Rapport BIPM-03/01

Bureau International des Poids et Mesures

Bilateral Comparison of 10 pF and 100 pF Capacitance Standards

(ongoing BIPM key comparisons BIPM.EM-K14.a and BIPM.EM-K14.b)

between the NPL and the BIPM, April/May 2002

by F. Delahaye * and S.A. Awan**

*Bureau International des Poids et Mesures, F-92312 Sèvres Cedex

** National Physical Laboratory, Teddington, Middlesex TW11 0LW, United Kingdom

January 2003, revised July 2004

Pavillon de Breteuil, F-92312 Sèvres Cedex

Bilateral Comparison of 10 pF and 100 pF Capacitance Standards between the NPL and the BIPM, April/May 2002

by F. Delahaye * and S.A. Awan**

*Bureau International des Poids et Mesures, F-92312 Sèvres Cedex

** National Physical Laboratory, Teddington, Middlesex TW11 0LW, United Kingdom

Introduction

This comparison is a subsequent bilateral comparison which follows comparisons CCEM-K4 (10 pF at 1592 Hz) and EUROMET-345 (10 pF and 100 pF at 1592 Hz and some other frequencies, including 1000 Hz). The present bilateral comparison was carried out on 10 pF and 100 pF capacitance standards measured at 1592 Hz and 1000 Hz. The measurements were made in April/May 2002. The comparison procedure follows those parts of the "Guidelines for CIPM key comparisons" (Appendix F of the MRA) that are appropriate for bilateral comparisons. The BIPM was the pilot laboratory.

Travelling standards

The comparison was somewhat unusual in that two sets of travelling standards were used, one belonging to the NPL, the other to the BIPM. The NPL standards are two Andeen-Hagerling model AH11A capacitance modules having nominal values of 10 pF (S/N 01031) and 100 pF (S/N 01032), mounted in a frame model AH1100 (S/N 00010). These are the same standards and frame which were used in EUROMET-345. The BIPM standards are four Andeen-Hagerling model AH11A capacitance modules having nominal values of 10 pF (S/N 01309 and 01310) and 100 pF (S/N 01312 and 01313), mounted in a frame model AH1100 (S/N 00105).

The two NPL standards have been modified with additional internal screening to ensure a true two-terminal pair definition. This is not the case for the BIPM standards. The effect of ambient temperature on both the NPL and BIPM standards mounted in their frames has been tested in the range 20 °C to 25 °C. No changes in the capacitance values greater than 1 part in 10^8 have been detected. The rms values of the ac voltage applied to the standards for their measurement are identical for both laboratories: 10 V for the 100 pF standards and 100 V for the 10 pF standards.

Measurement principle

Both laboratories measured the capacitance standards in terms of the recommended value of the von Klitzing constant, R_{K-90} = 25 812. 807 Ω, through the use of a capacitance bridge with ratio 10/1, a quadrature bridge, an ac-dc resistor with calculable frequency dependence of resistance, and a quantum Hall device operated at dc (NPL) or at 1 Hz (BIPM). The NPL capacitance bridge is a four terminal-pair bridge, that of the BIPM a two terminal-pair one. The NPL calculable resistor is quadrifilar with nominal value 1000 Ω; that of the BIPM is coaxial with nominal value 1 290.6 Ω.

Results

- Measurements at 1592 Hz

Tables 1 to 6 gives the values measured at 1592 Hz by the two laboratories for the six travelling capacitance standards. All values are expressed as relative deviations from the nominal capacitance value, expressed in parts in 10^6. The results are presented in graphical form in Figures 1 to 6. The last line of each table gives the NPL and BIPM evaluations of the capacitance values at the reference date of the measurements (09/05/2002). These evaluations are obtained applying linear least-squares fits to the data. Also given in the last line is the value of $D_{\mathrm{NPL\text{-}BIPM}}$, the difference between the NPL and BIPM measurement results at the reference date, and an estimate of its standard uncertainty, u_{D} (in this report, all uncertainties are one standard-deviation estimates). For the results obtained with the NPL travelling standards (Tables 1 and 2), u_{D} is equal to 0.059×10^{-6} and is the rss sum of the uncertainty of the NPL measurements (0.041×10^{-6}, see Annex 1), of that of the BIPM measurements (0.037×10^{-6}, see Annex 1), and of the transfer uncertainty which is estimated to be 0.020×10^{-6} , based on the consistency between the initial and return measurements of the travelling standards. For the results obtained with the BIPM travelling standards (Tables 3 to 6), u_{D} is equal to 0.071×10^{-6} and includes an additional uncertainty of 0.040×10^{-6} arising from the imperfect two terminal-pair definition of the standards. This uncertainty was estimated from the imperfect closure (40 parts in 10^9) of capacitance-ratio measurements carried out at the NPL and involving the BIPM unmodified AH standards as well as standards with true two terminal-pair definition. In contrast, closure of similar measurements carried out at the NPL and involving the NPL modified AH standards was achieved to within 1 part in 10^9.

Table 1: 10 pF capacitance S/N 01031 at 1592 Hz.

Date	Deviation measured at the NPL / 10^{-6}	Deviation measured at the BIPM / 10^{-6}		
12/04/2002	-1.0600			
16/04/2002	-1.0640			
26/04/2002		-1.1302		
29/04/2002		-1.1291		
01/05/2002		-1.1314		
06/05/2002		-1.1276		
13/05/2002		-1.1295		
21/05/2002		-1.1246		
24/05/2002	-1.0594		$\boldsymbol{D_{\mathrm{NPL\text{-}BIPM}} / 10^{-6}}$	$\boldsymbol{u_{\mathrm{D}} / 10^{-6}}$
09/05/2002	**-1.0605**	**-1.1282**	**0.068**	**0.059**

Table 2: 100 pF capacitance S/N 01032 at 1592 Hz.

Date	Deviation measured at the NPL / 10^{-6}	Deviation measured at the BIPM / 10^{-6}		
12/04/2002	-3.2160			
16/04/2002	-3.2160			
26/04/2002		-3.2861		
29/04/2002		-3.2822		
01/05/2002		-3.2875		
06/05/2002		-3.2819		
13/05/2002		-3.2885		
21/05/2002		-3.2806		
24/05/2002	-3.1750		**$D_{NPL-BIPM}$ /10^{-6}**	**u_D /10^{-6}**
09/05/2002	**-3.1905**	**-3.2842**	**0.094**	**0.059**

Table 3: 10 pF capacitance S/N 01309 at 1592 Hz.

Date	Deviation measured at the NPL / 10^{-6}	Deviation measured at the BIPM / 10^{-6}		
05/03/2002		0.0211		
07/03/2002		0.0215		
04/04/2002		0.0155		
12/04/2002		0.0193		
22/04/2002		0.0433		
09/05/2002	0.1160			
21/05/2002		0.0342		
23/05/2002		0.0034		
28/05/2002		0.0018	**$D_{NPL-BIPM}$ /10^{-6}**	**u_D /10^{-6}**
09/05/2002	**0.1160**	**0.0180**	**0.098**	**0.071**

Table 4: 10 pF capacitance S/N 01310 at 1592 Hz.

Date	Deviation measured at the NPL / 10^{-6}	Deviation measured at the BIPM / 10^{-6}		
05/03/2002		0.0047		
07/03/2002		0.0048		
04/04/2002		0.0012		
12/04/2002		-0.0152		
22/04/2002		-0.0122		
09/05/2002	0.0940			
21/05/2002		-0.0198		
23/05/2002		-0.0202		
28/05/2002		-0.0220	**$D_{NPL-BIPM}$ /10^{-6}**	**u_D /10^{-6}**
09/05/2002	**0.0940**	**-0.0164**	**0.110**	**0.071**

Table 5: 100 pF capacitance S/N 01312 at 1592 Hz.

Date	Deviation measured at the NPL / 10^{-6}	Deviation measured at the BIPM / 10^{-6}		
05/03/2002		0.3023		
07/03/2002		0.3039		
04/04/2002		0.3135		
12/04/2002		0.3259		
22/04/2002		0.3320		
09/05/2002	0.4140			
21/05/2002		0.3466		
23/05/2002		0.3427		
28/05/2002		0.3449	$\boldsymbol{D}_{\mathbf{NPL\text{-}BIPM}}$ **/10^{-6}**	$\boldsymbol{u}_{\mathbf{D}}$ **/10^{-6}**
09/05/2002	**0.4140**	**0.3373**	**0.077**	**0.071**

Table 6: 100 pF capacitance S/N 01313 at 1592 Hz.

Date	Deviation measured at the NPL / 10^{-6}	Deviation measured at the BIPM / 10^{-6}		
05/03/2002		-0.0144		
07/03/2002		-0.0198		
04/04/2002		-0.0383		
12/04/2002		-0.0276		
22/04/2002		-0.0292		
09/05/2002	0.0330			
21/05/2002		-0.0261		
23/05/2002		-0.0325		
28/05/2002		-0.0346	$\boldsymbol{D}_{\mathbf{NPL\text{-}BIPM}}$ **/10^{-6}**	$\boldsymbol{u}_{\mathbf{D}}$ **/10^{-6}**
09/05/2002	**0.0330**	**-0.0308**	**0.064**	**0.071**

For each nominal value of capacitance (10 pF and 100 pF) we proceed in two steps to obtain the final comparison result. First, we calculate the simple mean of the two results obtained with the two BIPM travelling standards. Second, we take the weighted mean of that mean result and of the result obtained with the NPL travelling standard. For the result obtained with the NPL standard, the weight is proportional to t^{-2}, where t is the transfer uncertainty (2×10^{-8}). For the mean of the two results obtained with the BIPM standards the weight is proportional to $(t^2/2 + s^2)^{-1}$, where s is the uncertainty associated with the imperfect two terminal-pair definition (4×10^{-8}). All other uncertainties, which correspond essentially to systematic errors common to all measurements of $D_{\text{NPL-BIPM}}$, are not taken into account for the evaluation of the weights. The total uncertainty of the weighted mean is not significantly different from that of the result obtained with the NPL travelling standard.

The final comparison result at the 10 pF level and at 1592 Hz is:

$\boldsymbol{D}_{\mathbf{NPL\text{-}BIPM}}$ **= 0.075 ×10^{-6}** with a combined standard uncertainty of **0.059 ×10^{-6}**.

The final comparison result at the 100 pF level and at 1592 Hz is:

$\boldsymbol{D}_{\mathbf{NPL\text{-}BIPM}}$ **= 0.090 ×10^{-6}** with a combined standard uncertainty of **0.059 ×10^{-6}**.

- Measurements at 1000 Hz

The results for the six travelling standards are given in Table 7, in the form $d = (C_{1592\ \mathrm{Hz}} - C_{1000\ \mathrm{Hz}})/C_{1592\ \mathrm{Hz}}$, where $C_{1592\ \mathrm{Hz}}$ is the capacitance value measured at 1592 Hz and $C_{1000\ \mathrm{Hz}}$ the capacitance value measured at 1000 Hz. The last line of the table gives the difference d_{NPL}-d_{BIPM} between the values of d as measured by the NPL and the BIPM. The standard uncertainty of d is 0.058×10^{-6} for the NPL (see Annex 1) and 0.034×10^{-6} for the BIPM (see Annex 1), giving a combined rss sum of 0.067×10^{-6} for the uncertainty on d_{NPL}-d_{BIPM}.

Table 7: Values of $d = (C_{1592\ \mathrm{Hz}} - C_{1000\ \mathrm{Hz}})/C_{1592\ \mathrm{Hz}}$ as measured by the two laboratories.

	10 pF 01031	100 pF 01032	10 pF 01309	10 pF 01310	100 pF 01312	100 pF 01313
NPL	$+0.006\times10^{-6}$	$+0.110\times10^{-6}$	$+0.011\times10^{-6}$	$+0.013\times10^{-6}$	$+0.123\times10^{-6}$	$+0.108\times10^{-6}$
BIPM	-0.038×10^{-6}	-0.024×10^{-6}	-0.038×10^{-6}	-0.032×10^{-6}	-0.029×10^{-6}	-0.047×10^{-6}
$\boldsymbol{d_{\mathrm{NPL}}\text{-}d_{\mathrm{BIPM}}}$	$\mathbf{+0.044\times10^{-6}}$	$\mathbf{+0.134\times10^{-6}}$	$\mathbf{+0.049\times10^{-6}}$	$\mathbf{+0.045\times10^{-6}}$	$\mathbf{+0.152\times10^{-6}}$	$\mathbf{+0.155\times10^{-6}}$

Taking mean values, at the 10 pF level, the result is:

d_{NPL}-$d_{\mathrm{BIPM}} = 0.047 \times 10^{-6}$ with a combined standard uncertainty of 0.067×10^{-6},

and at the 100 pF level:

d_{NPL}-$d_{\mathrm{BIPM}} = 0.147 \times 10^{-6}$ with a combined standard uncertainty of 0.067×10^{-6}.

Combining these differences and uncertainties with those in the comparison results at 1592 Hz, we obtain the final comparison results at 1000 Hz, again expressed as $D_{\mathrm{NPL\text{-}BIPM}}$, the difference between the NPL and BIPM capacitance measurement results at the reference date.

The final comparison result at the 10 pF level and at 1000 Hz is:

$\boldsymbol{D_{\mathrm{NPL\text{-}BIPM}} = 0.028 \times 10^{-6}}$ with a combined standard uncertainty of $\mathbf{0.089 \times 10^{-6}}$.

The final comparison result at the 100 pF level and at 1000 Hz is:

$\boldsymbol{D_{\mathrm{NPL\text{-}BIPM}} = -\ 0.057 \times 10^{-6}}$ with a combined standard uncertainty of $\mathbf{0.089 \times 10^{-6}}$.

Figure 1: 10 pF S/N 01031 at 1592 Hz
values and expanded uncertainties (*k* = 2) of the measurements at each laboratory

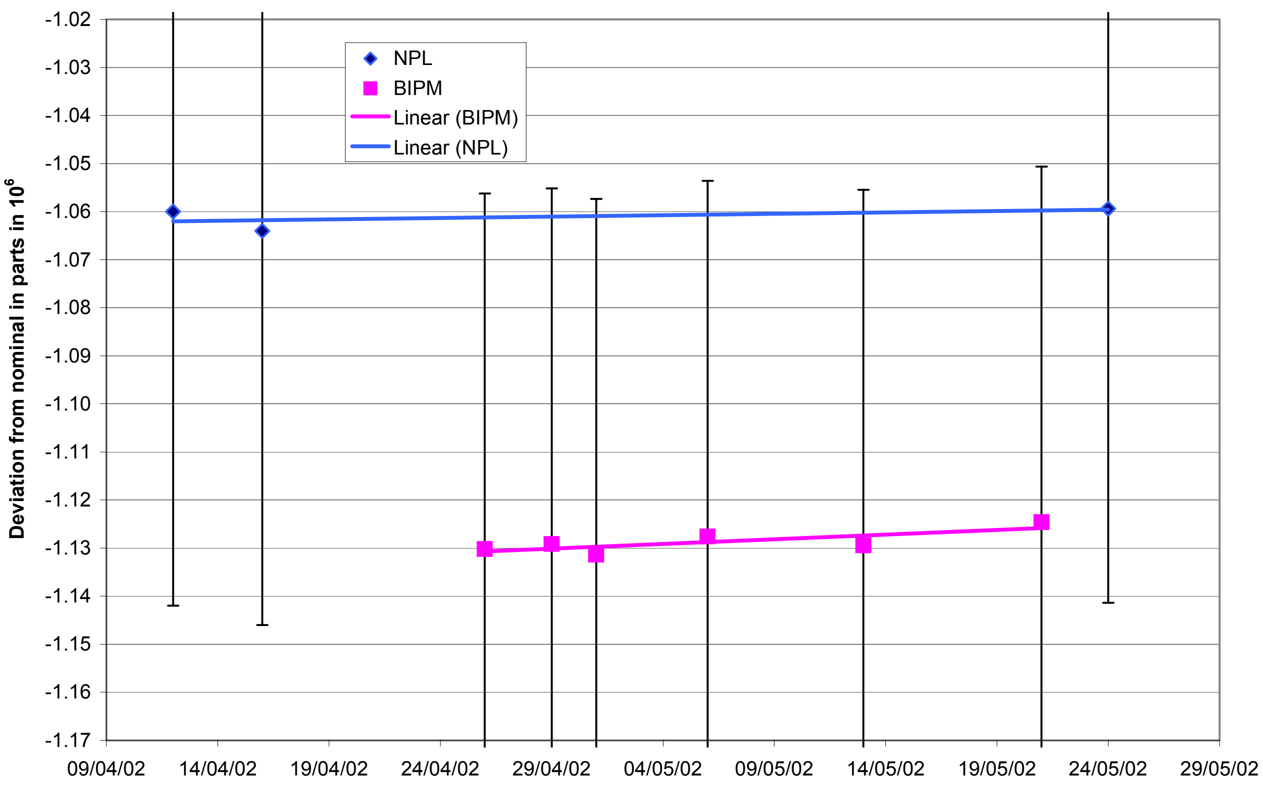
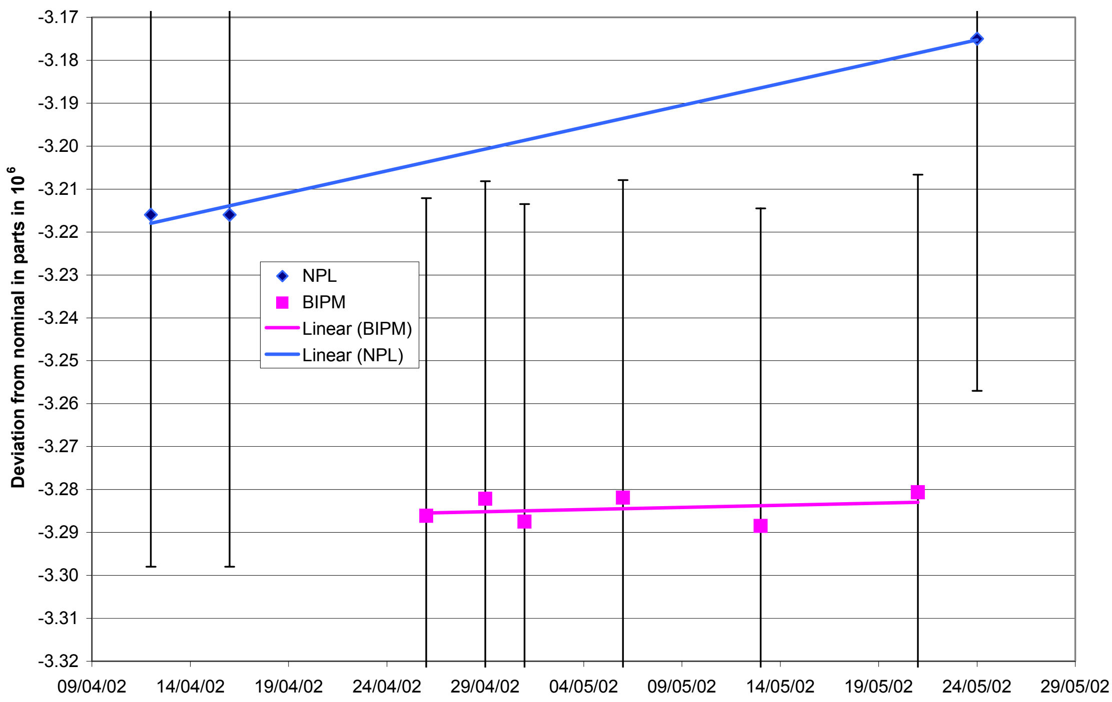


Figure 2: 100 pF S/N 01032 at 1592 Hz
values and expanded uncertainties (*k* = 2) of the measurements at each laboratory



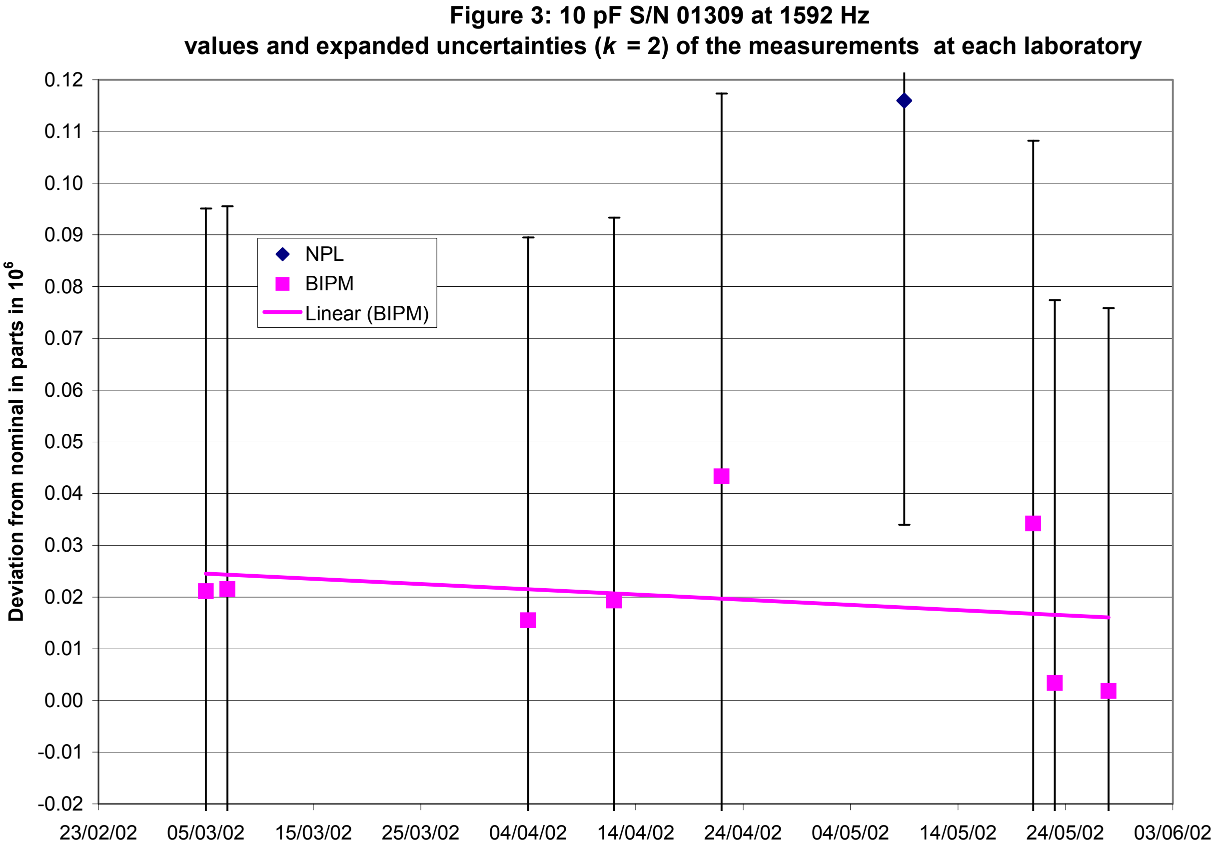


Figure 3: 10 pF S/N 01309 at 1592 Hz
values and expanded uncertainties (k = 2) of the measurements at each laboratory
NPL
BIPM
Linear (BIPM)
Deviation from nominal in parts in 10^6
0.12
0.11
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
-0.01
-0.02
23/02/02
05/03/02
15/03/02
25/03/02
04/04/02
14/04/02
24/04/02
04/05/02
14/05/02
24/05/02
03/06/02

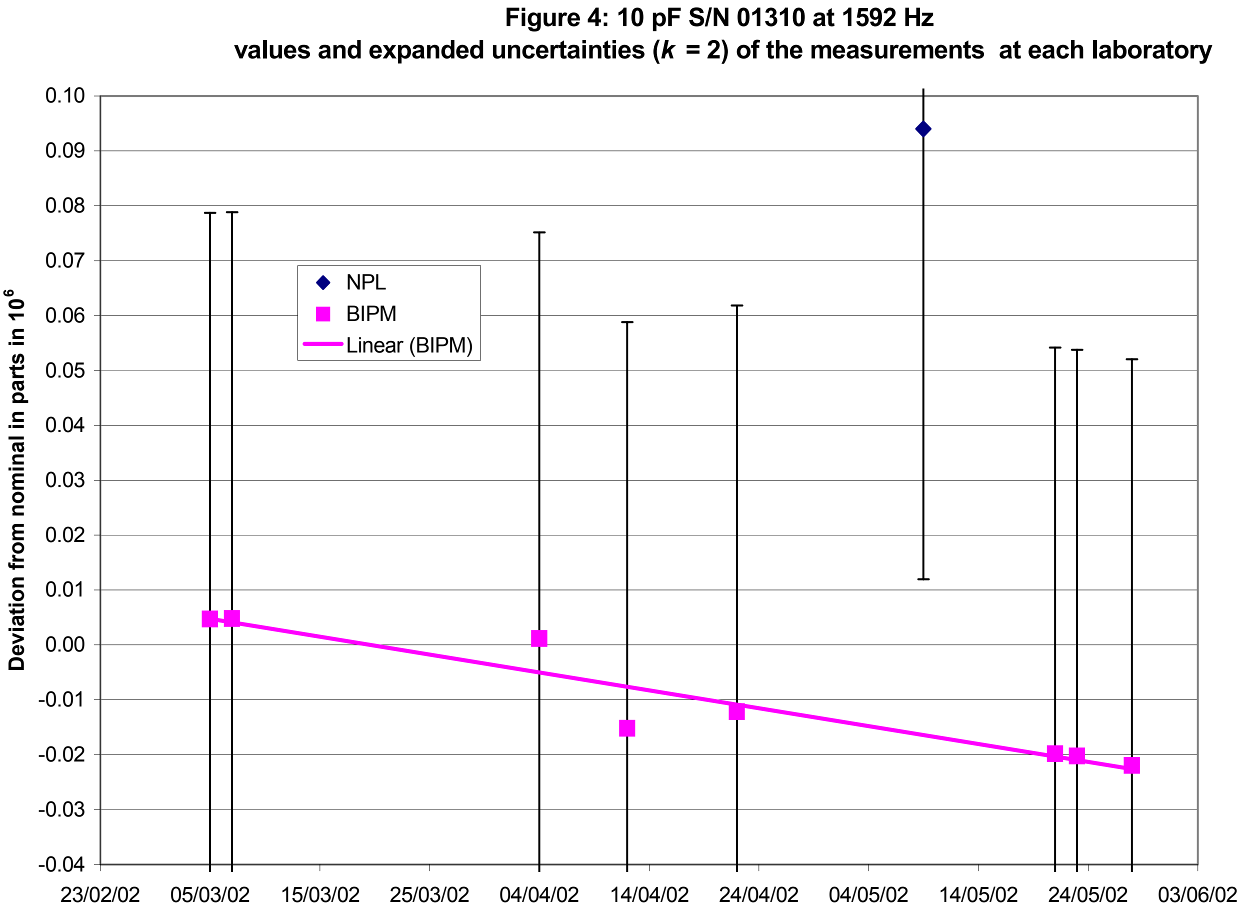


Figure 4: 10 pF S/N 01310 at 1592 Hz
values and expanded uncertainties (k = 2) of the measurements at each laboratory
NPL
BIPM
Linear (BIPM)
Deviation from nominal in parts in 10^6
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
-0.01
-0.02
-0.03
-0.04
23/02/02
05/03/02
15/03/02
25/03/02
04/04/02
14/04/02
24/04/02
04/05/02
14/05/02
24/05/02
03/06/02

Figure 5: 100 pF S/N 01312 at 1592 Hz
values and expanded uncertainties (*k* = 2) of the measurements at each laboratory

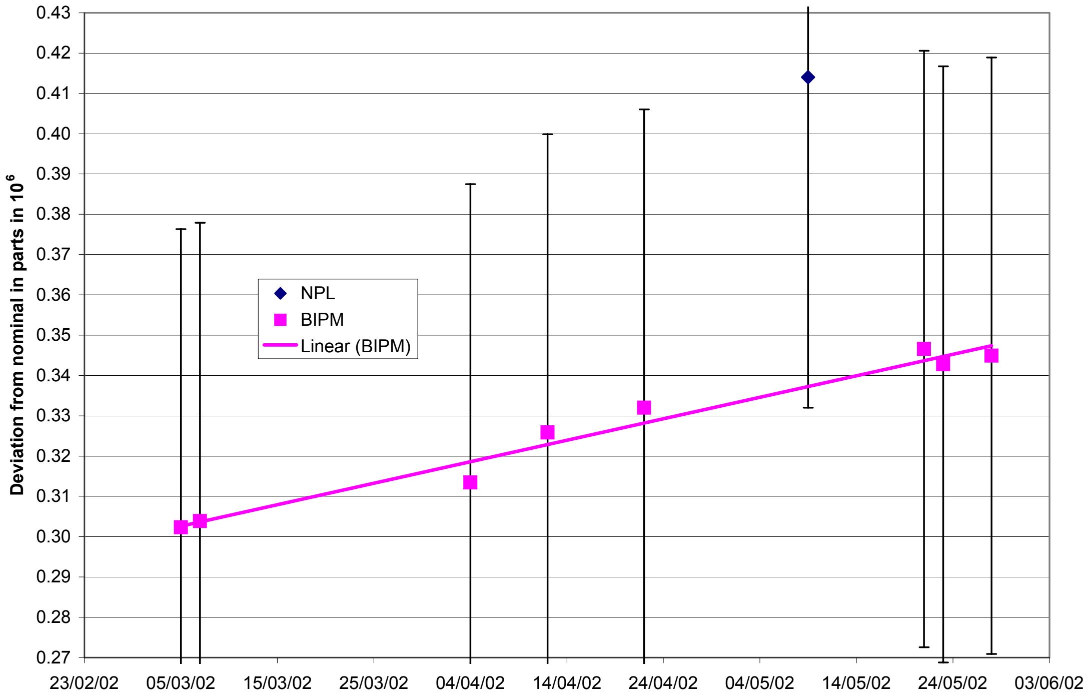
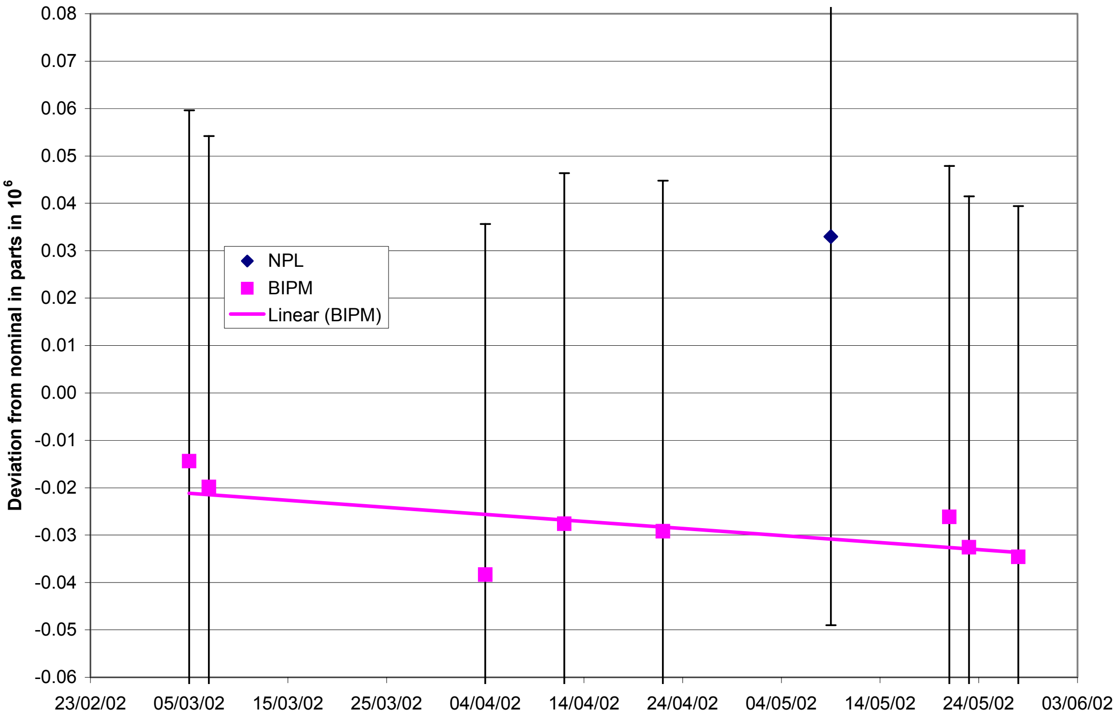


Figure 6: 100 pF S/N 01313 at 1592 Hz
values and expanded uncertainties (*k* = 2) of the measurements at each laboratory



Annex 1. Uncertainty budgets

NPL uncertainty budget:

The relative standard uncertainties (1σ) in the measurement at 1592 Hz of the 10 pF or 100 pF capacitances with respect to the quantized Hall resistance measured at dc are, in parts in 10^9 :

Measurement	Component	nΩ/Ω or nF/F
$R_H(2) \rightarrow 1$ kΩ	RH(2) to 100 Ohm Transport of 100 Ohm 100 Ohm to 1 kOhm	20 10 5 **(23)**
1 kΩ → 100 kΩ	Repeatability Current transformer Bridge network Voltage transformer Temperature / drift	5 14 10 6 6 **(20)**
100 kΩ → 1 nF	Repeatability Frequency Harmonics Bridge network Temperature	2 14 5 10 4 **(19)**
1 nF → 100pF or 10 pF	Repeatability Voltage correction Bridge network Voltage transformer Voltage injection Temperature	2 10 10 9 5 6 **(19)**
	Total	**41**

For the evaluation of the capacitance change from 1592 Hz to 1000 Hz, the relative standard uncertainties are :

Bridge correction from 1592 Hz to 1000 Hz : 30×10^{-9}

Frequency dependence of 10 pF reference standard : 50×10^{-9}

Total rss uncertainty: 58×10^{-9}

BIPM uncertainty budget:

The relative standard uncertainties (1σ) in the measurement at 1592 Hz of the 10 pF or 100 pF capacitances with respect to the quantized Hall resistance measured at 1 Hz are, in parts in 10^9 :

Source of uncertainty	Relative standard uncertainty in parts in 10^9	
Comparison with 10 pF BIPM group:		
Repeatability	5	
Change of 10 pF reference from 1541 Hz to 1592 Hz	5	
Bridge imperfection including divider ratio	10	**(12)**
10 pF/2000 pF link :		
Repeatability	2	
Voltage divider calibration	6	
Voltage injection	5	
Imperfect current equalizer	4	**(9)**
Quad bridge (2000 pF to 51.6 kΩ)		
Repeatability	5	
Effect of harmonics	5	
Two-terminal pair definition of capacitors	10	
Imperfect current equalizers	5	
Frequency	1	**(13)**
Measurement of 51.6 kΩ/ R_K ratio at 1 Hz		
Repeatability	10	
R_K/100 Ω ratio measurement	5	
400 Ω/ 100 Ω Hamon divider	5	
51.6 kΩ / 400 Ω ratio measurement	5	**(13)**
1 Hz-1541 Hz difference for 51.6 kΩ resistances		
Reference coaxial 1290.6 Ω resistance	2	
Link coaxial resistance to intermediate 12.6 kΩ resistance	20	
Link 12.6 kΩ to 51.6 kΩ	20	**(28)**
Combined standard uncertainty		**37**

For the evaluation of the capacitance change from 1592 Hz to 1000 Hz, the relative standard uncertainties are :

Bridge measurement uncertainty: 15×10^{-9}

Frequency dependence of 10 pF reference standard. : 30×10^{-9}

Total rss uncertainty: 34×10^{-9}