Quantum Hall Resistance Traceability for the NIST-4 Watt Balance

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Abstract **— Scaling from the quantum Hall resistance to 100 Ω standard resistors used by the NIST-4 watt balance involves multiple resistance standards and bridges to provide the lowest possible uncertainty. Described here is the infrastructure and procedures developed to support these measurements at better than 20 x 10^{-9} standard uncertainty levels.**

Index Terms **— quantum Hall resistance, cryogenic current comparator, direct current comparator, standard resistor, watt balance.**

I. Introduction

The multinational effort to replace the last artifact-based SI definition, the kilogram (kg), has had much attention from the international community and extensive efforts by many national metrology institutes (NMI) in the building of watt balances [1] or in the counting of the number of atoms in a kg of pure silicon [2]. Those experiments are well documented and rely on low uncertainty in voltage, resistance, mass, and gravity. Described here is the infrastructure now in place to provide the NIST-4 watt balance with traceability to the quantum Hall resistance [3] at the 100 Ω level.

At the National Institute of Standards and Technology (NIST), the resistance project has been providing ongoing support for the watt balance work for many years. The NIST-3 and earlier watt balances were all situated in a remote building on the NIST campus. An adequate solution for that situation was to carefully transport 100 Ω resistance standards on a periodic basis between the two locations and maintain control charts to track the drift rates and changes in resistance.

As the NIST Advanced Measurement Laboratory (AML) was conceived twenty years ago, having a future watt balance located in close proximity to the quantum standards of resistance and voltage was a design feature. Transporting resistors less than 50 m or calibrating them in-situ within the AML is a better situation than having to transport them 1.5 km from one building to another on the NIST campus. Reducing handling and shorter calibration intervals of the 100 Ω resistors for NIST-4 reduces uncertainty.

II. Traceability from QHR to 100 Ω

The NIST quantum Hall resistance (QHR) has been the national standard for resistance since January 1, 1990 [3]. Typically the system is operated two to three times a year to calibrate and adjust the drift rates of several banks of reference standards. The most direct link to the QHR is a bank of five 100 Ω standard resistors which are calibrated directly against the QHR $i = 2$ plateau of 12 906.4035 Ω during the operation of the QHR. A cryogenic current comparator (CCC), with a turn ratio of 4130:32, has been used to make this transfer for many years [3]. NIST has recently brought into service a binary cryogenic current comparator (BCCC) with multiple turn ratios, up to 2065:16, which can also be used for this first step from the QHR as well as other ratios such as 10:1 [4]. Other 100 Ω resistors, such as those used for NIST-4, may also be calibrated by the CCC or BCCC with the QHR as a standard when the QHR is being operated. Due to the time, labor, and expense of keeping the QHR system cold at 0.3 K, it is not practical to operate year round. During times when the QHR is not being operated, 100 Ω resistors may be calibrated with the 100 Ω reference bank. Resistors in this bank have relative drift rates ranging from 0.025 x 10^{-6} / year to 0.351 x 10^{-6} / year. Calibrations using the 100 Ω reference bank may be done by the CCC, the BCCC, or one of the direct current comparator (DCC) bridges with matrix scanners [5]. All three of these systems provide the lowest Type A uncertainty with a two-step process which calibrates a 10 Ω, 1 kΩ, or 12.9 kΩ standard resistor before calibrating a 100 Ω resistor. Power coefficients need to be taken into consideration if transferring through a 10 Ω resistor at different current levels. The 10:1, 2065:16, or 4130:32 bridge ratios have lower Type A uncertainty than a 1:1 ratio [6].

III. Location of Bridges and Infrastructure

Figure 1 shows that most of these bridges and standard resistors are located in the main resistance laboratory in room F013 of the AML. The QHR is in this lab in an isolated pit. The NIST-4 watt balance is located in the next corridor in room E024, also in an isolated pit. Due to limited space in E024, the 100 Ω resistors are located in a different room via a shielded four-terminal cable (as had been done for NIST-3). The availability of space in room F023, which is adjacent to F013 and directly across the corridor from E024, was an appropriate location. F023 is a shielded laboratory space with less activity than the main resistance laboratory of F013, providing isolation of the 100 Ω resistors and NIST-4 measurements from other activities taking place in the main resistance lab of F013. A DCC and matrix scanner are located in F023 which calibrates the 100 Ω resistors for NIST-4 regularly. Dedicated air and oil baths and check standards are also in F023. A four-terminal double-shielded junction-box is installed in F023 to allow connection to any of the 100 Ω resistors in F023 to NIST-4, the DCC bridges, the CCC bridge, or the BCCC bridge. A 30 m double-shielded cable goes from NIST-4 in E024 to the junction box in F023. Likewise, two double-shielded cables of length 30 m go from the junction box in F023 to the CCC and BCCC bridges and 100 Ω reference bank in F013. The double-shielded cables and junction box have made it possible to calibrate the 100 Ω resistors used by NIST-4 in-situ without having to move or disturb them for calibration or connection to the experiment, reducing errors due to transportation and handling.

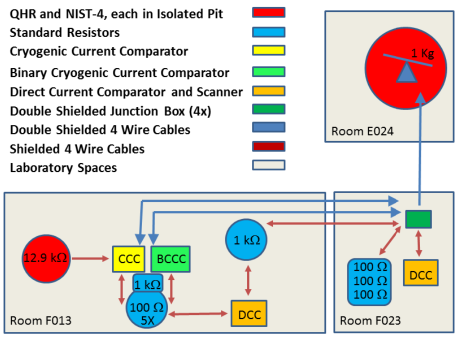

Fig. 1. Location of the QHR, NIST-4, CCC, BCCC, DCCs, resistors, double-shielded junction box, and 4 wire cables. Multiple paths are shown to scale from the QHR to resistors used by NIST-4.

IV. Measurement Results

The infrastructure described has been in place and refined since 2015. Routine measurement of the 100 Ω resistors, located in F023, has been done by a DCC located there to calibrate and track the drift of the resistors. The automated switching of the matrix scanner has made weekly measurement of these resistors and check standards possible. Less frequently, the 100 Ω resistors have been calibrated using the CCC and BCCC and 100 Ω reference bank in F013. Resistors must be manually connected to the CCC or BCCC so these processes are more labor intensive than using the DCC and matrix scanner. A comparison of the DCC and BCCC to calibrate the 100 Ω resistors in F023 yielded agreement of 3 x 10^{-9} for these systems, using resistors in the 100 Ω reference bank in F013 as the standards. We have recently been successful at remote calibration of the 100 Ω resistors in F023, through the double-shielded cable, using the QHR standard and the CCC and BCCC bridges. Additional measurements are planned when the QHR is operated in 2016.

Figure 2 shows a recent test using both lengths of the 30 m double-shielded cables connected in series (60 m) with the DCC and 100 Ω reference bank in F013, without moving resistors. The 100 Ω measurements made with and without the 60 m cable agreed within 4 x 10^{-9} for the DCC and BCCC. Initial measurements were 10 x 10^{-9} from the predicted value of the 100 Ω. Updating the calibration of the 10 Ω and 1 kΩ reference resistors brought the 100 Ω measurements within 5 x 10^{-9} of the predicted value. Changes in barometric pressure have been correlated to the post-calibration change in the measurements made using the 1 kΩ standard.

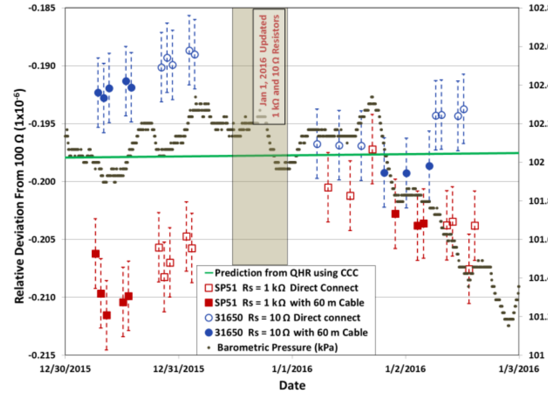

Fig. 2. Test of double-shielded cables without moving the standard resistors. 100 Ω resistors in F013 were measured by the DCC and BCCC with a direct connection and with 60 m of double-shielded cable from F013 to F023 and back to F013 inserted agreed within 4 x 10^{-9}. Only DCC measurements are shown. Error bars are typical 1σ standard deviation of the measurements.

V. Conclusion

The system of bridges, standard resistors, and connections for providing traceability from the NIST QHR to the NIST-4 watt balance is described. The system provides in-situ calibration of the 100 Ω standard resistors used by NIST-4. A comparison of the BCCC and DCC bridges agreed within 3 x 10^{-9}. Recent tests of the double-shielded cables with the DCC and BCCC demonstrated a difference of less than 4 x 10^{-9} for measurements made with and without the 60 m of double-shielded cable. Frequent calibration of 10 Ω and 1 kΩ reference resistors is critical for measurements to agree within 5 x 10^{-9}. Additional tests of the scaling from the QHR to the 100 Ω standard resistors for NIST-4 are ongoing.

References

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