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DES POIDS ET MESURES

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

◆◆◆ Ongoing key comparison BIPM.EM-K12 ◆◆◆

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

In late October – early November 2019 a new BIPM.EM-K12 comparison was carried out at the Korea Research Institute of Standards and Science (KRISS), Republic of Korea. It was the first time the KRISS 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 (KRISS 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 $(R_{KRISS} - R_{BIPM})/R_{BIPM}$ where R_{BIPM} and R_{KRISS} are the values attributed to $R_{100\Omega}$ by the BIPM and KRISS, 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 $(K1_{KRISS} - K1_{BIPM})/K1_{BIPM}$ where $K1_{BIPM}$ and $K1_{KRISS}$ are the values attributed to $K1$ by the BIPM and the KRISS, 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 $(K2_{KRISS} - K2_{BIPM})/K2_{BIPM}$ where $K2_{BIPM}$ and $K2_{KRISS}$ are the values attributed to $K2$ by the BIPM and the KRISS, respectively.

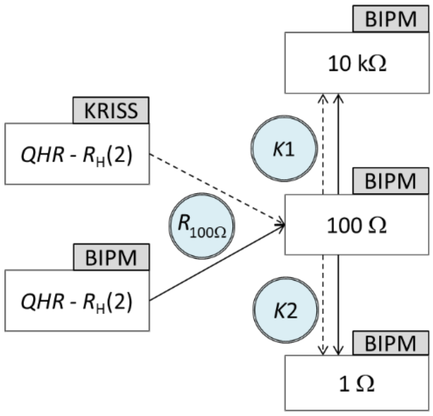

Figure 1: Schematic of the on-site comparison carried out at the KRISS in October-November 2019. Rectangles represent the resistances to be compared and circles correspond to the resistance $R_{100\Omega}$ or the ratios $K1$ and $K2$ to be measured. Solid and dashed arrows stand for the measurements with the 1 Hz bridge of the BIPM or with the CCC bridge of the KRISS, 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, have reached a stable value. The influence of the Peltier effect on precision resistance measurements has already been discussed in several papers [2-7], 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 [8] 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 [9]. 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 [10] 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 1 Hz 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 [11,12].

3.2. Transfer standards

Four transfer resistance standards were used during the comparison, two of value 100 Ω and the two others of value 1 Ω and 10 kΩ. The values assigned by the BIPM and the KRISS to one of the two 100 Ω resistors 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 two 100 Ω standards were SR102 type resistors from IET Labs (s/n: J2-1425644) and Tegam (s/n: A 2030405SR102). The 1 Ω standard was a 9331R series resistor from Measurement International (s/n: 1103856) and the 10 kΩ was a SR104 type resistor from Tegam (s/n: K 201119630104). All four 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 [13], 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	100 Ω transfer standard used for the comparison	1 Hz-'dc' correction/10^{-9}	Standard uncertainty/10^{-9}
($R_{100\Omega}$(1 Hz) - $R_{100\Omega}$(dc)) / 100	s/n: A 2030405SR102	-5.2	1.1
($K1$(1 Hz) - $K1$(dc)) / 100	s/n: J2-1425644	-4.7	1.0
($K2$(1 Hz) - $K2$(dc)) / 100	s/n: J2-1425644	10.0	1.5

Table 1: Value of the 1 Hz to 'dc' corrections applied to the BIPM measurements carried out at 1 Hz (Value('dc')=Value(1 Hz)–Correction). These values are specific to the standards used in this 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 driven 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.

In that respect, in case different reversal current cycles (shape and/or magnitude) 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.

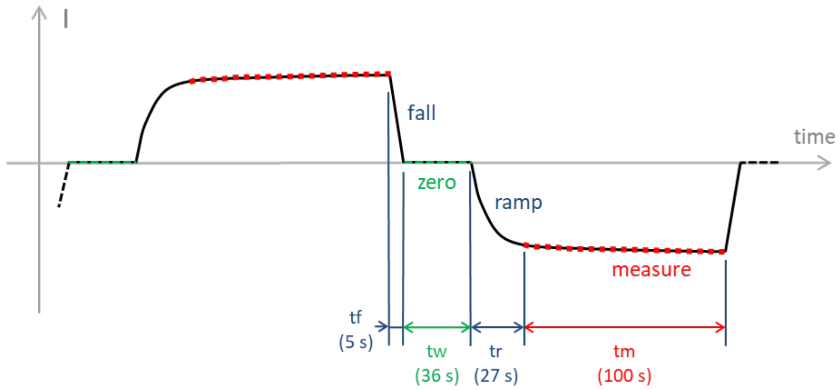

Figure 2: Schematic representation of the reference current cycle with polarity reversals used in the BIPM CCC bridge. Each half-cycle comprises a waiting time at zero current of 36 s, a ramp time of 27 s, a measuring (sampling) time of 100 s and a fall time of 5 s. The complete reversal cycle time is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

Measurement Parameters	*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
Uncertainty contributions (type-B)	*Relative standard uncertainties / 10^{-9}*		
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 standard 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 KRISS measurement system

4.1. Implementation of the QHE

The QHE system of the KRISS has been used since 2008. It comprises a 12 T superconducting magnet and a wet ^{3}He cryostat with a base temperature of 0.3 K [14]. In 2011, a bilateral comparison BIPM.EM-K13.b between the KRISS and the BIPM was performed using this QHE system [15].

The QHE system was moved to a precision building in 2013 in order to improve the measurement environment. It has been re-installed in a sand-filled well built in an isolated concrete foundation.

A PTB-made GaAs quantum Hall device (P579-10-2) is used to realize the quantized Hall resistance at a base temperature of 0.3 K and a magnetic field of 9.4 T, corresponding to the filling factor 2. Typically, a cyclic bipolar current of 38.74 μA is applied for the comparison.

4.2. Resistance bridge

The KRISS routinely uses a commercial 12-bit CCC bridge (Magnicon GmbH) to measure resistances from 1 Ω to 1 MΩ [16,17]. This bridge was employed for the comparison. The CCC bridge comprises 18 windings with turn numbers from 1 to 2048, a DC-SQUID electronics module, and a PC-controlled electronics module. The last module is equipped with two digital current sources [18], a binary compensation unit [19], and a low-noise voltmeter based on a chopper amplifier [20].

The current driven in the resistors is reversed periodically as depicted in Figure 3. Table 3 summarizes the timing details of the current reversal cycles which were employed by the KRISS during the present comparison measurements.

For $R_{100\Omega}$ and $K1$ comparison measurements, a full cycle time of 20 s was used (standard cycle used routinely by KRISS). Because the standard full cycle time of the BIPM CCC is 340 s (Figure 2), preliminary measurements for $R_{100\Omega}$ and $K1$ were made in advance by KRISS with a full cycle time of 340 s. The relative difference between the standard 20 s measurement and the 340 s measurement was then determined and used as a correction of the KRISS results obtained in the 20 s timing configuration, allowing the comparison with the BIPM measurement results. However, as it will be seen later (section 5.2), a power correction to take into account for the shape difference of the current reversal cycles of the BIPM and the KRISS (mainly due to the waiting time that exists in the BIPM cycle but not in the KRISS cycle) was also applied.

For reasons detailed in section 7, the full cycle time of 5 s reported in Table 3 was used to perform the comparison measurements of ratio $K2$. The full cycle time 10 s was used for the study of the cycle time dependence of $K2$ (also reported in section 7).

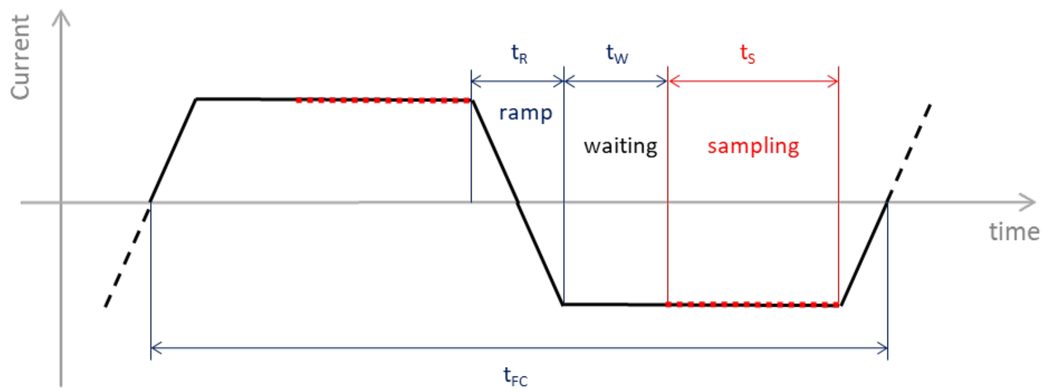

Figure 3: Current reversal timing of the KRISS measurement. t_R, t_W, t_S, and t_{FC} are the ramp time, waiting time, sampling time, and full cycle time, respectively

Full cycle time /s	t_{FC} /s	t_R /s	t_W /s	t_S /s
340	340	10	77.5	82.5
20	20	2	3.5	4.5
10	10	0.4	2.5	2.5
5	5	0.4	1.25	1.25

Table 3: Timing details of the current reversal cycles used for the comparison measurements.

4.3. Measuring environmental conditions

During the whole period of the comparison, the laboratory maintained an ambient temperature at (23.1±0.1) °C and relative humidity at (45±5) %. The atmospheric pressure during the period on which the comparison measurements were performed, from 31 October to 4 November 2019, was in the range of 1010.0 hPa to 1014.8 hPa with a mean value of 1013.0 hPa.

4.4. Uncertainty budget

Table 4 summarizes the type-B contributions to the uncertainty budget of the KRISS measurements for the mentioned three resistance ratios.

Measurement Parameters	*Resistance ratio*		
	$R_H(2)$/100 Ω	10 kΩ/100 Ω	100 Ω/1 Ω
Number of turns N_1/N_2	4001/31	4100/41	400/4
Voltage drop $\Delta(IR)$ in V	1	1	0.1
Compensation ratio k	-1790/2048/64	-653/2048/64	+1199/2048/512
Uncertainty contributions (type-B)	*Relative standard uncertainties / 10^{-9}*		
Compensation ratio k	0.6	0.6	0.6
CCC winding ratio	0.6	0.6	0.6
Bridge voltage measurement (SQUID)	< 0.1	<0.1	0.3
Voltage drop Δ(IR) measurement	< 0.1	<0.1	<0.1
Insulation resistance	< 0.1	<0.1	<0.1
Imperfect quantization of $R_H(2)$	<0.1	NA	NA
Combined type B standard uncertainty, u_B=	**0.9**	**0.9**	**0.9**

Table 4: Type-B contributions to the standard uncertainty budget of the KRISS measurements for the measurement of the three different ratios $R_H(2)$/100 Ω, 10 kΩ/100 Ω and 100 Ω/1 Ω.

The more significant uncertainty contributions are from the binary compensation ratio and winding ratio errors [20]. Although the binary compensation unit was calibrated just before the comparison, we conservatively assume an error of one part in 10^9. The corresponding relative uncertainty, taking into account a rectangular distribution, becomes a 0.6 part in 10^9. The winding ratio error test showed that the uncertainty was smaller than a few parts in 10^{10}. Nevertheless, the corresponding uncertainty was assigned a 0.6 part in 10^9, coming from an assumed error of one part in 10^9 and considering a rectangular distribution.

For the $K2$ ratio, the uncertainty of the bridge voltage measurement attributed to the flux resolution of SQUID electronics becomes significant because relatively small currents are driven to minimize measurement errors from the Joule heating and the Peltier effect.

The imperfect quantization of the Hall plateau at the filling factor 2 was investigated in advance before the comparison. The longitudinal resistance measured in the diagonal Hall measurement configuration [10] was smaller than 0.1 μΩ (see section 5.2.1). By considering an s-parameter of 0.2 for the employed QHE device, the relative deviation from the nominal value for $h/2e^2$ was smaller than 0.1×10^{-9}.

The voltage measurement and insulation resistance negligibly contribute to the measurement uncertainty.

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

5.1. BIPM measurements

5.1.1. Preliminary tests

The first attempts of the BIPM to operate its QHR based on the LEP-514 devices at KRISS were quite unsatisfying. Indeed, as from the first cooling to 1.3 K of the two devices installed on the sample probe, defects of quantization of both devices were evidenced through the measurement of the two terminal-pair Hall resistances between any pair of the device terminals. The measured resistance values were all higher by 100 Ω to 1 kΩ (or even more) from $R_H(2)$, or, were initially equal to $R_H(2)$ (within less than 10 Ω) but with a fast increase after a short waiting time or after having performed a few measurements. The same findings were made for repeated cooling cycles through room temperature of the LEP devices, even for quite long cooling times. The same observation was made by replacing one of the two mounted devices by a third spare BIPM LEP-514 device.

This issue was first attributed to a possible degradation of the QHE devices, that could have happened during transportation, but without having a clear understanding of the physical processes that could lead to the actual experimental observations. It was then decided to check this hypothesis by replacing one of the BIPM LEP-type devices by a spare PTB-type QHE device belonging to the KRISS.

However, at that point, considering the time already spent trying to implement the QHR, the limited time of the comparison and the uncertainty that the issue could actually be overcome, it was decided to carry out the measurement of the ratios $K1$ and $K2$ first (sections 6 and 7), before re-trying the measurement of the ratio $R_H(2)/100$ Ω. Indeed, as these measurements do not employ the QHR, they are, normally, more straightforward to perform.

As soon as the measurements of $K1$ and $K2$ were finalized, one of the two BIPM LEP-514 devices installed on the sample probe was replaced by a spare PTB-type QHE device from KRISS. After cooling to 1.3 K, it was observed that the PTB device was perfectly quantized whereas the LEP device was again not fully quantized and unusable. This was actually confirming our first thought, but, after a few measurements with the PTB device, a similar degradation of the device quantization was also observed.

It was then suspected that the quantization lost could arise from electromagnetic perturbations injected in the QHE devices through the measuring cable due to an inappropriate grounding of the bridge, an unexpected coupling or a grounding loop catching external perturbations, or even a connection to a noisy ground terminal in the laboratory. The hint supporting this hypothesis was the observation on the bridge balance signal of an intermittent series of fast and strong current pulses. These were not observed continuously, only from time to time during more or less time, but several times on the same day. They were sometimes strong enough to perturb and even degrade sensitive amplifiers of the 1 Hz BIPM bridge electronics.

Different grounding configurations of the bridge, of the cryostat and of the attached temperature and liquid helium level control equipment were then tested, as well as the use of different wall grounding points. It was finally found that the magnitude of the impulse noise was conducted through the ground of the power cable of the BIPM system from the wall mains/ground socket and that it was significantly reduced when using one of the available mains/ground sockets, probably having a weaker coupling to the source of the noise (not identified in the lab and probably from outside the lab).

In this modified powering and grounding configuration, markedly attenuated impulse perturbations were still observed but it was possible to perform measurements in good metrological conditions. However, considering that the remaining perturbations could still be problematic for the operation of a QHR based on the BIPM LEP-type devices, and, as it was noted that the KRISS PTB-type devices were apparently less sensitive to those perturbations, it was decided to keep utilizing the latter type of devices for the comparison.

Therefore, two spare PTB QHE devices from KRISS were installed on the BIPM sample probe and cooled down to 1.3 K. Both devices were operational but only one, referenced PTB 137-20, was subsequently used for the comparison measurements. This device was previously fully characterized both at PTB and KRISS and was found to have the required qualities to be used as a QHR reference according to the specifications detailed in [10]. As the device was used during the comparison in experimental conditions similar to those used for its characterization, it was not fully re-characterized at this time.

The device 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 10.8 T. The two-terminal Hall resistance of the four terminal-pairs of the device were checked before and after each series of measurements, showing that the contact resistances were smaller than a few ohms (and in any case not larger than 5 Ω - measurements limited by the resolution of the DVM used).

The longitudinal dissipation along both sides of the device PTB 137-20 was tested as described in [10] 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). In the best conditions of measurement that could be found at KRISS (i.e. the best measurement configuration limiting the residual noise on the balance signal of the bridge and therefore the dispersion of the measurements it implies), the absence of dissipation was demonstrated only within 0.7×10^{-9} in relative terms with a standard deviation of the order of 3×10^{-10} (note that the s-parameter was evaluated to be 0.8). The uncertainty component for the imperfect realization of the QHR (Table 2) takes into account a possible error due to the longitudinal dissipation.

The series of measurements performed subsequently for the purpose of the comparison were taken from the central pair of contacts only.

5.1.2. BIPM results

On November 4-5, 2019, the QHE system of the BIPM was finally operational for carrying out the 100 Ω comparison. A series of five KRISS measurements of the 100 Ω standard based on $R_H(2)$ were interleaved with four measurements by BIPM. For these measurements, the 100 Ω standard Tegam s/n: A 2030405SR102 was used.

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 5.16 mA, which corresponds to a Joule heating dissipation of about 2.66 mW.

The 1 Hz measured values of the 100 Ω standard performed by the BIPM are reported in Table 5 as well as the 'dc' corrected values (1 Hz-'dc' correction of Table 1). Both are expressed as the relative difference from the 100 Ω nominal value: (R_{BIPM}/100 Ω) - 1. Each measurement reported in the table is the mean value of a set of nine individual measurements corresponding to a total integration time of about 30 minutes.

Date and Time	$(R_{\mathrm{BIPM}}/100\ \Omega)$-1 /$10^{-6}$		Dispersion /10^{-6}
	1 Hz measurements	'dc' corrected (1 Hz-'dc' correction)	
4/11/19 23:46	-0.299 55	-0.294 32	0.000 69
5/11/19 1:21	-0.299 44	-0.294 21	0.000 73
5/11/19 2:57	-0.300 06	-0.294 83	0.000 88
5/11/19 4:25	-0.299 54	-0.294 31	0.000 59
	Mean value =	**-0.294 42**	
	Standard deviation, u_A =	**0.000 28**	

Table 5: BIPM measurements of the 100 Ω standard in terms of $R_{\mathrm{H}}(2)$ on November 4 and 5, 2019. Each measurement corresponds to an integration time of about 30 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 resistance value $\boldsymbol{R_{\mathrm{BIPM}}}$ reported below correspond to the mean of the corrected measurements carried out by the BIPM on November 4-5, 2019:

Mean value: $\boldsymbol{R_{\mathrm{BIPM}} = 100 \times (1 - 0.294\,4 \times 10^{-6})\ \Omega}$

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

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

5.2. KRISS measurements of $R_{\mathrm{H}}(2)/100\ \Omega$

5.2.1. Preliminary tests

For this comparison, the GaAs quantum Hall device was cooled down to a base temperature of 0.3 K in the ^{3}He cryostat. A magnetic field of 9.4 T, corresponding to the mid B-field position of the quantized Hall plateau for the filling factor 2, was applied. Reversal current cycles of magnitude 38.74 μA were driven through the QHE device.

To investigate the dissipation of the QHE device in the quantum Hall state, the longitudinal resistance was measured as follows. In the bridge configuration corresponding to the measurement of the ratio $R_{\mathrm{H}}(2)/100\ \Omega$ (BIPM resistor), the longitudinal resistance was obtained by subtracting the measured Hall resistance in the usual measurement configuration using two middle Hall voltage probes from the Hall resistance measured in a diagonal configuration. The determined longitudinal resistance was approximately 0.05 μΩ. By considering an *s*-parameter of 0.2 for the employed device, the relative deviation from the nominal value of $h/2e^2$ is smaller than 1×10^{-12}.

A test of proper operation of the measurement setup, comprising the QHE device and the CCC bridge, was performed using a triangular consistency check. First, the 10 kΩ BIPM resistance was directly determined with respect to $R_{\mathrm{H}}(2)$, realized by the GaAs quantum Hall device, with the CCC bridge. Then, the same resistance was indirectly determined in two steps via the calibration of the 100 Ω BIPM resistance from $R_{\mathrm{H}}(2)$. A relative deviation of 2×10^{-9} between the above two determined 10 kΩ values was comparable with the expanded measurement uncertainty of 2.4×10^{-9}. This simple self-consistent test confirmed that the measurement setup itself was reliably working within the measurement uncertainty.

As mentioned in section 4.2, the standard full cycle time used by the KRISS is 20 s. The measurement duration which corresponds typically to 96 full cycles then becomes approximately 32 minutes (sampling time of about 15 minutes). In order to be able to compare the KRISS results obtained for 20 s standard cycles to the BIPM results based on the BIPM CCC which uses a cycle time of 340 s, preliminary measurements of the 100 Ω BIPM resistor were alternately made for 20 s and 340 s cycle times. The measurements carried out for 340 s cycles comprised only 6 full cycles corresponding to an overall measurement duration of approximately 34 minutes (sampling time of about 17 minutes). The cycle time dependence was then determined as follows, $R_{340\mathrm{s}}/R_{20\mathrm{s}} - 1$=(1.5±0.8)×10^{-9}.

5.2.2. KRISS results

On November 4-5, 2019 five measurements by KRISS, interleaved with four BIPM measurements were conducted. As mentioned in the previous section, the comparison measurements of the 100 Ω resistance standard were carried out using a cycled current of 38.74 μA in the QHR (i.e. 5 mA in the 100 Ω) with a standard reversal rate of 20 s. Each KRISS measurement consisted of a set of 96 consecutive cycles corresponding to an effective sampling time of about 15 minutes.

The raw and corrected measurement results obtained on November 4-5 are reported in Table 6 along with the mean time of measurement and dispersion (standard deviation of the mean). The 'corrected' measurements correspond to the raw measurements corrected from the cycle time dependence (1.5±0.8)×10^{-9} and from the residual difference of the dissipated powers in the 100 Ω resulting from the difference in the waveform of the reversal current cycles used by KRISS and BIPM (see Figures 2 and 3). An estimation of the latter correction is given in section 5.2.3.

Date and Time	(R_{KRISS}/100 Ω)-1 /10^{-6}		Dispersion /10^{-6}
	Raw measurements	Corrected measurements	
4/11/19 22:52	-0.296 75	-0.294 79	0.000 10
5/11/19 0:38	-0.296 90	-0.294 94	0.000 08
5/11/19 2:12	-0.296 73	-0.294 77	0.000 09
5/11/19 3:40	-0.296 77	-0.294 81	0.000 08
5/11/19 5:10	-0.296 96	-0.295 00	0.000 08
	Mean value =	**-0.294 86**	
	Standard deviation, u_A =	**0.000 10**	

Table 6: KRISS measurements of the 100 Ω standard in terms of $R_{\mathrm{H}}(2)$, on November 4-5, 2019. Each measurement corresponds to measuring time of about 32 minutes (sampling time about 15 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 resistance values R_{KRISS} reported below correspond to the mean of 100 Ω measurements carried out by the KRISS, corrected from the cycle time dependence and from difference of powers dissipated in the resistor, on November 4-5, 2019.

Mean value: **R_{KRISS} = 100 × (1 - 0.294 9 × 10^{-6}) Ω**

Relative standard uncertainty: **u_{KRISS} = 1.3 × 10^{-9}**

where u_{KRISS} is calculated as the quadratic sum of: u_{A} = 0.1 × 10^{-9} from Table 6, u_{cycle} = 0.8 × 10^{-9} the standard uncertainty on cycle time dependence correction, u_{power} = 0.4 × 10^{-9} the standard uncertainty on power correction and, from Table 2, u_{B} = 0.9 × 10^{-9}.

Notice that the above given value of u_{KRISS} would have been only about 0.9 × 10^{-9} if no corrections were applied on the measured value of R_{KRISS}.

5.2.3. Estimation of the power correction of the KRISS 100 Ω measurements

Although the measurements performed by both the KRISS and the BIPM were made for approximately the same current driven in the 100 Ω, the non-zero power coefficient of that resistor had nevertheless a small influence due to the difference in the effective powers dissipated in the resistor, resulting from the differences in the reversal cycle timing (cycle time dependence correction) and shapes (residual dissipated powers difference correction).

From the magnitude and waveform differences of the 340 s cycles used by the BIPM and KRISS CCC bridges, it was estimated that the effective power dissipated in 100 Ω by KRISS is (0.53 ± 0.05) mW higher than that dissipated by BIPM. Considering the power coefficient of the 100 Ω standard, estimated as (-0.87 ± 0.34) parts in 10^9 per mW from repeated measurements at two different currents (40 μA and 30 μA in $R_H(2)$), a power correction was computed and applied to the KRISS measurement results. This correction was estimated as (0.46 ± 0.35) parts in 10^9.

5.3. 100 Ω measurements comparison

Figure 4 presents the corrected interleaved measurements from KRISS and BIPM on November 4-5, 2019 (from data in Tables 5 and 6). 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 KRISS and BIPM was then calculated as the difference between the mean of the series of measurements carried out by both institutes on November 4-5, 2019 (mean corrected values reported in Tables 5 and 6):

Relative difference KRISS-BIPM: $\mathbf{(R_{KRISS} - R_{BIPM}) / R_{BIPM} = -0.4 \times 10^{-9}}$

with a 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 $u_{KRISS} = 1.3 \times 10^{-9}$.

…/…

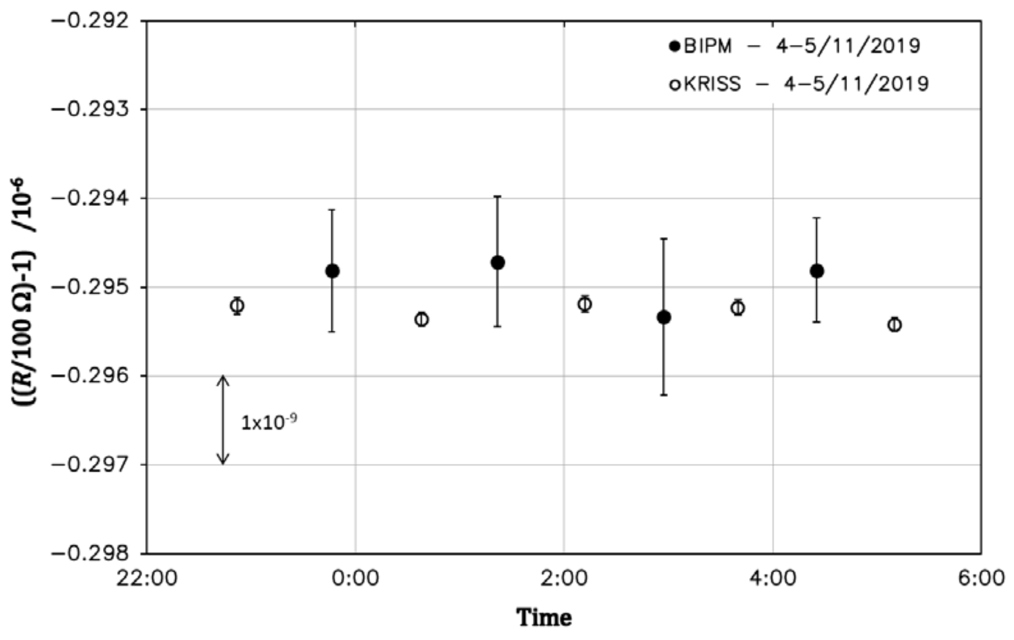

Figure 4: KRISS (open circles) and BIPM (black dots) corrected measurements of the 100 Ω resistance $R_{100\Omega}$ in terms of $R_H(2)$ on November 4-5, 2019. The error bars correspond to the dispersion observed for each measurement.

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 Ω ratio measurement was replaced by a 100:1 LFCC. The 100 Ω and 10 kΩ standards referenced s/n: J2-1425644 and s/n: K 201119630104, respectively, were used (note that the 100 Ω standard used for *K*1 measurements is not the same as that used for the 100 Ω measurements against $R_H(2)$ reported in the previous section).

The rms current in the 10 kΩ standard was 52 μA corresponding to 5.2 mA in the 100 Ω standard. For the reason discussed in section 5.1.1, the measurement of *K*1 was performed before the comparison measurements of $R_{100\Omega}$.

On October 31-November 1, 2019, the 10 kΩ and 100 Ω standards were connected alternately to the BIPM and KRISS bridges and six BIPM measurements at 1 Hz were interleaved with five KRISS measurements. The raw and corrected BIPM measurements are reported in Table 7.

Each of the raw measurements corresponds to the mean value of eight individual measurements corresponding to a total integration time of about 27 minutes. The corrected measurements correspond to those to which the 1 Hz - dc correction given in Table 1 was applied.

As it will be seen in section 6.3, ratio *K*1 experienced a linear drift for the duration of the measurements. The standard deviation (u_A) reported in Table 7, corresponding to the standard deviation of the six individual measurements, was computed after having corrected the raw measurements from this drift.

Date and Time	$(K1_{BIPM}/100)-1$ /10^{-6}		Dispersion /10^{-6}
	1 Hz measurements	'dc' corrected (1 Hz-'dc' correction)	
31/10/19 19:29	-1.229 27	-1.224 57	0.000 44
31/10/19 21:00	-1.234 07	-1.229 37	0.000 71
31/10/19 22:28	-1.236 25	-1.231 55	0.000 62
31/10/19 23:51	-1.240 42	-1.235 72	0.000 53
1/11/19 1:18	-1.240 82	-1.236 12	0.000 87
1/11/19 3:01	-1.245 43	-1.240 73	0.000 62
	Mean value =	**-1.233 01**	
	Standard deviation, u_A =	**0.000 97**	

Table 7: BIPM measurements of the ratio $K1$ on October 31-November 1, 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 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 has been computed after having corrected the measurement results for drift.

The $K1$ ratio value reported below corresponds to the mean of the corrected ratio measurements carried out by the BIPM on October 31-November 1, 2019.

Mean value: $\boldsymbol{K1_{BIPM} = 100 \times (1 - 1.233\ 0 \times 10^{-6})}$

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

where u_{BIPM} is calculated as the quadratic sum of $u_A = 1.0 \times 10^{-9}$ and, from Table 2, $u_B = 1.8 \times 10^{-9}$.

6.2. KRISS measurements of $K1$

For the measurement of the $K1$ ratio, the currents through the 100 Ω and 10 kΩ resistance standards were 5 mA and 50 µA, respectively. The standard 20 s current reversal cycle of Table 3 was used. The turns ratio of the KRISS CCC resistance bridge was set to 4100/41.

As for the measurement of $R_{100\Omega}$, a correction for the cycle time dependence was applied to the KRISS raw measurements as well as a correction for taking into account the residual difference of dissipated powers between BIPM and KRISS in the 100 Ω and 10 kΩ standards.

The cycle time dependence correction on $K1$ measurements was estimated by KRISS as $(-1.5 \pm 0.8) \times 10^{-9}$ from preliminary measurements of $K1$ for different cycle times.

The correction due to the residual difference of dissipated powers was estimated from the power coefficient of the ratio $K1$ and from the effective difference of power dissipated in the resistors between the KRISS and the BIPM. The latter was computed from the exact current magnitudes and cycle timing parameters used by each of them, and considering that the power was only dissipated in the 100 Ω standard (negligible dissipation in the 10 kΩ standard). It was estimated that the power dissipated by KRISS in the 100 Ω was (0.50 ± 0.05) mW higher than that dissipated by BIPM. Then, using the power coefficient $(-1.15 \pm 0.47) \times 10^{-9}$ per mW of the ratio $K1$ – determined by the BIPM prior to the comparison and checked after – the residual power difference correction of the $K1$ ratio was estimated in turn as $(0.58 \pm 0.47) \times 10^{-9}$.

As previously reported, five KRISS measurements interleaved with six BIPM measurements were carried out on October 31- November 1, 2019. Each KRISS measurement consisted of a set of 96 consecutive current reversal cycles corresponding to a time of measurement of about 32 minutes (effective sampling time of about 15 minutes).

The raw and corrected measurement results of KRISS are reported in Table 8. 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 individual measurements.

As mentioned earlier, ratio $K1$ experienced a linear drift for the duration of the measurements (see section 6.3). The standard deviation (u_A) reported in Table 8 was then computed after having corrected the measurements from this drift.

Date and Time	$(K1_{KRISS}/100)-1$ $/10^{-6}$		Dispersion $/10^{-6}$
	Raw measurements	'power' corrected measurements	
31/10/19 20:16	-1.224 40	-1.225 32	0.000 62
31/10/19 21:47	-1.228 67	-1.229 59	0.000 61
31/10/19 23:11	-1.232 47	-1.233 39	0.000 61
1/11/19 0:33	-1.234 21	-1.235 13	0.000 61
1/11/19 2:17	-1.236 70	-1.237 62	0.000 65
	Mean value =	**-1.232 21**	
	Standard deviation, u_A =	**0.000 89**	

Table 8: KRISS measurements of the ratio $K1$ on October 31-November 1, 2019. Each measurement corresponds to a measurement time of about 32 minutes (sampling time about 15 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 standard deviation u_A for the measurement series has been computed after having corrected the measurement results for drift.

The $K1$ ratio value reported below corresponds to the mean of the ratio measurements carried out by the KRISS on October 31 – November 1, 2019.

Mean value: $\boldsymbol{K1_{KRISS} = 100 \times (1 - 1.232\ 2 \times 10^{-6})}$

Relative standard uncertainty: $\boldsymbol{u_{KRISS} = 1.6 \times 10^{-9}}$

where u_{KRISS} is calculated as the quadratic sum of: $u_A = 0.9 \times 10^{-9}$ from Table 8, $u_{cycle} = 0.8 \times 10^{-9}$ the standard uncertainty on cycle time dependence correction, $u_{power} = 0.5 \times 10^{-9}$ the standard uncertainty on power correction and, from Table 4, $u_B = 0.9 \times 10^{-9}$.

Notice that the above given value of u_{KRISS} would have been of only about 1.3×10^{-9} if no corrections were applied on the measured value of $K1_{KRISS}$.

6.3. Comparison of *K*1 measurements

Figure 5 presents the corrected measurements from KRISS and BIPM on October 31 - November 1, 2019 (data from Tables 7 and 8). Error bars correspond to the dispersion observed for each measurement.

As can be seen on this figure, a relatively large drift of the ratio $K1$ was observed for the whole duration of the measurements. It was found that this drift was only correlated with the drift of the 100 Ω standard used. No drift of the 10 kΩ standard was recorded.

The drift of the 100 Ω standard can be attributed to a temperature coefficient higher than expected for this resistor or to some de-tuning or malfunctioning of the temperature control electronics. However, this drift is not an issue for the comparison as long as it remains linear, which is the actually the case (solid and dotted lines on Figure 5).

The drift is perfectly followed by both the KRISS and the BIPM measuring systems and the comparison of the measurements can be directly carry out by computing the mean of the BIPM and KRISS series of measurements. Notice that for the purpose of computing the dispersion of measurements in Tables 7 and 8, drift corrected values were used (see Figure 6).

Apart from the drift, no significant instabilities of the measured ratio $K1$ were observed within the limit of the measurement uncertainties. Therefore, no specific additional uncertainty component was included in the final comparison results.

Consequently, the difference between KRISS and BIPM was calculated as the difference of the means of the series of measurements, uncorrected from the drift, carried out by both institutes on October 31 – November 1, 2019 (mean values reported in Tables 7 and 8):

Relative difference KRISS-BIPM: $\mathbf{(K1_{KRISS} - K1_{BIPM}) / K1_{BIPM} = 0.8 \times 10^{-9}}$

with a relative combined standard uncertainty: $\mathbf{u_{comp} = 2.6 \times 10^{-9}}$

where u_{comp} is calculated as the quadratic sum of $u_{BIPM} = 2.1 \times 10^{-9}$ and $u_{KRISS} = 1.6 \times 10^{-9}$.

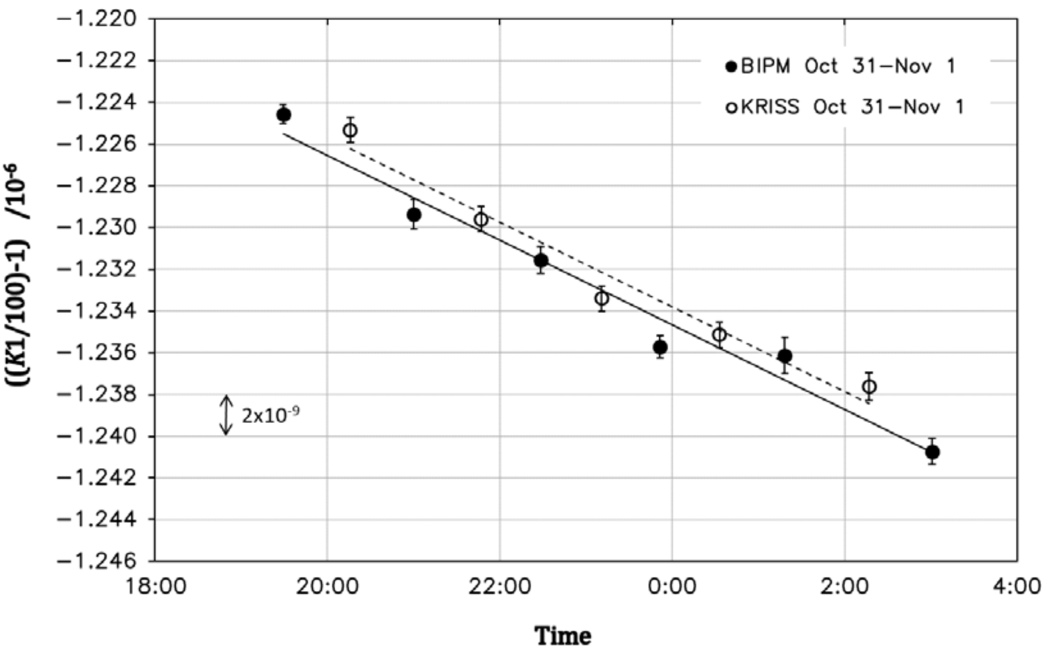

Figure 5: KRISS (open circles) and BIPM (black dots) corrected measurements of the ratio $K1$ on October 31 – November 1, 2019. The error bars correspond to the dispersion observed during each measurement. Solid and dotted lines correspond to the linear fits of the BIPM and KRISS sets of measurements, respectively.

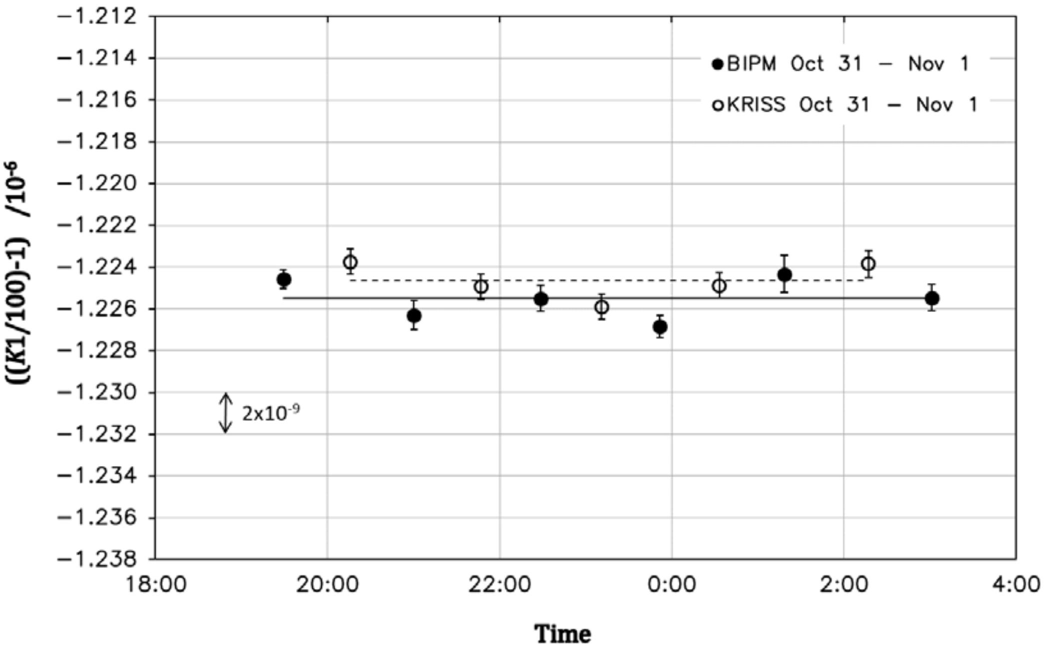

Figure 6: Same as Figure 5 but for BIPM and KRISS measurements corrected from the linear drift. Solid and dotted lines correspond to the linear fits of the BIPM and KRISS sets of measurements, respectively.

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

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

Previous studies [2-7] have shown that close attention must be paid to the Peltier effect in the 1 Ω standard when measuring the ratio $K2$. In particular, it has been shown in [2,4,5] that,

- the Peltier effect does not allow a true 'dc' value of this ratio to be reached when increasing the current reversal cycle duration (at least up to the standard BIPM CCC cycle duration of ≈340 s),
- there exists a threshold cycle time duration (typically of the order of 10 s to few tens of seconds) below which $K2$ measurements remain stable within the uncertainty of measurements.

In such a case, it seems preferable to perform the comparison of $K2$ 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 (since 2013) because the measurements performed by the participating NMI using a short cycle time, to be 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 was carried out by KRISS in order to determine the influence of the cycle time on $K2$ when the latter time was varied from 5 s to 340 s. We note that the measurements were performed in the sequence of 5 s, 10 s, 20 s, 340 s and 20 s cycle time to exclude unwanted dependences except that due to the cycle time. Two measures for the cycle time of 20 s coincide with each other within the error bars as depicted in Figure 7. The timing details of the cycles are reported in Table 3. The 5 s cycle period was the shortest one allowing an acceptable dispersion of the results, and the 340 s cycle time corresponds approximately to the BIPM CCC standard cycle time. The current in the 100 Ω and 1 Ω standards were 0.5 mA and 50 mA, respectively, and all the other experimental conditions were the same as those used for the measurement of $K1$ ratio.

The results of the preliminary KRISS measurements are reported in Figure 7, as well as the BIPM results for 1 Hz and for a 340 s cycle time. The BIPM measurements are not direct measurements but have been deduced from the measured difference between KRISS and BIPM for the ratio $K2$ at short cycle times (5 s, see section 7.7), 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 340 s reversal cycles of the BIPM and KRISS are not the same, the BIPM estimated 340 s measurement in Figure 7 is also corrected for a residual difference of the powers dissipated in the 1 Ω standard (power dissipated in the 100 Ω is negligible).

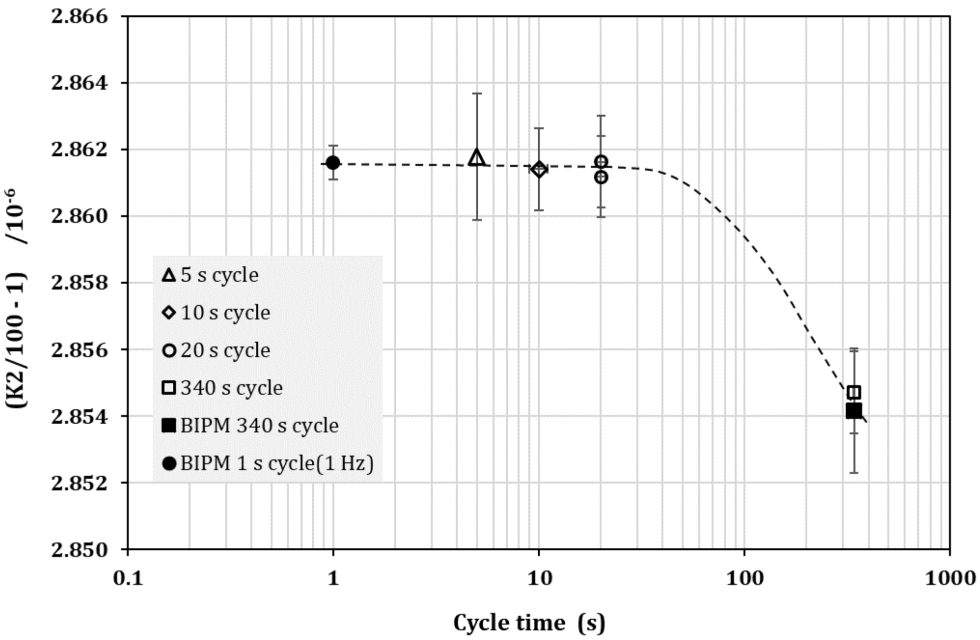

Figure 7: Preliminary measurements of the ratio *K*2 performed by KRISS when the current reversal cycle time is varied from 5 s to 340 s. The dotted line is just a guide for the eye.

The results of Figure 7 are broadly similar to those obtained in [2-5,7]. As can be seen, the measured value of *K*2 remains unchanged (within the dispersion of measurement) from 5 s to at least 20 s cycle times and then, starts to decrease for longer cycles from a threshold cycle time that could be estimated within 30 to 50 s.

It is interesting to note that the threshold time for which *K*2 starts to decrease is higher than those observed during previous comparisons [2-5], but similar to that observed in [7]. This could be due to the fact that the resistors used for the present comparison and the one reported in [7] were not the same as those used in other comparisons, in particular the 1 Ω resistor which was made by different technology. Indeed, the 1 Ω standard used at KRISS and in [7] are made of multiple oil-filled metal foil resistors (Vishay type) enclosed in a sealed case (model 9331R from Measurement International) whereas, in [5] and previous comparisons, a CSIRO-type 1 Ω standard was used, which is composed of a single coil of Evanohm S wire fitted into a mount and enclosed in a perforated case intended to be immersed in oil. Details about these resistors can be found in [21-22].

Finally, it can be remarked that the difference between *K*2 values measured by KRISS and BIPM for the 340 s cycle is within 1×10^{-9}.

7.2. Choice of the comparison cycle waveform

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 *K*2 to the KRISS measurements performed with the shortest cycle time (5 s in the present case). The main reason of this choice was to keep a better comparability with the previous comparisons (same analysis of *K*2 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 [11]. The uncertainty budget for the use of the BIPM 1 Hz bridge for the measurement of the ratio $K2$ is reported in Table 9.

Furthermore, in order to cover for the assumption that the plot of $K2$ versus cycle time (Figure 7) comprises actually a plateau corresponding to a negligible Peltier effect below the threshold cycle time of about 30 to 50 s, a relative standard uncertainty of $u_{\text{Peltier}} = 1 \times 10^{-9}$ 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 standard uncertainty, u_B=	**1.2**

Table 9: 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 $K2$

Five successive measurements of $K2$, interleaved with four KRISS measurements, were carried out on November 1, 2019. For these measurements, the 100 Ω and 1 Ω standards were fed by 0.53 mA and 53 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 the Table 10 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 individual measurement sets.

Date and Time	$(K2_{\text{BIPM}}/100)-1$ $/10^{-6}$	Dispersion $/10^{-6}$
	1 Hz measurements	
1/11/19 13:00	2.866 02	0.000 57
1/11/19 14:20	2.866 41	0.000 58
1/11/19 15:36	2.866 88	0.000 60
1/11/19 16:52	2.868 40	0.000 46
1/11/19 18:18	2.867 93	0.000 19
Mean value =	**2.867 13**	
Standard deviation, u_A =	**0.001 01**	

Table 10: BIPM measurements of the ratio $K2$ carried out on November 1, 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 correspond 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 corresponds to the mean of the 1 Hz ratio measurements carried out by the BIPM on November 1, 2019.

Mean value: **$K2_{BIPM} = 100 \times (1 + 2.867\,1 \times 10^{-6})$**

Relative standard uncertainty: **$u_{BIPM} = 1.6 \times 10^{-9}$**

where u_{BIPM} is calculated as the quadratic sum of $u_A = 1.0 \times 10^{-9}$ and, from Table 9, $u_B = 1.2 \times 10^{-9}$.

7.5. KRISS measurements of $K2$

As mentioned above, on the same day, November 1, 2019, the KRISS carried out four measurements interleaved with the five BIPM measurements. They were conducted using the 5 s current reversal cycle (see timing details in Table 3). Each of the KRISS measurements consisted of a set 250 consecutive cycles corresponding to an effective time of measurement of 24 minutes (about 10 minutes sampling time).

The raw measurement results from KRISS are summarized in Table 11. These values correspond to the means of each of the four 24 minutes sets of measurements. A 'power' correction was estimated on the same basis as for the $K1$ ratio and applied to the KRISS raw measurements (see section 7.6). Date and time correspond to the time of measurement and the dispersion to the standard deviation of the mean.

Date and Time	$(K1_{KRISS}/100)-1$ /10^{-6}		Dispersion /10^{-6}
	Raw measurements	'power' corrected measurements	
1/11/19 13:37	2.865 44	2.867 37	0.002 95
1/11/19 14:57	2.864 94	2.866 87	0.001 58
1/11/19 16:12	2.865 59	2.867 52	0.001 32
1/11/19 17:38	2.864 07	2.866 00	0.001 52
	Mean value =	**2.866 94**	
	Standard deviation, u_A =	**0.000 69**	

Table 11: KRISS measurements of the ratio $K2$ carried out on November 1, 2019. 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 each series of measurements.

The $K2$ ratio value reported below corresponds to the mean of the corrected ratio measurements carried out by the KRISS on November 1, 2019.

Mean value: **$K2_{KRISS} = 100 \times (1 + 2.866\,9 \times 10^{-6})$**

Relative standard uncertainty: **$u_{KRISS} = 1.1 \times 10^{-9}$**

where u_{KRISS} is calculated as the quadratic sum of $u_A = 0.7 \times 10^{-9}$ and, from Table 4, $u_B = 0.9 \times 10^{-9}$.

7.6. Estimation of the power correction of the KRISS $K2$ measurements

The currents driven in the 1 Ω and 100 Ω standards by the KRISS and the BIPM were similar but not exactly the same: 50 mA and 53 mA in the 1 Ω for the KRISS and the BIPM, respectively, and 100 times less in the 100 Ω. Also, the waveform of the current reversal cycles was different: 1 Hz measurement for the BIPM and 5 s 'square' reversal cycle for the KRISS. 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 KRISS.

A 'power' correction was then estimated and applied on the raw measurements of Table 11. This correction was computed from the difference of the effective powers dissipated in the 1 Ω standard between the KRISS 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 prior and following the comparison.

The difference between the effective powers and the power coefficient of *K*2, having been evaluated to (0.49 ± 0.05) mW and (3.93 ± 0.75) parts in 10^9 per mW, respectively, the 'power' correction was estimated to be equal to (1.93 ± 0.77) part in 10^9 (a higher power was dissipated by the BIPM in the 1 Ω standard).

7.7. Comparison of *K*2 measurements

For the reasons detailed in the previous sections 7.1 and 7.2, the comparison between BIPM and KRISS measurements of *K*2 ratio was performed using the 1 Hz measurements of the BIPM and the 5 s cycle time measurements of the KRISS. The five *K*2 BIPM measurements made on November 1, 2019 at 1 Hz (Table 10) were then compared to the four interleaved 5 s cycle time KRISS measurements (Table 11) performed on the same day.

Figure 8 presents the series of interleaved measurements with error bars corresponding to the dispersion observed for each measurement. It can be noted that the dispersion of the last BIPM measurement has a reduced value compared to that of the first four measurements. This is possibly due to the combination of a reduced electromagnetic background noise after 6 pm and to the absence of the impulse noise randomly observed at any time during measurements (although randomly observed, this impulse noise is probably linked to some machine/equipment non-random process running in the close vicinity of the lab).

It appears that, within the limit of the dispersion, there are no significant instabilities of the measurements that could raise the need to include a specific additional uncertainty component in the final comparison results. A slight drift of *K*2 can be detected in the BIPM results but cannot be confirmed by KRISS measurements.

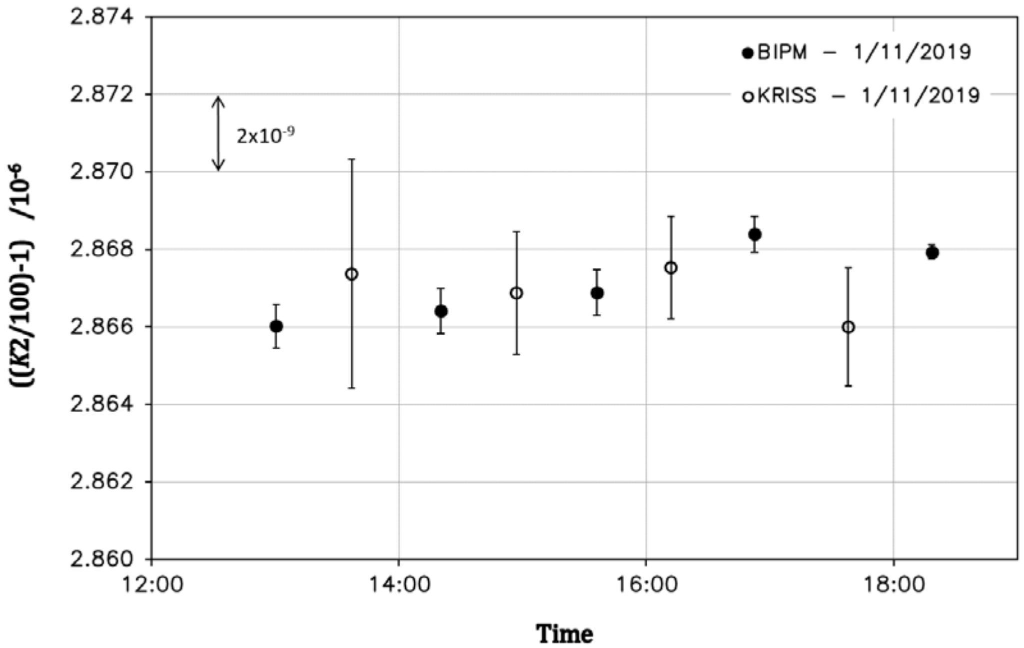

Figure 8: Measurement results for *K*2 ratio on November 1, 2019: BIPM at 1 Hz (black dots) and KRISS for a 5 s cycle time (open circles). Error bars correspond to the dispersion observed for each measurement.

The difference between the KRISS and the BIPM was then computed as the difference of the means of the measurement values of Tables 10 and 11:

Relative difference KRISS-BIPM: $\mathbf{(\mathit{K}2_{KRISS} - \mathit{K}2_{BIPM}) / \mathit{K}2_{BIPM} = -0.2 \times 10^{-9}}$

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

where u_{comp} is calculated as the quadratic sum of $u_{\text{BIPM}} = 1.6 \times 10^{-9}$, $u_{\text{KRISS}} = 1.1 \times 10^{-9}$, $u_{\text{Peltier}} = 1.0 \times 10^{-9}$ (defined in section 7.3) and $u_{\text{power}} = 0.8 \times 10^{-9}$ (defined in section 7.6).

8. Conclusion

The on-site key comparison BIPM.EM-K12 carried out in October-November 2019 between the KRISS and the BIPM 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 ratios $K1$ (10 kΩ/100 Ω) and $K2$ (100 Ω/1 Ω).

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 12.

$R_{100\Omega}$ in terms of $R_H(2)$	$(R_{\text{KRISS}} - R_{\text{BIPM}}) / R_{\text{BIPM}}$ = **-0.4×10^{-9}**	u_{comp} = **2.4×10^{-9}**
$K1 = R_{10k\Omega}/R_{100\Omega}$	$(K1_{\text{KRISS}} - K1_{\text{BIPM}}) / K1_{\text{BIPM}}$ = **0.8×10^{-9}**	u_{comp} = **2.6×10^{-9}**
$K2 = R_{100\Omega}/R_{1\Omega}$	$(K2_{\text{KRISS}} - K2_{\text{BIPM}}) / K2_{\text{BIPM}}$ = **-0.2×10^{-9}**	u_{comp} = **2.3×10^{-9}**

Table 12: Summary of the results of the KRISS-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 5 s by the KRISS.

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 13.

	Degree of equivalence D /10^{-9}	Expanded uncertainty U /10^{-9}
$R_{100\Omega}$ in terms of $R_H(2)$	**-0.4**	**4.8**
$K1 = R_{10k\Omega}/R_{100\Omega}$	**0.8**	**5.2**
$K2 = R_{100\Omega}/R_{1\Omega}$	**-0.2**	**4.6**

Table 13: 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*, 2014, **51**, 01011.

[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*, 2015, **52**, 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*, 2017, **54**, 01014.

[5] P. Gournay, B. Rolland, C. Sanchez, "On-site comparison of quantum Hall effect resistance standards of the NRC-CNRC and the BIPM", *Metrologia*, 2019, **56**, 1A, 01002.

[6] F. Delahaye, "DC and AC techniques for resistance and impedance measurements", *Metrologia*, 1992, **29**, 81-93.

[7] P. Gournay, B. Rolland, Y. Lu and J. Zhao, "On-site comparison of quantum Hall effect resistance standards of the NIM and the BIPM", *Metrologia*, 2020, **57**, 1A, 01009.

[8] 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.*, 1995, **44**, n°2, 258-261.

[9] 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.*, 1993, **42**, n°2, 264-268.

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

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

[12] 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.*, 2017, **66**, n°6, 1417-1424.

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

[14] W.-S. Kim, K. Yu, M.-S. Kim, P. Park and K.-T. Kim, "Precise measurement of the quantized Hall resistance on the basis of a cryogenic current comparator", *J. Korean Phys. Soc.*, 2011, **58**, 1339-1342.

[15] R. Goebel, W.-S. Kim, N. Fletcher and M. Stock, "Bilateral comparison of 10 kΩ standards (ongoing BIPM key comparison BIPM.EM-K13.b) between the KRISS and the BIPM", *Metrologia*, 2011, **49**, 01006.

[16] D.-H. Chae, W.-S. Kim, T. Oe, and N.-H. Kaneko, "Direct comparison of 1 MΩ quantized Hall array resistance and quantum Hall resistance standard", *Metrologia*, 2018, **55**, 645-653.

[17] D.-H. Chae, M.-S. Kim, W.-S. Kim, T. Oe, and N.-H. Kaneko, "Quantum mechanical current-to-voltage conversion with quantum Hall resistance array", *Metrologia*, 2019, **57**, 025004.

[18] M. Götz, D. Drung, E. Pesel, H.-J. Barthelmess, C. Hinnrichs, C. Aßmann, M. Peters, H. Scherer, B. Schumacher, and T. Schurig, "Improved cryogenic current comparator setup with digital current sources", *IEEE Trans. Instrum. Meas.*, 2009, **58**, 1176-1182.

[19] D. Drung and J.-H. Storm,"Ultra-low noise chopper amplifier with low input charge injection", *IEEE Trans. Instrum. Meas.*, 2011, **60**, 2347-2352.

[20] D. Drung, M. Götz, E. Pesel, H.-J. Barthelmess, and C. Hinnrichs,"Aspects of application and calibration of a binary compensation unit for cryogenic current comparator setups", *IEEE Trans. Instrum. Meas.*, 2013, **62**, 2820-2827.

[21] B.J. Pritchard and R.C. Grime, "Fabrication of reference standard 1 ohm resistors from Evanohm S alloy", *CPEM Conference Digest*, 1990, 290-291.

[22] https://mintl.com/products/9331r-series/