BUREAU INTERNATIONAL
DES POIDS ET MESURES

Bilateral comparison of 10 pF and 100 pF standards (ongoing BIPM key comparisons BIPM.EM-K14.a and K14.b) between the CENAM (Mexico) and the BIPM

Final Report

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1 Introduction

This report presents the results of a bilateral comparison of capacitance standards between the Centro Nacional de Metrología (CENAM), Mexico, and the Bureau International des Poids et Mesures (BIPM). The comparison followed an *"A-B-A"* pattern using two 10 pF and two 100 pF travelling standards belonging to the BIPM, during a total time of 19 weeks, from January to May 2025, and was piloted by the BIPM.

The measurand in this comparison was the two-terminal pair capacitance of the travelling standards at frequencies of 1000 Hz and 1592 Hz, and voltages of 100 V (rms) for the 10 pF standards and 10 V (rms) for the 100 pF standards.

This report covers the comparison of both 10 pF standards (BIPM.EM-K14.a) and 100 pF standards (BIPM.EM-K14.b) [1] as the two comparisons were carried out simultaneously, but they are analyzed separately.

2 Travelling standards

The four travelling standards employed in this comparison are Andeen-Hagerling model AH11A capacitance modules, comprising two nominal 10 pF units (SN 02213 and 02295) and two nominal 100 pF units (SN 01574 and 02188). These modules were mounted together in an Andeen-Hagerling model AH1100 frame (SN 00200368).

The influence of ambient temperature on the capacitance values of the standards mounted in the frame corresponds to their temperature coefficient, which is approximately 1 part in 10^8 per °C. According to previous characterization conducted at the BIPM under typical conditions and since the AH11A capacitance modules are sealed devices, the effects of variations in relative humidity and atmospheric pressure on the capacitance values were determined to be negligible.

During the comparison, the frequency and the voltage coefficients of capacitance were evaluated at the BIPM. These evaluations were performed using a 100 pF reference capacitor with known characteristics. The results of these evaluations are summarized in Table 1.

Table 1 Frequency and voltage coefficients of the 10 pF (SN 02213 and 02295) and 100 pF (SN 01574 and 02188) travelling standards.

Capacitor	Frequency coefficient ± standard uncertainty (pF / Hz)	Voltage coefficient ± standard uncertainty (pF / V)
10 pF SN 02213	$(- 0.34 \pm 0.61) \times 10^{-9}$	$(0.0 \pm 2.2) \times 10^{-9}$
10 pF SN 02295	$(- 0.21 \pm 0.59) \times 10^{-9}$	$(+ 0.2 \pm 2.0) \times 10^{-9}$
100 pF SN 01574	$(+ 0.2 \pm 6.3) \times 10^{-9}$	$(+ 0.01 \pm 0.20) \times 10^{-6}$
100 pF SN 02188	$(+ 1.0 \pm 6.2) \times 10^{-9}$	$(+ 0.01 \pm 0.20) \times 10^{-6}$

Both laboratories measured the travelling standards within the environmental conditions summarized in Table 2.

Table 2 Environmental measurement conditions at BIPM and CENAM during the bilateral comparison.

Quantity	BIPM	CENAM
Temperature	(23.2 ± 0.2) °C	(22.9 ± 0.2) °C
Relative Humidity	(44 ± 5) %	(32 ± 10) %
Atmospheric pressure	(1010 ± 12) hPa	(811 ± 3) hPa

Due to the difference in ambient temperatures between the BIPM and CENAM laboratories, an additional uncertainty contribution was incorporated in the BIPM uncertainty budget, shown in the annex of this report.

For completeness, the “DRIFT (PPM)” and “CHASSIS TEMP (°C)” indications from the AH1100 frame were monitored and recorded throughout all measurement periods, but they are not included in this report.

3 Measurement principle

3.1 BIPM capacitance standard and measurement method

The BIPM maintains its capacitance reference by measuring a group of fused silica capacitors twice a year, using a measurement chain linking the value of these capacitors to the value of the von Klitzing constant R_K, defined directly from the Planck constant h and the elementary charge e [2], according to:

$$R_K = h / e^2 = 25\ 812.807\ 459\ 304\ 5\ \Omega$$

The mentioned measurement chain involves different measurement systems, such as a 10:1 ratio capacitance bridge, a multi-frequency quadrature bridge, a resistance bridge, an ac-dc coaxial resistor with calculable frequency dependence of resistance, and a quantum Hall device operated at 1 Hz [3, 4].

The repeated BIPM capacitance measurements were performed under standard conditions of 1592 Hz and at voltages of 100 V for 10 pF standards and 10 V for 100 pF standards. These measurements employed a 10:1 ratio capacitance bridge and 100 pF and 10 pF reference capacitors, respectively.

In order to align the frequency and voltage conditions of this comparison with those at CENAM, the evaluated frequency coefficients were employed to correct the BIPM 10 pF and 100 pF measurements, while the evaluated voltage coefficients were used to correct exclusively the BIPM 10 pF measurement (see frequency and voltage coefficients in Table 1).

The BIPM measurements were performed during the following two periods: from 7 January to 3 March 2025, and from 28 April to 16 May 2025.

3.2 CENAM capacitance standard and measurement method

Traceability to the SI

The values of the reference capacitance standards used at CENAM are traceable to the International System of Units (SI) through a set of capacitance standards maintained by the BIPM. Biannually, a set consisting of two 10 pF and two 100 pF standard capacitors has been sent to the BIPM for calibration since 2003. The most recent calibration of CENAM's standards was performed in October 2022.

Measurement Conditions

CENAM measured the travelling standards according to the comparison technical protocol [1]. However, in order to carry out measurements related to its CMCs, defined at 1000 Hz and 50 V, CENAM also carried out 10 pF measurements at 50 V for both frequencies.

The CENAM measurements were performed from 18 March to 7 April 2025.

Measurement Method

The travelling standard capacitors were measured using a two-terminal-pair coaxial capacitance bridge based on inductive voltage dividers (IVD) developed at CENAM, which can be configured in 1:1, 10:1 or 1:10 ratio. Figure 1 shows a simplified diagram of the bridge circuit. The bridge voltage ratio is generated by an inductive voltage divider (IVD-C), and balance is achieved by means of a capacitor *C* and a conductance *G* in conjunction with two six-decades IVD (IVD-A, IVD-B) with ratios α and β, and of an auxiliary Wagner arm (not shown).

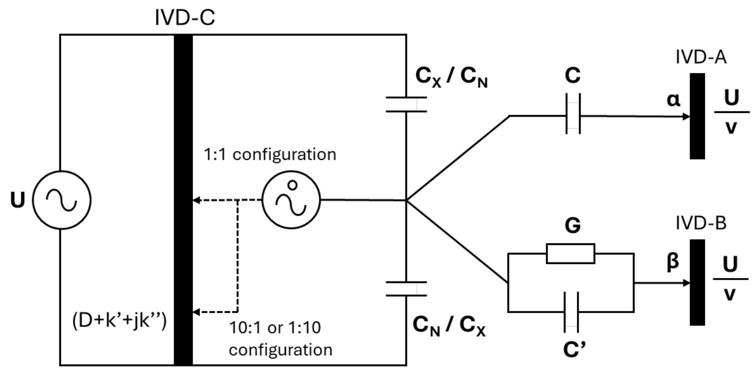

Figure 1 Simplified diagram of the CENAM's bridge circuit.

The value of the unknown capacitor C_X is determined in terms of the reference capacitor C_N, the IVD ratios α and β (measured in both normal and swapped configurations for the 1:1 ratio), the capacitance *C*, the parasitic capacitance *C*' associated with the conductance *G*, and a predefined value of a voltage divider $\nu = 100$ for the 1:1 configuration and $\nu = 110$ for the 10:1 and 1:10 configurations, respectively.

In the 10:1 and 1:10 configurations, the value of C_X additionally depends on the ratio value of the IVD-C ($D = 1/11$), its phase and quadrature error values *k'* and *k''*, the cable compensation coefficients α_{FX} and α_{FN} for the connections to C_X and C_N, respectively, and the dissipation factor of the reference capacitor $\tan \delta_S$.

Equations (1), (2), and (3) present the bridge balance equations for the 1:1, 10:1, and 1:10 configurations, respectively.

$$C_X = C_N + \frac{C}{\nu} (\alpha_1 - \alpha_2) + \frac{C'}{\nu} (\beta_1 - \beta_2) \tag{1}$$

$$C_X = \left(\frac{\alpha_{FX}}{D + k'} \right) \left[\frac{(1 - D - k') C_N}{\alpha_{FN}} + \frac{(\alpha C + \beta C')}{\nu} - \frac{k''}{D + k'} \left(\frac{C_N \tan \delta_S}{\alpha_{FN}} + \frac{\beta G}{\omega \nu} \right) \right] \tag{2}$$

$$C_X = \left(\frac{\alpha_{FX}}{1 - D - k'} \right) \left[\frac{(D + k') C_N}{\alpha_{FN}} - \frac{(\alpha C + \beta C')}{\nu} + \frac{k''}{1 - D - k'} \left(\frac{C_N \tan \delta_S}{\alpha_{FN}} - \frac{\beta G}{\omega \nu} \right) \right] \tag{3}$$

For the 10 pF standards measurements at 50 V, the bridge was configured in a 1:1 ratio, using an Andeen-Hagerling 11A 10 pF standard capacitor (SN 01067) as the reference. In this 1:1 configuration, bridge cable corrections and IVD error can be effectively cancelled by performing a second balance with the connections between the reference and unknown capacitors swapped.

For the 10 pF standards measurements at 100 V, the bridge was configured in a 1:10 ratio, using an Andeen-Hagerling 11A 100 pF standard capacitor (SN 01071) as reference.

For the 100 pF standards measurements at 10 V, the bridge was configured in a 10:1 ratio, using a 10 pF standard capacitor (SN 01067) as reference.

Both the 1:10 and 10:1 configurations require a complete characterization of the bridge cables and knowledge of the bridge's main IVD errors. The in-phase IVD error k' is determined by using the same coaxial capacitance bridge and the standard capacitors that have been calibrated at the BIPM, immediately after their stabilization upon return from the calibration. The quadrature IVD error k'' was characterized at the Physikalisch-Technische Bundesanstalt – Germany, after the development of the IVD, and its contribution to the measurements is less than 1 part in 10^{15}.

The reference values for the two standard capacitors (SN 01067 and 01071) at the time of the comparison were obtained by least-squares extrapolation of previous calibration measurements performed at the BIPM. A linear approximation was used for the 10 pF reference capacitor, and a quadratic one for the 100 pF reference capacitor. A recent analysis on the stability of the bridge's main IVD for over 15 years shows a linear drift of 5 parts in 10^{11} per year with a dispersion of around 3 parts in 10^9. This estimation was used to support the extrapolations mentioned.

In this comparison, the uncertainty contribution of the IVD error was considered in the corresponding uncertainty budget for 10:1 and 1:10 measurements.

4 Measurement results

In order to establish a clearer context for explaining the 10 pF measurements later on, the results for the 100 pF standards are presented first.

4.1 Comparison of 100 pF standards (BIPM.EM-K14.b)

The individual measurements obtained at the BIPM and the CENAM for the 100 pF capacitors at frequencies of 1000 Hz and 1592 Hz, and voltage of 10 V are presented in Figures 2 and 3 for capacitor SN 01574, and in Figures 4 and 5 for capacitor SN 02188. Each figure reports the relative difference from the nominal capacitance value (with *C* the measured capacitance value in pF) expressed as a function of the measurement date.

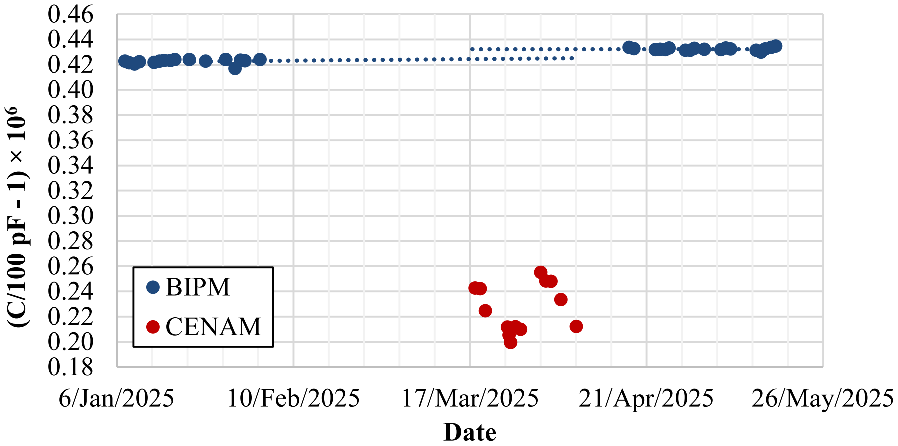

Figure 2 BIPM and CENAM measurements for the 100 pF capacitor SN 01574 at 1000 Hz and 10 V.

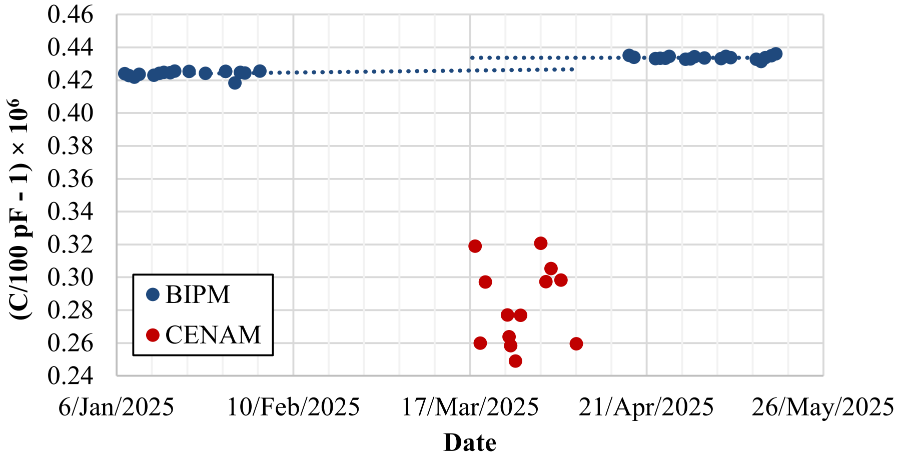

Figure 3 BIPM and CENAM measurements for the 100 pF capacitor SN 01574 at 1592 Hz and 10 V.

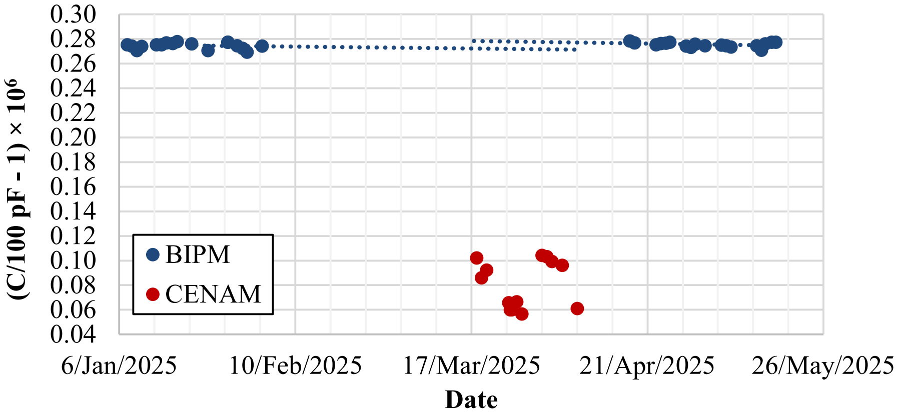

Figure 4 **BIPM and CENAM measurements for the 100 pF capacitor SN 02188 at 1000 Hz and 10 V.**

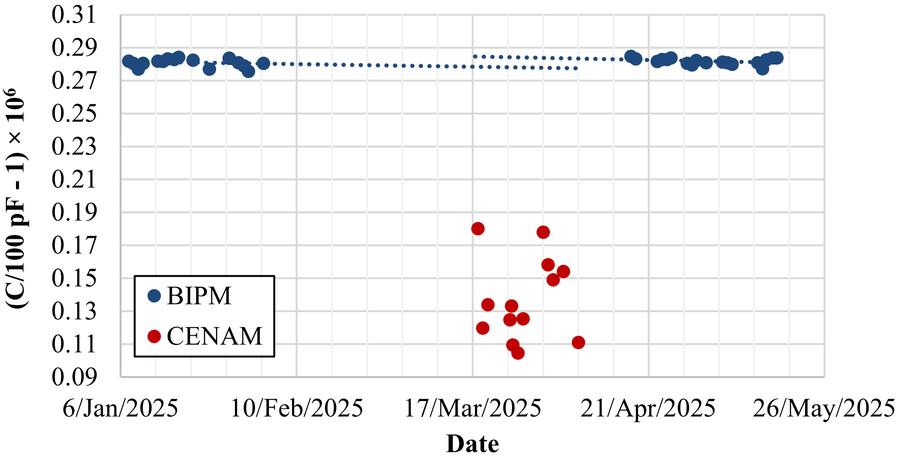

Figure 5 **BIPM and CENAM measurements for the 100 pF capacitor SN 02188 at 1592 Hz and 10 V.**

Both capacitors, SN 01574 and SN 02188, demonstrated excellent stability during the comparison, as evidenced by the corresponding figures. The standard deviation of each group of BIPM measurements did not exceed 0.003 µF/F, and the maximum difference between the mean values of the two BIPM measurement periods was not higher than 0.007 µF/F. Based on this behavior, the reference value for each capacitor was determined simply as the arithmetic mean of all BIPM measurements for each travelling standard. An additional uncertainty contribution was included to take into account the transport effect observed.

Tables 3 and 4 present a summary of the estimated capacitance values and associated standard uncertainties (at the 1σ level) obtained by both the BIPM and the CENAM for the 100 pF capacitors SN 01574 and SN 02188, respectively. Detailed uncertainty budgets for both laboratories are provided in the annex of this report.

Table 3 Estimated capacitance values for the 100 pF travelling standard SN 01574 at frequencies of 1000 Hz and 1592 Hz, and voltage of 10 V.

	1000 Hz		1592 Hz	
Laboratory	**Capacitance (pF)**	**Standard uncertainty (µF/F)**	**Capacitance (pF)**	**Standard uncertainty (µF/F)**
BIPM	100.000 042 8	0.056	100.000 042 9	0.041
CENAM	100.000 023	0.22	100.000 028	0.17

Table 4 Estimated capacitance values for the 100 pF travelling standard SN 02188 at frequencies of 1000 Hz and 1592 Hz, and voltage of 10 V.

	1000 Hz		1592 Hz	
Laboratory	**Capacitance (pF)**	**Standard uncertainty (µF/F)**	**Capacitance (pF)**	**Standard uncertainty (µF/F)**
BIPM	100.000 027 5	0.056	100.000 028 1	0.041
CENAM	100.000 008	0.22	100.000 014	0.17

The degree of equivalence D_{CENAM} between the BIPM and the CENAM, for the 100 pF standards at frequencies of 1000 Hz and 1592 Hz, and voltage of 10 V, was computed using the Equation 4. $\overline{C_{\mathrm{BIPM}}}$ is the mean value of the BIPM estimations for the two travelling standards, and $\overline{C_{\mathrm{CENAM}}}$ is the mean value of the CENAM estimations for the two same travelling standards.

$$D_{\mathrm{CENAM}} = \frac{\overline{C_{\mathrm{CENAM}}} - \overline{C_{\mathrm{BIPM}}}}{\overline{C_{\mathrm{BIPM}}}} \tag{4}$$

The combined and expanded uncertainties associated with D_{CENAM}, u and U_{DCENAM} ($k = 2$, for a nominal confidence level of 95.45 %), were computed using the Equations 5 and 6, respectively.

$$u = \sqrt{u_{\mathrm{BIPM}}^2 + u_{\mathrm{CENAM}}^2} \tag{5}$$

$$U_{\mathrm{DCENAM}} = 2\,u \tag{6}$$

For 100 pF at 1000 Hz and 10 V (rms):

$\boldsymbol{D_{\mathrm{CENAM}}}$ **= -0.20 µF/F** $\boldsymbol{U_{\mathrm{DCENAM}}}$ **= 0.45 µF/F**

For 100 pF at 1592 Hz and 10 V (rms):

$\boldsymbol{D_{CENAM}} = \mathbf{-0.14\ \mu F/F}$ $\boldsymbol{U_{DCENAM}} = \mathbf{0.35\ \mu F/F}$

4.2 Comparison of 10 pF standards (BIPM.EM-K14.a).

The individual measurements obtained at the BIPM and the CENAM for the 10 pF capacitors at frequencies of 1000 Hz and 1592 Hz, and voltages of 100 V and 50 V are presented in Figures 6 to 9 for capacitor SN 02213, and in Figures 10 to 13 for capacitor SN 02295. Each figure reports the relative difference from the nominal capacitance value (with *C* the measured capacitance value in pF) expressed as a function of the measurement date.

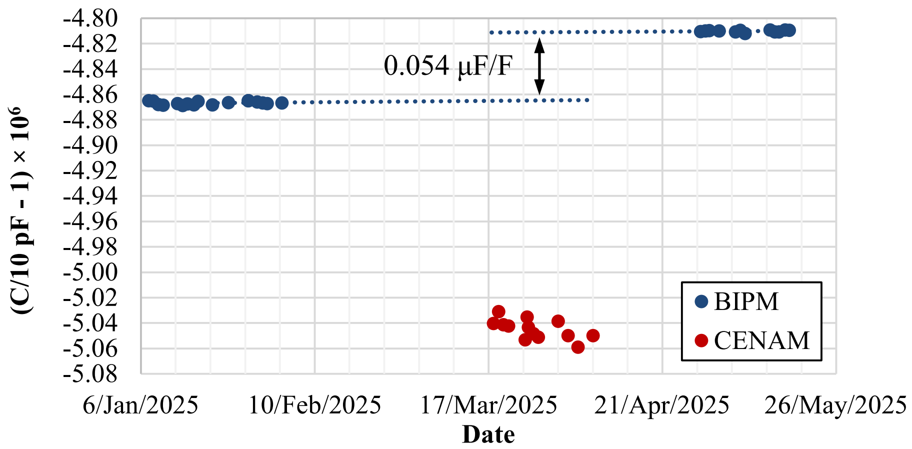

Figure 6 BIPM and CENAM measurements for the 10 pF capacitor SN 02213 at 1000 Hz and 100 V.

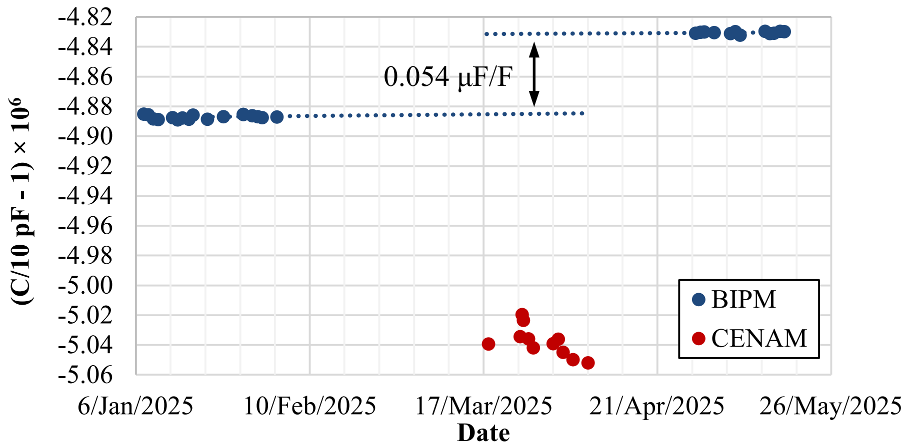

Figure 7 BIPM and CENAM measurements for the 10 pF capacitor SN 02213 at 1592 Hz and 100 V.

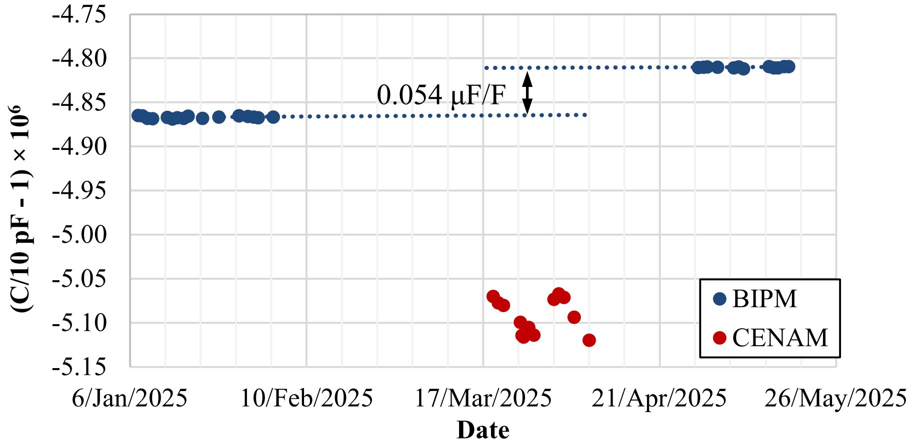

Figure 8 BIPM and CENAM measurements for the 10 pF capacitor SN 02213 at 1000 Hz and 50 V.

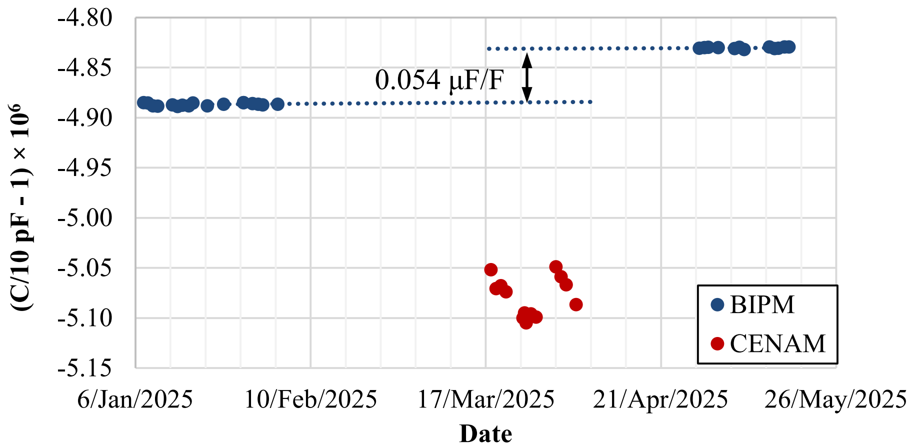

Figure 9 BIPM and CENAM measurements for the 10 pF capacitor SN 02213 at 1592 Hz and 50 V.

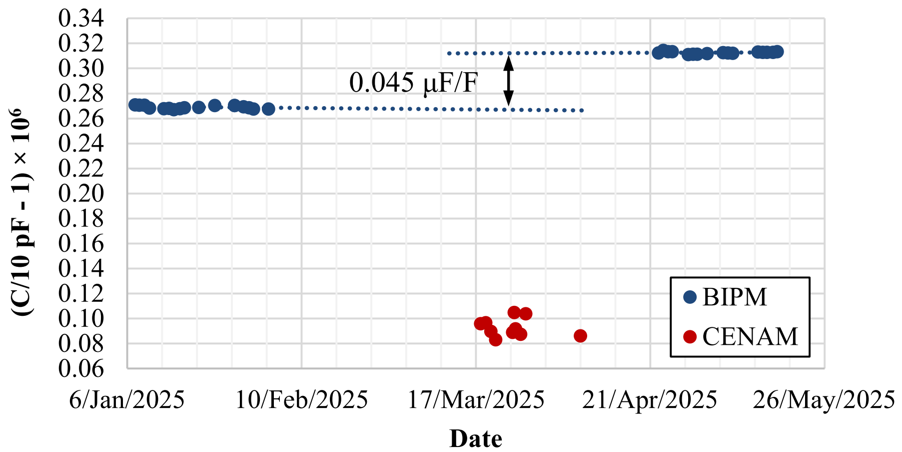

Figure 10 BIPM and CENAM measurements for the 10 pF capacitor SN 02295 at 1000 Hz and 100 V.

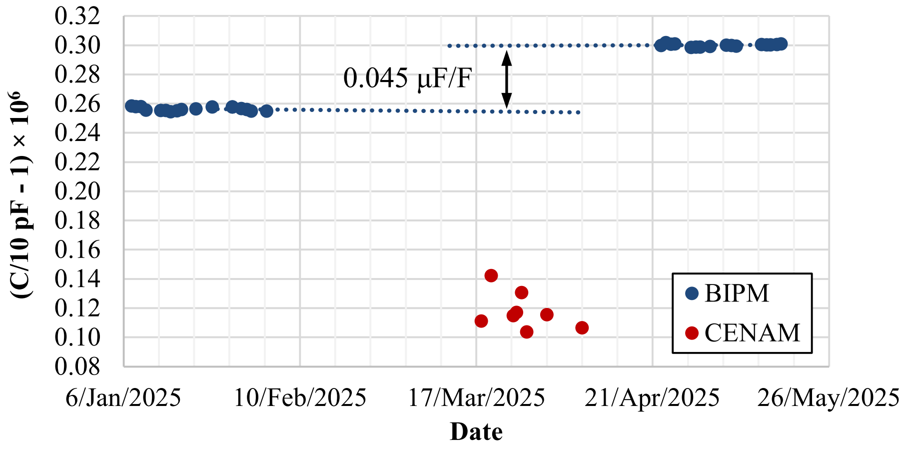

Figure 11 BIPM and CENAM measurements for the 10 pF capacitor SN 02295 at 1592 Hz and 100 V.

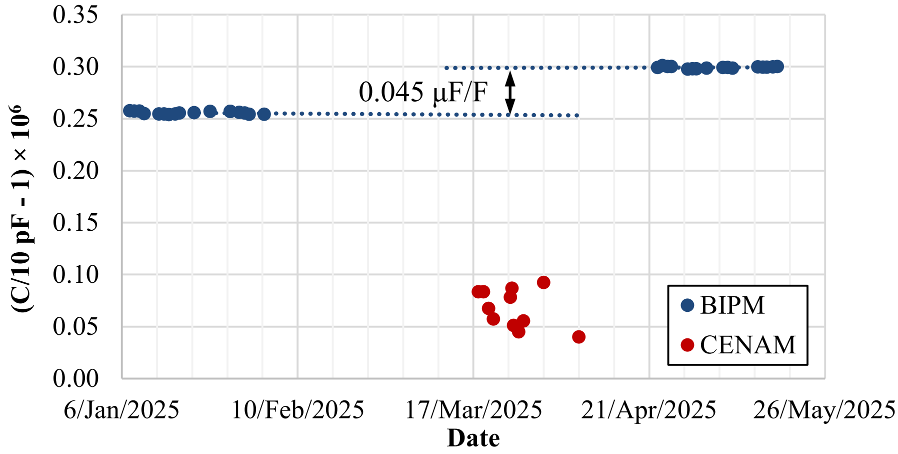

Figure 12 BIPM and CENAM measurements for the 10 pF capacitor SN 02295 at 1000 Hz and 50 V.

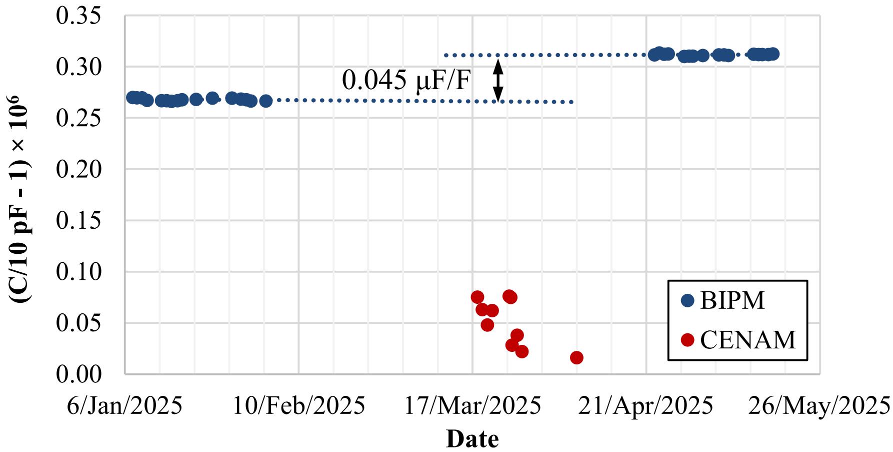

Figure 13 BIPM and CENAM measurements for the 10 pF capacitor SN 02295 at 1592 Hz and 50 V.

As can be observed, both capacitors suffered a change in value during the transport BIPM-CENAM-BIPM. Based on a linear extrapolation of BIPM measurement results to the CENAM's mean date, it was estimated that capacitor SN 02213 underwent a change of 0.054 µF/F, while capacitor SN 02295 changed by 0.045 µF/F. To try to determine the moment at which the capacitors changed, the 100 pF travelling standards measurements, which proved to be very stable throughout the comparison, were used as an auxiliary reference.

The ratios of the measured capacitance values of 100 pF capacitor SN 01574 to those of the 10 pF capacitors SN 02213 and SN 02295 (measured at 100 V and 1592 Hz) were computed. Figures 14 and 15 show the ratios SN 01574 / SN 02213 and SN 01574 / SN 02295 respectively, reported as relative difference from the nominal ratio (with *C* the measured capacitance value in pF) expressed as a function of the measurement date.

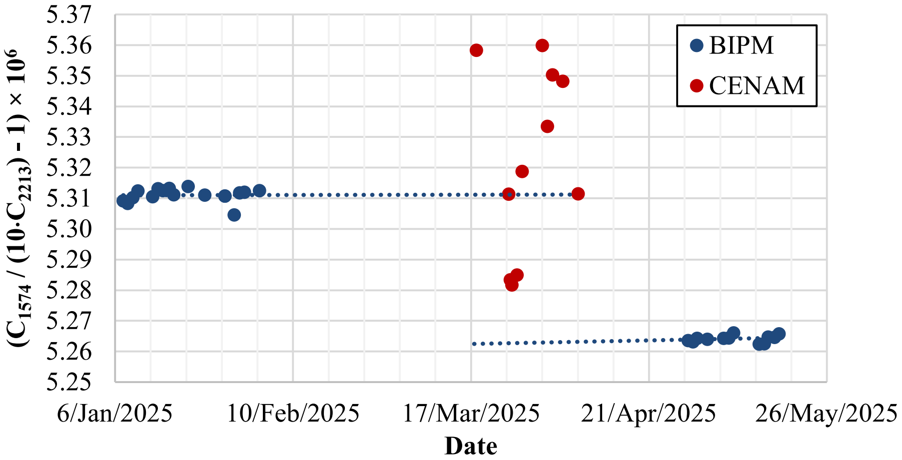

Figure 14 **Ratio of capacitances of 100pF SN 01574 and 10 pF SN 02213 capacitors measured at 1592 Hz, and voltage of 10 V and 100 V, respectively.**

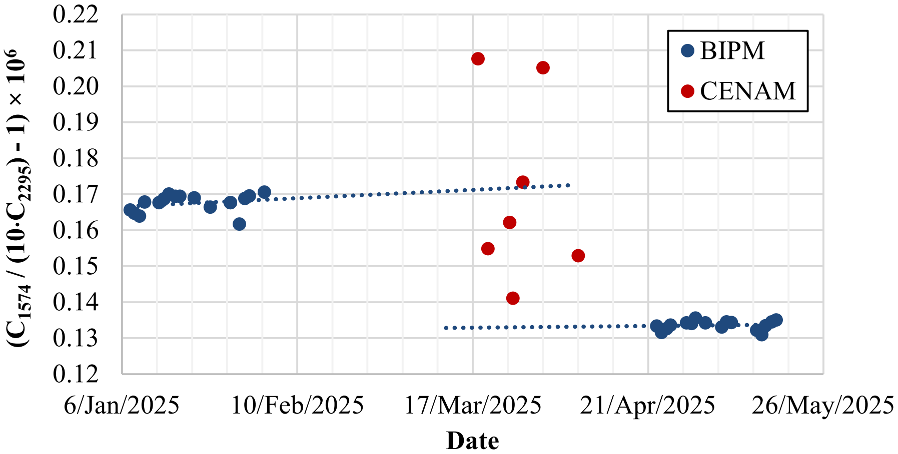

Figure 15 **Ratio of capacitances of 100pF SN 01574 and 10 pF SN 02295 capacitors measured at 1592 Hz, and voltage of 10 V and 100 V, respectively.**

In the two figures above, it can be seen that the extrapolated ratio derived from the BIPM measurements performed before the BIPM–CENAM transport lies very close to the mean ratio obtained from the CENAM measurements. A similar analysis, performed using the 100 pF capacitor SN 02188 (not shown in this report), produced equivalent results. These findings support the conclusion that the observed changes in the 10 pF capacitors most likely occurred during the return transport from CENAM to BIPM.

Based on this analysis, it was decided to estimate the BIPM reference values using only the measurements performed before the BIPM–CENAM transport, extrapolated to the CENAM's mean date. Consequently, an additional uncertainty contribution was included due to this extrapolation, but no uncertainty contribution for the observed change in transport was considered.

Tables 5 to 8 present a summary of the estimated capacitance values and associated standard uncertainties (at the 1σ level) obtained by both the BIPM and CENAM for the 10 pF capacitors SN 02213 and SN 02295, measured at frequencies of 1000 Hz and 1592 Hz and voltages of 100 V and 50 V. Detailed uncertainty budgets for both laboratories are provided in the annex of this report.

Table 5 Estimated capacitance values for the 10 pF travelling standard SN 02213 at frequencies of 1000 Hz and 1592 Hz, and voltage of 100 V.

	1000 Hz		1592 Hz	
Laboratory	**Capacitance (pF)**	**Standard uncertainty (µF/F)**	**Capacitance (pF)**	**Standard uncertainty (µF/F)**
BIPM	9.999 951 35	0.055	9.999 951 15	0.042
CENAM	9.999 949 6	0.21	9.999 949 6	0.17

Table 6 Estimated capacitance values for the 10 pF travelling standard SN 02213 at frequencies of 1000 Hz and 1592 Hz, and voltage of 50 V.

	1000 Hz		1592 Hz	
Laboratory	**Capacitance (pF)**	**Standard uncertainty (µF/F)**	**Capacitance (pF)**	**Standard uncertainty (µF/F)**
BIPM	9.999 951 36	0.056	9.999 951 15	0.043
CENAM	9.999 949 1	0.16	9.999 949 2	0.13

Table 7 Estimated capacitance values for the 10 pF travelling standard SN 02295 at frequencies of 1000 Hz and 1592 Hz, and voltage of 100 V.

	1000 Hz		1592 Hz	
Laboratory	**Capacitance (pF)**	**Standard uncertainty (µF/F)**	**Capacitance (pF)**	**Standard uncertainty (µF/F)**
BIPM	10.000 002 67	0.054	10.000 002 54	0.042
CENAM	10.000 000 9	0.21	10.000 001 2	0.17

Table 8 Estimated capacitance values for the 10 pF travelling standard SN 02295 at frequencies of 1000 Hz and 1592 Hz, and voltage of 50 V.

	1000 Hz		1592 Hz	
Laboratory	**Capacitance (pF)**	**Standard uncertainty (µF/F)**	**Capacitance (pF)**	**Standard uncertainty (µF/F)**
BIPM	10.000 002 66	0.055	10.000 002 54	0.043
CENAM	10.000 000 5	0.16	10.000 000 7	0.13

The degree of equivalence D_{CENAM} between the BIPM and the CENAM, for the 10 pF standards at frequencies of 1000 Hz and 1592 Hz, and voltages of 100 V and 50 V, was computed using the Equation 4. $\overline{C_{BIPM}}$ is the mean value of the BIPM estimations for the two travelling standards, and $\overline{C_{CENAM}}$ is the mean value of the CENAM estimations for the same two travelling standards.

The combined and expanded uncertainties associated with D_{CENAM}, u and U_{DCENAM} (k = 2, for a nominal confidence level of 95.45 %), were computed using the Equations 5 and 6, respectively.

For 10 pF at 1000 Hz and 100 V (rms):

$\boldsymbol{D_{CENAM}}$ **= -0.18 µF/F** $\boldsymbol{U_{DCENAM}}$ **= 0.43 µF/F**

For 10 pF at 1592 Hz and 100 V (rms):

$\boldsymbol{D_{CENAM}}$ **= -0.14 µF/F** $\boldsymbol{U_{DCENAM}}$ **= 0.35 µF/F**

For 10 pF at 1000 Hz and 50 V (rms):

$\boldsymbol{D_{CENAM}}$ **= -0.22 µF/F** $\boldsymbol{U_{DCENAM}}$ **= 0.34 µF/F**

For 10 pF at 1592 Hz and 50 V (rms):

$\boldsymbol{D_{CENAM}}$ **= -0.19 µF/F** $\boldsymbol{U_{DCENAM}}$ **= 0.27 µF/F**

4.3 Summary of results.

The degree of equivalence for the comparison of 10 pF and 100 pF standards (BIPM.EM-K14.a and BIPM.EM-K14.b respectively), are summarized in Table 9 and Figure 16.

Table 9 Degrees of equivalence between the BIPM and the CENAM for 10 pF and 100 pF capacitance measurements and associated uncertainty (*k* = 2).

Nominal Value, Voltage	1000 Hz		1592 Hz	
	D_{CENAM} (µF/F)	U_{DCENAM} (µF/F)	D_{CENAM} (µF/F)	U_{DCENAM} (µF/F)
10 pF, 100 V	-0.18	0.43	-0.14	0.35
10 pF, 50 V	-0.22	0.34	-0.19	0.27
100 pF, 10 V	-0.20	0.45	-0.14	0.35

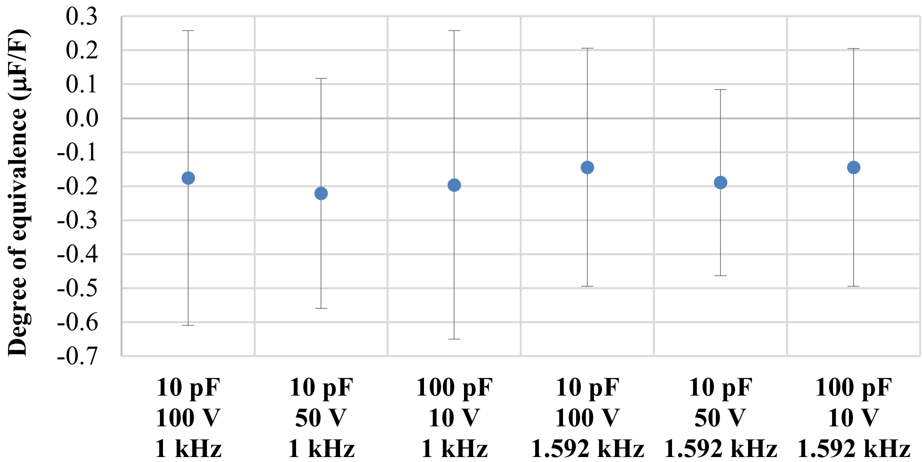

Figure 16 Degrees of equivalence between the BIPM and the CENAM for 10 pF and 100 pF capacitance standards and associated uncertainty (*k* = 2).

5 Comments and conclusion

The CENAM capacitance measurements are traceable to the quantized Hall resistance through periodic calibrations performed by the BIPM since 2003. Based on the calibration history and stability of an IVD, the temporal drift of the reference standards since their last calibration in 2022 has been well characterized, allowing the evaluation of consistent extrapolated values within the estimated uncertainty.

The BIPM.EM-K14.a and BIPM.EM-K14.b bilateral key comparisons between the CENAM and the BIPM were completed successfully, despite some transport effects for the 10 pF travelling standards. The results will be useful for the CENAM to support its current CMCs and maintain traceability of their capacitance references.

As there is no independent realization of the farad at the CENAM, the results of BIPM.EM-K14.a and BIPM.EM-K14.b comparisons only provide evidence confirming that the drift of the CENAM capacitance references is well considered, and the estimated uncertainty effectively reflects the actual state of the CENAM calibration system used to provide continuous calibration services to its customers.

References

[1] Protocol for BIPM on-going key comparisons of 10 pF and 100 pF capacitance standards (BIPM.EM-K14a and BIPM.EM-K14b), BIPM publication.

[2] Consultative Committee for Electricity and Magnetism, 'Mise en pratique for the definition of the ampere and other electric units in the SI', SI Brochure 9th edition - Appendix 2, 2019. https://www.bipm.org/documents/20126/41489676/SI-App2-ampere.pdf

[3] J. Angel Moreno and Pierre Gournay, 'Capacitance metrology at the BIPM to support National Metrology Institutes', 19th International Congress of Metrology, 2019, https://doi.org/10.1051/metrology/201914001

[4] F. Delahaye and R. Goebel, 'Evaluation of the frequency dependence of the resistance and capacitance standards in the BIPM quadrature bridge', IEEE. Trans. Instrum. Meas., 54, no 2, pp 533-537 (2005).

Annex - Uncertainty budgets

A.1 BIPM Uncertainty Budget for 10 pF measurements

The total uncertainty values reported in this Table correspond to the uncertainty on a single capacitance measurement at the BIPM. The uncertainties related to the extrapolation of the value of the travelling standard, and to the effect of ambient temperature difference between BIPM and CENAM were also included.

Component	**Relative uncertainty (10^{-9})**			
	1000 Hz		**1592 Hz**	
	100 V	**50 V**	**100 V**	**50 V**
Values at 1 Hz of 51.6 kΩ resistors used in quadrature bridge, with respect to R_K	14	14	14	14
1 Hz – 1541 Hz difference of 51.6 kΩ resistors	22	22	22	22
Operation of quadrature bridge at 1541 Hz	13	13	13	13
Scaling from 2000 pF capacitors of quadrature bridge to 10 pF and 100 pF references	16	16	16	16
Time extrapolation of the value of the 100 pF reference	14	14	14	14
Link between travelling standards and 100 pF reference	20	20	20	20
Uncertainty on frequency correction (from 1592 Hz to 1000 Hz)	36	36	---	---
Uncertainty on voltage correction (change from 100 V to 50 V)	---	11	---	11
Repeatability of measurements	3	3	3	3
Extrapolation of the value of the travelling standard	3	3	3	3
Difference of ambient temperatures at BIPM and CENAM	3	3	3	3
Combined uncertainty	**55**	**56**	**42**	**43**

All values are standard uncertainties (1σ estimates).

A.2 BIPM Uncertainty Budget for 100 pF measurements

The total uncertainty values reported in this Table correspond to the uncertainty on a single capacitance measurement at the BIPM. The uncertainties related to the stability of the capacitor during transport to CENAM and back, and to the effect of ambient temperature difference between BIPM and CENAM were also included.

Component	**Relative uncertainty (10^{-9})**	
	1000 Hz	**1592 Hz**
Values at 1 Hz of 51.6 kΩ resistors used in quadrature bridge, with respect to R_K	14	14
1 Hz – 1541 Hz difference of 51.6 kΩ resistors	22	22
Operation of quadrature bridge at 1541 Hz	13	13
Scaling from 2000 pF capacitors of quadrature bridge to 10 pF and 100 pF references	16	16
Time extrapolation of the value of the 10 pF reference	14	14
Link between travelling standards and 10 pF	20	20
Uncertainty on frequency correction (from 1592 Hz to 1000 Hz)	37	---
Repeatability of measurements	2	2
Transport effect	2	2
Difference of ambient temperatures at BIPM and CENAM	3	3
Combined uncertainty at 10 V	**56**	**41**

All values are standard uncertainties (1σ estimates).

A.3 CENAM Uncertainty Budget for 10 pF measurements

The uncertainty budget of the CENAM measurements is shown in the following Table.

Component	Relative uncertainty (10^{-6})			
	1000 Hz		1592 Hz	
	100 V	50 V	100 V	50 V
Experimental standard uncertainty	0.002	0.007	0.005	0.006
Reference standard value	0.110	0.130	0.100	0.110
Reference standard linear approximation	0.050	0.054	0.040	0.041
Main IVD Error	0.155	---	0.114	---
Bridge parameters (C, ν, C', G)	0.014	0.006	0.014	0.006
Bridge balance (α, β)	0.006	0.008	0.006	0.008
Cable effects	0.001	---	0.001	---
Bridge current equalizers imperfections	0.050	0.050	0.050	0.050
Relative capacitance change due to frequency $(C_{1592} - C_{1000})/C_{1000}$	0.037	0.056	---	---
Voltage coefficient	---	0.011	---	0.011
Combined uncertainty	**0.207**	**0.160**	**0.165**	**0.129**

All values are standard uncertainties (1σ estimates).

A.4 CENAM Uncertainty Budget for 100 pF measurements

The uncertainty budget of the CENAM measurements is shown in the following Table.

Component	Relative uncertainty (10^{-6})	
	1000 Hz	1592 Hz
Experimental standard uncertainty	0.005	0.007
Reference standard value	0.130	0.110
Reference standard quadratic approximation	0.054	0.041
Main IVD Error	0.155	0.114
Bridge parameters (C, ν, C', G)	0.007	0.007
Bridge balance (α, β)	0.006	0.006
Cable effects	0.001	0.001
Bridge current equalizers imperfections	0.050	0.050
Relative capacitance change due to frequency $(C_{1592} - C_{1000})/C_{1000}$	0.056	---
Combined uncertainty at 10 V	**0.223**	**0.171**

All values are standard uncertainties (1σ estimates).