BUREAU INTERNATIONAL
DES POIDS ET MESURES

Bilateral comparison of 10 pF and 100 pF standards (ongoing BIPM key comparisons BIPM.EM-K14.a and 14.b) between the NIMT (Thailand) and the BIPM

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Final report

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1 Introduction

This report presents the results of two bilateral comparisons of capacitance standards at 10 pF and 100 pF performed within the framework of the BIPM programme of on-going key comparisons BIPM.EM-K14.a (10 pF standards) and BIPM.EM-K14.b (100 pF standards), [1]. These comparisons were carried out simultaneously from April to September 2018 and were piloted by the BIPM.

Two 10 pF and one 100 pF travelling standards belonging to the NIMT were used. The comparison was carried out with an *"A-B-A"* pattern of measurements in which each of the three standards was measured first at NIMT, then at the BIPM, and finally again at NIMT. The measurement periods are referred to as:

- "Before" measurements at NIMT: April - May 2018
- BIPM measurements: June - July 2018
- "After" measurements at NIMT: August - September 2018

The measurand was the two terminal-pair capacitance at a frequency of 1592 Hz and 1000 Hz, and for a measuring rms voltage of 15 V and 10 V for the 10 pF and 100 pF capacitance values, respectively.

2 Travelling standards

The three NIMT travelling standards are Andeen-Hagerling model AH11A capacitance modules having nominal values of 10 pF (s/n 01359 and s/n 01693) and 100 pF (s/n 01360) mounted in a frame model AH1100 (s/n 00119).
The effect of ambient temperature on the standards mounted in the frame is known in the range 23°C ± 1°C. No changes in the capacitance values greater than 1 part in 10^8 are expected over this range. Both laboratories measured the travelling standards at ambient temperatures between 22°C and 24 °C. Under these conditions, the temperature correction was negligible.
The "drift" and temperature indications of the AH1100 frame were recorded for completeness during all measurement periods but these are not reported here. The effects of normal variations in atmospheric pressure and humidity are also negligible and, therefore, no corrections have been applied for changes in ambient conditions. The AH1100 frame was shipped between the two laboratories by standard air freight.

The standard conditions for capacitance measurements at the BIPM are 1592 Hz and a rms voltage of either 100 V for 10 pF or 10 V for 100 pF. The repeated BIPM measurements are made at these values. The travelling standards have been separately characterized for frequency and voltage dependence against known BIPM references. The ultimate reference for these measurements is the BIPM multi-frequency quadrature bridge and calculable coaxial resistors [2]. The uncertainties for these corrections are included in the BIPM uncertainty budget. Whilst the uncertainty on the frequency correction of the measurements is the largest component in the BIPM uncertainty budget, it does not limit the overall uncertainty of the comparison.

Measurements at NIMT were carried out at both frequencies 1000 Hz and 1592 Hz and at a rms voltage of 15 V for 10 pF and 10 V for 100 pF. The comparison voltage for the 10 pF is chosen to be 15 V meaning that only the BIPM results are corrected for voltage effect.

3 Measurement principle

3.1 NIMT reference capacitance standard and measurement method

The 10 pF travelling standards (s/n 01359 and s/n 01693) were compared to a reference group of four capacitance standards of the same type and nominal value (10 pF fused silica capacitors AH11A). The comparison measurements were performed via an Ultra-Precision Capacitance Bridge type AH2700A and a coaxial switching box. The AH2700A capacitance bridge was setup to compensate for the coaxial cable effect on the measured capacitance value. Each bridge reading was the average of 12 single measurements.

Since 2012, the mean value of the capacitance reference group at 10 pF at NIMT is maintained through periodic calibrations at the BIPM (every two years). The relative drift rate of the mean value of the reference group is as low as about 1 part in 10^9 per year.

The 100 pF travelling standard (s/n 01360) was measured by comparison with a 10 pF NIMT reference standard (s/n 01359) using a voltage transformer ratio bridge - type GR1621 - of ratio 10:1. Every two years, since 2004, the 10 pF NIMT reference standard used has been periodically calibrated through the calibration services of the BIPM. Its relative drift rate is about 1 part in 10^8 per year. Drift corrections at the date of measurement were applied on the final results.
The 10:1 ratio errors of the bridge at 1592 Hz and 1000 Hz are estimated to 30 and 41 parts in 10^8, respectively. Corrections were applied to compensate for these ratio errors and uncertainties related to their estimations have been taken into account in the uncertainty budget.

The travelling standards were measured at both frequencies 1592 Hz and 1000 Hz. The 10 pF capacitors were measured at 15 V, whereas the 100 pF capacitor was measured at 10 V. The ambient temperature was kept within (23 ± 1) °C, so no corrections relative to ambient temperature changes were applied. All measurements were carried out from 11 April to 30 May 2018 for the “before” series and from 14 August to 7 September for the “After” series.

3.2 BIPM reference capacitance standard and measurement method

The BIPM maintains reference sets of 10 pF and 100 pF capacitors whose capacitance values are measured twice a year using a measurement chain linking them to the recommended value of the von Klitzing constant, $R_{K-90} = 25\ 812.807\ \Omega$. The chain includes a capacitance bridge with a ratio of 10:1, a multi-frequency quadrature bridge, an ac-dc coaxial resistor with calculable frequency dependence of resistance, and a quantum Hall device operated at 1 Hz.

The travelling standards were measured in terms of one of the 100 pF BIPM reference standards (AH11A s/n 01642) using a two terminal pair coaxial transformer bridge with a 10:1 ratio. The relative drift rate of the value of the selected reference standard is about 3 parts in 10^9 per year.
The measurements were made using the standard BIPM conditions: nominal frequency of 1592 Hz and nominal rms voltage of 100 V and 10 V for 10 pF and 100 pF capacitance standards, respectively.

The frequency and voltage coefficients of the travelling standards were measured separately against the known properties of the 100 pF reference. When necessary these coefficients were used to correct the BIPM results to match the conditions of 1000 Hz (for all standards) and 15 V (for 10 pF standards), and this transfer is covered in the BIPM uncertainty.

The mean room temperature during the measurement was kept within 23.2 °C ± 0.3 °C and the relative humidity within 45% ± 5%.

4 Measurement results

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

All the individual measurements of the travelling standards (s/n 01359 and s/n 01693) performed at both the NIMT and the BIPM are shown on figures 1 and 2 for operating conditions of 1592 Hz and 15 V (rms), and on figures 3 and 4 for 1000 Hz and the same voltage. In these figures are also shown the mean value of the BIPM measurements along with their uncertainty bars (1σ), and a fit of the NIMT “before” and “after” series of measurements.

As can be seen on figures 1 to 4, the behavior over time of both standards are reasonably well fitted by linear models which are used to predict the NIMT capacitance value of these standards at the mean date (C_{NIMT}, black square dots on mean date 30 June 2018). The standard uncertainty on the predicted value (u_{NIMT}) is the root sum of squares of the prediction uncertainty ($u_{\mathrm{NIMT\_pred}}$, from propagation law applied to the fitting equation) and the standard measurement uncertainty at the NIMT ($u_{\mathrm{NIMT\_Single}}$, see annexed uncertainty budget of NIMT). A transport uncertainty ($u_{\mathrm{transport}}$) is also estimated for all standards; it is calculated from the residuals to the linear fit in the usual way.

The NIMT and BIPM results for standards s/n 01359 and 01693 are reported in tables 1 and 2 for 1592 Hz and 1000 Hz together with the values of the uncertainty components $u_{\mathrm{NIMT\_Single}}$, $u_{\mathrm{NIMT\_pred}}$, $u_{\mathrm{transport}}$ and of the combined standard uncertainties u_{NIMT} and u_{BIPM}. The uncertainty bars reported on figures 1 to 4 correspond to u_{NIMT} and u_{BIPM} (1σ).

	Standard s/n 01359	
	1592 Hz	**1000 Hz**
C_{BIPM}	10.000 002 56 pF	10.000 003 35 pF
u_{BIPM} (1σ, *rel*)	0.043×10^{-6}	0.052×10^{-6}
C_{NIMT}	10.000 002 51 pF	10.000 003 53 pF
$u_{\mathrm{NIMT\_Single}}$ (1σ, *rel*)	0.041×10^{-6}	0.061×10^{-6}
$U_{\mathrm{NIMT\_pred}}$ (1σ, *rel*)	0.004×10^{-6}	0.003×10^{-6}
u_{NIMT} (1σ, *rel*)	0.041×10^{-6}	0.061×10^{-6}
$u_{\mathrm{transport}}$ (1σ, *rel*)	0.014×10^{-6}	0.013×10^{-6}
$\Delta_{01359} = (C_{\mathrm{NIMT}} - C_{\mathrm{BIPM}})/10$ pF	**-0.005×10^{-6}**	**0.017×10^{-6}**

Table 1: Results along with measurement, prediction and transport uncertainties for standard s/n 01359 at 1592 Hz and 1000 Hz, and an applied voltage of 15 V (rms).

	Standard s/n 01693	
	1592 Hz	**1000 Hz**
C_{BIPM}	9.999 999 93 pF	9.999 999 89 pF
u_{BIPM} (1σ, *rel*)	0.043×10^{-6}	0.052×10^{-6}
C_{NIMT}	9.999 999 99 pF	10.000 000 12 pF
$u_{\mathrm{NIMT\_Single}}$ (1σ, *rel*)	0.041×10^{-6}	0.061×10^{-6}
$U_{\mathrm{NIMT\_pred}}$ (1σ, *rel*)	0.003×10^{-6}	0.003×10^{-6}
u_{NIMT} (1σ, *rel*)	0.041×10^{-6}	0.061×10^{-6}
$u_{\mathrm{transport}}$ (1σ, *rel*)	0.012×10^{-6}	0.012×10^{-6}
$\Delta_{01693} = (C_{\mathrm{NIMT}} - C_{\mathrm{BIPM}})/10$ pF	**0.006×10^{-6}**	**0.024×10^{-6}**

Table 2: Results along with measurement, prediction and transport uncertainties for standard s/n 01693 at 1592 Hz and 1000 Hz, and an applied voltage of 15 V (rms).

The difference between the NIMT and the BIPM for the measurement of a 10 pF standard is estimated as the weighted mean of the two differences Δ_{01359} and Δ_{01693} (tables 1 and 2), using the transport uncertainties ($u_{\mathrm{transport}}$) as weights, computed in the standard way:

$$\bar{x}_w = \frac{\sum_i w_i x_i}{\sum_i w_i} \quad \text{where} \quad w_i = \frac{1}{u_i^2}$$

$$\text{and} \quad u_{\bar{x}_w} = \frac{1}{\sqrt{\sum_i w_i}} \quad \text{(corresponding to } u_{transfer} \text{ hereafter)}$$

<u>At 1592 Hz</u>, this lead to the mean difference, Δ_{mean}= 0.001×10^{-6}

$u_{transfer}$ = 0.009×10^{-6}

with the combined relative standard uncertainty on the difference,

$$u = \sqrt{u_{BIPM}{}^2 + u_{NIMT}{}^2 + u_{transfer}{}^2} = 0.060\times10^{-6}$$

This result can be summarized in the form of a degree of equivalence, $\boldsymbol{D}_{\mathbf{NIMT}}$, between the NIMT and the BIPM for measurements for 10 pF standards at 1592 Hz and 15 V (rms), with its associated uncertainty, $\boldsymbol{U}_{\mathbf{DNIMT}}$ (k = 2.08, 95% confidence):

$$\boldsymbol{D_{\mathrm{NIMT}} = (C_{\mathrm{NIMT}} - C_{\mathrm{BIPM}}) / 10\ \mathrm{pF} = 0.00\times10^{-6}} \qquad \textbf{with} \qquad \boldsymbol{U_{\mathrm{DNIMT}} = 0.13\times10^{-6}}$$

The expansion factor of 2.08 is estimated using the Welch-Satterthwaith formula [3] and values of degree of freedom equal to 5 for u_{NIMT} and >150 for u_{BIPM}.

<u>At 1000 Hz</u>, this lead to the mean difference, Δ_{mean}= 0.021×10^{-6}

$u_{transfer}$ = 0.009×10^{-6}

with the combined relative standard uncertainty on the difference,

$$u = \sqrt{u_{BIPM}{}^2 + u_{NIMT}{}^2 + u_{transfer}{}^2} = 0.081\times10^{-6}$$

This result can be summarized in the form of a degree of equivalence, $\boldsymbol{D}_{\mathbf{NIMT}}$, between the NIMT and the BIPM for measurements for 10 pF standards at 1592 Hz and 15 V (rms), with its associated uncertainty, $\boldsymbol{U}_{\mathbf{DNIMT}}$ (k = 2.13, 95% confidence).

$$\boldsymbol{D_{\mathrm{NIMT}} = (C_{\mathrm{NIMT}} - C_{\mathrm{BIPM}}) / 10\ \mathrm{pF} = 0.02\times10^{-6}} \qquad \textbf{with} \qquad \boldsymbol{U_{\mathrm{DNIMT}} = 0.17\times10^{-6}}$$

The expansion factor of 2.13 is estimated using the Welch-Satterthwaith formula [3] and values of degree of freedom equal to 5 for u_{NIMT} and >150 for u_{BIPM}.

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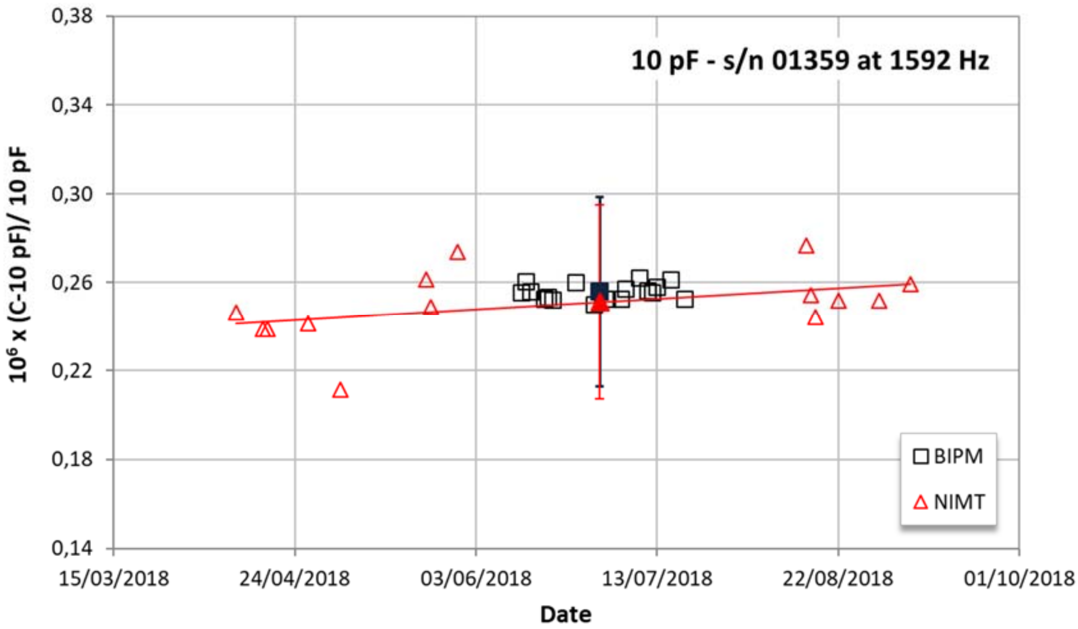

Figure 1: Individual measurements for 10 pF standard s/n 01359 showing NIMT measurements and linear fit, BIPM measurements, BIPM mean value at the mean date (black square dot) with 1σ uncertainty bar, and NIMT predicted value at the mean time of BIPM measurements (red square dot) with 1σ uncertainty bar. Measurement conditions: 1592 Hz and 15 V (rms).

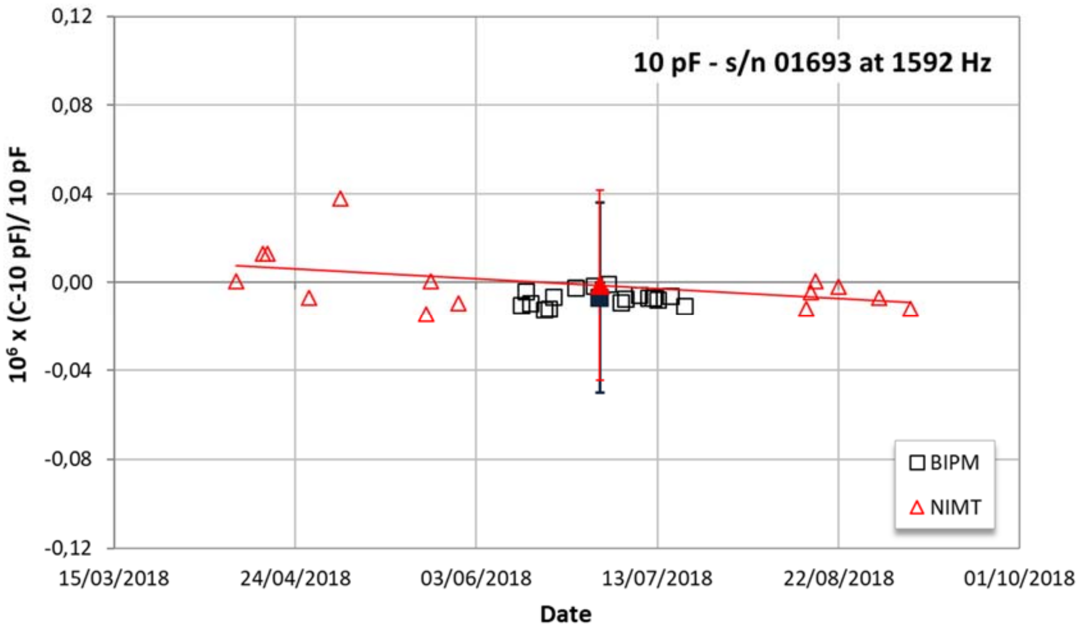

Figure 2: Individual measurements for 10 pF standard s/n 01693 showing NIMT measurements and linear fit, BIPM measurements, BIPM mean value at the mean date (black square dot) with 1σ uncertainty bar, and NIMT predicted value at the mean time of BIPM measurements (red square dot) with 1σ uncertainty bar. Measurement conditions: 1592 Hz and 15 V (rms).

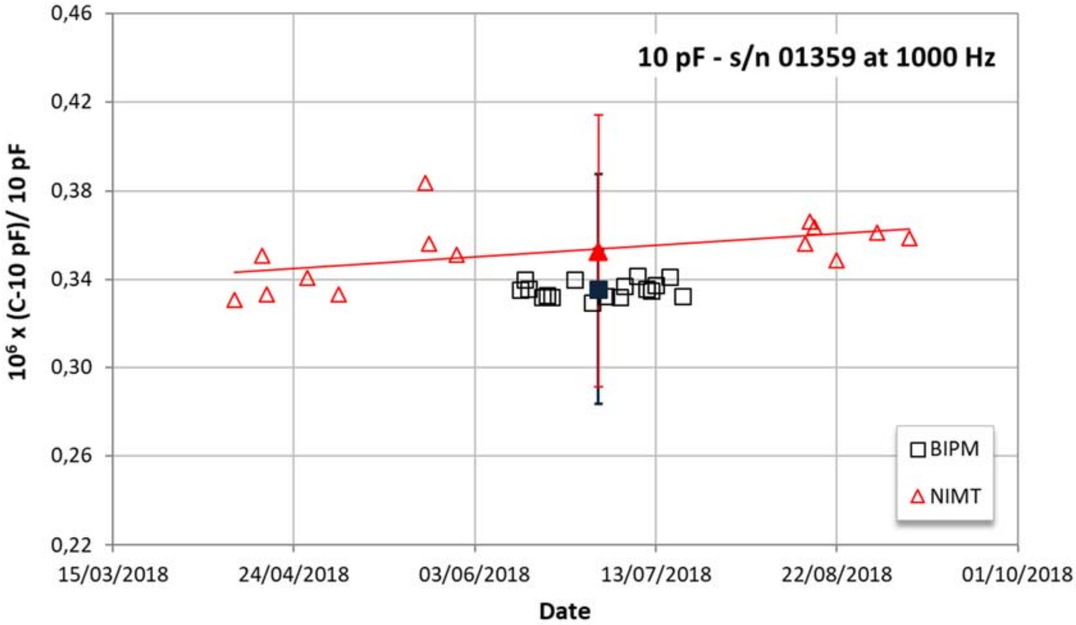

Figure 3: Individual measurements for 10 pF standard s/n 01359 showing NIMT measurements and linear fit, BIPM measurements, BIPM mean value at the mean date (black square dot) with 1σ uncertainty bar, and NIMT predicted value at the mean time of BIPM measurements (red square dot) with 1σ uncertainty bar. Measurement conditions: 1000 Hz and 15 V (rms).

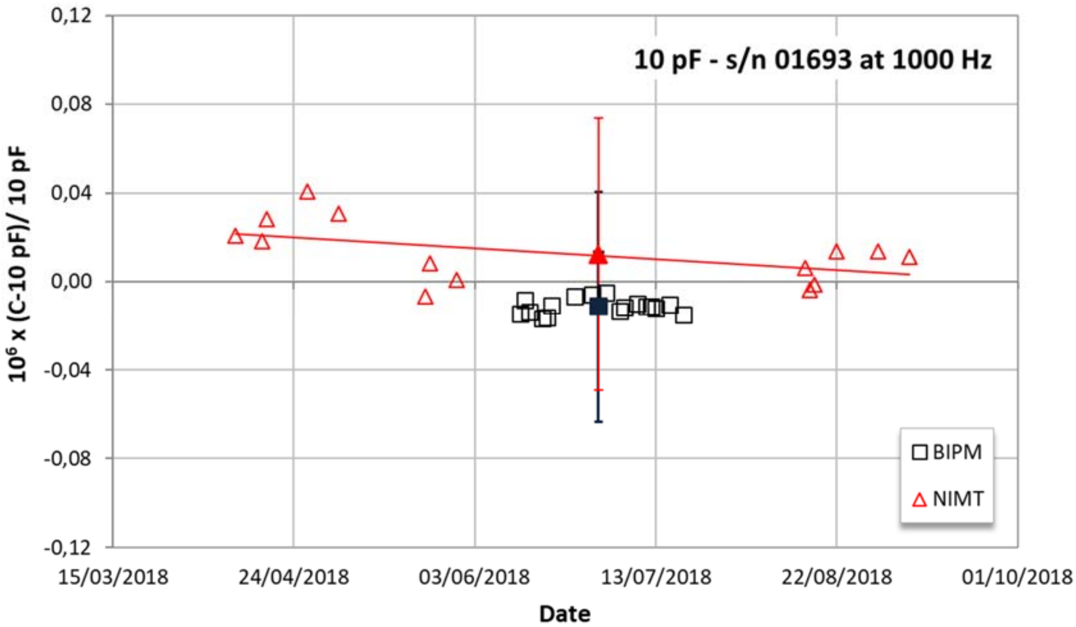

Figure 4: Individual measurements for 10 pF standard s/n 01693 showing NIMT measurements and linear fit, BIPM measurements, BIPM mean value at the mean date (black square dot) with 1σ uncertainty bar, and NIMT predicted value at the mean time of BIPM measurements (red square dot) with 1σ uncertainty bar. Measurement conditions: 1000 Hz and 15 V (rms).

4.2 Comparison of the 100 pF standard (BIPM.EM-K14.b)

All the individual measurements performed at both the NIMT and the BIPM are shown on figure 5 for operating conditions of 1592 Hz and 10 V (rms), and on figure 6 for 1000 Hz and the same voltage. In these figures are also shown the mean value of the BIPM measurements along with their uncertainty bars (1σ), and a fit of the NIMT "before" and "after" series of measurements.

As can be seen from these figures, the behavior over time of the 100 pF standard s/n 01360 is well fitted by a linear model which is used to predict the capacitance value of this standard at the mean date (C_{NIMT}, black square dot on mean date 30 June 2018). The standard uncertainty on the predicted value (u_{NIMT}) is the root sum of squares of the prediction uncertainty ($u_{\mathrm{NIMT\_pred}}$, from propagation law applied to the fitting equation) and the standard measurement uncertainty at NIMT ($u_{\mathrm{NIMT\_Single}}$, from annexed uncertainty budget of NIMT). A transport uncertainty ($u_{\mathrm{transport}}$) is also estimated for this standard; it is calculated from the residuals to the linear fit in the usual way.

The NIMT and BIPM results for standards s/n 01360 are reported in table 3 for 1592 Hz and 1000 Hz together with the values of the uncertainty components $u_{\mathrm{NIMT\_Single}}$, $u_{\mathrm{NIMT\_pred}}$, $u_{\mathrm{transport}}$ and of the combined standard uncertainties u_{NIMT} and u_{BIPM}. The uncertainty bars reported on figures 5 and 6 correspond to u_{NIMT} and u_{BIPM} (1σ).

	Standard s/n 01360	
	1592 Hz	**1000 Hz**
C_{BIPM}	99.999 998 35 pF	99.999 999 95 pF
u_{BIPM} (1σ, *rel*)	0.039×10^{-6}	0.049×10^{-6}
C_{NIMT}	99.999 998 27 pF	100.000 003 27 pF
$u_{\mathrm{NIMT\_Single}}$ (1σ, *rel*)	0.084×10^{-6}	0.115×10^{-6}
$U_{\mathrm{NIMT\_pred}}$ (1σ, *rel*)	0.007×10^{-6}	0.002×10^{-6}
u_{NIMT} (1σ, *rel*)	0.084×10^{-6}	0.115×10^{-6}
$u_{\mathrm{transport}}$ (1σ, *rel*)	0.025×10^{-6}	0.007×10^{-6}
Δ_{01360} = (C_{NIMT}- C_{BIPM})/100 pF	**-0.001×10^{-6}**	**0.033×10^{-6}**

Table 3: Results along with measurement, prediction and transport uncertainties for standard s/n 01360 at 1592 Hz and 1000 Hz, and an applied voltage of 10 V (rms).

The value of the relative difference between the NIMT and the BIPM at 100 pF is then, from table 3:

At 1592 Hz, Δ_{01360}= -0.001×10^{-6}

with the combined relative standard uncertainty on the difference given by,

$$u = \sqrt{u_{BIPM}{}^2 + u_{NIMT}{}^2 + u_{transport}{}^2} = -0.096\times10^{-6}$$

This result can be summarized in the form of a degree of equivalence, D_{NIMT}, between the NIMT and the BIPM for measurements for 100 pF standards at 1592 Hz and 10 V (rms), with its associated uncertainty, U_{DNIMT} (k=2, 95% confidence):

$$\boldsymbol{D_{\mathrm{NIMT}} = (C_{\mathrm{NIMT}}-C_{\mathrm{BIPM}}) / 100\ \mathrm{pF} = 0.00\times10^{-6} \quad \text{with} \quad U_{\mathrm{DNIMT}} = 0.19\times10^{-6}}$$

At 1000 Hz, Δ_{01360} = 0.033×10⁻⁶

with the combined relative standard uncertainty on the difference given by,

$$u = \sqrt{u_{BIPM}{}^2 + u_{NIMT}{}^2 + u_{transport}{}^2} = 0.125\times10^{-6}$$

This result can be summarized in the form of a degree of equivalence, D_{NIMT}, between the NIMT and the BIPM for measurements for 100 pF standards at 1000 Hz and 10 V (rms), with its associated uncertainty, U_{DNIMT} (k=2, 95% confidence):

$$\boldsymbol{D_{\text{NIMT}} = (C_{\text{NIMT}} - C_{\text{BIPM}}) / 100\ \text{pF} = 0.03\times10^{-6} \quad \text{with} \quad U_{\text{DNIMT}} = 0.25\times10^{-6}}$$

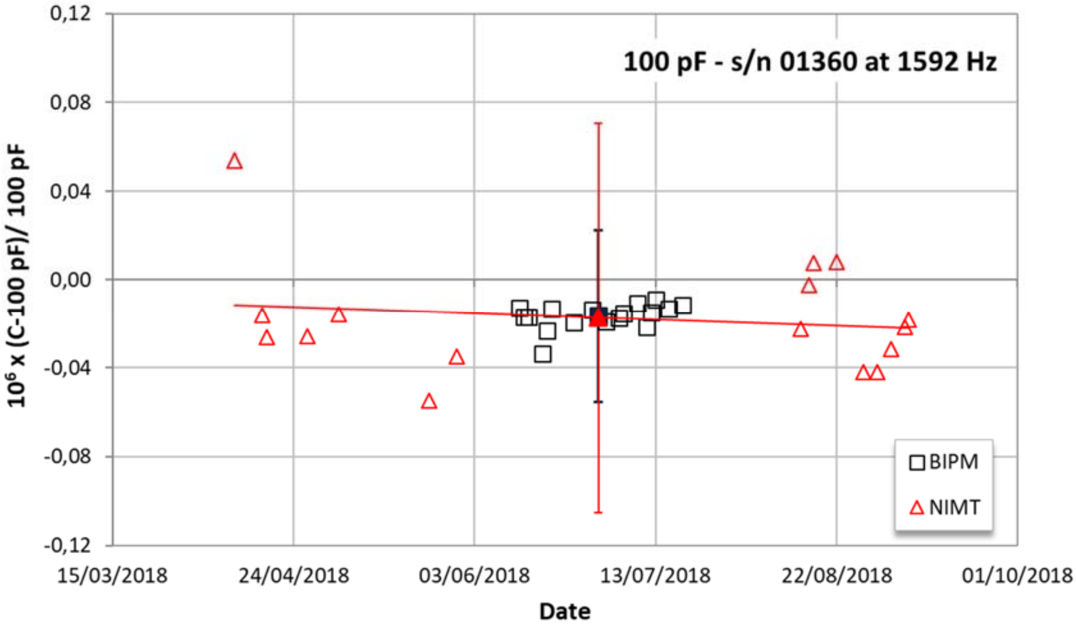

Figure 5: Individual measurements for 100 pF standard s/n 01360 showing NIMT measurements and linear fit, BIPM measurements, BIPM mean value at the mean date (black square dot) with 1σ uncertainty bar, and NIMT predicted value at the mean time of BIPM measurements (red square dot) with 1σ uncertainty bar. Measurement conditions: 1592 Hz and 10 V (rms).

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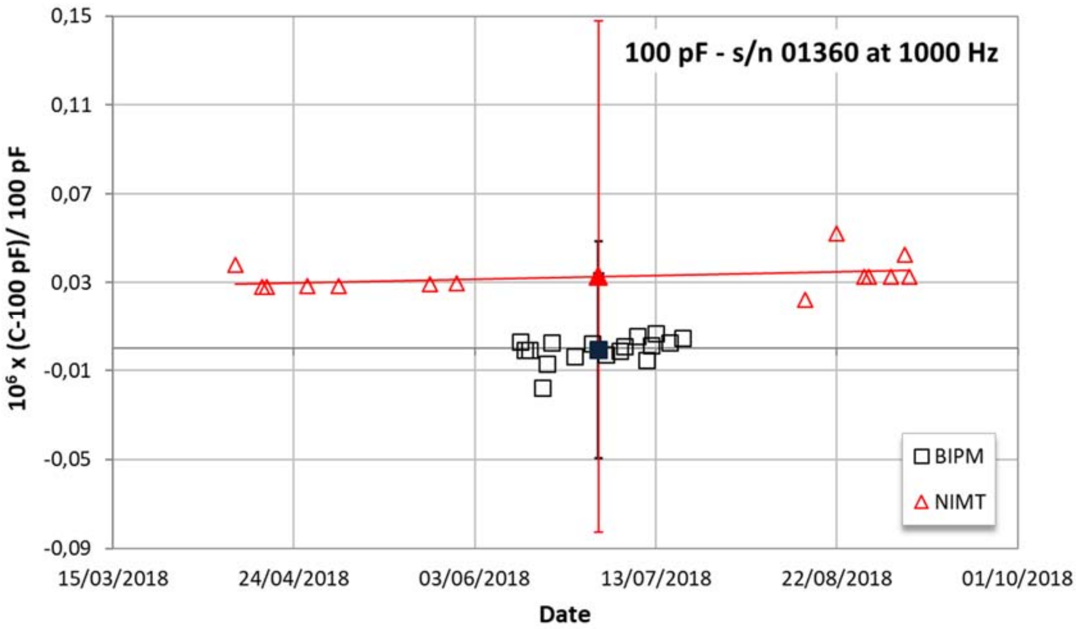

Figure 5: Individual measurements for 100 pF standard s/n 01360 showing NIMT measurements and linear fit, BIPM measurements, BIPM mean value at the mean date (black square dot) with 1σ uncertainty bar, and NIMT predicted value at the mean time of BIPM measurements (red square dot) with 1σ uncertainty bar. Measurement conditions: 1000 Hz and 10 V (rms).

5 Comments and conclusion

In this comparison both the 10 pF and 100 pF travelling standards remained stable. No drift or discontinuity of their capacitance values were observed in the 'before' and 'after' series of measurements at NMIT. The transport uncertainty components are then very small and have no effect on the final results of the comparison.

As mentioned earlier in this report, the NIMT takes its capacitance traceability from the BIPM via the calibration of its reference standards (since 2004 for two of the capacitors of the reference base and since 2012 for the two others). The interpretation of the present bilateral comparison may therefore not be clear as there is no independent realization of the farad at the NIMT which is being tested. However, what is being tested is the ability of the NIMT to extrapolate the value of its reference standard from previous calibration results and to provide a continuous calibration service to its clients.

References

[1] Protocol for BIPM on-going key comparisons of 10 pF and 100 pF capacitance standards (BIPM.EM-14a and BIPM.EM-K14b), *BIPM publication*

[2] 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**, n°2, pp 533-537 (2005)

[3] Guide to the expression of uncertainty in measurement, GUM, JCGM 100:2008, https://www.bipm.org/utils/common/documents/jcgm/JCGM_100_2008_E.pdf

Annex - Uncertainty budgets

A.1 BIPM uncertainty budget

The total uncertainty values reported in this table correspond to the uncertainty on a single capacitance measurement at the BIPM, referred as u_{BIPM_Single} in the report. The repeatability of the measurements (type A) is not reported in the table but it remains low enough (5×10^{-9} or less) to not modify the total uncertainty values (in bold).
Degrees of freedom are large enough to consider an expansion factor of k=2 at 95% of confidence.

Component	**Relative Uncertainty /10^{-9}**
Values at 1 Hz of 51.6 kΩ resistors used in quadrature bridge, with respect to R_{K-90}	14
1 Hz – 1541 Hz difference of 51.6 kΩ resistors	22
Operation of quadrature bridge at 1541 Hz	13
Scaling from 2000 pF capacitors of quadrature bridge to 10 pF reference	15
Extrapolation of the value of the 10 pF reference group	14
Link between unknown and 100 pF reference standard	18.5 @ 10 pF 21.5 @ 100 pF
Uncertainty on voltage correction (change from 100 V to 15 V)	20
Uncertainty on frequency correction (change from 1592 Hz to 1000 Hz)	30
Total for 10 pF at 1592 Hz and 15 V rms	**43**
Total for 10 pF at 1000 Hz and 15 V rms	**52**
Total for 100 pF at 1592 Hz and 10 V rms	**39**
Total for 100 pF at 1000 Hz and 10 V rms	**49**

All values are standard uncertainties (1σ estimates).

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A.2 NIMT uncertainty budget

The following tables report the uncertainty budgets for the measurement by NIMT of the 10 pF and 100 pF travelling standards (referred as u_{NIMT_Single} in the report). The principle of measurement is described in a previous section of the report.

Uncertainty Budget for 10 pF standard @ 1592 Hz

Component	Relative Uncertainty / 10^{-9}
Drift of group standard	0.87
Capacitance change with frequency	0.8
Resolution of capacitance bridge AH 2700	2.9
Temperature coefficient of standard	3.3
Standard uncertainty of standard group (AH11A s/n 01693) at 100 V	13.3
Voltage coefficient for s/n 01693	3.3
Standard uncertainty of standard group (AH11A s/n 01694) at 100 V	13.3
Voltage coefficient for s/n 01694	3.3
Standard uncertainty of standard group (AH11A s/n 01695) at 100 V	13.3
Voltage coefficient for s/n 01695	3.3
Measured difference between s/n 01359 and s/n 01693	3.2
Measured difference between s/n 01359 and s/n 01694	2.5
Measured difference between s/n 01695 and s/n 01359	2.2
Repeatability	1.3
Combined uncertainty @ 1 σ (*)	**41.0**
Expanded uncertainty @ confident level 95.45 %, k = 2.65 ($\nu = 5$)	**110**

(*) The correlation in the calibration measurements of the capacitance of the base capacitors is taken into account in the computation of the combined uncertainty.

Uncertainty Budget for 100 pF standard @ 1592 Hz

Component	Relative Uncertainty /10^{-8}
Reference standard AH1A (s/n 01359)	4.00
Temperature coefficient of reference standard	0.60
Error in bridge transformer ratio of 1:10	6.4
Uncorrected due to lead inductance and capacitance	0.10
Voltage coefficient of reference standard	0.17
Hysteresis resulting from temperature cycling	2.89
Resolution of Capacitance Bridge at 100 pF	0.29
Drift of reference standard	1.50
Repeatability	0.73
Combined uncertainty @ 1 σ	**8.4**
Expanded uncertainty @ confidence level 95.45 %, k = 2.00	**16.8**

Uncertainty Budget for 10 pF standard @ 1000 Hz

Component	Relative Uncertainty / 10^{-9}
Drift of group standard	0.87
Resolution of capacitance bridge AH 2700	2.9
Temperature coefficient of standard	3.3
Standard uncertainty of standard group (AH11A s/n 01693) at 100 V	20.0
Voltage coefficient for s/n 01693	3.3
Standard uncertainty of standard group (AH11A s/n 01694) at 100 V	20.0
Voltage coefficient for s/n 01694	3.3
Standard uncertainty of standard group (AH11A s/n 01695) at 100 V	20.0
Voltage coefficient for s/n 01695	3.3
Measured difference between s/n 01359 and s/n 01693	3.3
Measured difference between s/n 01359 and s/n 01694	2.3
Measured difference between s/n 01695 and s/n 01359	2.7
Repeatability	1.2
Combined uncertainty @ 1 σ (*)	**60.6**
Expanded uncertainty @ confidence level 95.45 %, *k* = 2.65 ($\nu = 5$)	**161**

(*) *The correlation in the calibration measurements of the capacitance of the base capacitors is taken into account in the computation of the combined uncertainty.*

Uncertainty Budget for 100 pF standard @ 1000 Hz

Component	Relative Uncertainty / 10^{-8}
Reference standard AH1A (s/n 01359)	6.00
Temperature coefficient of reference standard	0.58
Error in bridge transformer ratio of 1:10	9.10
Uncorrected due to lead inductance and capacitance	0.04
Voltage coefficient of reference standard	0.17
Hysteresis resulting from temperature cycling	2.89
Resolution of Capacitance Bridge at 100 pF	0.29
Drift of reference standard	1.62
Repeatability	0.36
Combined uncertainty @ 1 σ	**11.5**
Expanded uncertainty @ confidence level 95.45 %, *k* = 2.00	**23.1**