Interamerican Metrology System (SIM) Regional Metrology Organization (RMO) Capacitance Comparison, Final Report

SIM.EM-K4.1, 10 pF fused-silica standard capacitor at 1000 Hz
SIM.EM-S4.1, 100 pF fused-silica standard capacitor at 1000 Hz

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2010-2012 Comparison
Pilot Laboratory: National Institute of Standards and Technology, Gaithersburg, Maryland USA

1 Introduction

ICE participated in three related capacitance comparisons during 2006. SIM.EM-K4 was a comparison of a 10 pF fused-silica standard at 1000 Hz and 1600 Hz. SIM.EM-S4 was a comparison of a 100 pF fused-silica standard at 1000 Hz and 1600 Hz. SIM.EM-S3 was a comparison of a 1000 pF nitrogen gas standard capacitor at 1000 Hz.

The results for this comparison were not adequate for ICE, resulting in the need to improve the measurement methods as well as the calibration equipment and standards.

Also, Costa Rican Accreditation Board policies dictate that in the case of non-satisfactory results in an intercomparison, the Laboratory must to participate as soon as possible in the next intercomparison in order to evaluate the Laboratory improvement.

The objective of this comparison was to compare the measurement capabilities of ICE in the field of capacitance and evaluate the improvements achieved since the SIM.EM-K4 Comparison. This action was aimed at redetermining the degree of equivalence of measurement capabilities in capacitance. The proposed test points were selected to evaluate the measuring capabilities of ICE, both their measurement standards and their measurement procedures, as compared with SIM.EM-K4.

This bilateral comparison consists of two related capacitance comparisons. **SIM.EM-K4.1** is a comparison of a **10 pF** fused-silica standard at 1000 Hz. **SIM.EM-S4.1** is a comparison of a **100 pF** fused-silica standard at 1000 Hz.

The participant institutes are listed in Table 1.

Table 1. Capacitance comparison participants

Country	**Institute**	**Acronym**
Costa Rica	Instituto Costarricense de Electricidad	ICE
United States	National Institute of Standards and Technology	NIST

The results of this set of intercomparisons will be statistically linked to the SIM.EM-K4 10 pF comparison and the SIM.EM-S4 100 pF comparison.

2 Traveling Standards

2.1 Description of the standards

The traveling standard for the SIM.EM-K4.1 comparison was an Andeen-Hagerling AH11A 10 pF fused-silica standard capacitor, with serial number 01688. The traveling standard for the SIM.EM-S4.1 comparison was an Andeen-Hagerling AH11A 100 pF fused-silica standard capacitor with serial number 01689. Both the traveling standards were housed in the Andeen-Hagerling AH1100 enclosure with serial number 00200231.

The AH1100 enclosure contains a temperature controller to maintain stability of the AH11A standards. The enclosure must be powered on to operate. The AH1100 permits operation at voltages of 100 V, 120 V, 220 V, or 240 V. The proper fuse corresponding to the voltage of operation must be inserted into the fuse holder on the rear of the AH1100 enclosure prior to operation.

2.2 Transport Package Description

A wooden container was filled with polyurethane foam to hold the traveling standards and equipment. The parts contained in the transport package consisted of

- Andeen-Hagerling AH1100 enclosure SN 00200231 containing
    - AH11A 100 pF fused-silica standard capacitor SN 01688
    - AH11A 10 pF fused-silica standard capacitor SN 01689

2.3 Quantities to be measured

Participants measured the AH11A 10 pF and 100 pF standards at 1000 Hz. All capacitance measurements with corresponding combined standard uncertainties were reported. Enclosure temperature was recorded with each AH11A measurement. At least five measurements were reported for this frequency point.

3 Organization

The National Institute of Standards and Technology (NIST) was the pilot laboratory for the SIM.EM-K4.1 and SIM.EM-S4.1 comparisons. NIST used an AH2700A Capacitance Bridge with AH11A 10 pF and 100 pF standards characterized over 50 Hz to 20 kHz as reference standards for the measurements. A direct substitution was used. Measurements were taken on the ICE standard and a reference standard. The difference between the measured value of the reference and the characterized value of the reference was added to the measured value of the ICE standard to achieve the reported value.

The ICE standards were measured at NIST at the beginning of the comparison schedule. The ICE standards travelled to ICE laboratory. NIST sent the calibration certificates to Laboratorio Costarricense de Metrología (LACOMET) that kept those certificates, without ICE´s knowledge of the calibrated values, until ICE calibrated both capacitors and sent the results to NIST.

The schedule of measurements is shown in Table 2.

Table 2. Schedule of measurements

Laboratory	Approximate measurement dates
NIST (United States)	December 7, 2010 to December 17, 2010
ICE (Costa Rica)	October 2011 to August 2012

4 Pilot Laboratory Measurement Results

The pilot laboratory measurement results are listed in Table 1 and shown graphically in Figure 1. Results at 1 kHz consist only of measurements from an Andeen-Hagerling AH2700A Capacitance Bridge with corrections applied. The comparison reference value (CRV) will be based on a weighted mean of all results.

4.1 SIM.EM-K4.1 10 pF results at 1 kHz

Table 3. Pilot measurements for 10 pF at 1 kHz

Date	Capacitance (pF)	Frequency (Hz)	Expanded Uncertainty µF/F (k=2)
7 December 2010	10.00002056	1000	
9 December 2010	10.00002106	1000	
13 December 2010	10.00001840	1000	
15 December 2010	10.00001820	1000	
17 December 2010	10.00002025	1000	
Mean (12 Dec 2010)	10.00001970	1000	0.246

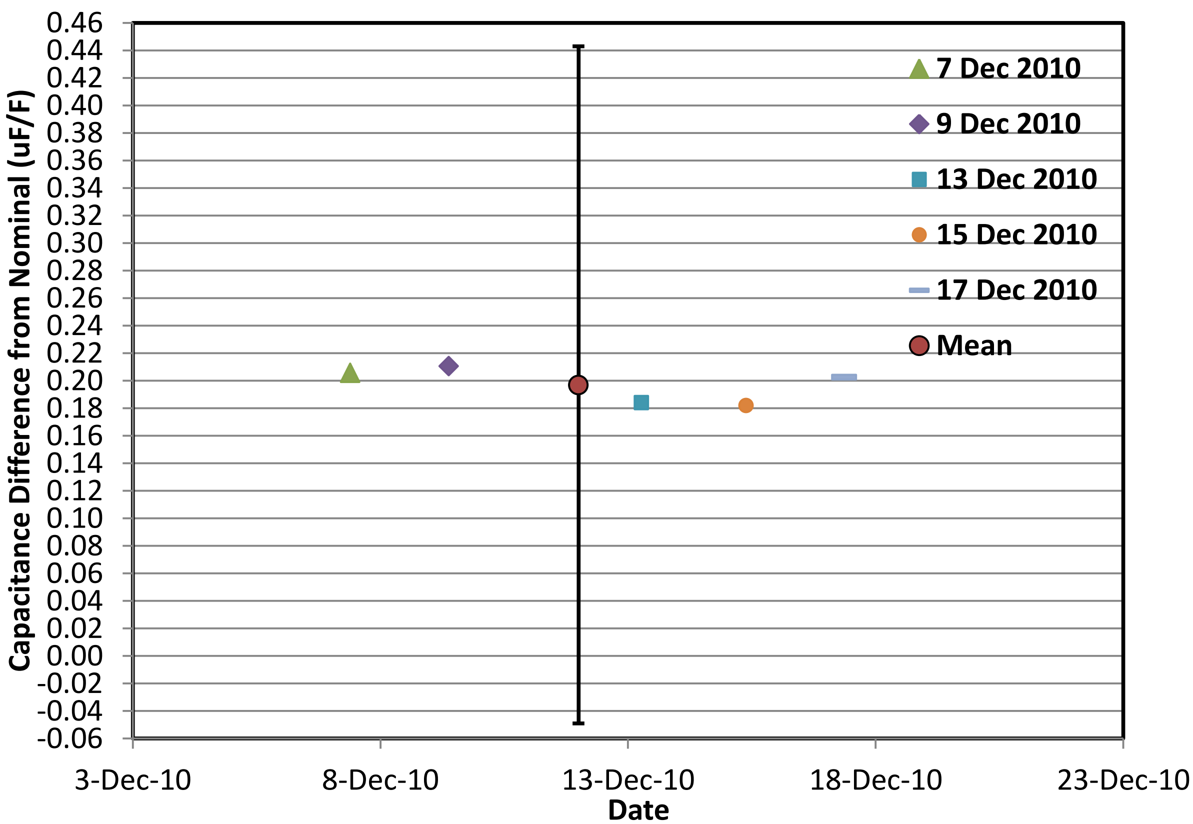

Fig. 1. Pilot laboratory measurements of AH11A SN 01688 10 pF standard capacitor at 1 kHz with error bar on the mean value, showing expanded uncertainty (k=2).

4.2 SIM.EM-S4.1 100 pF results at 1 kHz

Table 4. Pilot measurements for 100 pF at 1 kHz

Date	Capacitance (pF)	Frequency (Hz)	Expanded Uncertainty µF/F (k=2)
7 December 2010	99.9999550	1000	
9 December 2010	99.9999565	1000	
13 December 2010	99.9999540	1000	
15 December 2010	99.9999555	1000	
17 December 2010	99.9999561	1000	
Mean (12 Dec 2010)	99.9999554	1000	0.211

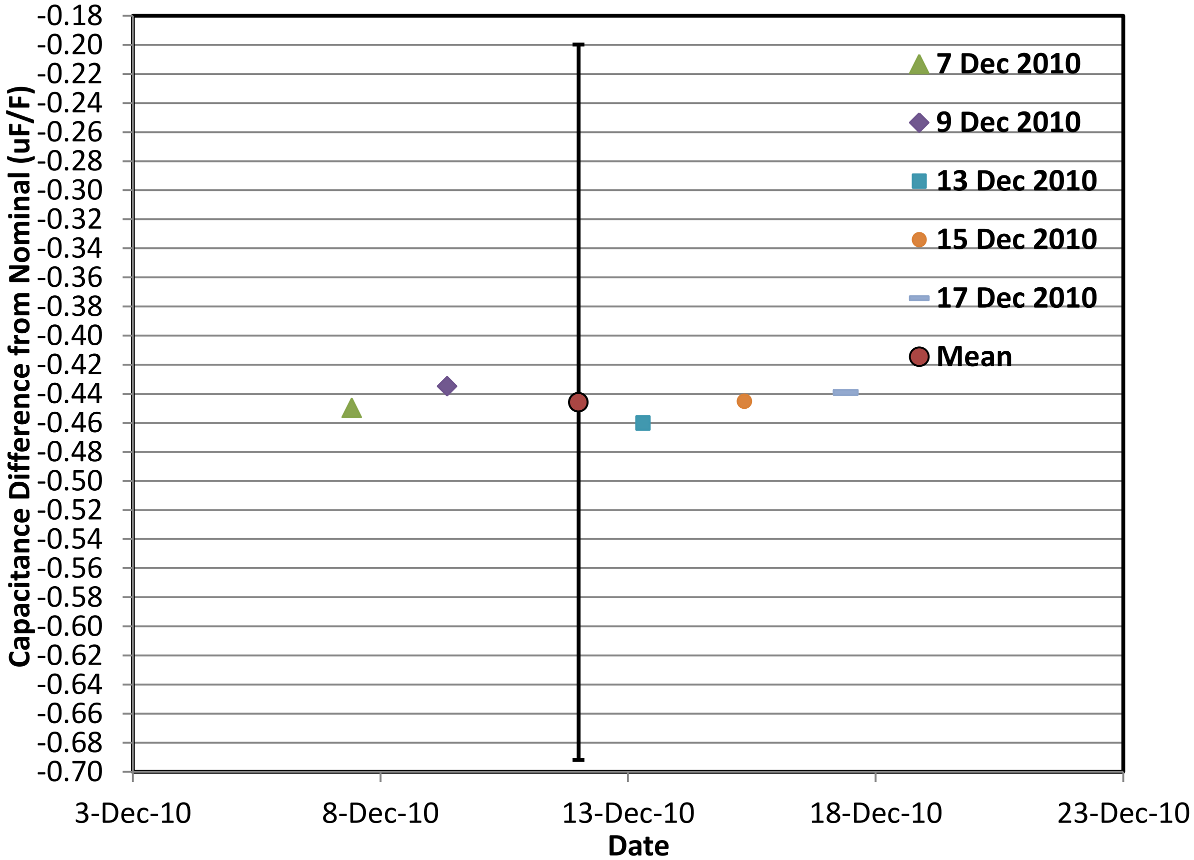

Fig. 2. Pilot laboratory measurements of AH11A SN 01690 100 pF standard capacitor at 1 kHz with error bar on the mean value, showing expanded uncertainty (k=2).

5 Reported Results of Comparisons

5.1 SIM.EM-K4.1 10 pF results at 1 kHz

Table 3. Mean 1000 Hz measurement data for the participant laboratories.

Laboratory	Mean Date	Mean 1 kHz Capacitance Deviation from Nominal Value (μF/F)	Combined Standard Uncertainty (μF/F)
NIST USA	2010-12	0.20	0.123
ICE Costa Rica Substitution. Using standards calibrated by INTI.	2011-10	34	39.6
ICE Costa Rica Substitution. Using standards calibrated by METAS	2012-07	12	23.6
ICE Costa Rica Direct Comparison. Using a AH 2700A as a reference Standard.	2012-08	-0.35	0.81

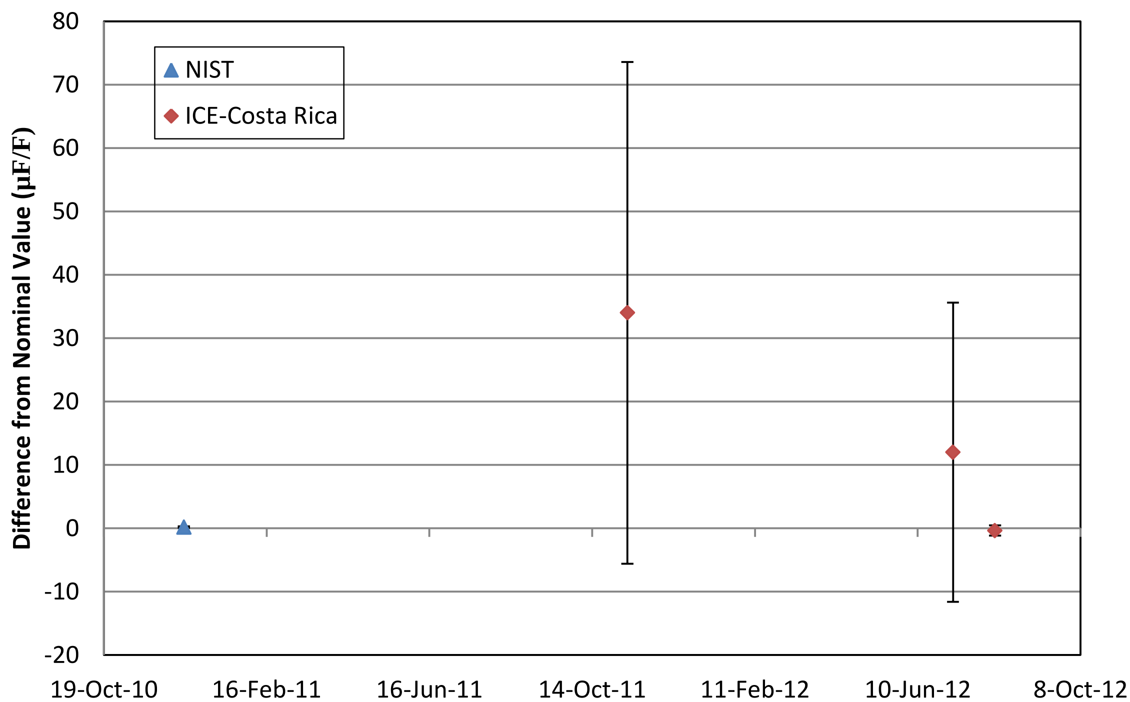

Fig. 3. Participant results of measurement of AH11A SN 01688 10 pF at 1 kHz

5.2 SIM.EM-S4.1 100 pF results at 1 kHz

Table 4. Mean 1000 Hz measurement data for the participant laboratories.

Laboratory	Mean Date	Mean 1 kHz Capacitance Deviation from Nominal Value (µF/F)	Combined Standard Uncertainty (µF/F)
NIST USA	2010-12	-0.45	0.106
ICE Costa Rica Substitution. Using standards calibrated by INTI.	2011-10	69	44.9
ICE Costa Rica Substitution. Using standards calibrated by METAS	2012-07	20.55	25.0
ICE Costa Rica Direct Comparison. Using a AH 2700A as a reference Standard.	2012-08	-0.56	0.77

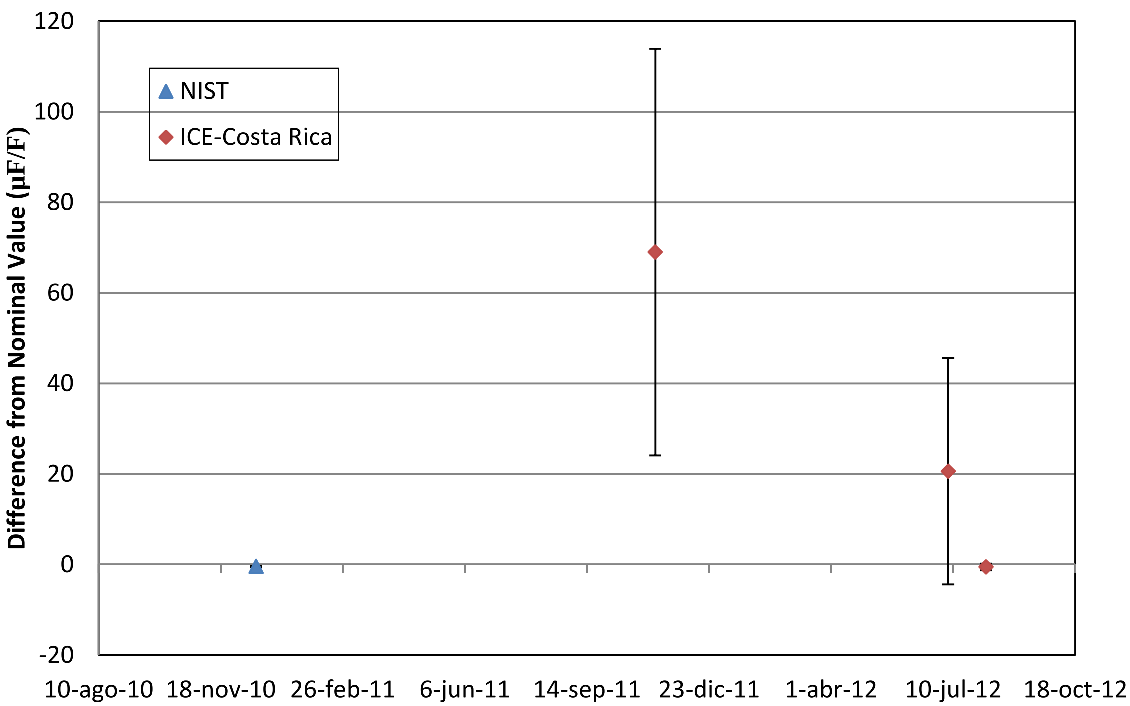

Fig. 4. Participant results of measurement of AH11A SN 01689 100 pF at 1 kHz

6 References

[1] M. G. Cox, The evaluation of key comparison data: An introduction, Metrologia, 39, pp. 587-588, 2012.

[2] N. F. Zhang, Statistical analysis for interlaboratory comparisons with linear trends in multiple loops, Metrologia, 49, pp. 390-394, 2012.

[3] M. Cazabat, L.M. Ogino, G.A. Kyriazis, R.T.B. Vasconcellos, B. Wood, K. Kochav, H. Sanchez, B.I. Castro, J.A. Moreno, A. Koffman, N.F. Zhang, Y. Wang, S. Shields, D. Slomovitz, D. Izquierdo, C. Faverio, Final Report Inter-American Metrology System (SIM) Regional Metrology Organization (RMO) Capacitance Comparison, SIM.EM-K4 10 pF, SIM.EM-S4 100 pF, and SIM.EM-S3 1000 pF (Pilot: NIST), 2012.

Appendix A: Analysis Procedure

The bilateral comparisons consist of two related capacitance comparisons between ICE and NIST. SIM.EM-K4.1 is a comparison of 10 pF fused-silica standard at 1000Hz. SIM.EM-S4.1 is a comparison of a 100 pF standard at 1000 Hz. The two participant laboratories each measured both traveling standards for one measurement period. The period at NIST was approximately ten days, resulting in one reported mean value. The period at ICE was much longer and three measurement methods were applied, resulting in three reported values.

1. **Comparison reference value (CRV) and degrees of equivalence (DOE) for the bilateral comparison**

We used a weighted mean approach to combine the three reported values of ICE measurements with the weights proportional to the inverses of the square of the standard uncertainties. That is, assume that Y_i , $i = 1, 2, 3$ are the measurements of ICE. The combined value for the second lab, ICE, denoted by X_2 is given by

$$X_2 = \sum_{i=1}^{3} p_i Y_i \qquad \text{(A.1)}$$

with

$$p_i = \frac{\frac{1}{u_i^2}}{\sum_{j=1}^{3} \frac{1}{u_j^2}} , \qquad \text{(A.2)}$$

where u_i is the standard uncertainty of Y_i. The standard uncertainty of X_2 is given by

$$u_{X_2} = \frac{1}{\sum_{j=1}^{3} \frac{1}{u_j^2}} . \qquad \text{(A.3)}$$

Denote the mean of the NIST measurement by X_1 with a standard uncertainty of u_{X_1} . Similarly, by a weighted mean for NIST and ICE, the CRV is given by

$$CRV = \sum_{k=1}^{2} w_k X_k \ , \quad \text{with } w_k = \frac{\frac{1}{u_{X_k}^2}}{\sum_{j=1}^{2} \frac{1}{u_{X_j}^2}} , \ k = 1, 2 \ . \qquad \text{(A.4)}$$

Similarly, the standard uncertainty of the CRV of the bilateral comparison is given by

$$u_{CRV} = \frac{1}{\sum_{j=1}^{2} \frac{1}{u_{X_j}^2}} . \qquad \text{(A.5)}$$

The degree of equivalence for the kth (k = 1,2) lab with respect to the CRV is given by

$$D_{k,CRV} = X_k - CRV \qquad \text{(A.6)}$$

with the uncertainty of [1]

$$u_{d_{k,CRV}}^2 = u_{X_k}^2 - u_{CRV}^2 . \qquad \text{(A.7)}$$

For the pair-wise DOE, it is given by

$$d_{1,2} = X_1 - X_2$$

with its standard uncertainty $u_{d_{1,2}}$ given by

$$u_{d_{1,2}}^2 = u_{X_1}^2 + u_{X_2}^2 \ . \qquad \text{(A.8)}$$

2. Linking the bilateral comparisons to the SIM comparisons

For the linkge to the SIM.EM-K4 and SIM.EM-S4 comparisons, NIST is the only linking lab. Note that although ICE participated in the SIM comparisons and ICE's results were included in calculating the CRVs of the SIM comparisons, practically, the effect of ICE in calculating the CRV and the DOE between other labs and the CRV was negligent because the measurements of ICE were out of the range with large uncertainty, leading to an almost zero weight in the CRV calculation. This bilateral comparison provides an improved set of DOEs between ICE and the other labs that participated in the SIM comparisons. As in [2], for the SIM comparisons, there are M (M = 7) labs with NIST being the first lab. We need to compute the DOE between ICE (2nd lab) in the bilateral (2nd) comparison and the M-1 labs in the SIM.EM-K4 and SIM.EM-S4 (1st) comparisons. We denote it by $D_{2,j}(2,1)$ $j = 2,...,M$ due to the fact that in the bilateral comparison, ICE is the second lab and NIST is the first lab in both comparisons. Note that the DOE between NIST and ICE is just the difference between the NIST and ICE reported values in the bilateral comparison. Namely, using our previous notations as in Section 1, it is

$$d_{1,2} = X_1 - X_2 . \qquad \text{(A.9)}$$

From equation (19) in reference [2],

$$D_{j,2}(1,2) = D_{j,1}(1,1) - D_{2,1}(2,2) \ , \quad j = 2,...,M \ , \qquad \text{(A.10)}$$

where $D_{2,1}(2,2) = d_{2,1} = -d_{1,2}$ as shown in (9). Thus,

$$\begin{aligned} D_{2,j}(2,1) &= -D_{j,1}(1,1) + D_{2,1}(2,2) \\ &= D_{1,j}(1,1) - d_{12} \end{aligned} \quad . \tag{A.11}$$

From (11), the corresponding standard uncertainty $u_{D_{2,j}(2,1)}$ is given by

$$u^2_{D_{2,j}(2,1)} = u^2_{D_{j,1}(1,1)} + u^2_{2,1(2,2)} \quad . \tag{A.12}$$

Appendix B: Analysis Results

1. **10 pF at 1000 Hz**

From Table 3 in the main text above, ICE has three measurements using different calibration methods. The means, given as µF/F deviations from the nominal value of 10 pF, are 34, 12, and -0.35, with standard uncertainties of 39.6, 23.6, and 0.81 µF/F. The NIST reported measurement value is 0.20 µF/F, with a standard uncertainty of 0.123 µF/F.

From (A.1) – (A.3), X_2 = -0.3211 µF/F with the standard uncertainty of 0.8094 µF/F. From (A.4) and (A.5), for the bilateral comparison, SIM.EM-K4.1, the CRV = 0.1882 µF/F with a standard uncertainty of 0.1216 µF/F.

For the linkage between the bilateral comparison, SIM.EM-K4.1, and the SIM.EM-K4 comparison, from (A.11), the DOEs between ICE and the other labs in the SIM.EM-K4 comparison are given below in µF/F

[-0.521 -0.521 * -1.022 4.014 -0.528 -0.795],

where * indicates ICE vs. ICE which is meaningless. Note that the first value in the set of DOEs is based on the bilateral comparison, SIM.EM-K4.1, and thus, $d_{2,1} = -d_{1,2}$. The corresponding standard uncertainties of the DOE are given below in µF/F

[0.819 0.844 * 0.918 3.497 0.851 0.831].

Table B1 below is an update of the pair-wise degree of equivalences in Table B2 from the SIM.EM-K4 Final Report [3] for 10 pF at 1000 Hz by replacing the DOE between ICE and other labs by the results given above. All values are given in µF/F.

Table B1. Updated pair-wise degree of equivalence with (standard uncertainties)

	NIST	CENAM	ICE	INTI	UTE	INMETRO	NRC
NIST		0.000214 (0.205)	0.521 (0.819)	-0.501 (0.416)	4.535 (3.40)	-0.00643 (0.231)	-0.274 (0.141)
CENAM	-0.000214 (0.205)		0.521 (0.844)	-0.5008 (0.435)	4.534 (3.40)	-0.00664 (0.264)	-0.274 (0.191)
ICE	-0.521 (0.819)	-0.521 (0.844)		-1.022 (0.918)	4.014 (3.497)	-0.528 (0.851)	-0.795 (0.831)
INTI	0.501 (0.416)	0.501 (0.435)	1.022 (0.918)		5.035 (3.42)	0.494 (0.447)	0.226 (0.408)
UTE	-4.535 (3.40)	-4.534 (3.40)	-4.014 (3.497)	-5.035 (3.42)		-4.541 (3.41)	-4.809 (3.40)
INMETRO	0.00643 (0.231)	0.00664 (0.264)	0.528 (0.851)	-0.494 (0.447)	4.541 (3.41)		-0.268 (0.215)
NRC	0.274 (0.141)	0.274 (0.191)	0.795 (0.831)	-0.226 (0.408)	4.809 (3.40)	0.268 (0.215)	

2. 100 pF at 1000 Hz

From Table 4 in the main text above, ICE has three measurements using different calibration methods. The means are 69, 20.55, and -0.56 with combined standard uncertainties of 44.9, 25.0, and 0.77. NIST's measurement was -0.45 with a standard uncertainty of 0.106. From (A.1) – (A.3), X_2 = -0.5196 µF/F with the standard uncertainty of 0.7695. From (A.4) and (A.5), for the bilateral comparison, SIM.EM-S4.1, CRV = -0.4513 µF/F with standard uncertainty of 0.1050 µF/F.

For the linkage between the bilateral comparison, SIM.EM-S4.1 and SIM.EM-S4 comparison, from (A.11), the DOE between ICE and other labs in the SIM.EM-S4 comparison are given below

[-0.0696 0.454 * -0.182 2.777 -0.0868 -0.510]

where * indicates ICE vs. ICE which is meaningless. Note that the first one is based on the bilateral comparison, SIM.EM-S4.1 and thus, $d_{2,1} = -d_{1,2}$. The corresponding standard uncertainties are given below in µF/F

[0.777 0.806 * 0.929 3.390 0.809 0.791].

Table B2 below is an update of the pair-wise degree of equivalences in Table B6 from the SIM.EM-S4 Final Report [3] for 100 pF at 1000 Hz by replacing the DOE between ICE and other labs by the results given in the above. All values are given in µF/F.

Table B2. Updated pair-wise degree of equivalence with (standard uncertainties)

	NIST	CENAM	ICE	INTI	UTE	INMETRO	NRC
NIST		0.000214 (0.205)	0.0696 (0.777)	-0.501 (0.416)	4.535 (3.40)	-0.00643 (0.231)	-0.274 (0.141)
CENAM	-0.000214 (0.205)		-0.454 (0.806)	-0.5008 (0.435)	4.534 (3.40)	-0.00664 (0.264)	-0.274 (0.191)
ICE	-0.0696 (0.777)	0.454 (0.806)		-0.182 (0.929)	2.777 (3.390)	-0.0868 (0.809)	-0.510 (0.791)
INTI	0.501 (0.416)	0.501 (0.435)	0.182 (0.929)		5.035 (3.42)	0.494 (0.447)	0.226 (0.408)
UTE	-4.535 (3.40)	-4.534 (3.40)	-2.777 (3.390)	-5.035 (3.42)		-4.541 (3.41)	-4.809 (3.40)
INMETRO	0.00643 (0.231)	0.00664 (0.264)	0.0868 (0.809)	-0.494 (0.447)	4.541 (3.41)		-0.268 (0.215)
NRC	0.274 (0.141)	0.274 (0.191)	0.510 (0.791)	-0.226 (0.408)	4.809 (3.40)	0.268 (0.215)	

Appendix C: Uncertainty Budgets for 10 pF

Table C1. ICE-Costa Rica 10 pF 1000 Hz Uncertainty Budget Substitution.
Using standards calibrated by INTI.

Quantity	Type	Uncertainty (µF/F)	Sensitivity coefficient	Standard uncertainty (µF/F)
Reference Standard	Combined	36.17	1	36.17
Test Standard	Type A	2.58	1	2.58
Test Standard	Type B	0.01	1	0.01
Other	Type B	-	-	15.69
Combined Standard Uncertainty				39.6

Table C2. ICE-Costa Rica 10 pF 1000 Hz Uncertainty Budget Substitution.
Using standards calibrated by METAS

Quantity	Type	Uncertainty (µF/F)	Sensitivity coefficient	Standard uncertainty (µF/F)
Reference Standard	Combined	22.85	1	22.85
Test Standard	Type A	1.55	1	1.55
Test Standard	Type B	0.01	1	0.01
Other	Type B	-	-	5.70
Combined Standard Uncertainty				23.6

Table C3. ICE-Costa Rica 10 pF 1000 Hz Uncertainty Budget Direct Comparison.
Using a AH 2700A as a reference Standard.

Quantity	Type	Uncertainty (µF/F)	Sensitivity coefficient	Standard uncertainty (µF/F)
Reference Standard	Combined	0.8	1	0.8
Test Standard	Type A	0.14	1	0.14
Test Standard	Type B	0.01	1	0.01
Other	Type B	-	-	0.01
Combined Standard Uncertainty				0.81

Table C4. NIST AH Bridge 10 pF 1000 Hz Uncertainty Budget

Quantity	**Type**	**Standard uncertainty (μF/F)**
Reference Standard	Type B	0.050
Reference Drift	Type B	0.030
Test Drift	Type B	0.030
Bridge Thermal	Type B	0.050
Bridge Mechanical	Type B	0.050
Bridge Linearity	Type B	0.050
Bridge Loading	Type B	0.000
Stability	Type A	0.030
Combined Standard Uncertainty		0.123

Appendix D: Uncertainty Budgets for 100 pF

Table D1. ICE-Costa Rica 10 pF 1000 Hz Uncertainty Budget Substitution.
Using standards calibrated by INTI.

Quantity	Type	Uncertainty (µF/F)	Sensitivity coefficient	Standard uncertainty (µF/F)
Reference Standard	Combined	42.85	1	42.85
Test Standard	Type A	2.85	1	2.85
Test Standard	Type B	0.001	1	0.001
Other	Type B	-	-	13.10
Combined Standard Uncertainty				44.9

Table D2. ICE-Costa Rica 10 pF 1000 Hz Uncertainty Budget Substitution.
Using standards calibrated by METAS

Quantity	Type	Uncertainty (µF/F)	Sensitivity coefficient	Standard uncertainty (µF/F)
Reference Standard	Combined	24.44	1	24.44
Test Standard	Type A	1.53	1	1.53
Test Standard	Type B	0.001	1	0.001
Other	Type B	-	-	5.05
Combined Standard Uncertainty				25

Table D3. ICE-Costa Rica 10 pF 1000 Hz Uncertainty Budget Direct Comparison.
Using a AH 2700A as a reference Standard.

Quantity	Type	Uncertainty (µF/F)	Sensitivity coefficient	Standard uncertainty (µF/F)
Reference Standard	Combined	0.76	1	0.76
Test Standard	Type A	0.01	1	0.01
Test Standard	Type B	0.001	1	0.001
Other	Type B	-	-	0.12
Combined Standard Uncertainty				0.77

Table D4. NIST AH Bridge 10 pF 1000 Hz Uncertainty Budget

Quantity	Type	Standard uncertainty (μF/F)
Reference Standard	Type B	0.050
Reference Drift	Type B	0.030
Test Drift	Type B	0.030
Bridge Thermal	Type B	0.050
Bridge Mechanical	Type B	0.050
Bridge Linearity	Type B	0.030
Bridge Loading	Type B	0.004
Stability	Type A	0.030
Combined Standard Uncertainty		0.105