Uncertainty of the Ohm Using Cryogenic and Non-Cryogenic Bridges

Alireza R. Panna[*], Marlin E. Kraft[*], Albert F. Rigosi[*], George R. Jones[*], Shamith U. Payagala[*], Mattias Kruskopf[*,‡], Dean G. Jarrett[*], and Randolph E. Elmquist[*]

[*]National Institute of Standards and Technology, 100 Bureau Drive, Stop 8171, Gaithersburg, MD, 20899, USA
alireza.panna@nist.gov

[‡]University of Maryland, Joint Quantum Institute, College Park, MD, 20742, USA

***Abstract* — We describe recent scaling measurements to decade resistance levels based on both cryogenic and non-cryogenic current comparator bridges. National measurement institutes and the International Bureau of Weights and Measures derive traceability for the SI ohm using the quantum Hall effect, with the primary comparisons made at the resistance value $R_{K\text{-}90}/2$ = 12906.4035 Ω. Cryogenic current comparator scaling methods are preferred since large resistance ratios of 100 or more are achieved with unsurpassed uncertainty. The quantized Hall resistance standard based on graphene allow less complex and more cost-effective room-temperature resistance bridges to provide SI traceability.**

***Index Terms* — quantized Hall resistance, traceability, cryogenic current comparator, direct current comparator, standard resistor.**

I. INTRODUCTION

The National Institute of Standards and Technology (NIST) uses comparisons based on a bank of five 100 Ω standards and several cryogenic current comparator (CCC) bridges to initiate the traceability chain that ties four-terminal resistance standards to the quantized Hall resistance (QHR). The resistor bank has over 25 years of continuous measurement history at approximately half-yearly intervals based on a GaAs/AlGaAs heterostructure QHR device, prior to which traceability was derived from a bank of 1 Ω standards [1]. International consistency has been verified by resistor intercomparisons and on-site QHR comparisons [2]. One of the CCC bridges is a commercial system with binary windings and a wideband superconducting quantum interference device (SQUID) feedback [3]. This system allows exploration of many new measurement paths in scaling for four-terminal resistors, including precise direct comparisons between 1 kΩ and the QHR. Higher resistance levels from 100 kΩ to 10 MΩ are compared directly to the QHR using two-terminal CCC bridges with similar high stability obtained using DC SQUID feedback and a single voltage source [4].

Room-temperature direct current comparator (DCC) and dual-source bridge (DSB) systems can provide alternate resistance scaling paths without the need for cryogens and superconducting electronics. After the initial expense of the measurement system, these systems allow continuous operation with low maintenance cost. However, room-temperature bridge systems cannot achieve the sensitivity offered by high-turns CCC bridges, and an acceptable uncertainty level may be difficult to reach when scaling with a QHR standard. Higher current (or voltage) levels as required for good sensitivity and low type A uncertainty may introduce unwanted power dissipation in the standard resistor or quantized resistance breakdown [5] in the QHR device. Furthermore, since for many years liquid He and a high-field superconducting magnet have been required for operating the QHR device, most users have chosen to pursue CCC technology with the QHR standard.

Recently, the outlook for room-temperature QHR scaling has changed due to improvements in devices and instrumentation. The availability of graphene QHR standards with broad thermal and magnetic operating range [6, 7] allows their use with small superconducting magnets in tabletop cryocooler systems [8, 9]. The sensitivity of newer DCC bridges has also improved, providing QHR scaling at slightly higher device currents with uncertainty levels comparable to CCC bridges.

II. MEASUREMENT DESIGN

In resistance metrology, the bridge ratio must be well known and stable to maintain reproducible uncertainties comparable to the stability of the standard resistors of the laboratory. If such ratios are maintained, room-temperature bridge systems could provide improved reliability at low cost based on year-round availability of the QHR standard. The precise ratios of a CCC system are used to calibrate DCC bridges and thus to improve the type B uncertainty; likewise, the digital voltage sources of the high-resistance DSB can be calibrated using Josephson array systems or resistance ratio voltage dividers so that the ratio uncertainty is known.

By direct comparison to CCC ratios, our measurements are intended as a step towards the determination of the long-term uncertainty of scaling using DCC bridges. Some ratios at NIST utilize a robust graphene QHR device in a table-top magnet system, as described in a separate report [9]. This ensures that the measurements have excellent long-term stability. Precision resistance standards are maintained at constant temperature for scaling and the type A uncertainty for each CCC ratio is derived as the standard deviation (SD) of a sequence of repeated measurement sets under very similar measurement conditions. The total time for each measurement set was of order 30 minutes, to compare type A results. The commercial binary-winding CCC (BCCC) was used to define most of the ratio values, with the number of windings giving optimum uncertainty for the current levels used. A two-terminal CCC

978-1-5386-0974-3/18/$31.00 ©2018 IEEE

(2TCCC) with winding ratio of 310-to-40 was used for measurements between the QHR standard and air-type 100 kΩ standard resistors.

III. DATA AND RESULTS

DCC scaling results between the QHR standard and a 1 kΩ standard resistor are shown in Fig. 1. Here, the number of points averaged was varied inversely with the square of the applied voltage to obtain similar type A uncertainty for each point. The durations of the resulting data sets ranged from 110 min for the lowest measurement voltage (0.5 V) to 24 min for the highest (1.2 V), with the data from the first 10 min of each set discarded to allow the bridge nanovoltmeter balance to reach equilibrium. The error bars are SDs of the means, which underestimate the type A uncertainties due to short-term drift.

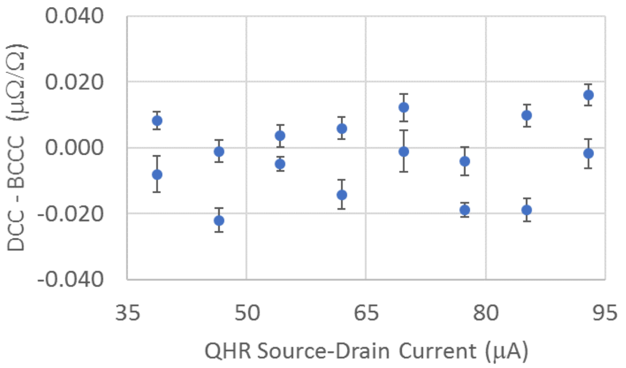

Figure 1. DCC bridge scaling from the QHR to a 1 kΩ standard using a range of source-drain currents. Results are normalized to the average results of BCCC scaling at 38.7 µA and 77.5 µA.

Preliminary standard uncertainty estimates (k = 1) of type A and type B influences in resistance scaling with the non-cryogenic DCC method are presented in Table 1. Some of these ratios were measured at the National Research Council (NRC) laboratory in Ottawa, Canada, in the initial calibration of the DCC bridge, and the values shown depend on those calibrations to help estimate long-term drift in the bridge ratios. Type B values represent combined estimates for all known influences.

Table 1. DCC standard uncertainty estimates

Resistance values (Ω)	Primary current (mA)	Secondary current (mA)	Meas. Time (min)	Type A (µΩ/Ω)	Type B (µΩ/Ω)
1 k, 100	1	10	20	0.003	0.007
10 k, 1 k	0.1	1	36	0.008	0.009
10 k, 1 k	0.32	3.2	36	0.004	0.009
$R_K/2$, 1 k	0.077	1	36	0.012	0.010
100 k, 10 k	0.01	0.1	32	0.096	0.062
100 k, 10 k	0.05	0.5	32	0.021	0.062

Similar results are given in Table 2, showing the uncertainty estimates (k = 1) of type A and type B influences in scaling ratios for the CCC bridges. Ratios with 100 kΩ use the 2TCCC.

Table 2. CCC standard uncertainty estimates

Resistance values (Ω)	Primary current (mA)	Secondary current (mA)	Meas. Time (min)	Type A (µΩ/Ω)	Type B (µΩ/Ω)
1 k, 100	1	10	20	0.0023	0.001
10 k, 100	0.1	10	20	0.0011	0.001
10 k, 1 k	0.1	1	20	0.0005	0.001
$R_K/2$, 100	0.0387	5	20	0.0008	0.001
$R_K/2$, 100	0.0775	10	20	0.0007	0.002
$R_K/2$, 1 k	0.0387	0.5	20	0.0005	0.001
$R_K/2$, 1 k	0.0775	1	20	0.0003	0.002
100 k, $R_K/2$	0.01	0.0775	30	0.011	0.025

IV. CONCLUSION

DCC scaling results between the QHR standard and decade resistance values from 100 Ω to 100 kΩ are compared to similar results from CCC measurements as a preliminary study of DCC suitability for traceability of the ohm based on the QHR. Relative uncertainties are estimated from these results, and will be more accurately determined for presentation at CPEM 2018.

REFERENCES

[1] R. E. Elmquist, M. E. Cage, Y. Tang, A.-M. Jeffery, J. R. Kinard, Jr., R. F. Dziuba, N. M. Oldham, and E. R. Williams, "The Ampere and Electrical Standards," *J. Res., Natl. Inst. Stand. Technol.*, **106**, 65-103 (2001).

[2] F. Delahaye, T. J. Witt, R. E. Elmquist, and R. F. Dziuba, "Comparison of Quantum Hall Effect Resistance Standards of the NIST and the BIPM," *Metrologia* **37**, 173 – 176 (2000).

[3] D. Drung, M. Gotz, E. Pesel, H. J. Barthelmess, and C. Hinnrichs, *IEEE Trans. Instrum. Meas.* 62, 2820 (2013).

[4] F. L. Hernandez-Marquez, M. E. Bierzychudek, G. R. Jones Jr, and R. E. Elmquist, "Precision high-value resistance scaling with a two-terminal cryogenic current comparator" *Rev. Sci. Instrum.* 85 (4), 044701 (2014).

[5] B. Jeckelmann and B. Jeanneret, "The quantum Hall effect as an electrical resistance standard" *Rep. Prog. Phys.* 64 1603–1655 (2001).

[6] R. Ribeiro-Palau, R. F. Lafont, J. Brun-Picard, *et al.* "Quantum Hall resistance standard in graphene devices under relaxed experimental conditions" *Nature Nanotechnol.* 10, 965 (2015).

[7] Y. Yang, G. Cheng, P. Mende, *et al.* "Epitaxial graphene homogeneity and quantum Hall effect in millimeter-scale devices" Carbon 215, 229–236 (2017).

[8] T. J. B. M. Janssen, S. Rozhko, I. Antonov, A. Tzalenchuk, J. M. Williams, Z. Melhem, H. He, S. Lara-Avila, S. Kubatkin, and R. Yakimova, "Operation of a Graphene quantum Hall resistance standard in cryogen-free table-top system," *2D Mater.*, 2, 035015 (2015).

[9] A. F. Rigosi, et al., "A Table-Top Graphene Quantized Hall Standard" Submitted to CPEM 2018 (2018).