SIM Comparison of DC Resistance Standards at 1 Ω, 1 MΩ, and 1 GΩ

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***Abstract*—A set of regional comparisons of the dc resistance standards at the nominal values of 1 Ω, 1 MΩ, and 1 GΩ has recently been completed in the Sistema Interamericano de Metrogia (SIM) region. The motivation, design, standards, and results of these regional comparisons are reported. The resistance standards were characterized for drift rate, temperature coefficient, pressure coefficient, and voltage coefficient so that the participants would be able to measure the transport standards using procedures routinely used in their calibration services. Data that show the transport behavior of several standards are also presented. The pilot and participant laboratory data sets were used to determine a linear regression for each transport standard. The comparison reference values (CRVs) are reported, and each participant's difference from the CRV at each nominal value is reported at 1 Ω, 1 MΩ, and 1 GΩ. The linking of the regional comparison results at 1 Ω and 1 GΩ to bilateral and key comparison results is also reported. Degrees of equivalence for nonlinking SIM laboratories are reported with respect to key CRVs.**

***Index Terms*—Measurement, resistors, standards, statistics, uncertainty.**

I. INTRODUCTION

THE working group for electricity and magnetism (EM) of the Sistema Interamericano de Metrogia (SIM) initiated the key (K) and supplemental (S) comparisons SIM.EM-K1 (at 1 Ω), SIM.EM-K2 (at 1 GΩ), and SIM.EM-S6 (at 1 MΩ) to provide the first internationally recognized comparisons of precision resistance measurements for the nations of the western hemisphere [1], [2]. The participants in these comparisons include the national metrology institutes (NMIs) of the six members of SIM and follow the guidelines for key comparisons under the 1999 Comité International des Poids et Mesures (CIPM) Mutual Recognition Arrangement (MRA). The National Institute of Standards and Technology (NIST) provided the comparison standards and acted as the pilot laboratory in the SIM.EM-K1, SIM.EM-K2, and SIM.EM-S6 comparisons, which began in December 2005 and were completed in September 2007.

The results of this set of regional metrology organization (RMO) comparisons provided verification of the calibration and measurement capabilities (CMCs) [3] of laboratories and support international trade in the SIM region. In addition to NIST, the NMIs participating in these comparisons were the Instituto Nacional de Technologia Industrial (INTI) of Argentina, the National Institute of Metrology Standardization and Industrial Quality (INMETRO) of Brazil, the Administración Nacional de Usinas y Transmisiones Eléctricas (UTE) of Uruguay, the National Research Council (NRC) of Canada, and the Centro Nacional de Metrologia (CENAM) of México.

II. PROTOCOL AND RESISTORS

The protocol for this set of comparisons was designed to meet the needs of NMIs in the SIM region without placing unreasonable constraints on the participants. The comparison was planned to last 12–18 months with each nonpilot NMI having two opportunities to measure the transport standards. The participants were expected to be able to measure the standards with expanded uncertainties ($k = 2$) of better than 0.5×10^{-6} at the 1 Ω level, better than 5×10^{-6} at the 1 MΩ level, and better than 50×10^{-6} at the 1 GΩ level.

The approach that was taken for this SIM comparison was to test the endpoints of a wide range of resistance and thereby verify the scaling processes. If an NMI can demonstrate equivalence at 1 Ω and 1 GΩ, then it is reasonable to infer that the NMI can also demonstrate equivalence at the decades that they have used to build up from their primary standards at 1 Ω or 10 kΩ to the endpoints of 1 Ω and 1 GΩ [4], [5]. The supplemental resistance level of 1 MΩ was selected for several reasons. Well-characterized air-type resistors with very low temperature coefficients were available at that level. It is also a level at which the pilot laboratory (i.e., NIST) has an automated Warshawsky bridge [6] and several cryogenic current comparator bridges

Manuscript received June 10, 2008; revised October 17, 2008. First published December 22, 2008; current version published March 10, 2009. This work was supported by the National Institute of Standards and Technology. The Associate Editor coordinating the review process for this paper was Dr. Yi-Hua Tang.

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Digital Object Identifier 10.1109/TIM.2008.2008582

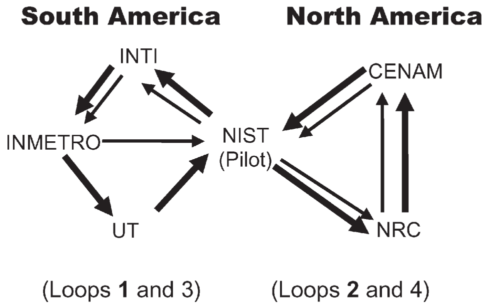

Fig. 1. Transport of standards between the pilot and the participant laboratories. The pilot laboratory (NIST) measured the standards five times and each participant once or twice. The participant laboratories were divided into two groups by geography to minimize shipping of the standards over great distances.

[7] that allow for a direct comparison against the quantized Hall resistance [8]. Finally, all of the participating NMIs have relatively uniform uncertainties at this range. At the higher range of 1 GΩ, there are several orders of magnitude in the uncertainties reported in the CMCs by SIM laboratories.

The NIST characterized the resistance standards that were used in this comparison for parameters such as drift rate, temperature coefficient, pressure coefficient, and voltage coefficient. The establishment of these parameters allowed for data to be corrected when participants measured the standards under the test conditions generally employed in their laboratories and described in their CMCs. Two standards were used at each resistance level to provide redundancy and increase the statistical significance of the results.

The standard resistors used at the 1 Ω level were wire-wound Thomas-type resistors with drift rates of less than $\pm 0.10 \times 10^{-6}$/year. These 1 Ω resistors had been used as traveling standards for the previous ten years in the NIST Measurement Assurance Program (MAP) [9], where they have demonstrated good transport behavior. At the 1 MΩ level, commercially available air-enclosure film-type resistors were used. The resistors had drift rates of less than $\pm 0.05 \times 10^{-6}$/year at the start of the comparison and almost negligible temperature coefficient. The absence of any detectable voltage dependence has been demonstrated in these standards. The NIST-designed film-type resistors were used at the 1 GΩ level. These resistors are identical in design to the 1 GΩ resistors used in the Consultative Committee for Electricity and Magnetism (CCEM) key comparison CCEM.EM-K2 and were constructed along with the 1 GΩ CCEM.EM-K2 traveling standards in 1996. The resistance elements were hermetically sealed in metal canisters. A new determination of the temperature and voltage coefficients of resistance was made prior to the comparison. The drift rates for these resistors were less than 5×10^{-6}/year.

The NIST measured the transport standards five times during the comparison, and most of the other participants measured the transport standards twice, i.e., about six months apart, as shown in Fig. 1. To minimize shipping over great distances between the NMIs, the participants in Argentina, Brazil, and Uruguay comprised one group of participants, whereas the participants in Canada and México comprised the second group. The second round of measurements repeated those of the first in the same order except that the UTE in Uruguay agreed not to participate due to delays encountered in customs in the first round. Each week, preliminary results were reported to the pilot laboratory to evaluate how well the resistors shipped and to determine when they had stabilized. This quality control measure ensured that each laboratory would have approximately three weeks to collect data with minimal impact due to transport-induced variations. These preliminary results were also used to encourage participants to not keep the resistors longer than necessary and to adhere as closely as possible to the schedule established in the technical protocol.

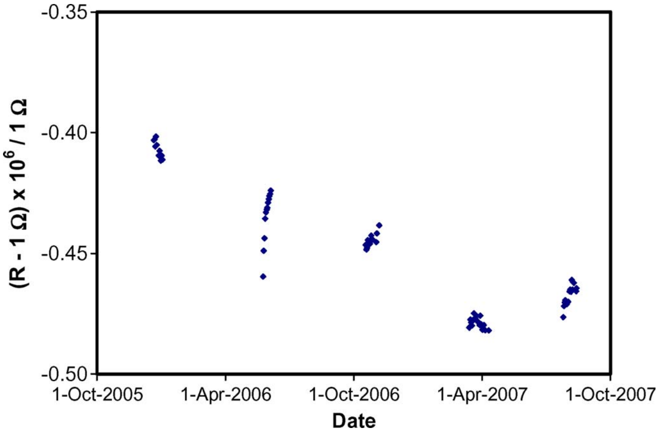

Fig. 2. Pilot laboratory measurements of a 1 Ω resistor. A short-term transport-induced drift can be seen in the June 2006 set of measurements at the conclusion of measurement loop 1.

Fig. 2 shows the pilot laboratory measurements of a 1 Ω standard resistor. A transport-induced short-term drift is observed in the data collected after the resistors returned from the first loop in June 2006. This short-term drift was observed in both 1 Ω resistors when they returned to NIST at the conclusion of measurement loop 1. After several weeks, the 1 Ω resistors stabilized and returned to their predicted values based on the historical pilot laboratory data. The transport behavior of 1 Ω resistors has been investigated, and a detailed report is in preparation [10].

III. STATISTICAL ANALYSIS

It is well known that for a standard resistor, the measurements typically show a trend in time, which we assume can be modeled as a linear trend [5]. For the measurements of the SIM.EM-K1-K2-S6 comparisons, the linear trends were obvious. As in [11], we assume that the measurements of any particular laboratory have a linear trend in time, and the slopes of the linear trends for the laboratories are the same, whereas we allow for different intercepts for different laboratories. In addition, since two traveling standards were used for each SIM comparison, the procedure proposed in [11] was considered. However, differing from the case in CCEM.EM-K2, in the SIM.EM-K1-K2-S6 comparisons, most of the nonpilot laboratories made measurements in two separate periods, and the Type B uncertainties assigned for different time periods are not the same for each of the three laboratories. The decision to allow each participant to measure the transport standards twice during the comparison provided an additional information about the linear drift rates of the standard resistors. Thus, a statistical analysis procedure related to [11] was developed to deal with this kind of data, which is briefly described below.

Our model also assumes the following: 1) $K = 2$ traveling artifacts; and 2) for all the artifacts, the ith laboratory ($i = 1, \ldots, P$, here $P = 6$) makes k_i measurements with $k_i \geq 1$. For the lth artifact and the jth measurement (or the average of the measurements) made at laboratory i, $X_{ij}(l)$ is measured at time t_{ij} $(j = 1, \ldots k_i)$.

For a fixed artifact, for example, l $(l = 1, \ldots, K)$, we assume that a simple linear regression holds for the measurements, i.e.,

$$X_{ij}(l) = \alpha_i(l) + \beta(l)t_{ij} + e_{ij}(l) \tag{1}$$

for $j = 1, \ldots k_i$, $i = 1, \ldots, P$, and $l = 1, \ldots, K$, where the random components $e_{ij}(l)$'s are statistically independent of each other and have zero mean and standard uncertainty of $\sigma_{ij}(l)$, which is the combination of the Type A and Type B evaluations of uncertainty. Specifically

$$\sigma_{ij}(l) = \sqrt{\sigma^2_{ij,A}(l) + \sigma^2_{ij,B}(l)} \tag{2}$$

where $\sigma_{ij,A}(l)$ and $\sigma_{ij,B}(l)$ are the Type A and Type B uncertainties for the lth artifact measured at the jth time period by the ith laboratory, respectively. The generalized least-square estimators of the regression parameters are $\hat{\alpha}_i(l)$ for the intercept for the ith laboratory and the lth artifact and $\hat{\beta}(l)$ of the joint slope for the lth artifact. The predicted value of the regression line for the measurement from the ith laboratory made with the lth artifact at time t is given by

$$L_{il}(t) = \hat{\alpha}_i(l) + \hat{\beta}(l)t. \tag{3}$$

For the comparison reference value (CRV) at any time t (denoted by CRV_t), we use a weighted mean of $\hat{\alpha} + \hat{\beta}t$ over all the laboratories $i = 1, \ldots, P$ and all the artifacts $l = 1, \ldots, K$, i.e.,

$$CRV_t(\omega, v) = \sum_{i=1}^{P} \omega_i \left(\sum_{l=1}^{K} v_{il} L_{il}(t) \right) \tag{4}$$

where $L_{il}(t)$ given earlier is the prediction for the value of the lth artifact (based on the lth regression line) for the ith laboratory at time t, and $\{\omega_i\}$ and $\{\nu_{il}\}$ are the weights. The time t is allowed to be different for the different artifacts. An optimal time t^* and the corresponding weights are chosen when the uncertainty of $CRV_t(\omega, v)$ is minimized. We use this optimal value as the CRV. The degrees of equivalence (DOEs) between the national measurement standards and the CRV, as well as the DOEs between pairs of national measurement standards, are defined and calculated as in [11]. A detailed and complete description of the statistical analysis procedures and formulas is presented in [1].

IV. COMPARISON RESULTS

After consultation with the pilot, each participant was asked to submit a final printed and signed report by mail within six weeks after completing the measurements. The data contained in the participants' final reports represented no less than two weeks of consecutive measurements for each traveling standard. The participants' reports contained the following information: a description of the measuring setup used for each level, a description of the participant's source of traceability to the SI, the dates of the three most recent calibrations used to establish the SI traceability for each standard, a description of the measurement procedure used for each level, the test current or voltage used for the measurements, the ambient conditions of the measurement (temperature, pressure, and humidity at the time of each measurement), the mean resistance value for each transport standard (including the corresponding mean date of measurement), and a complete uncertainty budget in accordance with the principles of the International Organization for Standardization (ISO) Guide to the Expression of Uncertainty in Measurement [12], [13].

Figs. 3–5 show the reported resistance (in deviation from nominal value) and the expanded uncertainty ($k = 2$) for one of the two standard resistors measured at 1 Ω, 1 MΩ, and 1 GΩ by the pilot and each participant laboratory during the comparison. Similar results for the other three resistors of the same nominal values used in these comparisons are shown in [1].

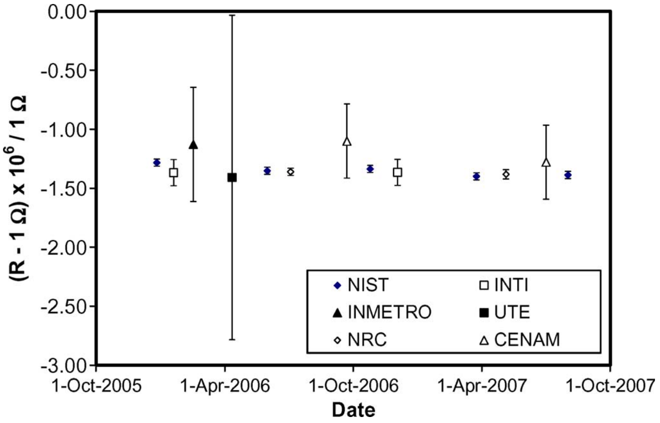

Fig. 3. Reported resistance and expanded uncertainty ($k = 2$) for a 1 Ω standard resistor. Each data point represents the mean of several weeks of measurements by the pilot or a participant laboratory. Similar data were observed for the other 1 Ω resistor.

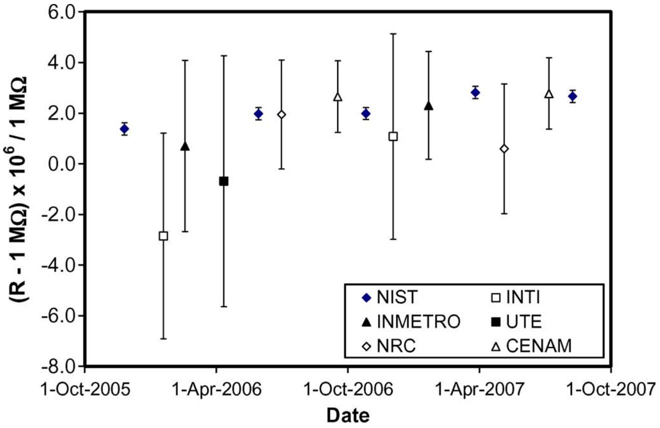

Fig. 4. Reported resistance and expanded uncertainty ($k = 2$) for a 1 MΩ standard resistor. Each data point represents the mean of several weeks of measurements by the pilot or a participant laboratory. Similar data were observed for the other 1 MΩ resistor.

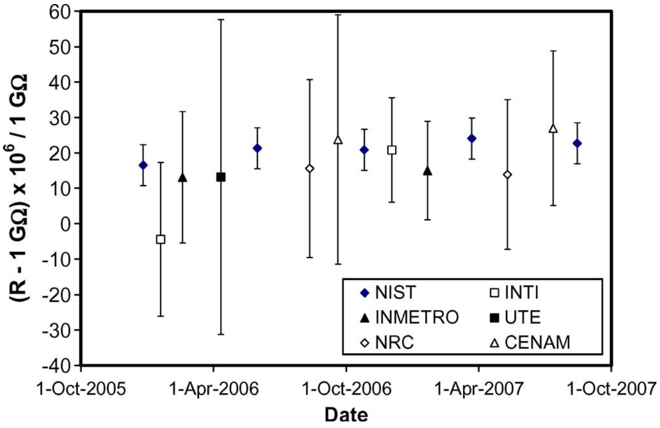

Fig. 5. Reported resistance and expanded uncertainty $(k = 2)$ for a 1 GΩ standard resistor. Each data point represents the mean of several weeks of measurements by the pilot or a participant laboratory. Similar data were observed for the other 1 GΩ resistor.

TABLE I
CRVs AND EXPANDED UNCERTAINTIES $(k = 2)$

Comparison	Nominal Value	Comp. Reference Value (CRV)	Uncertainty $(k = 2)$ (U_{CRV})
SIM.EM-K1	1 Ω	-0.5962×10^{-6}	0.0094×10^{-6}
SIM.EM-S6	1 MΩ	2.687×10^{-6}	0.0846×10^{-6}
SIM.EM-K2	1 GΩ	10.240×10^{-6}	1.895×10^{-6}

The CRV, uncertainty of the CRV (U_{CRV}), tables of equivalence, and linking to key comparison CCEM.EM-K2 and the Bureau International des et Poids Mesures (BIPM) bilateral comparison BIPM.EM-K13.a are all described in detail in [1]. Table I shows the CRV (in deviation from nominal value) and the expanded uncertainty $(k = 2)$ associated with the computation of the CRV for each of the three SIM comparisons. The weighted mean method was used to determine the CRV.

Once the CRV was determined for each comparison, the differences from the CRV $(D_{i\mathrm{CRV}})$ and the expanded uncertainties $(U_{Di\mathrm{CRV}})$ were calculated for the pilot and participant NMIs for each comparison. The $D_{i\mathrm{CRV}}$ and $U_{Di\mathrm{CRV}}$ for each NMI are shown in Figs. 6–8 for the measurements at 1 Ω, 1 MΩ, and 1 GΩ, respectively. The weighted mean method was used to determine the CRV, so laboratories with the smallest expanded uncertainty $(k = 2)$ had a large influence in determining the CRV for each comparison. Pair-wise DOEs and expanded uncertainties $(k = 2)$ were determined between any two NMIs participating in the comparison. The tables showing these pair-wise DOEs are shown in [1].

V. LINKING TO KEY COMPARISONS

The results of the regional comparisons SIM.EM-K1 and SIM.EM-K2 are linked to the key comparison results at the 1 Ω and 1 GΩ levels, respectively.

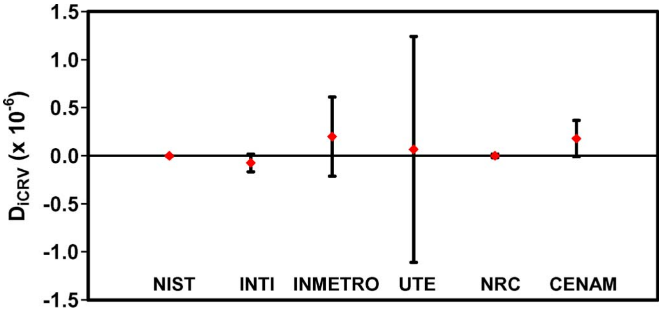

Fig. 6. Graph of equivalence for comparison SIM.EM-K1 at the 1 Ω resistance level. The graph shows the differences from the CRV at 1 Ω. The error bars denote the expanded uncertainty $(k = 2)$ for each measurement laboratory with respect to the CRV.

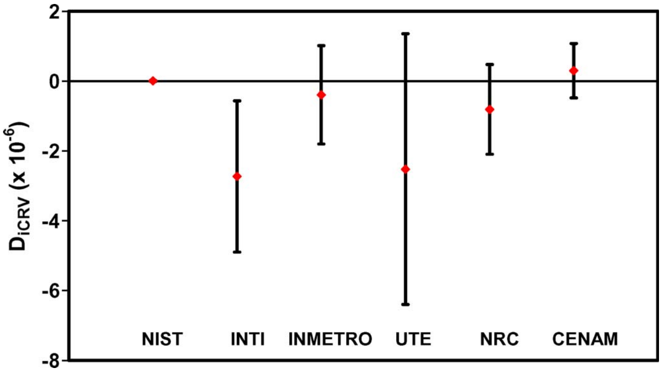

Fig. 7. Graph of equivalence for comparison SIM.EM-S6 at the 1 MΩ resistance level. The graph shows the differences from the CRV at 1 MΩ. The error bars denote the expanded uncertainty $(k = 2)$ for each measurement laboratory with respect to the CRV.

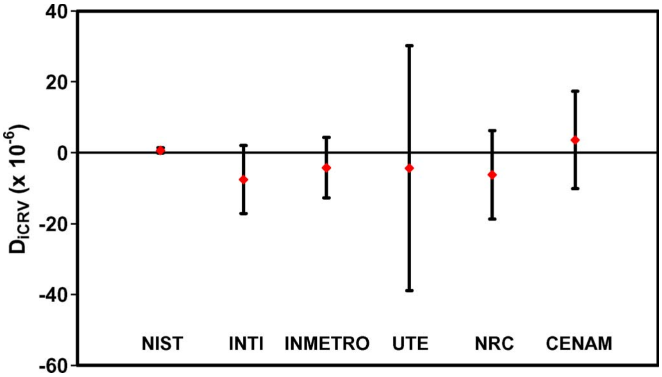

Fig. 8. Graph of equivalence for comparison SIM.EM-K2 at the 1 GΩ resistance level. The graph shows the differences from the CRV at 1 GΩ. The error bars denote the expanded uncertainty $(k = 2)$ for each measurement laboratory with respect to the CRV.

A 2007 bilateral comparison of 1 Ω resistance standards BIPM.EM-K13.a [14] was used to link the SIM.EM-K1 resistance comparison with other CCEM results. The BIPM and NIST participated in this comparison, specifically for the purpose of linkage, because the much earlier CCEM.EM-K1 comparison is considered to be provisional, and the results of that comparison are not available in the key comparison database (KCDB) [3]. The BIPM.EM-K13.a bilateral comparison is part of an ongoing sequence of bilateral comparisons conducted by the BIPM for the linking of regional comparison results with key comparison results. The BIPM provided three traveling 1 Ω standards that were measured by the BIPM before and after the NIST measurement of the traveling standards. The final result of the bilateral comparison established a difference of

-0.014×10^{-6} between NIST and BIPM with an expanded uncertainty $(k = 2)$ of 0.042×10^{-6}.

For the CCEM.EM-K2 and SIM.EM-K2 comparisons, there are two linking laboratories, i.e., NIST and NRC. In general, we assume that there are K linking laboratories. Based on [15], a correction or a difference between the two comparisons is estimated from the DOEs between the key CRV (KCRV) and the CRV for linking laboratories in these two comparisons. Specifically, we denote the DOE between the nth laboratory and the KCRV in CCEM.EM-K2 by $D_{n,\text{KCRV}}$. The results can be found in the final report of CCEM.EM-K2 [5]. Similarly, we denote the DOE between the mth lab and the CRV in the SIM.EM-K2 comparison by $D_{m,\text{CRV}}$. The results can be found in [1].

For the kth linking laboratory $(k = 1, \ldots, K)$, the difference between the two DOEs is defined as

$$D_k = D_{k,\text{KCRV}} - D_{k,\text{CRV}} \tag{5}$$

for $k = 1, \ldots, K$. From [15], the correction or the difference of the two comparisons is estimated by a weighted mean of $\{D_k\}$. Namely

$$\hat{D} = \sum_{k=1}^{K} \psi_k D_k \tag{6}$$

where $\{\psi\}$'s are the weights, e.g., $\psi_k = 1/k$, which leads to a simple average or

$$\psi_k = \frac{1/u_{D_k}^2}{\sum_{j=1}^{K} 1/u_{D_j}^2} \tag{7}$$

where u_{D_j} is the uncertainty for the jth laboratory including Type A and Type B uncertainties. The quantity $\hat{D}$ is used to estimate the differences between pairs of laboratories for which one laboratory only participated in the CCEM.EM-K2 comparison, and the second laboratory only participated in the SIM.EM-K2 comparison.

Specifically, for the mth laboratory, which participated only in the SIM.EM-K2 comparison, the $D_{m,\text{CRV}}$ needs to have an adjustment to get an estimator of $D_{m,\text{KCRV}}$. The estimator is given by

$$D'_{m,\text{KCRV}} = D_{m,\text{CRV}} + \hat{D} \tag{8}$$

where $\hat{D}$ is the estimated difference between the two comparisons. $D'_{m,\text{KCRV}}$ is the estimated DOE between the KCRV of CCEM.EM-K2 and the mth laboratory that participated in SIM.EM-K2 had this laboratory participated in CCEM.EM-K2. For the pair-wise comparisons, the DOEs of the pairs of national measurement standards can similarly be obtained. The details of the calculation of the linkage can be found in [1].

Fig. 9 shows the pair-wise comparison between each nonlinking laboratory in the SIM.EM-K1 comparison and the BIPM. The calculation of the pair-wise differences and the uncertainty for each nonlinking SIM laboratory are described in [1].

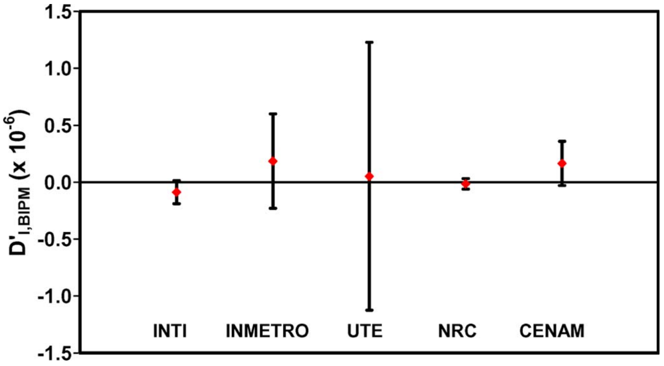

Fig. 9. Graph of equivalence at 1 Ω that links the regional comparison SIM.EM-K1 to the bilateral comparison BIPM.EM-K13a. The NIST is the linking laboratory. The graph shows the differences from the BIPM.EM-K13.a bilateral CRV. The error bars denote the expanded uncertainty $(k = 2)$ for each measurement laboratory with respect to the bilateral CRV.

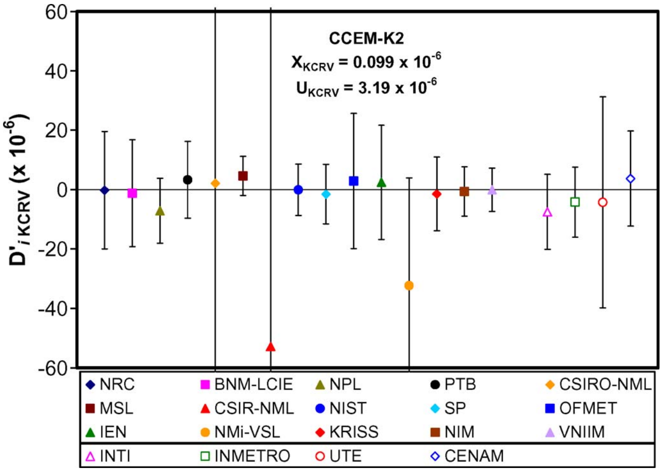

Fig. 10. Graph of equivalence at 1 GΩ that links the regional comparison SIM.EM-K2 with the key comparison CCEM.EM-K2. The NIST and NRC are the linking laboratories. The graph shows the differences from the CCEM.EM-K2 KCRV. The error bars denote the expanded uncertainty $(k = 2)$ for each measurement laboratory with respect to the KCRV. The 15 laboratories that participated in CCEM.EM-K2 are shown to the left (solid symbols) and the four nonlinking SIM laboratories are shown to the right (open symbols).

At the 1 GΩ resistance level, the link to key comparison CCEM.EM-K2 [5] was made through the two linking laboratories (i.e., NIST and NRC) that had participated in both key comparison CCEM.EM-K2 and regional comparison SIM.EM-K2. A difference between the two comparisons is estimated from the DOEs with respect to the KCRV and the CRV for the two linking laboratories that participated in both comparisons [15]. The DOEs between any of the four nonlinking laboratories that participated only in SIM.EM-K2 and any of the 13 laboratories that only participated in CCEM.EM-K2 are available in a 4 × 13 pair-wise matrix of equivalence that is in [1]. The equivalence between the 15 CCEM.EM-K2 laboratories are in [5], and the equivalence between the six SIM laboratories are in [1]. Fig. 10 shows the graph of equivalence for the 15 laboratories that participated in CCEM.EM-K2 and the four nonlinking SIM laboratories that participated in SIM.EM-K2 with respect to the KCRV of CCEM.EM-K2.

VI. CONCLUSION

The first set of regional comparisons of resistance in the western hemisphere has quantified the equality in measurements between the nations organized in SIM and the participants in the CCEM key comparisons. The results of the regional comparisons SIM.EM-K1 and SIM.EM-K2 show that all the participant differences from the CRV $(D_{i\mathrm{CRV}})$ are within the expanded uncertainty $U_{Di\mathrm{CRV}}$ for the individual NMIs at 1 Ω and 1 GΩ $(k = 2)$, where the linkage to the results of CCEM key comparisons is available. The linking of these regional comparison results to key comparison results has demonstrated equivalence within the expanded uncertainties $(k = 2)$ between the nonlinking laboratories that participated in SIM.EM-K1 and BIPM.EM-K13a at 1 Ω and likewise for the nonlinking laboratories that participated in SIM.EM-K2 and CCEM.EM-K2 at 1 GΩ. The supplemental comparison SIM.EM-S6 at 1 MΩ served as an additional check at a resistance value between the 1 Ω and 1 GΩ resistance levels. There are no key comparison results at 1 MΩ to link to the supplemental comparison, but the comparison does provide a check of each laboratory's scaling techniques. Seventeen out of the 18 results from the three comparisons were within the $k = 2$ limits. One supplemental comparison result missed the CRV by 1/4 of the $k = 2$ limit and is being investigated by the laboratory. The results have demonstrated a successful set of comparisons in the SIM region.

ACKNOWLEDGMENT

The authors would like to thank the many people who had a role in making this comparison successful. W. Zhang and H. K. Liu of the NIST Statistical Engineering Division, together with N. F. Zhang, developed the analysis for this comparison. The authors would also like to thank those who made measurements on many of the resistors used in this comparison: M. E. Kraft and G. R. Jones of NIST and many more individuals at the participating laboratories. Finally, the authors would like to thank H. Sánchez of the Instituto Costarricense de Electricidad (ICE), Costa Rica, who provided guidance and assistance to make this comparison successful. NIST is part of the U.S. Department of Commerce. Official contribution of the National Institute of Standards and Technology; not subject to copyright in the United States.

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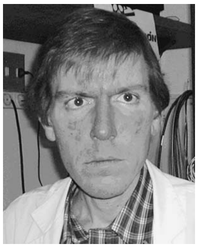

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