CCEM-K2 Key Comparison of 10-MΩ and 1-GΩ Resistance Standards

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***Abstract*—An international comparison of dc resistance at 10 MΩ and 1 GΩ was organized under the auspices of the Consultative Committee for Electricity and Magnetism (CCEM) and piloted by the National Institute of Standards and Technology (NIST) with 14 other national metrology institutes (NMIs) participating. The transport standards were measured by the participating NMIs during a three-and-a-half year period beginning August 1996 and concluding March 2000. The transport standards used for this comparison were a set of three wirewound 10-MΩ standard resistors and three film-type 1-GΩ standard resistors, all packaged at NIST for this key comparison. The comparison demonstrated that all participating NMIs agree with the key comparison reference value at 10 MΩ and 1 GΩ within the 95% confidence level.**

***Index Terms*—Bridge, key comparison, measurement, National Metrology Institute, pilot laboratory, quantum hall, reference value, standard resistor, transport standard, uncertainty.**

I. INTRODUCTION

SINCE January 1, 1990, the international system of units (SI) representation of the ohm has been based on the quantum Hall effect in which a measured resistance value is equal to the von Klitzing constant R_K, believed to be equal to h/e^2, divided by an integer i of the quantum Hall state [1]. The value at a quantized Hall resistance (QHR) plateau is used to assign a value to one or more transfer standards which in turn assign values to banks of working standards through a resistance scaling process. The scaling process from the QHR to nominal decade values may require the use of several types of standard resistors, resistance bridges, and transfer devices. Key comparisons of resistance standards have been carried out at the 1-Ω and 10-kΩ levels in the past. In 1995, the Consultative Committee for Electricity and Magnetism (CCEM), formerly CCE, decided to extend the scope of some key comparisons to demonstrate equivalence of national metrology institutes' (NMIs') standards more effectively, and identified dc resistance $\geq 10^9\ \Omega\ (1\ \mathrm{G}\Omega)$ as one of the critical measurement areas. NIST volunteered to be the pilot laboratory for this key comparison and recommended using three wirewound 10 MΩ and three film-type 1-GΩ standard resistors as the transport resistors. Although, in general, wirewound resistors are more stable than film-type resistors, wirewound 1-GΩ resistors were not available to the pilot laboratory at that time. Thus, it was decided to include wirewound 10-MΩ standards in the comparison in the event that problems arose with the film-type 1-GΩ standards. In addition, the comparison at two different resistance levels would serve as a check of each NMIs resistance scaling process [2].

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TABLE I
PARTICIPATING NMIS AND ACRONYMS ORDERED BY MEAN DATE OF MEASUREMENT. THE PILOT LABORATORY (NIST) MEASURED THE TRANSPORT STANDARDS OVER SEVEN DISTINCT PERIODS OF TIME

National Research Council, Canada, **(NRC)**
Bureau National de Métrologie-Laboratorie Central des Industries Électriques, France, **(BNM-LCIE)**
National Physical Laboratory, U. K., **(NPL)**
Physikalisch-Technische Bundesanstalt, Germany, **(PTB)**
Commonwealth Scientific and Industrial Research Organization-National Measurement Laboratory, Australia, **(CSIRO-NML)**
Measurements Standards Laboratory, New Zealand, **(MSL)**
Council for Scientific and Industrial Research-National Measurement Laboratory, South Africa, **(CSIR-NML)**
National Institute of Standards and Technology (Pilot), U. S. A., **(NIST)**
Swedish National Testing and Research Institute, Sweden, **(SP)**
Office Fédéral de Métrologie, Switzerland, **(OFMET)**
Istituto Elettrotecnico Nazionale, Italy, **(IEN)**
Nederlands Meetinstituut-Van Swinden Laboratorium, The Netherlands, **(NMi-VSL)**
Korea Reasearch Institude of Standards and Science, The Republic of Korea, **(KRISS)**
National Institute of Metrology, China, **(NIM)**
D. I. Mendeleyev Institute for Metrology, Russia, **(VNIIM)**

II. PARTICIPANTS AND PROTOCOL

The transport standards were measured by the participating NMIs during a three-and-a-half year period beginning August 1996 and concluding March 2000. Table I shows the participating NMIs in chronological order by mean date of measurement. During the comparison, the pilot laboratory measured the transport standards over seven distinct periods of time. The pilot laboratory's measurements were made using two measurement systems, a guarded Wheatstone bridge system [3] and a guarded dual-voltage-source bridge system [4]. The measurement protocol did not specify to the participants what method to use to measure the transport standards. It was assumed that each NMI would use its normal measurement method, thus providing a more realistic assessment of the quality of the NMIs measurement process.

Among the 15 NMIs, five different methods were used to measure the transport standards. Table II shows the NMIs and which measurement systems they used at 10 MΩ and 1 GΩ. Three of the NMIs used several measurement systems providing additional redundancy to the measurement of the transport standards. Column one lists the NMI acronyms in

TABLE II
MEASUREMENT SYSTEMS USED BY PARTICIPATING NMIs AT 10 MΩ (M) AND 1 GΩ (G). COLUMN ONE LIST THE NMI ACRONYMS IN ORDER OF MEAN MEASUREMENT DATE AND COLUMNS TWO THROUGH SIX INDICATE WHICH MEASUREMENT SYSTEMS WERE USED AT THE 10-MΩ (M) AND 1-GΩ (G) RESISTANCE LEVELS. THE FIVE MEASUREMENT SYSTEMS USED WERE: WHEATSTONE BRIDGE WITH RESISTIVE ARMS (WB), BRIDGE WITH DUAL-VOLTAGE SOURCE ARMS (DVS), AUTOMATED BRIDGE WITH BINARY VOLTAGE DIVIDER (BVD), TERAOHMMETER (TM), AND DIGITAL MULTIMETER METHOD (DMM)

NMI	Measurement System				
	WB	DVS	BVD	TM	DMM
NRC		M,G			
BNM-LCIE	M,G		M		
NPL		M,G			
PTB		M,G	M,G		
CSIRO-NML	M,G				
MSL		M,G			
CSIR-NML				M,G	
NIST	M,G	M,G			
SP		M,G			
OFMET		G	M		
IEN					M,G
NMi-VSL		M,G			
KRISS		M,G			
NIM			M,G		
VNIIM	M,G				

order of mean measurement date and columns two through six indicate which measurement systems were used at the 10-MΩ (M) and 1-GΩ (G) resistance levels. The five measurement systems used were: Wheatstone bridge with resistive arms (WB), bridge with dual-voltage source arms (DVS), automated bridge with binary voltage divider (BVD) [5], teraohmmeter (TM) [6], and digital multimeter method (DMM) [7]. Only measurements made using the teraohmmeter system showed an offset that could possibly be attributed to the type of measurement system. However, the uncertainties of the measurements made using the teraohmmeter are an order of magnitude larger than those associated with the other measurement systems and these results are well within the reported uncertainty.

The protocol requested that the participating NMIs complete their measurements during their two-month period permitted by the schedule, that the standards be measured at 10 and 100 V, and that the measurements be made at a preferred ambient temperature of 23 °C. Calibrated thermistors were mounted in each transport standard to monitor the temperature. The 10-MΩ and 1-GΩ transport standards have temperature coefficients averaging $+1.5 \times 10^{-6}/°\mathrm{C}$ and $-28 \times 10^{-6}/°\mathrm{C}$ respectively, and results are corrected to 23°C. The 1-GΩ film-type transport standards have a voltage coefficient of approximately $-0.1 \times 10^{-6}/\mathrm{V}$. Each participating NMI was to report a measured value and mean date of measurement for each transport standard, the thermistor value for each transport standard, the test voltage, the ambient temperature and humidity, the combined standard uncertainties, and the ground/guard configuration of the transport standards to the pilot laboratory. Later, during the report preparation stage, NMIs were requested to submit uncertainty budgets for inclusion in Appendix B of the Key Comparison Database (KCDB) in support of the mutual recognition arrangement (MRA).

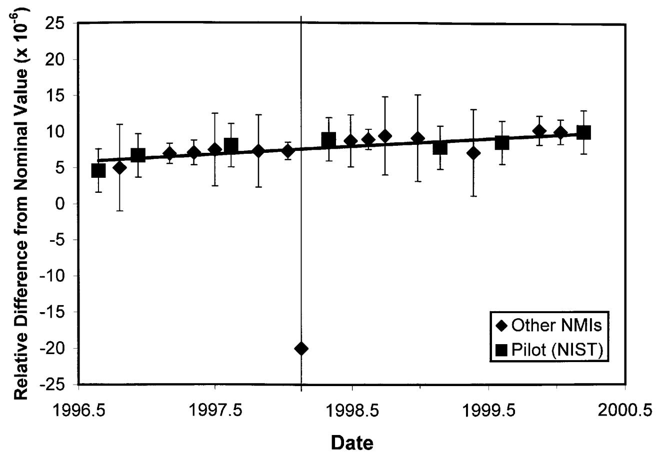

Fig. 1. Measurements of a 10-MΩ transport standard by all participating NMIs. The seven pilot laboratory measurements are denoted by ■ and the other NMI measurements are denoted by ◇. Error bars denote individual NMIs expanded relative uncertainty using $k = 2$. Least-squares linear regression line is based only on the pilot laboratory measurements.

III. MEASUREMENT RESULTS

After the measurements were completed, an uncertainty analysis was developed to account for correlations which are introduced by the use of pilot laboratory data to determine time-dependent reference values (TDRV) for the six transport standards. The results reported in this paper use the most recent analysis which is described in detail in a separate manuscript [8] as well as an erratum to the final report [2]. The TDRVs are the drift-rates of the transport standards and the key comparison reference value (KCRV) is the value of a virtual NMI for defining the NMIs' degrees of equivalence.

A. Time-Dependent Reference Values

For each transport standard at the 10-MΩ and 1-GΩ resistance levels, a time-dependent reference value (TDRV or x_{iP}) is calculated based on a least-squares linear regression of the pilot laboratory values. The three 10-MΩ transport standards were found to have drift-rates of 1.7×10^{-6}/year, 1.1×10^{-6}/year, and 4.5×10^{-6}/year during the course of this experiment. Fig. 1 shows NMI measurements of one of the 10-MΩ transport standards. Likewise, the three 1-GΩ transport standards were found to have drift-rates of 6.3×10^{-6}/year, 9.7×10^{-6}/year, and 7.6×10^{-6}/year during the course of this experiment. The assumption is made that the transport standards drift in a linear fashion and that any nonlinear effects are caused by severe physical or mechanical changes during transport.

Several other models for the transport standards' behavior have been investigated, but without additional information a better model of the drift behavior could not be determined. One approach considered for modeling the transport standards' behavior was to split the pilot laboratory data into two subsets and apply linear least-squares regressions since there was indication that a travel incident had occurred between the fourth and fifth sets of pilot laboratory measurements. However, there was no ideal approach for modeling the behavior of the transport standards in the region between the fourth and fifth sets of pilot labo-

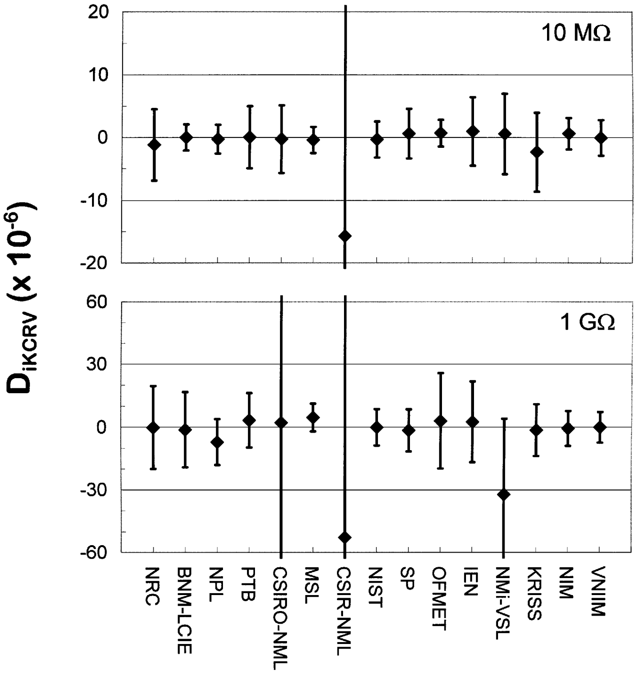

Fig. 2. Differences from key comparison reference value, $D_{i\mathrm{KCRV}}$, at 10 MΩ and 1 GΩ. Error bars denote expanded relative uncertainty for the individual NMIs using $k = 2$. NMIs are ordered by mean date of meaurement.

ratory measurements. None of the options provided a clear path to meeting all concerns. The consensus of the review group was that a single linear regression was an acceptable drift model for each transport standard for this key comparison.

For each NMI measurement of the three transport standards (x_i) at 10 MΩ and 1 GΩ, a difference from the time-dependant reference value $(D_i = x_i - x_{iP})$ is determined. The three differences are combined as a weighted average $(D_{i\mathrm{COMB}})$ at 10 MΩ and 1 GΩ. The reciprocal of the variance of the linear least-squares regression for each of the three transport standards determines the weights [8].

B. Key Comparison Reference Value

The $D_{i\mathrm{COMB}}s$ and the expanded relative uncertainty $(k = 2)$ for each NMI, $U_{i\mathrm{COMB}}$, are used to determine a key comparison reference value, KCRV or X_{KCRV}, and an uncertainty of the key comparison reference value, U_{KCRV}, for the 10-MΩ and 1-GΩ resistance levels. The KCRV is the weighted mean of the $D_{i\mathrm{COMB}}s$ where the $U_{i\mathrm{COMB}}s$ determine the weighting of each NMI [8]. For the 10-MΩ resistance level, the $X_{\mathrm{KCRV}} = 0.343 \times 10^{-6}$ and $U_{\mathrm{KCRV}} = 1.03 \times 10^{-6}$, and for the 1-GΩ resistance level, the $X_{\mathrm{KCRV}} = 0.099 \times 10^{-6}$ and $U_{\mathrm{KCRV}} = 3.96 \times 10^{-6}$. It should be noted that these uncertainties are 20% and 24% higher than those reported in the final report due to the addition of a term for the correlation of the TDRVs.

Fig. 2 shows for each NMI the difference from the key comparison reference value $(D_{i\mathrm{KCRV}})$ at 10 MΩ and 1 GΩ. For each NMI, the difference from the X_{KCRV} is less than the NMIs expanded relative uncertainty $(k = 2)$. For many of the NMIs, their difference from the X_{KCRV} is quite small compared to their expanded relative uncertainty. The data reported in Fig. 2 has been corrected to a nominal temperature of 23 °C. The participating NMIs were requested to measure the transport standards at both 10 and 100 V, although this was not always possible. The 100 V data are used when available due to the improvement in the signal-to-noise ratio at the higher voltage.

IV. CONCLUSION

The results of this key comparison have demonstrated good agreement among the participating NMIs at 10 MΩ and 1 GΩ. All of the participating NMIs agree within the 95% confidence level. It has been demonstrated that many NMIs can successfully use a buildup scaling process from SI standards to 1 GΩ and obtain results that agree within the uncertainty evaluations determined by each NMI. The fifteen participating NMIs used five different measurement methods to measure the transport standards demonstrating that accurate transfer ratios can be obtained by multiple measurement techniques with careful attention to reduction of errors caused by the effects of ambient conditions, lead and contact resistances, loading, and leakage currents. Despite indications of nonlinear behavior by the transport standards during shipment, the transport standards appeared to have functioned satisfactorily during the 43-month period of this comparison. The final report on this key comparison has been accepted by the CCEM and included in Appendix B of the Key Comparison Database in support of the Mutual Recognition Arrangement.

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