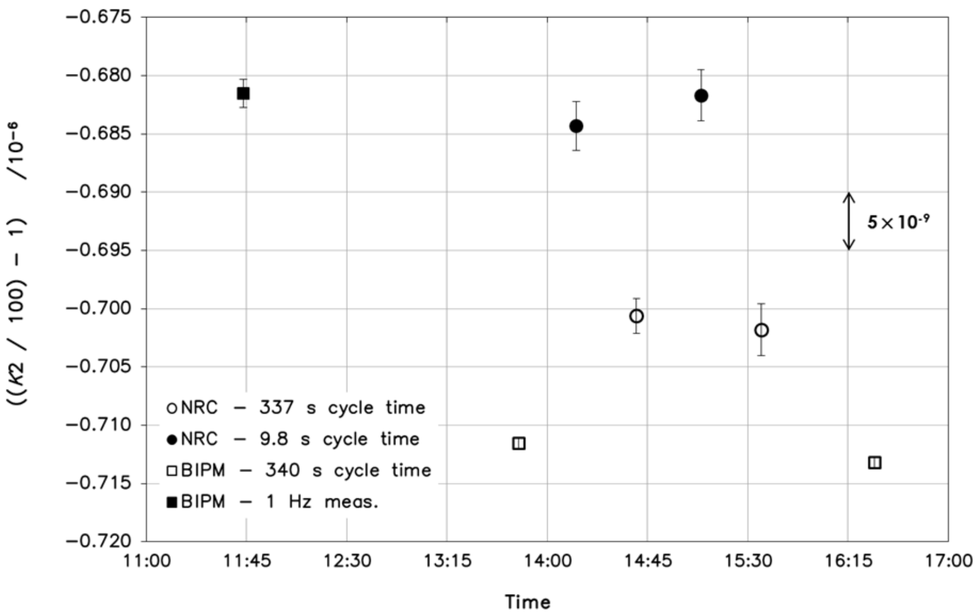

Figure 11: NRC interleaved measurements at short (9.8 s) and long (337 s) cycle times (from table 13). For comparison, BIPM measurements for long cycle time (336 s) have been added to the graph as well as the mean value at 1 Hz from Table 11. For BIPM measurements, the square dot height corresponds to the size of the error bars (measurement dispersion).

No clear conclusion can be drawn from these additional measurements except that even with similar current reversal cycles, a significant difference of about 1.5×10^{-8} in relative is still observed between the NRC and the BIPM measurements. Also, the difference between the NRC measurements at 9.8 s and 337 s cycle times remains the same as that already observed on figure 8, although the latter had been obtained with a 340 s cycle having no time at zero current after reversal.

These two observations seem to suggest that there is no significant effect of the time at zero current after current reversal on the final measurement, at least for long cycle times. Further investigations would be necessary to confirm this point.

8. Conclusion

The on-site key comparison BIPM.EM-K12 carried out from June 25 to July 2, 2018 between BIPM and NRC showed a very 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 ratios $K1$ and $K2$ (ie. 10 000 Ω/100 Ω and 100 Ω/1 Ω, respectively).

The results of the comparison are summarized in table 14. The relative difference between BIPM and NRC is less than of 1 part in 10^9 for $R_{100\Omega}$ and $K2$, and of 1.3 parts in 10^9 for $K1$. Standard relative uncertainties are within 2.1 and 4 parts in 10^9.

As already noticed in previous comparisons [2,4,14], the current reversal cycle time has been proved to have a significant influence on the measurement of the ratio $K2$. In particular, it has been once again observed that a cycle time threshold of about 10 s seems to exist, below which the Peltier effect in the 1 Ω standard becomes negligible. Consequently, in the present work, the compared $K2$ ratio values of the BIPM and the NRC were measured for cycle time below 10 s.

$R_{100\Omega}$ in terms of $R_H(2)$	$(R_{NRC} - R_{BIPM}) / R_{BIPM}$ = **-0.5×10^{-9}**	u_{comp} = **2.3×10^{-9}**
$K1 = R_{10k\Omega}/R_{100\Omega}$	$(K1_{NRC} - K1_{BIPM}) / K1_{BIPM}$ = **$+1.3\times10^{-9}$**	u_{comp} = **2.1×10^{-9}**
$K2 = R_{100\Omega}/R_{1\Omega}$	$(K2_{NRC} - K2_{BIPM}) / K2_{BIPM}$ = **$+0.1\times10^{-9}$**	u_{comp} = **4.0×10^{-9}**

Table 14: Summary of the results and associated relative standard uncertainties of the NRC-BIPM onsite comparison BIPM.EM-K12. The comparison measurements of $K2$ were carried out at 1 Hz without 'dc' correction by the BIPM and with a cycle time of 9.8 s by the NRC.

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 15.

	Degree of equivalence D /10^{-9}	Expanded uncertainty U /10^{-9}
$R_{100\Omega}$ in terms of $R_H(2)$	**-0.5**	**4.6**
$K1 = R_{10k\Omega}/R_{100\Omega}$	**+1.3**	**4.2**
$K2 = R_{100\Omega}/R_{1\Omega}$	**+0.1**	**8.0**

Table 15: Summary of the comparison results expressed as degrees of equivalence (DoEs): difference from the BIPM reference value and expanded uncertainty U (k=2).

References

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

[2] R. Goebel, N. Fletcher, B. Rolland, M. Götz, E. Pesel, “Final report on the on-going comparison BIPM.EM-K12: comparison of quantum Hall effect resistance standards of the PTB and the BIPM”, Metrologia, 51, 01011, 2014

[3] N. Fletcher, M. Götz, B. Rolland and E. Pesel, “Behavior of 1Ω resistors at frequencies below 1 Hz and the problem of assigning a dc value”, Metrologia, 52, 2015, 509-513

[4] P. Gournay, B. Rolland, J. Kučera, L. Vojáčková, P. Chrobok, “On-site comparison of quantum Hall effect resistance standards of the CMI and the BIPM”, Metrologia, 54, 01014, 2017.

[5] F. Delahaye, “DC and AC techniques for resistance and impedance measurements”, Metrologia, 29, 1992, 81-93.

[6] F. Delahaye, T.J. Witt, F. Piquemal and G. Genevès, “Comparison of quantum Hall effect resistance standards of the BNM/LCIE and the BIPM”, IEEE Trans on Instr. and Meas., Vol. 44, n°2, 1995, 258-261

[7] F. Piquemal, G. Genevès, F. Delahaye, J.P. André, J.N. Patillon and P. Frijlink, “Report on a joint BIPM-EUROMET project for the fabrication of QHE samples by the LEP”, IEEE Trans on Instr. and Meas., Vol. 42, n°2, 1993, 264-268

[8] F. Delahaye and B. Jeckelmann, “Revised technical guidelines for reliable dc measurements of the quantized Hall resistance”, Metrologia, 40, 2003, 217-223

[9] F. Delahaye and D. Bournaud, “Accurate ac measurements of standard resistors between 1 and 20 Hz”, IEEE Trans on Instr. and Meas., Vol. 42, n°2, 1993, 287-291

[10] A. Satrapinski, M. Götz, E. Pesel, N. Fletcher, P. Gournay, B. Rolland, “New Generation of Low-Frequency Current Comparators Operated at Room Temperature”, IEEE Trans. on Instr. and Meas., Vol. 66, n°6, 2017, 1417-1424

[11] F. Delahaye, “An ac-bridge for low frequency measurements of the quantized Hall resistance”, IEEE Trans. on Instr. and Meas., Vol. 40, n°6, 1991, 883-888.

[12] A. D. Inglis, "A cheaper, simpler quantized Hall resistance standard,” IEEE Trans. Instrum. Meas., Vol. 48, no. 2, 1999, 289 – 292.

[13] C. A. Sanchez, B. M. Wood, and A. D. Inglis, "CCC bridge with digitally controlled current sources,” IEEE Trans. Instrum. Meas., Vol. 58, no. 4, 2009, 1202 – 1205.

[14] F. Delahaye, T.J. Witt, A. Hartland, J.M. Williams, “Comparison of quantum hall effect resistance standards of the NPL and the BIPM, Rapport BIPM-99/18, kcdb.bipm.org/appendixB/