Final Report
Inter-American Metrology System (SIM)
Regional Metrology Organization (RMO)
Capacitance Comparison

SIM.EM-K4, 10 pF fused-silica standard capacitor at 1000 Hz and 1600 Hz
SIM.EM-S4, 100 pF fused-silica standard capacitor at 1000 Hz and 1600 Hz
SIM.EM-S3, 1000 pF nitrogen gas standard capacitor at 1000 Hz

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2003 – 2006 Comparison
Pilot Laboratory: National Institute of Standards and Technology

1 Introduction

In order to strengthen the Interamerican Metrology System (SIM), interaction among its National Metrology Institutes (NMI´s) must be promoted. At the same time, in accordance with the CIPM Mutual Recognition Agreement (MRA) objectives, NMI´s must establish the degree of equivalence between their national measurement standards by performing regional comparisons, among other activities.

The objective of this comparison was to compare the measurement capabilities of NMI´s within SIM in the field of capacitance. This action was aimed at determining the degree of equivalence of measuring capabilities in capacitance. The proposed test points were selected to evaluate the measuring capabilities of the participants, both their measurement standards and their measurement procedures.

SIM has undertaken three related capacitance comparisons. **SIM.EM-K4** is a comparison of a **10 pF** fused-silica standard at 1000 Hz and 1600 Hz. **SIM.EM-S4** is a comparison of a **100 pF** fused-silica standard at 1000 Hz and 1600 Hz. **SIM.EM-S3** is a comparison of a **1000 pF** nitrogen gas standard capacitor at 1000 Hz.

The participant institutes are listed in Table 1. The individual contacts are listed in Appendix I.

Table 1. Capacitance comparison participants

Country	Institute	Acronym
Argentina	Instituto Nacional de Technologia Industrial	INTI
Brazil	Instituto Nacional de Metrologia, Qualidade e Tecnologia	INMETRO
Canada	National Research Council	NRC
Costa Rica	Instituto Costarricense de Electricidad	ICE
Mexico	Centro Nacional de Metrologia	CENAM
United States	National Institute of Standards and Technology	NIST
Uruguay	Administracion Nacional de Usinas y Transmissiones Electricas	UTE

2 Traveling Standards

2.1 Description of the standards

The traveling standard for the SIM.EM-K4 comparison was an Andeen-Hagerling AH11A 10 pF fused-silica standard capacitor, with serial number 01238. The traveling standard for the SIM.EM-S4 was an Andeen-Hagerling AH11A 100 pF fused-silica standard capacitor with serial number 01237. Both the SIM.EM-K4 and SIM.EM-S4 traveling standards were housed in the Andeen-Hagerling AH1100 enclosure with serial number 00078. The traveling standard for the SIM.EM-S3 comparison was a General Radio GR1404-A 1000 pF nitrogen standard capacitor with serial number 2151.

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 00078containing
  - AH11A 100 pF fused-silica standard capacitor SN 01237
  - AH11A 10 pF fused-silica standard capacitor SN 01238
- Power cord for AH1100 (110 V, three-prong)
- General Radio GR1404-A 1000 pF nitrogen standard capacitor SN 2151
- one set one-meter four-terminal-pair coaxial BNC cables
- one set one-meter three-terminal coaxial BNC cables
- two GR874-to-BNC adapters
- four female-to-female BNC connectors (barrels)
- two BNC T-connectors
- two BNC 90 degree (elbow) adapters
- two BNC male-to-alligator connectors
- one shorting cable for shorting the GR1404-A high terminal to case
- one box of five 0.5 Amp fuses for the AH1100 enclosure
- one bag of seven 0.25 Amp fuses for the AH1100 enclosure
- one AH1100/11A Operation and Maintenance Manual

Photographs of the parts included within the shipping container are shown in Appendix I.

2.3 Quantities to be measured

Participants measured the AH11A 10 pF and 100 pF standards at 1000 Hz and 1600 Hz. The GR1404-A 1000 pF standard was measured at 1000 Hz. All capacitance measurements with corresponding combined standard uncertainties were reported. Enclosure temperature was recorded with each AH11A measurement and ambient temperature was recorded with each GR1404-A measurement. At least five measurements were reported for each frequency point.

3 Organization

The National Institute of Standards and Technology (NIST) was the pilot laboratory for SIM.EM-K4, SIM.EM-S3, and SIM.EM-S4 comparisons. NIST used two measurement methods. One method employed 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 for this method. Measurements were taken on a traveling 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 traveling standard to achieve the reported value.

The second method employed the NIST two-pair capacitance bridge for accurate 1592 Hz measurements of the 10 pF and 100 pF AH11A traveling standards. This method was used sparingly to check the results of the substitution method.

In order to participate in the SIM.EM-K4 10 pF fused-silica measurement at 1000 Hz and 1600 Hz, participants were to have capacitance measurement capability (including reference) with a combined standard uncertainty of 500×10^{-6} at 1600 Hz. For participation in the SIM.EM-S4 100 pF fused-silica measurement at 1000 Hz and 1600 Hz, participants were to have capacitance measurement capability (including reference) with a combined standard uncertainty of 500×10^{-6} at 1600 Hz.

For participation in the SIM.EM-S3 1000 pF gas standard measurement at 1000 Hz, participants must have capacitance measurement capability (including reference) with a combined standard uncertainty of 1000×10^{-6}.

The traveling standards were measured at NIST at the beginning and ending of the comparison schedule. The traveling standards travelled regionally between participant laboratories, with two intermediate stops at NIST. The schedule of measurements is shown in Table 2.

Table 2. Schedule of measurements

Laboratory	Approximate measurement dates
NIST (United States)	November 2003 to April 2004
CENAM (México)	July to August 2004
ICE (Costa Rica)	September to November 2004
NIST (United States)	December 2004 to February 2005
INTI (Argentina)	March 2005
UTE (Uruguay)	July 2005
INMETRO (Brazil)	September 2005
NIST (United States)	December 2005 to January 2006
NRC (Canada)	February to March 2006
NIST (United States)	May 2006 to June 2006

4 Pilot Laboratory Measurement Results

The pilot laboratory measurement results are shown in Figures 1 through 5 below. Results at 1 kHz consist only of measurements from an Andeen-Hagerling AH2700A Capacitance Bridge. Results at 1.6 kHz consist of AH Bridge measurements as well as measurements from the NIST 2-pair Bridge.

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

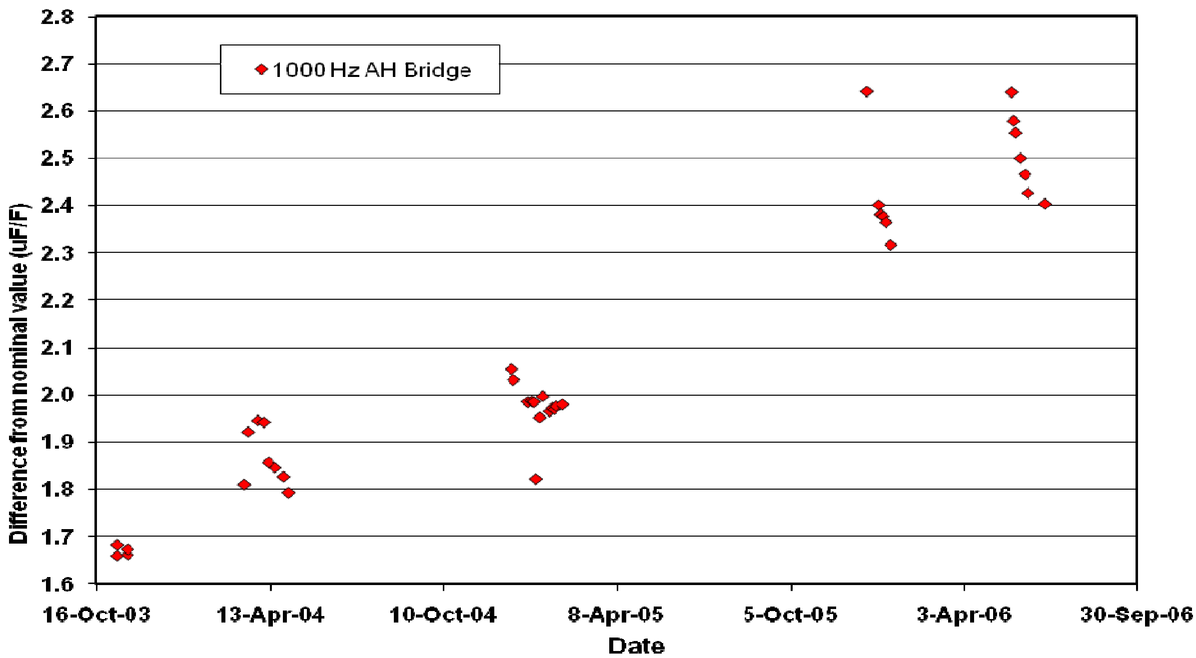

Fig. 1. Pilot laboratory measurements of AH11A SN 01238 10 pF standard capacitor at 1 kHz

4.2 SIM.EM-K4 10 pF results at 1.6 kHz

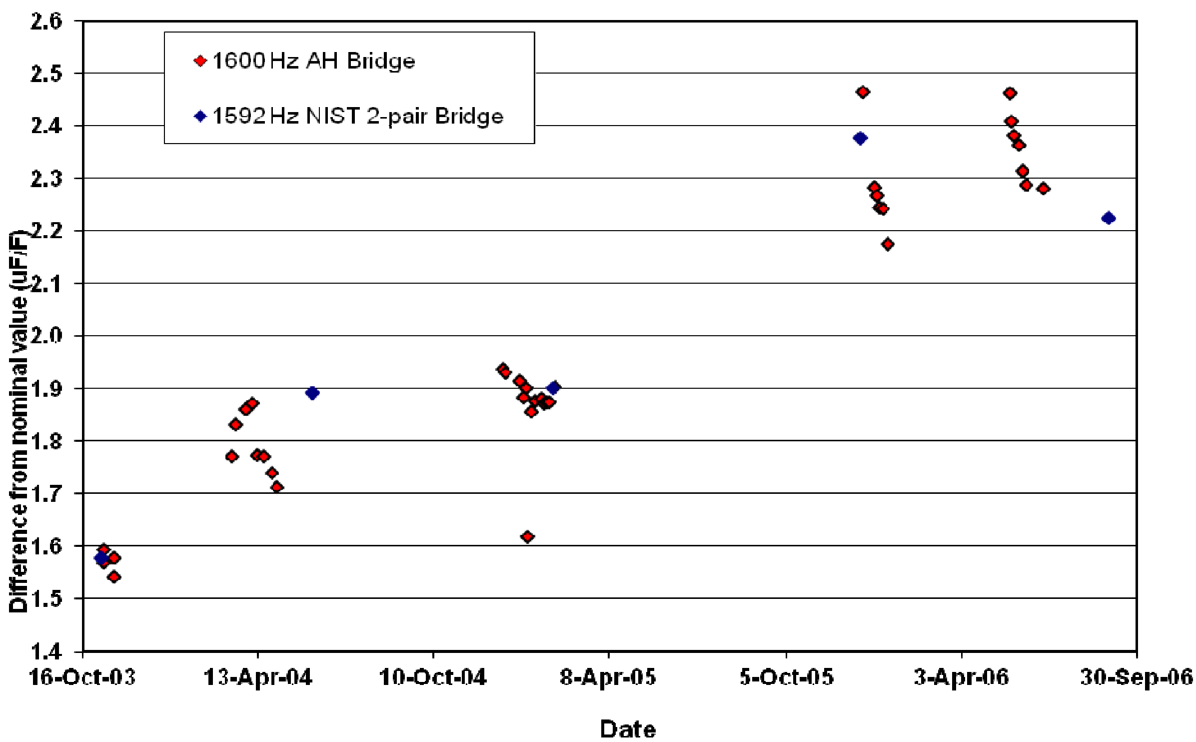

Fig. 2. Pilot laboratory measurements of AH11A SN 01238 10 pF standard capacitor at 1.6 kHz

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

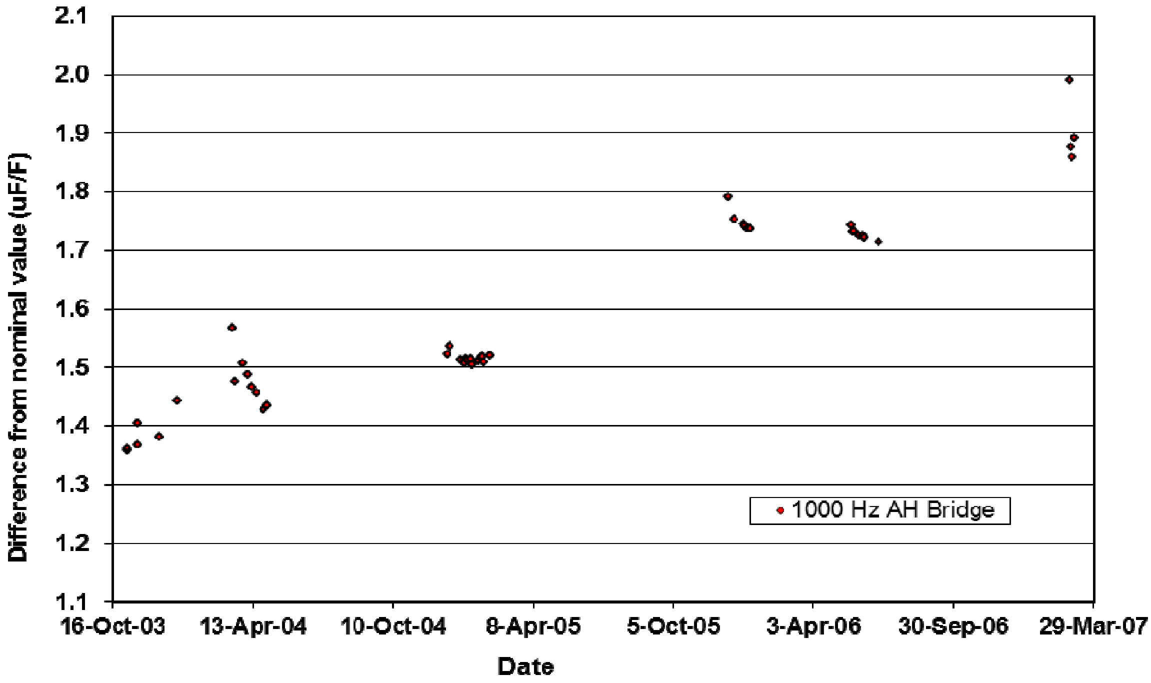

Fig. 3. Pilot laboratory measurements of AH11A SN 01237 100 pF standard capacitor at 1 kHz

4.4 SIM.EM-S4 100 pF results at 1.6 kHz

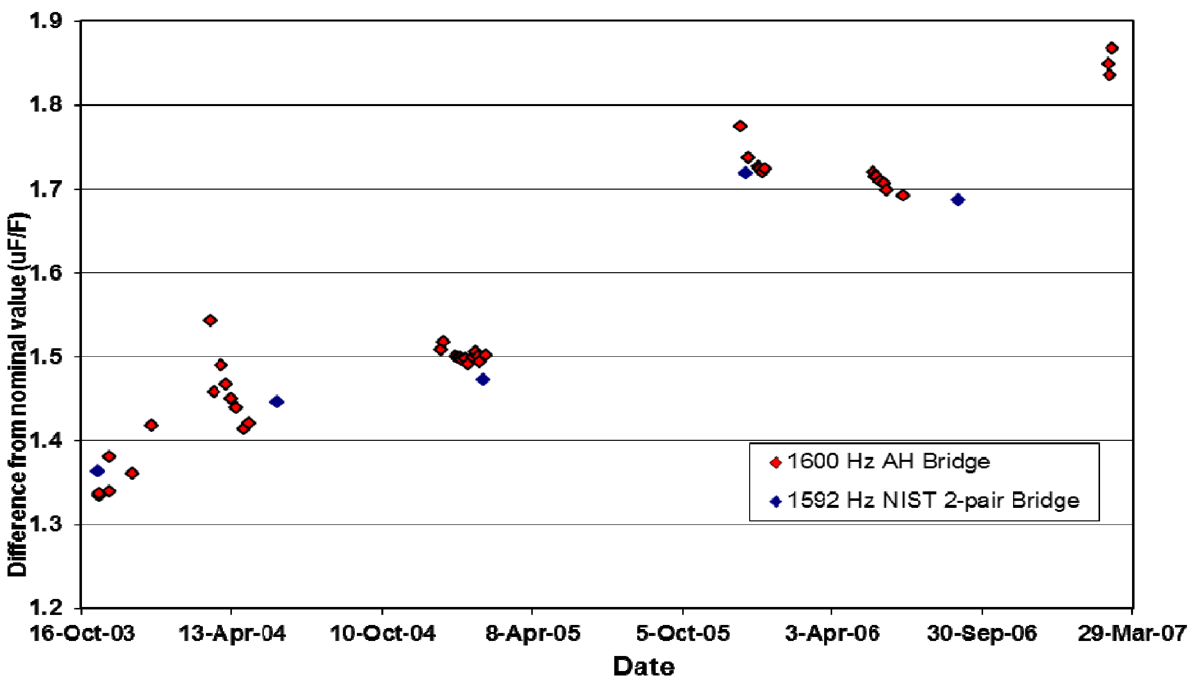

Fig. 4. Pilot laboratory measurements of AH11A SN 01237 100 pF standard capacitor at 1.6 kHz

4.5 SIM.EM-S3 1000 pF results at 1 kHz

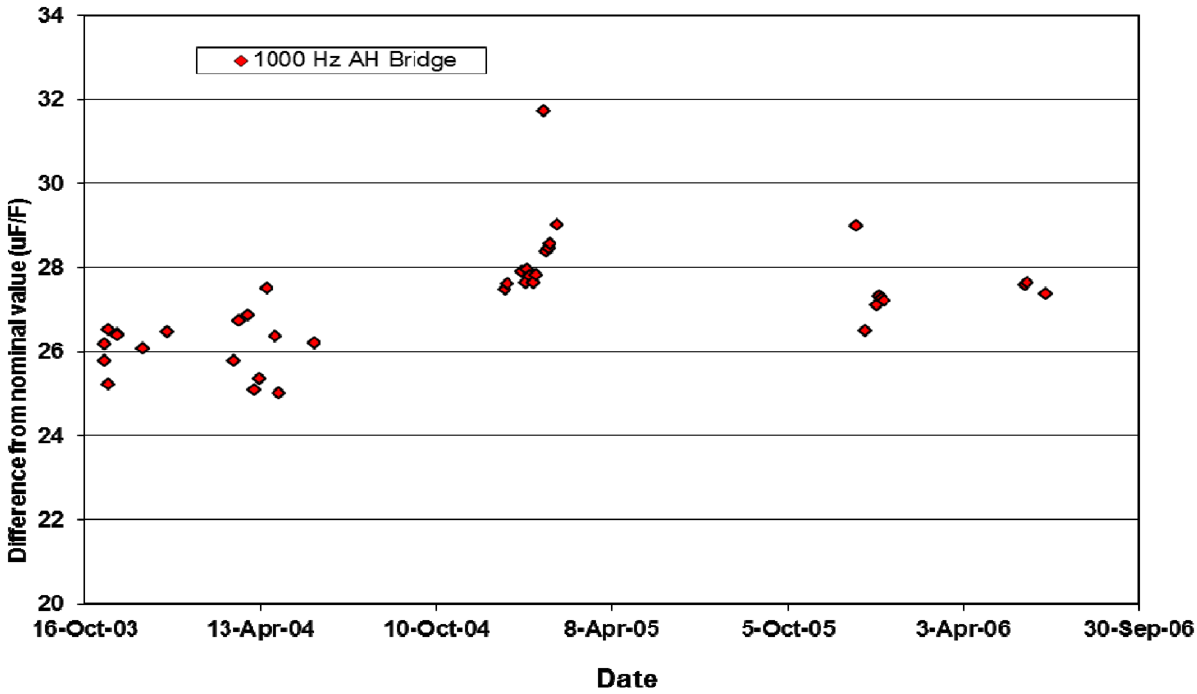

Fig. 5. Pilot laboratory measurements of GR1404-A SN 2151 1000 pF standard at 1 kHz

5 Reported Results of Comparisons

Seven laboratories participated in these comparisons and provided results. Two of these laboratories participated in follow-up bilateral comparisons with the pilot laboratory. Those two and another laboratory submitted corrected data after the submission of the Draft A report was circulated. Descriptions of these corrections are included in Appendix G. Final analyses for these comparisons were performed using only original data. Original data are presented in the tables below and in accompanying figures. Corrected data are presented in Appendix G.

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

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

Laboratory	Mean Date	Mean 1 kHz Capacitance Deviation from Nominal Value (μF/F)	Combined Standard Uncertainty (μF/F)
NIST USA	2003.866	1.834	0.123
NIST USA	2004.273	1.868	0.123
CENAM Mexico	2004.574	1.967	0.17
ICE Costa Rica	2004.872	-2000	180000
NIST USA	2005.049	1.988	0.123
INTI Argentina	2005.219	2.65	0.4
UTE Uruguay	2005.521	-2.30	3.4
INMETRO Brazil	2005.726	2.299	0.2

NIST USA	2006.016	2.414	0.123
NRC Canada	2006.159	2. 689	0.079
NIST USA	2006.419	2.510	0.123

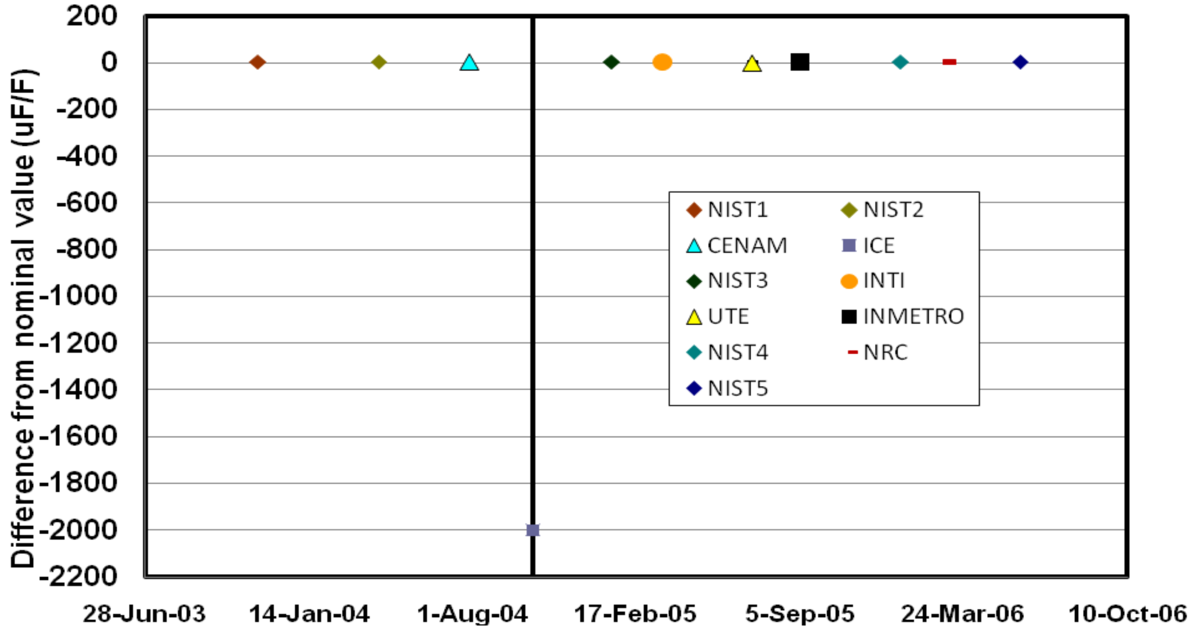

Fig. 6. All participant results of measurement of AH11A SN 01238 10 pF at 1 kHz

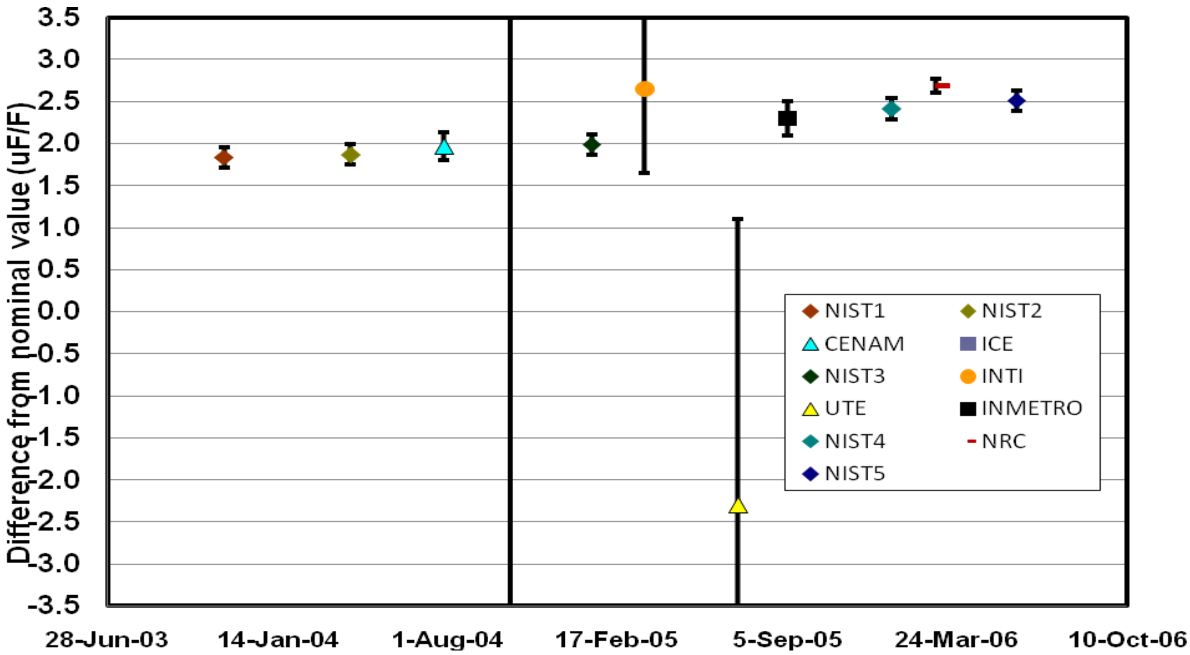

Fig. 7. Most participant results of measurement of AH11A SN 01238 10 pF at 1 kHz

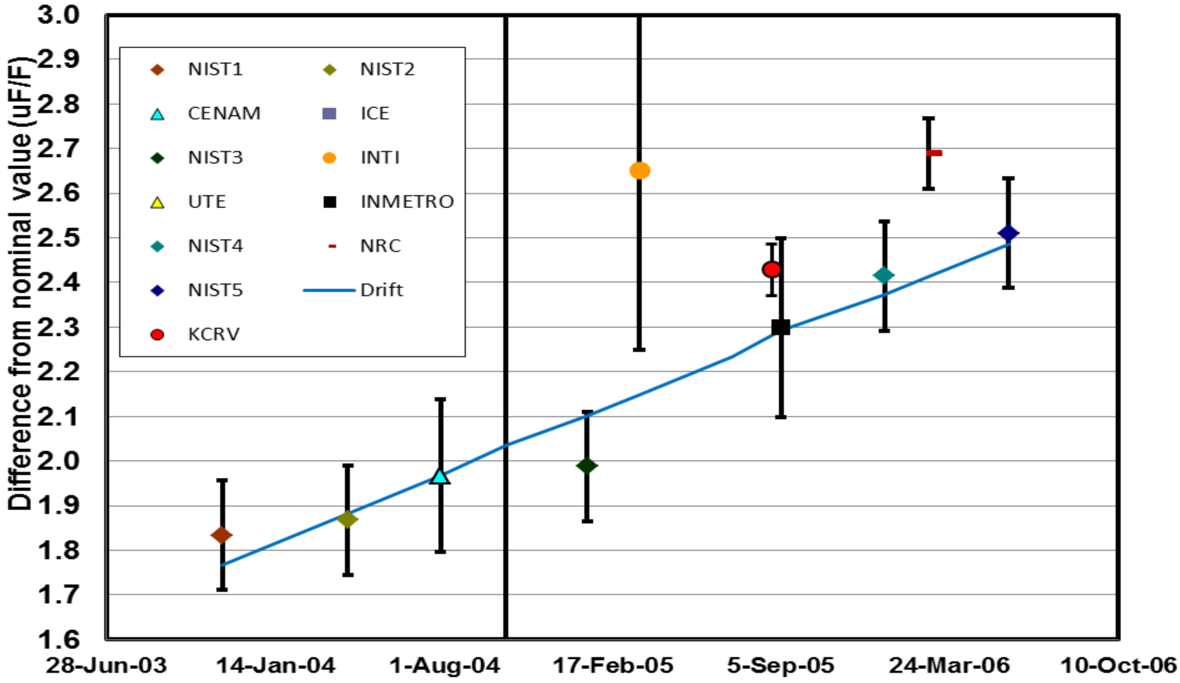

Fig. 8. Some participant results of measurement of AH11A SN 01238 10 pF at 1 kHz

5.2 SIM.EM-K4 10 pF results at 1.6 kHz

Table 4. Mean 1600 Hz measurement data for all participant laboratories.

Laboratory	Mean Date	Mean 1600 Hz Capacitance Deviation from Nominal Value (µF/F)	Combined Standard Uncertainty (µF/F)
NIST USA	2003.852	1.613	0.084
NIST USA	2004.273	1.791	0.114
CENAM Mexico	2004.568	1.822	0.17
ICE Costa Rica	2004.787	-2000	180000
NIST USA	2005.060	1.894	0.096
INTI Argentina	2005.219	1.510	0.35
UTE Uruguay		Did not participate	
INMETRO Brazil	2005.729	2.207	0.2
NIST USA	2005.995	2.324	0.093
NRC Canada	2006.159	2.847	0.069
NIST USA	2006.419	2.356	0.114

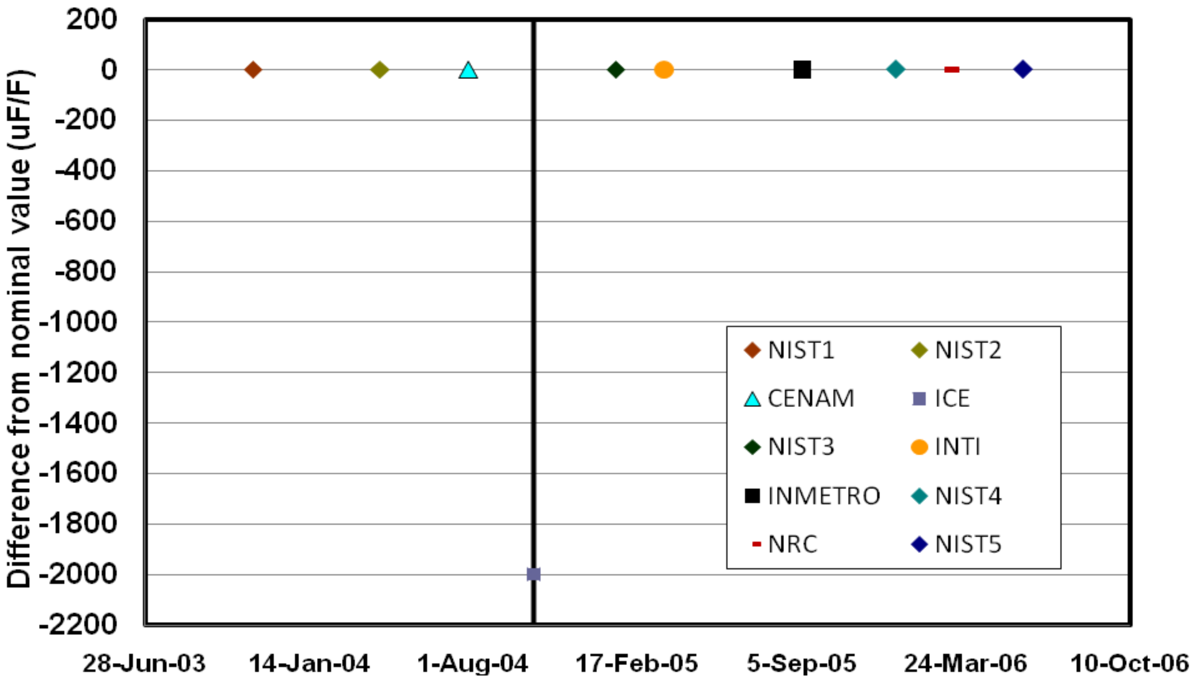

Fig. 9. All participant results of measurement of AH11A SN 01238 10 pF at 1.6 kHz

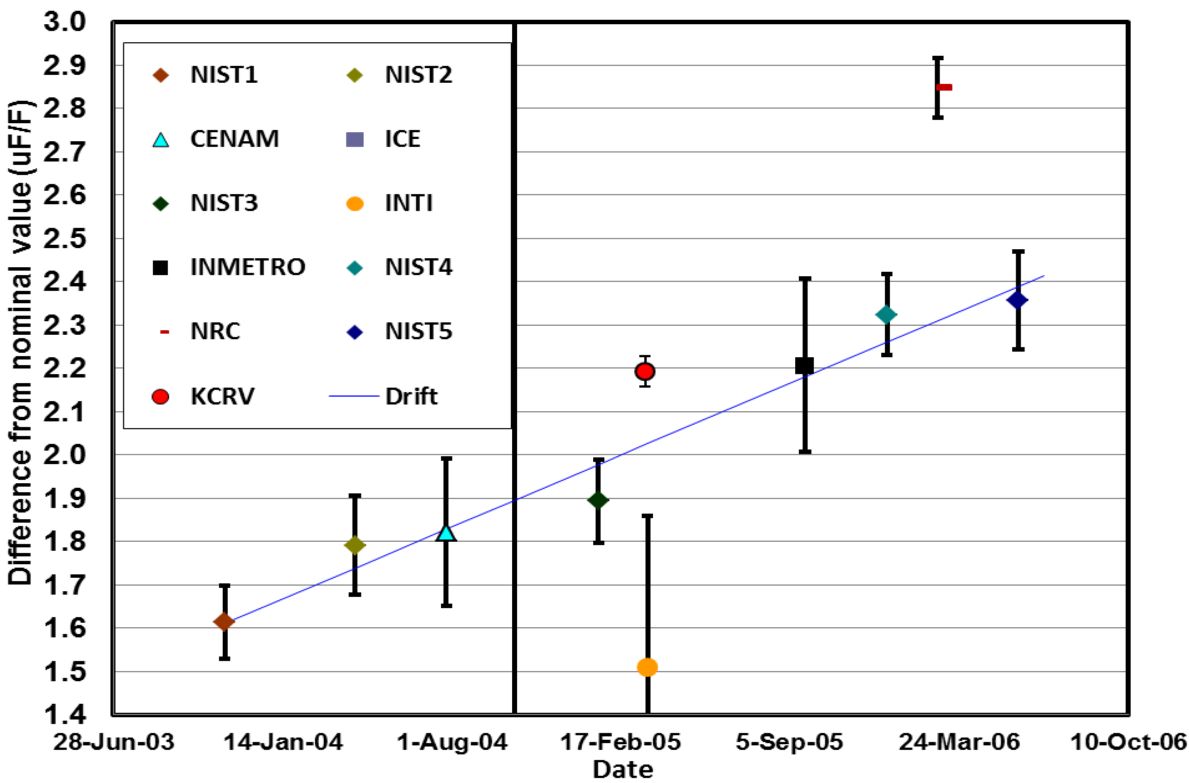

Fig. 10. Most participant results of measurement of AH11A SN 01238 10 pF at 1.6 kHz

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

Table 5. Mean 1000 Hz measurement data for all participant laboratories.

Laboratory	Mean Date	Mean 1 kHz Capacitance Deviation from Nominal Value (μF/F)	Combined Standard Uncertainty (μF/F)
NIST USA	2003.907	1.386	0.105
NIST USA	2004.273	1.477	0.105
CENAM Mexico	2004.571	0.970	0.19
ICE Costa Rica	2004.787	-600	19000
NIST USA	2005.047	1.515	0.105
INTI Argentina	2005.219	1.710	0.5
UTE Uruguay	2005.521	-1.200	3.3
INMETRO Brazil	2005.680	1.690	0.2
NIST USA	2006.003	1.750	0.105
NRC Canada	2006.159	2.190	0.110
NIST USA	2006.419	1.792	0.105

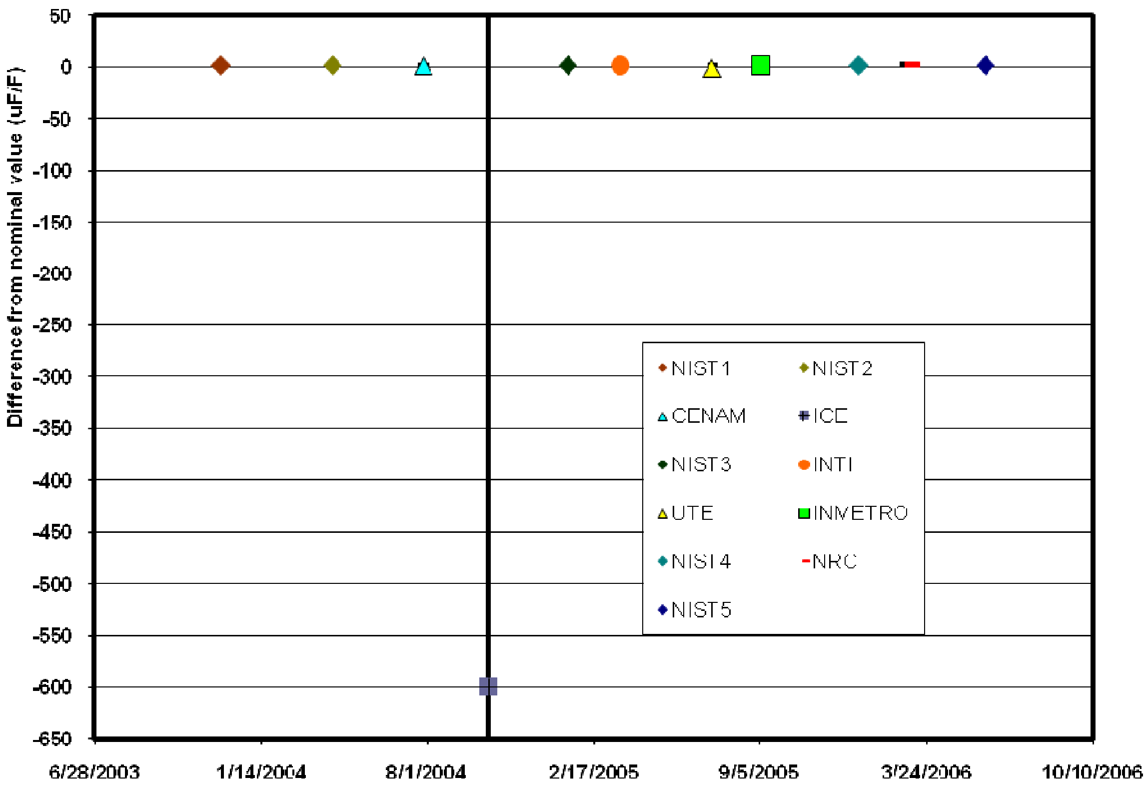

Fig. 11. All participant results of measurement of AH11A SN 01237 100 pF at 1 kHz

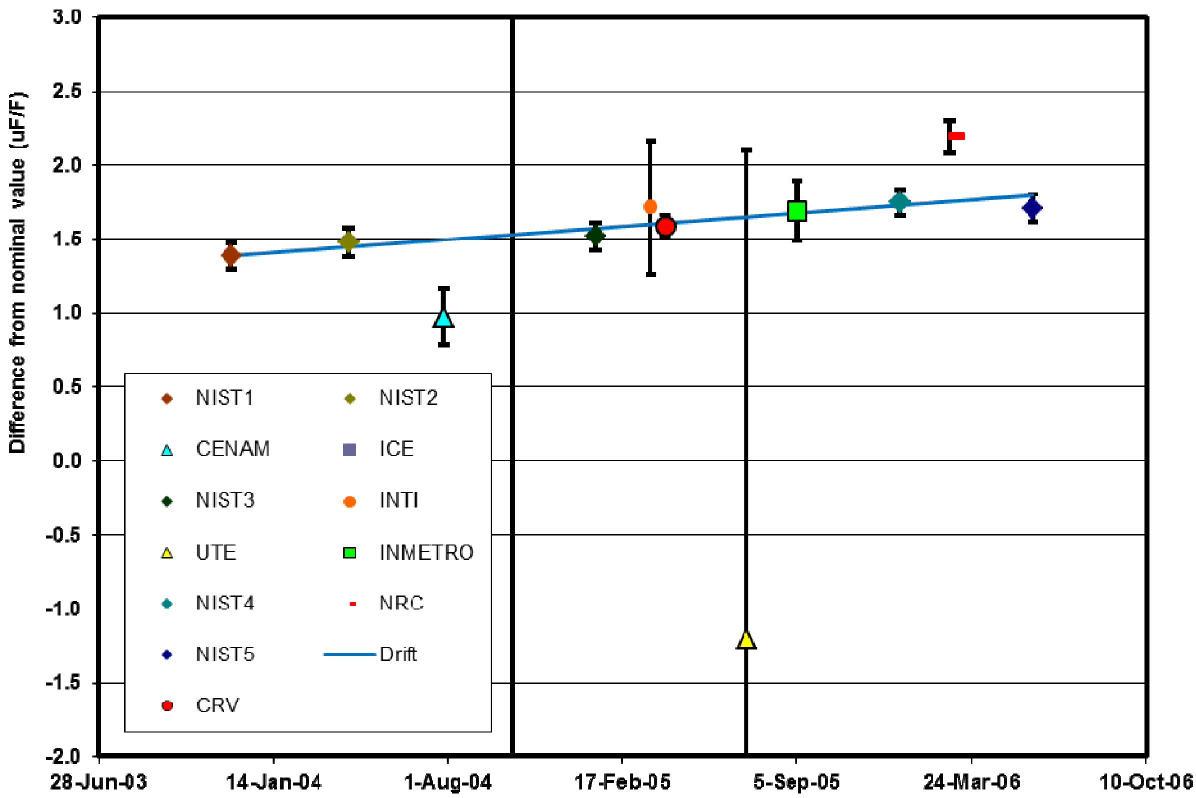

Fig. 12. Most participant results of measurement of AH11A SN 01237 100 pF at 1 kHz

5.4 SIM.EM-S4 100 pF results at 1.6 kHz

Table 6. Mean 1600 Hz measurement data for all participant laboratories.

Laboratory	Mean Date	Mean 1600 Hz Capacitance Deviation from Nominal Value (μF/F)	Combined Standard Uncertainty (μF/F)
NIST USA	2003.896	1.362	0.086
NIST USA	2004.273	1.460	0.095
CENAM Mexico	2004.568	1.380	0.190
ICE Costa Rica	2004.787	-100	19000
NIST USA	2005.052	1.499	0.092
INTI Argentina	2005.222	0.580	0.450
UTE Uruguay		Did not participate	
INMETRO Brazil	2005.682	1.650	0.200
NIST USA	2005.997	1.732	0.089
NRC Canada	2006.159	2.452	0.200
NIST USA	2006.419	1.708	0.095

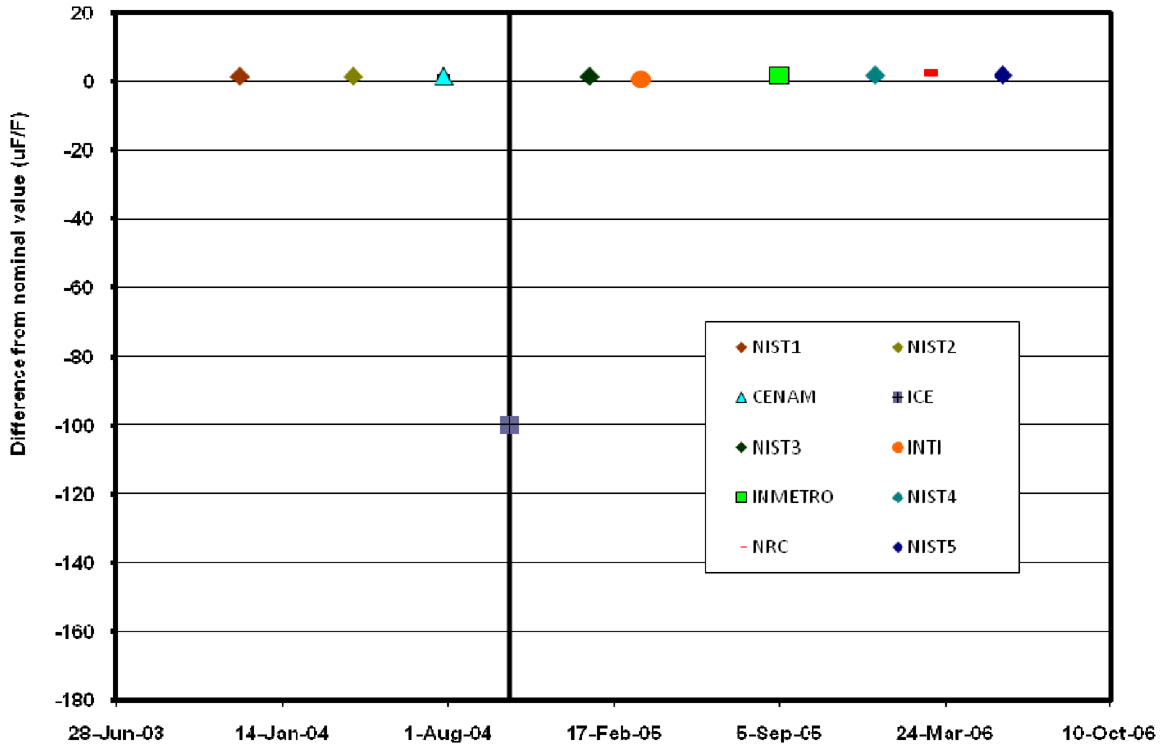

Fig. 13. All participant results of measurement of AH11A SN 01237 100 pF at 1.6 kHz

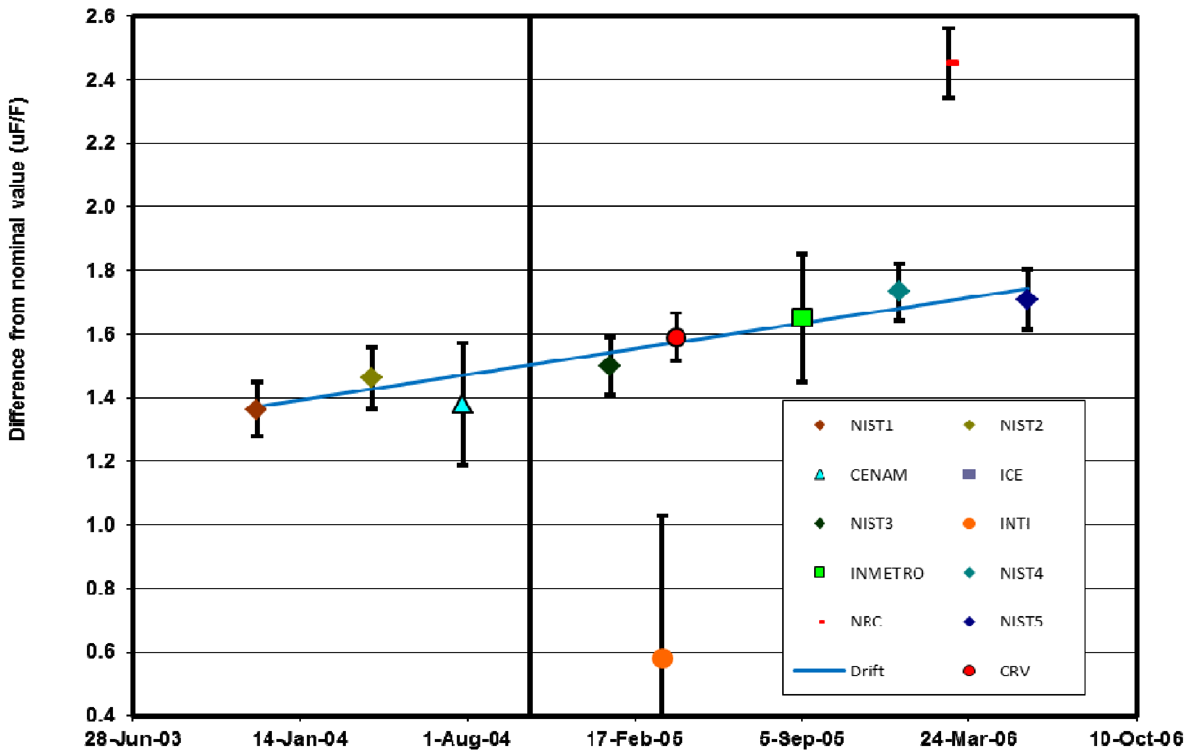

Fig. 14. Most participant results of measurement of AH11A SN 01237 100 pF at 1.6 kHz

5.5 SIM.EM-S3 1000 pF results at 1 kHz

Table 7 presents the 1000 pF, 1000 Hz data. It should be noted that no temperature corrections were provided. Therefore, laboratory temperature affects the comparison of results by as much as 4 µF/F per degree Celsius for labs with differing measurement temperatures.

Table 7. Mean 1000 Hz measurement data for all participant laboratories.

Laboratory	Mean Date	Mean 1 kHz Capacitance Deviation from Nominal Value (µF/F)	Combined Standard Uncertainty (µF/F)	Mean Measurement Temperature (degrees C)
NIST USA	2003.893	26.14	0.789	22.88
NIST USA	2004.292	26.10	0.789	22.84
CENAM Mexico	2004.571	25.67	0.250	23.02
ICE Costa Rica	2004.787	-220	1800	23.30
NIST USA	2005.047	28.31	0.789	23.01
INTI Argentina	2005.227	26.00	0.900	22.95
UTE Uruguay	2005.518	24.46	6.3	23.03
INMETRO Brazil	2005.688	25.41	0.200	22.10
NIST USA	2006.003	27.40	0.789	22.85
NRC Canada	2006.159	22.84	0.250	21.28
NIST USA	2006.449	27.54	0.789	22.80

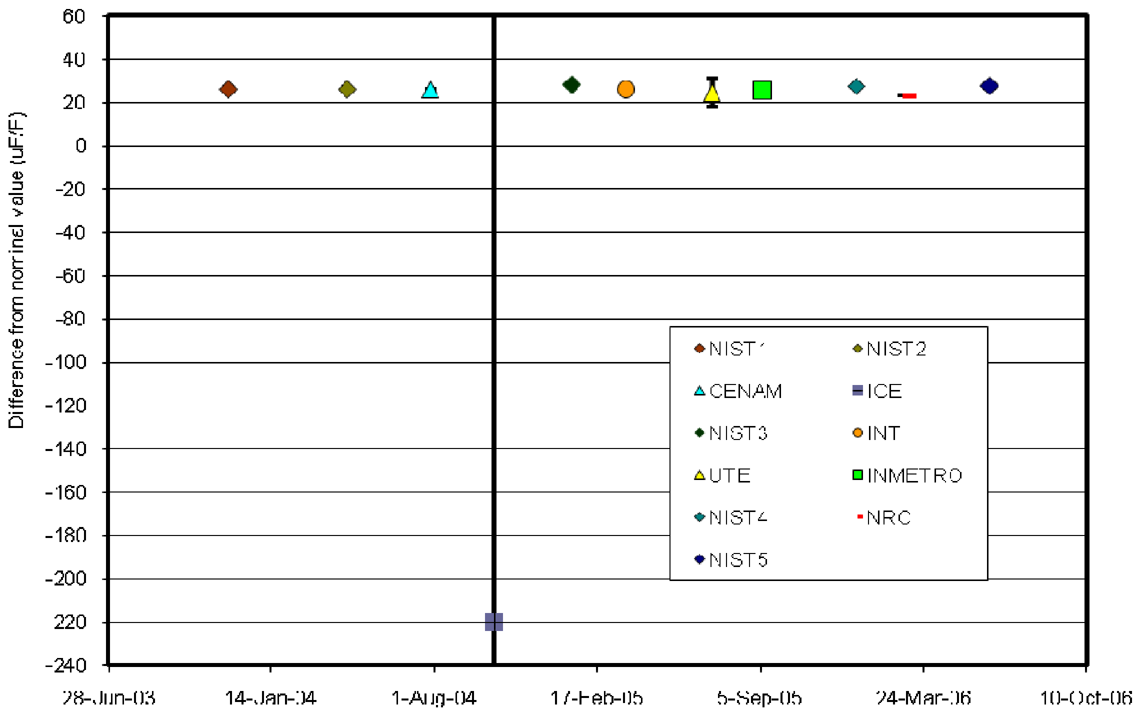

Fig. 15. All participant results of measurement of GR 1404-A SN 2151 1000 pF at 1 kHz

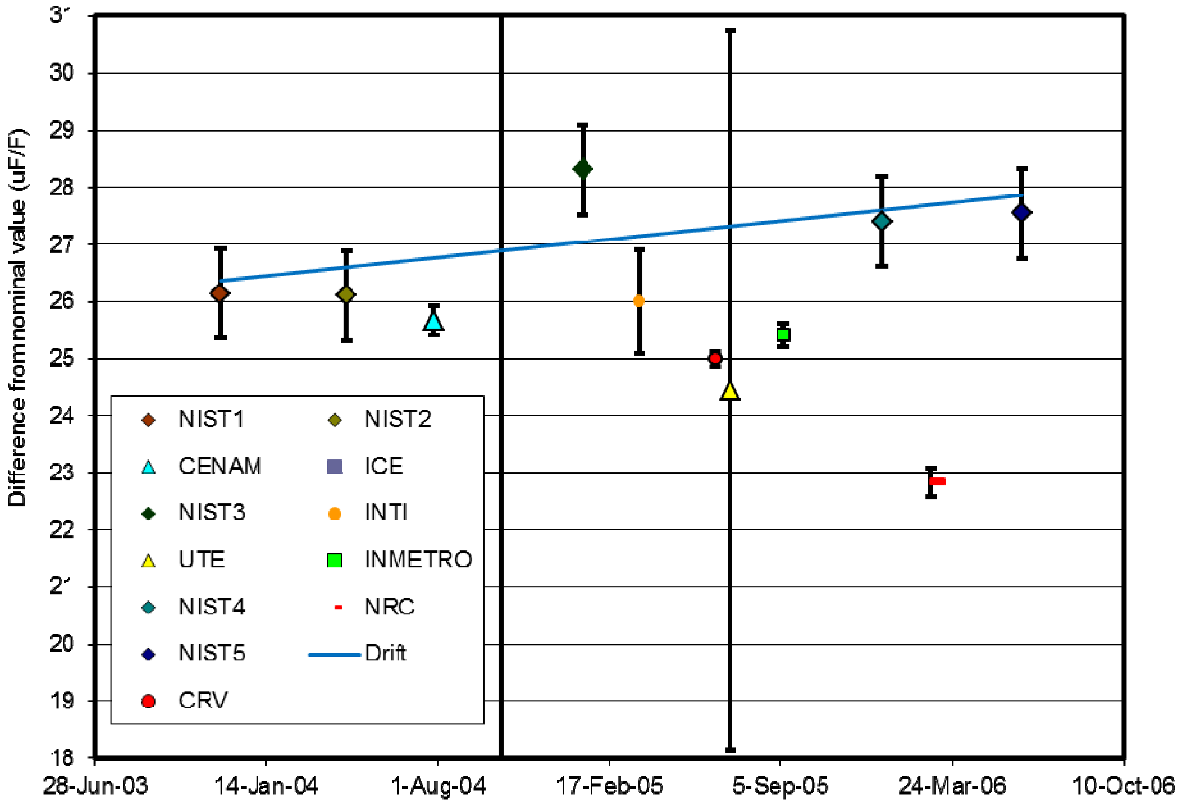

Fig. 16. Most participant results of measurement of GR 1404-A SN 2151 1000 pF at 1 kHz

6 References

[1] N.F. Zhang, H.-K. Liu, N. Sedransk, and W.E. Strawderman, *Statistical analysis of key comparisons with linear trends*, Metrologia, 41, pp. 231-237, 2004.

[2] A.-M. Jeffery, *Final Report CCEM-K4 Comparison of 10 pF Capacitance Standards*, March 2001.

[3] N. F. Zhang, W. E. Strawderman, H. K. Liu, and N. Sedransk, *Statistical analysis for multiple artifact problem in key comparisons with linear trends*, Metrologia, 43, pp. 21-26, 2006.

[4] W. Zhang, N. F. Zhang, and H. K. Liu, *A generalized method for the multiple artifacts problem in interlaboratory comparisons with linear trends*, Metrologia, 46, pp. 345-350, 2009.

[5] N. F. Zhang, *Linking the results of CIPM and RMO key comparisons with linear trends*, Journal of Research of the National Institute of Standards and Technology, 115, pp. 179-194, 2010.

Appendix A. Analysis Procedure

It is well known that for a standard of capacitance, the measurements typically show a trend in time, which under our assumption can be modeled as a linear trend with time. As in [1], [3], and [4], 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, while we allow different intercepts for different laboratories. In each of the SIM comparisons, only one traveling standard was used. In each comparison, the traveling standard was measured at the pilot laboratory – NIST – for five periods, while for each of the non-pilot laboratories it was measured for only one time period.

For each non-pilot laboratory, an uncertainty budget was reported and the combined standard uncertainty was calculated. For NIST, in each of the three 1000 Hz comparison points, i.e., for SIM.EM-K4 10 pF at 1000 Hz, SIM.EM.-S4 100 pF at 1000Hz, and SIM.EM-S3, the Type A uncertainties as well as the Type B uncertainties for each period are the same. However, for the two 1600 Hz comparison points, i.e., SIM.EM-K4 10 pF at 1600 Hz and SIM.EM-S4 100 pF at 1600 Hz, the Type A uncertainties as well as the Type B uncertainties for each period of NIST measurements are different. Thus, a general statistical analysis procedure proposed in [4] was used.

It should be noted that the time periods for measurement at each laboratory varied from one day to four or five weeks and the time periods for measurement at the pilot laboratory were sometimes much longer, from weeks to months.

Additionally, the laboratories performed measurements at varying ambient temperatures, with differences of greater than 1.5 ºC between pilot and some other laboratories. For the SIM.EM-S3 traveling standard (GR 1404-A), the temperature coefficient of capacitance is 2 ± 2 µF/F/ºC. Unfortunately, no temperature corrections were requested within the comparison protocol. Future comparisons should provide for either temperature enclosure for all standards or temperature correction of the results obtained under significantly differing environmental conditions.

For the cases of SIM.EM-K4 10 pF at 1000Hz, SIM.EM.-S4 100 pF at 1000Hz, and SIM.EM-S3, the statistical analysis in [1] was used. Here is a brief summary of that approach. Without loss of generality, we assume that the pilot laboratory (NIST) is the first one among all I laboratories. Denote the time and the result of the k^{th} measurement by the pilot laboratory by t_{1k} , $k = 1,...,K$, and X_{1k} , $k = 1,...,K$ with $K > 2$, respectively (here $K = 5$). In practice, t_{1k} can be an average value of the time when the measurements are made in the k^{th} period and then X_{1k} is the average value of the corresponding measurements in that period.

We assume that a simple linear regression model holds for the measurements made by the pilot laboratory,

$$X_{1k} = \alpha_1 + \beta t_{1k} + \varepsilon_{1k} \qquad \text{(A.1)}$$

for $k = 1,...,K$. We assume that the random error ε_{1k} has a zero mean and standard uncertainty u_{1k} with $u_{1k}^2 = \sigma_{1,A}^2 + \sigma_{1,B}^2$, where $\sigma_{1,A}$ and $\sigma_{1,B}$ are the Type A and Type B evaluations of the uncertainty for the first laboratory. Denote $X_1 = \sum_{k=1}^{K} X_{1k} \Big/ K$ and $t_1 = \sum_{k=1}^{K} t_{1k} \Big/ K$. The standard uncertainty of X_1 is given by $u_1^2 = \sigma_{1,A}^2 \big/ K + u_{1,B}^2$. When $i \neq 1$, each laboratory takes one measurement at time t_i and the corresponding model is

$$X_i = \alpha_i + \beta t_i + \varepsilon_i, \qquad \text{(A.2)}$$

where the random error ε_i has a zero mean and standard uncertainty of u_i with $u_i^2 = \sigma_{i,A}^2 + \sigma_{i,B}^2$ for $i = 2,...,I$, where $\sigma_{i,A}$ and $\sigma_{i,B}$ are the Type A and Type B evaluations of the i^{th} laboratory. From (3), (9), and (10) in [3], the least squares estimators of the regression parameters are given by

$$\hat{\beta} = \frac{\sum_{k=1}^{K} (t_{1k} - t_1)(X_{1k} - X_1)}{\sum_{k=1}^{K} (t_{1k} - t_1)^2}, \text{ and } \hat{\alpha}_i = X_i - \hat{\beta} t_i \quad \text{for } i = 2,...,I. \qquad \text{(A.3)}$$

The corresponding uncertainties are given by (11) and (16) in [3]. As discussed in [1], [3], and [4], the comparison reference value as a weighted mean of the predicted values over the laboratories is time dependent and is given by

$$CRV_t(w) = \sum_{i=1}^{I} w_i (\hat{\alpha}_i + \hat{\beta} t) = \sum_{i=1}^{I} w_i X_i - \hat{\beta} \sum_{i=1}^{I} w_i (t_i - t). \qquad \text{(A.4)}$$

For given weights, CRV is obviously a linear function of t with the slope of $\hat{\beta}$. For the optimal weights discussed in [1] and given by $w_i = \frac{1}{u_i^2} \Big/ \sum_{k=1}^{I} \frac{1}{u_k^2}$, the CRV at the optimal time $t^* = \sum_{i=1}^{I} w_i t_i$ is given by $CRV_{t^*} = \sum_{i=1}^{I} w_i X_i$ with the standard uncertainty given by

$$u_{CRV(t^*)}^2 = 1 \Big/ \sum_{i=1}^{I} \frac{1}{u_i^2}. \qquad \text{(A.5)}$$

The degrees of equivalence of the i^{th} national standard with respect to the CRV at time t is defined as the difference

$$D_{i,CRV} = \hat{\alpha}_i + \hat{\beta} t - CRV_t. \qquad \text{(A.6)}$$

It is shown by (30) in [3] that $D_{i,CRV}$ is independent of t. The standard uncertainty of $D_{i,CRV}$ is given by (33) in [3]. The degree of equivalence between the national measurement standards is defined as

$$D_{i,k} = \hat{\alpha}_i - \hat{\alpha}_k \qquad \text{(A.7)}$$

when $i \neq k$. The quantity is independent of t with its standard uncertainty given by (36) in [3].

As stated earlier, for the cases of SIM.EM-K4 10 pF at 1600Hz and SIM.EM.-S4 100 pF at 1600Hz the statistical analysis in [4] was used and the corresponding formulae can be found in [4].

Appendix B. Analysis Results

The results were calculated based on the statistical analysis in Appendix A and are listed below.

1. SIM.EM-K4 10 pF

   a. 1 kHz results

The 1000 Hz capacitance drift of the traveling standard, in µF/F, was determined from pilot laboratory measurements using a linear fit, $X_{ik} = \hat{\alpha}_1 + \hat{\beta}(t_{1k} - t_{init})$, where from (A.3) $\hat{\beta}$ = 0.282, $\hat{\alpha}_1$ = 1.767, and t_{init} = 2003.866. The comparison reference value (CRV) as a deviation from the nominal value of 10 pF, is 2.429 µF/F, with a standard uncertainty of 0.058 µF/F. The optimal time, t, for the CRV, is t = 2005.661. Statistics are computed according to reference [1].

The degree of equivalence of all laboratories with respect to the CRV for 1000 Hz is shown in Table B1 and the pair-wise degree of equivalence and their standard uncertainties are given in Table B2. Note that for Tables B1 and B2, the degree of equivalence and their standard uncertainties are given in µF/F. Fig. B1 shows a plot of the data in Table B1.

Table B1. 1000 Hz degree of equivalence of all laboratories with respect to the CRV.

Laboratory	Degree of Equivalence	Standard uncertainty of Degree of Equivalence
NIST	-0.155	0.100
CENAM	-0.155	0.162
ICE	-2002	180000
INTI	0.346	0.396
UTE	-4.689	3.400
INMETRO	-0.148	0.192
NRC	0.120	0.056

Table B2. Pair-wise 1000 Hz degree of equivalence with standard uncertainties in parentheses.

	NIST	CENAM	ICE	INTI	UTE	INMETRO	NRC
NIST		0.000214 (0.205)	2002 (180000)	-0.501 (0.416)	4.535 (3.40)	-0.00643 (0.231)	-0.274 (0.141)
CENAM	-0.000214 (0.205)		2002 (180000)	-0.5008 (0.435)	4.534 (3.40)	-0.00664 (0.264)	-0.274 (0.191)
ICE	-2002 (180000)	-2002 (180000)		-2003 (180000)	-1998 (180000)	-2002 (180000)	-2002 (180000)
INTI	0.501 (0.416)	0.501 (0.435)	2003 (180000)		5.035 (3.42)	0.494 (0.447)	0.226 (0.408)
UTE	-4.535 (3.40)	-4.534 (3.40)	1998 (180000)	-5.035 (3.42)		-4.541 (3.41)	-4.809 (3.40)
INMETRO	0.00643	0.00664	2002	-0.494	4.541		-0.268

	(0.231)	(0.264)	(180000)	(0.447)	(3.41)		(0.215)
NRC	0.274 (0.141)	0.274 (0.191)	2002 (180000)	-0.226 (0.408)	4.809 (3.40)	0.268 (0.215)	

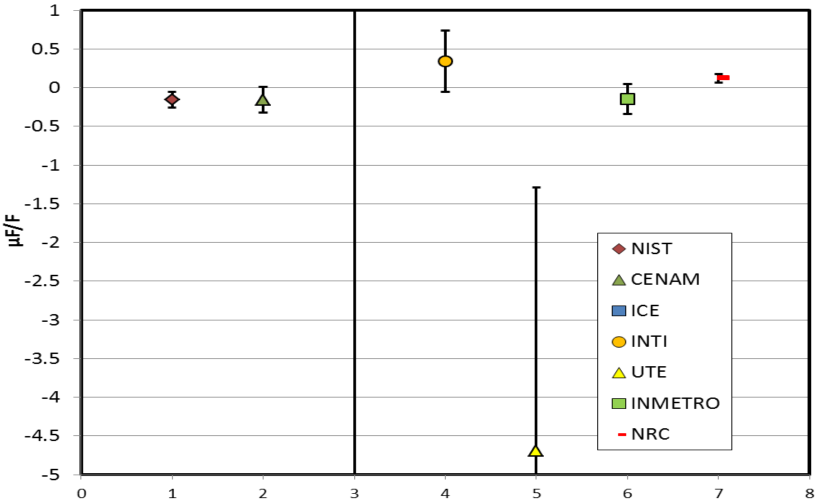

Fig. B1. 10 pF 1000 Hz degree of equivalence of laboratories with respect to the CRV.

b. 1.6 kHz results

The 1600 Hz capacitance drift of the traveling standard, in µF/F, was determined from pilot laboratory measurements using a linear fit, $X_{ik} = \hat{\alpha}_1 + \hat{\beta}(t_{1k} - t_{init})$, where from (A.3) $\hat{\beta}$ = 0.303, $\hat{\alpha}_1$ = 1.612, and t_{init} = 2003.852. The comparison reference value (CRV) as a deviation from the nominal value of 10 pF, is 2.458 µF/F, with a standard uncertainty of 0.052 µF/F. The optimal t = 2005.692.

Table B3. 1600 Hz degree of equivalence of all laboratories with respect to the CRV.

Laboratory	Degree of Equivalence	Standard Uncertainty of Degree of Equivalence
NIST	-0.290	0.090
CENAM	-0.296	0.170
ICE	-2002	180000
INTI	-0.805	0.347
INMETRO	-0.263	0.193
NRC	0.247	0.050

Table B4. Pair-wise 1600 Hz degree of equivalence with standard uncertainties in parentheses.

	NIST	CENAM	ICE	INTI	INMETRO	NRC
NIST		0.00659 (0.199)	2002 (180000)	0.516 (0.364)	-0.0270 (0.226)	-0.537 (0.131)
CENAM	-0.00659 (0.199)		2002 (180000)	0.509 (0.390)	-0.0336 (0.268)	-0.543 (0.197)
ICE	-2002 (180000)	-2002 (180000)		-2001 (180000)	-2002 (180000)	-2002 (180000)
INTI	-0.516 (0.364)	-0.509 (0.390)	2001 (180000)		-0.543 (0.404)	-1.052 (0.359)

INMETRO	0.0270 (0.226)	0.0336 (0.268)	2002 (180000)	0.543 (0.404)		-0.510 (0.212)
NRC	0.537 (0.131)	0.543 (0.197)	2002 (180000)	1.052 (0.359)	0.510 (0.212)	

The degree of equivalence of all laboratories with respect to the CRV for 1600 Hz is shown in Table B3 and the pair-wise degree of equivalence and their standard uncertainties are given in Table B4. Note that for Tables B3 and B4, the degree of equivalence and standard uncertainties are given in units of µF/F. Fig. B2 shows a plot of the data in Table B3. Note that the horizontal axis is an index only.

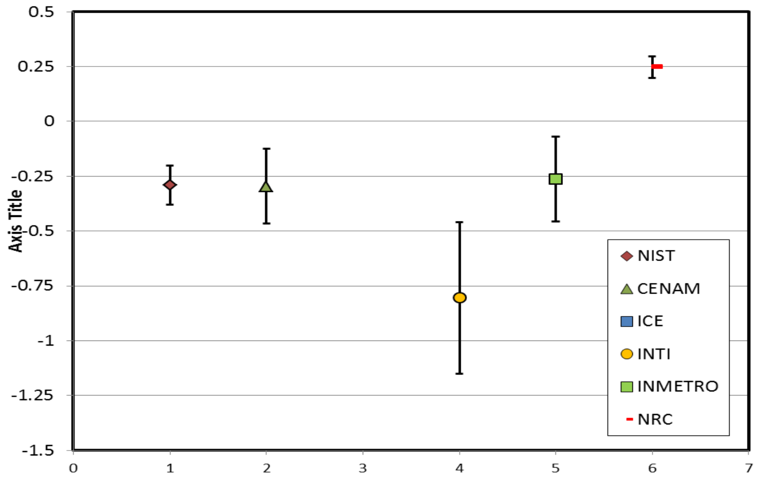

Fig. B2. 10 pF 1600 Hz degree of equivalence of all laboratories with respect to the CRV.

2. SIM.EM-S4 100 pF

a. 1 kHz results

The 1000 Hz capacitance drift of the traveling standard, in µF/F, was determined from pilot laboratory measurements using a linear fit, $X_{ik} = \hat{\alpha}_1 + \hat{\beta}(t_{1k} - t_{init})$, where from (A.3) $\hat{\beta}$ = 0.162, $\hat{\alpha}_1$ = 1.387, and t_{init} = 2003.907. The comparison reference value (CRV) as a deviation from the nominal value of 100 pF, is 1.737 µF/F, with a standard uncertainty of 0.065 µF/F. The optimal time for the CRV, is t = 2005.485. Statistics are computed according to reference [1].

The degree of equivalence of all laboratories with respect to the CRV for 1000 Hz is shown in Table B5 and the pair-wise degree of equivalence and their standard uncertainties are given in Table B6. Note that for Tables B5 and B6, the degree of equivalence and their standard uncertainties are given in µF/F. Fig. B3 shows a plot of the data in Table B5.

Table B5. 1000 Hz degree of equivalence of all laboratories with respect to the CRV.

Laboratory	Degree of Equivalence	Standard Uncertainty of Degree of Equivalence
NIST	-0.095	0.079
CENAM	-0.619	0.179
ICE	-610.6	19000

INTI	0.016	0.496
UTE	-2.94	3.30
INMETRO	-0.078	0.189
NRC	0.345	0.089

Table B6. Pair-wise 1000 Hz degree of equivalence with standard uncertainties in parentheses.

	NIST	CENAM	ICE	INTI	UTE	INMETRO	NRC
NIST		0.524 (0.216)	601.5 (19000)	-0.112 (0.510)	2.847 (3.30)	-0.0172 (0.225)	-0.440 (0.151)
CENAM	-0.524 (0.216)		601.0 (19000)	-0.635 (0.535)	2.323 (3.31)	-0.541 (0.276)	-0.964 (0.221)
ICE	-601.5 (19000)	-601.0 (19000)		-601.6 (19000)	-598.7 (19000)	-601.5 (19000)	-602.0 (19000)
INTI	0.112 (0.510)	0.635 (0.535)	601.6 (19000)		2.959 (3.34)	0.0943 (0.539)	-0.328 (0.512)
UTE	-2.847 (3.302)	-2.323 (3.305)	598.7 (19000)	-2.959 (3.338)		-2.864 (3.306)	-3.287 (3.302)
INMETRO	0.0172 (0.225)	0.541 (0.276)	601.5 (19000)	-0.0943 (0.539)	2.864 (3.31)		-0.423 (0.228)
NRC	0.440 (0.151)	0.964 (0.221)	602.0 (19000)	0.328 (0.512)	3.287 (3.302)	0.423 (0.228)	

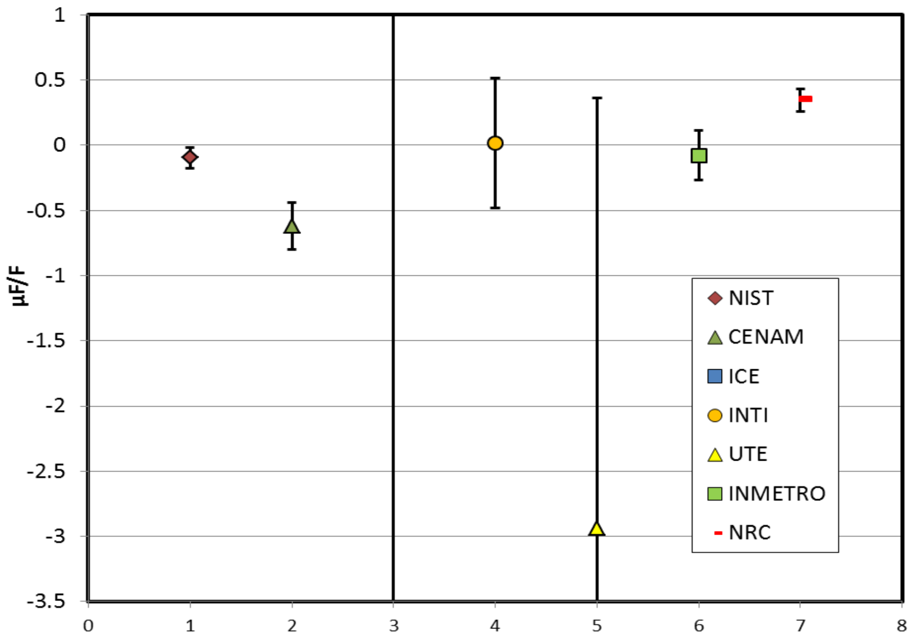

Fig. B3. 100 pF 1000 Hz degree of equivalence of all laboratories with respect to the CRV.

b. 1.6 kHz results

The 1600 Hz capacitance drift of the traveling standard, in μF/F, was determined from pilot laboratory measurements using a linear fit, $X_{ik} = \hat{\alpha}_1 + \hat{\beta}(t_{1k} - t_{init})$, where from (A.3) $\hat{\beta}$ = 0.147, $\hat{\alpha}_1$ = 1.372, and t_{init} = 2003.896. The comparison reference value (CRV) as a deviation from the nominal value of 100 pF, is 1.811 μF/F, with a standard uncertainty of 0.062 μF/F. The optimal t = 2005.545.

The degree of equivalence of all laboratories with respect to the CRV for 1000 Hz is shown in Table B7 and the pair-wise degree of equivalence and their standard uncertainties are given in Table B8. Note that for Tables B7 and B8 the degree of equivalence and corresponding standard uncertainties are given in units of µF/F. Fig. B4 shows a plot of the data in Table B7. The horizontal axis is an index only.

Table B7. 1600 Hz degree of equivalence of all laboratories with respect to the CRV.

Laboratory	Degree of Equivalence	Standard Uncertainty of Degree of Equivalence
NIST	-0.212	0.069
CENAM	-0.302	0.183
ICE	-102	19000
INTI	-1.20	0.446
INMETRO	-0.195	0.190
NRC	0.537	0.096

Table B8. Pair-wise 1600 Hz degree of equivalence with standard uncertainties in parentheses.

	NIST	CENAM	ICE	INTI	INMETRO	NRC
NIST		0.0902 (0.212)	101.5 (19000)	0.986 (0.459)	-0.0165 (0.221)	-0.749 (0.150)
CENAM	-0.0902 (0.212)		101.4 (19000)	0.896 (0.489)	-0.107 (0.280)	-0.839 (0.229)
ICE	-101.5 (19000)	-101.4 (19000)		-100.5 (19000)	-101.5 (19000)	-102.3 (19000)
INTI	-0.986 (0.459)	-0.896 (0.489)	100.5 (19000)		-1.003 (0.493)	-1.735 (0.465)
INMETRO	0.0165 (0.221)	0.107 (0.280)	101.5 (19000)	1.003 (0.493)		-0.732 (0.229)
NRC	0.749 (0.150)	0.839 (0.229)	102.3 (19000)	1.735 (0.465)	0.732 (0.229)	

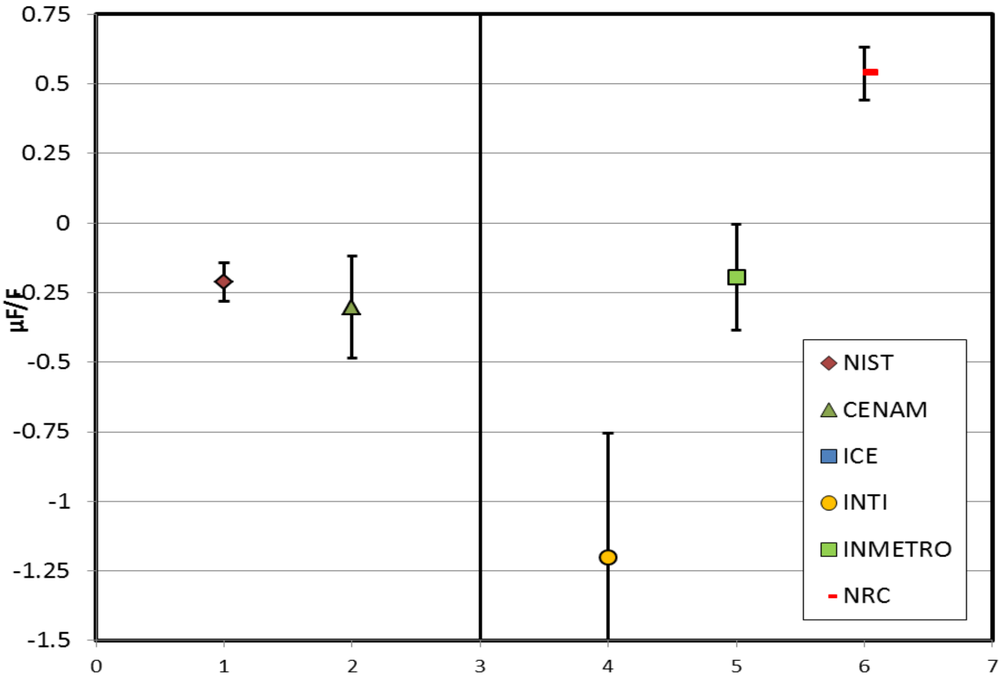

Fig. B4. 100 pF 1600 Hz degree of equivalence of all laboratories with respect to the CRV.

3. SIM.EM-S3 1000 pF

a. 1 kHz results

The 1000 Hz capacitance drift of the traveling standard, in µF/F, was determined from pilot laboratory measurements using a linear fit, $X_{ik} = \hat{\alpha}_1 + \hat{\beta}(t_{1k} - t_{init})$, where from (A.3) $\hat{\beta}$ = 0.584, $\hat{\alpha}_1$ = 26.369, and t_{init} = 2003.893. The comparison reference value (CRV) as a deviation from the nominal value of 1000 pF, is 24.997 µF/F, with a standard uncertainty of 0.125 µF/F. The optimal time, t, for the CRV, is t = 2005.468. Statistics are computed according to reference [1].

The degree of equivalence of all laboratories with respect to the CRV for 1000 Hz is shown in Table B9 and the pair-wise degree of equivalence and their standard uncertainties are given in Table B10. Note that for Tables B9 and B10, the degree of equivalence and their standard uncertainties are given in µF/F. Fig. B5 shows a plot of the data in Table B9. The horizontal axis is an index only and is not chronological.

Table B9. 1000 Hz degree of equivalence of all laboratories with respect to the CRV.

Laboratory	Degree of Equivalence	Standard Uncertainty of Degree of Equivalence
NIST	2.292	0.412
CENAM	1.197	0.377
ICE	-244.6	1800
INTI	1.148	0.895

UTE	-0.570	6.299
INMETRO	0.285	0.174
NRC	-2.562	0.322

Table B10. Pair-wise 1000 Hz degree of equivalence with standard uncertainties in parentheses.

	NIST	CENAM	ICE	INTI	UTE	INMETRO	NRC
NIST		1.095 (0.522)	246.9 (1800)	1.148 (0.992)	2.862 (6.32)	2.007 (0.498)	4.854 (0.599)
CENAM	-1.095 (0.522)		245.8 (1800)	0.0532 (0.961)	1.767 (6.31)	0.9120 (0.501)	3.759 (0.651)
ICE	-246.9 (1800)	-245.8 (1800)		-245.7 (1800)	-244.0 (1800)	-244.9 (1800)	-242.0 (1800)
INTI	-1.148 (0.992)	-0.0532 (0.961)	245.7 (1800)		1.714 (6.36)	0.8587 (0.936)	3.706 (0.988)
UTE	-2.862 (6.32)	-1.767 (6.31)	244.0 (1800)	-1.714 (6.36)		-0.8548 (6.30)	1.992 (6.31)
INMETRO	-2.007 (0.498)	-0.912 (0.501)	244.9 (1800)	-0.8587 (0.936)	0.8548 (6.30)		2.847 (0.359)
NRC	-4.854 (0.598)	-3.759 (0.651)	242.0 (1800)	-3.706 (0.988)	-1.992 (6.31)	-2.847 (0.359)	

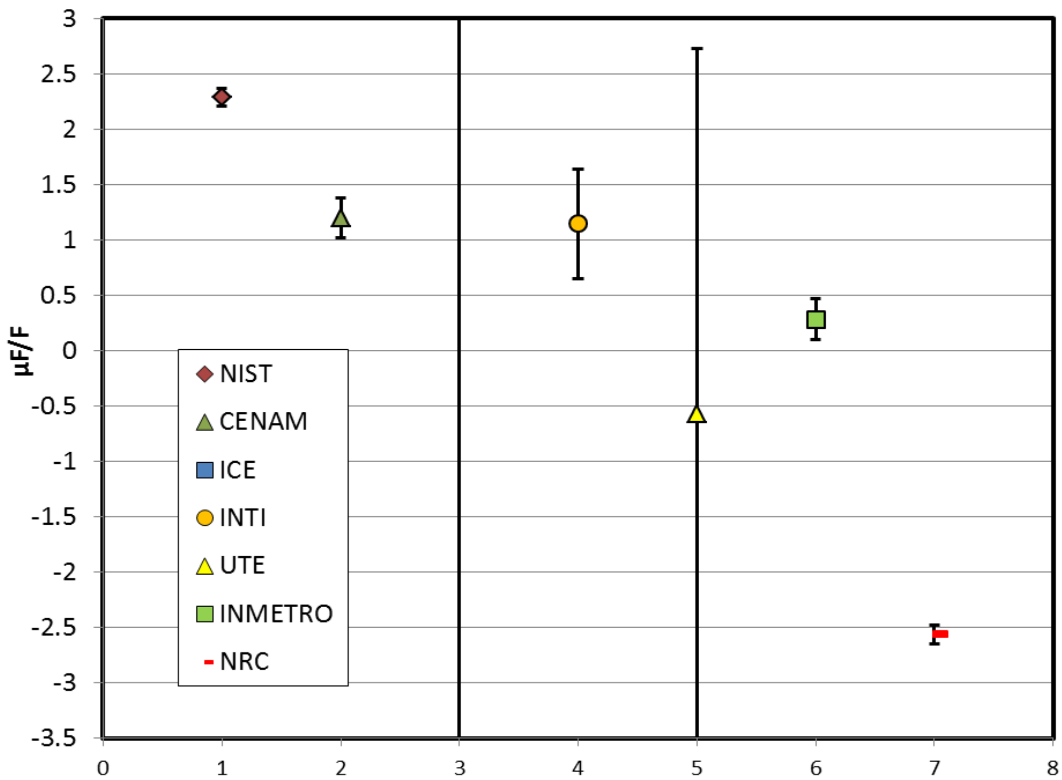

Fig. B5. 1000 pF 1000 Hz degree of equivalence of all laboratories with respect to the CRV.

Appendix C. Uncertainty Budgets for 10 pF

1. INTI

The INTI traceability is derived through a capacitance calibration from PTB, Germany.

Table C1. INTI 10 pF 1000 Hz Uncertainty Budget

Component	**Uncertainty (µF/F)**
Reference capacitor uncertainty	0.4
Short-term stability	0.01
1:1 comparison uncertainty	0.03
Combined standard uncertainty	0.4

Table C2. INTI 10 pF 1600 Hz Uncertainty Budget

Component	**Uncertainty (µF/F)**
Reference capacitor uncertainty	0.35
Short-term stability	0.0082
1:1 comparison uncertainty	0.03
Combined standard uncertainty	0.35

2. INMETRO

The INMETRO traceability is derived through a calibration from the Bureau International des Poids et Mesures (BIPM).

Table C3. INMETRO 10 pF 1000 Hz Uncertainty Budget

Quantity	**Standard uncertainty**	**Sensitivity coefficient**	**Type**
C_N (1)	5.0E-07 pF	1	Type B
$\Delta\alpha$	3.72E-06	1.00E-02 pF	Type A
$\Delta\beta$	4.90E-07	1.80E-05 pF	Type A
C	5E-08 pF	6.63E-05	Type B
C'	0.0018 pF	2.60E-07	Type B
ν	0.1	6.63E-07 pF	Type B
ε_R	1E-08 pF	1	Type B
$C_X \sim C_N$ (2)	8E-08 pF	1	Combined
Error (3)	1.0E-07 pF	1	Type B
C_X (4)	5.2E-07 pF	1	Combined
R_{K-90} (5)	1.00E-06 pF	1	Type B
Biannual Drift (6)	1.00E-06 pF	1	Type A
C_X (7)	0.0000020 pF		Combined

Table C4. INMETRO 10 pF 1600 Hz Uncertainty Budget

Quantity	**Standard uncertainty**	**Sensitivity coefficient**	**Type**
C_N (1)	4.0E-07 pF	1	Type B
$\Delta\alpha$	3.16E-06	1.00E-02 pF	Type A
$\Delta\beta$	7.48E-07	8.00E-06 pF	Type A
C	4E-08 pF	6.56E-05	Type B
$\boldsymbol{C'}$	0.0008 pF	8.00E-07	Type B
ν	0.1	6.56E-07 pF	Type B
ε_R	1E-08 pF	1	Type B
C_X C_N (2)	7E-08 pF	1	Combined
Error (3)	1.50E-07 pF	1	Type B
C_X (4)	4.3E-07 pF	1	Combined
R_{K-90} (5)	1.00E-06 pF	1	Type B
Biannual Drift (6)	1.00E-06 pF	1	Type A
C_X (7)	0.0000020 pF		Combined

(1) Relative combined standard uncertainty reported in the BIPM calibration certificate. This does not include the standard uncertainty associated with the recommended value of R_{K-90}.
(2) Combined standard uncertainty associated with the difference between the capacitances of the standards being compared. This uncertainty contribution is only due to the capacitance bridge.
(3) Systematic error of unknown origin that is detected when comparing several standards for consistency in the results.
(4) Combined standard uncertainty associated with C_X without taking into account the uncertainty contributions associated with R_{K-90} and the reference standard biannual drift.
(5) Standard uncertainty associated with the recommended value of R_{K-90}.
(6) Drift evaluated by linear fit to data reported in BIPM calibration certificates in the last six years.
(7) Combined standard uncertainty for C_X taking into account all known uncertainty contributions.

3. NRC

Table C5. NRC 10 pF 1000 Hz Uncertainty Budget

Quantity	**Type**	**Uncertainty (μF/F)**	**Prob Dist/ Method of Eval (A/B)**	**Sensitivity Coefficient c_i**	**Standard uncertainty (μF/F)**	**Degrees of freedom**
Reference Standard	Combined	0.078	Nor/AB	1	0.078	15.0
Test Standard	Type A	0.005	Nor/A	1	0.005	9.0
Voltage Dependence	Type B	0.000	Nor/B	1	0.000	4.9
Frequency Dependence	Type B	0.000	Nor/B	1	0.000	4.9
Meter Nonlinearity	Type B	0.004	1	1	0.004	4.9
Loading and Cable Corr.	Type B	0.005	0	1	0.000	4.9
Combined					0.079	15.2

The NRC capacitance reference is derived from infrequent comparisons to various calculable capacitors (National Institute of Standards and Technology, National Measurement Institute of Australia).

Table C6. NRC 10 pF 1600 Hz Uncertainty Budget

Quantity	**Type**	**Uncertainty (µF/F)**	**Sensitivity coefficient**	**Sensitivity factor**	**Standard uncertainty (µF/F)**	**Degrees of freedom**
Reference Standard	Combined	0.068	1	1	0.068	10.5
Test Standard	Type A	0.005	1	1	0.005	9.0
Voltage Dependence	Type B	0.000	1	1	0.000	4.9
Frequency Dependence	Type B	0.000	1	1	0.000	4.9
10:1 Ratio	Type B	0.000	1	1	0.000	4.9
Meter Nonlinearity	Type B	0.004	1	1	0.004	4.9
Other	Type B	0.005	0	1	0.000	4.9
Combined					0.069	10.6

4. ICE

ICE measurement traceability is maintained through manufacturer calibration of the QuadTech model 1413 decade capacitor.

Table C7. ICE 10 pF 1000 Hz Uncertainty Budget

Component	**Uncertainty (µF/F)**
Type B	90900
Type A	155000
Combined standard uncertainty	180000

Table C8. ICE 10 pF 1600 Hz Uncertainty Budget

Component	**Uncertainty (µF/F)**
Type B	90900
Type A	155000
Combined standard uncertainty	180000

5. CENAM

The CENAM traceability is derived through a calibration from the Bureau International des Poids et Mesures (BIPM).

Table C9. CENAM 10 pF 1000 Hz Uncertainty Budget

Uncertainty Component	**Estimate x_i**	**Relative Standard Uncertainty $u(x_i)$ (μF/F)**	**Probability Distribution / Method of Evaluation (A,B)**	**Sensitivity Coefficient c_i**	**Uncertainty Contribution ui (c_X) (μF/F)**	Degrees of Freedom ν_i
Reference Standard Value	10 pF + 23,0 aF	0.115	Normal	1	0,115	60
Reference Standard Long Term Stability	---	0.085	Normal	1.5	0,128	60
Test Standard	---	0.010	Normal	1	0,010	16
Voltage Dependence	---	0.005	Normal	1	0,005	60
Frequency Dependence	---	---	---	---	---	---
Capacitance Bridge	-3,06 aF	0.011	Normal	1	0,011	60
Cables Correction	---	0.001	Normal	1	0,001	60
C_X	**10 pF + 19.9 aF**				**0.17**	120

Table C10. CENAM 10 pF 1600 Hz Uncertainty Budget

Uncertainty Component	**Estimate x_i**	**Relative Standard Uncertainty $u(x_i)$ (μF/F)**	**Probability Distribution / Method of Evaluation (A,B)**	**Sensitivity Coefficient c_i**	**Uncertainty Contribution ui (c_X) (μF/F)**	Degrees of Freedom ν_i
Reference Standard Value	10 pF + 22,5 aF	0.115	Normal	1	0.115	60
Reference Standard Long Term Stability	---	0.085	Normal	1.5	0.128	60
Test Standard	---	0.010	Normal	1	0.010	16
Voltage Dependence	---	0.005	Normal	1	0.005	60
Frequency Dependence	---	---	---	---	---	---
Capacitance Bridge	-3,06 aF	0.011	Normal	1	0.011	60
Cables Correction	---	0.001	Normal	1	0.001	60
C_X	**10 pF + 19.9 aF**				**0.17**	120

6. NIST

The NIST traceability is independently derived from the NIST Calculable Capacitor through the NIST farad bank of four 10 pF primary capacitors.

Table C11. 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
Test Variation	Type A	0.030
Combined		0.123

Table C12. NIST AH Bridge 10 pF 1600 Hz Uncertainty Budget

Quantity	**Type**	**Standard uncertainty (μF/F)**
Reference Standard	Type B	0.020
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	0.010
Test Variation	Type A	0.030
Combined		0.114

Table C13. NIST 2-Pair Bridge 10 pF 1592 Hz Uncertainty Budget

Quantity	**Type**	**Standard uncertainty (μF/F)**
Calculable Capacitor	Type B	0.019
Transformer Bridge	Type B	0.005
10 pF Correction Calculation	Type B	0.002
Test Variation	Type A	0.002
Combined		0.020

7. UTE

The UTE capacitance traceability is derived from a 10 kΩ resistance standard calibrated against the Quantum Hall Resistance at PTB, Germany.

Table C14. UTE 10 pF 1000 Hz Uncertainty Budget

Uncertainty Component	Standard Uncertainty $u(x_i)$		Probability Distribution	Sensitivity coefficient c_i		Uncertainty contribution $u_i(y)$ k=1	
Capacitance dispersion	1.68E-6	pF	6	1		1.7E-6	pF
Test current (I)	3.05E-11	A	Rectangular	-5,71E-11	F/A	-1.7E-9	pF
Reference standard (C_2)	3.32E-4	pF	Normal	1,00E-1	F/F	3.3E-5	pF
Detector current angle (α)	5.03E-2	rad	Rectangular	-1,13E-16	F	-5.7E-6	pF
Detector current amplitude (I_d)	4.62E-14	A	Rectangular	4,88E-06	F/A	2.3E-7	pF
IVD deviation (ε)	5.00E-07	V/V	Normal	1,10E-11	F	5.5E-6	pF
Combined						**3.4E-5**	**pF**

Appendix D. Uncertainty Budgets for 100 pF

1. INTI

The INTI traceability is derived through a capacitance calibration from PTB, Germany.

Table D1. INTI 100 pF 1000 Hz Uncertainty Budget

Component	**Uncertainty (µF/F)**
Reference capacitor uncertainty	0.5
Short-term stability	0.012
1:1 comparison uncertainty	0.03
Combined standard uncertainty	0.5

Table D2. INTI 100 pF 1600 Hz Uncertainty Budget

Component	**Uncertainty (µF/F)**
Reference capacitor uncertainty	0.45
Short-term stability	0.015
1:1 comparison uncertainty	0.03
Combined standard uncertainty	0.45

2. INMETRO

The INMETRO traceability is derived through a calibration from the Bureau International des Poids et Mesures (BIPM).

Table D3. INMETRO 100 pF 1000 Hz Uncertainty Budget

Quantity	**Standard uncertainty**	**Sensitivity coefficient**	**Type**
C_N (1)	5.0E-06 pF	1	Type B
$\Delta\alpha$	2.24E-05	1.00E-02 pF	Type A
$\Delta\beta$	2.56E-06	1.80E-05 pF	Type A
C	5E-08 pF	6.15E-04	Type B
C'	0.0018 pF	5.80E-06	Type B
ν	0.1	6.15E-06 pF	Type B
ε_R	1E-08 pF	1	Type B
C_X ~ C_N (2)	7E-07 pF	1	Combined
Error (3)	1.0E-06 pF	1	Type B
C_X (4)	5.1E-06 pF	1	Combined
R_{K-90} (5)	1.00E-05 pF	1	Type B
Biannual Drift (6)	1.00E-05 pF	1	Type A
	0.000020 pF		Combined

Table D4. INMETRO 100 pF 1600 Hz Uncertainty Budget

Quantity	**Standard uncertainty**	**Sensitivity coefficient**	**Type**
C_N (1)	4.0E-06 pF	1	Type B
$\Delta\alpha$	2.24E-05	1.00E-02 pF	Type A
$\Delta\beta$	4.54E-06	8.00E-06 pF	Type A
C	4E-08 pF	6.14E-04	Type B
C'	0.0008 pF	8.94E-06	Type B
ν	0.1	6.14E-06 pF	Type B
ε_R	1E-08 pF	1	Type B
C_X ~ C_N (2)	7E-07 pF	1	Combined
Error (3)	1.50E-06 pF	1	Type B
C_X (4)	4.3E-06 pF	1	Combined
R_{K-90} (5)	1.00E-05 pF	1	Type B
Biannual Drift (6)	1.00E-05 pF	1	Type A
C_X (7)	0.000020 pF		Combined

(1) Relative combined standard uncertainty reported in the BIPM calibration certificate. This does not include the standard uncertainty associated with the recommended value of R_{K-90}.
(2) Combined standard uncertainty associated with the difference between the capacitances of the standards being compared. This uncertainty contribution is only due to the capacitance bridge.
(3) Systematic error of unknown origin that is detected when comparing several standards for consistency in the results.
(4) Combined standard uncertainty associated with C_X without taking into account the uncertainty contributions associated with R_{K-90} and the reference standard biannual drift.
(5) Standard uncertainty associated with the recommended value of R_{K-90}.
(6) Drift evaluated by linear fit to data reported in BIPM calibration certificates in the last six years.
(7) Combined standard uncertainty for C_X taking into account all known uncertainty contributions.

3. NRC

Table D5. NRC 100 pF 1000 Hz Uncertainty Budget

Quantity	**Type**	**Uncertainty (µF/F)**	**Sensitivity coefficient**	**Sensitivity factor**	**Standard uncertainty (µF/F)**	**Degrees of freedom**
Reference Standard	Combined	0.100	1	1	0.100	14.2
Test Standard	Type A	0.002	1	1	0.002	9.0
Voltage Dependence	Type B	0.000	1	1	0.000	4.9
Frequency Dependence	Type B	0.000	1	1	0.000	4.9
10:1 Ratio	Type B	0.000	1	1	0.000	4.9
Meter Nonlinearity	Type B	0.040	1	1	0.040	4.9
Other	Type B	0.004	0	1	0.000	4.9
Combined					0.11	17.8

The NRC capacitance reference is derived from infrequent comparisons to various calculable capacitors (National Institute of Standards and Technology, National Measurement Institute of Australia).

Table D6. NRC 100 pF 1600 Hz Uncertainty Budget

Quantity	**Type**	**Uncertainty (µF/F)**	**Sensitivity coefficient**	**Sensitivity factor**	**Standard uncertainty (µF/F)**	**Degrees of freedom**
Reference Standard	Combined	0.100	1	1	0.100	14.2
Test Standard	Type A	0.002	1	1	0.002	9.0
Voltage Dependence	Type B	0.000	1	1	0.000	4.9
Frequency Dependence	Type B	0.000	1	1	0.000	4.9
10:1 Ratio	Type B	0.000	1	1	0.000	4.9
Meter Nonlinearity	Type B	0.040	1	1	0.040	4.9
Other	Type B	0.018	0	1	0.000	4.9
Combined					0.11	17.8

4. ICE

ICE measurement traceability is maintained through manufacturer calibration of the QuadTech model 1413 decade capacitor.

Table D7. ICE 100 pF 1000 Hz Uncertainty Budget

Component	**Uncertainty (µF/F)**
Type B	9090
Type A	16600
Combined standard uncertainty	19000

Table D8. ICE 100 pF 1600 Hz Uncertainty Budget

Component	**Uncertainty (µF/F)**
Type B	9090
Type A	16600
Combined standard uncertainty	19000

5. CENAM

The CENAM traceability is derived through a calibration from the Bureau International des Poids et Mesures (BIPM).

Table D9. CENAM 100 pF 1000 Hz Uncertainty Budget

Uncertainty Component	**Relative Standard Uncertainty $u(x_i)$ (µF/F)**	**Probability Distribution / Method of Evaluation (A,B)**	**Sensitivity Coefficient c_i**	**Uncertainty Contribution ui (c_X) (µF/F)**	Degrees of Freedom ν_i
Reference Standard Value	0,115	Normal	10	0,115	60
Reference Standard Long Term Stability	0,0085	Normal	15	0,128	60
Test Standard	0,007	Normal	1	0,007	16
Voltage Dependence	0,0005	Normal	10	0,005	60
Frequency Dependence	---	---	---	---	---
Capacitance Bridge	0,079	Normal	1	0,079	60
Cables Correction	0,001	Normal	1	0,001	60
				0.19	160

Table D10. CENAM 100 pF 1600 Hz Uncertainty Budget

Uncertainty Component	**Relative Standard Uncertainty $u(x_i)$ (µF/F)**	**Probability Distribution / Method of Evaluation (A,B)**	**Sensitivity Coefficient c_i**	**Uncertainty Contribution ui (c_X) (µF/F)**	Degrees of Freedom ν_i
Reference Standard Value	0,0115	Normal	10	0,115	60
Reference Standard Long Term Stability	0,0085	Normal	15	0,128	60
Test Standard	0,005	Normal	1	0,005	16
Voltage Dependence	0,0005	Normal	10	0,005	60
Frequency Dependence	0.0001	Normal	10	0.001	60
Capacitance Bridge	0,073	Normal	1	0,073	60
Cables Correction	0,001	Normal	1	0,001	60
				0.19	156

6. NIST

The NIST traceability is independently derived from the NIST Calculable Capacitor through the NIST farad bank of four 10 pF primary capacitors.

Table D11. NIST AH Bridge 100 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
Test Variation	Type A	0.030
Combined		0.105

Table D12. NIST AH Bridge 100 pF 1600 Hz Uncertainty Budget

Quantity	**Type**	**Standard uncertainty (µF/F)**
Reference Standard	Type B	0.020
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	0.010
Test Variation	Type A	0.030
Combined		0.095

Table D13. NIST 2-Pair Bridge 100 pF 1592 Hz Uncertainty Budget

Quantity	**Type**	**Standard uncertainty (µF/F)**
Calculable Capacitor	Type B	0.019
Transformer Bridge	Type B	0.005
10 pF Correction Calculation	Type B	0.002
10:1 Ratio	Type B	0.005
Test Variation	Type A	0.002
Combined		0.020

7. UTE

The UTE capacitance traceability is derived from a 10 kΩ resistance standard calibrated against the Quantum Hall Resistance at PTB, Germany.

Table D14. UTE 100 pF 1000 Hz Uncertainty Budget

Uncertainty Component	Standard Uncertainty $u(x_i)$		Probability Distribution	Sensitivity coefficient c_i		Uncertainty contribution $u_i(y)$ k=1	
Capacitance dispersion	2,2E-5	pF	6	1		2,2E-5	pF
Test current (I)	1,39E-10	A	Rectangular	8,8E-10	F/A	1,2E-7	pF
Reference standard (C_2)	3,10E-3	pF	Normal	1,00E-1	F/F	3,1E-4	pF
Detector current angle (α)	5,04E-2	rad	Rectangular	-1,80E-15	F	-9,1E-5	pF
Detector current amplitude (I_d)	4,62E-13	A	Rectangular	-3,20E-05	F/A	-1,5E-5	pF
IVD deviation (ε)	5,00E-07	V/V	Normal	1,10E-10	F	5,5E-5	pF
Combined						**3,3E-4**	**pF**

Appendix E. Uncertainty Budgets for 1000 pF

1. INTI

The INTI traceability is derived through a capacitance calibration from PTB, Germany.

Table E1. INTI 1000 pF 1000 Hz Uncertainty Budget

Component	Uncertainty (µF/F)
Reference capacitor uncertainty	0.5
Short-term stability	0.06
10:1 comparison uncertainty	0.7
Combined standard uncertainty	0.9

2. INMETRO

The INMETRO traceability is derived through a calibration from the Bureau International des Poids et Mesures (BIPM).

Table E2. INMETRO 1000 pF 1000 Hz Uncertainty Budget

Quantity	Standard uncertainty	Sensitivity coefficient	Type
C_N (1)	5.0E-06 pF	1	Type B
$\Delta\alpha$	9.75E-05	1.00E-01 pF	Type A
ν	0.11	2.56E-04 pF	Type B
k'	7.00E-09	-1.21E+04 pF	Type B
C_X (2)	1.03E-04 pF	1	Combined
R_{K-90} (3)	1.00E-05 pF	1	Type B
Biannual Drift (4)	1.00E-04 pF	1	Type A
C_X (5)	0.00020 pF		Combined

(1) Relative combined standard uncertainty reported in the BIPM calibration certificate. This does not include the standard uncertainty associated with the recommended value of R_{K-90}.
(2) Combined standard uncertainty associated with C_X without taking into account the uncertainty contributions associated with R_{K-90} and the reference standard biannual drift.
(3) Standard uncertainty associated with the recommended value of R_{K-90}.
(4) Drift evaluated by linear fit to data reported in BIPM calibration certificates in the last six years.
(5) Combined standard uncertainty for C_X taking into account all known uncertainty contributions.

3. NRC

The NRC capacitance reference is derived from infrequent comparisons to various calculable capacitors (National Institute of Standards and Technology, National Measurement Institute of Australia).

Table E3. NRC 1000 pF 1000 Hz Uncertainty Budget

Quantity	**Type**	**Uncertainty (µF/F)**	**Sensitivity coefficient**	**Sensitivity factor**	**Standard uncertainty (µF/F)**	**Degrees of freedom**
Reference Standard	Combined	0.100	1	1	0.130	22.5
Test Standard	Type A	0.002	1	1	0.003	9.0
Voltage Dependence	Type B	0.000	1	1	0.000	4.9
Frequency Dependence	Type B	0.000	1	1	0.000	4.9
10:1 Ratio	Type B	0.000	1	1	0.000	4.9
Meter Nonlinearity	Type B	0.040	1	1	0.010	4.9
Other	Type B	0.004	0	1	0.022	4.9
Combined					0.13	22.8

4. ICE

ICE measurement traceability is maintained through manufacturer calibration of the QuadTech model 1413 decade capacitor.

Table E4. ICE 1000 pF 1000 Hz Uncertainty Budget

Component	**Uncertainty (µF/F)**
Type B	909
Type A	1550
Combined standard uncertainty	1800

5. CENAM

The CENAM traceability is derived through a calibration from the Bureau International des Poids et Mesures (BIPM).

Table E5. CENAM 1000 pF 1000 Hz Uncertainty Budget

Uncertainty Component	**Relative Standard Uncertainty $u(x_i)$ (µF/F)**	**Probability Distribution / Method of Evaluation (A,B)**	**Sensitivity Coefficient c_i**	**Uncertainty Contribution ui (c_X) (µF/F)**	Degrees of Freedom ν_i
Reference Standard Value	0,0189	Normal	10	0,189	60
Test Standard	0,018	Normal	1	0,018	16
Voltage Dependence	0,0052	Normal	10	0,052	60
Frequency Dependence	---	---	---	---	---
Capacitance Bridge (ratio 10:1)	0,089	Normal	1	0,089	60
Cables Correction	0,002	Normal	1	0,002	60
Temperature Correction	0,128	Uniform	1	0,128	1000
				0,25	175

6. NIST

The NIST traceability is independently derived from the NIST Calculable Capacitor through the NIST farad bank of four 10 pF primary capacitors.

Table E6. NIST AH Bridge 1000 pF 1000 Hz Uncertainty Budget

Quantity	**Type**	**Standard uncertainty (µF/F)**
Reference Standard	Type B	0.05
Reference Drift	Type B	0.03
10:1 Ratio	Type B	0.10
Test Drift	Type B	0.03
Bridge Thermal	Type B	0.05
Bridge Mechanical	Type B	0.05
Bridge Linearity	Type B	0.20
Bridge Loading	Type B	0.00
Test Variation	Type A	0.75
Combined		0.79

7. UTE

The UTE capacitance traceability is derived from a 10 kΩ resistance standard calibrated against the Quantum Hall Resistance at PTB, Germany.

Table E7. UTE 1000 pF 1000 Hz Uncertainty Budget

Uncertainty Component	Standard Uncertainty $u(x_i)$		Probability Distribution	Sensitivity coefficient c_i		Uncertainty contribution $u_i(y)$ k=1	
Ratio dispersion (r)	1.68E-6	pF	2,88E-05	V/V	9	-69	pF
Reference standard (R)	3.05E-11	A	2,15E-02	Ω	Normal	-0,092	pF/Ω
Voltmeter ratio (r)	3.32E-4	pF	1,92E-05	V/V	Normal	-69	pF
Frequency (f)	5.03E-2	rad	5,00E-04	Hz	Normal	-1,00	pF/Hz
Combined						**3,1E-3**	**pF**

Appendix F. CCEM-K4 10 pF Capacitance Linkage Analysis and Results

Data for Tables F1, and F2 are taken from [2], the CCEM-K4 Final Report of March 2001, Tables 5 and 6, respectively. The CCEM-K4 comparison evaluated a 10 pF capacitance standard at 1.592 kHz. Herein we presume equivalence between capacitance at 1.592 kHz and at 1.6 kHz. For the CCEM-K4 and SIM.EM-K4 Comparisons, there are two linking laboratories: NIST and NRC.

Table F1. 10 pF 1600 Hz degree of equivalence relative to the CCEM-K4 KCRV, with corresponding standard uncertainties (µF/F).

Laboratory	Degree of Equivalence	Standard Uncertainty of Degree of Equivalence
BIPM	-0.018	0.050
BNM-LCIE	-0.216	0.043
CSIRO-NML	0.035	0.039
MSL	-0.026	0.064
NIM	-0.04	0.132
NIST (pilot)	-0.003	0.022
NMi	-0.772	0.600
NPL	0.198	0.056
NRC	0.037	0.161
PTB	-0.004	0.049
VNIIM	-0.318	0.201

Table F2. 10 pF 1600 Hz pairwise degrees of equivalence for CCEM-K4 (above diagonal) and corresponding standard uncertainties (below diagonal), all in µF/F.

	BIPM	BNM-LCIE	CSIRO-NML	MSL	NIM	NIST	NMi	NPL	NRC	PTB	VNIIM
BIPM		0.20	-0.05	0.01	0.02	-0.02	0.75	-0.22	-0.06	-0.01	0.30
BNM-LCIE	0.13		-0.25	-0.19	-0.18	-0.21	0.56	-0.41	-0.25	-0.21	0.10
CSIRO-NML	0.13	0.12		0.06	0.08	0.04	0.81	-0.16	0.00	0.04	0.35
MSL	0.16	0.15	0.15		0.01	-0.02	0.74	-0.22	-0.06	-0.02	0.29
NIM	0.28	0.28	0.27	0.29		-0.04	0.73	-0.24	-0.08	-0.04	0.28
NIST	0.11	0.10	0.09	0.13	0.27		0.77	-0.20	-0.04	0.00	0.32
NMi	1.20	1.20	1.20	1.21	1.23	1.20		-0.97	-0.81	-0.77	-0.45
NPL	0.15	0.14	0.14	0.17	0.29	0.12	1.21		0.16	0.20	0.52
NRC	0.34	0.33	0.33	0.35	0.42	0.33	1.24	0.34		0.04	0.36
PTB	0.15	0.14	0.13	0.17	0.28	0.12	1.20	0.16	0.34		0.31
VNIIM	0.41	0.41	0.41	0.42	0.48	0.40	1.27	0.42	0.52	0.42	

Linkage Analysis Results

The results of statistically linking the SIM.EM-K4 10 pF Comparison at 1600 Hz to the CCEM-K4 10 pF Comparison were calculated based on the statistical analysis in reference [5] and are listed below.

Of the six NMIs which participated in the SIM.EM-K4 10 pF 1600 Hz Comparison, two participated in the CCEM-K4 Comparison (NIST and NRC) and four did not participate (CENAM, ICE, INTI, and INMETRO).

As assumed in [5], each measurand of the CCEM-K4 10 pF Comparison and of the SIM.EM-K4 10 pF 1600 Hz Comparison has a linear trend. The linear trends are described by simple linear regression models as (A.1) and (A.2) in Appendix A. For each of the two comparisons, the CRV at the optimal time was obtained by (A.4) with its standard uncertainty given by (A.5) in Appendix A. In addition, for each of the two comparisons, the degree of equivalence of one laboratory with respect to the CRV is given by (A.6) in Appendix A. We assume that there are K linking laboratories. Without loss of generality, we assume that the K linking laboratories are the first K laboratories in both comparisons. In our case, there are two linking laboratories, i.e., NIST and NRC. Namely, K = 2. Using the same symbols in [5], we denote the degree of equivalence of the k^{th} linking laboratory with respect to the CRV in the first comparison by $D_{k,CRV}$ for the CCEM-K4 and $D'_{k,CRV'}$ for SIM.EM-K4 10 pF 1600 Hz Comparison. The difference between the two degrees of equivalence is given by

$$D_k = D_{k,\mathrm{KCRV}} - D'_{k,\mathrm{KCRV'}}. \qquad \text{(F.1)}$$

A weighted mean of D_k $(k = 1,...,K)$ is used to estimate the true value between the degrees of equivalence of the two comparisons. Namely,

$$\hat{D} = \sum_{k=1}^{K} \psi_k D_k \qquad \text{(F.2)}$$

with the weights given by

$$\psi_k = \frac{1/\mathrm{Var}[D_k]}{\sum_{j=1}^{K} 1/\mathrm{Var}[D_j]}. \qquad \text{(F.3)}$$

The quantity $\hat{D}$ is used to estimate the differences between the degrees of equivalence of two laboratories of which one only participated in the CCEM-K4 and the second one only participated in the SIM comparison or vice versa. The uncertainty of $\hat{D}$ is given by (22) in [5]. For the case of one laboratory only participated in the SIM comparison, we need to find the degree of equivalence of this laboratory with respect to the KCRV of the CCEM-K4 comparison. Because the mth laboratory only participated in the SIM comparison, $m > K$, we use the estimator below (denoted by $D^{\#}_{m,\mathrm{KCRV}}$) to estimate the degree of equivalence of the mth laboratory with respect to the KCRV for the CCEM-K4 comparison had this laboratory participated in the CCEM-K4 comparison,

$$D^{\#}_{m,\mathrm{KCRV}} = D'_{m,\mathrm{KCRV'}} + \hat{D} \qquad \text{(F.4)}$$

with the corresponding uncertainty given by (28) in [5]. In [5], the degrees of equivalence for any pair of two different laboratories in the two comparisons were determined as follows:

(1) For any two laboratories participating in the first comparison, i.e., the CCEM-K4 (regardless of whether they participated in the second comparisons, i.e., SIM comparison or not), their degrees of equivalence and the corresponding uncertainties are based on the results from the first comparison.

(2) If two laboratories participated only in the second comparison or one laboratory participated in both comparisons and the second one only participated in the second comparison, then their degree of equivalence is the corresponding one in the second comparison with its uncertainty.

(3) In the case that one laboratory only participated in the first comparison and the second laboratory only participated in the second comparison, the degree of equivalence between the nth laboratory $(n > K)$, which participated only in the first comparison and the mth laboratory $(m > K)$, which participated only in the second comparison, is estimated from (F.4) and given by

$$\begin{aligned} D^{\#}_{nm} &= D_{n,\mathrm{KCRV}} - D^{\#}_{m,\mathrm{KCRV}} \\ &= D_{n,\mathrm{KCRV}} - D^{'}_{m,\mathrm{KCRV'}} - \hat{D} \end{aligned} . \qquad \text{(F.5)}$$

The corresponding uncertainty is given by (30) and (31) in [5].

Table F3 lists the degree of equivalence of the four non-participating laboratories with respect to the CCEM-K4 key comparison reference value (KCRV) for CCEM-K4 based on (F.4). The four NMIs listed in Table F3 participated in the SIM.EM-K4 Comparison, but not in the CCEM K4 Comparison. Tables F4 and F5 provide the pair-wise degree of equivalence and uncertainty, respectively, based on (F.5), for the same four SIM NMIs. The degrees of equivalence and their uncertainties are given in µF/F.

Table F3. 1600 Hz degree of equivalence relative to the CCEM-K4 KCRV.

Laboratory	Degree of Equivalence	Standard Uncertainty of Degree of Equivalence
CENAM	-0.125	0.245
ICE	-2002	18000
INTI	-0.634	0.391
INMETRO	-0.091	0.265

Table F4. Pair-wise 10 pF 1600 Hz degree of equivalence.

	CENAM	ICE	INTI	INMETRO
BIPM	0.107	2002	0.616	0.073
BNM-LCIE	-0.091	2002	0.418	-0.125
CSIRO-NML	0.160	2002	0.669	0.126
MSL	0.099	2002	0.608	0.065
NIM	0.085	2002	0.594	0.051
NMi	-0.647	2001	-0.138	-0.681
NPL	0.323	2002	0.832	0.289
PTB	0.121	2002	0.630	0.087
VNIIM	-0.193	2002	0.316	-0.227

Table F5. Pair-wise 10 pF 1600 Hz standard uncertainties.

	CENAM	ICE	INTI	INMETRO
BIPM	0.035	18000	0.303	0.091
BNM-LCIE	0.024	18000	0.302	0.088
CSIRO-NML	0.016	18000	0.302	0.086
MSL	0.053	18000	0.306	0.010
NIM	0.127	18000	0.327	0.153
NMi	0.599	18000	0.670	0.605
NPL	0.043	18000	0.304	0.095
PTB	0.033	18000	0.303	0.091
VNIIM	0.198	18000	0.360	0.215

Appendix G. Corrective Actions and Results

Several participant laboratories provided post-comparison corrections to their comparison results. The corrections could not be included in the comparison results but are shown below.

CENAM

CENAM reported after the submission of their results that they had made a slight error in the computation of the 1 kHz results for the 100 pF and 1000 pF standards. These measurements required a 10:1 ratio factor with which an incorrect sign was used. The corrected results are given in Table G1.

Table G1. CENAM Corrective Results

Date	Nominal Value (pF)	Frequency (Hz)	Capacitance (pF)	Uncertainty (µF/F)
2004.571	100	1000	100.000140	0.38
2004.571	1000	1000	1000.02655	0.5

ICE

The ICE results were corrected based upon an improved calibration, performed by INMETRO in 2006, of the reference standards used by ICE in the comparison. The corrected results are shown in Table G2.

Table G2. ICE Corrective Results

Date	Nominal Value (pF)	Frequency (Hz)	Capacitance (pF)	Uncertainty (µF/F)
2004.787	10	1000	9.9958	44.2
2004.787	10	1600	9.9957	75.3
2004.787	100	1000	99.9832	6.3
2004.787	100	1600	99.9890	57.8
2004.787	1000	1000	999.954	4.3

INTI

The INTI results were corrected using an improved calibration from BIPM in 2008 of the reference standards used in the comparison. The corrected INTI results are shown in Table G3.

Table G3. INTI Corrective Results

Date	**Nominal Value (pF)**	**Frequency (Hz)**	**Capacitance (pF)**	**Uncertainty (µF/F)**
2005.219	10	1000	10.0000223	0.40
2005.219	10	1600	10.0000207	0.35
2005.219	100	1000	100.000143	0.50
2005.219	100	1600	100.000136	0.45
2005.227	1000	1000	1000.0257	0.9

NRC

The NRC results were corrected based upon an improved analysis using data from previous calibrations from other NMIs as well as from the CCEM-K4 report. The corrected data are shown in Table G4.

Table G4. NRC Corrective Results

Date	**Nominal Value (pF)**	**Frequency (Hz)**	**Capacitance (pF)**	**Uncertainty (µF/F)**
2005.219	10	1000	10.00002766	0.15
2005.219	10	1600	10.00002376	0.14
2006.159	100	1000	100.0002310	0.2
2006.159	100	1600	100.0001922	0.2
2006.159	1000	1000	1000.02262	0.25

Appendix H. List of Participants

Table H1. List of Participants

Organization	Country	Contact Person	E-mail	Shipping Address
NIST	United States	Andrew Koffman	andrew.koffman@nist.gov	NIST, 100 Bureau Drive, MS 8171, Gaithersburg, Maryland, 20899-8171 USA
NRC	Canada	Dave Inglis	Dave.Inglis@nrc-cnrc.gc.ca	National Research Council of Canada M-36, 1200 Montreal Road, Ottawa, Ontario K1A 0R6, Canada
CENAM	Mexico	Jose A Moreno	jmoreno@cenam.mx	CENAM, Queretaro, Mexico
ICE	Costa Rica	Harold Sanchez	hsanchez@ice.co.cr	Laboratorio Metrologico, ICE - San Pedro, San Jose, Costa Rica
INTI	Argentina	Marcelo Cazabat	cazamar@inti.gov.ar	Instituto Nacional de Tecnología Industrial (INTI), Centro de Investigación y Desarrollo en Física (CEFIS), Div. Electricidad, Av. Gral. Paz y Albarellos CP 1650. San Martín. Pcia. Bs. As. Argentina
UTE	Uruguay	Sergio Teliz	STeliz@ute.com.uy	UTE, Montevideo, Uruguay
INMETRO	Brazil	Luiz Macoto Ogino	lmogino@inmetro.gov.br	Laboratorio de Capactancia e Indutancia – Diele/Dimci/Incetro, Av. Nossa Senhora das Gracas 50, Xerem, Duque de Caxias, RJ, Brazil, CEP:25 250-02

Appendix I.   Photographs of included parts

Figure I1. Front view of AH1100 Enclosure

Figure I2. Rear view of AH1100 Enclosure with fuse removed

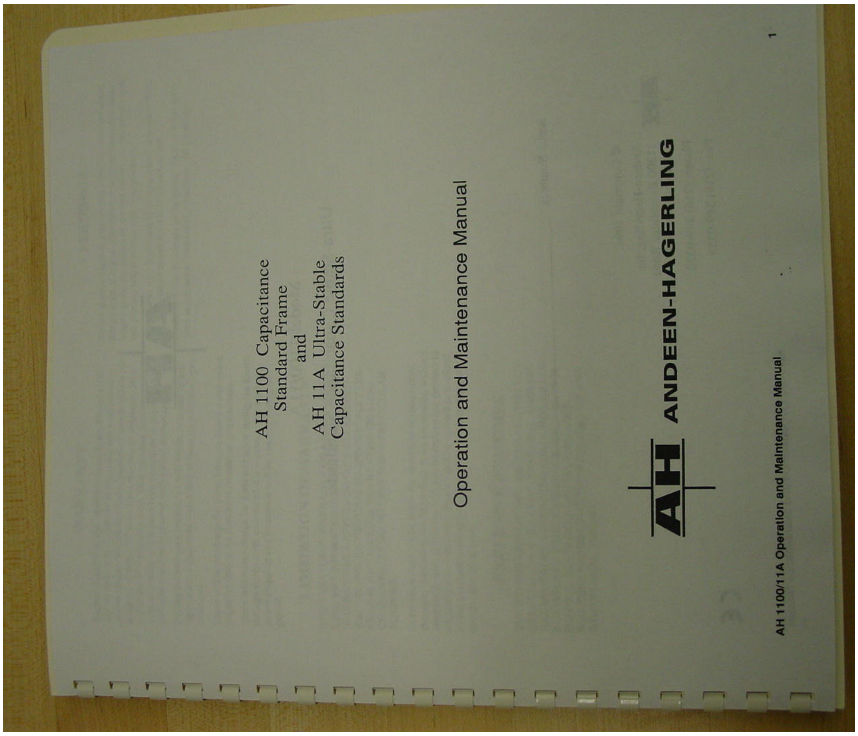

Figure I3. AH1100/11A Operation and Maintenance Manual

Figure I4. GR1404-A Capacitance Standard in foam carton

Figure I5. 0.25 A fuses and 0.5 A fuses

Figure I6. Shorting cable

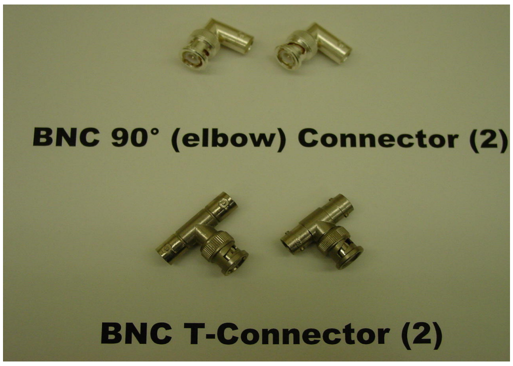

Figure I7. BNC elbow and T-connectors

Figure I8. BNC-to-GR874 connectors

Figure I9. BNC barrel adapters

Figure I10. BNC-to-alligator clips

Figure I11. Two-terminal-pair twisted BNC cable

Figure I12. Four-terminal-pair BNC cable