Procedures for the Traceability of High Resistance Standards Using a Teraohmmeter

Dean G. Jarrett, Marlin Kraft, Isabel Castro, Brett Degler and Mark Evans

Abstract: The Metrology of the Ohm Project in the Quantum Electrical Metrology Division at the National Institute of Standards and Technology (NIST) routinely disseminates the U. S. representation of the ohm through calibration services and measurement assurance programs. The measurement systems and procedures used to calibrate standard resistors and current shunts of nominal decade values in the range 10^{-5} Ω to 10^{12} Ω provide NIST customers with traceability to U. S. and international standards based on the quantum Hall effect. In recent years, a number of requests have been received regarding the best practices for dissemination of high resistance (10^{7} Ω to 10^{12} Ω) from primary standard resistors calibrated by NIST to secondary standard resistors calibrated by our customers. The availability of a new generation of high resistance bridges, meters, and instruments with improved specifications, microprocessor based automation, software packages, and programmable parameters has given the measurement community more options for this dissemination, but has also raised many questions regarding how to best disseminate the ohm in the high resistance range. Over the past year, NIST has worked with several customers and manufacturers to develop a set of procedures to meet today's needs for disseminating the ohm at high resistance values. NIST has provided designs and guidance for the development of improved high resistance standards with low voltage coefficients, low temperature coefficients, low drift rates, rapid settling times, and guarded components. Customers, such as the U. S. Department of Defense primary standards laboratories and Costa Rica's National Metrology Institute Laboratorio Costarricense de Metrologia and the Instituto Costarricense de Electricidad, have asked for guidance in supporting their ability to maintain and disseminate the ohm from the NIST calibrations of their primary high resistance standards to secondary standards laboratories using a digital teraohmmeter as the transfer device. NIST, our customers, and the teraohmmeter manufacturer have worked together to develop procedures and make the necessary measurements to meet customers' needs for traceability to NIST by using the teraohmmeter as a transfer device.

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1. Introduction and Traceability Paths

The U. S. representation of the ohm is disseminated by the National Institute of Standards and Technology (NIST) from the quantum Hall effect (QHE) [1] to customers through a robust calibration service. Over 300 tests on standard resistors are performed annually by NIST for other U. S. Government agencies, public utilities, instrument manufacturers, and foreign governments. Many of the primary standards laboratories that send resistance standards to NIST are providing support to secondary labs that ultimately provide calibration support to many end users. A traceability path is normally required when a resistance

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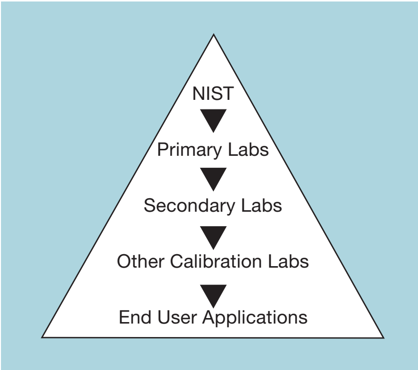

Figure 1. Traceability pyramid from NIST calibration services at the top to end user applications at the bottom, that are transferred by primary standards laboratories, secondary standards laboratories, and other calibration laboratories.

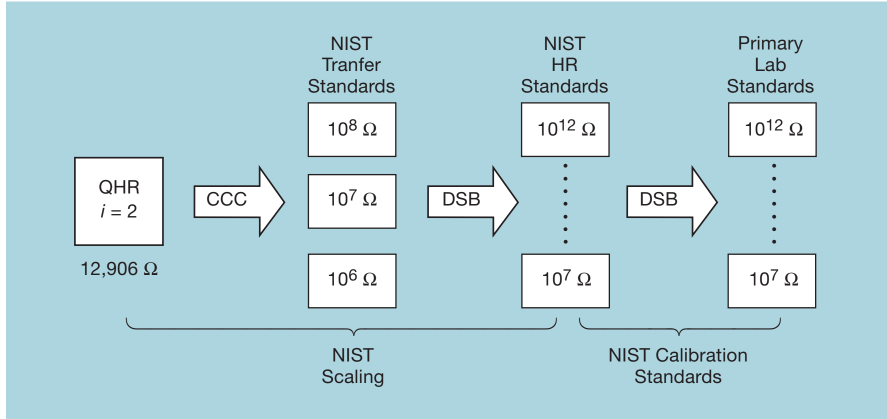

Figure 2. Traceability chain for the ohm starting from the quantum Hall resistance to the high-value standard resistors sent to NIST for calibration.

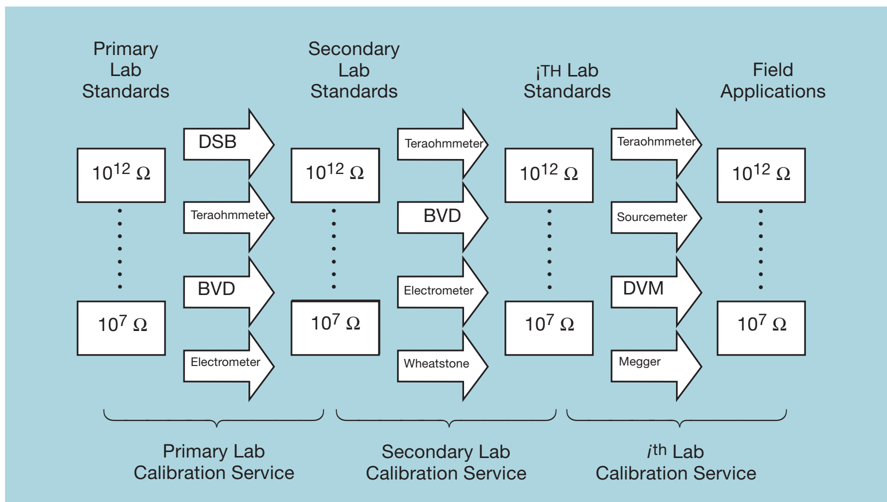

Figure 3. Traceability from primary standards laboratories to end user applications. Many methods are available to provide a NIST traceable calibration to end users. Instruments such as dual source bridges, teraohmmeters, binary voltage divider bridges, electrometer-source meters, Wheatstone bridges, digital multimeters, and Meggers® may be used at different levels in the traceability chain.

measurement is applied to evaluate a process, a material, a component, or some other quantity. Figure 1 shows a pyramid where NIST provides the best possible uncertainty, at the top, that supports customers at the primary standards laboratory level. The primary standards laboratories in turn disseminate the U. S. representation of the ohm to their customers at the secondary standards laboratory level. Ultimately, end user applications are supported by a NIST traceable measurement to meet a specific need. As one proceeds from the apex to the base of the pyramid, the uncertainties increase, the users become more numerous, the calibration instrumentation becomes less specialized and less expensive, and the applications become more diverse. While the end user applications and experiments may be very expensive and specialized, they usually have less rigorous calibration uncertainty requirements than a primary or secondary calibration lab.

Over the past two decades, NIST has put considerable resources into improving the standard resistor measurement services that are provided to customers at the primary standards laboratory level. [2] In the high resistance range of 10^7 Ω to 10^{12} Ω, improved measurement techniques [3, 4] and standards [5, 6] have been developed and implemented permitting an order of magnitude reduction in the expanded uncertainties (k = 2) that NIST reports to customers. With new resistance standards and new instrumentation, some of which are commercially available, lower uncertainties can be achieved at all levels of the pyramid. Note that different test methods, different equipment, and different standards may be used at each level of the traceability pyramid.

Figure 2 shows the traceability path at NIST from the QHR to high resistance standards sent to NIST by primary standards laboratories. Semiannually the QHR system is operated to check and update the drift rate of NIST high resistance (HR) standard resistors used by the calibration services. For the high resistance range, sets of NIST transfer standards of nominal values 10^6 Ω, 10^7 Ω, and 10^8 Ω are measured directly against the QHR using cryogenic current comparators (CCCs). [4] These NIST transfer standards are in turn used, together with the NIST guarded dual-source bridge (DSB) [3], to calibrate a set of NIST HR standards in the range 10^7 Ω to 10^{12} Ω. At the conclusion of the NIST scaling process, the drift rates of the NIST HR standards are updated and, together with the DSB, used to calibrate primary laboratory standard resistors.

Once a customer's standard resistor is calibrated, a calibration certificate is produced and provided to the customer. The returned resistor can then be used, together with suitable instrumentation in the customer's laboratory, in turn to calibrate standard resistors for secondary laboratories. Figure 3 shows the traceability chain for resistance once a resistor

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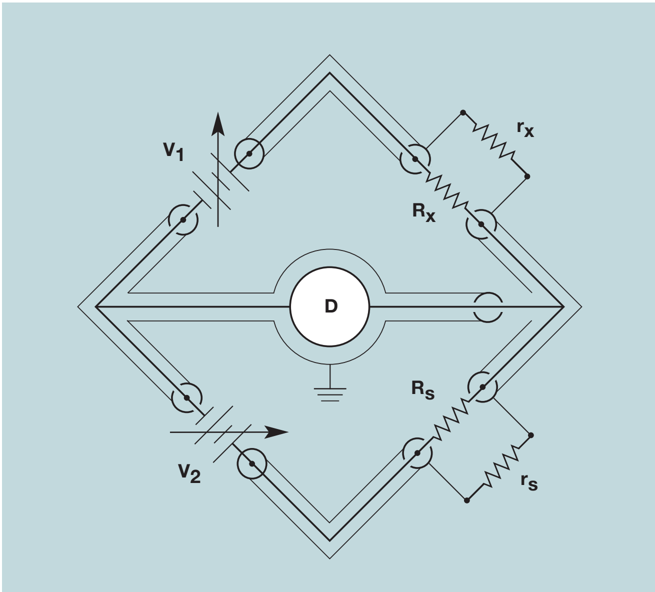

Figure 4. Guarded Dual Source Resistance Bridge.

leaves NIST. Between the primary standards laboratory level and an end user's field application, there may be many different instruments, procedures, and transfer standards in use.

Today, there are new standard resistors and instruments manufactured for the measurement community that support lower calibration uncertainties than in the past. Because of this new equipment, several primary standards laboratories have asked NIST for guidance regarding the best practices for transferring the U. S. ohm from their primary standards to the standards calibrated by their secondary laboratories. To obtain the lowest uncertainties from the newest and most advanced instruments requires the development and verification of procedures that ensure accurate dissemination of the ohm. Sections 2 and 3 provide brief descriptions of the instrumentation available, as well as the standards in use today. Finally, Section 4 presents several examples that illustrate how primary standards laboratories have chosen to disseminate the ohm using a teraohmmeter [7] as the transfer device.

2. High Resistance Bridges, Meters, and Instruments

While there are a number of measurement techniques available for high resistance measurements, detailed descriptions of all methods and instruments are beyond the scope of this paper which will focus in detail only on the teraohmmeter. However, several other methods used by NIST [8], primary labs, and/or secondary labs are briefly discussed and referenced since they are cited in the traceability chain and are appropriate for some applications. Many factors such as workload volume, level of uncertainty, lab staffing, funding, measurement application, and available resources need to be considered by all standards labs when determining a method for dissemination of the ohm. No single instrument or method is suitable for all standards laboratories.

2.1 Guarded Dual Source Bridge

The bridge used at NIST to calibrate customer standards in the range 10 MΩ to 1 TΩ is the guarded dual source bridge. [3] Expanded uncertainties ($k = 2$) for this bridge range from 3×10^{-6} at 10^7 Ω (10 MΩ) to 100×10^{-6} at 10^{12} Ω (1 TΩ). The bridge is formed by replacing two of the resistive arms of a Wheatstone bridge with low impedance programmable voltage calibrators. The bridge is shown in Fig. 4 where V_1 and V_2 are programmable voltage calibrators and the detector, D, is an electrometer with a resolution of ±3 fA in the current mode.

The outputs of V_1 and V_2 drive bridge resistances (R_X and R_S) and guard resistances (r_x and r_s). Leakage currents that affect the Wheatstone bridge above 10 GΩ are reduced by the low impedance calibrators and by guarding the high side of the detector with r_x and r_s. The low voltage side of the detector, where V_1 and V_2 are joined, is a virtual ground. Multiple bridge ratios up to 1000:1 can be selected by changing the output of the sources. The guarded dual source bridge is able to calibrate standard resistors of nominal values up to 100 TΩ and at voltages up to 1000 V. Guarded switching techniques [12] have also been developed to provide automated substitution of standard and unknown resistors into the bridge.

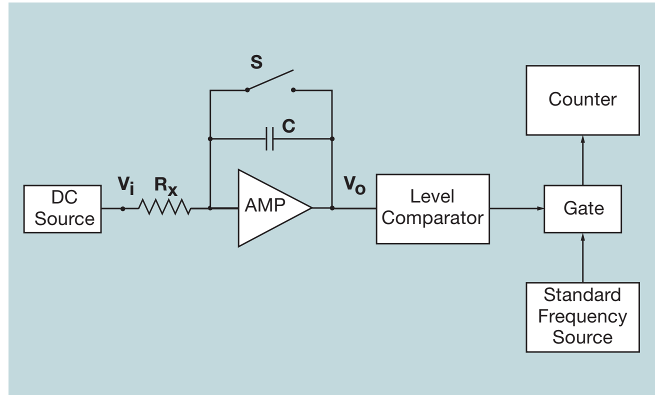

Figure 5. Teraohmmeter system.

2.2 Teraohmmeter

The teraohmmeter is an instrument that uses an analog integrator technique to measure resistances by forming a resistor-capacitor network with the test resistor and an internal fixed air capacitor. Figure 5 shows a simplified diagram of the teraohmmeter. The unknown resistor R_X and capacitor C are used to form a RC network that is charged by a dc source when switch S is opened. The time Δt required for the output voltage V_0 to change by a known amount, ΔV_0, is measured by a counter circuit. From the test voltage V_i, change in output voltage ΔV_0, capacitance C, and measured time Δt, the resistance R_X can be calculated as:

$$R_X = -(1/C)(V_i/\Delta V_0)\,\Delta t\,. \tag{1}$$

Teraohmmeters can measure standard resistors in the range 100 kΩ to 10 PΩ . Typical expanded uncertainties ($k = 2$) for the ranges 10 MΩ to 1 TΩ are 150×10^{-6} to 1000×10^{-6}.

2.3 Electrometer/Source Meter

Electrometer / source meters and source-measure units [9] are

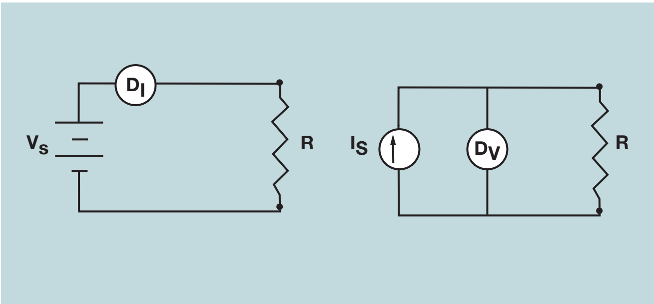

Figure 6. Sourced-voltage measured-current and source-current measured-voltage methods for high resistance measurement.

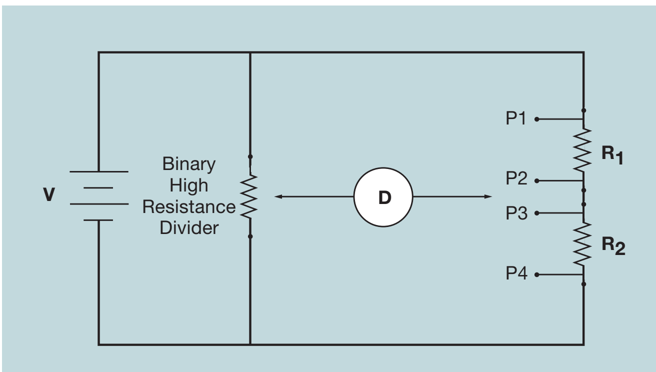

Figure 7. Binary voltage divider, voltage source, DVM detector, and resistors R_1 (standard) and R_2 (unknown) which form the automated resistance ratio bridge.

another class of instrument used in the high resistance traceability chain. They are of interest to the U. S. Air Force since they are deployed in their secondary laboratories. These instruments have both sourcing and measuring capabilities. They can source a voltage (V_S) or a current (I_S) to a resistor under test, measure a current (D_I) or a voltage (D_V), and display the resistance determined from the sourced and measured parameters. Figure 6 shows the basic circuit diagram for both configurations. Having sourcing and measuring capability in one instrument provides for easier and more convenient use than using separate instruments for the measurement. The high impedance, typically 100 TΩ or more, and low current measurement sensitivity, typically 10 fA, makes these instruments well suited for high resistance and low current measurement.

2.4 Binary Voltage Divider Bridge

Another bridge used for high resistance measurement is the binary voltage divider bridge [10]. This commercially available automated resistance ratio bridge covers the resistance range 1 kΩ to 1 TΩ at voltages up 100 V. Using an internal binary resistance divider [11], the bridge determines the ratio between the two resistors and assigns a value to the unknown resistor based on the value of the standard resistor. Resistance ratios up to 1000:1 can be measured on the bridge. An external digital volt meter (DVM) having 100 nV resolution is used as a differential detector, D, to provide a system resolution of 8 digits. Figure 7 shows the binary high resistance divider, power supply (V), DVM detector, and resistors that complete the measurement circuit. Typical expanded uncertainties ($k = 2$) for the ranges 1 kΩ to 1 GΩ are 0.1×10^{-6} to 5×10^{-6}. The 10 GΩ input impedance of the detector requires that resistors in the range 10 GΩ to 1 TΩ be measured in parallel with a standard resistor of nominal value no larger than 1 GΩ . Typical expanded uncertainties ($k = 2$) for the ranges 10 GΩ to 1 TΩ are 20×10^{-6} to 500×10^{-6}.

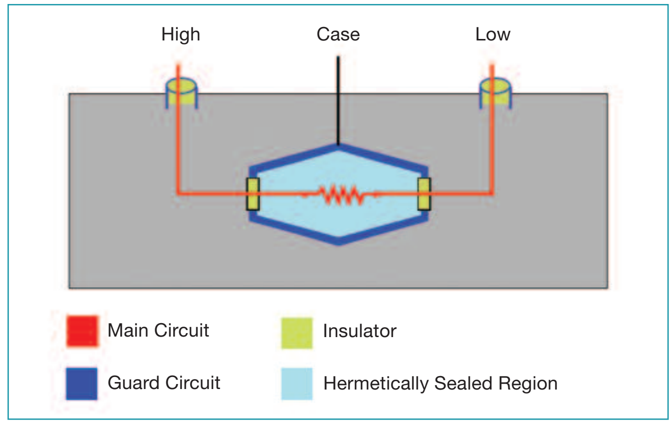

Figure 8. Schematic of a three terminal resistor. Coaxial connector shields (High and Low), resistor case, and hermetically sealed canister are all connected to grounding terminal of the resistor.

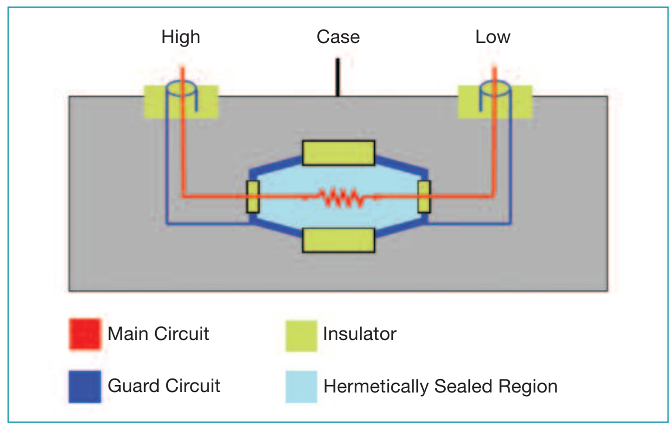

Figure 9. Schematic of a guarded split can resistor design. Coaxial connector shields (High and Low) are isolated from the case and can be used to drive each half of the hermetically sealed canister at a guard potential, suppressing leakage currents to the case which is at ground potential.

3. Standard Resistors for High Resistance

NIST has provided designs and guidance for the development of improved high resistance standards with low voltage coefficient, low temperature coefficient, low drift rate, rapid settling time, and guarded components [5, 6]. Figure 8 shows a three-terminal high resistance standard which has been available for many years. The connections to this type of resistor are often coaxial connectors, but in some instances may be banana plugs isolated from the case. The three terminals are high, low, and case connections, where the case connection is typically connected to ground potential. To limit leakage current to ground, the resistance of the insulation must be several orders of magnitude greater than the resistance element, otherwise non-negligible leakage currents can flow from the main resistor circuit to the case which is at ground potential.

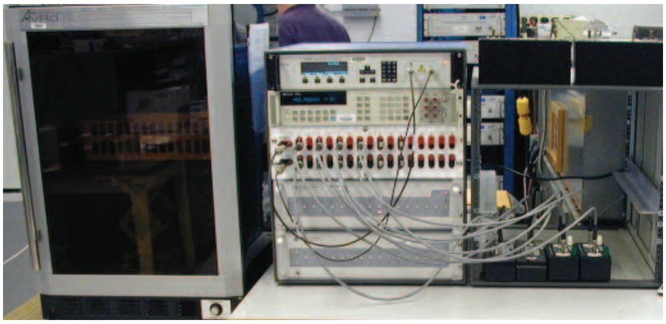

Figure 10. U. S. Air Force measurement system consisting of a teraohmmeter and guarded scanners for the measurement of high resistance standards. An air bath is shown on left where NIST traceable primary standard resistors are placed. The PMEL resistors being calibrated are placed on the bench to the right of the scanners as shown in the picture. The teraohmmeter, connector panel and guarded scanners are shown between the air bath and test resistors.

Figure 9 shows a split-can guarded resistor where the coaxial connector shields are isolated from the case. These shields are internally connected to each half of a metal-insulator-metal (MIM) canister which allows the entire main circuit to be surrounded by a driven guard circuit, suppressing leakages to the case and ground. To utilize the guard circuit, the coaxial shields are driven at the same potential as the center conductors and a guard resistor (not shown) is attached to the guard circuit.

4. Specific Examples of Traceability Using a Teraohmmeter

In this section, two specific examples are illustrated that use a teraohmmeter as a transfer device to disseminate the ohm from NIST calibrated standard resistors to customer standards. As described earlier, there are several choices of bridges and instruments available, which are appropriate for many applications. Some NIST customers are using the Guildline Model 6520* Digital Teraohmmeter as a transfer device. NIST has been contacted by customers in the U. S. Department of Defense and U. S. Department of Energy with questions regarding the use of this instrument as a transfer device for high resistance measurements. Collaborative efforts are reported here to illustrate two measurement techniques that have been developed for low uncertainty calibration using this instrument.

4.1 U. S. Air Force Metrology and Calibration Program (AFMETCAL)

The U.S. Air Force is in the process of acquiring high resistance standards in the range of $10^9\ \Omega$ to $10^{12}\ \Omega$ to support electrometers and other low current / high resistance equipment. One set of four standards will be supplied to each of their 75 Precision Measurement Equipment Laboratories (PMELs), which will result in the need to calibrate 300 individual resistors. The new resistance standards will have low temperature coefficient of resistance (TCR) and internal thermistors to allow use on a bench without a temperature controlled air bath. In order to support these resistors at the Air Force Primary Standards Laboratory (AFPSL), an automated resistance measurement system needed to be developed for the range $10^9\ \Omega$ to $10^{12}\ \Omega$. The system consists of a teraohmmeter, two guarded scanners [12], and an air bath [13], as shown in Fig. 10. Two connector panels allow for easy connection of up to 32 resistors at a time, including standard resistors calibrated at NIST and the resistors under test. Using the substitution technique [2], the standard resistors are measured first, followed by the test resistors. The difference between the certified value of the standard resistors and the value measured with the teraohmmeter is used to assign a certified value to the test resistor. This method lowers the effect of offsets introduced by the scanner, and allows the utilization of the transfer measurement specifications of the teraohmmeter instead of the larger 1-year absolute measurement specifications. The software monitors the measurements over time until an acceptable standard deviation is achieved. This standard deviation represents a typical Type A evaluation of standard uncertainty.

Because this system is still being developed, an uncertainty analysis is not yet available. Initial measurements from the automated system at 1 TΩ are shown in Fig. 11, while measurements at 10 GΩ are shown in Fig. 12. In both figures, two standard resistors were measured first when directly connected to the teraohmmeter and second when connected to the teraohmmeter through several channels of the guarded scanner. Error bars on individual data points represent the teraohmmeter transfer expanded uncertainty ($k = 2$) of 25×10^{-6} at 10 GΩ and 80×10^{-6} at 1 TΩ. The one-year teraohmmeter absolute measurement expanded uncertainty ($k = 2$) is 600×10^{-6} at 10 GΩ and 1200×10^{-6} at 1 TΩ. The specifications that the U. S. Air Force needs to support their PMELs expanded uncertainties ($k = 2$) are 600×10^{-6} at 10 GΩ and 1000×10^{-6} at 1 TΩ and are show to the right of Fig. 11 and Fig. 12. By using the teraohmmeter as a transfer device and the guarded scanners for connecting resistors to the teraohmmeter, the specification uncertainty can be achieved using a fully automated measurement system. These preliminary tests were made at NIST using both U. S. Air Force and NIST standard resistors, a NIST guarded scanner, and the U. S. Air Force teraohmmeter.

4.2 Instituto Costarricense de Electricidad

To support the calibration and measurement capabilities (CMCs) that Costa Rica's Instituto Costarricense de Electricidad (ICE) has included in Appendix C of the Bureau International des Poids et Mesures (BIPM) Key Comparison Database (KCDB) [14], a timely calibration procedure was developed. This procedure is an alternative to performing a full calibration of the teraohmmeter and may be used at a few specific test voltages. The manufacturer's user manual describes a full calibration procedure which results in a maximum parameter test space. The alternative procedure, described in Section 5, was developed in consultation with the manufacturer, has been verified at NIST, and is currently deployed at ICE in order to provide a traceability path for Costa Rica's CMCs. Similar to the U. S. Air Force application, the teraohmmeter is used as a trans-

* Certain commercial equipment is identified in this article in order to adequately specify the experimental procedure. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the equipment identified is necessarily the best for the purpose.

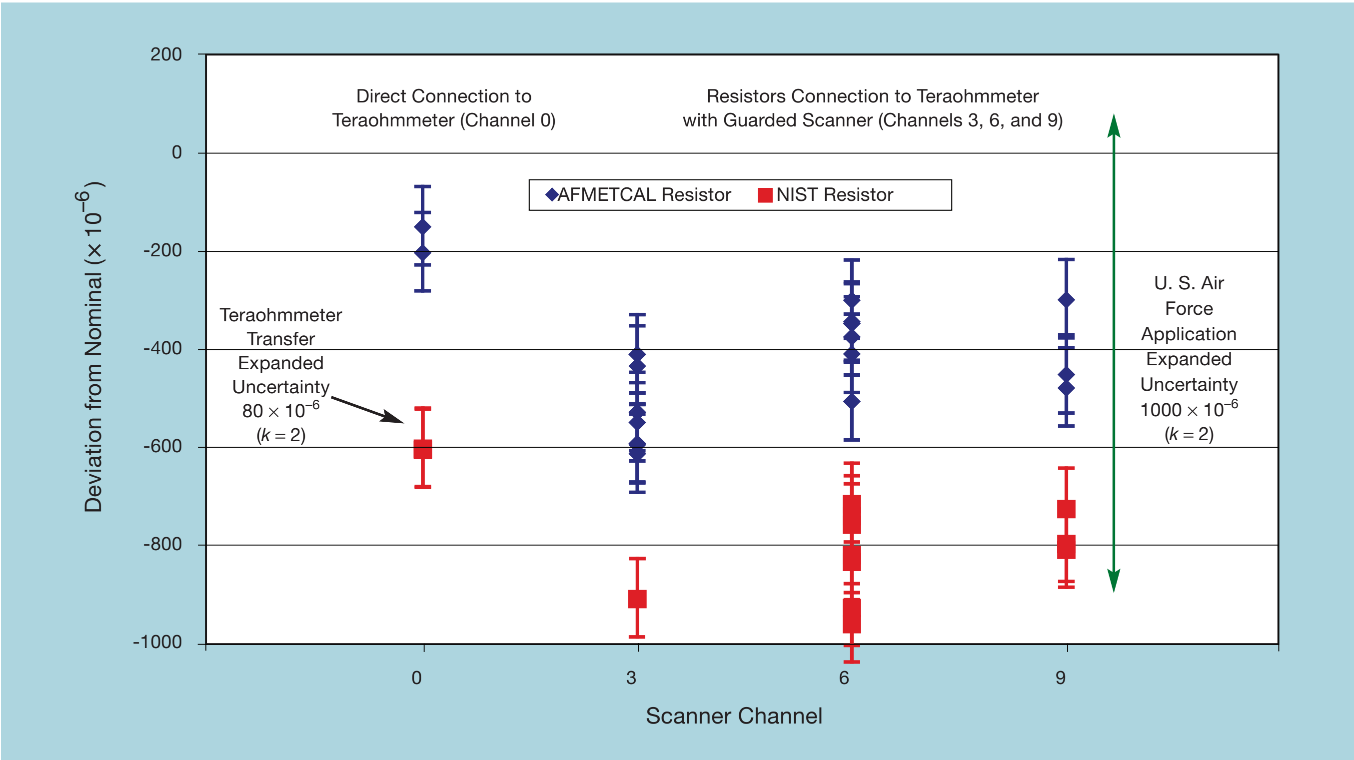

Figure 11. Preliminary measurements at 1 TΩ on the proposed system. Using the teraohmmeter as a transfer device, the expanded uncertainty ($k = 2$) of 1000×10^{-6} can be supported by the automated system (green arrow at right). Corrections can be applied to individual scanner channels once the system is fully characterized and verified. Preliminary data taken at 1 TΩ on the NIST scanner show offsets of approximately -300×10^{-6} for channel 3 and approximately -200×10^{-6} for channels 6 and 9, as compared to the direct connection (channel 0).

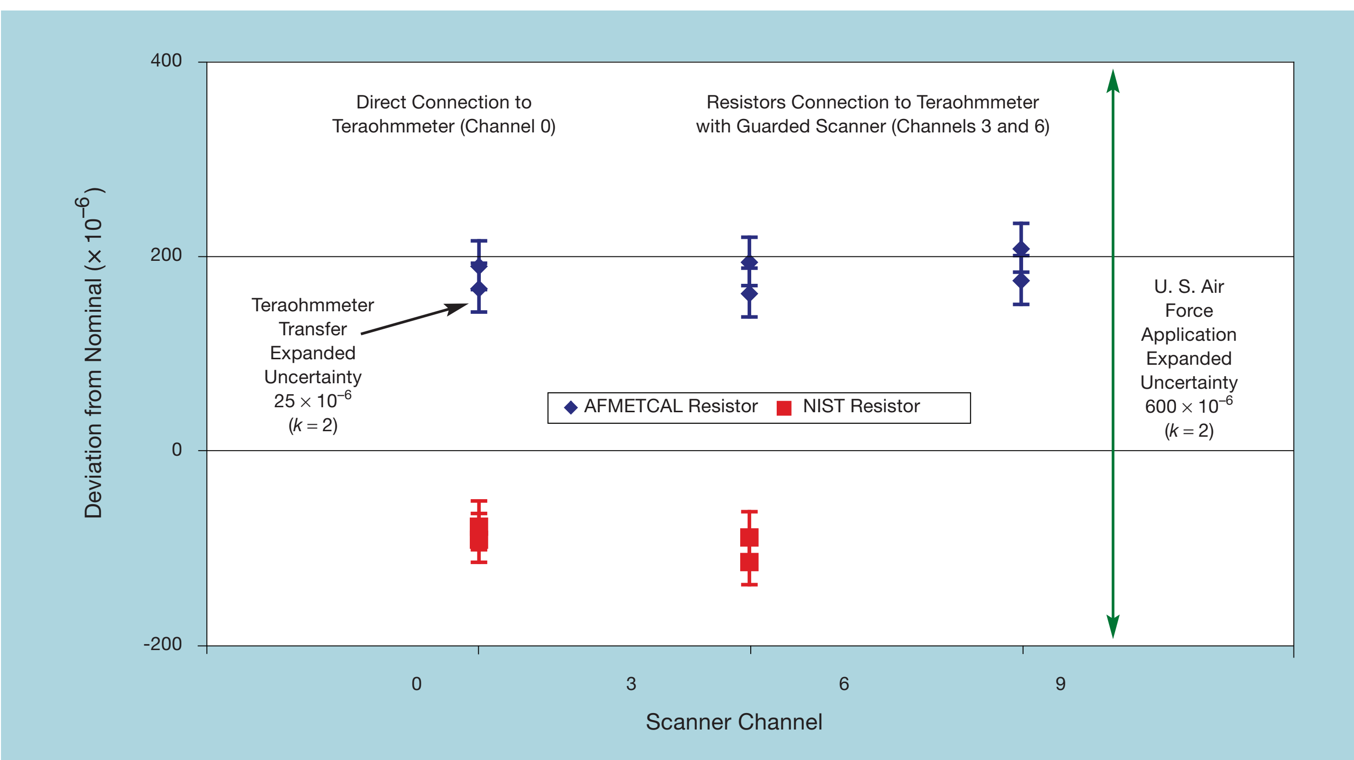

Figure 12. Preliminary measurements at 10 GΩ on the proposed system. Transfer expanded uncertainty ($k = 2$) of 25×10^{-6} will meet the required expanded uncertainty of 600×10^{-6} (green arrow at right). Standard resistors are measured by both direct connection to the Teraohmmeter (channel 0) and by connection through different channels of the guarded scanner. Preliminary data taken at 10 GΩ show no significant offsets for the channels tested. The NIST resistor was not tested on channel 6 of the guarded scanner.

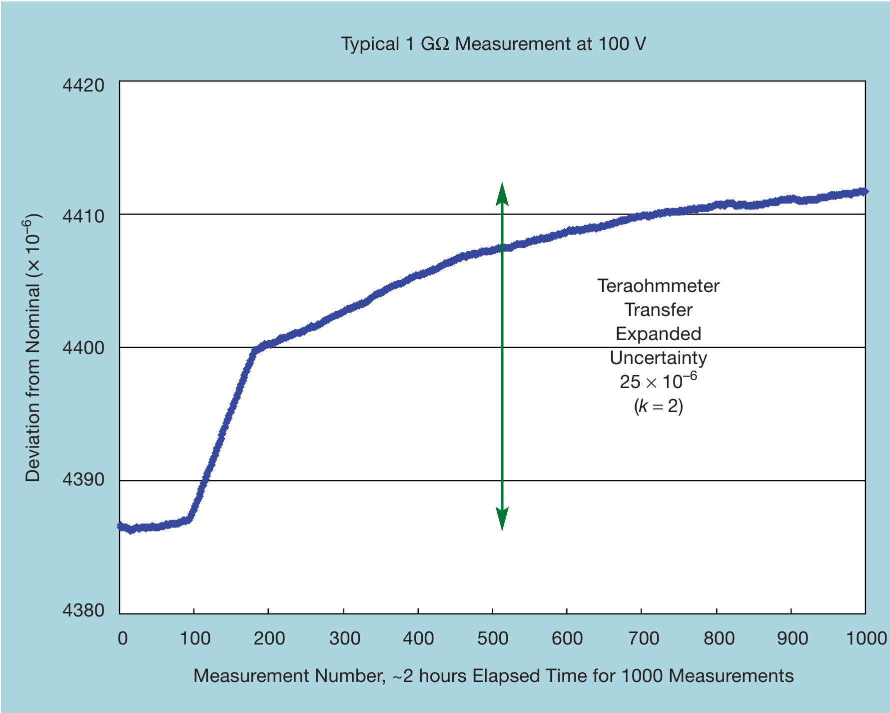

Figure 13. Typical data set from measurement of 1 GΩ standard resistor. The teraohmmeter transfer expanded uncertainty ($k = 2$) of 25×10^{-6} is shown by the error bar.

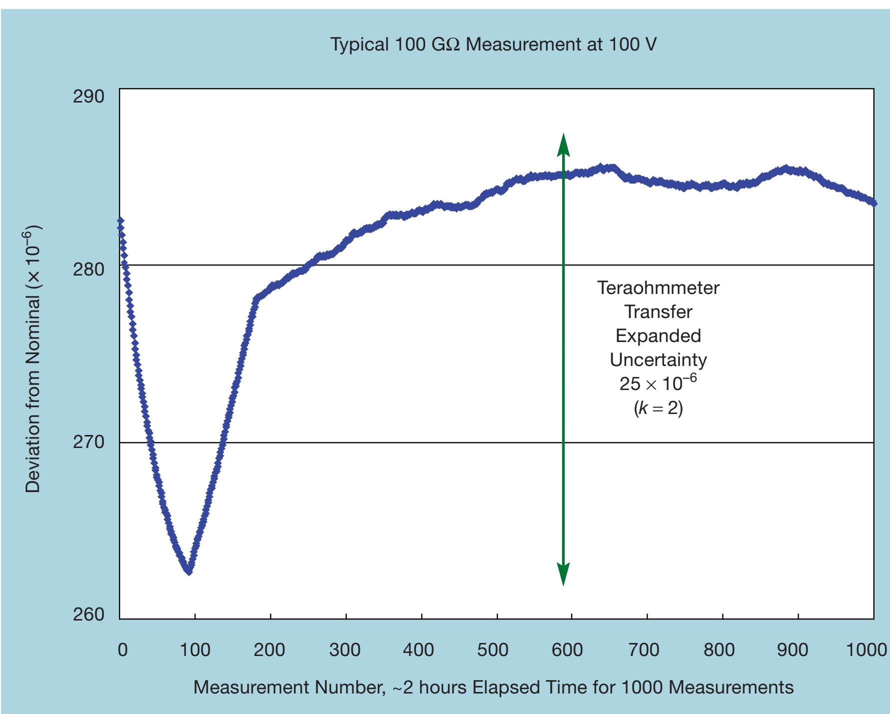

Figure 14. Typical data set from measurement of 100 GΩ standard resistor. The teraohmmeter transfer expanded uncertainty ($k = 2$) of 25×10^{-6} is shown by the error bar.

fer device to take full advantage of the transfer expanded uncertainty ($k = 2$) over the range 10 MΩ to 100 GΩ.

To verify and develop this test procedure, ICE participated in the development phase of this project by sending their teraohmmeter and standard resistors to NIST. Both NIST check standards and ICE standard resistors were calibrated at NIST using the guarded dual-source bridge over the resistance range of 10 MΩ to 100 GΩ at one or two test voltages. Measurements were made at 100 V for all five decades of resistance and additional 10 V measurements were made at the 10 MΩ and 100 MΩ decades of resistance. Once the resistors were characterized, they were then measured with the teraohmmeter to verify the transfer expanded uncertainty ($k = 2$) of the teraohmmeter. The NIST check standards were used in an iterative process to adjust the teraohmmeter at a single test voltage (100 V) when measuring each decade resistor from 10 MΩ to 100 GΩ.

Figures 13 and 14 show typical teraohmmeter data over a 2 hr. time period (1000 measurements) for 1 GΩ and 100 GΩ resistors. All of the data were within the teraohmmeter transfer expanded uncertainty ($k = 2$) of 25×10^{-6} as shown on each plot. The large slopes shown during the first 200 measurements are believed to be due to settling responses when a resistor is measured with the teraohmmeter. Filtering within the teraohmmeter lengthens the time for this initial response to settle. The pattern is repeatable for a given resistor. These patterns were not observed when the same resistors were measured with the guarded dual source bridge. The lowest Type A standard uncertainty can be achieved when only data points after the first 200 measurements are considered for analysis. Therefore, it is recommended that the first 200 data points are not included in data analysis that assigns a correction to a resistor. Further investigation of this data pattern is planned.

There were several important goals involved in this collaboration. First, the standard resistors used by ICE with the teraohmmeter needed to be calibrated and their performance characteristics, such as drift rates and voltage coefficients, had to be established. This was done by measuring these resistors first on the NIST guarded dual source bridge which provided a traceability path through NIST. The next goal was to develop a transfer procedure that ICE could use with their NIST traceable resistors to easily calibrate high resistance standards for their customers. NIST consulted with the teraohmmeter manufacturer to develop the calibration procedure described in Section 5, which is a short calibration procedure, applicable only at a specific voltage. The third goal of this collaboration was to gain first-hand working knowledge of the teraohmmeter and independently verify the teraohmmeter's specified transfer uncertainties.

5. Teraohmmeter Transfer Procedure

In collaboration with the manufacturer, a procedure has been developed to use this teraohmmeter as a transfer standard. Through the "Sofcal" Menu of the teraohmmeter, the test parameters at a specific test voltage can be adjusted so that they agree with the parameters stated on the calibration certificate assigned to a standard resistor. This procedure was used to provide traceability from a calibrated standard resistors to customer resistors of the same nominal value and at the same test voltage. When using this shortened calibration procedure, it is recommended that the test voltages be verified using the diagnostic volt test function in the "Sofcal" menu.

The four screen pictures shown in Figs. 15 through 18 illustrate the process for modifying a specific test setup calibration coefficient. Only the most important screens are shown in this paper; some intermediate screen menus are omitted. The figure caption explains the significance of each step. Additional information and flow charts are available in the January 2006 and newer versions of the manufacturer's user manual.

Through an iterative set of two to three adjustments of the settings in the "System Parameters" menu, a user can adjust the final measured value of the reference standard resistor to match the value reported on the resistor calibration certificate, thus allowing for the direct reading to be traceable to the standard resistor at a predetermined test voltage. The "Positive Coefficient" and "Negative Coefficient" terms are expressed in units of 1×10^{-6}.

Once the user exits the "Softcal" menu to the main menu, pressing the "Ohm Measurement" button will start the measurement sequence. A two minute "Soak Time" and use of the "Auto Polarity Reverse" function are recommended. The soak time is the initial settling wait time after a change in the voltage polarity. This process may be repeated untill the displayed value indicates the value of the resistor as reported on the calibration certificate within an acceptable difference for the application, expressed in units of 1×10^{-6}. These steps can be performed for other nominal values in the meter range. It is also important to ensure that the difference between soak time and delay time is understood. The *soak* time is the time the resistor is *under the applied voltage before* measurement samples are taken. The *delay* is the time that is *elapsed before the voltage is applied*.

Using the substitution method, the calibrated standard resistor and a check standard would be measured in order to verify that the test is within the desired tolerance before proceeding to measure other customer standard resistors.

6. Summary

It has been demonstrated that the teraohmmeters evaluated by NIST, the U. S. Air Force, and ICE may be used as transfer devices in the traceability chain from primary to secondary standards laboratories. While a rigorous uncertainty budget has not been completed at this time, it has been demonstrated that

Figure 15. "Sofcal Menu" screen is shown. This menu is entered from the main menu screen by pressing the "Sofcal" function key. This menu structure is true for all Teraohmmeters Rev. J and newer. From this screen, the user presses the "Password" function key to enter subsequent screens for parameter adjustment.

Figure 16. "Sofcal Calibrate Menu" screen is shown. The user adjusts the calibration constants of the teraohmmeter through either direct entry or through automated calibration routines. Access to this screen is password protected to prevent unintentional changes to calibration constants. Press "Cal. Vals" to bring up the next screen in the sequence.

Figure 17. "Cal Values Menu 2" is shown; this is the second of three screens in the "Cal Values" menu. The "System Parameters" screen is entered by pressing the second function key from the left. The far right button allows one to toggle between the three "Cal Values" menus.

Figure 18. "System Parameters" menu is shown. This menu is accessed from the "Cal. Vals" menu 2 when the "Sys Params" function key is pressed. The user can directly modify the teraohmmeter correction coefficients for any given test setup. The determination of any meter errors can be compensated directly by using the coefficients presented here. By default the menu enters the coefficient table at the last parameters used. The user can however access the coefficient for any test parameter setup within the matrix of valid test setups by selecting the measurement resistance range and excitation voltage.

expanded uncertainties (k = 2) of 600 × 10^{-6} at 10 GΩ and 1000 × 10^{-6} at 1 TΩ can be obtained by using the teraohmmeter as a transfer instrument. In the future, further measurement analysis is planned including intercomparing different resistor designs with the guarded dual source bridge, the teraohmmeter, and the binary voltage divider bridge.

7. References

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