BUREAU INTERNATIONAL
DES POIDS ET MESURES

Consultative Committee for Electricity and Magnetism

Comparison CCEM-K4.2017
of 10 pF and 100 pF Capacitance Standards

Final report, November 2018

BIPM, International *: P. Gournay, R. Chayramy and B. Rolland*
METAS, Switzerland *: F. Overney*
NIM, China *: Y. Yang, L. Huang and Z. Lu*
NIST, United States of America *: Y. Wang and A. Koffman*
NMIA, Australia *: L. Johnson and R. Xie*
NPL, United Kingdom : *J. Belliss, S. Giblin and B. Thornton*
PTB, Germany *: J. Schurr and J. Lee*
VNIIM, Russia : *Y. Semenov*

Pierre Gournay
Bureau International des Poids et Mesures, BIPM
Pavillon de Breteuil, Sèvres, France

Abstract

In 2017 the Consultative Committee for Electricity and Magnetism (CCEM) commissioned a key comparison of electrical capacitance standards, the second time this quantity has been compared since the implementation of the Mutual Recognition Agreement by the Comité International des Poids et Mesures (CIPM-MRA) in 1999. This comparison - CCEM-K4.2017 - was piloted by the Bureau International des Poids et Mesures (BIPM) and included seven National Metrology Institutes (NMI) belonging to four Regional Metrology Organizations.

The measuring scheme adopted for the comparison was that of a star comparison consisting of a set of bilateral comparisons between the participating NMIs and the BIPM, whose capacitance reference base served as a common reference. For each of the bilateral comparisons, the measurands were the capacitance values of 10 pF travelling standard capacitors belonging to the NMIs and, optionally, the values of 100 pF standards.

All the participants have been chosen from those able to realize and maintain a representation of the farad at the best known level of accuracy. Four of them, including the BIPM, were taking their traceability from dc or ac quantum Hall effect standards and, the four others, from a calculable capacitor.

The comparison results analysis have evidenced an agreement within about ±5 parts in 10^8 for the mandatory 10 pF measurements and within about ±10 parts in 10^8 for the optional 100 pF measurements. Also, excepted for one of the participants, a good agreement has been found for the ratio 100 pF:10 pF (within ±5 parts in 10^8).

In addition to the comparison, it has been possible to evaluate the difference between the value of R_K (von Klitzing constant) measured by electrical means from calculable capacitors and its last CODATA recommended value (CODATA 2014 adjustment). A difference of (43 ± 23) parts in 10^9 ($k = 1$) has been found which is consistent with the difference that can be computed from the experimental data used in the CODATA 2014 adjustment of fundamental constants.

This report presents the details of the measurements and analysis having led to these results.

Table of contents

1. Introduction

The Mutual Recognition Agreement (MRA) drawn up by the Comité International des Poids et Mesures (CIPM) provides the framework within which National Metrology Institutes (NMIs) demonstrate the equivalence of their measurement standards. The technical basis underpinning the CIPM MRA consists of international comparisons of standards for several key quantities identified by the different Consultative Committees (CCs) of the CIPM. These key comparisons are carried out by the CCs, the Bureau International des Poids et Mesures (BIPM) and the Regional Metrology Organizations (RMOs), usually at the lowest possible level of uncertainty. They most often include a limited number of NMIs from each RMOs and are complemented with regional key comparisons within the RMOs.

Among the electromagnetic quantities the Consultative Committee for Electricity and Magnetism (CCEM) has identified electrical capacitance, at a value of 10 pF, as one of those key quantities. As such, it is regularly compared within the framework of the CCEM-K4 key comparison.

The last CCEM-K4 comparison was carried out between 1996 and 1999 and has involved ten NMIs from four RMOs and the BIPM. The travelling standards were two 10 pF capacitors belonging to the National Institute of Standards and Technology (NIST), which was also the pilot institute of the comparison. A set of regional key comparisons carried out within EURAMET (European Association of National Metrology Institutes), SIM (Inter-American Metrology System) and APMP (Asia Pacific Metrology Program) has subsequently complemented the comparison CCEM-K4. The results of all these comparisons are reported in references [1] to [4].

During the 12th meeting of the Working Group on Low Frequency Quantities (WGLF) of the CCEM in March 2013 it was decided to repeat this comparison. The general principles of the comparison were discussed during the 13th WGLF meeting in March 2015 and the BIPM was designated as the pilot institute. Measurements took place between late February 2017 and late October 2017. Seven NMIs and the BIPM were involved in this comparison, all with an independent realization of the Farad, either from a quantum Hall resistor (QHR) by means of a quadrature bridge, or from a calculable capacitor.

General rules for "Measurement comparisons in the CIPM MRA" detailed in the document CIPM-MRA-D-05 [5] as well as the complementary recommendations of the "CCEM Guidelines for Planning, Organizing, Conducting and Reporting Key, Supplementary and Pilot Comparisons" [6] have been applied throughout the preparation and the realization of the comparison.

The following sections will report on the general principles of the comparison and the travelling standards, on the quantities to be measured and the measuring conditions, on the measurement method and traceability chain implemented by the participating NMIs and, finally, on the measurement results and their analysis.

2. Principle of the comparison measurements

The measuring scheme which has been passed by the CCEM for this comparison is that of a star-comparison consisting in carrying out simultaneously a large number of bilateral comparisons piloted by the BIPM. In such a scheme, each participating institute has to send its own capacitance standards to the BIPM for measurement against the BIPM reference capacitance standards over the same time period. These measurements are preceded and followed by 'initial' and 'return' series of measurements carried out by the NMIs of their own standards (participant-BIPM-participant measuring scheme). Initial and return measurements are reported to the BIPM, which is in charge of the reporting and analysis of the comparison results.

The benefit of this organizational scheme is to shorten the comparison duration and to be more robust against possible transport problems. It has already been successfully used for the key comparison CCEM-K1 of 1 Ω and 10 kΩ in 1990 [7].

3. Participants

Seven institutes from four RMOs (APMP, COOMET, EURAMET, SIM) plus the BIPM were involved in this comparison:

BIPM, International

METAS, Switzerland, EURAMET

NIM, China, APMP

NIST, United States of America, SIM

NMIA, Australia, APMP

NPL, United Kingdom, EURAMET

PTB, Germany, EURAMET

VNIIM, Russia, COOMET

The details regarding the contact persons designated for the comparison are given in annex 1.

4. Travelling standards

4.1. General requirement

In the comparison scheme adopted the travelling standards are those of the participating institutes. Each institute sent two 10 pF standard capacitors for measurement at the BIPM. Sending more than one capacitor reduces the risk of unexpected mechanical or thermal shocks to the artefacts during transportation invalidating the comparison measurements. Our experience at the BIPM is that individual standard capacitors, even when mounted in the same thermo-regulated frame, may respond differently to transportation events.

An optional measurement at 100 pF was proposed to the participants as well. All the participants have also sent one or two 100 pF capacitance standards.

It was asked that the capacitance standards sent out to the BIPM for measurement be suitable for measurement at an uncertainty level of a few parts in 10^8 or less and that the capacitance values be close to the nominal values within 1 part in 10^4. All participants sent commercial thermo-regulated fused-silica capacitor of type AH11A from Andeen-Hagerling enclosed in a single AH1100 frame.

4.2. Travelling capacitance standards

As said above, only sets of fused silica standards type AH11A from Andeen-Hagerling, Inc. were sent by the participants at the BIPM for measurement. All sets were contained in their own AH1100 frame.

Detailed technical information about AH11A standard capacitors and AH1100 frame can be obtained from the supplier's web site [8].

Table 1 summarizes the identification numbers of the travelling standards and frames sent by the participants.

Institute	**ID of the AH11A capacitance standards sent**		**ID number of the AH1100 frame**
	10 pF	**100 pF**	
METAS	s/n 1191 s/n 1300	s/n 1188 s/n 1189	00049
NIM	s/n 1606 s/n 1682	s/n 1596 s/n 2090	00200342
NIST	s/n 1423 s/n 1424	s/n 1442 s/n 1452	00141
NMIA	s/n 1416 s/n 1479	s/n 1677 s/n 1459	00139
NPL	s/n 1186 s/n 1101	s/n 1100 s/n 1185	00039
PTB	s/n 1257 s/n 1258	s/n 1256 s/n 1157	00088
VNIIM	s/n 2204 s/n 2205	s/n 2207	00200366

Table 1: Summary of the identification numbers of the travelling standards and frames used in the comparison.

4.3. Quantities to be measured

4.3.1. Measurand

The measurand is the two-terminal pair capacitance value at the front panel input sockets of the measured standard capacitor (i.e. corrected for possible effect of the connecting cables, if required). For this measurement, each institute used the measuring method it usually implements for the realization and dissemination of the farad.

With a view of making directly comparable the measurement results reported by each of the participating institutes, it was asked to provide the pilot with the capacitance measurements in the SI farad unit. This means, for those institutes whose traceability is based on a quantized Hall resistance, that the value of the von Klitzing constant used for the computation of their results is not $R_{\mathrm{K\text{-}90}}$ but the value issued from the last CODATA adjustment of fundamental constants [9]. This value is R_{K} = 25 812.807 4555 Ω with a relative uncertainty of 2.3×10^{-10}.

4.3.2. Measurement voltages and frequencies

The recommended rms voltage values to be applied on the mandatory 10 pF and the optional 100 pF standard capacitors were 100 V and 10 V, respectively. This recommendation was respected by all the participants either because the capacitance measurements have effectively been carried out at these voltages or because the voltage coefficient of the standards have been determined and a correction applied.

The recommended measurement frequency was 1592 Hz. However, the optional frequency value of 1233 Hz was possible for NMIs running their quadrature transfer at this frequency.

Only two institutes performed their measurements at 1233 Hz, the PTB and METAS. However, the PTB determined the frequency dependence of its standards through a series of measurements at a second frequency, 2466 Hz, and reported its capacitance measurements at 1592 Hz. Regarding METAS, for which only measurements at 1233 Hz were possible, the BIPM determined the frequency coefficients of its standards (during the series of measurements carried out at the BIPM) and applied the required corrections to the measurements reported by this institute.

4.3.3. Environmental conditions

The recommended ambient temperature and relative humidity were (23 ± 1)°C and (50 ± 10)% respectively. These two quantities were recorded and reported by all participants for each capacitance measurement, together with the atmospheric pressure.

While the relative humidity is not expected to impact the capacitance value of the AH11A standard capacitors, its sensitivity to ambient temperature changes may in some cases be non-negligible at the level of uncertainty targeted in this comparison. In effect, possibly due to differences in their temperature control electronics, some AH11A standards exhibit a very low temperature sensitivity while others may see their capacitance value change by 1 or 2 parts in 10^8 per degree of ambient temperature fluctuation [10]. Consequently, each participant was ask to consider this known possible error source and apply if necessary the required correction and/or consider this error in its uncertainty budget.

As for relative humidity, atmospheric pressure was not expected to have any effect on the measurements. Nevertheless, some of the capacitance standards belonging to one of the participants have shown a small dependence on pressure. The pressure coefficients of these standards, determined from the recording of the atmospheric pressure during capacitance measurements, were of the order of 1 part in 10^9 per hPa (see section 10.6). A correction for atmospheric pressure was subsequently applied to the capacitance measurements for these standards.

It must be noticed that the atmospheric pressure dependence has been possible to evaluate thanks to the reduced measuring noise of those standards (resulting from shielding improvement of their input terminals). It should not been excluded that other standards in this comparison, subjected to higher measuring noise or fluctuations, have such pressure dependence that cannot be detected (extracted from measuring noise).

5. Time schedule

As described earlier, 'initial' and 'return' measurements were carried out by the participating NMIs and, in between, all standards were sent to the BIPM where they were measured simultaneously.

Five weeks were scheduled for each of the measurement series performed at the NMIs, and eight weeks for those at the BIPM. All the participants carried out at least 10 measurements during each of the initial and return series (typically two measurements per week separated by three or four days). As the period of measurement at the BIPM was longer, a greater number of measurements were taken. This number may differ from one NMI to another depending on the time the standards stayed effectively at the BIPM and on the short time stability of the standards.

Before and after the measurements at the BIPM, a period of four weeks was scheduled for transportation, customs clearance formalities and thermal stabilization of the standards. Globally, this time period has been respected by the participants and has been found to be sufficient.

Except for a short delay in the start date for one participant, the comparison progressed as planned. Also, all the measurement reports were sent within a reasonable timeframe (within two months of the end of the last series of measurements).

The initial schedule planned in the comparison technical protocol is reported in annex 2 and the actual schedule of the comparison is reported in table 2 below.

		METAS	NIM	NIST	NMIA	NPL	PTB	VNIIM
1st series of measurements	Meas. starting date	06-Mar-17	02-Mar-17	01-Mar-17	08-Mar-17	27-Feb-17	27-Feb-17	14-Mar-17
	Meas. ending date	07-Apr-17	31-Mar-17	31-Mar-17	31-Mar-17	05-Apr-17	31-Mar-17	15-May-17
	No. of measurements	11	10	10	14	10	15	11
2nd series of measurements	Standards at BIPM on	12-Apr-17	12-Apr-17	12-Apr-17	11-Apr-17	13-Apr-17	11-Apr-17	26-May-17
	Meas. starting date	02-May-17	02-May-17	02-May-17	02-May-17	02-May-17	02-May-17	31-May-17
	Meas. ending date	05-Jul-17	13-Jul-17	05-Jul-17	04-Jul-17	22-Jun-17	04-Jul-17	07-Aug-17
	No. of measurements	33	31	23	23	24	33	32
	Standards left BIPM on	05-Jul-17	13-Jul-17	06-Jul-17	05-Jul-17	22-Jun-17	04-Jul-17	07-Aug-17
3rd series of measurements	Meas. starting date	02-Aug-17	01-Aug-17	25-Jul-17	31-Jul-17	24-Jul-17	24-Jul-17	25-Aug-17
	Meas. ending date	07-Sep-17	30-Aug-17	01-Sep-17	22-Aug-17	31-Aug-17	01-Sep-17	26-Oct-17
	No. of measurements	10	10	10	14	12	18	15
Sending of the report of measurements		25-Oct-17	17-Nov-17	29-Sep-17	23-Nov-17	17-Oct-17	27-Sep-17	06-Nov-17

Table 2: Actual schedule of the CCEM-K4.2017 comparison

6. Transportation and stability of travelling standards

Organization of the shipping of the standards has been well managed by all the participants. They opted for three different modes of transportation: by private car while standards were remaining powered (METAS, PTB), by airplane with the unpowered standards as accompanied luggage (NIM), and by airfreight with the standards unpowered (NIST, NMIA, NPL, VNIIM).

In common with other types of standard capacitors, the AH capacitance standards occasionally show unstable behaviour after transportation and repowering. The lack of stability may appear as fluctuations in the capacitance value of the order of a few parts in 10^8 around the mean value for a limited period of time, or as an increased drift with a stabilization time longer than the duration of the comparison.

To avoid too much dispersion of the measurements due to possible initial fluctuations of the standards after repowering, the simple thing to do is to wait a time long enough before starting measurements. However, without knowledge of the behaviour of each individual standard at repowering, this waiting time must be fixed arbitrarily. For most of the standards, a 'safety' delay of three weeks was kept between their arrival at the BIPM and the starting date of measurements. Only the VNIIM standards have had a lower stabilization time due to some delay in their arrival time at the BIPM, but no unexpected capacitance fluctuations were observed (see section10.7).

Even with these precautions some of the standard capacitors have shown limited fluctuations of their capacitance value within several parts in 10^8. However, except for these residual fluctuations, the great majority of the standards don't appear to have been significantly affected by transportation, whatever the mode of transportation. Notice that the stabilization time before the return series was chosen by the participants and was not necessarily of three weeks duration.

Two standards from NPL of nominal values 10 pF (#1186) and 100 pF (#1185) showed a significant long-duration drift of 3 and 1 parts in 10^7, respectively, even after the three weeks delay (see section 10.5). Those two standards were removed from the comparison but without excluding NPL from the comparison as two capacitance standards of each value had been sent for measurement at the BIPM. Also, one of the two 10 pF standards from NIM (#1682) has experienced a step change during the measurements at the BIPM and has been removed from the comparison as well.

No other standards have been removed from the comparison.

7. Principles of capacitance measurements

The principles and the traceability of the measurements carried out by the participating NMIs are reported in annex 3.

A feature of this comparison is that one half of the participants take their traceability from a calculable capacitor and the other half from the last CODATA adjustment of the von Klitzing constant R_K.

This will provide the opportunity, as part of the comparison, to realize a determination of the difference between the estimated value of R_K from the comparison measurements and its adjusted CODATA value (section 14).

8. Measurements carried out at other frequencies than 1592 Hz

The reference frequency was fixed in the protocol to 1592 Hz. Most of the participants carried out their measurements at this frequency excepted METAS and PTB whose usual reference operating frequency is 1233 Hz. The results presented in this report for these two NMIs are therefore extrapolated measurements at 1592 Hz.

The PTB determined the frequency dependence of its standards and corrected its own measurements by extrapolating from 1233 Hz to 1592 Hz. The estimation of the frequency coefficients of the PTB's standards is detailed below. METAS provided its measurements to the pilot at the frequency of 1233 Hz and the pilot determined the frequency coefficient of METAS's standards during the series of measurements carried out at BIPM. The method used by BIPM to estimate the frequency coefficients is similar to that used by PTB.

8.1. Determination of frequency dependence of standards from PTB

To determine the frequency dependence, all capacitance standards have been measured by PTB at the end of both calibration periods within one day at 1233 Hz and 2466 Hz. The reproducibility of the capacitance change is found to be worse than the calculated measurement uncertainty. PTB explains this as follows: compared to the measurements at only one frequency, the number of steps to be carried out is two times larger and requires two times more measuring time. Consequently, the increase of the ambient temperature during the measurements is two times larger. It is also inevitable that some standards are measured at the two frequencies with a time lag of several hours. As a result, the influence of the instability of the travelling and the transfer standards is much larger. This may explain the observed scatter of the frequency dependence. However, the mean value is taken as the best estimate and the measured standard deviation is taken as the type A uncertainty. The resulting frequency dependences are quoted in Table 3 (and agree with previous measurements of PTB).

$\Delta C_N/C_{nominal} = (C_N(2466\text{ Hz}) - C_N(1233\text{ Hz}))/C_{nominal}$ and combined uncertainty (k = 1) (µF/F)			
AH#1256	AH#1157	AH#1257	AH#1258
-0.062 ± 0.042	-0.012 ± 0.028	-0.117 ± 0.029	-0.130 ± 0.028

Table 3: Difference of the relative deviations of the capacitance standards from nominal measured at 2466 Hz and 1233 Hz, and the associated type A uncertainty (k = 1).

In the limited frequency range relevant here, the frequency dependence of the capacitance standards can be considered as being linear. This allows interpolation to any frequency *f* according to,

$$C_\mathrm{N}(f) = C_\mathrm{N}(1233.15\ \mathrm{Hz}) + \frac{f(\mathrm{Hz}) - 1233.15}{2466.30 - 1233.15} \cdot \Delta C_\mathrm{N} \text{ with } \Delta C_\mathrm{N} = C_\mathrm{N}(2466.30\ \mathrm{Hz}) - C_\mathrm{N}(1233.15\ \mathrm{Hz}) \quad (1)$$

with N being the serial number of the respective capacitance standard. C_N and ΔC_N can be considered to being either the absolute capacitance values in farad or the relative deviations from nominal in µF/F.

This equation is used to interpolate the capacitance values to the reference frequency *f* = 1591.55 Hz :

$$C_\mathrm{N}(1591.55\ \mathrm{Hz}) = C_\mathrm{N}(1233.15\ \mathrm{Hz}) + 0.2906 \cdot \Delta C_\mathrm{N} \quad (2)$$

with ΔC_N being defined in equation (1) and given in Table 3.

The measurement of the frequency dependence of the standards from PTB has also been carried out at the BIPM. The measurement procedure is strictly the same as the one used by PTB but between the two frequencies 1027 Hz and 1592 Hz.

The relative deviations of the capacitance of each of the PTB's standards between 1027 Hz and 1592 Hz have been regularly measured ten times between 05/05/2017 and 03/07/2017 in order to reduce the type A component. For all standards it has been reduced to 0.6 parts in 10^8 or less.

In Table 4 are reported the frequency coefficients measured by BIPM together with those measured by PTB. These coefficients are expressed in ppm/kHz and correspond for PTB to the value ΔC_N divided by (2466.30 Hz – 1233.15 Hz).

	For PTB: C_N(2466 Hz) - C_N(1233 Hz) / (2466.30 - 1233.15) and combined uncertainty (*k* = 1) *For BIPM:* C_N(1592 Hz) - C_N(1027 Hz) / (1591.55 - 1027.62) and combined uncertainty (*k* = 1) (µF/F per kHz)			
	AH#1256	AH#1157	AH#1257	AH#1258
PTB	-0.050 ± 0.034	-0.010 ± 0.023	-0.095 ± 0.024	-0.105 ± 0.023
BIPM	-0.047 ± 0.098	0.012 ± 0.098	-0.075 ± 0.089	-0.095 ± 0.089

Table 4: Frequency coefficients of the standards from PTB as measured by PTB and BIPM and the associated combined uncertainty (*k* = 1).

8.2. Determination of frequency dependence of standards from METAS

In a similar manner as PTB, the BIPM measured the frequency dependence of the standards from METAS. A series of ten measurements of their capacitance deviation between 1027 Hz and 1592 Hz have been carried out between 05/05/2017 and 30/06/2017. Type A uncertainties of the frequency corrections were reduced down to about 3 parts in 10^9 for the two 100 pF standards (standards #01188 and #01189) but were significantly higher for the two 10 pF standards, of the order of 10 and 20 parts in 10^9 (standards #01300 and #01191).

Differences ΔC_N between the relative deviations from nominal at 1027 Hz and 1592 Hz for the four METAS's capacitance standards, as well as the frequency coefficient value between these two frequencies (linear variation hypothesis) are given in Table 5.

	AH#1191	AH#1300	AH#1188	AH#1189
ΔC_N in μF/F	-0.024 ± 0.050	-0.012 ± 0.050	-0.006 ± 0.055	-0.166 ± 0.055
Frequency coefficient in μF/F per kHz	-0.043 ± 0.089	-0.021 ± 0.089	-0.011 ± 0.098	-0.294 ± 0.098

Table 5: Differences between the relative deviations from nominal at 1027.62 Hz and 1591.55 Hz of the capacitance standards from METAS, and related frequency coefficients between these two frequencies. Measurements carried out at the BIPM. Uncertainty values correspond to the combined standard uncertainty (k = 1).

The capacitance values $C_\mathrm{N}(1233.15\ \mathrm{Hz})$ measured at 1233 Hz by METAS and reported to the pilot have been interpolated to 1592 Hz using values of ΔC_N of Table 5 and according to the following relationship:

$$C_\mathrm{N}(1591.55\ \mathrm{Hz}) = C_\mathrm{N}(1233.15\ \mathrm{Hz}) + \left(\frac{1591.55 - 1233.15}{1591.55 - 1027.62}\right) \times \Delta C_\mathrm{N}$$

The uncertainty on this extrapolation is estimated at 0.032×10^{-6} and 0.035×10^{-6} for 10 pF and 100 pF standards, respectively.

9. Method for computing the difference between the institutes and the BIPM

The measurement results obtained during this comparison were analyzed according to the basic principle that a set of N bilateral comparisons have been carried out simultaneously, N corresponding to the number of participating institutes. Since all these comparisons were performed using N different sets of travelling capacitance standards, the BIPM serves as a common reference. The group of reference capacitors of the BIPM and its traceability are described in annex 3, section A3-1.

We present below the way the results of the comparison measurements will be analyzed in the next section. The method chosen is the one usually used by the BIPM for bilateral comparisons. It is considered to be the most reliable in particular when some dispersion is observed on the measurement results of one or several series of measurements (from the institute or from the BIPM). Moreover, it is the 'natural' way to proceed (linear drift hypothesis) if there is no specific and large perturbation related to transportation of the standards, which is the case in this comparison as previously mentioned.

According to the comparison scheme, each of the participating institutes performed initial and return measurements of their own capacitance standards. Between the initial and return measurements, the BIPM measured all standards from all NMIs during the same limited time period.

For each of the institutes, the reference capacitance value corresponding to a particular standard is defined as the value interpolated from the measurement series of the BIPM at the mean date of its measurement period. This reference capacitance value is then compared to the value measured by the institute, the latter being interpolated from the set of data composed of both the initial and return series of measurements, at the mean date of measurement at BIPM.

From our knowledge of the normal ageing of fused silica capacitors linear drifts are expected, at least over the short duration of the comparison. The BIPM's reference value at the mean comparison date and the corresponding institute's measurement value are then obtained from the interpolations of simple linear least square fittings.

Below are detailed the successive calculation steps followed to determine the difference between the reference value and the institute value. The index i is used to differentiate between the institutes and the index j is the number of the measurement in a series of n measurements carried out at the institute or at the BIPM.

Let us consider the three data sets obtained for a single capacitance standard belonging to the institute *i*, where the notation *D* stands for the date of the measurement and *C* for the capacitance measurement (corrected for all necessary effects and in particular from cable influence):

- the initial measurement series at the institute: $(D_{i,j}^{Init};\,C_{i,j}^{Init})$ with u_i^{Init} the standard uncertainty on $C_{i,j}^{Init}$,
- the intermediate series at the BIPM: $(D_{i,j}^{BIPM};\,C_{i,j}^{BIPM})$ with u_i^{BIPM} the standard uncertainty on $C_{i,j}^{BIPM}$,
- and the return series at the institute: $(D_{i,j}^{Return};\,C_{i,j}^{Return})$ with u_i^{Return} the standard uncertainty on $C_{i,j}^{Return}$.

The reference capacitance value $\boldsymbol{C_i^{ref}}$ is computed from the linear least squares interpolation of the set of data points $(D_{i,j}^{BIPM};\,C_{i,j}^{BIPM})$ at the mean date $\overline{\boldsymbol{D_i^{BIPM}}}$ with,

$$\overline{D_i^{BIPM}} = \frac{1}{n}\sum_{j=1}^{n} D_{i,j}^{BIPM}$$

and the relative standard uncertainty associated with C_i^{Ref} is estimated as being,

$$u\left(C_i^{ref}\right) = \sqrt{\frac{s_{BIPM}^2}{n} + (u_i^{BIPM})^2},$$

where s_{BIPM}^2/n is the estimator of the relative variance of the interpolated capacitance value C_i^{ref} at the date $\overline{D_i^{BIPM}}$, and u_i^{BIPM} is the relative standard uncertainty of a single capacitance measurement $C_{i,j}^{BIPM}$.

In a similar way, the capacitance value $\boldsymbol{C_i}$ obtained by the institute *i* at the same mean date $\overline{D_i^{BIPM}}$ is calculated from the linear least squares interpolation of the set of data points composed of both the initial and return sets of data, $\left(D_{i,j}^{Init};\,C_{i,j}^{Init}\right) \cup \left(D_{i,j}^{Return};\,C_{i,j}^{Return}\right)$.

The relative combined uncertainty associated with C_i is estimated from the quadratic sum of the prediction uncertainty $u_{pred}(C_i)$ obtained by applying the law of propagation of uncertainty on the equation of the fitting line of the data set $\left(D_{i,j}^{Init};\,C_{i,j}^{Init}\right) \cup \left(D_{i,j}^{Return};\,C_{i,j}^{Return}\right)$, and of the relative standard uncertainty of a single measurement, u_i, reported by the NMI. The value of u_i corresponds to u_i^{Init} or u_i^{Return} if those two values are identical or, if not, to their mean value.

Thus, we have,

$$u(C_i) = \sqrt{u_{pred}^2(C_i) + (u_i)^2}\,.$$

From the above determined values of C_i^{Ref} and C_i the relative difference between the institute *i* and the BIPM is simply given by,

$$\Delta_i = \left(C_i - C_i^{ref}\right)/C_N\,,$$

where C_N is the nominal value of the standard capacitor considered (10 pF or 100 pF). It may be mentioned that for the institutes deriving their capacitance standards from R_K, there exists a correlation between the institute's measurements and the BIPM's measurements. This correlation has an impact which is negligible and has not been accounted for.

The relative combined uncertainty for the difference Δ_i is,

$$u(\Delta_i) = \sqrt{u(C_i)^2 + u\left(C_i^{ref}\right)^2}$$

with $u(C_i^{ref})$ and $u(C_i)$ defined as mentioned above.

In the particular case where an effect on the measurements due to transportation could be identified, and a corresponding uncertainty component u_{tr} estimated, then $u(\Delta_i)$ will correspond to,

$$u(\Delta_i) = \sqrt{u(C_i)^2 + u\left(C_i^{ref}\right)^2 + u_{tr}^2}$$

Also, in case the institute i has sent two standard capacitors of the same nominal value having both given exploitable measurement results, the relative difference Δ_i for this institute will be calculated as the arithmetic mean of the two calculated differences. We chose here to use an arithmetic mean rather than a weighted mean because the type A and B uncertainty components for the measurements of two different 10 pF and 100 pF standards are almost always the same and, if not, they are not significantly different (see NMI's uncertainty statements in annex 5). We thus would have:

$$\Delta_i = \frac{\Delta_{i,1} + \Delta_{i,2}}{2}$$

with $\Delta_{i,1}$ and $\Delta_{i,2}$ the relative differences between the measurements carried out by the institute i and the BIPM for two standards of same nominal value (numbered 1 and 2).

The calculation of the combined uncertainty of the mean Δ_i value, is computed taking into account both the correlation between the NMI measurements and the correlation between BIPM measurements. Only type B components are considered to be correlated and the combined uncertainty is estimated as being:

$$u(\Delta_i) = \sqrt{u_B^2(C_i) + u_B^2\left(C_i^{ref}\right) + \frac{1}{2}\left(u_A^2(C_i) + u_A^2\left(C_i^{ref}\right)\right) + u_{tr}^2}$$

with $u_A^2(C_i)$, $u_B^2(C_i)$, $u_A^2\left(C_i^{ref}\right)$ and $u_B^2\left(C_i^{ref}\right)$ the type A and B uncertainty components of the institute i and of the BIPM, respectively (the numerical values of these components are obtained from uncertainty statements in annex 5). It may be noticed that for a few participants some correlation could, to some extent, also be considered for the type A components. However, taking into account those correlations would change the final results of the comparison by only a few parts in 10^{10}. For this reason, these correlations have been omitted.

The above calculation procedure is repeated for each of the N institutes involved in the comparison that is to say for the N simultaneous bilateral comparisons carried out. We then obtain a set of N differences Δ_i between each of the NMIs and the BIPM capacitance reference group of capacitors.

In addition to the comparison of capacitance values at 10 pF and 100 pF, it is possible to compare the 100 pF:10 pF ratio of the participants. For the institute i, if $C_i(10pF)$ and $C_i(100pF)$ are, respectively, the measurements at 10 pF and 100 pF, this ratio is defined as,

$$\frac{C_i(100pF)}{C_i(10pF)} = 10\left(1 + \varepsilon_{i,100pF} - \varepsilon_{i,10pF}\right) = 10\left(1 + \varepsilon_{i,10:1}\right)$$

where $\varepsilon_{i,10pF}$, $\varepsilon_{i,100pF}$ and $\varepsilon_{i,10:1}$ are the deviations from nominal of $C_i(10pF)$, $C_i(100pF)$ and of the 10:1 ratio, respectively.

The standard combined uncertainty attributed to the deviation from nominal ratio $\varepsilon_{i,10:1}$ is estimated as,

$$u\left(\varepsilon_{i,10:1}\right) = \sqrt{u^2(C_i(10pF)) + u^2(C_i(100pF))}$$

with $u^2(C_i(10pF))$ and $u^2(C_i(100pF))$ the standard uncertainties on the measurements of the 10 pF and 100 pF standards, respectively, from which all the correlated contribution have been removed.

The comparison of the 10:1 ratio between participants can be achieved by comparing the differences of the deviations from the nominal 10:1 ratio measured by the NMIs ($\varepsilon_{i,10:1}$) and by the BIPM ($\varepsilon_{BIPM,10:1}$).

The difference between NMI *i* and the BIPM is simply,

$$\Delta\varepsilon_{i,10:1} = \varepsilon_{i,10:1} - \varepsilon_{BIPM,10:1}$$

with a standard uncertainty,

$$u(\Delta\varepsilon_{i,10:1}) = \sqrt{u^2(\varepsilon_{i,10:1}) + u^2(\varepsilon_{BIPM,10:1})}$$

In the case where the institute *i* has measured more than one 10 pF and/or 100 pF capacitance standards, several values of the 10:1 ratio and then several differences $\Delta\varepsilon_{i,10:1}$ can be computed. For this institute, the mean value of the calculated differences $\Delta\varepsilon_{i,10:1}$ will then be used for the comparison between participants with an uncertainty estimated to $u(\Delta\varepsilon_{i,10:1})$ – or to the mean value of the $u(\Delta\varepsilon_{i,10:1})$ if appropriate – in order to take into account the correlation between the individual computed ratios.

It is important to note that the comparison of the ratio 100 pF:10 pF was not specifically included in the comparison protocol. Therefore, the ratio values presented in the following sections have not been directly measured and reported by the participants but calculated by the pilot from the reported 100 pF and 10 pF measurements. This means in particular that the ratio uncertainty values reported hereafter don't necessarily reflect the best capabilities of the participants in terms of ratio measurements.

10. Results of the simultaneous bilateral comparisons

In this section we present the details of the measurement results for each of the bilateral comparisons between the BIPM and the participating institutes as well as the computed values of the quantities defined in the above section. As it could be remarked from these results, the linear interpolation of both the BIPM and the NMIs sets of measurements remains in any case the best way to analyse the results of the comparison and this even when, for some of the bilateral comparisons, measurements instabilities are noticeable in one or several of the measurement series.

Also, as mentioned earlier, and with the exception of three standards removed from the comparison (see section 6), no significant effect of transportation and repowering can be observed. Only small instabilities of the capacitance value may be noticed for some of the standards. They are typically of the order of 3 to 4 parts in 10^8. These instabilities are most probably attributable to the slow thermal stabilization of the capacitance standard including its temperature control electronics, or to the intrinsic stability of the capacitor itself. For all cases, taking into account their limited magnitude, it is considered in the following that their effect is already included in the type A uncertainty component calculated by the institutes (including the BIPM) and forming part of their combined standard uncertainty. In some way, their effect is also included in the uncertainty on the predicted value at the mean date of comparison computed from the linear fitting of the measurement series. Consequently, it is considered, for the calculation of $u(C_i^{ref})$ and $u(C_i)$ as previously defined, that the uncertainty components $u_{tr}(C_i)$ and $u_{tr}(C_i^{ref})$ are null.

For all the BIPM results presented below, the operating conditions were those fixed in the protocol regarding ambient conditions, applied voltage and frequency (see section 4.3). Except when otherwise indicated, this is also the case for all the participating institutes.

All the individual measurements of each of the participants, including the BIPM, are reported in the tables of annex 4. The corresponding uncertainty budgets stating the overall standard measurement uncertainties, u_i and u_i^{BIPM} in section 9, are gathered in annex 5. The type A and B components of u_i and u_i^{BIPM} are also obtained from those budgets.

General conditions of measurements for each of the participating NMIs are summarized in annex 6.

10.1. Comparison between BIPM and METAS

All the individual measurements performed at both the METAS and the BIPM are shown on Figures 1 and 2 for the 10 pF standards #01191 and #01300, and on Figures 3 and 4 for the 100 pF standards #01188 and #01189.

In these figures are also shown the interpolated value of the BIPM measurements (C_{METAS}^{ref}) at the mean date of measurement at the BIPM ($\overline{D_{METAS}^{BIPM}}$), as well as the linear fit of the METAS initial and return series of measurements along with the METAS predicted value (C_{METAS}) at the mean date. The uncertainty bars correspond to $u(C_{METAS}^{ref})$ and $u(C_{METAS})$ in 1σ.

As mentioned in section 8.2, measurements were carried out at METAS at 1233.15 Hz and reported to the pilot at the same frequency. These measurements were then corrected to 1591.55 Hz by the pilot using the frequency coefficients specified in 8.2 and a specific additional uncertainty component was combined to the measurement uncertainties reported by METAS. This additional uncertainty has a value of 3.2 parts in 10^8 at 10 pF and of 3.5 parts in 10^8 at 100 pF.

The values of C_{METAS}^{ref} and C_{METAS} at the mean date 2 June 2017 as well as their relative difference Δ_{METAS} are reported in Tables 6 and 7 for both the 10 pF and 100 pF standards, respectively. Tables also include the 1 σ value of the uncertainty components defined in section 9 and of u_{freq} the uncertainty on the frequency correction determined at the BIPM.

	Standard #01191	**Standard #01300**
Mean date of measurement	**2 June 2017**	**2 June 2017**
$\boldsymbol{C_{METAS}^{ref}}$	**9.999 978 84 pF**	**10.000 012 91 pF**
$u_{A,BIPM}$	0.016 µF/F	0.007 µF/F
$u_{B,BIPM}$	0.036 µF/F	0.036 µF/F
u_{BIPM}	0.039 µF/F	0.037 µF/F
$s_{BIPM}/\sqrt{n}$	0.003 µF/F	0.001 µF/F
$u(C_{METAS}^{ref})$	0.039 µF/F	0.037 µF/F
$\boldsymbol{C_{METAS}}$	**9.999 979 15 pF**	**10.000 012 94 pF**
$u_{A,METAS}$	0.010 µF/F	0.010 µF/F
$u_{B,METAS}$	0.078 µF/F	0.078 µF/F
u_{METAS}	0.079 µF/F	0.079 µF/F
u_{pred}	0.011 µF/F	0.009 µF/F
u_{freq}	0.032 µF/F	0.032 µF/F
$u(C_{METAS})$	0.086 µF/F	0.086 µF/F
$\boldsymbol{\Delta_{METAS}}$	**0.031 µF/F**	**0.003 µF/F**
$\boldsymbol{u(\Delta_{METAS})}$	**0.095 µF/F**	**0.093 µF/F**

Table 6: Results along with measurement uncertainties for the 10 pF standards #01191 and #01300 at 1592 Hz and 100 V (rms). All the uncertainty values are reported in 1σ.

	Standard #01188	**Standard #01189**
Mean date of measurement	**2 June 2017**	**2 June 2017**
$\boldsymbol{C_{METAS}^{ref}}$	**99.999 673 5 pF**	**99.999 722 0 pF**
$u_{A,BIPM}$	0.008 µF/F	0.011 µF/F
$u_{B,BIPM}$	0.035 µF/F	0.035 µF/F
u_{BIPM}	0.036 µF/F	0.037 µF/F
$s_{BIPM}/\sqrt{n}$	0.001 µF/F	0.002 µF/F
$u(C_{METAS}^{ref})$	0.036 µF/F	0.037 µF/F
$\boldsymbol{C_{METAS}}$	**99.999 677 6 pF**	**99.999 728 0 pF**
$u_{A,METAS}$	0.007 µF/F	0.010 µF/F
$u_{B,METAS}$	0.064 µF/F	0.064 µF/F
u_{METAS}	0.064 µF/F	0.065 µF/F
u_{pred}	0.007 µF/F	0.009 µF/F
u_{freq}	0.035 µF/F	0.035 µF/F
$u(C_{METAS})$	0.073 µF/F	0.074 µF/F
$\boldsymbol{\Delta_{METAS}}$	**0.041 µF/F**	**0.060 µF/F**
$\boldsymbol{u(\Delta_{METAS})}$	**0.082 µF/F**	**0.083 µF/F**

Table 7: Results along with measurement uncertainties for the 100 pF standards #01188 and #01189 at 1592 Hz and 10 V (rms). All the uncertainty values are reported in 1σ.

The relative differences Δ_{METAS} for both the 10 pF and the 100 pF standards are averaged to give the final differences between METAS and the BIPM:

- at 10 pF : $\boldsymbol{\Delta_{METAS}} = (\mathbf{0.017} \pm \mathbf{0.092}) \times \mathbf{10^{-6}}$ $(k = 1)$
- at 100 pF: $\boldsymbol{\Delta_{METAS}} = (\mathbf{0.051} \pm \mathbf{0.081}) \times \mathbf{10^{-6}}$ $(k = 1)$

As two 10 pF and two 100 pF capacitance standards have been measured, four 10:1 ratio values can be computed for both METAS and the BIPM. The individual capacitance measurements used for the computations and their standard uncertainty are summarized in Table 8 (from Tables 6 and 7).
The calculated relative deviations from the nominal 10:1 ratio are reported in Table 9 as well as the differences of the deviations computed for METAS and the BIPM. The mean of these differences and its combined standard uncertainty are also reported in this table.

	METAS	**BIPM**
Capacitance standard	Difference from nominal value, µF/F	Difference from nominal value, µF/F
100 pF #01188	-3.224 ± 0.073	-3.265 ± 0.036
100 pF #01189	-2.720 ± 0.074	-2.780 ± 0.037
10 pF #01191	-2.085 ± 0.086	-2.116 ± 0.039
10 pF #01300	1.294 ± 0.086	1.291 ± 0.037

Table 8: Summary of the deviations from nominal value of the four capacitance standards measured by METAS and BIPM.

	METAS	BIPM	
Ratio	Relative deviation from 10, µF/F	Relative deviation from 10, µF/F	METAS-BIPM difference of ratio deviations, µF/F
ratio #01188 / #01191	-1.139 ± 0.046	-1.149 ± 0.027	0.010 ± 0.053
ratio #01188 / #01300	-4.518 ± 0.046	-4.556 ± 0.027	0.038 ± 0.053
ratio #01189 / #01191	-0.635 ± 0.046	-0.664 ± 0.027	0.029 ± 0.053
ratio #01189 / #01300	-4.014 ± 0.046	-4.071 ± 0.027	0.057 ± 0.053
	Mean difference of ratio deviations, µF/F		**0.034**
	Standard combined uncertainty, µF/F		**0.053**

Table 9: Comparison of the individual deviations from the nominal 10:1 ratio measured by METAS and the BIPM and mean value of the differences of the ratio deviations with its combined uncertainty.

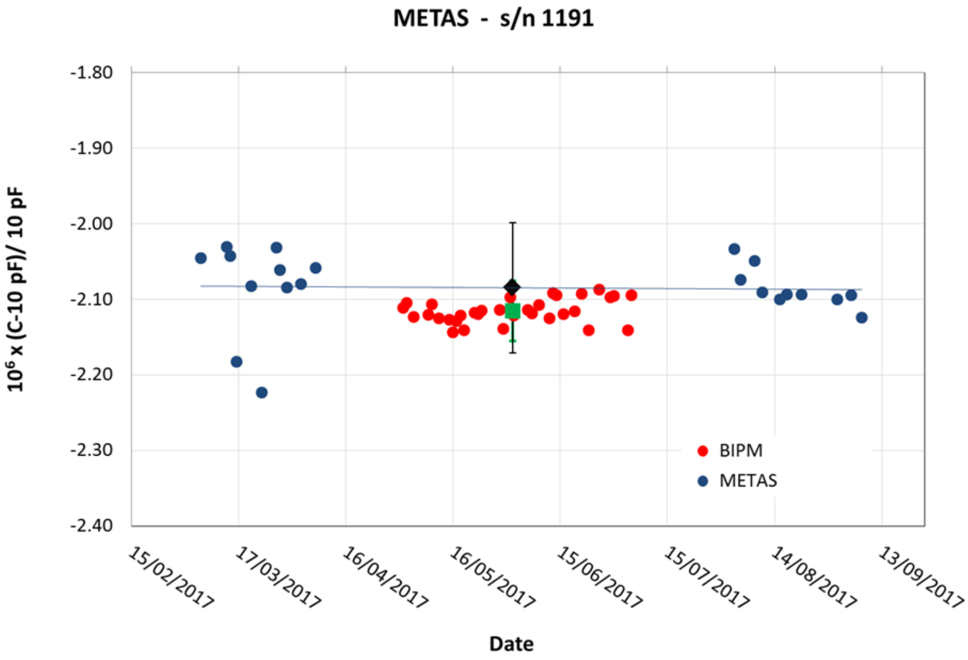


Figure 1: Individual measurements for 10 pF standard **#01191** showing METAS measurements and linear fit, BIPM measurements, METAS value interpolated at the mean date of BIPM measurements (black diamond dot) with 1σ uncertainty bar, BIPM predicted value at the mean date (green square dot) with 1σ uncertainty bar. Measurement conditions: 1592 Hz and 100 V (rms).

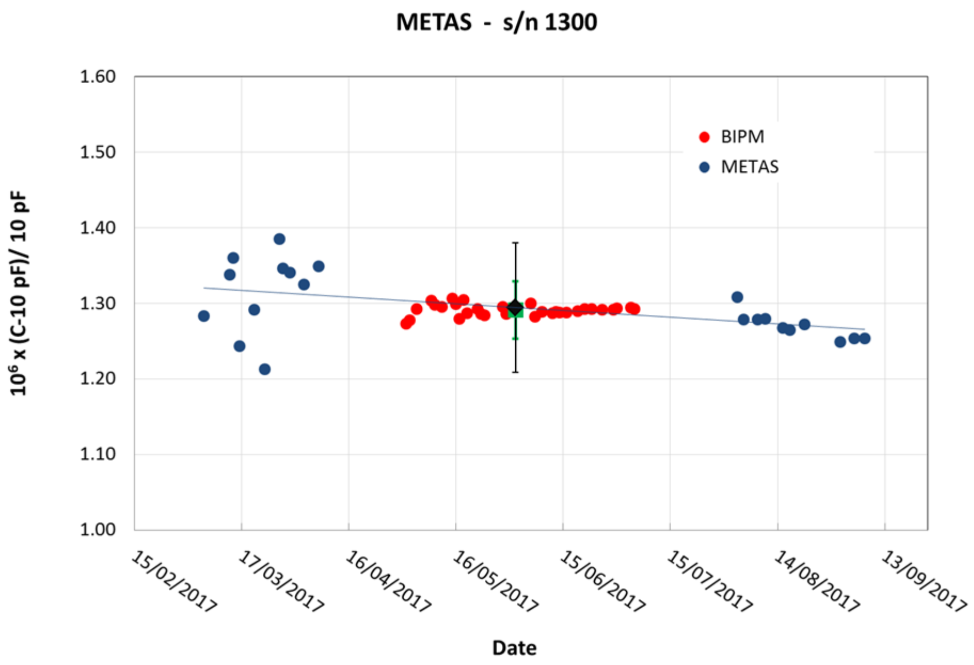


Figure 2: Individual measurements for 10 pF standard #**01300** showing METAS measurements and linear fit, BIPM measurements, METAS value interpolated at the mean date of BIPM measurements (black diamond dot) with 1σ uncertainty bar, BIPM predicted value at the mean date (green square dot) with 1σ uncertainty bar. Measurement conditions: 1592 Hz and 100 V (rms).

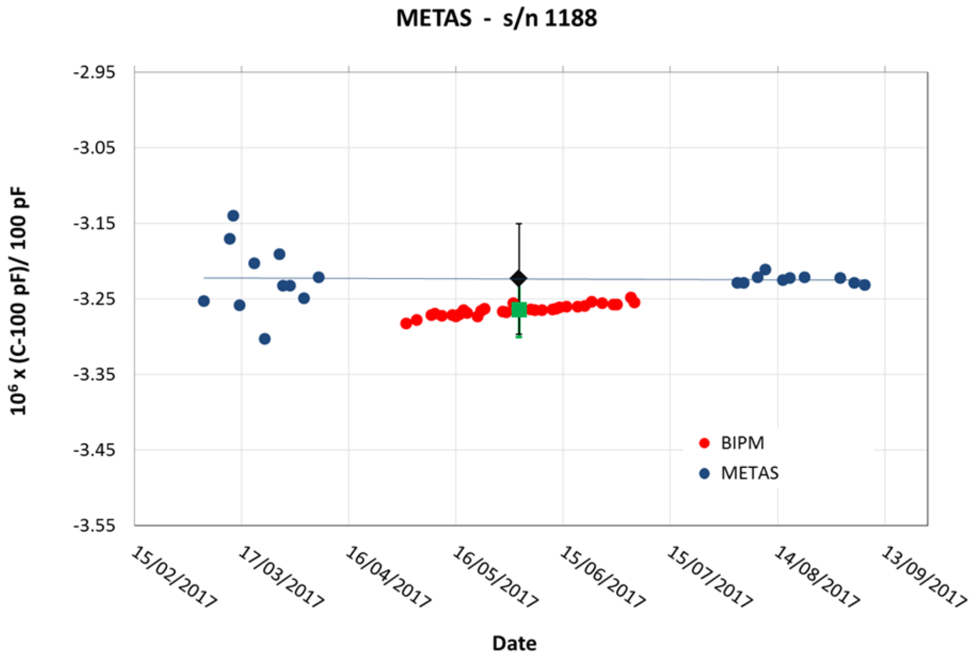


Figure 3: Individual measurements for 100 pF standard #**01188** showing METAS measurements and linear fit, BIPM measurements, METAS value interpolated at the mean date of BIPM measurements (black diamond dot) with 1σ uncertainty bar, BIPM predicted value at the mean date (green square dot) with 1σ uncertainty bar. Measurement conditions: 1592 Hz and 10 V (rms).

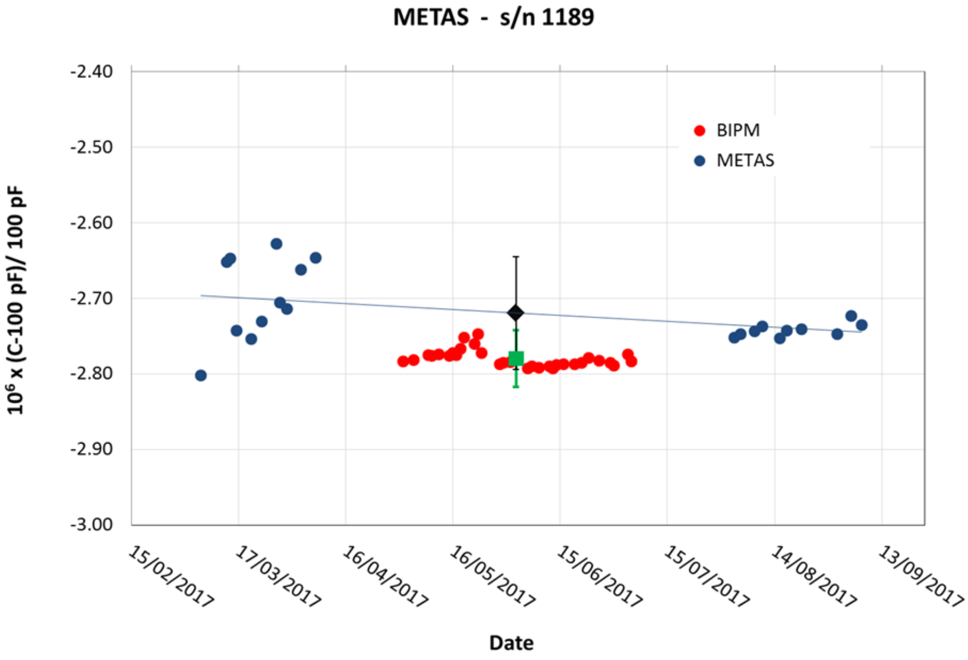


Figure 4: Individual measurements for 100 pF standard #**01189** showing METAS measurements and linear fit, BIPM measurements, METAS value interpolated at the mean date of BIPM measurements (black diamond dot) with 1σ uncertainty bar, BIPM predicted value at the mean date (green square dot) with 1σ uncertainty bar. Measurement conditions: 1592 Hz and 10 V (rms).

10.2. Comparison between BIPM and NIM

All the individual measurements performed at both the NIM and the BIPM are shown on Figures 5 and 6 for the 10 pF standards #01606 and #01682, and on Figures 7 and 8 for the 100 pF standards #01596 and #02090.

In these figures are also shown the interpolated value of the BIPM measurements (C_{NIM}^{ref}) at the mean date of measurement at the BIPM ($\overline{D_{NIM}^{BIPM}}$), as well as the linear fit of the NIM initial and return series of measurements along with the NIM predicted value (C_{NIM}) at the mean date. The uncertainty bars correspond to $u(C_{NIM}^{ref})$ and $u(C_{NIM})$ in 1σ.

As it can be seen on Figure 6, the 10 pF standard #01682 has experienced a temporary jump of its value during the measurement series carried out at the BIPM, making useless the results obtained for this capacitor. However, the second 10 pF standard #01606 remained quite stable during measurement at both NIM and BIPM, figure 5, and kept the NIM in the comparison.

The values of C_{NIM}^{ref} and C_{NIM} at the mean date 9 June 2017 as well as their relative difference Δ_{NIM} are reported in Tables 10 and 11 for both the 10 pF and 100 pF standards, respectively. Tables also include the 1 σ value of the uncertainty components defined in section 9.

It must be noticed that the uncertainties of the 100 pF measurements reported in Table 11 have been revised downwards by NIM after the issue of the first version of draft A (due to the reduction from 2 to 1 of the sensitivity coefficient applied to the voltage correction - see uncertainty statements annex A5-3). This revision had the effect to reduce the combined uncertainty by about 6 ppb for both #01596 and #02090 capacitance standards.

	Standard #01606	**Standard #01682**
Mean date of measurement	**9 June 2017**	**-**
$\boldsymbol{C_{NIM}^{ref}}$	**10,000 000 814 pF**	**-**
$u_{A,BIPM}$	0.005 µF/F	-
$u_{B,BIPM}$	0.036 µF/F	-
u_{BIPM}	0.036 µF/F	-
$s_{BIPM}/\sqrt{n}$	0.001 µF/F	-
$u(C_{NIM}^{ref})$	0.036 µF/F	-
$\boldsymbol{C_{NIM}}$	**10,000 000 817 pF**	**-**
$u_{A,NIM}$	0.004 µF/F	-
$u_{B,NIM}$	0.018 µF/F	-
u_{NIM}	0.018 µF/F	-
u_{pred}	0.001 µF/F	-
$u(C_{NIM})$	0.018 µF/F	-
$\boldsymbol{\Delta_{NIM}}$	**0,000 µF/F**	**-**
$\boldsymbol{u(\Delta_{NIM})}$	**0.041 µF/F**	**-**

Table 10: Results along with measurement uncertainties for the 10 pF standard #01606 at 1592 Hz and 100 V (rms). All the uncertainty values are reported in 1σ.

	Standard #01596	**Standard #02090**
Mean date of measurement	**9 June 2017**	**9 June 2017**
$\boldsymbol{C_{NIM}^{ref}}$	**100,000 006 95 pF**	**100,000 019 98 pF**
$u_{A,BIPM}$	0.003 µF/F	0.006 µF/F
$u_{B,BIPM}$	0.035 µF/F	0.035 µF/F
u_{BIPM}	0.035 µF/F	0.035 µF/F
$s_{BIPM}/\sqrt{n}$	0.001 µF/F	0.001 µF/F
$u(C_{NIM}^{ref})$	0.036 µF/F	0.036 µF/F
$\boldsymbol{C_{NIM}}$	**100,000 004 35 pF**	**100,000 015 91 pF**
$u_{A,NIM}$	0.004 µF/F	0.008 µF/F
$u_{B,NIM}$	0.021 µF/F	0.021 µF/F
u_{NIM}	0.021 µF/F	0.022 µF/F
u_{pred}	0.001 µF/F	0.002 µF/F
$u(C_{NIM})$	0.021 µF/F	0.022 µF/F
$\boldsymbol{\Delta_{NIM}}$	**-0,026 µF/F**	**-0,041 µF/F**
$\boldsymbol{u(\Delta_{NIM})}$	**0.041 µF/F**	**0.042 µF/F**

Table 11: Results along with measurement uncertainties for the 100 pF standards #01596 and #02090 at 1592 Hz and 10 V (rms). All the uncertainty values are reported in 1σ.

For the 100 pF standards, the final difference between NIM and BIPM is computed as the arithmetic mean of the individual differences Δ_{NIM}. For the 10 pF standards, the final difference is simply that measured for the standard #01606 (Table 10).

Thus, the differences NIM-BIPM are:

- at 10 pF : $\Delta_{NIM} = (\mathbf{0.000} \pm \mathbf{0.041}) \times \mathbf{10^{-6}}$ (k = 1)
- at 100 pF: $\Delta_{NIM} = (\mathbf{-0.034} \pm \mathbf{0.041}) \times \mathbf{10^{-6}}$ (k = 1)

As one 10 pF and two 100 pF capacitance standards have been measured, two 10:1 ratio values can be computed for both NIM and the BIPM. The individual capacitance measurements used for the computations and their standard uncertainty are summarized in Table 12 (from Tables 10 and 11).

The calculated relative deviations from the nominal 10:1 ratio are reported in Table 13 as well as the differences of the deviations computed for NIM and the BIPM. The mean of these differences and its combined standard uncertainty are also reported in this table.

	NIM	**BIPM**
Capacitance standard	Difference from nominal value, µF/F	Difference from nominal value, µF/F
100 pF #01596	0.043 ± 0.021	0.069 ± 0.036
100 pF #02090	0.159 ± 0.022	0.200 ± 0.036
10 pF #01606	0.082± 0.018	0.081 ± 0.036

Table 12: Summary of the deviations from nominal value of the three capacitance standards measured by NIM and BIPM.

	NIM	**BIPM**	
Ratio	Relative deviation from 10, µF/F	Relative deviation from 10, µF/F	NIM-BIPM difference of ratio deviations, µF/F
ratio #01596 / #01606	-0.038 ± 0.021	-0.012 ± 0.027	-0.026 ± 0.034
ratio #02090 / #01606	0.077 ± 0.021	0.118 ± 0.027	-0.041 ± 0.034
	Mean difference of ratio deviations, µF/F		**-0.034**
	Standard combined uncertainty, µF/F		**0.034**

Table 13: Comparison of the individual deviations from the nominal 10:1 ratio measured by NIM and the BIPM and mean value of the differences of the ratio deviations with its combined uncertainty.

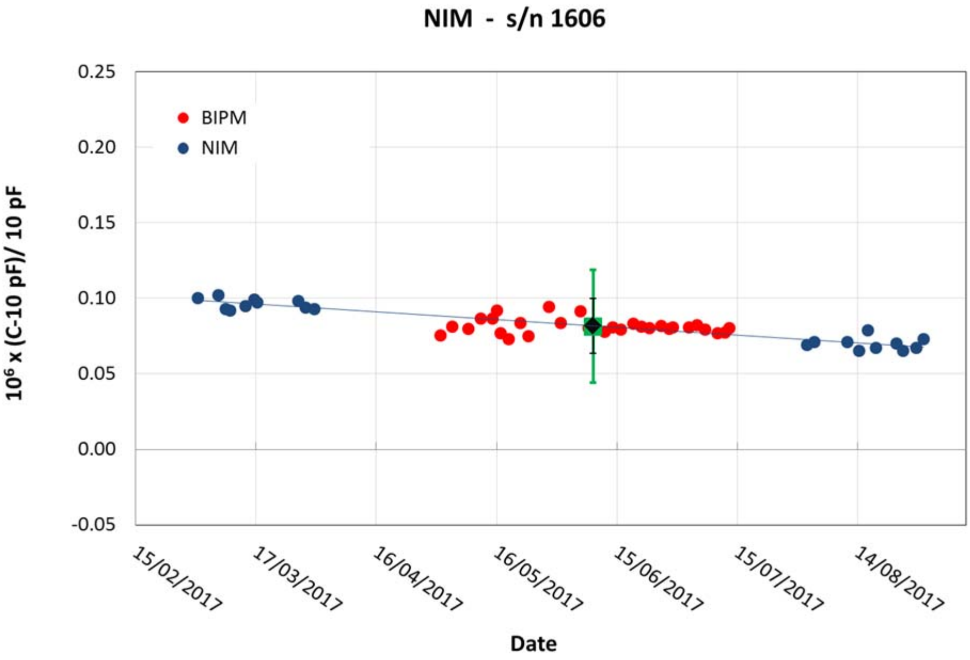


Figure 5: Individual measurements for 10 pF standard #**01606** showing NIM measurements and linear fit, BIPM measurements, NIM value interpolated at the mean date of BIPM measurements (black diamond dot) with 1σ uncertainty bar, BIPM predicted value at the mean date (green square dot) with 1σ uncertainty bar. Measurement conditions: 1592 Hz and 100 V (rms).

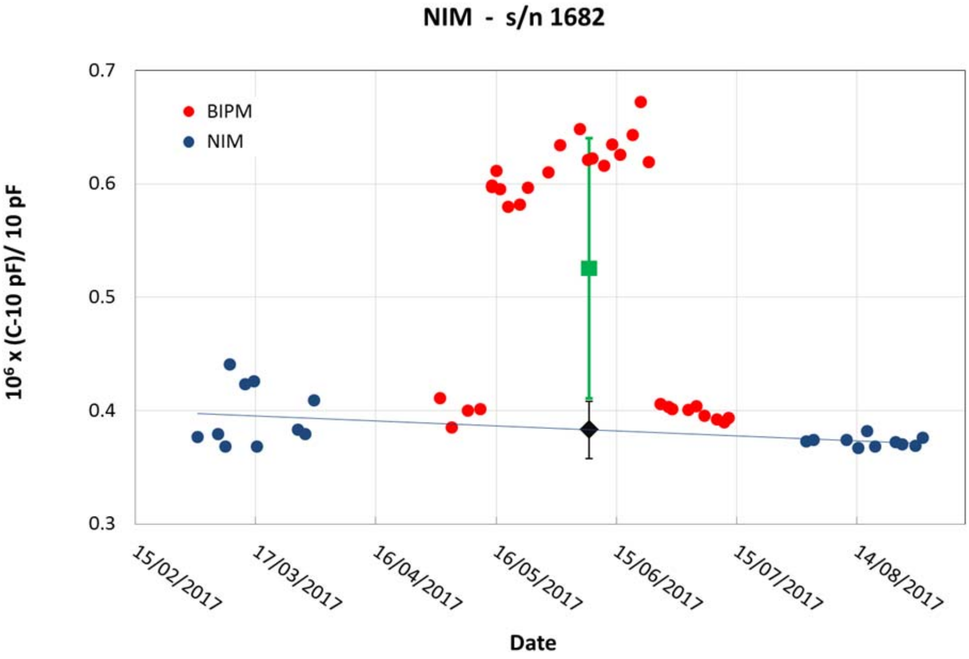


Figure 6: Individual measurements for 10 pF standard #**01682** showing NIM measurements and linear fit, BIPM measurements, NIM value interpolated at the mean date of BIPM measurements (black diamond dot) with 1σ uncertainty bar, BIPM predicted value at the mean date (green square dot) with 1σ uncertainty bar. Measurement conditions: 1592 Hz and 100 V (rms).

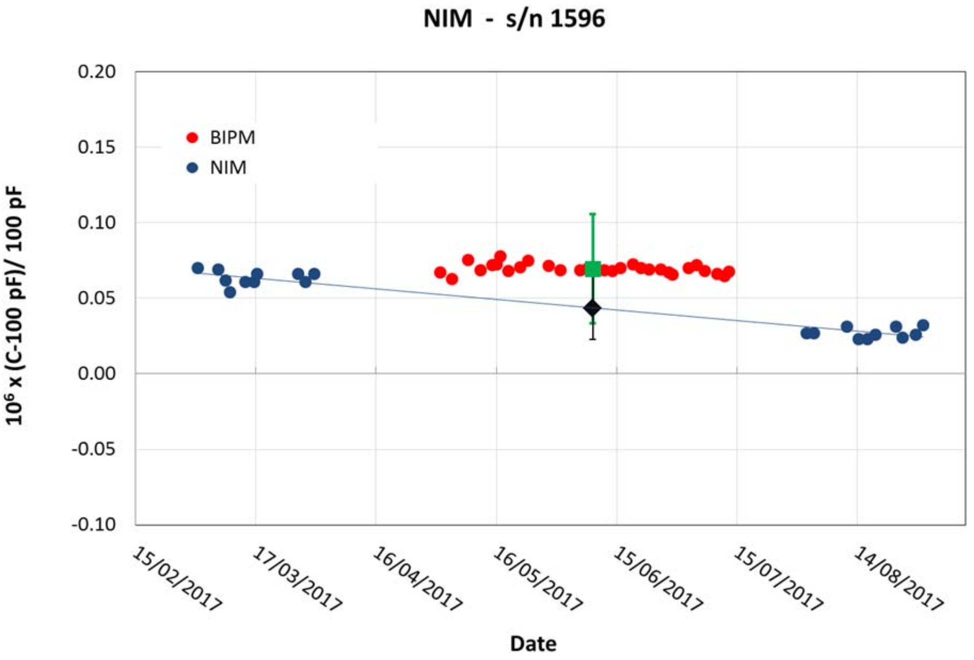


Figure 7: Individual measurements for 100 pF standard #**01596** showing NIM measurements and linear fit, BIPM measurements, NIM value interpolated at the mean date of BIPM measurements (black diamond dot) with 1σ uncertainty bar, BIPM predicted value at the mean date (green square dot) with 1σ uncertainty bar. Measurement conditions: 1592 Hz and 10 V (rms).

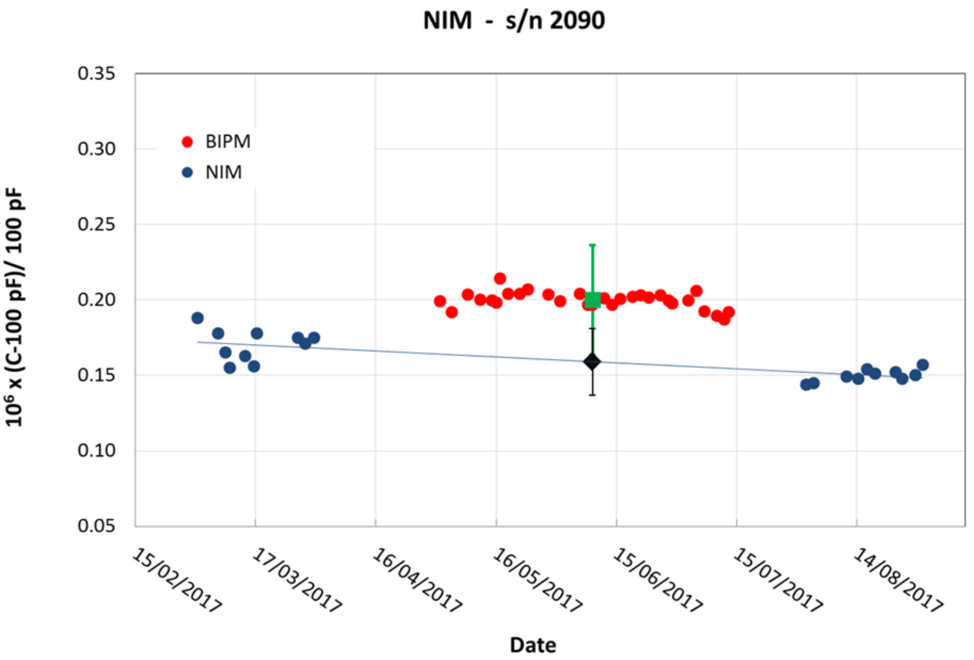


Figure 8: Individual measurements for 100 pF standard #**02090** showing NIM measurements and linear fit, BIPM measurements, NIM value interpolated at the mean date of BIPM measurements (black diamond dot) with 1σ uncertainty bar, BIPM predicted value at the mean date (green square dot) with 1σ uncertainty bar. Measurement conditions: 1592 Hz and 10 V (rms).

10.3. Comparison between BIPM and NIST

All the individual measurements performed at both the NIST and the BIPM are shown on Figures 9 and 10 for the 10 pF standards #01423 and #01424, and on Figures 11 and 12 for the 100 pF standards #01442 and #01452.

In these figures are also shown the interpolated value of the BIPM measurements (C_{NIST}^{ref}) at the mean date of measurement at the BIPM ($\overline{D_{NIST}^{BIPM}}$), as well as the linear fit of the NIST initial and return series of measurements along with the NIST predicted value (C_{NIST}) at the mean date. The uncertainty bars correspond to $u(C_{NIST}^{ref})$ and $u(C_{NIST})$ in 1σ.

For all the standards, the measurements are quite repeatable along the three series carried out at NIST and BIPM despite some measurement instabilities on the first part of the series at BIPM for the 10 pF standards (figures 9 and 10). They could be attributed to residual fluctuations following transportation and repowering of the standards but without any certainty. In contrast, the noticeable difference between NIST and BIPM results is clearly not due to some effect resulting from the transportation of the standards.

The values of C_{NIST}^{ref} and C_{NIST} at the mean date 3 June 2017 as well as their relative difference Δ_{NIST} are reported in Tables 14 and 15 for both the 10 pF and 100 pF standards, respectively. Tables also include the 1 σ value of the uncertainty components defined in section 9.

	Standard #01423	**Standard #01424**
Mean date of measurement	**3 June 2017**	**3 June 2017**
$\boldsymbol{C_{NIST}^{ref}}$	**9.999 952 002 pF**	**9.999 952 695 pF**
$u_{A,BIPM}$	0.008 µF/F	0.009 µF/F
$u_{B,BIPM}$	0.036 µF/F	0.036 µF/F
u_{BIPM}	0.037 µF/F	0.037 µF/F
$s_{BIPM}/\sqrt{n}$	0.002 µF/F	0.002 µF/F
$u(C_{NIST}^{ref})$	0.037 µF/F	0.037 µF/F
$\boldsymbol{C_{NIST}}$	**9.999 951 357 pF**	**9.999 952 196 pF**
$u_{A,NIST}$	0.001 µF/F	0.001 µF/F
$u_{B,NIST}$	0.020 µF/F	0.020 µF/F
u_{NIST}	0.020 µF/F	0.020 µF/F
u_{pred}	0.000 µF/F	0.000 µF/F
$u(C_{NIST})$	0.020 µF/F	0.020 µF/F
$\boldsymbol{\Delta_{NIST}}$	**-0.065 µF/F**	**-0.050 µF/F**
$\boldsymbol{u(\Delta_{NIST})}$	**0.042 µF/F**	**0.042 µF/F**

Table 14: Results along with measurement uncertainties for the 10 pF standards #01423 and #01424 at 1592 Hz and 100 V (rms). All the uncertainty values are reported in 1σ.

	Standard #01442	**Standard #01452**
Mean date of measurement	**3 June 2017**	**3 June 2017**
$\boldsymbol{C_{NIST}^{ref}}$	**99.999 535 15 pF**	**99.999 570 16pF**
$u_{A,BIPM}$	0.002 µF/F	0.003 µF/F
$u_{B,BIPM}$	0.035 µF/F	0.035 µF/F
u_{BIPM}	0.035 µF/F	0.035 µF/F
$s_{BIPM}/\sqrt{n}$	0.000 µF/F	0.001 µF/F
$u\left(C_{NIST}^{ref}\right)$	0.035 µF/F	0.035 µF/F
$\boldsymbol{C_{NIST}}$	**99.999 527 61 pF**	**99.999 562 83 pF**
$u_{A,NIST}$	0.001 µF/F	0.001 µF/F
$u_{B,NIST}$	0.020 µF/F	0.020 µF/F
u_{NIST}	0.020 µF/F	0.020 µF/F
u_{pred}	0.001 µF/F	0.001 µF/F
$u(C_{NIST})$	0.020 µF/F	0.020 µF/F
$\Delta_{\boldsymbol{NIST}}$	**-0.075 µF/F**	**-0.073 µF/F**
$\boldsymbol{u}(\Delta_{\boldsymbol{NIST}})$	**0.040 µF/F**	**0.040 µF/F**

Table 15: Results along with measurement uncertainties for 100 pF standards #01442 and #01452 at 1592 Hz and 10 V (rms). All the uncertainty values are reported in 1σ.

The relative differences Δ_{NIST} for both the 10 pF and the 100 pF standards are averaged to give the final differences between NIST and BIPM:

- at 10 pF : $\Delta_{\boldsymbol{NIST}} = (\boldsymbol{-0.057 \pm 0.042}) \times \boldsymbol{10^{-6}}$ $(k = 1)$
- at 100 pF: $\Delta_{\boldsymbol{NIST}} = (\boldsymbol{-0.074 \pm 0.040}) \times \boldsymbol{10^{-6}}$ $(k = 1)$

As two 10 pF and two 100 pF capacitance standards have been measured, four 10:1 ratio values can be computed for both NIST and the BIPM. The individual capacitance measurements used for the computations and their standard uncertainty are summarized in Table 16 (from Tables 14 and 15).

The calculated relative deviations from the nominal 10:1 ratio are reported in Table 17 as well as the differences of the deviations computed for NIST and the BIPM. The mean of these differences and its combined standard uncertainty are also reported in this table.

	NIST	**BIPM**
Capacitance standard	Difference from nominal value, µF/F	Difference from nominal value, µF/F
100 pF #01442	-4.724 ± 0.020	-4.649 ± 0.035
100 pF #01452	-4.372 ± 0.020	-4.298 ± 0.035
10 pF #01423	-4.864 ± 0.020	-4.800 ± 0.037
10 pF #01424	-4.780 ± 0.020	-4.731 ± 0.037

Table 16: Summary of the deviations from nominal value of the four capacitance standards measured by NIST and BIPM.

	NIST	BIPM	
Ratio	Relative deviation from 10, µF/F	Relative deviation from 10, µF/F	NIST-BIPM difference of ratio deviations, µF/F
ratio #01442 / #01423	0.140 ± 0.007	0.151 ± 0.027	-0.011 ± 0.028
ratio #01442 / #01424	0.056 ± 0.007	0.082 ± 0.027	-0.026 ± 0.028
ratio #01452 / #01423	0.493 ± 0.007	0.501 ± 0.027	-0.009 ± 0.028
ratio #01452 / #01424	0.409 ± 0.007	0.432 ± 0.027	-0.023 ± 0.028
	Mean difference of ratio deviations, µF/F		**-0.017**
	Standard combined uncertainty, µF/F		**0.028**

Table 17: Comparison of the individual deviations from the nominal 10:1 ratio measured by NIST and the BIPM and mean value of the differences of the ratio deviations with its combined uncertainty.

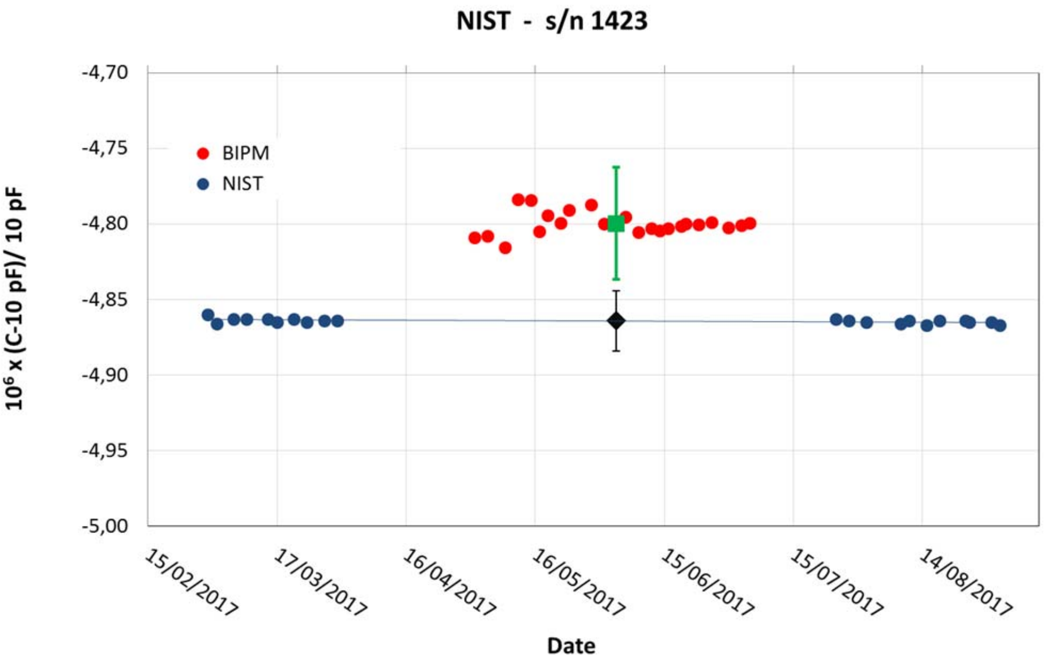


Figure 9: Individual measurements for 10 pF standard **#01423** showing NIST measurements and linear fit, BIPM measurements, NIST value interpolated at the mean date of BIPM measurements (black diamond dot) with 1σ uncertainty bar, BIPM predicted value at the mean date (green square dot) with 1σ uncertainty bar. Measurement conditions: 1592 Hz and 100 V (rms).

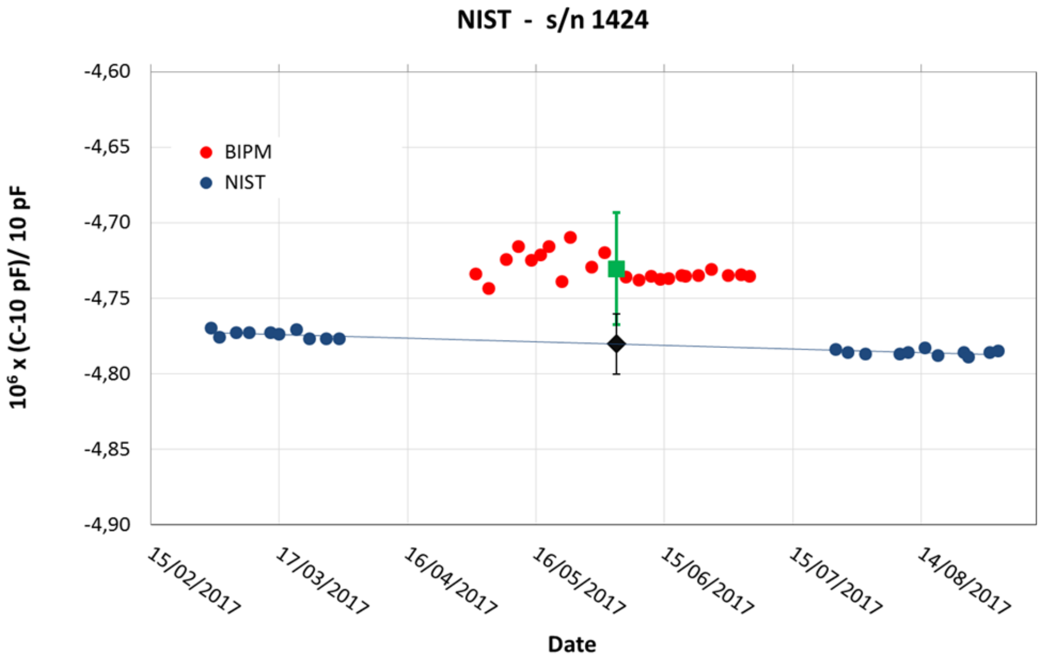


Figure 10: Individual measurements for 10 pF standard #**01424** showing NIST measurements and linear fit, BIPM measurements, NIST value interpolated at the mean date of BIPM measurements (black diamond dot) with 1σ uncertainty bar, BIPM predicted value at the mean date (green square dot) with 1σ uncertainty bar. Measurement conditions: 1592 Hz and 100 V (rms).

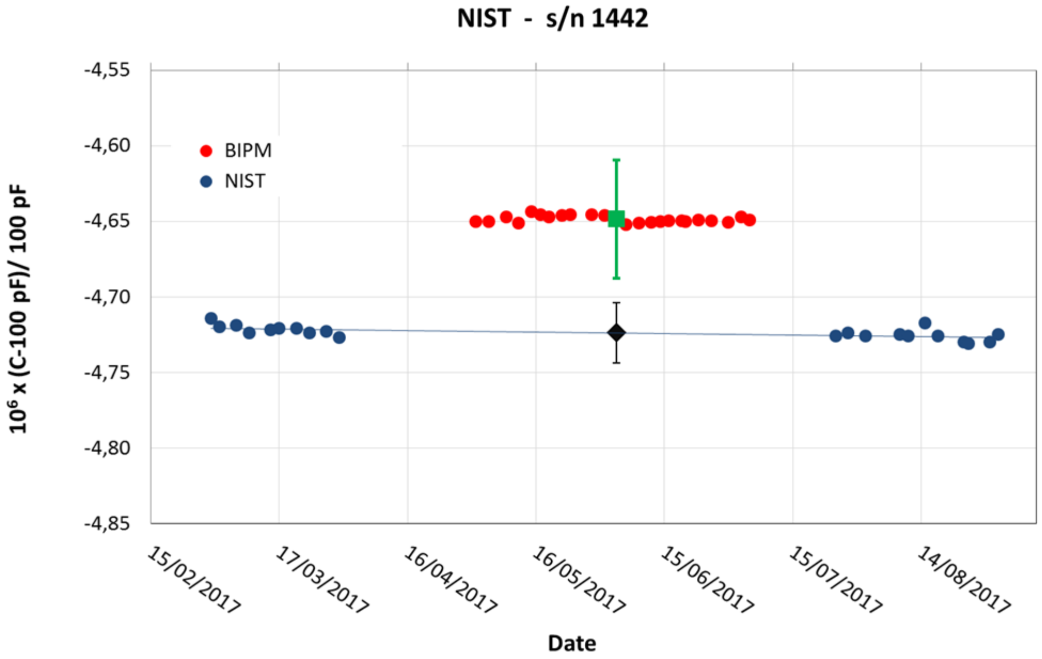


Figure 11: Individual measurements for 100 pF standard #**01442** showing NIST measurements and linear fit, BIPM measurements, NIST value interpolated at the mean date of BIPM measurements (black diamond dot) with 1σ uncertainty bar, BIPM predicted value at the mean date (green square dot) with 1σ uncertainty bar. Measurement conditions: 1592 Hz and 10 V (rms).

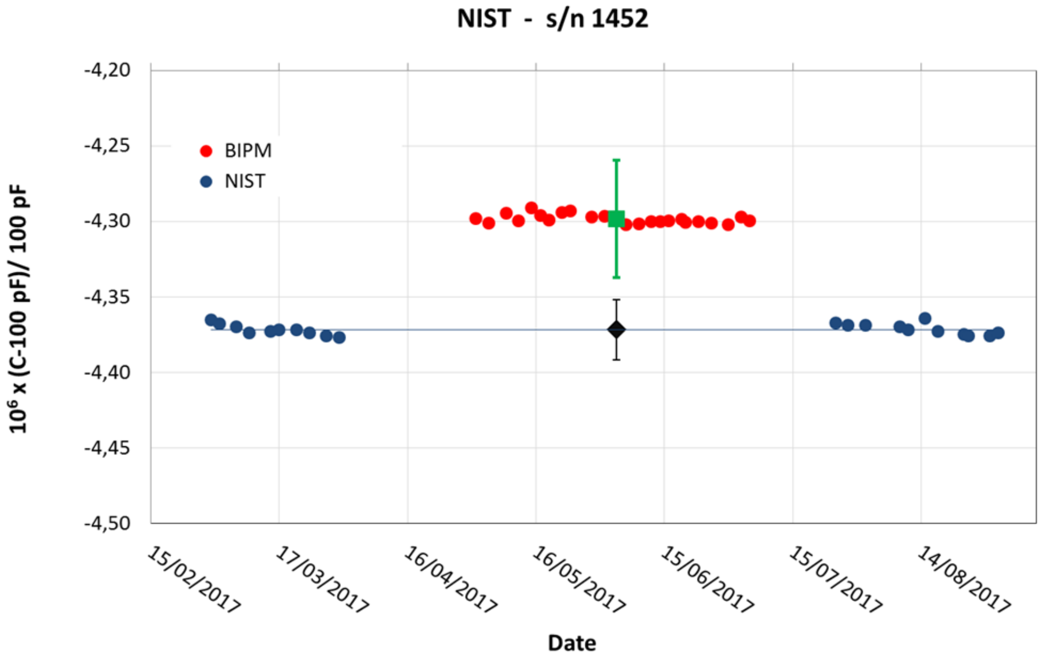


Figure 12: Individual measurements for 100 pF standard #**01452** showing NIST measurements and linear fit, BIPM measurements, NIST value interpolated at the mean date of BIPM measurements (black diamond dot) with 1σ uncertainty bar, BIPM predicted value at the mean date (green square dot) with 1σ uncertainty bar. Measurement conditions: 1592 Hz and 10 V (rms).

10.4. Comparison between BIPM and NMIA

All the individual measurements performed at both the NMIA and the BIPM are shown on Figures 13 and 14 for the 10 pF standards #01416 and #01479, and on Figures 15 and 16 for the 100 pF standards #01459 and #01677.

In these figures are also shown the interpolated value of the BIPM measurements (C_{NMIA}^{ref}) at the mean date of measurement at the BIPM ($\overline{D_{NMIA}^{BIPM}}$), as well as the linear fit of the NMIA initial and return series of measurements along with the NMIA predicted value (C_{NMIA}) at the mean date. The uncertainty bars correspond to $u\left(C_{NMIA}^{ref}\right)$ and $u(C_{NMIA})$ in 1σ.

The values of C_{NMIA}^{ref} and C_{NMIA} at the mean date 2 June 2017 as well as their relative difference Δ_{NMIA} are reported in Tables 18 and 19 for both the 10 pF and 100 pF standards, respectively. Tables also include the 1 σ value of the uncertainty components defined in section 9.

	Standard #01416	**Standard #01479**
Mean date of measurement	**2 June 2017**	**2 June 2017**
$\boldsymbol{C_{NMIA}^{ref}}$	**9.999 870 279 pF**	**9.999 956 571 pF**
$u_{A,BIPM}$	0.006 µF/F	0.006 µF/F
$u_{B,BIPM}$	0.036 µF/F	0.036 µF/F
u_{BIPM}	0.036 µF/F	0.036 µF/F
$s_{BIPM}/\sqrt{n}$	0.001 µF/F	0.001 µF/F
$u(C_{NMIA}^{ref})$	0.036 µF/F	0.036 µF/F
$\boldsymbol{C_{NMIA}}$	**9.999 870 328 pF**	**9.999 956 427 pF**
$u_{A,NMIA}$	0.012 µF/F	0.009 µF/F
$u_{B,NMIA}$	0.053 µF/F	0.053 µF/F
u_{NMIA}	0.054 µF/F	0.054 µF/F
u_{pred}	0.002 µF/F	0.002 µF/F
$u(C_{NMIA})$	0.054 µF/F	0.054 µF/F
$\boldsymbol{\Delta_{NMIA}}$	**0.005 µF/F**	**-0.014 µF/F**
$\boldsymbol{u(\Delta_{NMIA})}$	**0.065 µF/F**	**0.065 µF/F**

Table 18: Results along with measurement uncertainties for the 10 pF standards #01416 and #01479 at 1592 Hz and 100 V (rms). All the uncertainty values are reported in 1σ.

	Standard #01677	**Standard #01459**
Mean date of measurement	**2 June 2017**	**2 June 2017**
$\boldsymbol{C_{NMIA}^{ref}}$	**99.999 478 99 pF**	**99.999 517 43 pF**
$u_{A,BIPM}$	0.004 µF/F	0.007 µF/F
$u_{B,BIPM}$	0.035 µF/F	0.035 µF/F
u_{BIPM}	0.035 µF/F	0.036 µF/F
$s_{BIPM}/\sqrt{n}$	0.001 µF/F	0.001 µF/F
$u(C_{NMIA}^{ref})$	0.035 µF/F	0.036 µF/F
$\boldsymbol{C_{NMIA}}$	**99.999 478 98 pF**	**99.999 519 16 pF**
$u_{A,NMIA}$	0.004 µF/F	0.004 µF/F
$u_{B,NMIA}$	0.053 µF/F	0.053 µF/F
u_{NMIA}	0.053 µF/F	0.053 µF/F
u_{pred}	0.002 µF/F	0.002 µF/F
$u(C_{NMIA})$	0.053 µF/F	0.053 µF/F
$\boldsymbol{\Delta_{NMIA}}$	**0.000 µF/F**	**0.017 µF/F**
$\boldsymbol{u(\Delta_{NMIA})}$	**0.064 µF/F**	**0.064 µF/F**

Table 19: Results along with measurement uncertainties for the 100 pF standards #01459 and #01677 at 1592 Hz and 10 V (rms). All the uncertainty values are reported in 1σ.

The relative differences Δ_{NMIA} for both the 10 pF and the 100 pF standards are averaged to give the final differences between NMIA and BIPM:

- at 10 pF : $\Delta_{NMIA} = (\mathbf{-0.005 \pm 0.065}) \times \mathbf{10^{-6}}$ $(k = 1)$
- at 100 pF: $\Delta_{NMIA} = (\mathbf{0.009 \pm 0.064}) \times \mathbf{10^{-6}}$ $(k = 1)$

As two 10 pF and two 100 pF capacitance standards have been measured, four 10:1 ratio values can be computed for both NMIA and the BIPM. The individual capacitance measurements used for the computations and their standard uncertainty are summarized in Table 20 (from Tables 18 and 19).

The calculated relative deviations from the nominal 10:1 ratio are reported in Table 21 as well as the differences of the deviations computed for NMIA and the BIPM. The mean of these differences and its combined standard uncertainty are also reported in this table.

	NMIA	**BIPM**
Capacitance	Difference from nominal value, µF/F	Difference from nominal value, µF/F
100 pF #01677	-5.210 ± 0.053	-5.210 ± 0.035
100 pF #01459	-4.808 ± 0.053	-4.826 ± 0.037
10 pF #01416	-12.967 ± 0.054	-12.972 ± 0.036
10 pF #01479	-4.357 ± 0.054	-4.343 ± 0.036

Table 20: Summary of the deviations from nominal value of the four capacitance standards measured by NMIA and BIPM.

	NMIA	**BIPM**	
Ratio	Relative deviation from 10, µF/F	Relative deviation from 10, µF/F	NMIA-BIPM difference of ratio deviations, µF/F
ratio #01677 / #01416	7.757 ± 0.014	7.762 ± 0.027	-0.005 ± 0.031
ratio #01677 / #01479	-0.853 ± 0.011	-0.867 ± 0.027	0.014 ± 0.030
ratio #01459 / #01416	8.159 ± 0.014	8.146 ± 0.027	0.012 ± 0.031
ratio #01459 / #01479	-0.451 ± 0.011	-0.483 ± 0.027	0.032 ± 0.030
	Mean difference of ratio deviations, µF/F		**0.013**
	Standard combined uncertainty, µF/F		**0.031**

Table 21: Comparison of the individual deviations from the nominal 10:1 ratio measured by NMIA and the BIPM and mean value of the differences of the ratio deviations with its combined uncertainty.

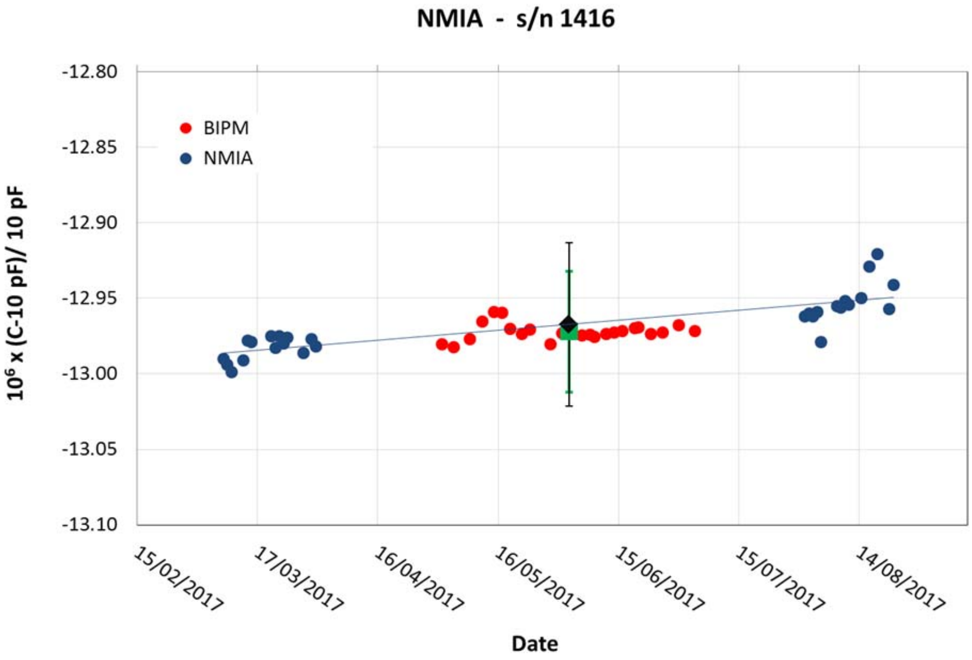


Figure 13: Individual measurements for 10 pF standard #**01416** showing NMIA measurements and linear fit, BIPM measurements, NMIA value interpolated at the mean date of BIPM measurements (black diamond dot) with 1σ uncertainty bar, BIPM predicted value at the mean date (green square dot) with 1σ uncertainty bar. Measurement conditions: 1592 Hz and 100 V (rms).

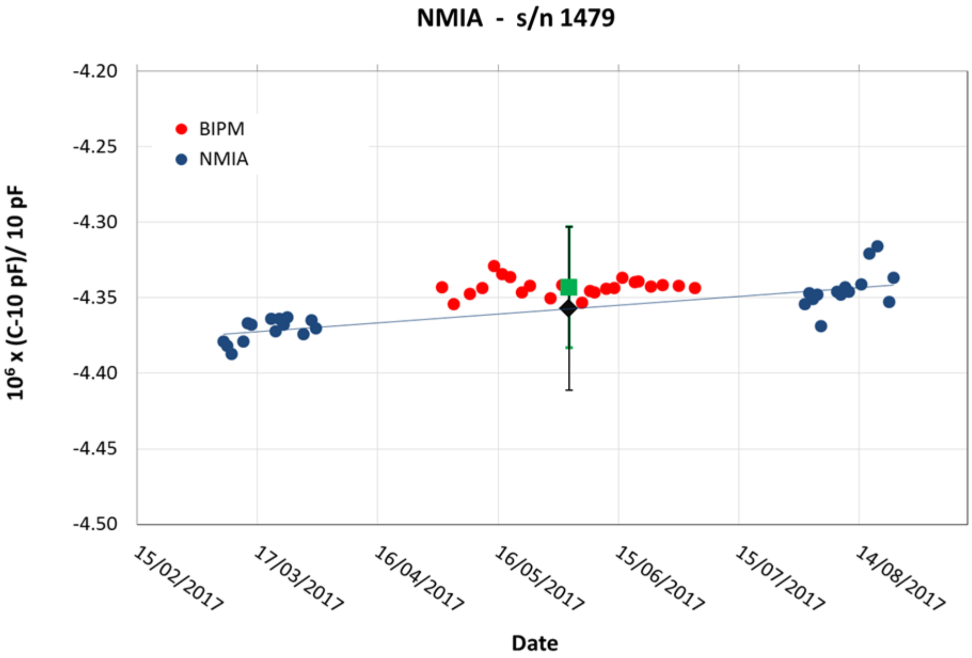


Figure 14: Individual measurements for 10 pF standard #**01479** showing NMIA measurements and linear fit, BIPM measurements, NMIA value interpolated at the mean date of BIPM measurements (black diamond dot) with 1σ uncertainty bar, BIPM predicted value at the mean date (green square dot) with 1σ uncertainty bar. Measurement conditions: 1592 Hz and 100 V (rms).

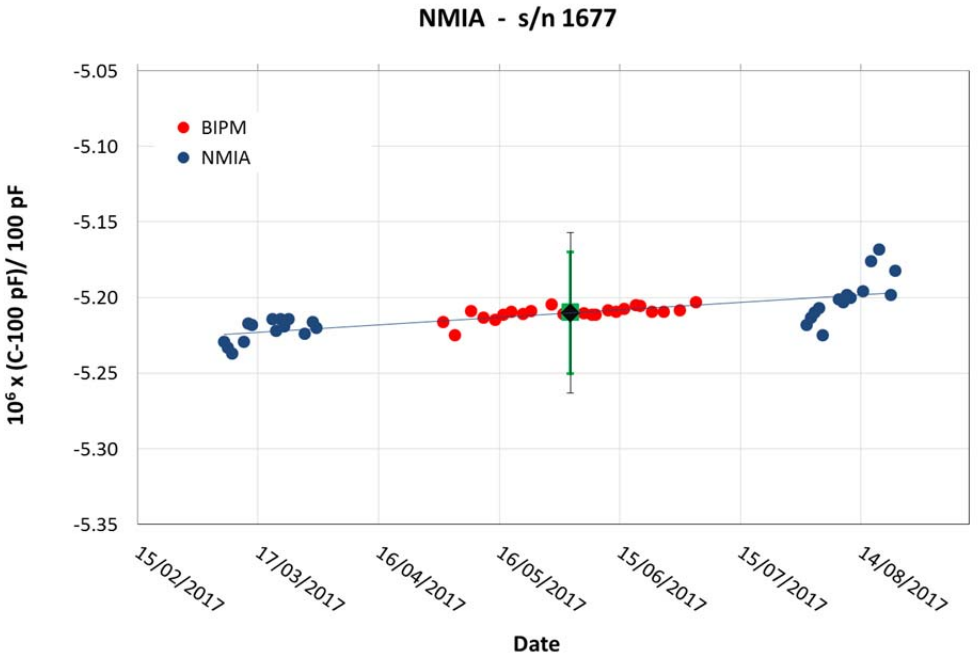


Figure 15: Individual measurements for 100 pF standard #**01677** showing NMIA measurements and linear fit, BIPM measurements, NMIA value interpolated at the mean date of BIPM measurements (black diamond dot) with 1σ uncertainty bar, BIPM predicted value at the mean date (green square dot) with 1σ uncertainty bar. Measurement conditions: 1592 Hz and 10 V (rms).

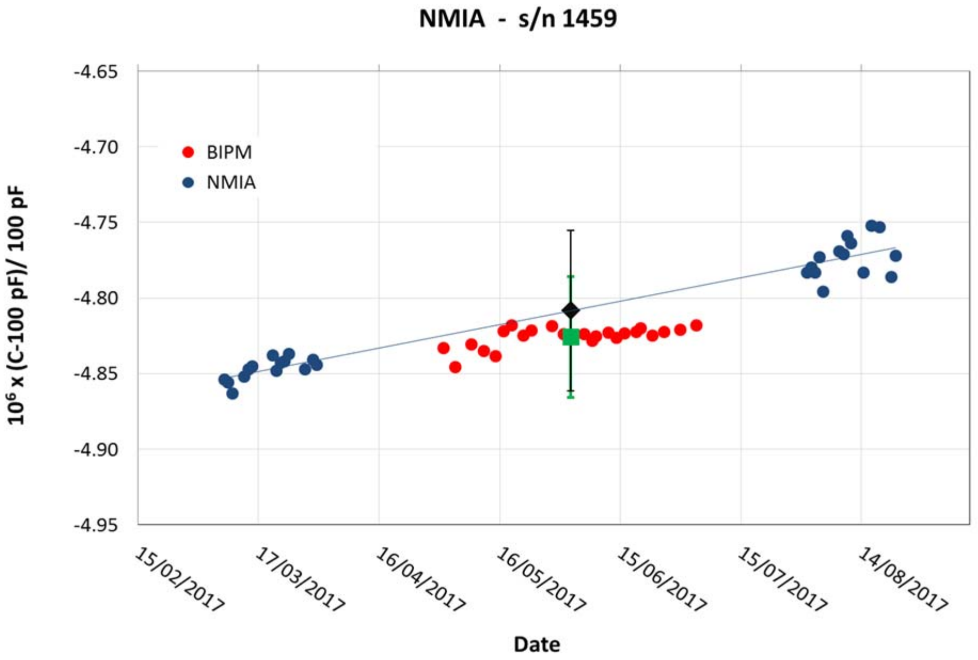


Figure 16: Individual measurements for 100 pF standard #**01459** showing NMIA measurements and linear fit, BIPM measurements, NMIA value interpolated at the mean date of BIPM measurements (black diamond dot) with 1σ uncertainty bar, BIPM predicted value at the mean date (green square dot) with 1σ uncertainty bar. Measurement conditions: 1592 Hz and 10 V (rms).

10.5. Comparison between BIPM and NPL

As already mentioned in section 6, two of the four standards sent by the NPL to the BIPM experienced an excessive drift during the series of measurements carried out at the BIPM, Figures 17 and 18. Those two standards, #01186 and #01185 of capacitance value 10 pF and 100 pF respectively, have been removed from the comparison.

The two standards remaining in the comparison are the 10 pF #01101 and the 100 pF #01100. For these two standards, all the individual measurements performed at both the NPL and the BIPM are reported on Figures 19 and 20.

In these figures are also shown the interpolated value of the BIPM measurements (C_{NPL}^{ref}) at the mean date of measurement at the BIPM ($\overline{D_{NPL}^{BIPM}}$), as well as the linear fit of the NPL initial and return series of measurements along with the NPL predicted value (C_{NPL}) at the mean date. The uncertainty bars correspond to $u(C_{NPL}^{ref})$ and $u(C_{NPL})$ in 1σ.

In spite of noticeable instabilities in the first series of measurements at NPL for the 10 pF standard (Figure 19), the best way to compare NPL and BIPM measurements remains the method proposed in section 9.

The values of C_{NPL}^{ref} and C_{NPL} at the mean date 28 May 2017 as well as their relative difference Δ_{NPL} are reported in Tables 22 and 23 for both the 10 pF and 100 pF standards, respectively. Tables also include the 1 σ value of the uncertainty components defined in section 9.

	Standard #01101
Mean date of measurement	**28 May 2017**
$\boldsymbol{C_{NPL}^{ref}}$	**9.999 957 871 pF**
$u_{A,BIPM}$	0.004 µF/F
$u_{B,BIPM}$	0.036 µF/F
u_{BIPM}	0.036µF/F
$s_{BIPM}/\sqrt{n}$	0.001 µF/F
$u(C_{NPL}^{ref})$	0.036 µF/F
$\boldsymbol{C_{NPL}}$	**9.999 957 540 pF**
$u_{A,NPL}$	0.101 µF/F
$u_{B,NPL}$	0.042 µF/F
u_{NPL}	0.110 µF/F
u_{pred}	0.008 µF/F
$u(C_{NPL})$	0.110 µF/F
$\boldsymbol{\Delta_{NPL}}$	**-0.033 µF/F**
$\boldsymbol{u(\Delta_{NPL})}$	**0.116 µF/F**

Table 22: Results along with measurement uncertainties for the 10 pF standard #01101 at 1592 Hz and 100 V (rms). All the uncertainty values are reported in 1σ.

	Standard #01100
Mean date of measurement	**28 May 2017**
$\boldsymbol{C_{NPL}^{ref}}$	**99.999 686 56 pF**
$u_{A,BIPM}$	0.010 µF/F
$u_{B,BIPM}$	0.035 µF/F
u_{BIPM}	0.036 µF/F
$s_{BIPM}/\sqrt{n}$	0.002 µF/F
$u(C_{NPL}^{ref})$	0.036 µF/F
$\boldsymbol{C_{NPL}}$	**99.999 680 39 pF**
$u_{A,NPL}$	0.082 µF/F
$u_{B,NPL}$	0.049 µF/F
u_{NPL}	0.096 µF/F
u_{pred}	0.002 µF/F
$u(C_{NPL})$	0.096 µF/F
$\Delta_{\mathbf{NPL}}$	**-0.062 µF/F**
$\boldsymbol{u}(\Delta_{\mathbf{NPL}})$	**0.103 µF/F**

Table 23: Results along with measurement uncertainties for 100 pF standard #01100 at 1592 Hz and 10 V (rms). All the uncertainty values are reported in 1σ.

The values of the relative differences Δ_{NPL} between NPL and BIPM at 10 pF and 100 pF as well as their estimated uncertainty $u(\Delta_{NPL})$ calculated from the above Tables 22 and 23 are,

- at 10 pF : $\Delta_{\mathbf{NPL}} = (\mathbf{-0.033 \pm 0.116}) \times \mathbf{10^{-6}}$ (k = 1)
- at 100 pF: $\Delta_{\mathbf{NPL}} = (\mathbf{-0.062 \pm 0.102}) \times \mathbf{10^{-6}}$ (k = 1)

As one 10 pF standard and one 100 pF standard have been measured, only one 10:1 ratio value can be computed for both NPL and the BIPM. The individual capacitance measurements used for the computation and their standard uncertainty are summarized in Table 24 (from Tables 22 and 23).
The calculated relative deviations from the nominal 10:1 ratio are reported in Table 25 for the NPL and the BIPM as well as their difference and its combined standard uncertainty.

	NPL	**BIPM**
Capacitance	Difference from nominal value, µF/F	Difference from nominal value, µF/F
100 pF #01100	-3.196 ± 0.096	-3.134 ± 0.036
10 pF #01101	-4.246 ± 0.110	-4.213 ± 0.036

Table 24: Summary of the deviations from nominal value of the four capacitance standards measured by NPL and BIPM.

	NPL	BIPM	
Ratio	Relative deviation from 10, µF/F	Relative deviation from 10, µF/F	NPL-BIPM difference of ratio deviations, µF/F
ratio #01101 / #01000	1.050 ± 0.074	1.078 ± 0.027	-0.029 ± 0.079
	Mean difference of ratio deviations, µF/F		**-0.029**
	Standard combined uncertainty, µF/F		**0.079**

Table 25: Comparison of the individual deviations from the nominal 10:1 ratio measured by NPL and the BIPM and mean value of the differences of the ratio deviations with its combined uncertainty.

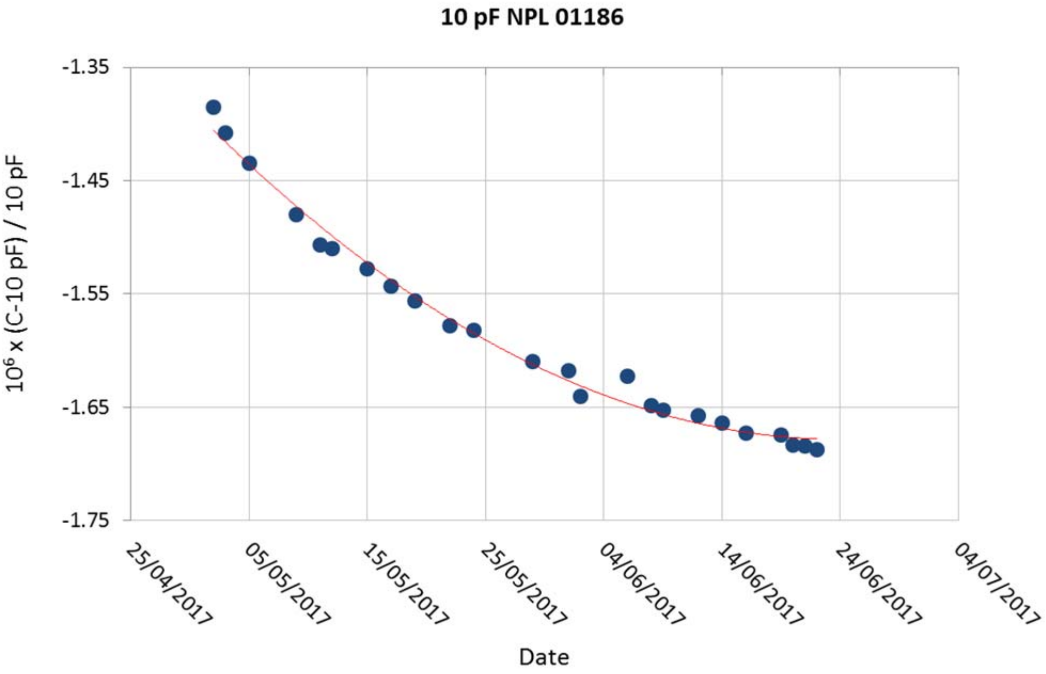


Figure 17: Individual measurements of the series carried out at the BIPM for the 10 pF standard #**01186.** Measurement conditions: 1592 Hz and 100 V (rms).

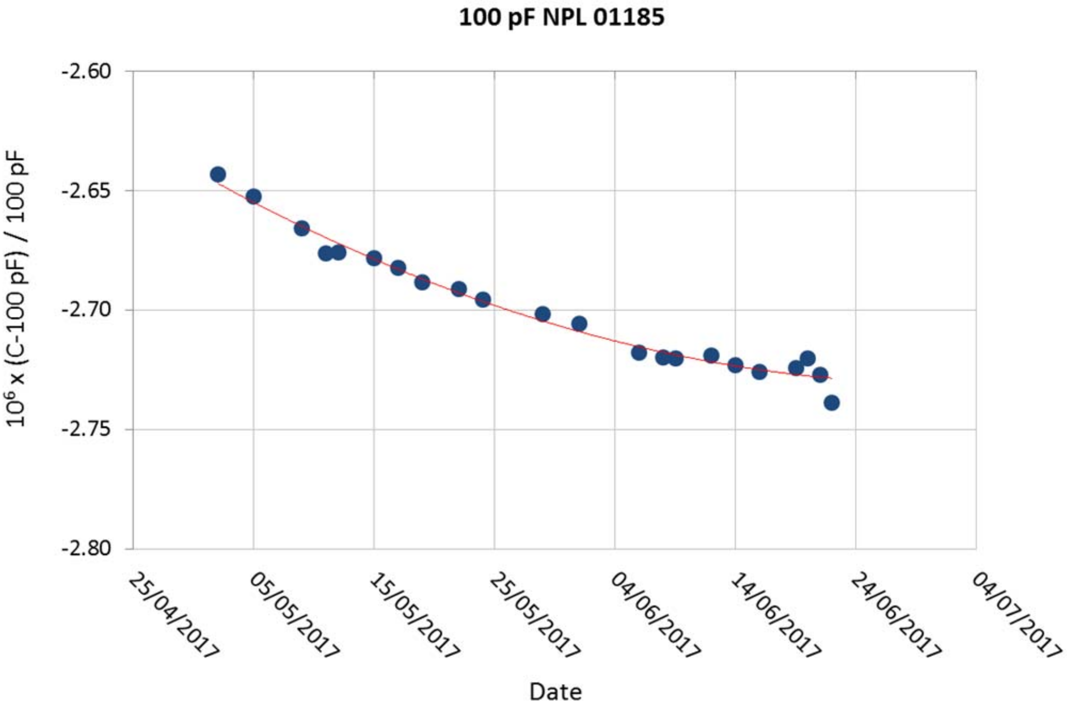


Figure 18: Individual measurements of the series carried out at the BIPM for the 100 pF standard #**01185**. Measurement conditions: 1592 Hz and 10 V (rms).

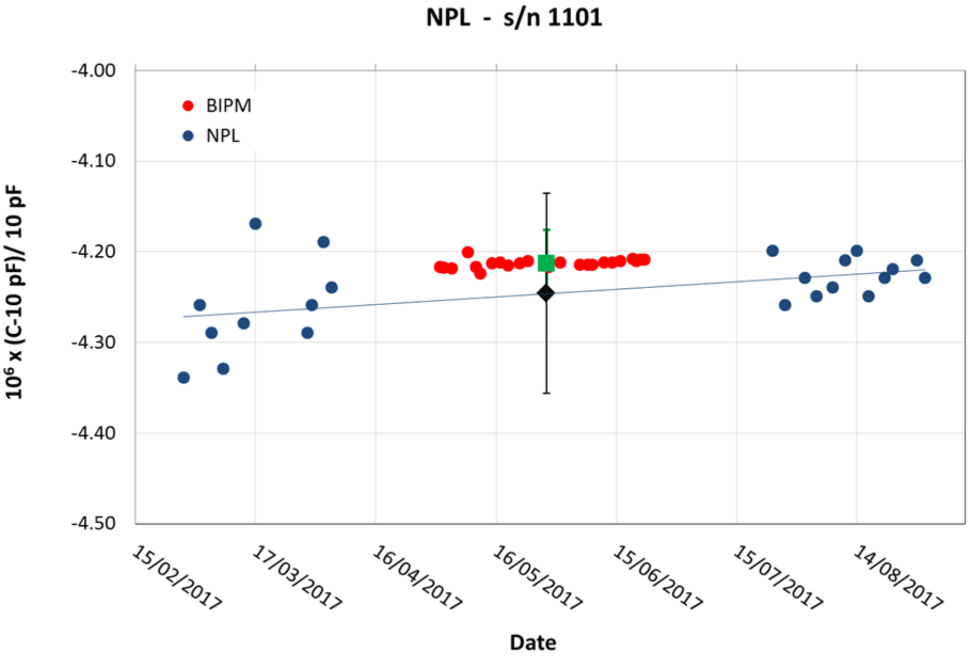


Figure 19: Individual measurements for 10 pF standard #**01101** showing NPL measurements and linear fit, BIPM measurements, NPL value interpolated at the mean date of BIPM measurements (black diamond dot) with 1σ uncertainty bar, BIPM predicted value at the mean date (green square dot) with 1σ uncertainty bar. Measurement conditions: 1592 Hz and 100 V (rms).

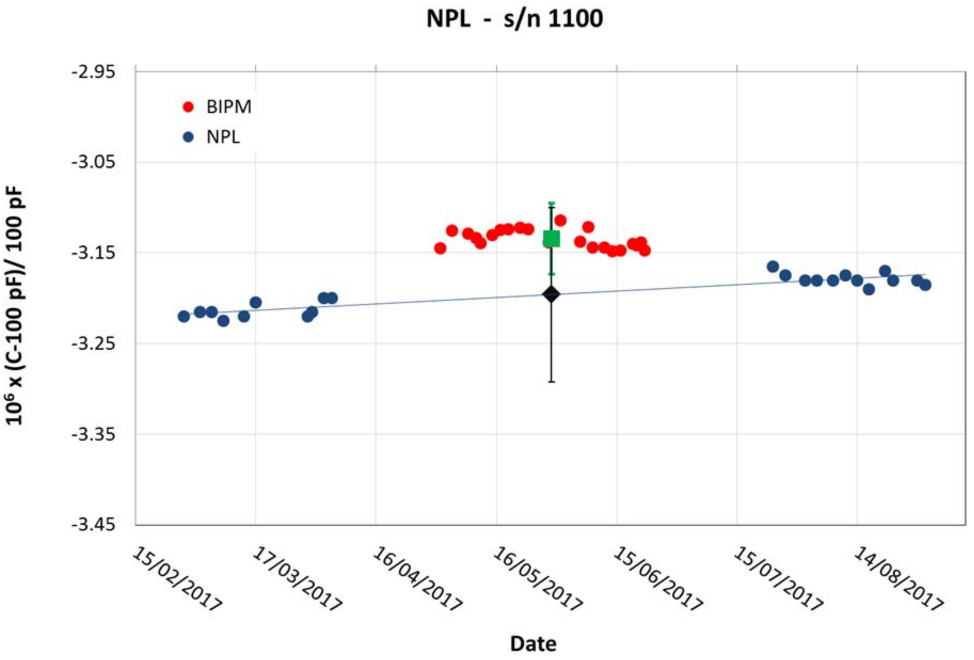


Figure 20: Individual measurements for 100 pF standard #**01100** showing NPL measurements and linear fit, BIPM measurements, NPL value interpolated at the mean date of BIPM measurements (black diamond dot) with 1σ uncertainty bar, BIPM predicted value at the mean date (green square dot) with 1σ uncertainty bar. Measurement conditions: 1592 Hz and 10 V (rms).

10.6. Comparison between BIPM and PTB

All the individual measurements performed at both the PTB and the BIPM are shown on Figures 21 and 22 for the 10 pF standards #01257 and #01258, and on Figures 23 and 24 for the 100 pF standards #01157 and #01256.

In these figures are also shown the interpolated value of the BIPM measurements (C_{PTB}^{ref}) at the mean date of measurement at the BIPM ($\overline{D_{PTB}^{BIPM}}$), as well as the linear fit of the PTB initial and return series of measurements along with the PTB predicted value (C_{PTB}) at the mean date. The uncertainty bars correspond to $u(C_{PTB}^{ref})$ and $u(C_{PTB})$ in 1σ.

A dependence of the capacitance value of the four standards from PTB has been observed during measurement at BIPM and PTB. This dependence is of the order of 1 part in 10^9 of the capacitance value per hPa of variation of the atmospheric pressure. No such effect was detected on the standards of the other NMIs within the resolution of measurement, or was possible to extract from the measuring noise.
As an example, Figure 25 presents the correlation between capacitance value and atmospheric pressure for the 100 pF standard #01256 during the measurement at the BIPM. On this figure are reported versus time both: (i) the difference between the measured capacitance and the mean capacitance of the series of measurements after correction from the drift, and (ii) the difference between the measured atmospheric pressure at the time of measurement and the mean atmospheric pressure over the series of measurements.

For each of the PTB's capacitors a pressure coefficient has been estimated from its measured capacitance variations with atmospheric pressure. However, the observed capacitance variations may not necessarily only be due to atmospheric pressure changes and may sometime be superimposed with other uncontrolled systematic errors. Then, only clear or larger capacitance variations with atmospheric pressure have been kept to estimate the pressure coefficients. The coefficients estimated by the BIPM are reported in Table 26 along with their standard deviation. These values are in good agreement with the pressure coefficient determined by PTB which value is $(1.0 \pm 0.2)\times10^{-9}$/hPa for all four PTB's standards.

Estimated pressure coefficient along with their standard deviation ($\times 10^{-9}$ / hPa)			
10 pF #1257	10 pF #1258	100 pF #1256	100 pF #1157
0.6 ± 1.1	0.7 ± 1.0	1.1 ± 0.3	1.4 ± 2.1

Table 26: Pressure coefficients of travelling capacitors from PTB measured at the BIPM.

Measurements at the BIPM and PTB were carried out at different mean atmospheric pressures of 1009.0 hPa and of 1005.5 hPa, respectively. In order to be able to compare PTB and BIPM measurements, all the individual measurements carried out both at PTB and BIPM have been corrected in order that they correspond to a measurement performed at the same reference atmospheric pressure of 1013.25 hPa (1 atm). The correction applied to each of the measurements is calculated using the corresponding pressure coefficient (Table 26) and the difference between the atmospheric pressure at the time of measurement and the reference pressure. The uncertainty on this correction is estimated from the standard deviation of the estimation of the pressure coefficient and from the uncertainty on the measurement of atmospheric pressure either at PTB or BIPM. This uncertainty is found to have a maximum value of 5 part in 10^9 which is combined quadratically to $u(C_{PTB})$ and $u(C_{PTB}^{ref})$. Results presented in the following Tables 27 and 28 and Figures 21 to 24 are the corrected ones.

The values of C_{PTB}^{ref} and C_{PTB} at the mean date 1 June 2017 as well as their relative difference Δ_{PTB} are reported in Tables 27 and 28 for both the 10 pF and 100 pF standards, respectively. Tables also include the 1 σ value of the uncertainty components defined in section 9 and $u_{Atm\_pressure}$ the uncertainty on the atmospheric pressure correction.

	Standard #01257	**Standard #01258**
Mean date of measurement	**1 June 2017**	**1 June 2017**
$\boldsymbol{C_{PTB}^{ref}}$	**10.000 015 848 pF**	**10.000 009 851pF**
$u_{A,BIPM}$	0.008 µF/F	0.007 µF/F
$u_{B,BIPM}$	0.036 µF/F	0.036 µF/F
u_{BIPM}	0.037 µF/F	0.037 µF/F
$s_{BIPM}/\sqrt{n}$	0.001 µF/F	0.001 µF/F
$u_{Atm\_pressure}$	0.005 µF/F	0.005 µF/F
$u(C_{PTB}^{ref})$	0.037 µF/F	0.037 µF/F
$\boldsymbol{C_{PTB}}$	**10.000 016 075 pF**	**10.000 010 113 pF**
$u_{A,PTB}$	0.008 µF/F	0.008 µF/F
$u_{B,PTB}$	0.022 µF/F	0.022 µF/F
u_{PTB}	0.023 µF/F	0.023 µF/F
u_{pred}	0.001 µF/F	0.002 µF/F
$u_{Atm\_pressure}$	0.005 µF/F	0.005 µF/F
$u(C_{PTB})$	0.024 µF/F	0.024 µF/F
$\boldsymbol{\Delta_{PTB}}$	**0.023 µF/F**	**0.026 µF/F**
$\boldsymbol{u(\Delta_{PTB})}$	**0.044 µF/F**	**0.044 µF/F**

Table 27: Results along with measurement uncertainties for the 10 pF standards #01257 and #01258 at 1592 Hz and 100 V (rms). All the uncertainty values are reported in 1σ.

	Standard #01157	**Standard #01256**
Mean date of measurement	**1 June 2017**	**1 June 2017**
$\boldsymbol{C_{PTB}^{ref}}$	**99.999 417 97 pF**	**100.000 189 83 pF**
$u_{A,BIPM}$	0.012 µF/F	0.009 µF/F
$u_{B,BIPM}$	0.035 µF/F	0.035 µF/F
u_{BIPM}	0.037 µF/F	0.036 µF/F
$s_{BIPM}/\sqrt{n}$	0.001 µF/F	0.001 µF/F
$u_{Atm\_pressure}$	0.005 µF/F	0.005 µF/F
$u(C_{PTB}^{ref})$	0.037 µF/F	0.037 µF/F
$\boldsymbol{C_{PTB}}$	**99.999 417 07 pF**	**100.000 189 33 pF**
$u_{A,PTB}$	0.011 µF/F	0.011 µF/F
$u_{B,PTB}$	0.019 µF/F	0.017 µF/F
u_{PTB}	0.022 µF/F	0.020 µF/F
u_{pred}	0.002 µF/F	0.002 µF/F
$u_{Atm\_pressure}$	0.005 µF/F	0.005 µF/F
$u(C_{PTB})$	0.023 µF/F	0.021 µF/F
$\boldsymbol{\Delta_{PTB}}$	**-0.009 µF/F**	**-0.005 µF/F**
$\boldsymbol{u(\Delta_{PTB})}$	**0.043 µF/F**	**0.043 µF/F**

Table 28: Results along with measurement uncertainties for the 100 pF standards #01157 and #01256 at 1592 Hz and 10 V (rms). All the uncertainty values are reported in 1σ.

The relative differences Δ_{PTB} for both the 10 pF and the 100 pF standards are averaged to give the final differences between PTB and BIPM:

- at 10 pF : $\boldsymbol{\Delta_{PTB}} = (\mathbf{0.025 \pm 0.043}) \times \mathbf{10^{-6}}$ $(k = 1)$
- at 100 pF: $\boldsymbol{\Delta_{PTB}} = (\mathbf{-0.007 \pm 0.041}) \times \mathbf{10^{-6}}$ $(k = 1)$

As two 10 pF and two 100 pF capacitance standards have been measured, four 10:1 ratio values can be computed for both PTB and the BIPM. The individual capacitance measurements used for the computations and their standard uncertainty are summarized in Table 29 (from Tables 27 and 28).

The calculated relative deviations from the nominal 10:1 ratio are reported in Table 30 as well as the differences of the deviations computed for the PTB and the BIPM. The mean of these differences and its combined standard uncertainty are also reported in this table.

	PTB	**BIPM**
Capacitance	Difference from nominal value, µF/F	Difference from nominal value, µF/F
100 pF #01256	1.893 ± 0.021	1.898 ± 0.037
100 pF #01157	-5.829 ± 0.023	-5.820 ± 0.037
10 pF #01257	1.607 ± 0.024	1.585 ± 0.037
10 pF #01258	1.011 ± 0.024	0.985 ± 0.037

Table 29: Summary of the deviations from nominal value of the four capacitance standards measured by PTB and BIPM.

	PTB	BIPM	
Ratio	Relative deviation from 10, µF/F	Relative deviation from 10, µF/F	PTB-BIPM difference of ratio deviations, µF/F
ratio #01256 / #01257	0.286 ± 0.006	0.313 ± 0.027	-0.028 ± 0.028
ratio #01256 / #01258	0.882 ± 0.006	0.913 ± 0.027	-0.031 ± 0.028
ratio #01157 / #01257	-7.437 ± 0.006	-7.405 ± 0.027	-0.032 ± 0.028
ratio #01157 / #01258	-6.841 ± 0.006	-6.805 ± 0.027	-0.035 ± 0.028
	Mean difference of ratio deviations, µF/F		**-0.031**
	Standard combined uncertainty, µF/F		**0.028**

Table 30: Comparison of the individual deviations from the nominal 10:1 ratio measured by PTB and the BIPM and mean value of the differences of the ratio deviations with its combined uncertainty.

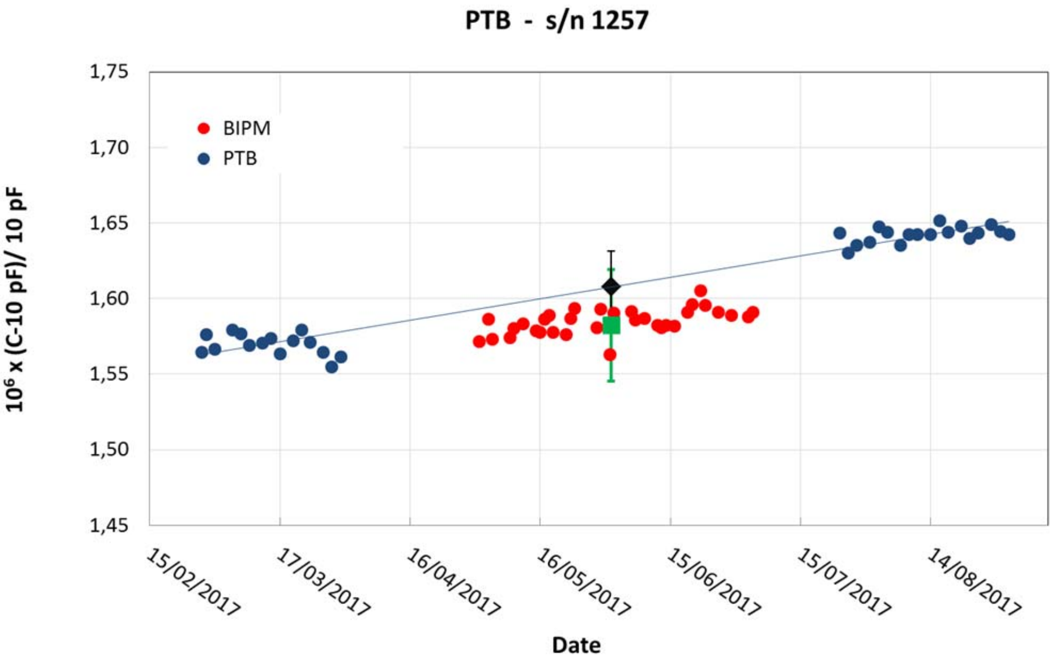


Figure 21: Individual measurements for 10 pF standard #**01257** showing PTB measurements and linear fit, BIPM measurements, PTB value interpolated at the mean date of BIPM measurements (black diamond dot) with 1σ uncertainty bar, BIPM predicted value at the mean date (green square dot) with 1σ uncertainty bar. Measurement conditions: 1592 Hz and 100 V (rms).

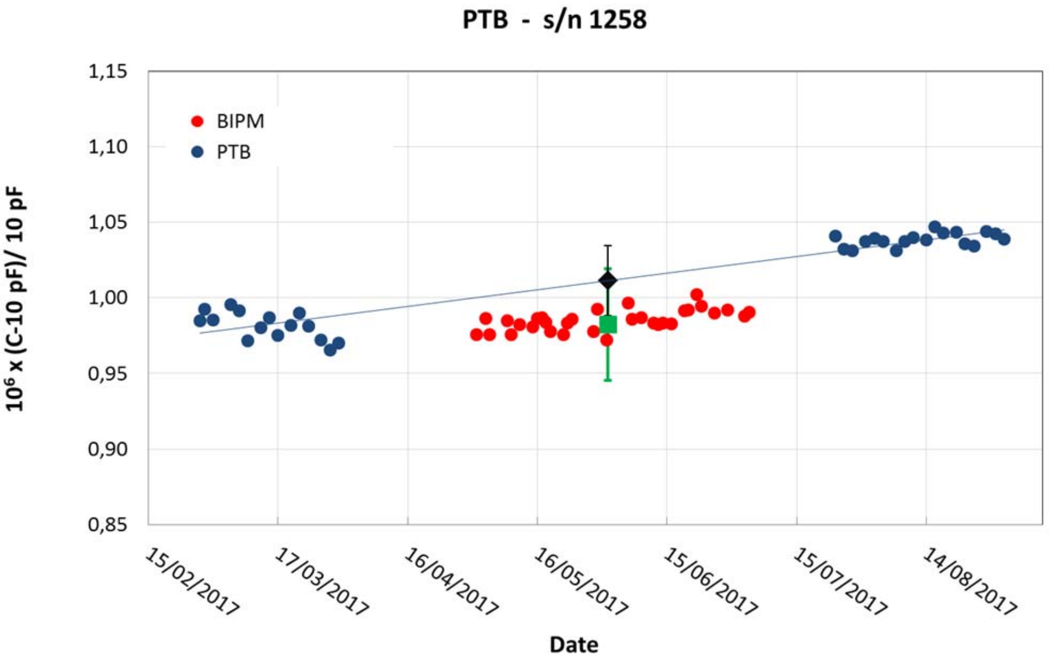


Figure 22: Individual measurements for 10 pF standard #**01258** showing PTB measurements and linear fit, BIPM measurements, PTB value interpolated at the mean date of BIPM measurements (black diamond dot) with 1σ uncertainty bar, BIPM predicted value at the mean date (green square dot) with 1σ uncertainty bar. Measurement conditions: 1592 Hz and 100 V (rms).

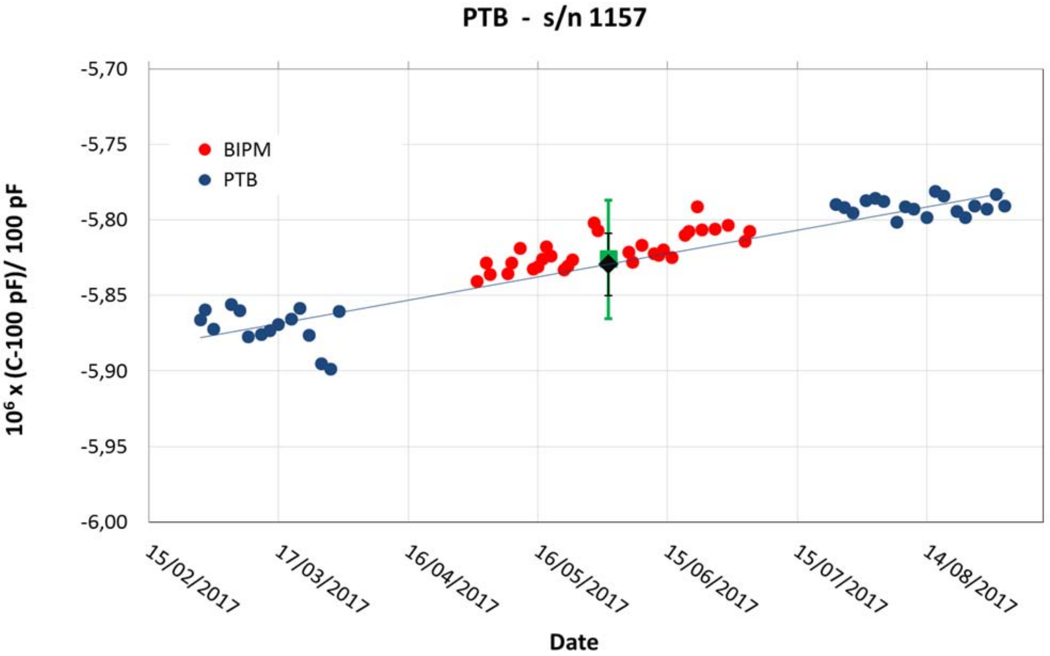


Figure 23: Individual measurements for 100 pF standard #**01157** showing PTB measurements and linear fit, BIPM measurements, PTB value interpolated at the mean date of BIPM measurements (black diamond dot) with 1σ uncertainty bar, BIPM predicted value at the mean date (green square dot) with 1σ uncertainty bar. Measurement conditions: 1592 Hz and 10 V (rms).

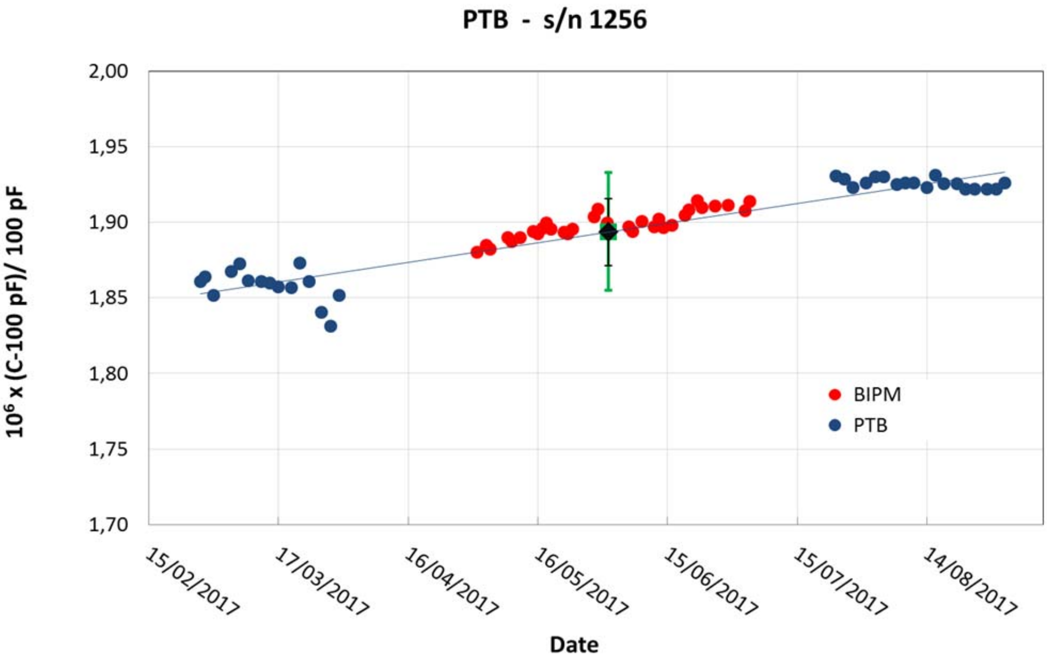


Figure 24: Individual measurements for 100 pF standard #**01256** showing PTB measurements and linear fit, BIPM measurements, PTB value interpolated at the mean date of BIPM measurements (black diamond dot) with 1σ uncertainty bar, BIPM predicted value at the mean date (green square dot) with 1σ uncertainty bar. Measurement conditions: 1592 Hz and 10 V (rms).

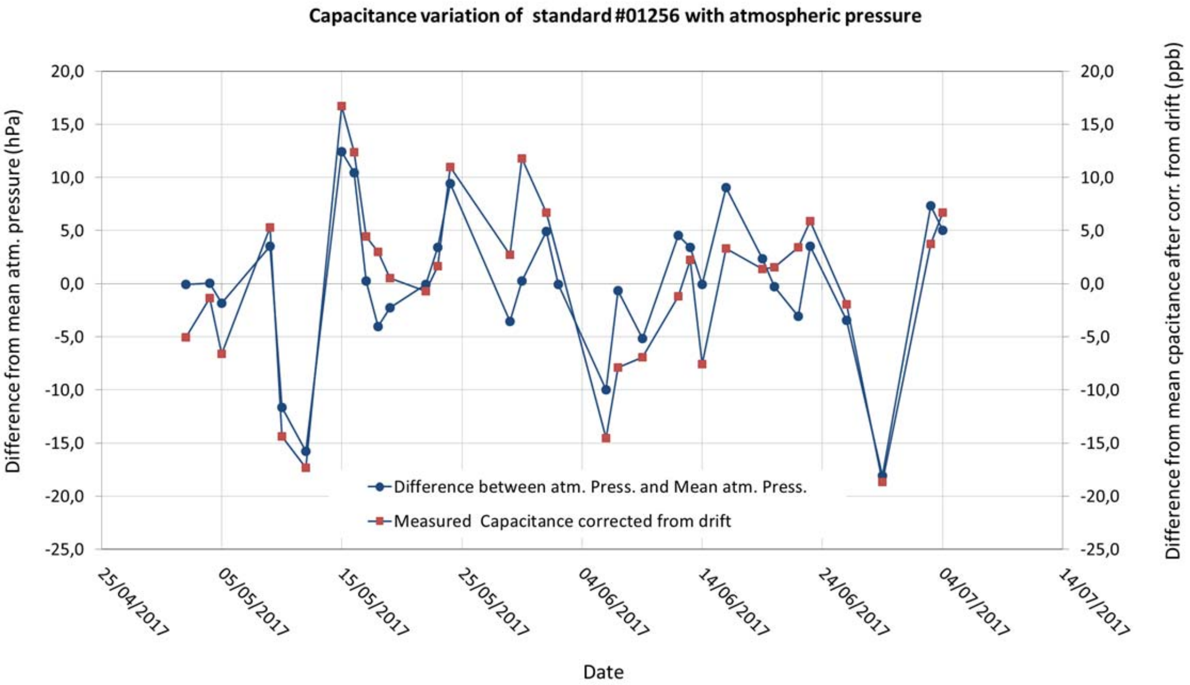


Figure 25: Dependence of the capacitance value of the 100 pF standard #01256 with atmospheric pressure.

10.7. Comparison between BIPM and VNIIM

All the individual measurements performed at both the VNIIM and the BIPM are shown on Figures 26 and 27 for the 10 pF standards #02204 and #02205, and on Figure 28 for the 100 pF standard #02207.

In these figures are also shown the interpolated value of the BIPM measurements (C_{VNIIM}^{ref}) at the mean date of measurement at the BIPM ($\overline{D_{VNIIM}^{BIPM}}$), as well as the linear fit of the VNIIM initial and return series of measurements along with the VNIIM predicted value (C_{VNIIM}) at the mean date. The uncertainty bars correspond to $u(C_{VNIIM}^{ref})$ and $u(C_{VNIIM})$ in 1σ.

Measurements of the standards from VNIIM were not carried out at the recommended temperature value of 23 °C but at the mean temperature of 20.1 °C. Consequently, the measurements reported by VNIIM at 20.1 °C have been corrected for 23 °C.
As the temperature coefficients of the three travelling standards have not been measured by VNIIM, the pilot has estimated the temperature coefficient from previous works [10] and from measurements performed by NIM in this comparison (see annex 3, section A3-3.1). In both cases it has been shown that AH capacitance standards may have a dependence with ambient temperature of the order of -10 part in 10^9 per °C. However, it must be underlined that the experience of the BIPM and other participants is that some AH standards may also have lower dependence with ambient temperature of the order of only few part in 10^9 per °C. Therefore, for a deviation of 3 °C from the agreed temperature of 23 °C, a relative correction of $(-15 \pm 10) \times 10^{-9}$ have been estimated by the pilot and applied to the results reported by VNIIM.

The values of C_{VNIIM}^{ref} and C_{VNIIM} at the mean date 4 July 2017 as well as their relative difference Δ_{VNIIM} are reported in Tables 31 and 32 for both the 10 pF and 100 pF standards, respectively. Tables also include the 1σ value of the uncertainty components defined in section 9 and $u_{Temperature}$ the uncertainty on the temperature correction.

It must be noticed that uncertainty of the 100 pF standard #02207 has been revised by VNIIM after the issue of the first version of draft A (increase of the uncertainty on the 10:1 ratio - see uncertainty statement annex A5-8). This revision had the effect to increase the combined uncertainty by about 55 ppb.

	Standard #02204	**Standard #02205**
Mean date of measurement	**4 July 2017**	**4 July 2017**
$\boldsymbol{C_{VNIIM}^{ref}}$	**9.999 953 384 pF**	**9.999 948 830 pF**
$u_{A,BIPM}$	0.017 µF/F	0.009 µF/F
$u_{B,BIPM}$	0.036 µF/F	0.036 µF/F
u_{BIPM}	0.040 µF/F	0.037 µF/F
$s_{BIPM}/\sqrt{n}$	0.001 µF/F	0.001 µF/F
$u(C_{VNIIM}^{ref})$	0.040 µF/F	0.037 µF/F
$\boldsymbol{C_{VNIIM}}$	**9.999 953 985 pF**	**9.999 949 052 pF**
$u_{A,VNIIM}$	0.015 µF/F	0.015 µF/F
$u_{B,VNIIM}$	0.093 µF/F	0.093 µF/F
u_{VNIIM}	0.094 µF/F	0.093 µF/F
u_{pred}	0.005 µF/F	0.007 µF/F
$u_{Temperature}$	0.010 µF/F	0.010 µF/F
$u(C_{VNIIM})$	0.095 µF/F	0.095 µF/F
$\boldsymbol{\Delta_{VNIIM}}$	**0.060 µF/F**	**0.022 µF/F**
$\boldsymbol{u(\Delta_{VNIIM})}$	**0.103 µF/F**	**0.102 µF/F**

Table 31: Results along with measurement uncertainties for the 10 pF standards #02204 and #02205 at 1592 Hz and 100 V (rms). All the uncertainty values are reported in 1σ.

	Standard #02207
Mean date of measurement	**4 July 2017**
$\boldsymbol{C_{VNIIM}^{ref}}$	**99.999 561 49 pF**
$u_{A,BIPM}$	0.018 μF/F
$u_{B,BIPM}$	0.035 μF/F
u_{BIPM}	0.039 μF/F
$s_{BIPM}/\sqrt{n}$	0.001 μF/F
$u\left(C_{VNIIM}^{ref}\right)$	0.039 μF/F
$\boldsymbol{C_{VNIIM}}$	**99.999 546 23 pF**
$u_{A,VNIIM}$	0.013 μF/F
$u_{B,VNIIM}$	0.142 μF/F
u_{VNIIM}	0.142 μF/F
u_{pred}	0.003 μF/F
$u_{Temperature}$	0.010 μF/F
$u(C_{VNIIM})$	0.143 μF/F
$\boldsymbol{\Delta_{VNIIM}}$	**-0.153 μF/F**
$\boldsymbol{u}(\boldsymbol{\Delta_{VNIIM}})$	**0.148 μF/F**

Table 32: Results along with measurement uncertainties for the 100 pF standard #02207 at 1592 Hz and 10 V (rms). All the uncertainty values are reported in 1σ.

Regarding the 10 pF standards, the calculated values of the relative differences Δ_{VNIIM} are averaged to give the final difference between VNIIM and BIPM. For the 100 pF standard, the final difference is simply that measured for the standard #02207 (Table 32).

Thus, the differences VNIIM-BIPM are:

- at 10 pF : $\boldsymbol{\Delta_{VNIIM}} = (\mathbf{0.041} \pm \mathbf{0.101}) \times \mathbf{10^{-6}}$ (k = 1)
- at 100 pF: $\boldsymbol{\Delta_{VNIIM}} = (\mathbf{-0.153} \pm \mathbf{0.148}) \times \mathbf{10^{-6}}$ (k = 1)

As two 10 pF and one 100 pF capacitance standards have been measured, two 10:1 ratio values can be computed for both VNIIM and the BIPM. The individual capacitance measurements used for the computations and their standard uncertainty are summarized in Table 33 (from Tables 31 and 32).
The calculated relative deviations from the nominal 10:1 ratio are reported in Table 34 as well as the differences of the deviations computed for VNIIM and the BIPM. The mean of these differences and its combined standard uncertainty are also reported in this table.

	VNIIM	**BIPM**
Capacitance	Difference from nominal value, μF/F	Difference from nominal value, μF/F
100 pF #02207	-4.538 ± 0.143	-4.385 ± 0.039
10 pF #02204	-4.602 ± 0.095	-4.662 ± 0.040
10 pF #02205	-5.095 ± 0.095	-5.117 ± 0.037

Table 33: Summary of the deviations from nominal value of the three capacitance standards measured by VNIIM and BIPM.

	VNIIM	BIPM	
Ratio	Relative deviation from 10, µF/F	Relative deviation from 10, µF/F	VNIIM-BIPM difference of ratio deviations, µF/F
ratio #02207 / #02204	0.064 ± 0.121	0.277 ± 0.027	-0.213 ± 0.124
ratio #02207 / #02205	0.557 ± 0.121	0.732 ± 0.027	-0.175 ± 0.124
	Mean difference of ratio deviations, µF/F		**-0.194**
	Standard combined uncertainty, µF/F		**0.124**

Table 34: Comparison of the individual deviations from the nominal 10:1 ratio measured by VNIIM and the BIPM and mean value of the differences of the ratio deviations with its combined uncertainty.

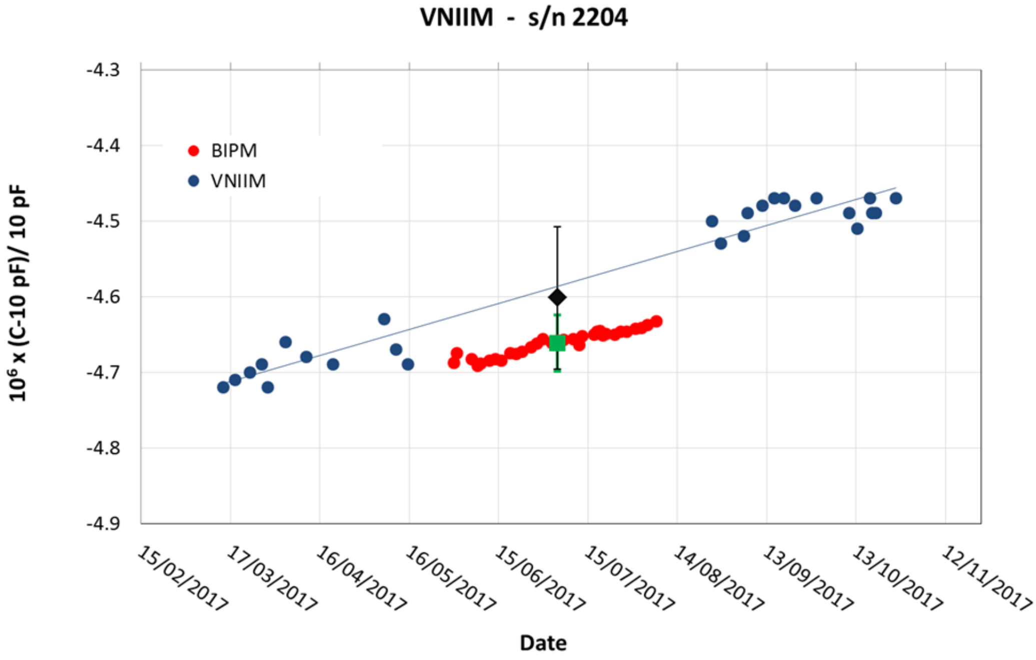


Figure 26: Individual measurements for 10 pF standard **#02204** showing VNIIM measurements and linear fit, BIPM measurements, VNIIM value interpolated at the mean date of BIPM measurements (black diamond dot) with 1σ uncertainty bar, BIPM predicted value at the mean date (green square dot) with 1σ uncertainty bar. Measurement conditions: 1592 Hz and 100 V (rms).

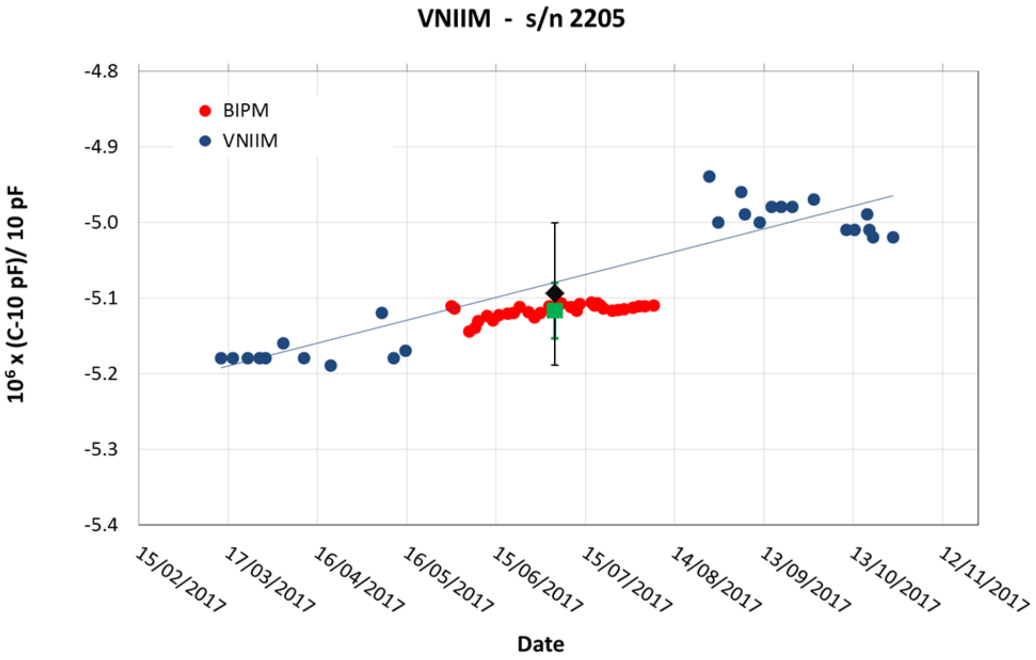


Figure 27: Individual measurements for 10 pF standard #**02205** showing VNIIM measurements and linear fit, BIPM measurements, VNIIM value interpolated at the mean date of BIPM measurements (black diamond dot) with 1σ uncertainty bar, BIPM predicted value at the mean date (green square dot) with 1σ uncertainty bar. Measurement conditions: 1592 Hz and 100 V (rms).

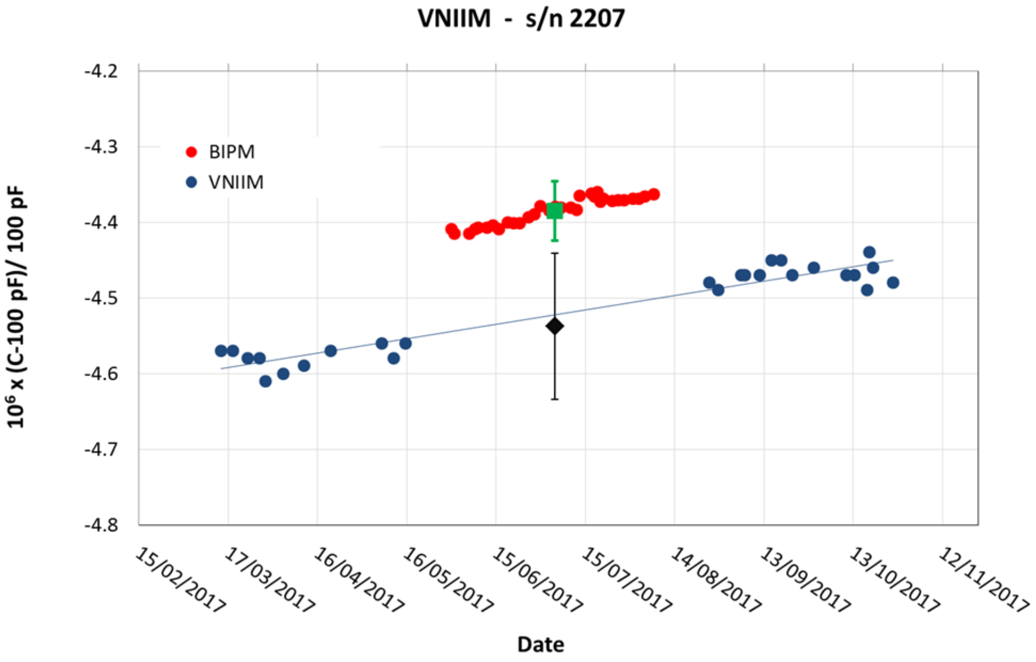


Figure 28: Individual measurements for 100 pF standard #**02207** showing VNIIM measurements and linear fit, BIPM measurements, VNIIM value interpolated at the mean date of BIPM measurements (black diamond dot) with 1σ uncertainty bar, BIPM predicted value at the mean date (green square dot) with 1σ uncertainty bar. Measurement conditions: 1592 Hz and 10 V (rms).

10.8. Measurement of BIPM standards following comparison protocol

The BIPM has carried out the measurement of one of its own set of standard capacitors composed of two 10 pF standards and two 100 pF standards (AH11A type) following the same time schedule as the other participants. Initial, intermediate and return series of measurements have been analysed in the same way as for all NMIs and, as no discrepancies between the different series is assumed, it is expected to obtain differences Δ_{BIPM} equal to zero to the precision of the method (and measurements) for both the 10 pF and 100 pF standards.

All the individual measurements are shown on Figures 29 and 30 for the 10 pF standards #01227 and #01310, and on Figures 31 and 32 for the 100 pF standards #01642 and #01225.

In these figures are also shown the interpolated value of the BIPM measurements (C_{BIPM}^{ref}) at the mean date of measurement of the second series, ($\overline{D_{BIPM}^{BIPM}}$), as well as the linear fit of the initial and return series of measurements along with the interpolated value C_{BIPM} at the mean date. The uncertainty bars corresponds to $u\left(C_{BIPM}^{ref}\right)$ and $u(C_{BIPM})$, in 1σ (these uncertainties are evidently very similar).

The values of C_{BIPM}^{ref} and C_{BIPM} at the mean date 30 May 2017 as well as their relative difference Δ_{BIPM} are reported in Tables 35 and 36 for both the 10 pF and 100 pF standards, respectively. Tables also include the 1σ value of the uncertainty components defined in section 9.

	Standard #01227	**Standard #01310**
Mean date of measurement	**30 May 2017**	**30 May 2017**
$\boldsymbol{C_{BIPM}^{ref}}$	**10.000 016 082 pF**	**9.999 999 511 pF**
$u_{A,BIPM}$	0.009 μF/F	0.011 μF/F
$u_{B,BIPM}$	0.036 μF/F	0.036 μF/F
u_{BIPM}	0.037 μF/F	0.038 μF/F
$s_{BIPM}/\sqrt{n}$	0.002 μF/F	0.002 μF/F
$u\left(C_{BIPM}^{ref}\right)$	0.037 μF/F	0.038 μF/F
$\boldsymbol{C_{BIPM}}$	**10.000 016 112 pF**	**9.999 999 460 pF**
$u_{A,BIPM}$	0.012 μF/F	0.006 μF/F
$u_{B,BIPM}$	0.036 μF/F	0.036 μF/F
u_{BIPM}	0.037 μF/F	0.037 μF/F
u_{pred}	0.001 μF/F	0.001 μF/F
$u(C_{BIPM})$	0.038 μF/F	0.037 μF/F
$\boldsymbol{\Delta_{BIPM}}$	**0.003 μF/F**	**-0.005 μF/F**
$\boldsymbol{u(\Delta_{BIPM})}$	**0.052 μF/F**	**0.052 μF/F**

Table 35: Results along with measurement uncertainties for the 10 pF standards #01227 and #01310 at 1592 Hz and 100 V (rms). All the uncertainty values are reported in 1σ.

	Standard #01225	**Standard #01642**
Mean date of measurement	**30 May 2017**	**30 May 2017**
$\boldsymbol{C_{BIPM}^{ref}}$	**100.000 513 70 pF**	**100.000 065 23 pF**
$u_{A,BIPM}$	0.006 µF/F	0.004 µF/F
$u_{B,BIPM}$	0.035 µF/F	0.035 µF/F
u_{BIPM}	0.036 µF/F	0.035 µF/F
$s_{BIPM}/\sqrt{n}$	0.001 µF/F	0.001 µF/F
$u(C_{BIPM}^{ref})$	0.036 µF/F	0.035 µF/F
$\boldsymbol{C_{BIPM}}$	**100.000 513 68 pF**	**100.000 065 23 pF**
$u_{A,BIPM}$	0.007 µF/F	0.005 µF/F
$u_{B,BIPM}$	0.035 µF/F	0.035 µF/F
u_{BIPM}	0.036 µF/F	0.035 µF/F
u_{pred}	0.001 µF/F	0.000 µF/F
$u(C_{BIPM})$	0.036 µF/F	0.035 µF/F
$\boldsymbol{\Delta_{BIPM}}$	**0.000 µF/F**	**0.000 µF/F**
$\boldsymbol{u(\Delta_{BIPM})}$	**0.050 µF/F**	**0.050 µF/F**

Table 36: Results along with measurement uncertainties for the 100 pF standards #01642 and #01225 at 1592 Hz and 10 V (rms). All the uncertainty values are reported in 1σ.

The arithmetic means of the individual differences $\boldsymbol{\Delta_{BIPM}}$ computed for both the 10 pF and 100 pF standards provide the final mean differences 'BIPM-BIPM':

- at 10 pF : $\boldsymbol{\Delta_{BIPM}} = (\mathbf{-0.001} \pm \mathbf{0.051}) \times \mathbf{10^{-6}}$ (k = 1)
- at 100 pF: $\boldsymbol{\Delta_{BIPM}} = (\mathbf{0.000} \pm \mathbf{0.050}) \times \mathbf{10^{-6}}$ (k = 1)

As expected the differences Δ_{BIPM} are very near zero; their values allow an estimate of the precision of the method when there is no transportation of the standards and that measurements are performed with the same measuring chain.

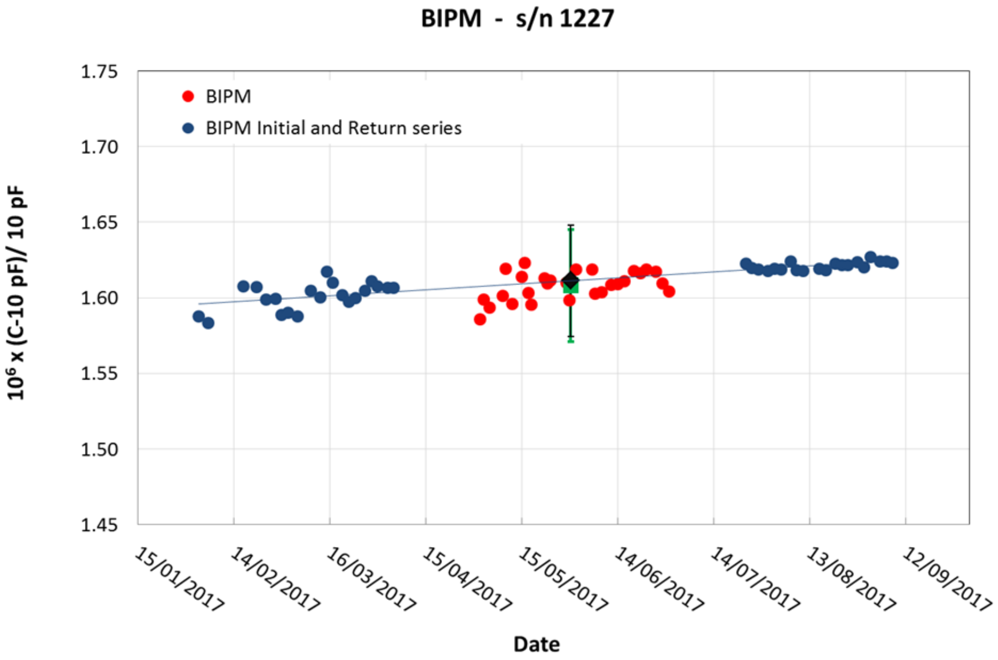


Figure 29: Individual measurements for 10 pF standard #**01227** showing the three series of measurements performed at the BIPM, the interpolated value at the mean date of the second series (green square dot) with 1σ uncertainty bar, and the linear fit of the 1st and 3rd series with the predicted value at the mean date (black diamond dot) with 1σ uncertainty bar. Measurement conditions: 1592 Hz and 100 V (rms).

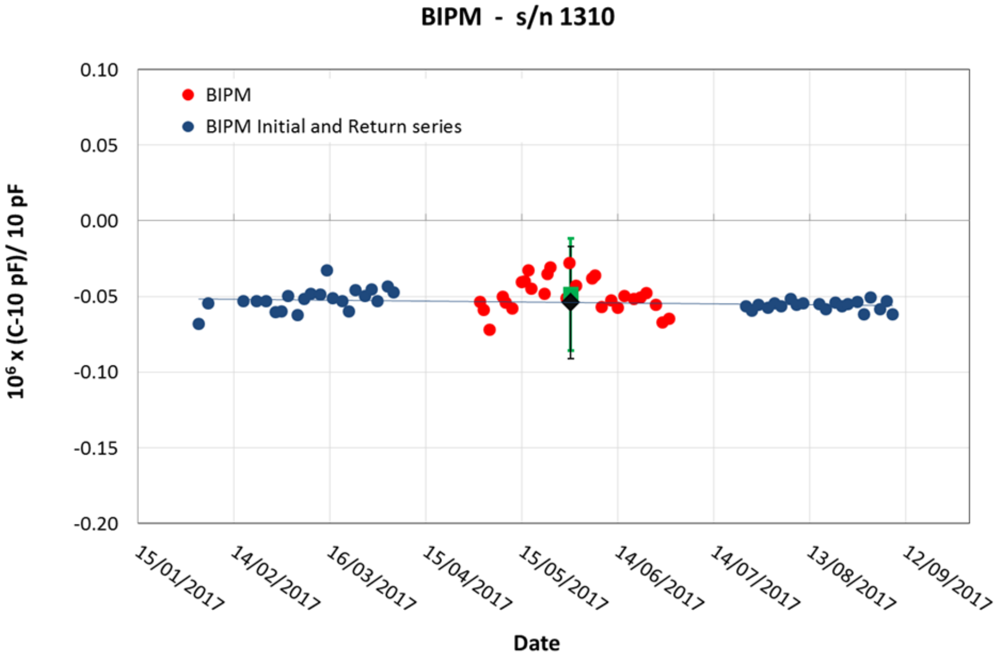


Figure 30: Individual measurements for 10 pF standard #**01310** showing the three series of measurements performed at the BIPM, the interpolated value at the mean date of the second series (green square dot) with 1σ uncertainty bar, and the linear fit of the 1st and 3rd series with the predicted value at the mean date (black diamond dot) with 1σ uncertainty bar. Measurement conditions: 1592 Hz and 100 V (rms).

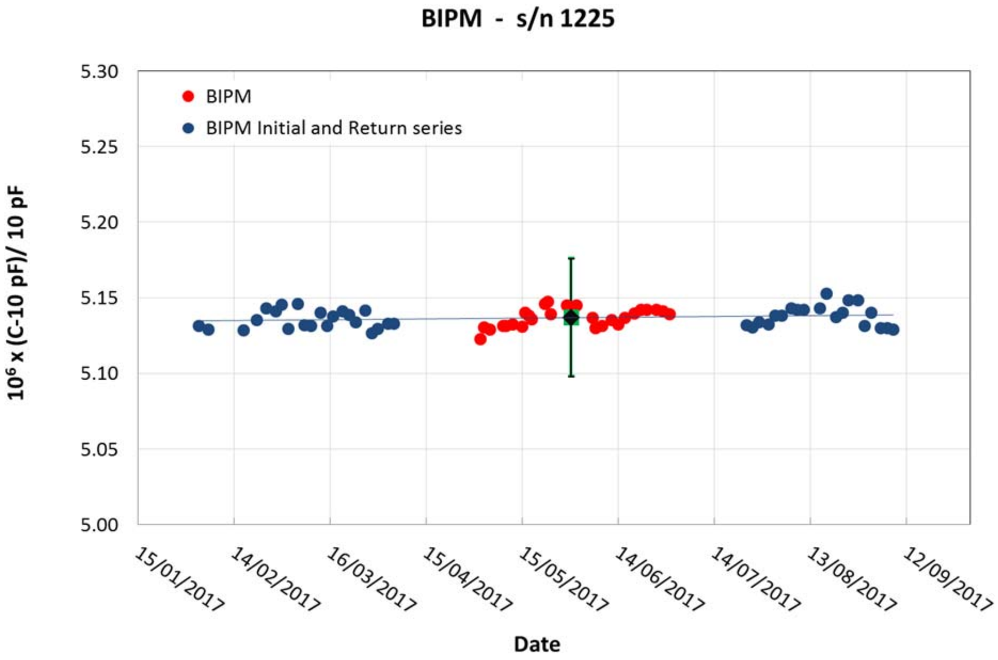


Figure 31: Individual measurements for 100 pF standard #**01225** showing the three series of measurements performed at the BIPM, the interpolated value at the mean date of the second series (green square dot) with 1σ uncertainty bar, and the linear fit of the 1st and 3rd series with the predicted value at the mean date (black diamond dot) with 1σ uncertainty bar. Measurement conditions: 1592 Hz and 10 V (rms).

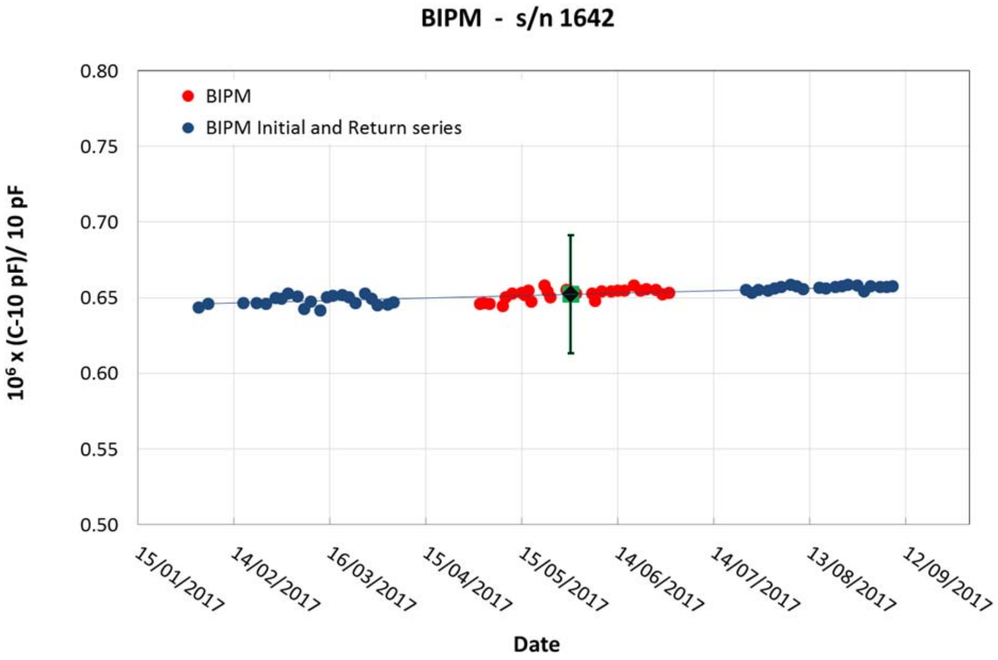


Figure 32: Individual measurements for 100 pF standard #**01642** showing the three series of measurements performed at the BIPM, the interpolated value at the mean date of the second series (green square dot) with 1σ uncertainty bar, and the linear fit of the 1st and 3rd series with the predicted value at the mean date (black diamond dot) with 1σ uncertainty bar. Measurements conditions: 1592 Hz and 10 V.

11. Calculation of the Key Comparison Reference Value (KCRV) and of the Degrees of Equivalence (DoE)

The usual way to determine the KCRV is to calculate the weighted mean of the set of the individual measurements of the quantity addressed in the comparison as performed by each of the participants. In the present case this quantity is the difference of capacitance measurements between a given NMI and the BIPM, and the set of individual measurements are the differences Δ_i computed in the previous section and reported in Table 37 (index *i* refers to the acronym of the NMIs).

The weights used for the computation of the weighted mean would normally be the standard uncertainties $u(\Delta_i)$ on the differences Δ_i. However, as all the Δ_i are correlated to the BIPM capacitance base, the uncorrelated uncertainties of the differences,

$$u_{uncorr}(\Delta_i) = \sqrt{u(\Delta_i)^2 - u_B^2\left(C_i^{ref}\right)},$$

have been considered for this calculation. Uncorrelated uncertainty values are reported in Table 37 along with the Δ_i.

	Δ_i and associated uncorrelated standard uncertainty $u(\Delta_i)$, in µF/F	
	10 pF standards	100 pF standards
Δ_{BIPM}	0.000 ± 0.036	0.000 ± 0.035
Δ_{METAS}	0.017 ± 0.085	0.051 ± 0.074
Δ_{NIM}	0.000 ± 0.019	−0.034 ± 0.022
Δ_{NIST}	−0.057 ± 0.021	−0.074 ± 0.020
Δ_{NMIA}	−0.005 ± 0.054	0.009 ± 0.053
Δ_{NPL}	−0.033 ± 0.110	−0.062 ± 0.096
Δ_{PTB}	0.025 ± 0.024	−0.007 ± 0.022
Δ_{VNIIM}	0.041 ± 0.095	−0.153 ± 0.144
Weighted mean, $\bar{\Delta}$, in µF/F	**−0.010 ± 0.011**	**−0.033 ± 0.011**
Observed χ^2 value, χ^2_{obs}	7.97	9.24
χ^2_{obs} per degree of freedom, χ^2_{obs}/ν	1.14	1.32
$Pr\{\chi^2(\nu) > \chi^2_{obs}\}$, $\nu = 7$	34 %	24 %

Table 37: Summary of the differences Δ_i between the participating NMIs and the BIPM along with their associated uncorrelated standard uncertainty (k = 1).

This way of determining the KCRV is acceptable only if the consistency of the distribution of the differences Δ_i may be established. This is done in performing a chi-squared test [11, 12] using the observed χ^2 value computed as,

$$\chi^2_{obs} = \sum_i \frac{(\Delta_i - \bar{\Delta})^2}{u^2_{uncorr}(\Delta_i)}$$

where $\bar{\Delta}$ is the weighted mean of the differences Δ_i computed using the inverses of the squares of their associated uncorrelated standard uncertainty as the weights,

$$\bar{\Delta} = \frac{\sum_i w_i \Delta_i}{\sum_i w_i} \qquad \text{with} \qquad w_i = \frac{1}{u^2_{uncorr}(\Delta_i)}.$$

The relative standard uncertainty of the weighted mean corresponds to the standard deviation associated with the computation of $\bar{\Delta}$, and is given by,

$$u(\bar{\Delta}) = \left(\sum_i w_i\right)^{-\frac{1}{2}}$$

The value χ^2_{obs} is expected to belong to a χ^2 distribution with $\nu = 7$ degrees of freedom from which the probability of finding $\chi^2(\nu) > \chi^2_{obs}$ can be computed. In Table 37 are reported χ^2_{obs} and its normalized value χ^2_{obs}/ν as well as the probability $Pr\{\chi^2(\nu) > \chi^2_{obs}\}$ for both the measurements at 10 pF and 100 pF.
According to the probability values computed, we can reasonably accept the weighted means of the Δ_i as the KCRV for both capacitance values. Then, the KCRVs are:

- For measurement at 10 pF: $\boldsymbol{KCRV_{10pF}} = (\mathbf{-0.010} \pm \mathbf{0.011}) \times \mathbf{10^{-6}}$
- For measurement at 100 pF: $\boldsymbol{KCRV_{100pF}} = (\mathbf{-0.033} \pm \mathbf{0.011}) \times \mathbf{10^{-6}}$

On Figures 33 and 34 are shown all the differences Δ_i between each participant and the BIPM as well as the KCRV values (red lines). The BIPM appear also on this graph with a difference equal to zero. Error bars correspond to the expanded uncertainties associated with each of the Δ_i and with the KCRVs (k = 2).

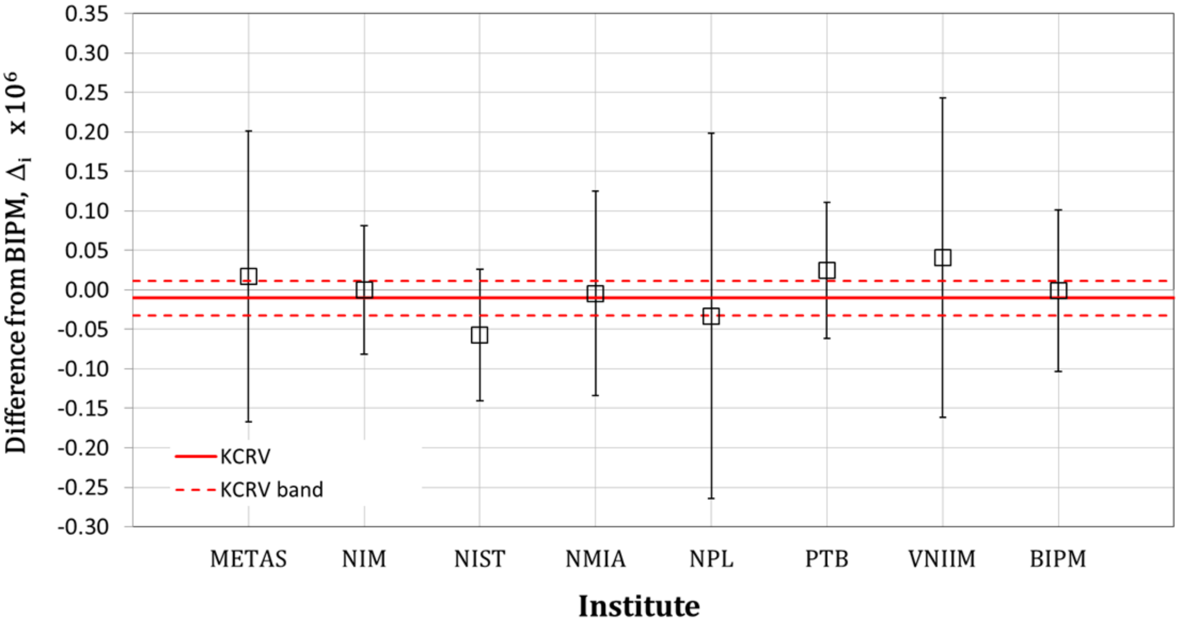


Figure 33: Differences Δ_i between each of the participants and the BIPM (black squares) together with the KCRV value (bold red line) for the measurement of **10 pF** capacitance standards. Error bars correspond to the expanded uncertainties associated with each of the Δ_i (k = 2), and the dotted lines to the high and low limit of the expanded error band of the KCRV (k = 2). BIPM appear in the graph with a difference Δ_{BIPM}= 0.

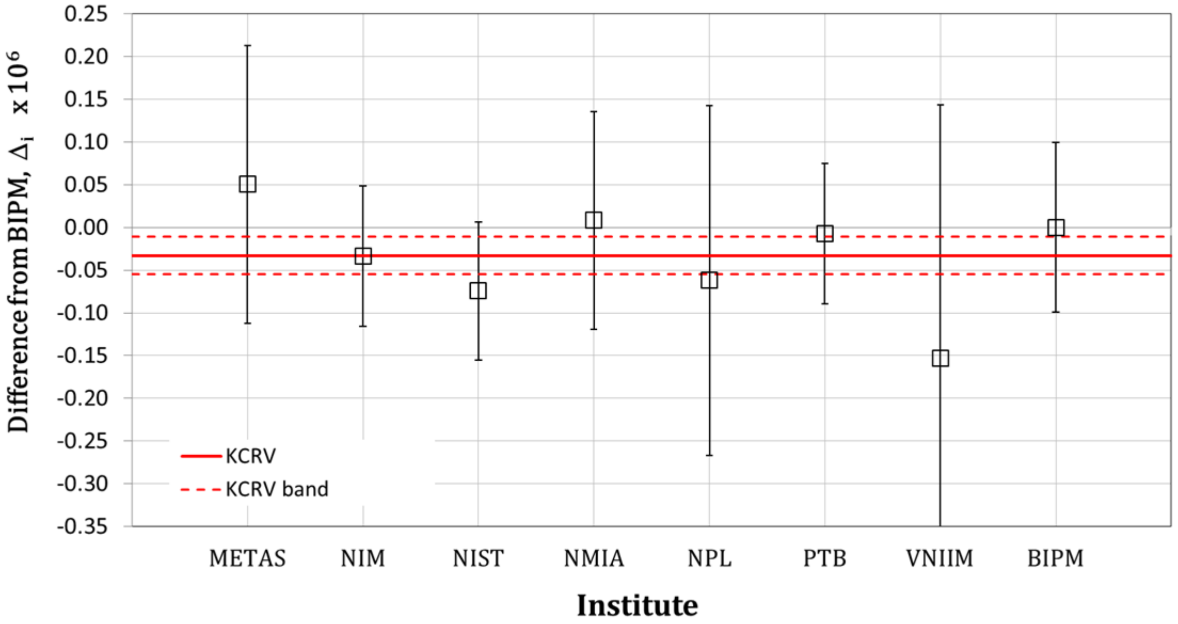


Figure 34: Differences Δ_i between each of the participants and the BIPM (black squares) together with the KCRV value (bold red line) for the measurement of **100 pF** capacitance standards. Error bars correspond to the expanded uncertainties associated with each of the Δ_i (k = 2), and the dotted lines to the high and low limit of the expanded error band of the KCRV (k = 2). BIPM appear in the graph with a difference Δ_{BIPM}= 0.

The comparison results can also be expressed in terms of degrees of equivalence (DoE), corresponding to the differences between the Δ_i and the KCRV. The DoE defines to what degree a given Δ_i is consistent with the KCRV ($\bar{\Delta}$).

The DoE is expressed quantitatively by two terms: the deviation of Δ_i from the KCRV, and its uncertainty at a 95 % level of confidence (coverage factor k = 2). Thus, the DoE of the institute of acronym i is formed as the pair $(d_i, U(d_i))$ with:

$$d_i = \Delta_i - \bar{\Delta} \qquad \text{and} \qquad U(d_i) = 2 \times u(d_i)$$

$$\text{where} \quad u(d_i) = [u_{uncorr}^2(\Delta_i) - u^2(\bar{\Delta})]^{1/2}$$

The DoE computed for each of the participants is reported in Table 38 for both 10 pF and 100 pF measurements. These DoEs are also reported on Figures 35 and 36.

	10 pF standards		**100 pF standards**	
	d_i (µF/F)	$U(d_i)$ (µF/F)	d_i (µF/F)	$U(d_i)$ (µF/F)
METAS	0.027	0.169	0.084	0.145
NIM	0.010	0.031	-0.001	0.037
NIST	-0.047	0.035	-0.041	0.034
NMIA	0.006	0.105	0.041	0.104
NPL	-0.023	0.219	-0.029	0.191
PTB	0.035	0.042	0.026	0.037
VNIIM	0.051	0.188	-0.120	0.287
BIPM	0.009	0.070	0.033	0.067

Table 38: Degrees of equivalence of the participating institutes for both 10 pF and 100 pF measurements.

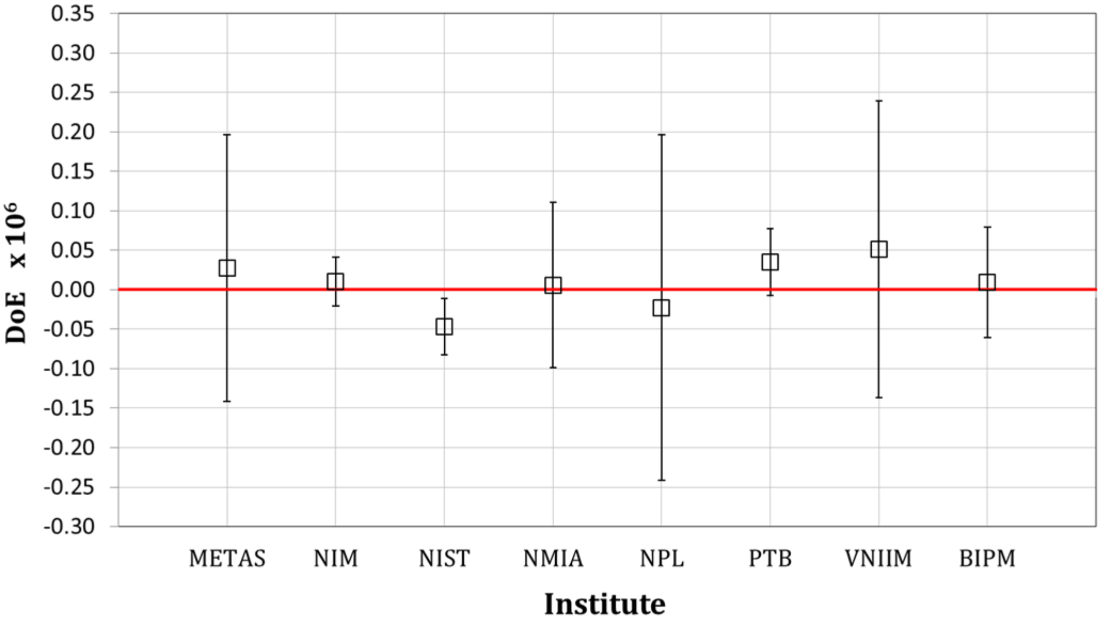


Figure 35: Degrees of equivalence of the participating NMIs (black squares) along with their expanded uncertainty (k = 2) for the measurement of **10 pF** capacitance standards. Red line indicates the DoE=0 line.

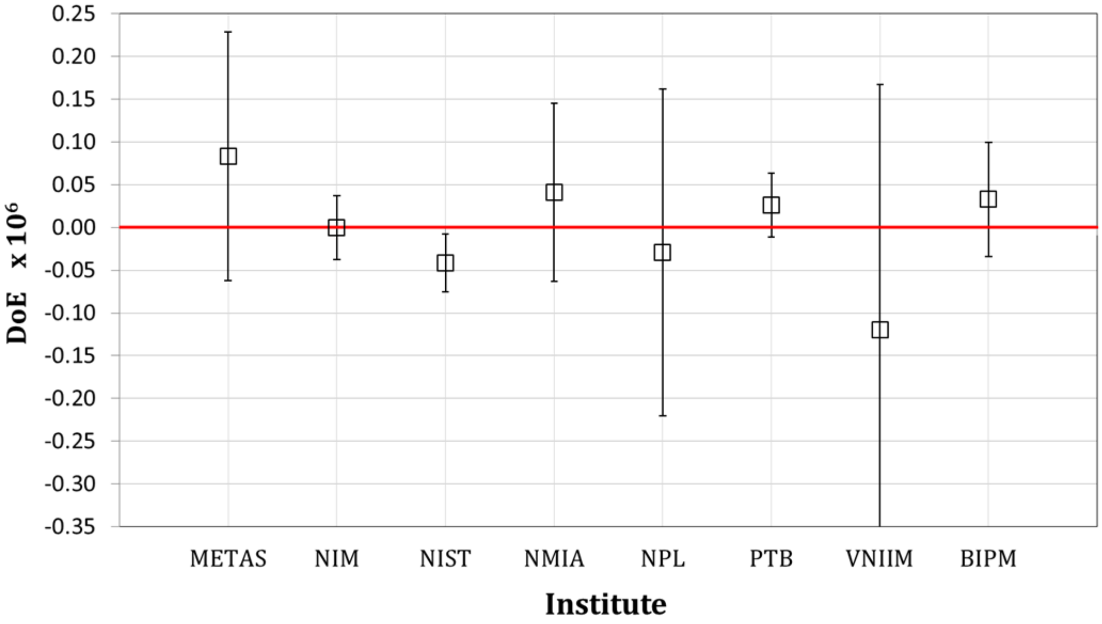


Figure 36: Degrees of equivalence of the participating NMIs (black squares) along with their expanded uncertainty (k = 2) for the measurement of **100 pF** capacitance standards. Red line indicates the DoE=0 line.

12. Comparison of DoE between comparisons CCEM-K4.1996 and CCEM-K4.2017

The degrees of equivalence determined in the CCEM-K4.2017 comparison can be compared directly to those from the previous CCEM-K4 comparison carried out between 1996 and 1999. At that time the traceability to the farad was mainly based on calculable capacitors and only 3 of 11 participating institutes were running a QHR for the realization of the farad (BIPM, BNM-LCIE, NRC). Only 10 pF standards were travelled in the CCEM-K4.1996 comparison.

As shown on figure 37, there is a good matching of the DoEs obtained in these two key comparisons. For institutes having participated to both comparisons the DoEs are either quite similar or clearly improved. Numerical values of the DoEs obtained in the CCEM-K4.1996 comparison are reported in Table 39.

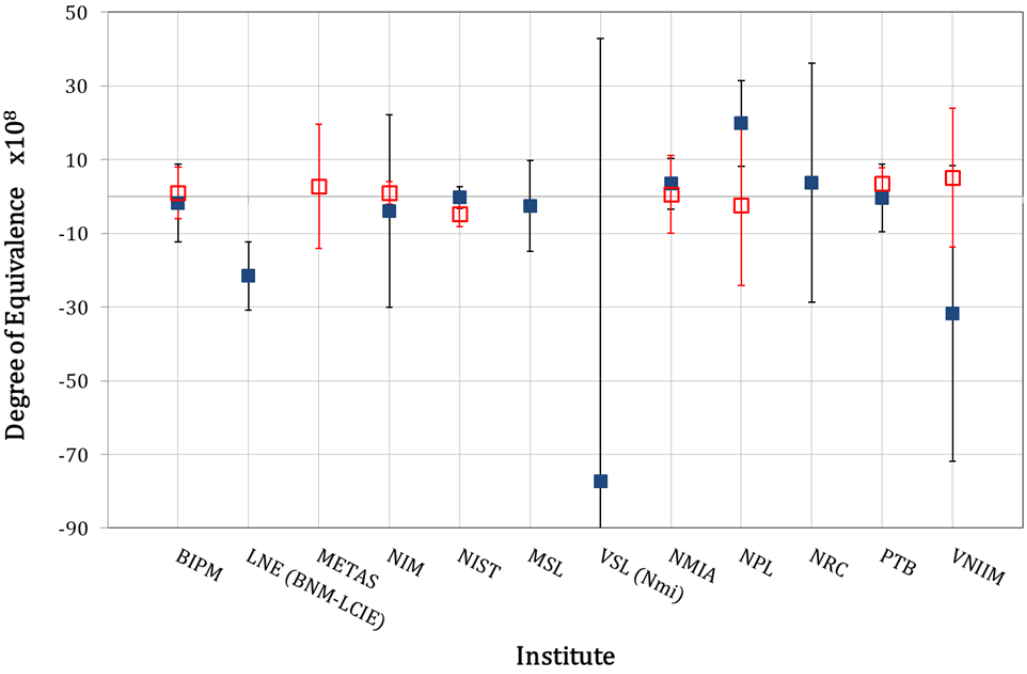


Figure 37: Comparison of degrees of equivalence, for the measurement of **10 pF** standards, between comparisons CCEM-K4.1996 (blue squares) and CCEM-K4.2017 (red squares). Uncertainty bars correspond to a coverage factor k = 2 (95% confidence level).

	d_i (µF/F)	$U(d_i)$ (µF/F)
BIPM	-0.018	0.105
LNE (formerly BNM-LCIE)	-0.216	0.092
NIM	-0.040	0.261
NIST	-0.003	0.029
MSL	-0.026	0.124
VSL (formerly Nmi)	-0.772	1.200
NMIA	0.035	0.069
NPL	0.198	0.116
NRC	0.037	0.324
PTB	-0.004	0.092
VNIIM	-0.318	0.401

Table 39: Degrees of equivalence obtained in the CCEM-K4.1996 comparison, [1].

13. Comparison of the deviations from nominal 100 pF/10 pF ratio

Table 40 summarizes the NMIs-BIPM differences of the deviations from the nominal 10:1 ratio calculated in sections 10.1 to 10.7.

As defined in section 9, the reported value $\Delta\varepsilon_{i,10:1}$ corresponds, for a given institute, to the difference between the deviations from the nominal 100 pF/10 pF ratio measured by the institute and by the BIPM. If, for this institute, several 100 pF and/or 10 pF measurements are available, the value $\Delta\varepsilon_{i,10:1}$ corresponds to the mean of all the 100 pF/10 pF ratios it is possible to compute.

According to the chi-squared test, the weighted mean of the computed ratios can be used as a 10:1 ratio KCRV. This value, $KCRV_{10:1}$, is reported in Table 40 along with its uncertainty and the chi-square test result. The value of $KCRV_{10:1}$ is calculated in a similar way as that described in section 11 for the calculation of $KCRV_{10pF}$ and $KCRV_{100pF}$. The weights are the uncorrelated uncertainties on $\Delta\varepsilon_{i,10:1}$ defined as,

$$u_{uncorr}(\Delta\varepsilon_{i,10:1}) = \sqrt{u(\Delta\varepsilon_{i,10:1})^2 - u_B^2(\varepsilon_{BIPM,10:1})}$$

Figure 38 presents the differences $\Delta\varepsilon_{i,10:1}$ for all the participants as well as $KCRV_{10:1}$ and its uncertainty band at 95 % confidence level (k = 2).

NMI	Mean NMI-BIPM difference of deviations from 10:1 ratio, $\Delta\varepsilon_{i,10:1}$ µF/F	Standard uncertainty on the difference, $u(\Delta\varepsilon_{i,10:1})$ µF/F
METAS	0.034	0.053
NIM	-0.034	0.034
NIST	-0.017	0.028
NMIA	0.013	0.031
NPL	-0.029	0.079
PTB	-0.031	0.028
VNIIM	-0.194	0.124
BIPM	0.000	0.038

Weighted mean, $KCRV_{10:1}$ µF/F	**−0.016 ± 0.008**
Observed χ^2 value, χ^2_{obs}	7.19
χ^2_{obs} per degree of freedom, χ^2_{obs}/ν	1.027
$Pr\{\chi^2(\nu) > \chi^2_{obs}\}$, $\nu = 7$	41 %

Table 40: Mean of the differences of the deviations from 10:1 ratio (100 pF/10pF) measured by each of the NMIs and the BIPM. Uncertainty on the difference is reported without expanding factor (k = 1).

These results can also be expressed in terms of degrees of equivalence corresponding for each of the NMI to the difference d_i between $\Delta\varepsilon_{i,10:1}$ and $KCRV_{10:1}$.

As already mentioned previously, the DoE is expressed quantitatively by two terms: the deviation of $\Delta\varepsilon_{i,10:1}$ from the KCRV, and its uncertainty at a 95 % level of confidence (coverage factor k = 2). Thus, the DoE of the institute of acronym i is formed as the pair (d_i, $U(d_i)$) with,

$$d_i = \Delta\varepsilon_{i,10:1} - KCRV_{10:1} \qquad \text{and} \qquad U(d_i) = 2 \times u(d_i)$$

$$\text{where,} \quad u(d_i) = \left[{u_{uncorr}}^2(\Delta\varepsilon_{i,10:1}) - u^2(KCRV_{10:1})\right]^{1/2}$$

The DoE computed for each of the participants is reported in Table 41 and on figure 39. As can be seen, there is a good agreement between the participants.

As already mentioned in section 9, it should be reminded here that the uncertainty attributed by the pilot to the 100 pF: 10 pF ratio (from uncertainty statements of the participants) don't necessarily reflect the best capabilities of the participants in terms of ratio measurements.

	10:1 ratio (100 pF/10 pF)	
	d_i (µF/F)	$U(d_i)$ (µF/F)
METAS	0.050	0.095
NIM	-0.018	0.047
NIST	-0.001	0.027
NMIA	0.029	0.036
NPL	-0.013	0.150
PTB	-0.015	0.025
VNIIM	-0.178	0.244
BIPM	0.016	0.058

Table 41: Degrees of equivalence of the participating institutes with the 100 pF:10 pF ratio KCRV. Expanded uncertainty $U(d_i)$ is given for the expansion factor k = 2.

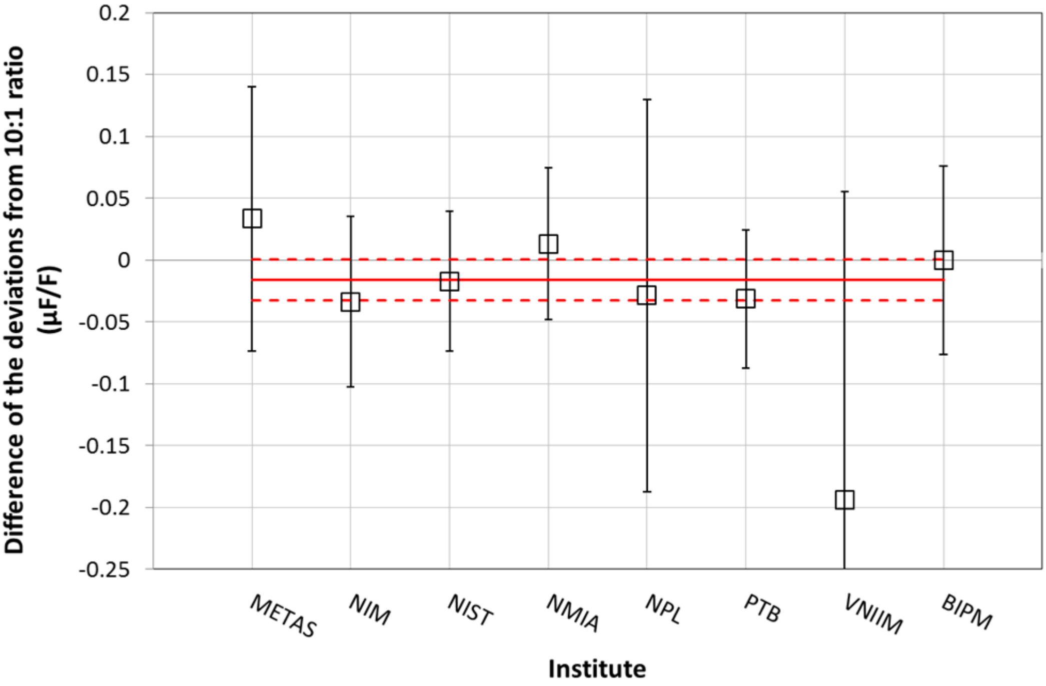


Figure 38: NMI-BIPM differences of the deviations from nominal 100 pF/10 pF ratio (black squares) and comparison reference ratio value (red line) with its expanded uncertainty band (k = 2). Error bars correspond to the expanded combined uncertainty of the NMI-BIPM differences (k = 2).

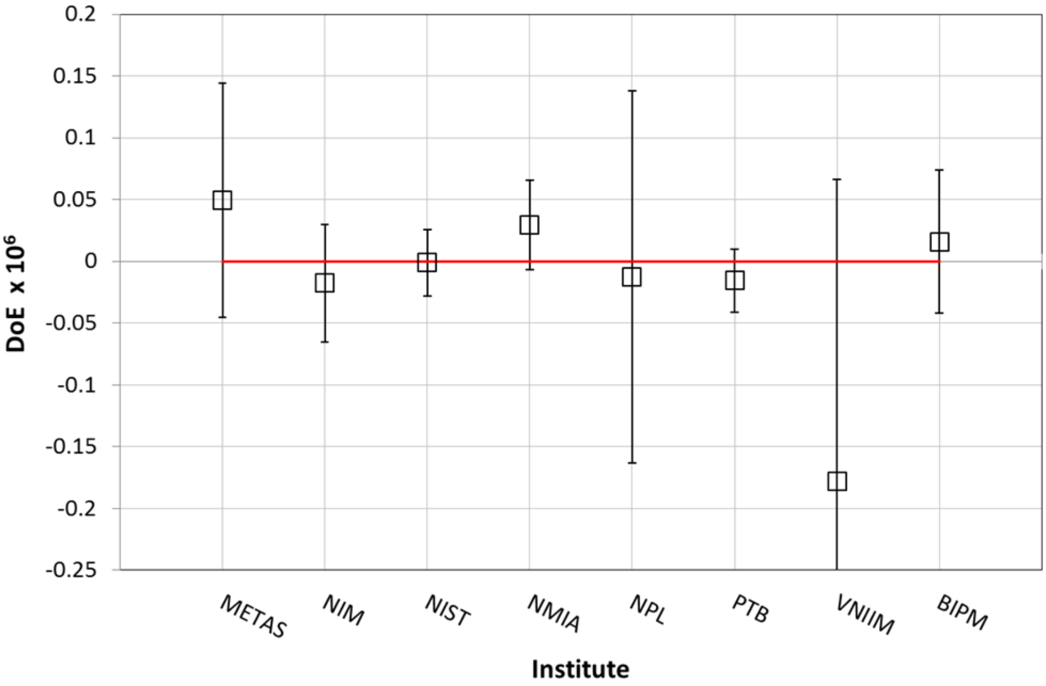


Figure 39: Degrees of equivalence of the participating NMIs (black squares) along with their expanded uncertainty (k = 2) for the measurement of the ratio 10:1 (100 pF/10 pF). Red line indicate the DoE=0 line.

14. Estimation of the von Klitzing constant

From the measurement results obtained in this comparison (Table 37), an estimation of the difference between the R_K value from the last CODATA adjustment and its actual determination from electrical means can be made. This is done by comparing the weighted means of the differences Δ_i issued either from measurements traceable to calculable capacitors or from measurements traceable to quantum Hall resistors. The difference between the weighted means simply gives the estimated difference between the R_K CODATA value (used in this comparison) and that which would be measured in SI units from measurements traceable to calculable capacitors.

In Table 42 are reported the computed weighted mean of the Δ_i of the NMIs having measurements traceable to a calculable capacitor, the computed weighted mean for those having a traceability based on a quantum Hall resistor, and the difference between the weighted means. The differences Δ_i are those obtained for the measurement of the 10 pF capacitance standards.
Table 43 reports the same calculations but for the Δ_i issued from the 100 pF standard measurements.

The differences of the weighted means along with their expanded uncertainties (k = 2) are reported on Figure 40 for both the measurements of the 10 pF and 100 pF capacitances standards.

	Computation from 10 pF standard measurements				
	NMI	Δ_i	$u(\Delta_i)$	Weighted mean and 1σ standard uncertainty, (µF/F)	Difference of weighted means and 1σ standard uncertainty, (µF/F)
Traceability to Calculable capacitor	NIM	0.0000	0.0191	-0.0233 ± 0.0135	**0.039 ± 0.023**
	NIST	-0.0572	0.0209		
	NMIA	-0.0045	0.0537		
	VNIIM	0.0410	0.0945		
QHR	METAS	0.0170	0.0850	0.0156 ± 0.0191	
	NPL	-0.0330	0.1099		
	PTB	0.0245	0.0239		
	BIPM	0.0000	0.0365		

Table 42: Computation of the weighted means of the differences between the BIPM and the NMIs having their traceability based either on a calculable capacitor or on a quantum Hall resistor, and of the difference of these weighted means. Computations are made from the measurements of the 10 pF standards.

	Computation from 100 pF standard measurements				
	NMI	Δ_i	$u(\Delta_i)$	Weighted mean and 1σ standard uncertainty, (µF/F)	Difference of weighted means and 1σ standard uncertainty, (µF/F)
Traceability to Calculable capacitor	NIM	-0.0335	0.0216	-0.0509 ± 0.0142	**0.047 ± 0.023**
	NIST	-0.0744	0.0201		
	NMIA	0.0085	0.0532		
	VNIIM	-0.1530	0.1441		
QHR	METAS	0.0505	0.0735	-0.0038 ± 0.0175	
	NPL	-0.0620	0.0961		
	PTB	-0.0070	0.0216		
	BIPM	0.0000	0.0352		

Table 43: Computation of the weighted means of the differences between the BIPM and the NMIs having their traceability based either on a calculable capacitor or on a quantum Hall resistor, and of the difference of these weighted means. Computations are made from the measurements of the 100 pF standards.

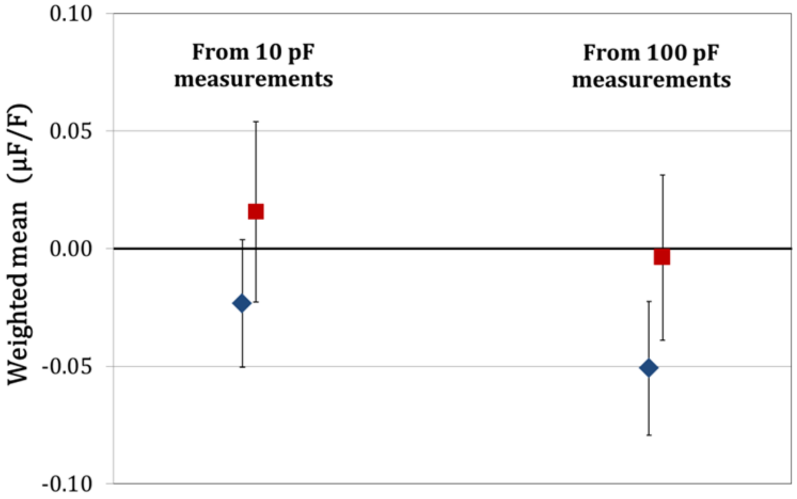


Figure 40: Weighted means computed from the differences Δ_i obtained from 10 pF and 100 pF measurement results (Table 37) and which traceability is based either on calculable capacitors (blue diamonds) or quantum Hall resistors (red squares). Error bars correspond to the expanded uncertainty (k = 2) of the weighted means.

To summarize, the difference between the value of R_K as it could be estimated from the results of this comparison and the CODATA value of R_K is equal to (uncertainty components in 1σ),

- from 10 pF measurements : **$(39 \pm 23)\times10^{-9}$**
- from 100 pF measurements : **$(47 \pm 23)\times10^{-9}$**

leading to a mean difference between the measured-R_K value and the CODATA-R_K value equal to :

$(43 \pm 23)\times10^{-9}$.

Notice that in the calculations performed with the results issued from the 100 pF measurements, the difference Δ_{VNIIM} (shaded in Table 43), have been omitted due to the large difference with the three other Δ_i obtained from calculable capacitors. However, taking into account Δ_{VNIIM} would change the mean difference between measured-R_K and CODATA-R_K values by only 2 parts in 10^9.

	Measured value of R_K (Ω)	Relative standard uncertainty (1σ) (µΩ/Ω)
NIST-97	25812.80831	0.024
NMI-97	25812.8071	0.044
NPL-88	25812.8092	0.054
NIM-95	25812.8084	0.13
LNE-01	25812.8081	0.053
Weighted mean and standard uncertainty	**25812.80817**	**0.018**

Table 44: Experimental values of R_K used in the last CODATA adjustment, from [13], and their weighted mean. Uncertainty values are reported in 1σ.

The above estimated difference (measured-R_K – CODATA-R_K) can be compared to the difference between the weighted mean of the experimental values of R_K obtained from calculable capacitors used for the last CODATA adjustment, Table 44 [13], and the R_K value fixed in this adjustment, CODATA-R_K = 25 812.807 4555(59) Ω, also used in the above analysis.

This difference along with its 1σ standard uncertainty is equal, in relative, to:

$$\mathbf{(28 \pm 18)\times 10^{-9}} .$$

This value is consistent with the difference $(43 \pm 23)\times10^{-9}$ determined from the actual comparison within the estimated uncertainties.

15. Conclusion

The key comparison CCEM-K4.2017 commissioned by the CCEM was carried out between March and November 2017. It allowed determining the current equivalence for the measurement of 10 pF and 100 pF capacitance standards between seven MNIs belonging to four regional metrology organizations and the BIPM.

All the participating NMIs have been chosen among those able to realize and maintain a representation of the farad traceable either to the quantum Hall effect or to a calculable capacitor. Degrees of equivalence have then been established with the lowest possible uncertainty. For NMIs ensuring their traceability from the quantum Hall effect, the measurements were expressed in term of the last CODATA value of the von Klitzing constant R_K in order to make them easily comparable to those of NMIs running calculable capacitors directly linked to the SI.

The measuring scheme adopted for this comparison was that of a 'star-comparison' consisting in carrying out simultaneously a large number of bilateral comparisons piloted by the BIPM, using capacitors from the NMIs as travelling standards. Only Andeen-Hagerling capacitors were sent by NMIs to the pilot which all behaved satisfactorily apart from a very small number of them. However, as several travelling standards of the same nominal value were sent by each participant, no results were invalidated due to issues related to defects or instability of these standards.

It has been found that the DoEs of the participants are consistent within the uncertainty of measurement with a confidence level of 95 % (DoEs are in the range from about -5×10^{-8} to 5×10^{-8} for 10 pF measurements). They are also in good agreement with the DoEs estimated during the previous and first CCEM-K4.1996 comparison which took place from 1996 and 1999. In particular, for institutes that participated in both comparisons the DoEs are either similar or improved.

In addition to the comparison of the measurements at 10 pF and 100 pF, the ratios 100 pF/10 pF computed from these measurements have also been compared. Here again agreement has been found between all the participants.

Finally, as four of the participating institutes take their traceability from a calculable capacitor and four from the quantum Hall effect, it has been possible to compute an estimate of the difference between the value of R_K measured from calculable capacitors and the CODATA-value of the von Klitzing constant R_K. This difference has been found to be equal to $(43 \pm 23)\times10^{-9}$ (for $k = 1$), which is consistent with the difference calculated at the last CODATA adjustment (2014).

16. References

[1] Final report: CCEM Comparison of 10 pF Capacitance Standards, A.M. Jeffery, March 2002, http://kcdb.bipm.org/appendixB/KCDB_ApB_info.asp?cmp_idy=42&cmp_cod=CCEM-K4&prov=exalead

[2] Final Report SIM.EM-K4
http://kcdb.bipm.org/AppendixB/KCDB_ApB_info.asp?cmp_idy=620&cmp_cod=SIM.EM-K4&page=

[3] Final Report EUROMET EM-K4 (EUROMET Project n°345)
http://kcdb.bipm.org/AppendixB/KCDB_ApB_info.asp?cmp_idy=104&cmp_cod=EUROMET.EM-K4&page=

[4] Final Report APMP.EM-K4.1
http://kcdb.bipm.org/appendixB/KCDB_ApB_info.asp?cmp_idy=607&cmp_cod=APMP.EM-K4.1&prov=exalead

[5] Measurement comparisons in the context of the CIPM MRA - CIPM-MRA-D-05
http://www.bipm.org/fr/cipm-mra/cipm-mra-documents/

[6] CCEM Guidelines for Planning, Organizing, Conducting and reporting Key, Supplementary and Pilot Comparisons, http://www.bipm.org/en/committees/cc/ccem/publications-cc.html#bibliography

[7] Report on the 1990 International Comparison of 1 Ω and 10 kΩ Resistance Standards at the BIPM, F. Delahaye, D. Bournaud and T.J. Witt, Metrologia, **29**, pp. 273-283, 1992

[8] http://www.andeen-hagerling.com/ah11a.htm.

[9] http://physics.nist.gov/cgi-bin/cuu/Value?rk

[10] Final report of supplementary EURAMET.EM-S31 comparison of capacitance and capacitance ratio, J. Schürr et al., *Metrologia*, vol. 54, Technical supplement, 2017.

[11] Evaluation of measurements by the method of least squares, L. Nielsen, http://www.bipm.org

[12] Evaluation of key comparison data, M.G. Cox, *Metrologia*, 39, pp. 589-595, 2002.

[13] CODATA recommended values of the fundamental physical constants: 2014, P. J. Mohr, D. B. Newell and B.N. Taylor, *Reviews of Modern Physics*, vol. 88, 2016.

ANNEX 1: Participants

Institute	Country	RMO	Contact			
			Name	Telephone	Fax	email
BIPM Bureau International des Poids et Mesures	International	NA	Pierre Gournay	+33 1 45 07 70 07	+33 1 45 07 70 07	pierre.gournay@bipm.org
METAS Federal Institute of Metrology	Switzerland	EURAMET	Fréderic Overney	+41 58 387 02 96		frederic.overney@metas.ch
NIM National Institute of Metrology	China	APMP	Yan Yang	+86 10 6452 4512	+86 10 6421 8629	yangyan@nim.ac.cn
NIST National Institute of Standards and Technology	United State of America	SIM	Yicheng Wang	+1 301 975 4278	+1 301 926 3972	yicheng.wang@nist.gov
NMIA National Metrology Institute of Australia	Australia	APMP	Leigh Johnson	+61 2 8467 3529	+61 2 8467 3752	Heather.Johnson@measurement.gov.au
NPL National Physical Laboratory	United Kingdom	EURAMET	Janet Belliss	+44 (0)20 8943 6294		janet.belliss@npl.co.uk
PTB Physikalisch Technische Bundesanstalt	Germany	EURAMET	Jürgen Schurr	0049 - 531 - 592 2114	0049 - 531 - 592 2105	Juergen.Schurr@ptb.de
VNIIM D.I. Mendeleyev Institute for Metrology	Russia	COOMET	Yuri Semenov	-	-	semyup@gmail.com

ANNEX 2: Initial time schedule of the comparison

	Beginning date	End date	Duration
Measurement by Institutes	27th February 2017	31th March 2017	5 weeks
Transport	1st April 2017	21th April 2017	3 weeks
Standards stabilization	22nd April 2017	30th April 2017	1 week
Measurement by BIPM	1st May 2017	23th June 2017	8 weeks
Transport	24th June 2017	14th July 2017	3 weeks
Standards stabilization	15th July 2017	23th July 2017	1 week
Measurement by Institutes	24th July 2017	1st September 2017	6 weeks
Measurement report of Institutes	2nd September 2017	13th October 2017	6 weeks
Comparison report (draft A)	14th October 2017	11th December 2017	8 weeks

ANNEX 3: Principles of capacitance measurements

A3-1 Principle of measurement at the BIPM

The BIPM maintains a reference group of four fused silica 10 pF capacitors (one of the NBS type and three of the GR 1408-A type). The four capacitors are placed in a temperature-controlled oil bath at a nominal temperature of 25.00 °C. A platinum resistance thermometer of nominal value 25 Ω is permanently placed in the central well of each of the three GR 1408-A capacitors and the NBS one is equipped with a built-in platinum resistance thermometer, also of nominal value 25 Ω. The capacitance of each capacitor is by definition referred to a fixed conventional value of the corresponding thermometer resistance chosen to be close to the thermometer resistance at 25 °C. A correction is applied to the capacitance value at the time of measurement to take into account the difference between the measured thermometer resistance and the corresponding conventional value. This correction is calculated from the known temperature coefficients of each of the four capacitors.

Each capacitor of the group is equipped with two coaxial cables without current equalizer by which it is connected to a capacitance comparison bridge. Their capacitance is defined as the two terminal-pair capacitance at the end of the cables.

Since 2001, the mean value of the group has been measured very regularly using a measurement chain linking the 10 pF capacitances to the recommended value of the von Klitzing constant R_{K-90} = 25 812.807 Ω. The chain includes,

- a two terminal-pair capacitance bridge with ratio 10/1, figure A-1,
- a multi-frequency quadrature bridge described on figure A-2,
- an ac-dc coaxial resistor with calculable frequency dependence of resistance allowing the calibration of the frequency coefficient of the pair of ac-resistors of the quadrature bridge using the four terminal-pair bridge of figure A-3,
- a quantum Hall device operated at 1 Hz, see references [A1, A2].

The relative drift rate of the mean value of the reference group is about 3.5 parts in 10^8 per year, figure A-4.

In the present CCEM-K4.2017 comparison, the mean value of the reference group of capacitors has been calibrated against the quantum Hall resistance before and after the series of measurements performed at the BIPM. The travelling standards of the participating institutes were measured against the mean 10 pF capacitance of the group, directly on the 10:-1 ratio bridge for the standards of 100 pF value, and via substitution measurement (i.e. two 10:1 steps against a 100 pF buffer) in the case of the 10 pF standards.

The 10:-1 standard inductive voltage divider used in the two and four-terminal pair bridges were calibrated before and after the comparison measurements using the step-up method schematized on figure A-5. It consists in comparing successively the voltage at the secondary winding of an 11:1 ratio calibration transformer with the voltages across the 11 sections of the standard inductive divider.

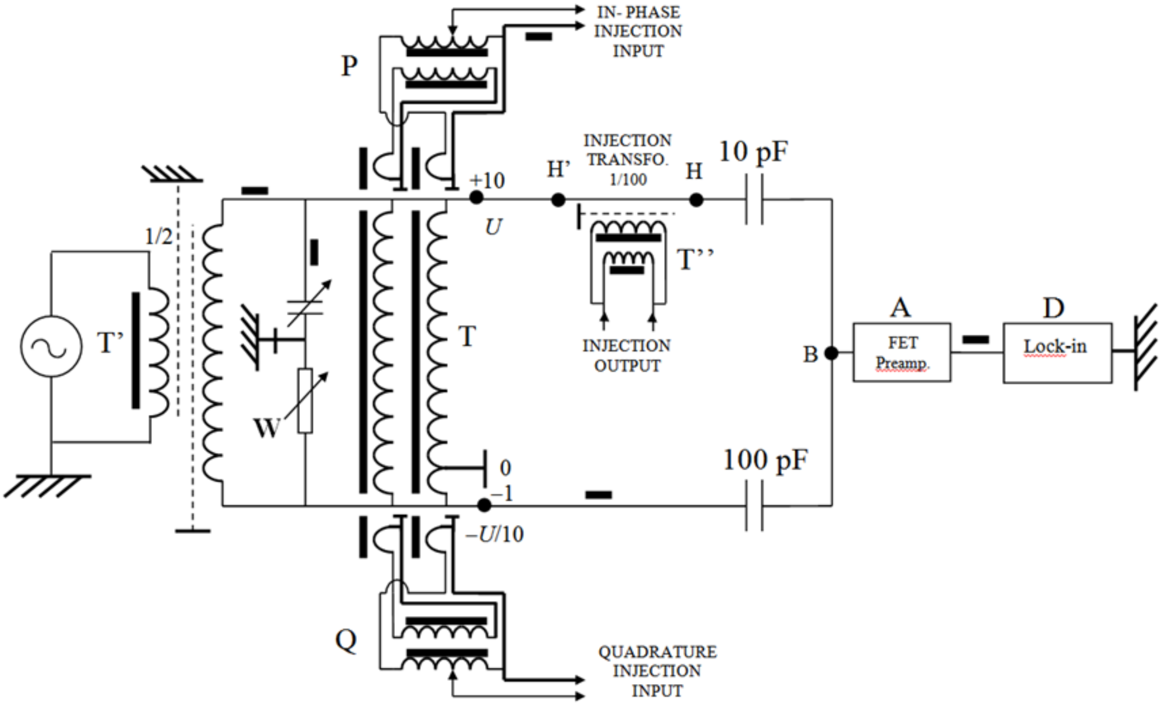


Figure A-1: Two terminal-pair capacitance bridge with ratio 10:-1 configured for 100 pF:10 pF measurements

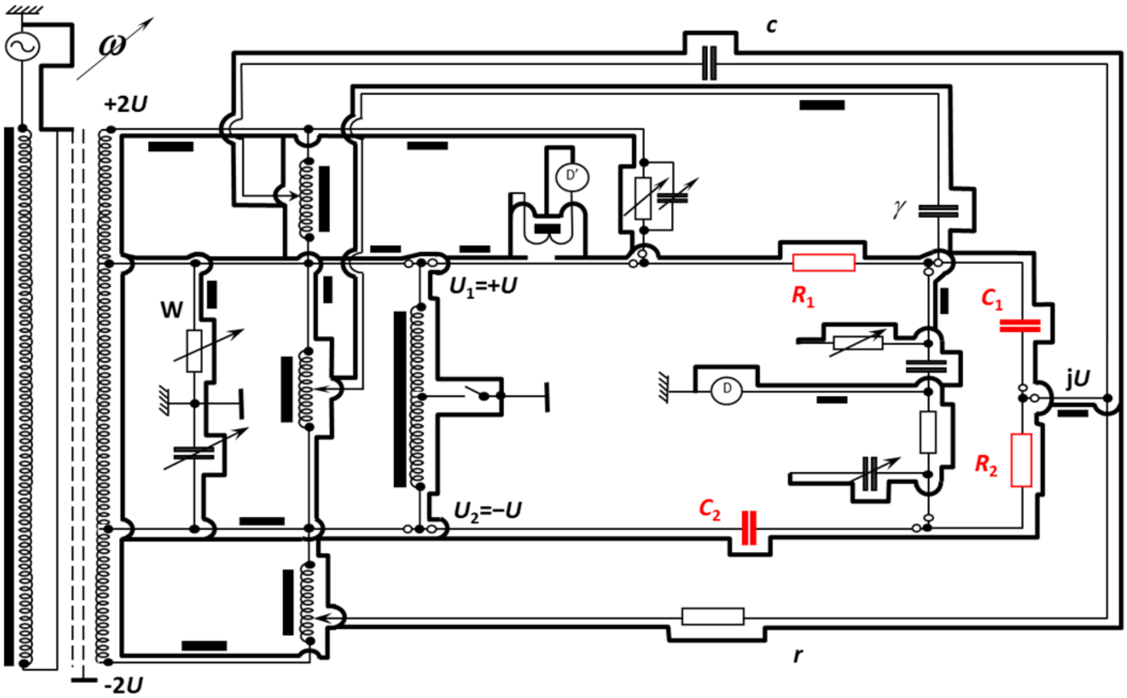


Figure A-2: Multi-frequency quadrature bridge. Resistors R1 and R2 have a value of 51.625 kΩ. The value of C1 and C2 is 2000 pF for measurements at 1541 Hz.

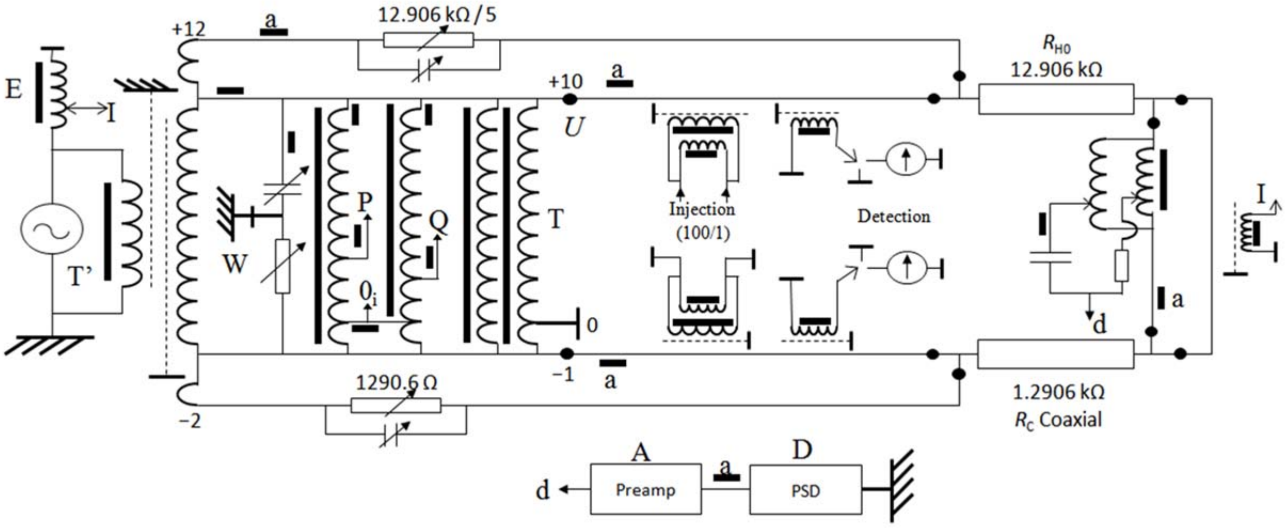


Figure A-3: Four terminal-pair bridge, in a 10:-1 configuration, for the comparison of an ac-resistor of 12906 Ω against a frequency-independent Haddad resistor of value 1290.6 Ω. The same bridge, in a configuration 4:-1; is used for determination of the frequency dependence of the two 51625 Ω resistors of the quadrature bridge (against the 12906 Ω standard). Injection loads 10:-1 voltages and are compensated by having an unused identical injector and exchange of arms. For measurement of the lowest impedances and at the lowest frequencies, active current equalizers are used.

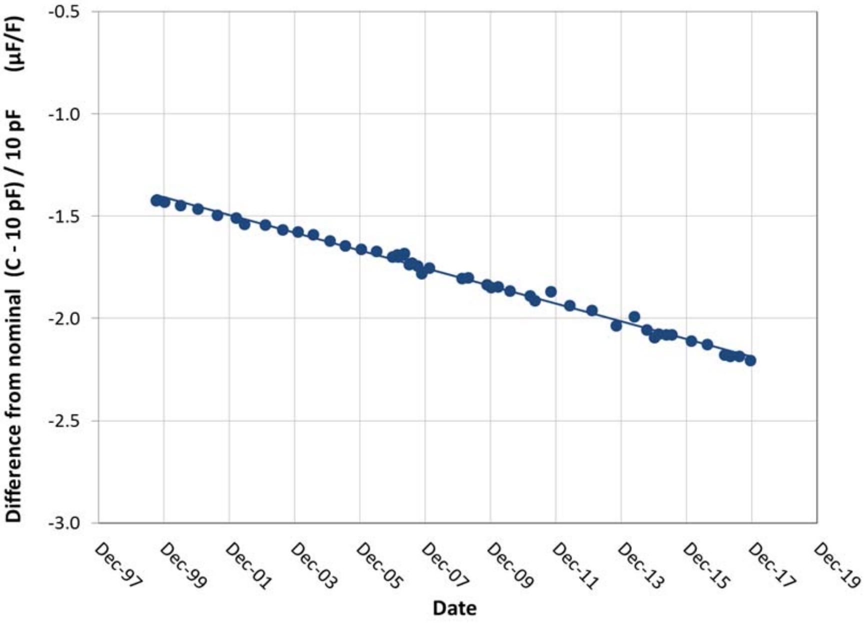


Figure A-4: Variation with time of the mean capacitance of the group of 10 pF reference standard capacitors of the BIPM since 2001 (measured from periodic quadrature transfer against the quantum Hall resistance standard of the BIPM). Each measurement has a combined uncertainty of 37 ppb. The size of the dots corresponds to about the range covered by the uncertainty bars (in 1σ).

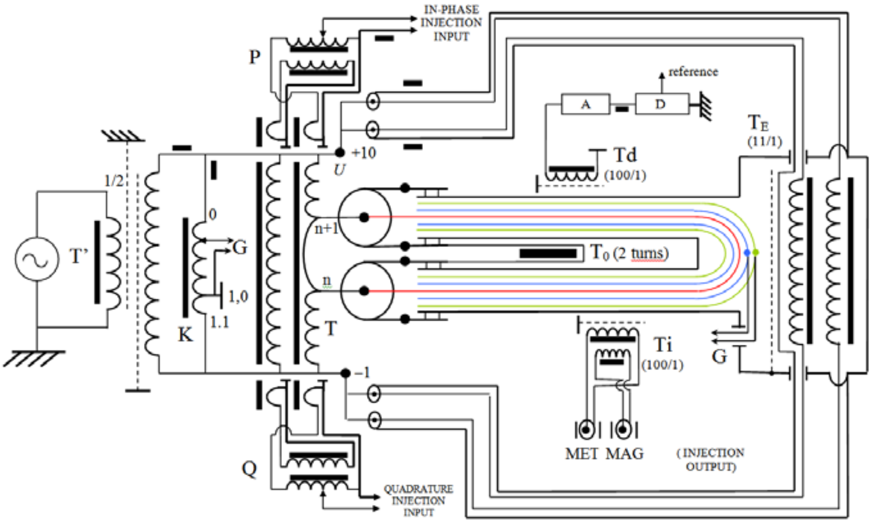


Figure A-5: Scheme of the circuit used for the calibration of the 10:-1 standard IVD used in the two and four-terminals impedance comparison bridges.

A3-2 Principle of measurement at METAS

The measurement procedure used at METAS to calibrate capacitance standards in terms of the quantum Hall effect and the conventional value of the von Klitzing constant R_{K-90} is described below. First an overview of different steps of the measurement chain is given, followed by a brief description of the different coaxial ac bridges it involves and by the timing of the different steps of the measurement chain.

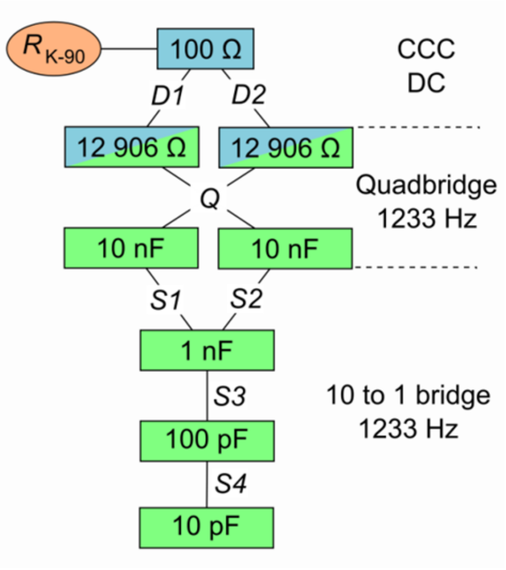


Figure A-6: Measuring chain for the calibration of capacitance standards at METAS. In blue are the standards that are measured at DC and in green are the standards that are measured in ac.

A3-2.1 Measurement chain

Figure A-6 shows the measuring chain for the calibration of capacitance standards at METAS. The starting point is a 100 Ω secondary resistance standard that is regularly compared to the quantum Hall resistance at DC. The DC value of the two calculable quadrifilar resistance standards used in the quadrature bridge are then calibrated by a direct comparison (***D1*** and ***D2***) to the 100 Ω secondary resistance standard using a direct cryogenic current comparator (CCC).

The values of the quadrifilar resistance standards at 1233 Hz are then calculated using their known frequency dependence.

A quadrature bridge is then used to compare a couple of 10 nF capacitance standards to the couple of quadrifilar resistance standards (comparison ***Q***).
The 10 nF capacitance standards are compared (***S1*** and ***S2***) to a 1 nF capacitance standard using a four-terminal pair bridge.
The 1 nF capacitance standard is compared (***S3***) to a 100-pF capacitance standard using the same four-terminal pair bridge.
Finally, the 100 pF capacitance standard is compared (***S4***) to the 10 pF capacitance standard using a three-terminal pair bridge.

A3-2.2 Quadrature bridge

Figure A-7 shows the quadrature bridge used to compare a couple of 10 nF capacitance standards to a couple of 12.906 kΩ resistance standards. It is a manual four terminal-pair comparison bridge.

The reference transformer has two secondary windings, the first is supplying the current and the second is making the 1 to -1 voltage ratio. This actual ratio slightly differs for the exact 1 to -1 ratio and therefore the bridge is balanced twice. A first time with the transformer in its forward position and a second time with the transformer in its reverse position. In such a way, the residual error of the 1 to -1 ratio is eliminated and the in-phase balance of the quadrature bridge is given by:

$$\alpha_{\mathrm{Q}} = \frac{1}{2}\{\alpha - \alpha'\}\frac{C_i}{C_{Nom}} + 2\frac{\Delta\nu}{\nu}$$

Where α and α' are the fraction of the reference voltage applied to the injection capacitor C_i in the forward and reverse position respectively. C_{Nom} is the nominal value of the 10 nF capacitance standard. $\Delta\nu$ is the deviation of the frequency from its nominal value ν.

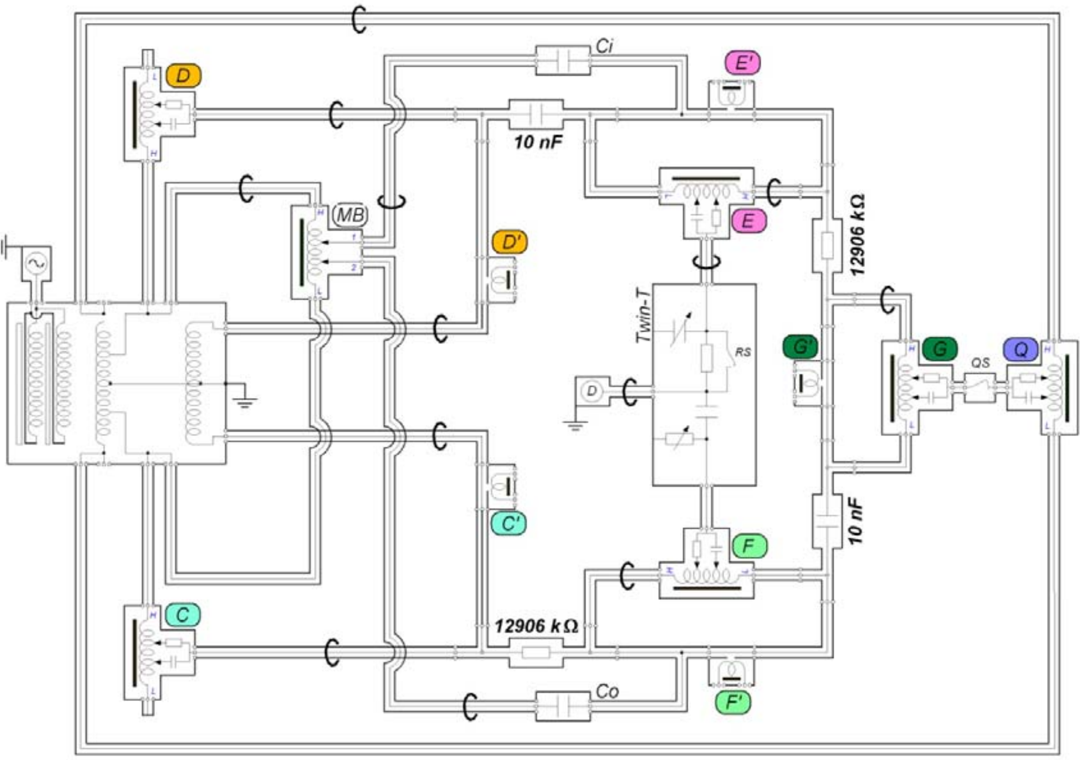


Figure A-7: Schematic of the quadrature bridge used to compare a couple of 10 nF capacitance standards to a couple of 12906.4035 Ω resistance standards at a frequency of 1233.1471 Hz.

A3-2.3 10 to -1 ratio bridge

Figure A-8 shows the 10 to -1 ratio bridges used to scale down the capacitance from 10 nF to 10 pF. On the left is the four terminal-pair bridge used for the 10 nF to 1 nF and 1 nF to 100 pF steps and on the right is the three terminal-pair bridge used for the 10 pF to 10 pF step.

These two bridges are computer controlled and the balance procedure is automated making the repetition of the comparisons easier.

The balance equation is given by, $\alpha_{\mathrm{C}} = \alpha_{10\mathrm{C}} + \alpha - \alpha_{10} + \alpha_c^b - \alpha_c^t$

Where α_{C} and $\alpha_{10\mathrm{C}}$ are relative deviations of the capacitance from the nominal value of the top and bottom capacitance standards respectively. α is the fraction of the reference voltage injected to balance the bridge. α_{10} is the error of the reference transformer from the 10 to -1 ratio and α_c^t and α_c^b are the cable corrections to apply to the top and bottom capacitance standards respectively.

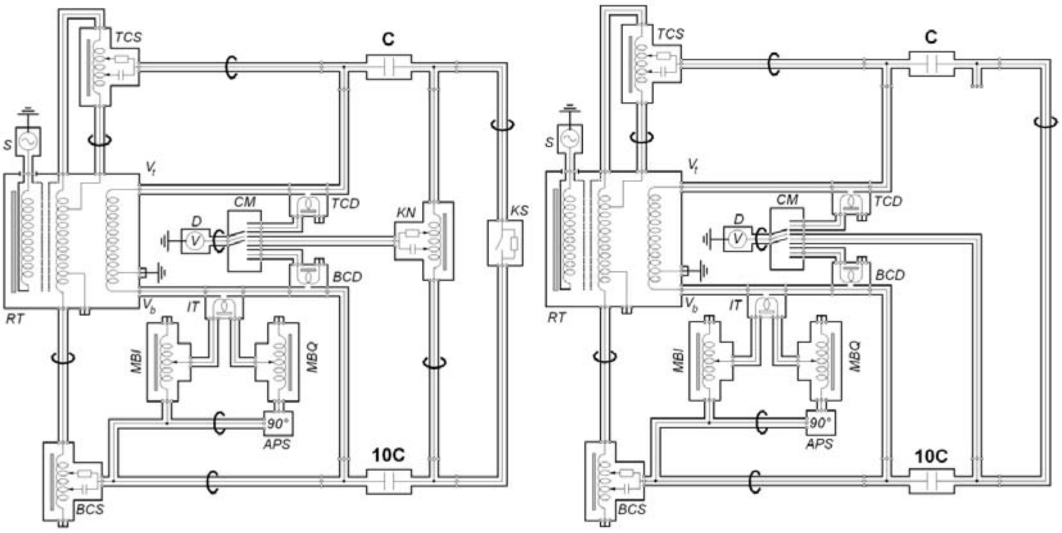


Figure A-8: Schematic of the 10 to -1 bridges used to scale down the capacitance from 10 nF to 10 pF. On the left is the four terminal-pair version and on the right is the three terminal-pair version used for the last 100 pF to 10 pF step.

A3-2.4 Timing of the measurement chain.

The realization of the whole measuring chain is a time consuming task requiring a good short term stability of the standards. To be independent of the linear drift of the standards, each step of the chain is repeated two times according to the time schedule represented in Figure A-9. From these measurements, the different bridge parameters (α_{G1}, α_{G1}, α_Q and α_{S1-4}) can be calculated for a common reference time.

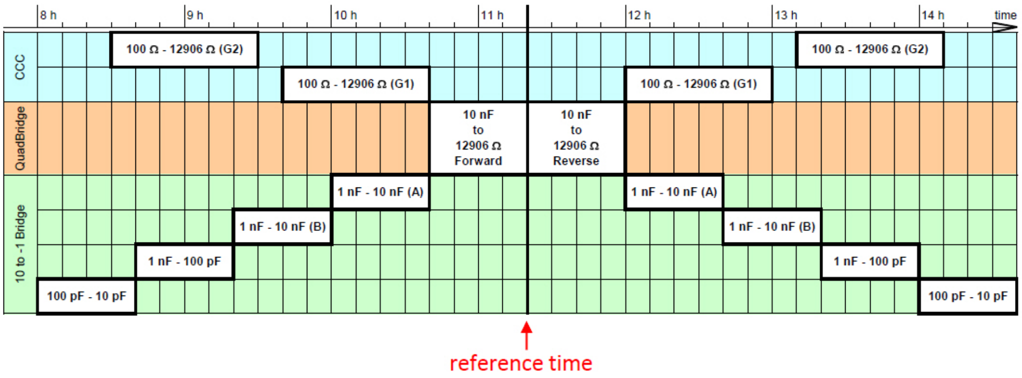


Figure A-9: Time schedule of the different measurements of the whole R-C chain.

A3-3 Principle of measurement at NIM

The assembling of the new NIM's calculable capacitor was completed in late 2013. It initially linked the capacitance unit to the SI unit of length with the relative standard uncertainty of 2.0 × 10^{-8} [A3]. A two terminal-pair capacitance bridge [A4] is associated to this calculable capacitor to form the measuring chain of capacitance at NIM, Figure A-10.

Since 2014, many improvements of this chain have been achieved. The laser wavelength stability has been improved by using a homemade iodine-stabilized He-Ne laser, and a standard uncertainty of 5.4 × 10^{-9} over the range of 205mm is now obtained on the displacement measurement [A5]. By improving the driving system of the movable guard electrode in the calculable capacitor and the dissemination method of calculable capacitance, a type A uncertainty of reproducing 1 pF capacitance are reduced from 10 × 10^{-9} to better than 5 × 10^{-9}.

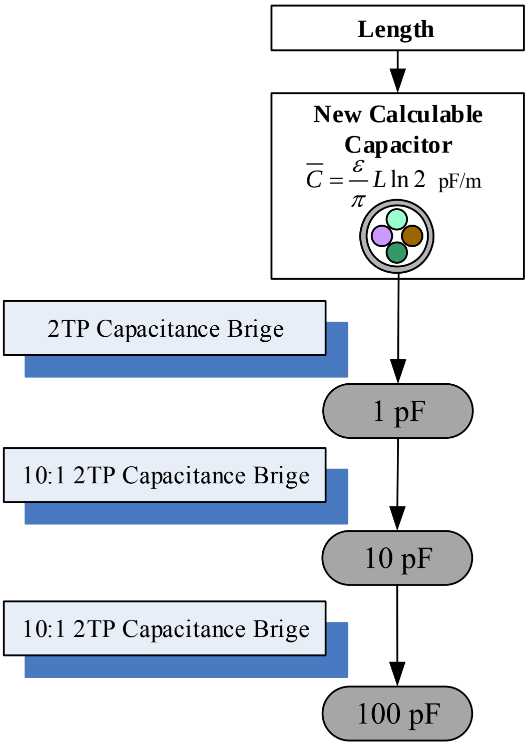


Figure A-10. The measuring chain realized at NIM

A3-3.1 Travelling standards for comparison

Four thermo-regulated Andeen-Hagerling type AH11A capacitors were chosen as travelling standards for both the key comparison and the optional comparison of CCEM-K4.2017 at 1592 Hz: (i) two 10 pF capacitors with serial numbers 01606 and 01682 and two 100 pF capacitors with serial numbers 01596 and 02090.

The travelling standards are assembled into the same AH1100 chassis. The chassis is cased into a custom-made portable instrument box which makes it possible for air travel by individuals carrying. The travelling standards were safely sent to BIPM at 12th April, 2017 and taken back to NIM at 8th July, 2017 by NIM's staffs.

The ambient temperature and relative humidity of the NIM's calculable capacitor laboratory are (20 ± 0.5)°C and (50 ± 10)% respectively. The ambient temperature is then deviated from recommended value of (23 ± 1)°C.

However, the chassis used for the comparison was stacked in between two other powered chassis in NIM's lab. This situation induced a change in the normal heat dissipation condition of this chassis resulting in an increase of its local temperature. In fact, the temperature readings of the chassis mainly varied between 31.2 °C and 31.5 °C which correspond almost to the same readings as for an ambient temperature of 23 °C. The drift (ppm) readings are also similar. Therefore, it is no longer needed to compensate for the difference between the actual measurement temperature (20°C) and the recommended temperature (23°C).

The possible equivalent temperature deviation to the recommended value of 23 °C can be estimated roughly within ± 0.5 °C. Placing the chassis into a temperature controlled air chamber (MI 9300A) and measuring capacitance values of the standards when the temperature of the chamber is varied from 20°C to 23°C showed a relative capacitance change within 3.0×10^{-8} for all the travelling standards. Considering a normal distribution for the temperature coefficient, a corresponding standard uncertainty of 3×10^{-9} has been added to the uncertainty budget of each travelling standard.

A3-3.2 The measuring bridge and transfer standards

The new NIM's calculable capacitor provides capacitance values of 0.6 pF and 0.2 pF, when the movable guard electrode locates at its upper and lower positions, respectively.

To transfer the calculable capacitance to a 1 pF standard capacitor at 1592 Hz, a two terminal-pair capacitance bridge with fixed ratio is used, Figure A-11. The transformer's taps "10", "4" and "-1" are used. The calculable capacitor $C_{\text{calc.}}$ is connected to "10", the 1 pF capacitor C_x to "4", and a 6 pF reference capacitor C_F to "-1". When the movable guard electrode locates at the upper or lower position, the low port of C_x is switched to ground or to the detector port respectively to make the bridge balance. Through two measurements, the 1 pF capacitance can be traced to the 0.4 pF nominal value of the calculable capacitance.

The 1 pF transfer standards are all AH11A capacitors. The two 1 pF AH11A capacitors (serial number 01603 and 01604) are never displaced and powered with an uninterrupted power supply.

When the bridge is used to transfer 1 pF to 100 pF by 10:1 comparison method, the standard C_x is removed from tap "4", and only taps "10" and "-1" are used.

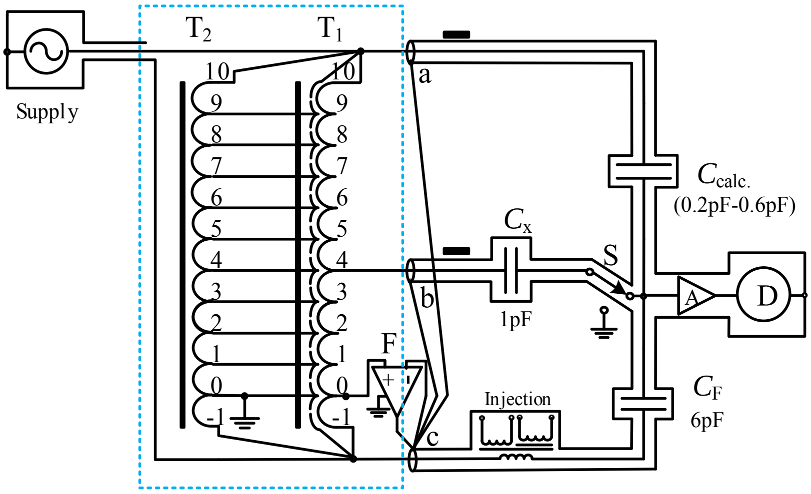


Figure A-11. The two terminal-pair capacitance bridge of NIM.

The bridge is designed to work at a maximum voltage of 275 V and normally at 110 V with the 10:1 ratio. As shown in Figure A-11, it has two transformers (T_1 and T_2) mounted in the same case and having the same ratio. Both transformers are designed with two-stage structure and 11 twisted ratio windings. Differing from using enameled wire as ratio windings of T_2, the ratio windings of T_1 are coaxial cables with outer conductor cut at the middle and the guard potentials supplied from the corresponding taps of the auxiliary transformer T_2. So the ratio windings of T_1 are fully guarded by equal potential to achieve high precision voltage ratio in audio frequency.

An improved bootstrap method (see Figure A-12) with equal potential guard is adopted to calibrate the main transformer's ratio. The floating reference ratio winding is winded with a triaxial cable. The inner and outer screens are cut into two equal lengths in the middle of the triaxial cable. The guard potential are provided from the auxiliary transformer T_2 at the two ends of the triaxial cable. The injector and detector is also designed with a triaxial and symmetric leakage structure. During the calibration, the area between two triaxial cables should be minimized to restrain stray coupling.

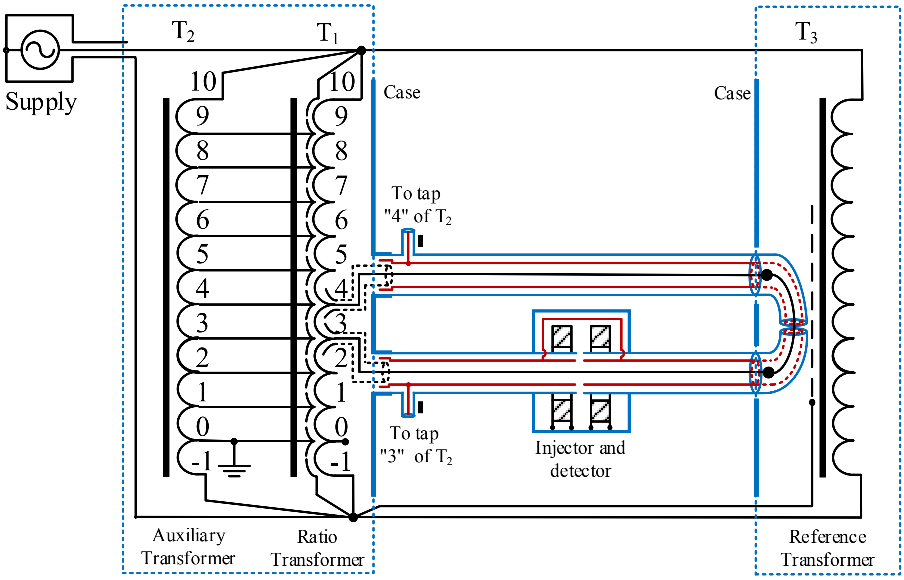


Figure A-12. Schematic diagram of the improved bootstrap method

A3-3.3 Measurement procedure

During the comparison, one measurement of the travelling standards follows the procedure shown in the Figure A-13. The travelling standards are drawn in the green frame. The other four AH11A standards drawn in the gray frame are assembled in another chassis AND are used as transfer and reference standards.

For each measurement, the 1 pF (AH#1603) value is first directly traced to the calculable capacitance. Then the 1 pF (AH#1604) can be calculated out by substitution method, and the 1 pF values can be transferred to 10 pF and 100 pF by 10:1 comparison using the two terminal-pair capacitance bridge. To guarantee the right transfer value of each capacitor, there are at least two paths for each capacitor in the measurement chain.

The chassis temperature and drift (ppm) of the AH11A capacitance standards are recorded during each measurement period. It was found that the heat dissipation of the lighted LED display on the chassis front panel lead to an increase of chassis temperature reading. So all readings are inconspicuous in normal conditions.

At last, the lead correction is carried out for each travelling standard to get its value of two-port on the panel.

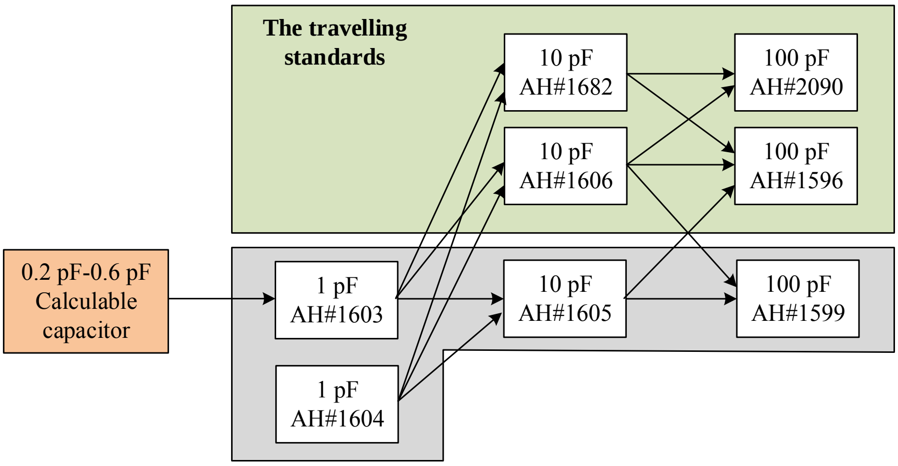


Figure A-13. Measurement procedure at NIM

A3-3.4 Operating voltage and voltage coefficient

In the measurement chain implemented at NIM, the 10 pF value can only be measured at 10 V_{rms} and 100 pF value can be only measured at 1 V_{rms} without considering voltage coefficient of capacitance standards. To carry out 10 pF measurement at 100 V_{rms} and 100 pF measurement at 10 V_{rms}, a corresponding voltage coefficient uncertainty has been evaluated and added to the uncertainty budget of each travelling standard.

A3-4 Principle of measurement at NIST

At NIST, the capacitance unit is traceable to a calculable capacitor and is described in the references listed below [A6-A8]. The primary maintenance standard for NIST capacitance calibrations consists of a bank of four 10 pF fused-silica standards (referred to as the Farad Bank) which are maintained in an oil bath at 25 °C. The Farad Bank is very stable, drifting linearly about 0.02×10^{-6} per year. The standards are calibrated twice a year indirectly against the calculable capacitor at a frequency of 1592 Hz, using a 10 pF transportable fused-silica capacitor, C_{112}.

The travelling standards were compared with the Farad Bank at NIST, using a coaxial bridge for two terminal-pair capacitances with a calibrated 10/1 ratio. The measurements were made at a nominal frequency of 1592 Hz and nominal voltage of 100 V for 10 pF standards and 10 V for 100 pF standards.

The four travelling standards are Andeen-Hagerling model AH11A capacitance modules mounted in a model AH1100 frame; two of the capacitance standards have nominal values of 10 pF while the other two have nominal values of 100 pF. Measurements were carried out in a lab with a nominal ambient temperature of 22 °C. Drifts of the capacitance values due to ambient temperature fluctuations were less than 2 parts in 10^9. No temperature corrections have been applied to the results. The effects of normal variations in atmospheric pressure and humidity are also negligible, and no corrections have been applied. The AH1100 frame was shipped between NIST and BIPM by standard air freight.

A3-5 Principle of measurement at NMIA

A3-5.1 Measurement set-up and traceability scheme

The NMIA derives its capacitance standard from a Thompson-Lampard calculable capacitor [A9-A12] traceable to the SI via NMIA's length standard.

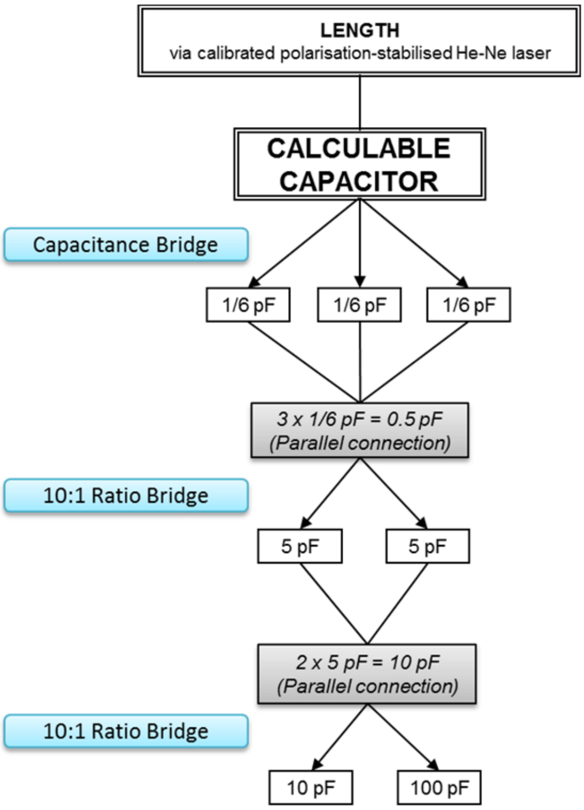


Figure A-14: Schematic diagram of NMIA measurement chain

The calculable capacitor ($^1\!/_6$ pF) is compared to three $^1\!/_6$ pF fixed capacitors using a two-terminal pair transformer ratio bridge (Figure A-15) and the substitution method. The calculable capacitor is in the top arm of the bridge and the stable, fixed capacitors of equivalent value in the lower arm of the bridge.

Capacitance and conductance balances are provided via additional windings on the main bridge transformer.

Initially, the cross-capacitance between bars 1 and 3 of the calculable capacitor, with the guard bar in the upper position, is compared with a ballast capacitance (refer to Figure A-15Figure (a)). The guard bar is then lowered, and the 1/6 pF reference capacitor to be measured is connected in parallel with the calculable capacitor. The bridge is rebalanced to compare this parallel connection with the ballast capacitance (refer to Figure A-15(b)). These measurements are then repeated with bars 2 and 4 of the calculable capacitor.

The same transformer substitution bridge is also used to compare the 1/6 pF reference capacitor with two further 1/6 pF reference capacitors, see Figure A-15(c).

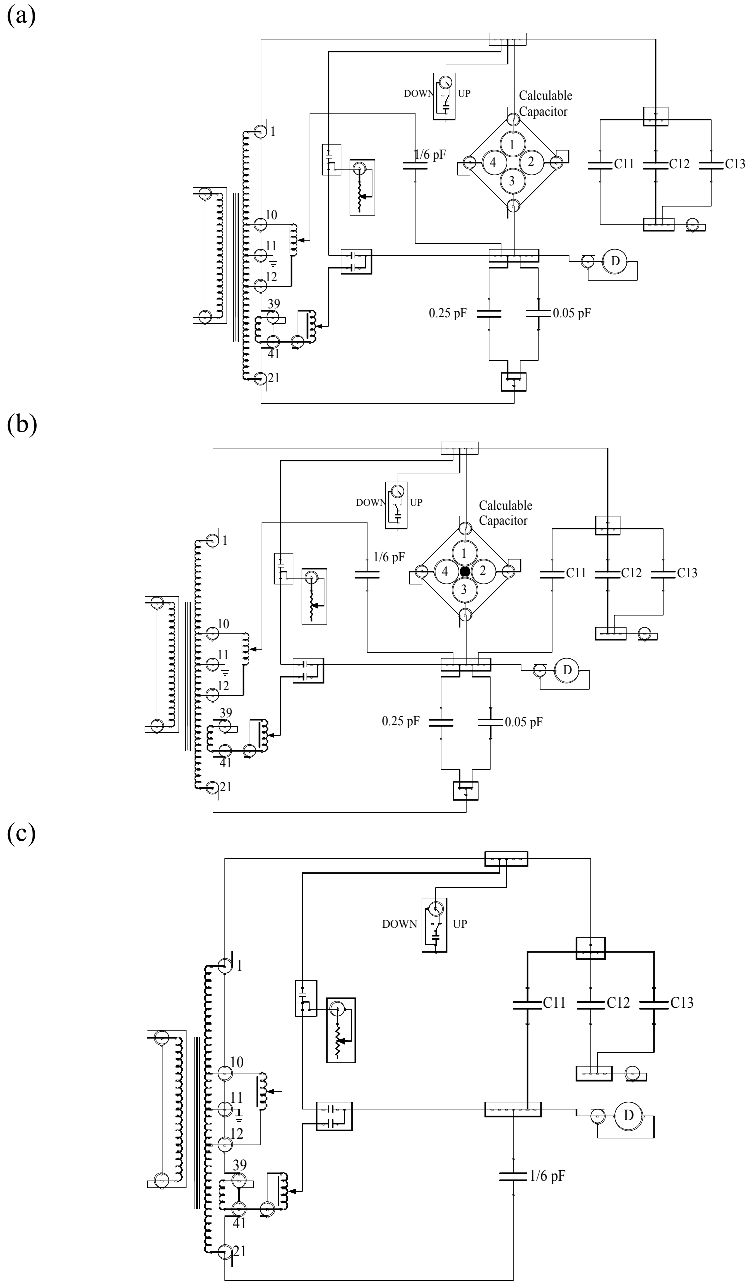


Figure A-15: Capacitance bridge to compare calculable capacitor to 1/6 pF reference capacitor, C11: calculable capacitor guard bar in (a) upper position and (b) lower position. (c) Capacitance bridge reconfigured to measure two further 1/6 pF reference capacitors, C12 and C13, with respect to C11.

The three $\frac{1}{6}$ pF capacitors are then connected in parallel to constitute a reference of known value, nominally 0.5 pF. This 0.5 pF reference is used to measure a 5 pF Invar reference capacitor (referred to as 5I) using a two-terminal pair 10:1 transformer ratio bridge (shown in Figure A-16), and the direct comparison method. The 10:1 ratio bridge is based on a three-winding voltage transformer. The main winding of the transformer has taps at n/11, where n = 0, 1,...11 which may be used to supply a precise 10:1 voltage ratio. Additional windings are used as the voltage input to a multi-dial ratio transformer to give an adjustable voltage of (± 500 ± 10j) μV/V relative to one step on the main winding with a resolution of 0.01 μV/V.

Another 5 pF reference capacitor (Andeen-Hagerling AH11A capacitance standard, SN 02190, housed in an Andeen-Hagerling 1100 frame SN 00200194), is measured against 5I using the same 10:1 transformer ratio bridge, and the substitution method. The two 5 pF reference capacitors are then connected in parallel to constitute a reference of known value, nominally 10 pF.

The comparison artefacts were measured relative to the 10 pF reference using the same 10:1 transformer ratio bridge and either the substitution method (for the 10 pF comparison artefacts) or the direct comparison method (for the 100 pF comparison artefacts).

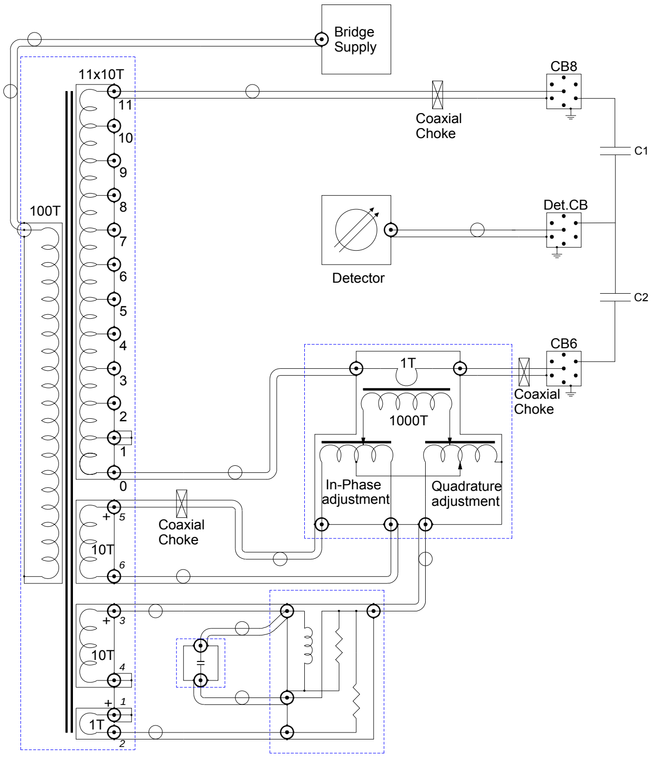


Figure A-16: 10:1 Ratio Bridge

A3-5.2 Measurement procedure

Measurements of each comparison artefact on each measurement date were made using the following procedure:

1. Measurements were made from the calculable capacitor to determine the value of the 5 pF reference capacitor, 5I.
2. The linear interpolated value of 5I was used as reference to measure the value of the second 5 pF reference capacitor SN 02190.

3. Each of the four comparison artefacts was measured in turn relative to the parallel combination of the two 5 pF reference capacitors, 5I and SN 02190.

A total of fourteen measurements of the capacitance of each comparison artefact were made between the 28th February 2017 and 31st March 2017. A further fourteen measurements were made between 31st July 2017 and 1st September 2017.

A3-6 Principle of measurement at NPL

A3-6.1 Traceability chain

At NPL the traceability for capacitance is to the von Klitzing constant, R_K using the latest CODATA value of 25 812.807 4555 Ω ± 2.3×10^{-10} through a quantum Hall resistance device.

The measurement chain starts with a 200 Ω resistor measured annually against the quantum Hall effect using a cryogenic current comparator bridge (CCC). The value of a 1000 Ω buffer resistor is determined from the 200 Ω using a CCC. Next a 1:1 DC ratio measurement determines the value of a 1000 Ω Quadrifilar resistor (S/N QB1000). The frequency dependence of the Quadrifilar resistor is calculated to be at most a few parts in 10^9 from DC to the AC bridge frequency of 1592 Hz.

Next a series of coaxial four terminal-pair AC bridges are used starting with a 100:1 equal-power resistance bridge which determines the values of two 100 kΩ resistors in terms of the Quadrifilar resistor (QB1000). Next a quadrature bridge determines from these 100 kΩ resistors the product of two 1nF capacitors (S/N QC1 and S/N QC2) from which the mean capacitance can be calculated. Finally a 10:1 capacitance bridge determines in succession the value of 100 pF capacitor (S/N 143) and from this the NPL primary 10 pF capacitor S/N NBS117, although the 10 pF primary capacitor played no direct role in the comparison measurements.

A3-6.2 Travelling capacitance standards

The two travelling capacitors were Andeen-Hagerling (AH) type 11A standards housed in a temperature controlled frame. As these capacitors have BPO connectors two BPO to BNC adaptors were supplied.

- Serial Number: 01101, Nominal Value 10 pF
- Serial Number: 01100, Nominal Value 100 pF

A3-6.3 Measuring bridges and transfer standards

- 100:1 equal-power resistance bridge.
- Quadrature bridge.
- 10:1 capacitance bridge.
- 1000 Ω Quadrifilar Resistor
- Two 100 kΩ Resistors (RESA & RESB)
- Two 1 nF Capacitors (QC1 & QC2).
- S/N: 143 – 100 pF capacitor.
- S/N: NBS117 NPL Primary 10 pF Capacitor.

A3.6.4 Measurement procedure

The two travelling capacitors were measured during the cycles of the comparison using the 10:1 capacitance bridge. The 100 pF was measured in terms of the values of the two 1 nF capacitors (QC1 and QC2) and the 10 pF from the value of the 100 pF (143). Also during the measurement cycles, a total of 6 traceability measurements were carried out to re-establish the values of the two 1 nF capacitors (QC1 & QC2), 100 pF (143) and 10 pF (NBS117).

A3.6.5 Measurement results

The results for the two travelling capacitors have been reported as instructed by the protocol document. As the measurements were carried out at an ambient temperature of 20 °C rather than 23°C a correction of −0.015 ppm has been applied. This correction was estimated, with reference to the EURAMET.EM-S31 comparison, as the mean temperature coefficient value between 0.0 and -0.03 ppm/°C.

A3-7 Principle of measurement at PTB

A3-7.1 General Principle

At PTB, the unit of capacitance is traced to the ac quantum Hall resistance, as schematically shown in Figure A-17, described in Ref. [A13], and declared in the CMC list. In that, PTB is the first, and the only, national metrology institute. As the first step, two 10 nF capacitance standards are linked to two ac quantum Hall resistances using a four-terminal-pair quadrature bridge. Then, using a four-terminal-pair 10:1 ratio bridge, three 10:1 steps are carried out from the 10 nF standards via a 1 nF capacitance standard to the 100 pF and 10 pF capacitance standards under calibration.

The quadrature bridge can be operated either with two 10 nF standards at a frequency of 1233 Hz or with two 5 nF standards at a frequency of 2466 Hz. The two 5 nF standards can be connected in parallel to yield a decade value of 10 nF from which the measuring chain is continued to 100 pF and 10 pF. Thereby, all capacitance standards can be measured at the two frequencies stated above. Finally, the 10:1 transformer of the ratio bridge is calibrated by a straddling bridge.

A bank of capacitance standards is located within each of the connecting cables of the 10:1 ratio bridge and the quadrature bridge. It comprises

- two SMD-based 10 nF standards,
- two SMD-based 5 nF standards,
- three 1 nF General Radio standards,
- one 100 pF General Radio standard,
- up to three Andeen Hagerling frames each with four fused-silica standards.

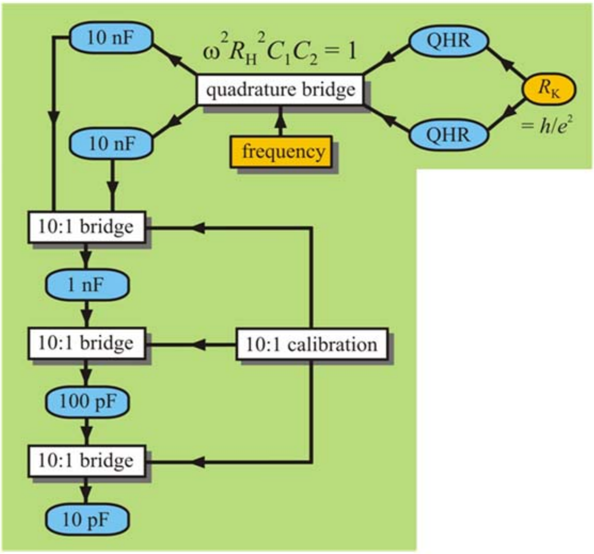


Figure A-17: The impedance chain realised at PTB.

All these standards are temperature-controlled and we have a history of about 8 years. The measuring bridges exhibit a very low level of noise and the main and auxiliary balances of the measuring bridges require at maximum only one iteration. Therefore, the whole bank of capacitance standards can be linked to the ac QHR within one day. However, the effort is considerable and can be reduced as follows: At about half of the measurement days (ideally every second measurement day), a 1 nF capacitance standard is used as the starting point of the capacitance chain. The 1 nF standard has a small, stable and predictable long-term drift and no significant short-term fluctuation. Therefore, it is possible to interpolate its actual numerical value without a significant increase of the uncertainty.

A3-7.2 Measuring bridges

A3-7.2.1 AC quantum Hall quadrature bridge

The quadrature bridge realises a link between two four-terminal-pair 10 nF capacitance standards, C1 and C2, and two ac quantum Hall resistances, R1 and R2 (see Figure A-18 and Ref. [A13]). The ac quantum Hall resistances are double-shielded GaAs devices operated at the $i = 2$ plateau and are connected in a triple-series scheme. This connection scheme constitutes a *two-terminal-pair* resistance at two star points outside of the cryomagnetic system, but eliminates the effect of lead and contact resistances like a *four-terminal-pair* component and can be combined with the four-terminal-pair capacitance standards without the need of Kelvin networks. T2 is a 1:1 ratio transformer; it is built into the same case as the supply transformer, but is shielded in such a way that it does not electromagnetically couple to the supply transformer. Its 1:1 deviation is eliminated by reversing the high and low input leads (which for this purpose are led through the case) as well as the high and low output leads at the zero-current detectors T5 and T9.

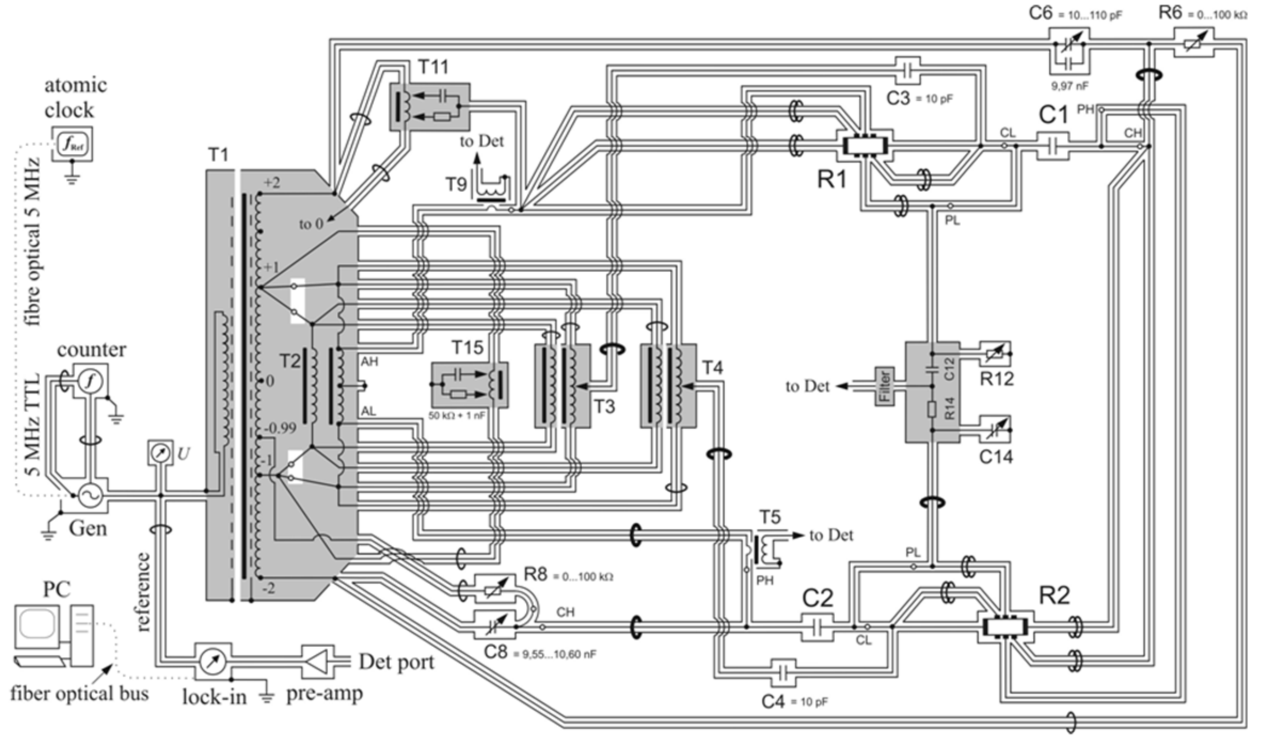


Figure A-18: Four-terminal-pair quadrature bridge with two ac quantum Hall resistances, R1 and R2, and two capacitance standards, C1 and C2, at a nominal value of either 5 nF or 10 nF.

The real and imaginary part of the main balance is accomplished by a current injection through two 10 pF capacitance standards, C4 and C3, supplied by the adjustable output voltages of two decade IVDs, T4 and

T3. T15 constitutes a Wagner arm. The components C6 and R6 provide the 90° phase-shifted voltage and R12, C12, R14 and C14 constitute a twin-T combining network. Resistor R12 is a fixed value resistor in series with an adjustable low-value room-temperature resistor (typically set to 6 Ω). R14 and the fixed-value part of R12 are mounted in a liquid-helium dewar because they are the only resistors in the bridge network whose thermal noise at room-temperature would limit the signal-to-noise ratio. The ac quantum Hall resistances R1 and R2 are operated in a ^{3}He cryo-magnet system at a temperature of 0.3 K; therefore, their thermal noise voltage is very small (0.5 nV/√Hz).

The null detector is a lock-in amplifier set up with an ultra-low-noise preamplifier at an equivalent input noise voltage of 0.5 nV/√Hz. A bridge voltage of 100 $\mathrm{mV_{rms}}$ is chosen so that the measuring chain (Figure A-17) ends at 10 pF at the desired 100 $\mathrm{V_{rms}}$, without need for a voltage step at any of the standards involved (and thus without need of an elaborate correction). At this bridge voltage and averaging the detector signal for 120 s, the resulting relative statistical uncertainty is $2\cdot10^{-9}$.

As already mentioned above, the quadrature bridge can be operated either with two 10 nF standards at a frequency of 1233 Hz or with two 5 nF standards at a frequency of 2466 Hz. The two 5 nF standards can be connected in parallel to yield a decade value of 10 nF. For this purpose, the star points of the transition from the internally two-terminal-pair SMD element to the four-terminal-pair front panel are realised directly at the freely accessible rear side of the front panel so that the two 5 nF standards can be connected in parallel at the rear side of the front panel without changing the length of the internal cables or affecting the thermostat of the standards.

The sinewave generator is a home-made low-distortion precision generator linked to PTB's 10 MHz reference frequency. The sinewave is synthesized of digital steps triggered by the reference signal, without use of a phase-locked loop. The advantage is a low distortion and a relative precision better than 10^{-11}. As a disadvantage, the frequency cannot be set to any value, but only to some discrete values; in our case, we can choose either $f = 1233.14699112$ Hz or twice this value. According to the quadrature bridge equation (see Sect. A3-7.2.4), the nominal frequencies are $f = 1/(2\pi\cdot R_{\mathrm{K-90}}/2\cdot10\ \mathrm{nF}) = 1233.14712028$ Hz and twice this value. This means that the actual generator frequencies differ from nominal by a relative amount of $1.047\cdot10^{-7}$ and this is taken into account as a precisely known, and highly stable, correction. The actual frequency is monitored by a counter, even though it did never show any significant change. (Due to the principle of construction, a change is only possible in the case of a damage.) Due to a harmonic filter built into the generator output, the harmonic content at the bridge output is so small that no complicated harmonic filter at the detector input is needed, which is very convenient.

A3-7.2.2 Four-terminal-pair bridge

A four-terminal-pair ratio bridge (Figure A-19) is used to measure the capacitance ratios 10 nF:1 nF, 1 nF:100 pF, and 100 pF:10 pF. For the 100 pF:10 pF ratio, a two-terminal-pair bridge would be sufficient, but frequently altering the bridge between a four-terminal-pair and a two-terminal-pair configuration is too laborious and error-prone, and having an extra two-terminal-pair bridge ready is too labour-intensive, whereas using the same four-terminal-pair bridge for all capacitance ratios has no disadvantage at all. To meet the four-terminal-pair defining conditions of the ratio bridge, two current sources, a Kelvin arm, and a Wagner arm are used.

The main balance is achieved by injecting an in-phase and a 90° phase-shifted voltage. The 90° injection system is realised in a two-staged manner to achieve a better long-term stability of the phase angle, which is very important to avoid frequent re-calibrations of the phase-shifter.

Due to a proper arrangement of the equalisers and the absence of any high ohmic resistor generating thermal noise, the total detector noise is quite small. (Since the thermal noise of the resistor in the Kelvin network fully contributes to the detector noise, a resistor with a low value of 50 Ω is chosen.) As a result, a relative statistical uncertainty of (1 to 2)$\cdot10^{-9}$ can be achieved for each capacitance ratio by using an averaging time ranging from 120 s (for 10 nF:1 nF) to 30 s (for 100 pF:10 pF).

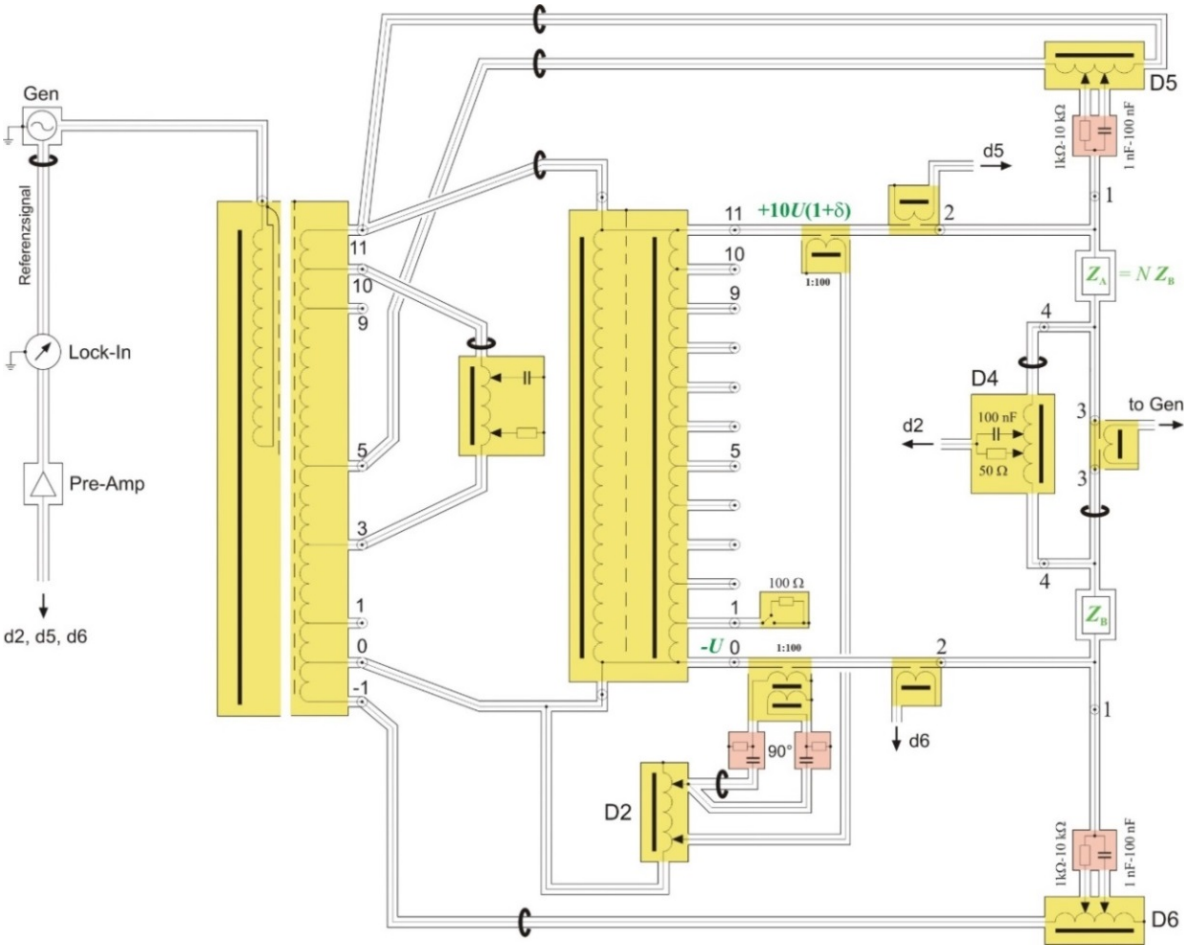


Figure A-19: Four-terminal-pair ratio bridge comparing two impedances Z_A and Z_B.

A3-7.2.3 Straddling bridge

The 10:1 deviation of the ratio transformer of the capacitance bridge is calibrated by the straddling method (see Figure A-20 and Ref. [A14]). This method makes use of the fact that a 10:1 ratio can be traced to four 1:1 ratios of a reference transformer whose 1:1 deviation can be eliminated by a reversal measurement. Indeed, the design of the 1:1 reference transformer requires some extra effort because its middle tap and the inner case are at an elevated potential which differs for each configuration. The measuring lead is a triaxial lead whose guard potential is set corresponding to the respective sub-configuration.

Usually, a straddling bridge uses *three* triaxial leads *simultaneously*, whereas we use only *one* triaxial lead *sequentially*. The high- and low-measurements are balanced by two auxiliary IVDs (KST-11 and KST-12) whereas the middle-point measurement is balanced by the main injection IVD. This allows a direct reading of the 1:1 deviation at the main injection IVD. Since a straddling bridge does not include any high ohmic resistor generating thermal noise, it has a very low noise level, corresponding to a statistical uncertainty of less than $1 \cdot 10^{-9}$ (with respect to the output ratio) using an averaging time of 10 s.

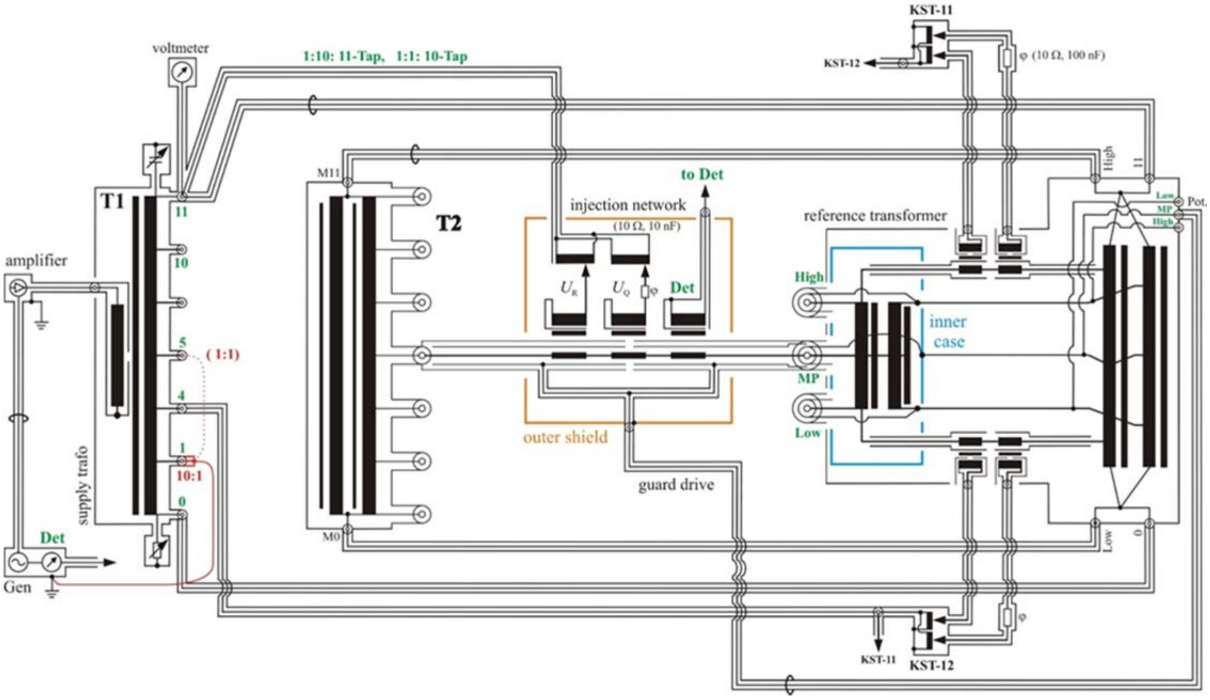


Figure A-20: Straddling bridge for calibration of a 10:1 ratio transformer T2.

A3-7.2.4 Quantitative analysis at a frequency of 1233 Hz

The bridge equation of the ac quantum Hall quadrature bridge (Figure A-18) is written here as

$$\omega^2 R_{\mathrm{H}}{}^2 C_1 C_2 = 1 + \Delta_{\mathrm{Q}}$$

R_{H} is the ac quantum Hall resistance at the $i = 2$ plateau, i.e., $R_{\mathrm{H}} = R_{\mathrm{K\text{-}90}}/2$ with $R_{\mathrm{K\text{-}90}}$ being the conventional value of the von Klitzing constant. C_1 and C_2 are the capacitance values of two standards at a nominal value of 10 nF. Δ_{Q} is a small deviation of the quadrature bridge balance from the nominal value 1 and is determined by balancing the bridge injection system. Usually, the frequency quoted in the quadrature bridge equation is the *actual* angular frequency, whereas here, for practical reasons, ω denotes the *nominal* angular frequency defined as $\omega = 1/(R_{\mathrm{K\text{-}90}}/2 \cdot 10\ \mathrm{nF})$ and Δ_{Q} includes a correction for the relative deviation of the *actual* frequency from nominal (see also Section A3-7.2.1).

The bridge equations of the ratio measurements according to Figure A-17 and Figure A-19 are written as

$$\frac{C_1}{C_{1\ \mathrm{nF}}} = 10 \cdot (1 + \delta + \Delta_1) \tag{1a}$$

$$\frac{C_2}{C_{1\ \mathrm{nF}}} = 10 \cdot (1 + \delta + \Delta_2) \tag{1b}$$

$$\frac{C_{1\mathrm{nF}}}{C_{100\ \mathrm{pF}}} = 10 \cdot (1 + \delta + \Delta_3) \tag{2}$$

$$\frac{C_{100\ \mathrm{pF}}}{C_{10\ \mathrm{pF}}} = 10 \cdot (1 + \delta + \Delta_4) \tag{3}$$

with $C_{1\ \mathrm{nF}}$, $C_{100\ \mathrm{pF}}$, and $C_{10\ \mathrm{pF}}$ being the capacitance values of the respective standards. Δ_1 to Δ_4 are the respective readings of the bridge injection system and include cable corrections. δ is the relative deviation of the transformer ratio from the nominal ratio 10:1. It is defined here by writing the output voltages of the ratio transformer as 10*U*(1 + δ) and -*U*, and is measured by the straddling bridge (Section A3-7.2.3).

From the above equations, the capacitance values of the 100 pF and 10 pF standards are expressed as:

$$C_{100\,\mathrm{pF}} = \frac{1}{100\,\omega R_\mathrm{H}} \cdot \left(1 - 2\delta - \Delta_3 + \frac{(\Delta_\mathrm{Q} - \Delta_1 - \Delta_2)}{2} \right) \tag{4}$$

$$C_{10\mathrm{pF}} = \frac{1}{1000\omega R_\mathrm{H}} \cdot \left(1 - 3\delta - \Delta_3 - \Delta_4 + \frac{(\Delta_\mathrm{Q} - \Delta_1 - \Delta_2)}{2} \right) \tag{5}$$

with the pre-factors being *exactly* equal to 100 pF and 10 pF, respectively (according to the definition of the angular frequency ω as given above).

We like to point out that the 10:1 deviations δ in equations (1) to (3) refer to different voltage levels, namely 1 V, 10 V and 100 V (each referring to 10*U*), even though for the sake of simplicity, the same symbol is used. It would be a large effort to always carry out three straddling measurements and particularly the measurement at 1 V would suffer from a low sensitivity. This can be avoided as follows. A possible voltage dependence of δ (if significant at all) is always linear, very weak, stable in time, and measured one-time. All regular straddling calibrations are carried out at a voltage level of 37 V, which is (1 V + 10 V + 100 V)/3. Consequently, equation (5) does not require a correction even if the linear voltage dependence of the 10:1 deviation would not be zero. The 10:1 deviation in equation (4) refers to (1 V + 10 V)/2 = 5.5 V. This means that when the value of the 10:1 deviation measured at 37 V is used (instead of carrying out an additional straddling measurement at 5.5 V), it is necessary either to correct the 100 pF values for a non-zero linear voltage dependence of the 10:1 deviation or to take an uncertainty contribution into account within which it is known that the voltage dependence of the 10:1 deviation is zero.

All capacitance values of PTB and the associated uncertainties are calculated according to the bridge equations stated above. All capacitance values reported to the pilot have been converted from farad-90 to the SI-farad by subtracting a relative amount of $(17.6 \pm 0.2)\cdot 10^{-9}$ according to the 2014 CODATA value of the von Klitzing constant R_K = 25 812.807 4555 Ω.

A3-8 Principle of measurement at VNIIM

Since 1980 the VNIIM capacitance unit is realized by means of the vertical cross-capacitor RKMP-2 (CC) of traditional design scheme with two shielding electrodes. The upper shielding electrode has two fixed positions at a distance of 102 mm along CC axis. The distance between the shielding electrodes is adjusted by means of a mechanism for displacement and tilting the lower electrode. The actual value of the distance between the electrodes is measured by a Fabry-Perot interferometer (FPI) with respect to the length of the second FPI defined by the length of fused silica tube (nominal distance is 102 mm). Second FPI is calibrated against the primary standard of length. This method of measurement of the CC effective length allows avoiding a counting of fringe numbers and an error at reversal movement of the upper shielding electrode.

The CC main electrodes (diameter of 50 mm, length of 450 mm) are made of non-magnetic stainless steel.

The studies and improvements carried out in the period of 1998-2003 allow to substantially increasing the accuracy of the CC. As the result, the VNIIM capacitance unit was corrected (approximately to 0.2 ppm) on March 2003.

The CC capacitance is measured by a transformer bridge-comparator (TMK) with a measurement range of 0.1 to 10 pF and voltage ratios of 1:1, 1:5, and 1:10. TMK comprises additional circuits for compensation of load currents and inter-turn capacitive currents in the ratio transformer (RT), internal double-screened winding to create reference EMF for self-calibration of the RT. The RT contains several magnetic cores strung on a short ratio winding made of a wire of a large cross-section.

Principle of load current compensation in TMK is presented at figure A-21 (CT – auxiliary current transformer; C_t – tare capacitor; R_1-R_2, C_1 – compensating RC-circuit).

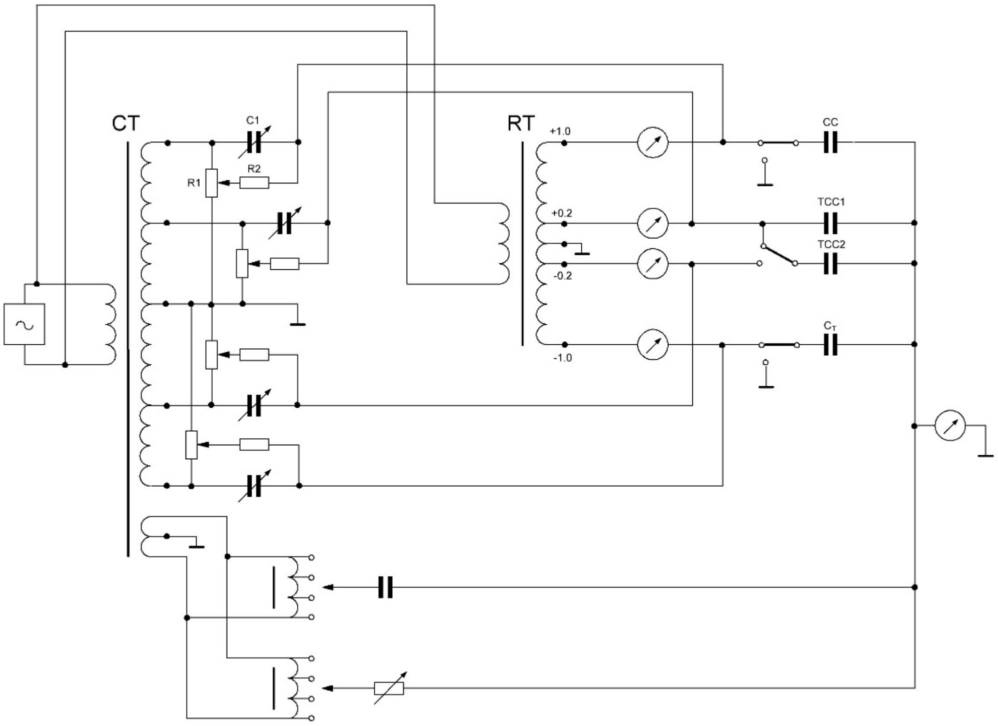


Figure A-21: Principle of load current compensation in TMK.

The CC capacitance of 0.2 pF is transferred in a ratio of 1:5 to the sum of the capacitances of two toroidal cross-capacitors (TCC1 and TCC2) of 0.5 pF each.

The sealed TCC1 is filled with dry nitrogen gas, TCC2 is evacuated. Capacitance value of TCC2 is determined by mutual comparison of TCC1 and TCC2. The TCC2 capacitance remains unchanged within 0.05 ppm if a residual pressure is less than 5 Pa.

The capacitances of TCC1 and TCC2 are transferred in a ratio of 1:10 to the group of 10 pF capacitance standards that maintains the VNIIM unit of capacitance.

The group consists of five fused silica capacitors of different shape of capacitive elements - disc (like NBS type) and hollow cylinder. The capacitors were produced many years ago, so their capacitance value is well stabilized. Four capacitors are placed in a liquid bath at a temperature of 20 °C controlled by 25 Ω and 100 Ω platinum resistance thermometers (PRTs). The temperature inside the capacitors is monitored by 20 kΩ thermistor thermometers. Uncertainty on the temperature measurement does not exceed 0.003 K. The fifth capacitor is supplied with its own thermo-regulated air bath which temperature stability is better than 0.006 K. Relative instability of its mean value is estimated to 0.01 ppm/year taking in account temperature corrections.

Capacitance measurements are carried out by means of a transformer bridge based on a ratio transformer with minimal value of stray impedance (0.81 μH and 0.032 Ω for bridge arm ‘10’). The ratio transformer construction corresponds to the one described in [A15].

In-phase correction of the 10:1 ratio is 0.34 ppm. The maximal voltage value on tap ‘10’ should not exceed 98 V in order to exclude possible nonlinear distortions of measured signal. The bridge has taps ‘1’, ‘2’, ‘3’, ‘4’ and ‘10’ in both arms. This allows calibrating the 10:1 ratio through cycling exchange of only four capacitors with the same nominal value. The bridge is balanced by means of variable capacitor of 0.001 pF with scale division of 1.24×10^{-7} pF.

The measured values of 10 pF and 100 pF are determined as two-port capacitance on coaxial connectors of capacitors.

A3-9 References of Annex 3

[A1] An ac-bridge for low-frequency measurements of the quantized Hall resistance, F. Delahaye, *IEEE Trans. on Instr. and Meas.* , Vol. 40, n°6, Dec. 1991.

[A2] Accurate ac measurements of standard resistors between 1 and 20 Hz, F. Delahaye and D. Bournaud, *IEEE Trans. on Instr. and Meas.* , vol. 42, n°2, Apr. 1993.

[A3] An initial reproduction of SI capacitance unit from a new calculable capacitor at NIM, Z. L. Lu, L. Huang, Y. Yang, *et al*., *IEEE Trans. Instr. Meas.,* vol. 64, no. 6, pp. 1496–1502, 2015.

[A4] An Improved Two Terminal-pair Capacitance Bridge at NIM, Y. Yang, W. Lu, J. Zhao, *et al*., in *Proc. CPEM 2014*, Brazil , Jul. 1-6, 2014.

[A5] Displacement Determination of the Guard Electrode for the New Calculable Capacitor at NIM, J. B. Wang, J. Qian, Z. Liu, *et al*., *IEEE Trans. Instr. Meas.,* vol. 65, no. 11, p. 2569, 2016.

[A6] New NBS measurements of the absolute farad and ohm, R.D. Cutkosky, *IEEE Trans. Instrum. Meas.*, vol. 23, no 4, p. 305, 1974.

[A7] New Realization of the Ohm and Farad Using the NBS Calculable Capacitor, J. Q.Shields, R. F. Dziuba, and H. P. Layer, *IEEE Trans. Instr. Meas.*, vol. 38, p. 249, 1989.

[A8] Determination of the von Klitzing constant and the fine-structure constant through a comparison of the quantized Hall resistance and the ohm derived from the NIST calculable capacitor, A. Jeffery, R. E. Elmquist, J. Q.Shields, L. H. Lee, M. E. Cage, and R. F. Dziuba, *Metrologia*, vol. 35, p. 83, 1998.

[A9] A New Theorem in Electrostatics and its Application to Calculable Standards of Capacitance, Thompson A. M. and Lampard D. G., *Nature*, vol. 177, p. 888, 1956.

[A10] The Cylindrical Cross-capacitor as a Calculable Standard, Thompson A. M., *Proc. IEE*, vol. 106, Part B, no. 27, p. 307, 1959.

[A11] A Calculable Standard of Capacitance, Clothier W. K., *Metrologia*, vol. 1, no. 2, p. 35, 1965.

[A12] Twenty Years of SI Ohm Determinations at NML, Small G. W., *IEEE Trans. Instr. Meas.*, Vol. IM-36, No. 2, 1987, pp. 190-195.

[A13] Realizing the farad from two ac quantum Hall resistances, J. Schurr, V. Bürkel, and B. P. Kibble, *Metrologia,* vol. 46, p. 619, 2009.

[A14] An improved straddling method with triaxial guards for the calibration of inductive voltage dividers at 1592 Hz, R. Hanke, *IEEE Trans. Instr. Meas.*, vol. 38, no 5, p. 974, 1989.

[A15] New Apparatus at the National Bureau of Standards for Absolute Capacitance Measurement, M. C. McGregor, J. F. Hersh, R. D. Cutkosky, F. K. Harris and F. R. Kotter, *IRE Trans. on Instr.*, vol. I-7, no. 3, p. 253, 1958.

ANNEX 4: Individual measurements of the participating NMIs

A4-1 BIPM Measurements

a) Measurement of standards from METAS

METAS **Measurement frequency: 1591.55 Hz**

		Ambient conditions			Temperature of standards					Deviation from nominal value (µF/F)			
	Date yyyy/mm/dd	Temperature (°C)	Relative Humidity (%)	Atmospheric Pressure (hPa)	AH frame Temperature (°C)	Drift #1191 (ppm)	Drift #1300 (ppm)	Drift #1188 (ppm)	Drift #1189 (ppm)	Standard # **1191** 10 pF / 100 V	Standard # **1300** 10 pF / 100 V	Standard # **1188** 100 pF / 10 V	Standard # **1189** 100 pF / 10 V
1	02/05/2017	23.4	46	1008.8	33.4	0.057	0.200	-0.016	0.012	-2.111	1.273	-3.283	-2.784
2	03/05/2017	23.3	48	1010.1	33.2	0.056	0.201	-	-	-2.105	1.277	-	-
3	05/05/2017	23.3	48	1011.1	33.3	0.057	0.200	-0.017	0.012	-2.123	1.293	-3.278	-2.782
4	09/05/2017	23.4	45	1011.0	33.3	0.057	0.200	-0.017	0.012	-2.120	1.303	-3.271	-2.775
5	10/05/2017	23.4	47	1000.7	33.3	0.057	0.200	-0.017	0.012	-2.106	1.298	-3.270	-2.777
6	12/05/2017	23.4	48	992.8	33.3	0.057	0.200	-0.017	0.012	-2.125	1.295	-3.272	-2.774
7	15/05/2017	23.4	48	1020.6	33.0	0.056	0.201	-0.018	0.013	-2.127	1.306	-3.272	-2.776
8	16/05/2017	23.4	51	1018.6	33.2	0.057	0.200	-0.018	0.012	-2.144	1.299	-3.273	-2.773
9	17/05/2017	23.4	49	1011.4	33.2	0.057	0.201	-0.018	0.012	-2.129	1.280	-3.270	-2.775
10	18/05/2017	23.3	49	1005.5	32.5	0.055	0.203	-0.022	0.013	-2.122	1.304	-3.265	-2.767
11	19/05/2017	23.3	47	1007.2	33.6	0.056	0.200	-0.016	0.012	-2.141	1.287	-3.269	-2.752
12	22/05/2017	23.3	46	1009.1	33.7	0.057	0.199	-0.015	0.012	-2.118	1.293	-3.274	-2.761
13	23/05/2017	23.3	48	1013.3	33.0	0.056	0.201	-0.019	0.013	-2.120	1.286	-3.266	-2.747
14	24/05/2017	23.4	49	1018.5	33.4	0.057	0.200	-0.017	0.012	-2.115	1.284	-3.263	-2.772
15	29/05/2017	23.2	56	1004.7	33.0	0.056	0.201	-0.019	0.013	-2.114	1.296	-3.267	-2.787
16	30/05/2017	23.3	50	1010.3	32.8	0.056	0.202	-0.019	0.013	-2.139	1.286	-3.268	-2.786
17	01/06/2017	23.4	51	1013.3	33.4	0.057	0.200	-0.016	0.013	-2.097	1.291	-3.255	-2.785
18	02/06/2017	23.3	51	1009.0	32.7	0.055	-	-	-	-2.121	-	-	-
19	06/06/2017	23.4	49	996.2	33.3	0.057	0.200	-0.017	0.013	-2.114	1.299	-3.264	-2.793
20	07/06/2017	23.4	47	1011.2	33.1	0.056	0.201	-0.018	0.013	-2.119	1.282	-3.265	-2.790
21	09/06/2017	23.4	49	1006.8	33.4	0.057	0.200	-0.017	0.012	-2.108	1.288	-3.265	-2.792
22	12/06/2017	23.4	47	1013.2	33.0	0.056	0.201	-0.018	0.013	-2.125	1.287	-3.264	-2.790
23	13/06/2017	23.3	47	1012.9	33.2	0.056	0.201	-0.017	0.013	-2.091	1.289	-3.263	-2.793
24	14/06/2017	23.3	51	1008.9	33.1	0.056	0.201	-0.018	0.013	-2.095	1.288	-3.261	-2.788
25	16/06/2017	23.3	48	1016.9	33.2	0.057	0.2	-0.018	0.012	-2.120	1.288	-3.260	-2.788
26	19/06/2017	23.2	52	1010.7	33.2	0.057	0.2	-0.017	0.013	-2.116	1.290	-3.261	-2.787
27	21/06/2017	23.2	56	1007.3	33.0	0.056	0.201	-0.018	0.013	-2.092	1.293	-3.259	-2.786
28	23/06/2017	23.2	53	1013.1	32.5	0.055	0.202	-0.021	0.014	-2.141	1.292	-3.254	-2.778
29	26/06/2017	23.3	51	1006.3	32.9	0.056	0.201	-0.018	0.013	-2.087	1.292	-3.256	-2.782
30	29/06/2017	23.3	41	991.1	32.9	0.056	0.201	-0.019	0.013	-2.097	1.291	-3.258	-2.786
31	30/06/2017	23.3	52	996.0	33.1	0.056	0.201	-0.018	0.013	-2.096	1.293	-3.258	-2.789
32	04/07/2017	23.3	53	1010.8	32.4	0.055	0.203	-0.022	0.014	-2.141	1.294	-3.249	-2.774
33	05/07/2017	23.3	51	1010.6	32.9	0.056	0.201	-0.01	0.013	-2.095	1.292	-3.255	-2.783
Mean	**01/06/2017**	**23.3**	**49.1**	**1008.7**	**33.1**	**0.056**	**0.201**	**-0.018**	**0.013**	**-2.116**	**1.291**	**-3.265**	**-2.780**
					Capacitance (pF)					9.99997884	10.00001291	99.9996735	99.9997220
					Type A uncertainty (µF/F)					**0.016**	**0.007**	**0.008**	**0.011**
					Type B uncertainty (µF/F)					**0.037**	**0.037**	**0.036**	**0.036**
					Standard combined uncertainty (µF/F)					**0.040**	**0.038**	**0.037**	**0.038**

b) Measurement of standards from NIM

NIM **Measurement frequency: 1591.55 Hz**

	Date	Ambient conditions			Temperature of standards					Deviation from nominal value (μF/F)			
	Date yyyy/mm/dd	Temperature (°C)	Relative Humidity (%)	Atmospheric Pressure (hPa)	AH frame Temperature (°C)	Drift #1606 (ppm)	Drift #1682 (ppm)	Drift #1596 (ppm)	Drift #2090 (ppm)	Standard # **1606** 10 pF / 100 V	Standard # **1682** 10 pF / 100 V	Standard # **1596** 100 pF / 10 V	Standard # **2090** 100 pF / 10 V
1	02/05/2017	23.3	44.7	1009.4	30.7	-0.013	-	-0.002	-0.011	0.076	-	0.067	0.199
2	05/05/2017	23.4	47.7	1008.1	30.8	-0.012	-	-0.002	-0.012	0.081	-	0.063	0.192
3	09/05/2017	23.3	45.1	1013.7	30.6	-0.011	-	-0.002	-0.010	0.080	-	0.075	0.204
4	12/05/2017	23.4	48.7	993.1	30.3	-0.012	-	-0.001	-0.010	0.086	-	0.068	0.200
5	15/05/2017	23.4	48.8	1021.0	31.0	-0.012	-	-0.002	-0.010	0.087	-	0.072	0.200
6	16/05/2017	23.4	49.8	1019.7	30.7	-0.012	-	-0.001	-0.010	0.092	-	0.072	0.198
7	17/05/2017	23.4	49.6	1010.9	30.4	-0.012	-	-0.001	-0.010	0.077	-	0.078	0.214
8	19/05/2017	23.3	45.7	1007.1	30.3	-0.012	-	-0.001	-0.010	0.073	-	0.068	0.204
9	22/05/2017	23.3	45.7	1009.1	30.5	-0.012	-	-0.001	-0.010	0.084	-	0.070	0.204
10	24/05/2017	23.3	49.0	1018.5	30.5	-0.013	-	-0.001	-0.010	0.075	-	0.075	0.207
11	29/05/2017	23.3	55.0	1005.2	30.7	-0.012	-	-0.003	-0.010	0.095	-	0.071	0.204
12	01/06/2017	23.3	50.3	1014.0	30.6	-0.013	-	-0.001	-0.010	0.084	-	0.069	0.199
13	06/06/2017	23.3	47.3	997.5	30.3	-0.013	-	-0.001	-0.010	0.092	-	0.069	0.204
14	08/06/2017	23.4	49.9	1005.5	30.8	-0.013	-	-0.001	-0.010	0.080	-	0.070	0.197
15	09/06/2017	23.4	49.5	1005.1	30.6	-0.013	-	-0.001	-0.010	0.080	-	0.069	0.197
16	12/06/2017	23.3	46.5	1013.5	30.5	-0.013	-	-0.002	-0.010	0.078	-	0.069	0.201
17	14/06/2017	23.3	50.0	1009.4	30.6	-0.014	-	-0.001	-0.010	0.081	-	0.068	0.197
18	16/06/2017	23.3	48.3	1017.6	30.5	-0.013	-	-0.001	-0.010	0.079	-	0.070	0.200
19	19/06/2017	23.2	51.0	1011.5	30.5	-0.013	-	-0.002	-0.010	0.083	-	0.072	0.202
20	21/06/2017	23.3	56.4	1007.5	30.3	-0.014	-	-0.001	-0.010	0.081	-	0.070	0.203
21	23/06/2017	23.3	53.0	1012.3	30.4	-0.013	-	-0.001	-0.010	0.080	-	0.069	0.202
22	26/06/2017	23.2	51.3	1006.2	30.2	-0.014	-	-0.001	-0.010	0.082	-	0.069	0.203
23	28/06/2017	23.4	54.0	989.5	30.3	-0.014	-	-0.001	-0.010	0.080	-	0.067	0.200
24	29/06/2017	23.3	42.5	990.8	30.4	-0.014	-	-0.001	-0.010	0.081	-	0.066	0.198
25	03/07/2017	23.4	50.9	1016.6	30.5	-0.015	-	-0.001	-0.010	0.081	-	0.070	0.200
26	05/07/2017	23.3	53.4	1010.2	30.0	-0.015	-	-0.001	-0.010	0.082	-	0.072	0.206
27	07/07/2017	23.5	59.7	1009.5	31.0	-0.014	-	-0.001	-0.010	0.079	-	0.068	0.193
28	10/07/2017	23.5	58.1	1004.1	30.9	-0.014	-	-0.001	-0.010	0.077	-	0.066	0.189
29	12/07/2017	23.5	55.9	1008.7	31.2	-0.014	-	-0.001	-0.010	0.077	-	0.065	0.187
30	13/07/2017	23.4	51.4	1014.1	31.1	-0.014	-	-0.002	-0.010	0.080	-	0.068	0.192
Mean	**09/06/2017**	**23.3**	**50.3**	**1008.6**	**30.6**	**-0.013**	**-**	**-0.001**	**-0.010**	**0.081**	**-**	**0.069**	**0.200**
					Capacitance (pF)					10.00000081	-	100.0000069	100.0000200
					Type A uncertainty (μF/F)					**0.005**	**-**	**0.0032**	**0.0056**
					Type B uncertainty (μF/F)					**0.037**	**-**	**0.036**	**0.036**
					Standard combined uncertainty (μF/F)					**0.037**	**-**	**0.036**	**0.036**

c) Measurement of standards from NIST

NIST **Measurement frequency: 1591.55 Hz**

	Date	Ambient conditions			Temperature of standards					Deviation from nominal value (µF/F)			
	yyyy/mm/dd	Temperature (°C)	Relative Humidity (%)	Atmospheric Pressure (hPa)	AH frame Temperature (°C)	Drift #1423 (ppm)	Drift #1424 (ppm)	Drift #1442 (ppm)	Drift #1452 (ppm)	Standard # **1423** 10 pF / 100 V	Standard # **1424** 10 pF / 100 V	Standard # **1442** 100 pF / 10 V	Standard # **1452** 100 pF / 10 V
1	02/05/2017	23.4	46.2	1008.9	30.7	-0.020	-0.036	-0.030	0.023	-4.809	-4.734	-4.650	-4.298
2	05/05/2017	23.3	47.5	1011.2	30.8	-0.020	-0.035	-0.030	0.023	-4.808	-4.744	-4.650	-4.301
3	09/05/2017	23.4	45.3	1011.1	30.8	-0.020	-0.035	-0.030	0.023	-4.816	-4.724	-4.647	-4.295
4	12/05/2017	23.4	47.7	992.7	30.7	-0.020	-0.035	-0.031	0.023	-4.784	-4.716	-4.651	-4.300
5	15/05/2017	23.4	47.6	1020.6	30.6	-0.019	-0.036	-0.031	0.024	-4.784	-4.725	-4.643	-4.291
6	17/05/2017	23.4	49.0	1011.7	30.4	-0.019	-0.037	-0.031	0.024	-4.805	-4.721	-4.645	-4.296
7	19/05/2017	23.3	44.9	1007.3	30.8	-0.020	-0.036	-0.030	0.023	-4.794	-4.716	-4.647	-4.299
8	22/05/2017	23.3	45.1	1009.3	30.8	-0.020	-0.035	-0.030	0.023	-4.800	-4.739	-4.646	-4.294
9	24/05/2017	23.4	49.4	1018.6	30.8	-0.020	-0.036	-0.030	0.023	-4.791	-4.710	-4.645	-4.293
10	29/05/2017	23.3	56.0	1004.6	30.2	-0.018	-0.037	-0.031	0.024	-4.787	-4.729	-4.646	-4.297
11	01/06/2017	23.3	50.8	1013.5	31.1	-0.020	-0.036	-0.031	0.023	-4.800	-4.720	-4.646	-4.297
12	06/06/2017	23.3	47.3	994.7	30.8	-0.020	-0.036	-0.030	0.022	-4.795	-4.736	-4.652	-4.302
13	09/06/2017	23.4	49.7	1006.6	30.9	-0.020	-0.036	-0.030	0.022	-4.806	-4.738	-4.651	-4.302
14	12/06/2017	23.3	47.3	1013.1	30.7	-0.019	-0.036	-0.030	0.022	-4.803	-4.735	-4.651	-4.300
15	14/06/2017	23.3	50.8	1009.3	30.7	-0.020	-0.036	-0.030	0.022	-4.804	-4.738	-4.650	-4.300
16	16/06/2017	23.3	48.1	1017.4	30.9	-0.020	-0.036	-0.030	0.023	-4.803	-4.737	-4.650	-4.299
17	19/06/2017	23.2	51.4	1010.0	30.9	-0.020	-0.036	-0.030	0.023	-4.802	-4.735	-4.650	-4.299
18	20/06/2017	23.3	55.9	1009.0	30.9	-0.020	-0.036	-0.030	0.023	-4.800	-4.735	-4.650	-4.301
19	23/06/2017	23.3	52.5	1013.3	30.6	-0.019	-0.037	-0.030	0.023	-4.801	-4.735	-4.649	-4.300
20	26/06/2017	23.2	51.2	1006.3	30.6	-0.019	-0.037	-0.030	0.024	-4.799	-4.731	-4.650	-4.301
21	30/06/2017	23.3	51.2	995.9	30.4	-0.019	-0.037	-0.030	0.023	-4.802	-4.735	-4.650	-4.302
22	03/07/2017	23.3	51.2	1012.5	30.4	-0.019	-0.037	-0.030	0.024	-4.801	-4.734	-4.647	-4.297
23	05/07/2017	23.3	56.1	1009.0	31.0	-0.021	-0.035	-0.03	0.023	-4.799	-4.735	-4.649	-4.300
Mean	**03/06/2017**	**23.3**	**49.7**	**1008.9**	**30.7**	**-0.020**	**-0.036**	**-0.030**	**0.023**	**-4.800**	**-4.731**	**-4.649**	**-4.298**
					Capacitance (pF)					9.99995200	9.99995269	99.99953515	99.99957016
					Type A uncertainty (µF/F)					**0.008**	**0.009**	**0.002**	**0.003**
					Type B uncertainty (µF/F)					**0.037**	**0.037**	**0.036**	**0.036**
					Standard combined uncertainty (µF/F)					**0.038**	**0.038**	**0.036**	**0.036**

d) Measurement of standards from NMIA

NMIA **Measurement frequency: 1591.55 Hz**

	Date	Ambient conditions			Temperature of standards					Deviation from nominal value (μF/F)			
	yyyy/mm/dd	Temperature (°C)	Relative Humidity (%)	Atmospheric Pressure (hPa)	AH frame Temperature (°C)	Drift #1416 (ppm)	Drift #1479 (ppm)	Drift #1677 (ppm)	Drift #1459 (ppm)	Standard # **1416** 10 pF / 100 V	Standard # **1479** 10 pF / 100 V	Standard # **1677** 100 pF / 10 V	Standard # **1459** 100 pF / 10 V
1	02/05/2017	23.3	44.7	1009.3	30.8	-0.017	-0.018	0.010	0.054	-12.980	-4.343	-5.216	-4.833
2	05/05/2017	23.3	46.7	1007.6	31.0	-0.017	-0.019	0.010	0.053	-12.982	-4.354	-5.225	-4.846
3	09/05/2017	23.3	46.7	1007.6	31.1	-0.017	-0.019	0.011	0.053	-12.977	-4.347	-5.209	-4.831
4	12/05/2017	23.4	48.7	993.2	30.8	-0.017	-0.018	0.011	0.053	-12.966	-4.343	-5.213	-4.835
5	15/05/2017	23.3	49.2	1020.7	31.3	-0.017	-0.020	0.010	0.051	-12.959	-4.329	-5.215	-4.838
6	17/05/2017	23.4	49.2	1010.3	30.7	-0.017	-0.019	0.011	0.053	-12.960	-4.335	-5.211	-4.822
7	19/05/2017	23.3	45.7	1006.9	30.6	-0.017	-0.018	0.011	0.053	-12.970	-4.336	-5.209	-4.818
8	22/05/2017	23.3	46.0	1008.7	31.2	-0.017	-0.020	0.011	0.052	-12.974	-4.346	-5.211	-4.825
9	24/05/2017	23.4	49.2	1017.6	30.9	-0.017	-0.019	0.011	0.053	-12.971	-4.342	-5.209	-4.822
10	29/05/2017	23.3	53.5	1005.5	30.8	-0.017	-0.019	0.011	0.053	-12.981	-4.350	-5.204	-4.819
11	01/06/2017	23.3	50.1	1014.0	31.0	-0.017	-0.020	0.010	0.052	-12.973	-4.342	-5.211	-4.824
12	06/06/2017	23.4	48.2	998.2	30.8	-0.017	-0.019	0.011	0.053	-12.975	-4.353	-5.210	-4.824
13	08/06/2017	23.4	49.6	1006.3	31.1	-0.017	-0.020	0.011	0.052	-12.974	-4.346	-5.211	-4.828
14	09/06/2017	23.4	49.7	1004.7	30.9	-0.017	-0.019	0.011	0.052	-12.976	-4.347	-5.211	-4.825
15	12/06/2017	23.3	46.2	1013.4	30.8	-0.017	-0.019	0.011	0.053	-12.973	-4.344	-5.208	-4.823
16	14/06/2017	23.3	49.5	1009.0	30.9	-0.017	-0.019	0.011	0.052	-12.972	-4.344	-5.209	-4.826
17	16/06/2017	23.3	49.8	1017.7	30.8	-0.017	-0.020	0.011	0.053	-12.972	-4.337	-5.208	-4.824
18	19/06/2017	23.2	50.2	1011.4	30.9	-0.017	-0.019	0.011	0.052	-12.970	-4.339	-5.205	-4.822
19	20/06/2017	23.2	58.3	1008.1	30.9	-0.017	-0.019	0.011	0.053	-12.969	-4.339	-5.205	-4.820
20	23/06/2017	23.3	52.1	1012.5	30.8	-0.017	-0.019	0.011	0.053	-12.974	-4.343	-5.209	-4.825
21	26/06/2017	23.2	51.3	1006.0	30.6	-0.017	-0.019	0.011	0.053	-12.973	-4.342	-5.209	-4.822
22	30/06/2017	23.3	50.8	995.5	30.8	-0.017	-0.019	0.011	0.053	-12.968	-4.342	-5.208	-4.821
23	04/07/2017	23.4	52.0	1011.8	30.5	-0.017	-0.019	0.011	0.053	-12.972	-4.344	-5.203	-4.818
Mean	**02/06/2017**	**23.3**	**49.5**	**1008.5**	**30.9**	**-0.017**	**-0.019**	**0.011**	**0.053**	**-12.972**	**-4.343**	**-5.210**	**-4.826**
					Capacitance (pF)					9.99987028	9.99995657	99.9994790	99.9995174
					Type A uncertainty (μF/F)					**0.006**	**0.006**	**0.004**	**0.007**
					Type B uncertainty (μF/F)					**0.037**	**0.037**	**0.036**	**0.036**
					Standard combined uncertainty (μF/F)					**0.037**	**0.037**	**0.036**	**0.037**

e) Measurement of standards from NPL

NPL **Measurement frequency: 1591.55 Hz**

	Date	Ambient conditions			Temperature of standards					Deviation from nominal value (μF/F)			
		Temperature	Relative Humidity	Atmospheric Pressure	AH frame Temperature	Drift #1101	Drift #1186	Drift #1100	Drift #1185	Standard # **1101**	Standard # **1186**	Standard # **1100**	Standard # **1185**
	yyyy/mm/dd	(°C)	(%)	(hPa)	(°C)	(ppm)	(ppm)	(ppm)	(ppm)	10 pF / 100 V	10 pF / 100 V	100 pF / 10 V	100 pF / 10 V
1	02/05/2017	23.4	45	1009.0	31.3	0.006	-	-0.024	-	-4.216	-	-3.145	-
2	03/05/2017	23.3	48	1010.1	31.0	0.006	-	-	-	-4.217	-	-	-
3	05/05/2017	23.3	48	1011.1	31.1	0.006	-	-0.025	-	-4.218	-	-3.126	-
4	09/05/2017	23.3	48	1011.1	31.1	0.006	-	-0.025	-	-4.201	-	-3.128	-
5	11/05/2017	23.4	48	988.5	31.3	0.006	-	-0.024	-	-4.217	-	-3.134	-
6	12/05/2017	23.4	48	993.2	31.2	0.006	-	-0.025	-	-4.224	-	-3.139	-
7	15/05/2017	23.4	48	1020.8	31.2	0.006	-	-0.025	-	-4.213	-	-3.130	-
8	17/05/2017	23.4	50	1021.2	31.2	0.006	-	-0.025	-	-4.212	-	-3.124	-
9	19/05/2017	23.3	47	1007.0	31.1	0.006	-	-0.025	-	-4.215	-	-3.123	-
10	22/05/2017	23.3	46	1009.2	31.3	0.006	-	-0.024	-	-4.213	-	-3.122	-
11	24/05/2017	23.4	48	1018.3	31.1	0.006	-	-0.025	-	-4.210	-	-3.124	-
12	29/05/2017	23.3	56	1004.9	30.9	0.006	-	-0.026	-	-4.216	-	-3.139	-
13	01/06/2017	23.4	51	1012.0	30.7	0.007	-	-0.026	-	-4.212	-	-3.114	-
14	06/06/2017	23.4	47	996.8	31.0	0.006	-	-0.025	-	-4.214	-	-3.138	-
15	08/06/2017	23.4	48	1008.2	31.1	0.006	-	-0.025	-	-4.214	-	-3.122	-
16	09/06/2017	23.4	49	1007.2	31.2	0.006	-	-0.024	-	-4.214	-	-3.144	-
17	12/06/2017	23.3	47	1013.4	31.0	0.006	-	-0.025	-	-4.212	-	-3.144	-
18	14/06/2017	23.3	50	1008.5	31.0	0.006	-	-0.025	-	-4.212	-	-3.148	-
19	16/06/2017	23.3	47	1016.8	31.1	0.006	-	-0.025	-	-4.210	-	-3.147	-
20	19/06/2017	23.2	51	1011.3	30.8	0.007	-	-0.026	-	-4.208	-	-3.140	-
21	20/06/2017	23.1	58	1007.3	30.4	0.007	-	-0.028	-	-4.210	-	-3.141	-
22	21/06/2017	23.1	60	1006.9	30.7	0.007	-	-0.026	-	-4.209	-	-3.138	-
23	22/06/2017	23.1	59	1005.7	30.8	0.007	-	-0.026	-	-4.208	-	-3.147	-
Mean	**28/05/2017**	**23.3**	**49.9**	**1008.6**	**31.0**	**0.006**	**-**	**-0.025**	**-**	**-4.213**	**-**	**-3.134**	**-**
					Capacitance (pF)					9.99995787	-	99.9996866	-
					Type A uncertainty (μF/F)					**0.004**	**-**	**0.010**	**-**
					Type B uncertainty (μF/F)					**0.037**	**-**	**0.036**	**-**
					Standard combined uncertainty (μF/F)					**0.037**	**-**	**0.037**	**-**

f) Measurement of standards from PTB

PTB **Measurement frequency: 1591.55 Hz**

		Ambient conditions			Temperature of standards					Deviation from nominal value (µF/F)			
	Date yyyy/mm/dd	Temperature (°C)	Relative Humidity (%)	Atmospheric Pressure (hPa)	AH frame Temperature (°C)	Drift #1257 (ppm)	Drift #1258 (ppm)	Drift #1256 (ppm)	Drift #1157 (ppm)	Standard # **1257** 10 pF / 100 V	Standard # **1258** 10 pF / 100 V	Standard # **1256** 100 pF / 10 V	Standard # **1157** 100 pF / 10 V
1	02/05/2017	23.3	44.7	1009.0	33.3	0.009	0.000	0.005	-0.103	1.572	0.975	1.880	-5.841
2	04/05/2017	23.2	46.9	1009.1	32.8	0.009	0.000	0.007	-0.105	1.587	0.986	1.885	-5.829
3	05/05/2017	23.3	47.5	1007.2	33.3	0.008	0.000	0.005	-0.102	1.573	0.976	1.882	-5.836
4	09/05/2017	23.3	44.9	1012.6	33.3	0.009	0.000	0.005	-0.102	1.574	0.985	1.890	-5.836
5	10/05/2017	23.4	47.4	997.4	33.5	0.008	0.000	0.004	-0.101	1.580	0.976	1.887	-5.829
6	12/05/2017	23.4	48.8	993.3	33.4	0.008	0.000	0.004	-0.102	1.583	0.982	1.890	-5.819
7	15/05/2017	23.4	48.1	1021.5	33.3	0.008	0.000	0.004	-0.102	1.579	0.981	1.894	-5.832
8	16/05/2017	23.4	49.2	1019.5	33.5	0.008	0.000	0.004	-0.102	1.578	0.986	1.892	-5.831
9	17/05/2017	23.4	49.4	1009.3	33.3	0.008	0.000	0.005	-0.103	1.586	0.987	1.896	-5.826
10	18/05/2017	23.3	48.9	1005.0	33.0	0.009	0.000	0.007	-0.105	1.589	0.984	1.900	-5.818
11	19/05/2017	23.4	45.7	1006.8	33.1	0.008	0.000	0.006	-0.103	1.578	0.978	1.896	-5.824
12	22/05/2017	23.3	46.1	1009.0	33.5	0.007	0.000	0.005	-0.103	1.576	0.976	1.893	-5.833
13	23/05/2017	23.3	47.7	1012.5	33.3	0.009	0.000	0.005	-0.102	1.587	0.983	1.892	-5.831
14	24/05/2017	23.3	49.2	1018.5	33.2	0.009	0.000	0.005	-0.103	1.593	0.986	1.895	-5.826
15	29/05/2017	23.2	55.8	1005.5	33.4	0.008	0.000	0.006	-0.103	1.581	0.978	1.904	-5.802
16	30/05/2017	23.3	49.7	1009.3	32.8	0.010	0.000	0.007	-0.106	1.593	0.993	1.909	-5.807
17	01/06/2017	23.4	50.7	1014.0	33.4	0.008	0.000	0.005	-0.103	1.563	0.972	1.899	-5.825
18	02/06/2017	23.3	51.2	1009.0	33.1	0.008	0.000	0.006	-0.103	1.591	0.996	1.897	-5.821
19	06/06/2017	23.4	48.1	999.1	33.2	0.009	-	-	-	1.591	-	-	-
20	07/06/2017	23.4	46.2	1008.4	33.4	0.009	0.000	0.005	-0.102	1.586	0.986	1.894	-5.828
21	09/06/2017	23.3	49.4	1003.9	33.2	0.009	0.000	0.005	-0.103	1.587	0.987	1.900	-5.817
22	12/06/2017	23.3	47.0	1013.6	33.3	0.009	0.000	0.005	-0.103	1.582	0.983	1.897	-5.822
23	13/06/2017	23.3	45.8	1012.5	33.0	0.008	0.000	0.006	-0.104	1.581	0.982	1.902	-5.824
24	14/06/2017	23.3	49.1	1009.0	33.3	0.009	0.000	0.005	-0.103	1.582	0.983	1.896	-5.820
25	16/06/2017	23.3	48.9	1018.1	33.5	0.009	0.000	0.004	-0.101	1.582	0.983	1.898	-5.825
26	19/06/2017	23.2	50.6	1011.4	33.3	0.009	0.000	0.005	-0.102	1.591	0.991	1.905	-5.810
27	20/06/2017	23.3	55.6	1008.8	33.0	0.009	0.000	0.007	-0.104	1.596	0.992	1.908	-5.807
28	22/06/2017	23.1	59.3	1006.0	33.0	0.009	0.000	0.007	-0.105	1.605	1.002	1.914	-5.791
29	23/06/2017	23.3	52.9	1012.6	33.3	0.009	0.000	0.005	-0.102	1.596	0.994	1.910	-5.807
30	26/06/2017	23.2	51.7	1005.6	33.1	0.009	0.000	0.006	-0.103	1.591	0.990	1.911	-5.806
31	29/06/2017	23.3	42.8	991.0	33.2	0.009	0.000	0.006	-0.103	1.589	0.992	1.911	-5.803
32	03/07/2017	23.4	51.2	1016.4	33.3	0.009	0.000	0.005	-0.103	1.588	0.988	1.908	-5.814
33	04/07/2017	23.4	50.8	1014.1	33.0	0.009	0.000	0.006	-0.104	1.591	0.990	1.913	-5.807
Mean	**01/06/2017**	**23.3**	**49.1**	**1009.0**	**33.2**	**0.009**	**0.000**	**0.005**	**-0.103**	**1.585**	**0.985**	**1.898**	**-5.820**
					Capacitance (pF)					10.00001585	10.00000985	100.0001898	99.9994180
					Type A uncertainty (µF/F)					**0.008**	**0.007**	**0.009**	**0.012**
					Type B uncertainty (µF/F)					**0.037**	**0.037**	**0.036**	**0.036**
					Standard combined uncertainty (µF/F)					**0.038**	**0.038**	**0.037**	**0.038**

g) Measurement of standards from VNIIM

VNIIM **Measurement frequency: 1591.55 Hz**

		Ambient conditions			Temperature of standards					Deviation from nominal value (µF/F)			
	Date yyyy/mm/dd	Temperature (°C)	Relative Humidity (%)	Atmospheric Pressure (hPa)	AH frame Temperature (°C)	Drift #2204 (ppm)	Drift #2205 (ppm)	Drift #2207 (ppm)	Drift - (ppm)	Standard # **2204** 10 pF / 100 V	Standard # **2205** 10 pF / 100 V	Standard # **2207** 100 pF / 10 V	Standard # **-** 100 pF / 10 V
1	31/05/2017	23.3	44.7	1009.0	29.9	-0.018	0.009	-0.013	-	-4.687	-5.111	-4.409	-
2	01/06/2017	23.4	51.0	1011.8	30.3	-0.017	0.011	-0.012	-	-4.675	-5.114	-4.415	-
3	06/06/2017	23.3	47.3	994.7	30.1	-0.019	0.013	-0.011	-	-4.682	-5.145	-4.415	-
4	08/06/2017	23.4	47.6	1009.0	29.9	-0.021	0.013	-0.010	-	-4.691	-5.140	-4.409	-
5	09/06/2017	23.4	49.4	1005.8	29.9	-0.022	0.013	-0.010	-	-4.688	-5.131	-4.407	-
6	12/06/2017	23.3	47.1	1013.1	29.8	-0.024	0.013	-0.010	-	-4.684	-5.124	-4.407	-
7	14/06/2017	23.3	50.1	1009.4	29.8	-0.024	0.012	-0.010	-	-4.682	-5.129	-4.405	-
8	16/06/2017	23.4	48.1	1017.6	30.0	-0.023	0.012	-0.008	-	-4.684	-5.123	-4.409	-
9	19/06/2017	23.3	50.8	1011.5	29.7	-0.028	0.011	-0.008	-	-4.674	-5.121	-4.400	-
10	21/06/2017	23.2	56.4	1007.3	29.9	-0.027	0.012	-0.007	-	-4.675	-5.120	-4.401	-
11	23/06/2017	23.2	52.5	1013.3	29.9	-0.027	0.012	-0.007	-	-4.673	-5.113	-4.401	-
12	26/06/2017	23.2	51.1	1006.7	29.4	-0.030	0.011	-0.007	-	-4.667	-5.119	-4.393	-
13	28/06/2017	23.4	53.8	989.4	29.2	-0.033	0.010	-0.007	-	-4.662	-5.126	-4.389	-
14	30/06/2017	23.3	51.2	995.6	28.9	-0.035	0.010	-0.008	-	-4.656	-5.120	-4.379	-
15	03/07/2017	23.4	50.2	1016.1	29.4	-0.029	0.012	-0.004	-	-4.661	-5.111	-4.385	-
16	05/07/2017	23.3	52.8	1010.6	29.3	-0.033	0.011	-0.003	-	-4.658	-5.113	-4.380	-
17	07/07/2017	23.5	58.9	1009.3	29.2	-0.033	0.010	-0.002	-	-4.657	-5.107	-4.381	-
18	10/07/2017	23.4	57.0	1003.5	29.3	-0.034	0.010	0.001	-	-4.657	-5.112	-4.380	-
19	12/07/2017	23.5	55.7	1008.6	29.5	-0.029	0.011	0.004	-	-4.664	-5.117	-4.384	-
20	13/07/2017	23.3	53.5	1012.3	28.8	-0.034	0.009	0.003	-	-4.652	-5.108	-4.365	-
21	17/07/2017	23.2	51.1	1014.5	29.0	-0.035	0.009	0.005	-	-4.650	-5.106	-4.363	-
22	18/07/2017	23.0	62.5	1003.4	29.1	-0.033	0.010	0.006	-	-4.646	-5.110	-4.366	-
23	19/07/2017	23.1	60.2	1001.6	28.9	-0.036	0.009	0.006	-	-4.645	-5.108	-4.360	-
24	20/07/2017	23.3	52.2	1005.7	29.3	-0.034	0.01	0.007	-	-4.651	-5.110	-4.373	-
25	21/07/2017	23.0	50.9	1003.3	29.2	-0.032	0.01	0.007	-	-4.649	-5.114	-4.369	-
26	24/07/2017	23.1	51.7	1005.4	29.4	-0.034	0.01	0.009	-	-4.650	-5.117	-4.371	-
27	26/07/2017	23.1	51.1	1004.3	29.5	-0.035	0.01	0.01	-	-4.647	-5.116	-4.371	-
28	28/07/2017	23.1	50.0	1006.9	29.5	-0.035	0.011	0.011	-	-4.647	-5.115	-4.371	-
29	31/07/2017	23.1	50.3	1007.1	29.4	-0.036	0.011	0.011	-	-4.642	-5.113	-4.369	-
30	02/08/2017	23.1	51.2	1010.6	29.5	-0.035	0.011	0.012	-	-4.642	-5.111	-4.369	-
31	04/08/2017	23.1	52.5	1008.1	29.5	-0.036	0.011	0.013	-	-4.637	-5.111	-4.366	-
32	07/08/2017	23.1	47.0	1012.4	29.4	-0.036	0.011	0.013	-	-4.633	-5.110	-4.363	-
Mean	**04/07/2017**	**23.3**	**51.9**	**1007.4**	**29.5**	**-0.030**	**0.011**	**-0.001**	**-**	**-4.662**	**-5.117**	**-4.385**	**-**
					Capacitance (pF)					9.99995338	9.99994883	99.9995615	-
					Type A uncertainty (µF/F)					**0.017**	**0.009**	**0.018**	**-**
					Type B uncertainty (µF/F)					**0.037**	**0.037**	**0.036**	**-**
					Standard combined uncertainty (µF/F)					**0.041**	**0.038**	**0.040**	**-**

h) Measurement of standards from BIPM

BIPM	**10 pF standards #1227 and 1310**	**Measurement frequency: 1591.55 Hz**

	Date	Ambient conditions			Temperature of standard			Deviation from nominal (µF/F)	
	yyyy/mm/dd	Temperature (°C)	Relative Humidity (%)	Atmospheric Pressure (hPa)	AH frame Temperature (°C)	Drift Std #1227 (ppm)	Drift Std #1310 (ppm)	Standard # **1227** 10 pF / 100 V	Standard # **1310** 10 pF / 100 V
1	03/02/2017	23.5	46	1008.0	35.1	0.047	-0.064	1.588	-0.068
2	06/02/2017	23.4	44	1004.8	35.2	0.046	-0.066	1.583	-0.054
3	17/02/2017	23.5	43	1005.3	35.6	0.046	-0.067	1.608	-0.053
4	21/02/2017	23.5	48	1001.2	35.0	0.047	-0.064	1.607	-0.053
5	24/02/2017	23.2	46	998.0	34.3	0.047	-0.060	1.599	-0.053
6	27/02/2017	23.2	46	990.0	34.4	0.047	-0.060	1.599	-0.060
7	01/03/2017	23.2	45	995.2	34.5	0.048	-0.060	1.589	-0.060
8	03/03/2017	23.1	44	992.7	35.3	0.047	-0.065	1.590	-0.050
9	06/03/2017	23.0	45	1008.5	34.5	0.048	-0.060	1.588	-0.062
10	10/03/2017	23.1	45	1016.3	35.4	0.047	-0.061	1.605	-0.052
11	13/03/2017	23.2	45	1017.0	34.5	0.048	-0.066	1.601	-0.048
12	15/03/2017	23.1	45	1023.4	34.5	0.047	-0.060	1.617	-0.049
13	17/03/2017	23.1	45	1011.0	35.1	0.047	-0.060	1.610	-0.033
14	20/03/2017	23.1	45	1004.0	34.5	0.047	-0.064	1.602	-0.051
15	22/03/2017	23.1	45	998.5	34.6	0.047	-0.064	1.597	-0.053
16	24/03/2017	23.1	46	1012.6	34.4	0.048	-0.061	1.600	-0.060
17	27/03/2017	23.2	46	1009.0	34.6	0.047	-0.060	1.605	-0.046
18	29/03/2017	23.1	46	1016.3	34.7	0.047	-0.061	1.611	-0.050
19	31/03/2017	23.1	46	1004.3	34.3	0.047	-0.062	1.608	-0.045
20	03/04/2017	23.0	45	1017.1	34.3	0.048	-0.060	1.606	-0.053
21	05/04/2017	23.2	46	1019.0	34.5	0.048	-0.059	1.607	-0.043
Mean	**10/03/2017**	**23.2**	**45.3**	**1007.2**	**34.7**	**0.047**	**-0.062**	**1.601**	**-0.052**
					Standard deviation (µF/F)			**0.009**	**0.008**
22	02/05/2017	23.3	46	1006.9	35.2	0.047	-0.061	1.586	-0.047
23	03/05/2017	23.2	48	1008.4	34.3	0.048	-0.066	1.599	-0.053
24	05/05/2017	23.3	47	1009.0	34.3	0.048	-0.06	1.594	-0.059
25	09/05/2017	23.3	45	1012.5	34.3	0.048	-0.06	1.601	-0.072
26	10/05/2017	23.4	48	994.8	34.6	0.048	-0.06	1.619	-0.050
27	12/05/2017	23.4	48	991.0	34.4	0.048	-0.061	1.596	-0.054
28	15/05/2017	23.4	48	1019.3	34.6	0.048	-0.06	1.614	-0.058
29	16/05/2017	23.4	49	1018.0	34.3	0.048	-0.061	1.623	-0.041
30	17/05/2017	23.4	51	1004.7	34.3	0.048	-0.061	1.603	-0.040
31	18/05/2017	23.3	46	1004.6	34.2	0.049	-0.059	1.596	-0.033
32	22/05/2017	23.3	47	1006.5	35.1	0.047	-0.059	1.613	-0.045
33	23/05/2017	23.3	48	1012.5	34.2	0.049	-0.064	1.609	-0.048
34	24/05/2017	23.4	49	1015.6	34.4	0.049	-0.059	1.611	-0.035
35	29/05/2017	23.3	55	1003.2	34.2	0.049	-0.06	1.610	-0.031
36	30/05/2017	23.3	50	1009.0	34.2	0.049	-0.059	1.598	-0.051
37	01/06/2017	23.3	50	1012.1	34.8	0.047	-0.059	1.619	-0.028
38	06/06/2017	23.4	47	998.9	34.2	0.049	-0.062	1.619	-0.043
39	07/06/2017	23.4	47	1009.5	34.2	0.049	-0.059	1.603	-0.038
40	09/06/2017	23.4	49	1005.5	34.7	0.047	-0.059	1.604	-0.036
41	12/06/2017	23.3	47	1011.8	34.3	0.049	-0.064	1.609	-0.057
42	14/06/2017	23.2	51	1005.6	34.6	0.048	-0.0593	1.609	-0.052
43	16/06/2017	23.3	48	1015.9	34.3	0.049	-0.061	1.611	-0.057
44	19/06/2017	23.2	53	1007.9	34.5	0.048	-0.059	1.618	-0.049
45	21/06/2017	23.2	59	1005.6	34.0	0.049	-0.06	1.616	-0.051
46	23/06/2017	23.3	53	1011.3	34.2	0.049	-0.057	1.619	-0.051
47	26/06/2017	23.2	52	1002.9	34.3	0.049	-0.059	1.617	-0.048
48	28/06/2017	23.3	54	988.0	34.3	0.049	-0.06	1.610	-0.055
49	30/06/2017	23.3	51	994.5	34.5	0.048	-0.06	1.604	-0.067
Mean	**30/05/2017**	**23.3**	**49.4**	**1006.6**	**34.4**	**0.048**	**-0.060**	**1.608**	**-0.048**
					Standard deviation (µF/F)			**0.009**	**0.010**
50	24/07/2017	23.1	52	1003.8	34.4	0.049	-0.061	1.623	-0.065
51	26/07/2017	23.2	51	1002.7	34.5	0.049	-0.06	1.620	-0.056
52	28/07/2017	23.1	50	1005.6	34.4	0.049	-0.061	1.619	-0.059
53	31/07/2017	23.1	51	1005.4	34.5	0.049	-0.06	1.618	-0.055
54	02/08/2017	23.1	51	1009.0	34.4	0.049	-0.061	1.619	-0.057
55	04/08/2017	23.1	52	1006.4	34.6	0.049	-0.06	1.619	-0.054
56	07/08/2017	23.1	48	1010.7	34.4	0.049	-0.061	1.624	-0.057
57	09/08/2017	23.1	50	1006.3	34.4	0.049	-0.06	1.618	-0.051
58	11/08/2017	23.1	50	1010.9	34.4	0.048	-0.06	1.618	-0.056
59	16/08/2017	23.1	52	1010.7	34.5	0.049	-0.061	1.619	-0.055
60	18/08/2017	23.1	53	1005.3	34.5	0.048	-0.061	1.618	-0.055
61	21/08/2017	23.1	52	1012.4	34.5	0.049	-0.061	1.623	-0.058
62	23/08/2017	23.1	55	1005.4	34.3	0.049	-0.061	1.622	-0.054
63	25/08/2017	23.1	52	1006.5	34.4	0.049	-0.06	1.622	-0.056
64	28/08/2017	23.0	54	1008.8	34.2	0.049	-0.06	1.624	-0.055
65	30/08/2017	23.2	57	1006.6	34.4	0.048	-0.059	1.620	-0.053
66	01/09/2017	23.1	49	1011.3	34.1	0.049	-0.061	1.627	-0.062
67	04/09/2017	23.3	51	1005.4	34.4	0.049	-0.059	1.624	-0.050
68	06/09/2017	23.3	48	1013.0	34.4	0.049	-0.061	1.624	-0.058
69	08/09/2017	23.3	51	997.0	34.5	0.049	-0.061	1.623	-0.053
Mean	**16/08/2017**	**23.1**	**51.3**	**1007.2**	**34.4**	**0.049**	**-0.060**	**1.621**	**-0.056**
					Standard deviation (µF/F)			**0.003**	**0.003**

BIPM **100 pF standards #1225 and 1642** **Measurement frequency: 1591.55 Hz**

	Date	Ambient conditions			Temperature of standard			Deviation from nominal (µF/F)	
	yyyy/mm/dd	Temperature (°C)	Relative Humidity (%)	Atmospheric Pressure (hPa)	AH frame Temperature (°C)	Drift Std #1225 (ppm)	Drift Std #1642 (ppm)	Standard # **1225** 100 pF / 10 V	Standard # **1642** 100 pF / 10 V
1	03/02/2017	23.5	46	1008.0	35.1	-0.030	0.017	5.132	0.643
2	06/02/2017	23.4	44	1004.8	35.2	-0.029	0.018	5.129	0.646
3	17/02/2017	23.5	43	1005.3	35.6	-0.031	0.019	5.128	0.647
4	21/02/2017	23.5	48	1001.2	35.0	-0.034	0.018	5.135	0.647
5	24/02/2017	23.2	46	998.0	34.3	-0.034	0.016	5.143	0.646
6	27/02/2017	23.2	46	990.0	34.4	-0.034	0.017	5.141	0.650
7	01/03/2017	23.2	45	995.2	34.5	-0.030	0.017	5.146	0.649
8	03/03/2017	23.1	44	992.7	35.3	-0.034	0.019	5.129	0.653
9	06/03/2017	23.0	45	1008.5	34.5	-0.033	0.017	5.146	0.651
10	10/03/2017	23.1	45	1016.3	35.4	-0.030	0.017	5.132	0.642
11	13/03/2017	23.2	45	1017.0	34.5	-0.034	0.019	5.131	0.648
12	15/03/2017	23.1	45	1023.4	34.5	-0.034	0.017	5.140	0.642
13	17/03/2017	23.1	45	1011.0	35.1	-0.032	0.018	5.132	0.650
14	20/03/2017	23.1	45	1004.0	34.5	-0.034	0.019	5.138	0.651
15	22/03/2017	23.1	45	998.5	34.6	-0.033	0.017	5.141	0.652
16	24/03/2017	23.1	46	1012.6	34.4	-0.034	0.017	5.139	0.650
17	27/03/2017	23.2	46	1009.0	34.6	-0.034	0.017	5.134	0.646
18	29/03/2017	23.1	46	1016.3	34.7	-0.033	0.018	5.142	0.653
19	31/03/2017	23.1	46	1004.3	34.3	-0.035	0.018	5.127	0.649
20	03/04/2017	23.0	45	1017.1	34.3	-0.035	0.017	5.130	0.645
21	05/04/2017	23.2	46	1019.0	34.5	-0.034	0.018	5.133	0.646
Mean	**10/03/2017**	**23.2**	**45.3**	**1007.2**	**34.7**	**-0.033**	**0.018**	**5.136**	**0.648**
					Standard deviation (µF/F)			**0.006**	**0.003**
22	02/05/2017	23.3	46	1006.9	35.2	-0.032	0.019	5.133	0.647
23	03/05/2017	23.2	48	1008.4	34.3	-0.036	0.021	5.123	0.646
24	05/05/2017	23.3	47	1009.0	34.3	-0.036	0.019	5.131	0.646
25	09/05/2017	23.3	45	1012.5	34.3	-0.035	0.019	5.129	0.646
26	10/05/2017	23.4	48	994.8	34.6	-0.034	0.019	5.132	0.645
27	12/05/2017	23.4	48	991.0	34.4	-0.035	0.02	5.132	0.650
28	15/05/2017	23.4	48	1019.3	34.6	-0.034	0.019	5.132	0.653
29	16/05/2017	23.4	49	1018.0	34.3	-0.036	0.02	5.131	0.653
30	17/05/2017	23.4	51	1004.7	34.3	-0.036	0.02	5.140	0.652
31	18/05/2017	23.3	46	1004.6	34.2	-0.036	0.019	5.138	0.655
32	22/05/2017	23.3	47	1006.5	35.1	-0.033	0.02	5.136	0.648
33	23/05/2017	23.3	48	1012.5	34.2	-0.036	0.021	5.146	0.658
34	24/05/2017	23.4	49	1015.6	34.4	-0.035	0.019	5.147	0.654
35	29/05/2017	23.3	55	1003.2	34.2	-0.037	0.02	5.139	0.650
36	30/05/2017	23.3	50	1009.0	34.2	-0.036	0.019	5.145	0.655
37	01/06/2017	23.3	50	1012.1	34.8	-0.035	0.02	5.142	0.655
38	06/06/2017	23.4	47	998.9	34.2	-0.036	0.021	5.145	0.653
39	07/06/2017	23.4	47	1009.5	34.2	-0.036	0.02	5.137	0.653
40	09/06/2017	23.4	49	1005.5	34.7	-0.033	0.02	5.130	0.648
41	12/06/2017	23.3	47	1011.8	34.3	-0.036	0.022	5.131	0.654
42	14/06/2017	23.2	51	1005.6	34.6	-0.035	0.021	5.135	0.654
43	16/06/2017	23.3	48	1015.9	34.3	-0.036	0.021	5.133	0.654
44	19/06/2017	23.2	53	1007.9	34.5	-0.036	0.021	5.137	0.655
45	21/06/2017	23.2	59	1005.6	34.0	-0.038	0.021	5.140	0.658
46	23/06/2017	23.3	53	1011.3	34.2	-0.037	0.02	5.142	0.655
47	26/06/2017	23.2	52	1002.9	34.3	-0.036	0.021	5.142	0.656
48	28/06/2017	23.3	54	988.0	34.3	-0.036	0.021	5.142	0.655
49	30/06/2017	23.3	51	994.5	34.5	-0.036	0.021	5.141	0.652
Mean	**06/06/2017**	**23.3**	**49.4**	**1006.6**	**34.4**	**-0.035**	**0.020**	**5.137**	**0.652**
					Standard deviation (µF/F)			**0.006**	**0.004**
50	24/07/2017	23.1	52	1003.8	34.4	-0.036	0.022	5.139	0.653
51	26/07/2017	23.2	51	1002.7	34.5	-0.036	0.022	5.132	0.655
52	28/07/2017	23.1	50	1005.6	34.4	-0.036	0.022	5.130	0.653
53	31/07/2017	23.1	51	1005.4	34.5	-0.036	0.022	5.134	0.655
54	02/08/2017	23.1	51	1009.0	34.4	-0.037	0.022	5.133	0.655
55	04/08/2017	23.1	52	1006.4	34.6	-0.036	0.022	5.138	0.656
56	07/08/2017	23.1	48	1010.7	34.4	-0.037	0.022	5.138	0.657
57	09/08/2017	23.1	50	1006.3	34.4	-0.037	0.022	5.143	0.659
58	11/08/2017	23.1	50	1010.9	34.4	-0.036	0.022	5.142	0.657
59	16/08/2017	23.1	52	1010.7	34.5	-0.036	0.022	5.142	0.655
60	18/08/2017	23.1	53	1005.3	34.5	-0.036	0.022	5.143	0.657
61	21/08/2017	23.1	52	1012.4	34.5	-0.036	0.022	5.153	0.656
62	23/08/2017	23.1	55	1005.4	34.3	-0.037	0.022	5.137	0.657
63	25/08/2017	23.1	52	1006.5	34.4	-0.036	0.022	5.140	0.658
64	28/08/2017	23.0	54	1008.8	34.2	-0.037	0.022	5.149	0.658
65	30/08/2017	23.2	57	1006.6	34.4	-0.037	0.022	5.148	0.658
66	01/09/2017	23.1	49	1011.3	34.1	-0.038	0.022	5.131	0.654
67	04/09/2017	23.3	51	1005.4	34.4	-0.037	0.022	5.140	0.657
68	06/09/2017	23.3	48	1013.0	34.4	-0.037	0.022	5.130	0.657
69	08/09/2017	23.3	51	997.0	34.5	-0.037	0.022	5.130	0.657
Mean	**27/05/2017**	**23.1**	**51.3**	**1007.2**	**34.4**	**-0.037**	**0.022**	**5.139**	**0.656**
					Standard deviation (µF/F)			**0.007**	**0.002**

A4-2 METAS

Serial number of the standard capacitor: **01191 (C10B)**
Nominal value: **10 pF** Measurement frequency: **1233.15 Hz** Applied voltage: **100 V**

	Date (yyyy/mm/dd) and Time (hh:mm)	Ambient conditions			Temperature of the standard		
		Temperature (°C)	Relative Humidity (%)	Atmospheric Pressure (hPa)	Chassis Temperature (°C)	Drift (ppm)	Deviation from nominal (µF/F)
1	2017/03/06 10:57	23.2	38.3	943.0	36.8	0.063	-2.013
2	2017/03/13 14:08	23.0	37.6	958.3	32.7	0.064	-1.998
3	2017/03/14 12:54	23.2	37.4	966.6	32.5	0.055	-2.010
4	2017/03/16 09:46	23.2	37.1	961.5	31.9	0.055	-2.150
5	2017/03/20 13:19	23.1	38.5	949.8	32.0	0.055	-2.050
6	2017/03/23 11:16	23.1	38.7	948.3	32.0	0.054	-2.191
7	2017/03/27 13:03	23.1	39.2	957.8	32.0	0.054	-1.999
8	2017/03/28 11:17	23.2	39.6	960.8	32.1	0.055	-2.028
9	2017/03/30 11:17	23.4	38.4	962.3	32.1	0.054	-2.052
10	2017/04/03 11:35	23.3	39.0	958.5	32.1	0.054	-2.047
11	2017/04/07 11:41	23.2	38.3	959.6	32.0	0.054	-2.026
12	2017/08/02 16:58	23.7	46.9	956.1	33.0	0.056	-2.001
13	2017/08/04 11:47	23.6	47.1	953.7	33.1	0.055	-2.041
14	2017/08/08 08:55	23.5	40.8	950.9	32.1	0.055	-2.016
15	2017/08/10 14:40	23.5	40.1	957.2	32.1	0.055	-2.058
16	2017/08/15 10:11	23.5	41.9	956.9	32.1	0.055	-2.067
17	2017/08/17 08:49	23.6	42.1	957.4	32.1	0.055	-2.061
18	2017/08/21 15:22	23.7	40.2	959.3	32.5	0.055	-2.061
19	2017/08/31 10:48	23.5	43.0	953.8	32.0	0.055	-2.067
20	2017/09/04 10:34	23.3	39.1	953.3	32.0	0.055	-2.062
21	2017/09/07 08:23	23.2	39.0	955.7	32.0	0.055	-2.091

Mean deviation from nominal (µF/F)	**-2.052**
Type A Uncertainty (µF/F)	**0.010**
Type B Uncertainty (µF/F)	**0.078**
Combined Uncertainty (µF/F)	**0.079**

Serial number of the standard capacitor: **01300 (C10C)**

Nominal value: **10 pF** Measurement frequency: **1233.15 Hz** Applied voltage: **100 V**

	Date (yyyy/mm/dd) and Time (hh:mm)	Ambient conditions			Temperature of the standard		
		Temperature (°C)	Relative Humidity (%)	Atmospheric Pressure (hPa)	Chassis Temperature (°C)	Drift (ppm)	Deviation from nominal (µF/F)
1	2017/03/06 10:57	23.2	38.3	943.0	36.8	0.188	1.308
2	2017/03/13 14:08	23.0	37.6	958.3	32.7	0.203	1.363
3	2017/03/14 12:54	23.2	37.4	966.6	32.5	0.204	1.385
4	2017/03/16 09:46	23.2	37.1	961.5	31.9	0.204	1.268
5	2017/03/20 13:19	23.1	38.5	949.8	32.0	0.204	1.317
6	2017/03/23 11:16	23.1	38.7	948.3	32.0	0.205	1.238
7	2017/03/27 13:03	23.1	39.2	957.8	32.0	0.204	1.410
8	2017/03/28 11:17	23.2	39.6	960.8	32.1	0.204	1.371
9	2017/03/30 11:17	23.4	38.4	962.3	32.1	0.204	1.366
10	2017/04/03 11:35	23.3	39.0	958.5	32.1	0.204	1.350
11	2017/04/07 11:41	23.2	38.3	959.6	32.0	0.204	1.374
12	2017/08/02 16:35	23.7	46.9	956.1	33.0	0.205	1.333
13	2017/08/04 15:41	23.7	47.2	953.0	33.1	0.208	1.304
14	2017/08/08 08:01	23.5	40.8	950.9	32.1	0.208	1.304
15	2017/08/10 11:14	23.5	40.0	956.6	32.1	0.208	1.305
16	2017/08/15 09:45	23.5	41.4	957.0	32.1	0.208	1.293
17	2017/08/17 09:07	23.6	42.1	957.5	32.1	0.208	1.290
18	2017/08/21 14:52	23.7	39.7	959.6	32.5	0.208	1.297
19	2017/08/31 10:25	23.5	43.0	953.8	32.0	0.208	1.274
20	2017/09/04 09:52	23.3	39.0	952.8	32.0	0.208	1.279
21	2017/09/07 08:56	23.3	39.0	955.7	32.0	0.208	1.279

Mean deviation from nominal (µF/F)	**1.319**
Type A Uncertainty (µF/F)	**0.010**
Type B Uncertainty (µF/F)	**0.078**
Combined Uncertainty (µF/F)	**0.079**

Serial number of the standard capacitor: **01188 (C100A)**

Nominal value: **100 pF** Measurement frequency: **1233.15 Hz** Applied voltage: **10 V**

	Date (yyyy/mm/dd) and Time (hh:mm)	Ambient conditions			Temperature of the standard		
		Temperature (°C)	Relative Humidity (%)	Atmospheric Pressure (hPa)	Chassis Temperature (°C)	Drift (ppm)	Deviation from nominal (µF/F)
1	2017/03/06 10:57	23.2	38.3	943.0	36.8	0.003	-3.231
2	2017/03/13 14:08	23.0	37.6	958.3	32.7	-0.022	-3.149
3	2017/03/14 12:54	23.2	37.4	966.6	32.5	-0.024	-3.118
4	2017/03/16 09:46	23.2	37.1	961.5	31.9	-0.023	-3.237
5	2017/03/20 13:19	23.1	38.5	949.8	32.0	-0.025	-3.181
6	2017/03/23 11:16	23.1	38.7	948.3	32.0	-0.025	-3.281
7	2017/03/27 13:03	23.1	39.2	957.8	32.0	-0.024	-3.169
8	2017/03/28 11:17	23.2	39.6	960.8	32.1	-0.024	-3.211
9	2017/03/30 11:17	23.4	38.4	962.3	32.1	-0.024	-3.211
10	2017/04/03 11:35	23.3	39.0	958.5	32.1	-0.024	-3.228
11	2017/04/07 11:41	23.2	38.3	959.6	32.0	-0.025	-3.200
12	2017/08/02 15:50	23.6	46.7	956.6	33.0	-0.024	-3.207
13	2017/08/04 13:21	23.6	47.7	953.4	33.1	-0.023	-3.207
14	2017/08/08 11:06	23.6	41.1	950.5	32.1	-0.024	-3.200
15	2017/08/10 08:14	23.4	40.4	955.9	32.1	-0.024	-3.190
16	2017/08/15 08:25	23.5	41.3	956.8	32.1	-0.023	-3.204
17	2017/08/17 10:45	23.6	42.3	957.4	32.1	-0.024	-3.201
18	2017/08/21 14:14	23.7	39.7	959.6	32.5	-0.024	-3.200
19	2017/08/31 09:07	23.5	42.9	954.9	32.0	-0.023	-3.201
20	2017/09/04 08:46	23.2	38.9	952.3	32.0	-0.024	-3.207
21	2017/09/07 10:09	23.3	39.1	955.7	32.0	-0.025	-3.210

Mean deviation from nominal (µF/F)	**-3.202**
Type A Uncertainty (µF/F)	**0.007**
Type B Uncertainty (µF/F)	**0.064**
Combined Uncertainty (µF/F)	**0.064**

Serial number of the standard capacitor: **01189 (C100B)**

Nominal value: **100 pF** Measurement frequency: **1233.15 Hz** Applied voltage: **10 V**

	Date (yyyy/mm/dd) and Time (hh:mm)	Ambient conditions			Temperature of the standard		
		Temperature (°C)	Relative Humidity (%)	Atmospheric Pressure (hPa)	Chassis Temperature (°C)	Drift (ppm)	Deviation from nominal (µF/F)
1	2017/03/06 10:57	23.2	38.3	943.0	36.8	0.006	-2.679
2	2017/03/13 14:08	23.0	37.6	958.3	32.7	0.012	-2.529
3	2017/03/14 12:54	23.2	37.4	966.6	32.5	0.014	-2.525
4	2017/03/16 09:46	23.2	37.1	961.5	31.9	0.012	-2.620
5	2017/03/20 13:19	23.1	38.5	949.8	32.0	0.015	-2.631
6	2017/03/23 11:16	23.1	38.7	948.3	32.0	0.015	-2.608
7	2017/03/27 13:03	23.1	39.2	957.8	32.0	0.014	-2.505
8	2017/03/28 11:17	23.2	39.6	960.8	32.1	0.015	-2.583
9	2017/03/30 11:17	23.4	38.4	962.3	32.1	0.014	-2.591
10	2017/04/03 11:35	23.3	39.0	958.5	32.1	0.014	-2.539
11	2017/04/07 11:41	23.2	38.3	959.6	32.0	0.014	-2.524
12	2017/08/02 16:13	23.7	46.9	956.1	33.0	0.013	-2.629
13	2017/08/04 12:42	23.6	47.1	953.7	33.1	0.015	-2.625
14	2017/08/08 10:07	23.5	41.3	949.7	32.1	0.015	-2.621
15	2017/08/10 10:06	23.5	40.2	956.2	32.1	0.015	-2.614
16	2017/08/15 08:46	23.5	41.3	956.8	32.1	0.015	-2.630
17	2017/08/17 10:25	23.6	42.3	957.4	32.1	0.015	-2.620
18	2017/08/21 14:32	23.7	39.7	959.6	32.5	0.015	-2.618
19	2017/08/31 10:00	23.5	42.9	953.8	32.0	0.013	-2.625
20	2017/09/04 09:13	23.2	39.0	952.8	32.0	0.015	-2.601
21	2017/09/07 09:46	23.3	39.0	955.8	32.0	0.015	-2.613

Mean deviation from nominal (µF/F)	**-2.597**
Type A Uncertainty (µF/F)	**0.010**
Type B Uncertainty (µF/F)	**0.064**
Combined Uncertainty (µF/F)	**0.065**

A4-3 NIM

Initial and return series 10 pF #01606

Serial number of the standard capacitor: AH#1606
Nominal value: 10 pF Measurement frequency: 1592Hz Applied voltage: 100V

	Date (yyyy/mm/dd) and Time (hh:mm)	Ambient conditions			Temperature of the standard		Deviation from nominal (μF/F)
		Temperature (°C)	Relative Humidity (%)	Atmospheric Pressure (hPa)	Chassis Temperature (°C)	Drift (ppm)	
1	2017/3/2 11:50	19.8	48.3	1007	31.5	-0.012	0.100
2	2017/3/7 17:00	19.8	51.2	1001	31.4	-0.012	0.102
3	2017/3/9 10:00	20.5	54.1	1004	31.4	-0.012	0.093
4	2017/3/10 15:00	19.8	49.7	1002	31.3	-0.012	0.092
5	2017/3/14 11:30	19.9	52.1	1015	31.5	-0.013	0.095
6	2017/3/16 15:35	19.8	51.9	1005	31.3	-0.013	0.099
7	2017/3/17 9:30	20.0	52.6	1009	31.4	-0.011	0.097
8	2017/3/27 14:30	19.7	56.1	1008	31.5	-0.013	0.098
9	2017/3/29 9:50	19.9	49.7	1008	31.3	-0.013	0.094
10	2017/3/31 11:50	19.9	49.0	1014	31.4	-0.013	0.093
				Mean deviation from nominal (μF/F)			0.096
				Type A uncertainty (μF/F)			0.0035
				Type B uncertainty (μF/F)			0.0178
				Combined standard uncertainty (μF/F)			0.018

Serial number of the standard capacitor: AH#1606
Nominal value: 10 pF Measurement frequency: 1592Hz Applied voltage: 100V

	Date (yyyy/mm/dd) and Time (hh:mm)	Ambient conditions			Temperature of the standard		Deviation from nominal (μF/F)
		Temperature (°C)	Relative Humidity (%)	Atmospheric Pressure (hPa)	Chassis Temperature (°C)	Drift (ppm)	
1	2017/8/1 10:20	19.8	50.8	1007	32.0	-0.014	0.069
2	2017/8/3 6:30	19.8	50.8	1014	32.4	-0.014	0.071
3	2017/8/11 11:50	19.9	51.0	1011	31.2	-0.014	0.071
4	2017/8/14 8:35	20.0	52.0	1005	31.2	-0.015	0.065
5	2017/8/16 11:40	19.9	50.1	1014	31.2	-0.015	0.079
6	2017/8/18 11:20	20.0	49.8	1009	31.3	-0.015	0.067
7	2017/8/23 16:15	20.0	49.5	1003	31.3	-0.016	0.070
8	2017/8/25 8:50	19.8	53.4	1001	31.4	-0.015	0.065
9	2017/8/28 15:21	19.8	49.4	1013	31.3	-0.016	0.067
10	2017/8/30 9:03	19.9	51.0	1012	31.5	-0.016	0.073
				Mean deviation from nominal (μF/F)			0.070
				Type A uncertainty (μF/F)			0.0042
				Type B uncertainty (μF/F)			0.0178
				Combined standard uncertainty (μF/F)			0.018

Initial and return series 10 pF #01682

Serial number of the standard capacitor: AH#1682
Nominal value: 10 pF Measurement frequency: 1592Hz Applied voltage: 100V

	Date (yyyy/mm/dd) and Time (hh:mm)	Ambient conditions			Temperature of the standard		Deviation from nominal (µF/F)
		Temperature (°C)	Relative Humidity (%)	Atmospheric Pressure (hPa)	Chassis Temperature (°C)	Drift (ppm)	
1	2017/3/2 11:50	19.8	48.3	1007	31.5	0.025	0.377
2	2017/3/7 17:00	19.8	51.2	1001	31.4	0.025	0.379
3	2017/3/9 10:00	20.5	54.1	1004	31.4	0.027	0.368
4	2017/3/10 15:00	19.8	49.7	1002	31.3	0.036	0.441
5	2017/3/14 11:30	19.9	52.1	1015	31.5	0.032	0.423
6	2017/3/16 15:35	19.8	51.9	1005	31.3	0.032	0.426
7	2017/3/17 9:30	20.0	52.6	1009	31.4	0.029	0.368
8	2017/3/27 14:30	19.7	56.1	1008	31.5	0.030	0.383
9	2017/3/29 9:50	19.9	49.7	1008	31.3	0.030	0.379
10	2017/3/31 11:50	19.9	49.0	1014	31.4	0.031	0.409

Mean deviation from nominal (µF/F)	0.395
Type A uncertainty (µF/F)	0.027
Type B uncertainty (µF/F)	0.0178
Combined standard uncertainty (µF/F)	0.032

Serial number of the standard capacitor: AH#1682
Nominal value: 10 pF Measurement frequency: 1592Hz Applied voltage: 100V

	Date (yyyy/mm/dd) and Time (hh:mm)	Ambient conditions			Temperature of the standard		Deviation from nominal (µF/F)
		Temperature (°C)	Relative Humidity (%)	Atmospheric Pressure (hPa)	Chassis Temperature (°C)	Drift (ppm)	
1	2017/8/1 10:20	19.8	50.8	1007	32.0	0.032	0.373
2	2017/8/3 6:30	19.8	50.8	1014	32.4	0.033	0.374
3	2017/8/11 11:50	19.9	51.0	1011	31.2	0.029	0.374
4	2017/8/14 8:35	20.0	52.0	1005	31.2	0.030	0.367
5	2017/8/16 11:40	19.9	50.1	1014	31.2	0.029	0.382
6	2017/8/18 11:20	20.0	49.8	1009	31.3	0.029	0.368
7	2017/8/23 16:15	20.0	49.5	1003	31.3	0.030	0.372
8	2017/8/25 8:50	19.8	53.4	1001	31.4	0.029	0.370
9	2017/8/28 15:21	19.8	49.4	1013	31.3	0.029	0.369
10	2017/8/30 9:03	19.9	51.0	1012	31.5	0.030	0.376

Mean deviation from nominal (µF/F)	0.372
Type A uncertainty (µF/F)	0.0044
Type B uncertainty (µF/F)	0.0178
Combined standard uncertainty (µF/F)	0.018

Initial and return series 100 pF #01596

Serial number of the standard capacitor: AH#1596
Nominal value: 100 pF Measurement frequency: 1592Hz Applied voltage: 10V

	Date (yyyy/mm/dd) and Time (hh:mm)	Ambient conditions			Temperature of the standard		Deviation from nominal (µF/F)
		Temperature (°C)	Relative Humidity (%)	Atmospheric Pressure (hPa)	Chassis Temperature (°C)	Drift (ppm)	
1	2017/3/2 11:50	19.8	48.3	1007	31.5	0.000	0.070
2	2017/3/7 17:00	19.8	51.2	1001	31.4	0.000	0.069
3	2017/3/9 10:00	20.5	54.1	1004	31.4	-0.001	0.062
4	2017/3/10 15:00	19.8	49.7	1002	31.3	0.000	0.054
5	2017/3/14 11:30	19.9	52.1	1015	31.5	0.000	0.061
6	2017/3/16 15:35	19.8	51.9	1005	31.3	0.000	0.061
7	2017/3/17 9:30	20.0	52.6	1009	31.4	0.001	0.066
8	2017/3/27 14:30	19.7	56.1	1008	31.5	0.001	0.066
9	2017/3/29 9:50	19.9	49.7	1008	31.3	0.000	0.061
10	2017/3/31 11:50	19.9	49.0	1014	31.4	0.001	0.066
				Mean deviation from nominal (µF/F)			0.064
				Type A uncertainty (µF/F)			0.0047
				Type B uncertainty (µF/F)			0.021
				Combined standard uncertainty (µF/F)			0.021

Serial number of the standard capacitor: AH#1596
Nominal value: 100 pF Measurement frequency: 1592Hz Applied voltage: 10V

	Date (yyyy/mm/dd) and Time (hh:mm)	Ambient conditions			Temperature of the standard		Deviation from nominal (µF/F)
		Temperature (°C)	Relative Humidity (%)	Atmospheric Pressure (hPa)	Chassis Temperature (°C)	Drift (ppm)	
1	2017/8/1 10:20	19.8	50.8	1007	32.0	-0.002	0.027
2	2017/8/3 6:30	19.8	50.8	1014	32.4	-0.002	0.027
3	2017/8/11 11:50	19.9	51.0	1011	31.2	0.000	0.031
4	2017/8/14 8:35	20.0	52.0	1005	31.2	0.000	0.023
5	2017/8/16 11:40	19.9	50.1	1014	31.2	0.000	0.023
6	2017/8/18 11:20	20.0	49.8	1009	31.3	-0.001	0.026
7	2017/8/23 16:15	20.0	49.5	1003	31.3	0.000	0.031
8	2017/8/25 8:50	19.8	53.4	1001	31.4	0.000	0.024
9	2017/8/28 15:21	19.8	49.4	1013	31.3	-0.001	0.026
10	2017/8/30 9:03	19.9	51.0	1012	31.5	0.000	0.032
				Mean deviation from nominal (µF/F)			0.027
				Type A uncertainty (µF/F)			0.0034
				Type B uncertainty (µF/F)			0.021
				Combined standard uncertainty (µF/F)			0.021

Initial and return series 100 pF #02090

Serial number of the standard capacitor: AH#2090
Nominal value: 100 pF Measurement frequency: 1592Hz Applied voltage: 10V

	Date (yyyy/mm/dd) and Time (hh:mm)	Ambient conditions			Temperature of the standard		Deviation from nominal (µF/F)
		Temperature (°C)	Relative Humidity (%)	Atmospheric Pressure (hPa)	Chassis Temperature (°C)	Drift (ppm)	
1	2017/3/2 11:50	19.8	48.3	1007	31.5	-0.007	0.188
2	2017/3/7 17:00	19.8	51.2	1001	31.4	-0.009	0.178
3	2017/3/9 10:00	20.5	54.1	1004	31.4	-0.009	0.165
4	2017/3/10 15:00	19.8	49.7	1002	31.3	-0.009	0.155
5	2017/3/14 11:30	19.9	52.1	1015	31.5	-0.009	0.163
6	2017/3/16 15:35	19.8	51.9	1005	31.3	-0.008	0.156
7	2017/3/17 9:30	20.0	52.6	1009	31.4	-0.009	0.178
8	2017/3/27 14:30	19.7	56.1	1008	31.5	-0.008	0.175
9	2017/3/29 9:50	19.9	49.7	1008	31.3	-0.009	0.171
10	2017/3/31 11:50	19.9	49.0	1014	31.4	-0.006	0.175
				Mean deviation from nominal (µF/F)			0.170
				Type A uncertainty (µF/F)			0.011
				Type B uncertainty (µF/F)			0.021
				Combined standard uncertainty (µF/F)			0.023

Serial number of the standard capacitor: AH#2090
Nominal value: 100 pF Measurement frequency: 1592Hz Applied voltage: 10V

	Date (yyyy/mm/dd) and Time (hh:mm)	Ambient conditions			Temperature of the standard		Deviation from nominal (µF/F)
		Temperature (°C)	Relative Humidity (%)	Atmospheric Pressure (hPa)	Chassis Temperature (°C)	Drift (ppm)	
1	2017/8/1 10:20	19.8	50.8	1007	32.0	-0.011	0.144
2	2017/8/3 6:30	19.8	50.8	1014	32.4	-0.011	0.145
3	2017/8/11 11:50	19.9	51.0	1011	31.2	-0.010	0.149
4	2017/8/14 8:35	20.0	52.0	1005	31.2	-0.010	0.148
5	2017/8/16 11:40	19.9	50.1	1014	31.2	-0.010	0.154
6	2017/8/18 11:20	20.0	49.8	1009	31.3	-0.011	0.151
7	2017/8/23 16:15	20.0	49.5	1003	31.3	-0.010	0.152
8	2017/8/25 8:50	19.8	53.4	1001	31.4	-0.010	0.148
9	2017/8/28 15:21	19.8	49.4	1013	31.3	-0.010	0.150
10	2017/8/30 9:03	19.9	51.0	1012	31.5	-0.010	0.157
				Mean deviation from nominal (µF/F)			0.150
				Type A uncertainty (µF/F)			0.004
				Type B uncertainty (µF/F)			0.021
				Combined standard uncertainty (µF/F)			0.021

A4-4 NIST

Initial and return measurements 10 pF #01423

Serial number of the standard capacitor: AH1423 (C143)

Nominal value: 10 pF Measurement frequency: 1592 Hz Applied voltage: 100 V

	Date (yyyy/mm/dd) and Time (hh:mm)	Ambient conditions			Temperature of the standard		
		Temperature (°C)	Relative Humidity (%)	Atmospheric Pressure (kPa)	Chassis Temperature (°C)	Drift (ppm)	Deviation from nominal (µF/F)
1	2017/3/1	21.7	44	99	28.2	-0.013	-4.86
2	2017/3/3	21.6	38	101	28.1	-0.012	-4.866
3	2017/3/7	21.6	47	101	28.2	-0.013	-4.863
4	2017/3/10	21.6	38	100	28.3	-0.012	-4.863
5	2017/3/15	21.6	38	100	28.2	-0.013	-4.863
6	2017/3/17	21.6	32	101	28.1	-0.012	-4.865
7	2017/3/21	21.7	44	100	27.7	-0.011	-4.863
8	2017/3/24	21.6	43	101	28.2	-0.013	-4.865
9	2017/3/28	21.6	43	100	28.3	-0.013	-4.864
10	2017/3/31	21.7	44	101	28.3	-0.013	-4.864

Mean deviation from nominal (µF/F)	-4.864
Type A Uncertainty (µF/F)	0.001
Type B Uncertainty (µF/F)	0.020
Combined Uncertainty (µF/F)	0.020

Serial number of the standard capacitor: AH1423 (C143)

Nominal value: 10 pF Measurement frequency: 1592 Hz Applied voltage: 100 V

	Date (yyyy/mm/dd) and Time (hh:mm)	Ambient conditions			Temperature of the standard		
		Temperature (°C)	Relative Humidity (%)	Atmospheric Pressure (kPa)	Chassis Temperature (°C)	Drift (ppm)	Deviation from nominal (µF/F)
1	2017/7/25	22.4	48	101	27.8	-0.011	-4.863
2	2017/7/28	22.6	48	100	27.9	-0.012	-4.864
3	2017/8/1	22.6	48	101	28.0	-0.012	-4.865
4	2017/8/9	22.1	48	101	27.8	-0.011	-4.866
5	2017/8/11	22.3	49	100	27.7	-0.011	-4.864
6	2017/8/15	22.1	49	100	27.5	-0.011	-4.867
7	2017/8/18	22.2	49	99	28.0	-0.012	-4.864
8	2017/8/24	22.1	48	100	27.8	-0.011	-4.864
9	2017/8/25	22.1	49	101	28.1	-0.012	-4.865
10	2017/8/30	22.2	49	100	27.9	-0.011	-4.865
11	2017/9/1	22.1	46	101	27.5	-0.011	-4.867

Mean deviation from nominal (µF/F)	-4.865
Type A Uncertainty (µF/F)	0.001
Type B Uncertainty (µF/F)	0.020
Combined Uncertainty (µF/F)	0.020

Initial and return measurements 10 pF #01424

Serial number of the standard capacitor: AH1424 (C144)

Nominal value: 10 pF Measurement frequency: 1592 Hz Applied voltage: 100 V

	Date (yyyy/mm/dd) and Time (hh:mm)	Ambient conditions			Temperature of the standard		
		Temperature (°C)	Relative Humidity (%)	Atmospheric Pressure (kPa)	Chassis Temperature (°C)	Drift (ppm)	Deviation from nominal (µF/F)
1	2017/3/1	21.7	44	99	28.2	-0.046	-4.77
2	2017/3/3	21.6	38	101	28.1	-0.046	-4.776
3	2017/3/7	21.6	47	101	28.2	-0.046	-4.773
4	2017/3/10	21.6	38	100	28.3	-0.047	-4.773
5	2017/3/15	21.6	38	100	28.2	-0.046	-4.773
6	2017/3/17	21.6	32	101	28.1	-0.046	-4.774
7	2017/3/21	21.7	44	100	27.7	-0.048	-4.771
8	2017/3/24	21.6	43	101	28.2	-0.046	-4.777
9	2017/3/28	21.6	43	100	28.3	-0.047	-4.777
10	2017/3/31	21.7	44	101	28.3	-0.046	-4.777

Mean deviation from nominal (µF/F)	-4.774
Type A Uncertainty (µF/F)	0.001
Type B Uncertainty (µF/F)	0.020
Combined Uncertainty (µF/F)	0.020

Serial number of the standard capacitor: AH1424 (C144)

Nominal value: 10 pF Measurement frequency: 1592 Hz Applied voltage: 100 V

	Date (yyyy/mm/dd) and Time (hh:mm)	Ambient conditions			Temperature of the standard		
		Temperature (°C)	Relative Humidity (%)	Atmospheric Pressure (kPa)	Chassis Temperature (°C)	Drift (ppm)	Deviation from nominal (µF/F)
1	2017/7/25	22.4	48	101	27.8	-.0.043	-4.784
2	2017/7/28	22.6	48	100	27.9	-.0.043	-4.786
3	2017/8/1	22.6	48	101	28.0	-.0.043	-4.787
4	2017/8/9	22.1	48	101	27.8	-.0.044	-4.787
5	2017/8/11	22.3	49	100	27.7	-.0.044	-4.786
6	2017/8/15	22.1	49	100	27.5	-.0.044	-4.783
7	2017/8/18	22.2	49	99	28.0	-.0.043	-4.788
8	2017/8/24	22.1	48	100	27.8	-.0.045	-4.786
9	2017/8/25	22.1	49	101	28.1	-.0.044	-4.789
10	2017/8/30	22.2	49	100	27.9	-.0.045	-4.786
11	2017/9/1	22.1	46	101	27.5	-.0.045	-4.785

Mean deviation from nominal (µF/F)	-4.786
Type A Uncertainty (µF/F)	0.001
Type B Uncertainty (µF/F)	0.020
Combined Uncertainty (µF/F)	0.020

Initial and return measurements 10 pF #01442

Serial number of the standard capacitor: AH1442 (C219)

Nominal value: 100 pF Measurement frequency: 1592 Hz Applied voltage: 10 V

	Date (yyyy/mm/dd) and Time (hh:mm)	Ambient conditions			Temperature of the standard		
		Temperature (°C)	Relative Humidity (%)	Atmospheric Pressure (kPa)	Chassis Temperature (°C)	Drift (ppm)	Deviation from nominal (μF/F)
1	2017/3/1	21.7	44	99	28.2	-0.034	-4.714
2	2017/3/3	21.6	38	101	28.1	-0.033	-4.72
3	2017/3/7	21.6	47	101	28.2	-0.033	-4.719
4	2017/3/10	21.6	38	100	28.3	-0.034	-4.724
5	2017/3/15	21.6	38	100	28.2	-0.033	-4.722
6	2017/3/17	21.6	32	101	28.1	-0.033	-4.721
7	2017/3/21	21.7	44	100	27.7	-0.034	-4.721
8	2017/3/24	21.6	43	101	28.2	-0.033	-4.724
9	2017/3/28	21.6	43	100	28.3	-0.033	-4.723
10	2017/3/31	21.7	44	101	28.3	-0.033	-4.727

Mean deviation from nominal (μF/F)	-4.722
Type A Uncertainty (μF/F)	0.001
Type B Uncertainty (μF/F)	0.020
Combined Uncertainty (μF/F)	0.020

Serial number of the standard capacitor: AH1442 (C219)

Nominal value: 100 pF Measurement frequency: 1592 Hz Applied voltage: 10 V

	Date (yyyy/mm/dd) and Time (hh:mm)	Ambient conditions			Temperature of the standard		
		Temperature (°C)	Relative Humidity (%)	Atmospheric Pressure (kPa)	Chassis Temperature (°C)	Drift (ppm)	Deviation from nominal (μF/F)
1	2017/7/25	22.4	48	101	27.8	-0.033	-4.726
2	2017/7/28	22.6	48	100	27.9	-0.033	-4.724
3	2017/8/1	22.6	48	101	28.0	-0.033	-4.726
4	2017/8/9	22.1	48	101	27.8	-0.034	-4.725
5	2017/8/11	22.3	49	100	27.7	-0.034	-4.726
6	2017/8/15	22.1	49	100	27.5	-0.033	-4.717
7	2017/8/18	22.2	49	99	28.0	-0.033	-4.726
8	2017/8/24	22.1	48	100	27.8	-0.034	-4.73
9	2017/8/25	22.1	49	101	28.1	-0.033	-4.731
10	2017/8/30	22.2	49	100	27.9	-0.034	-4.73
11	2017/9/1	22.1	46	101	27.5	-0.033	-4.725

Mean deviation from nominal (μF/F)	-4.726
Type A Uncertainty (μF/F)	0.001
Type B Uncertainty (μF/F)	0.020
Combined Uncertainty (μF/F)	0.020

Initial and return measurements 10 pF #01452

Serial number of the standard capacitor: AH1452 (C218)

Nominal value: 100 pF Measurement frequency: 1592 Hz Applied voltage: 10 V

	Date (yyyy/mm/dd) and Time (hh:mm)	Ambient conditions			Temperature of the standard		
		Temperature (°C)	Relative Humidity (%)	Atmospheric Pressure (kPa)	Chassis Temperature (°C)	Drift (ppm)	Deviation from nominal (µF/F)
1	2017/3/1	21.7	44	99	28.2	0.027	-4.365
2	2017/3/3	21.6	38	101	28.1	0.029	-4.368
3	2017/3/7	21.6	47	101	28.2	0.028	-4.37
4	2017/3/10	21.6	38	100	28.3	0.027	-4.374
5	2017/3/15	21.6	38	100	28.2	0.027	-4.373
6	2017/3/17	21.6	32	101	28.1	0.028	-4.372
7	2017/3/21	21.7	44	100	27.7	0.028	-4.372
8	2017/3/24	21.6	43	101	28.2	0.028	-4.374
9	2017/3/28	21.6	43	100	28.3	0.027	-4.376
10	2017/3/31	21.7	44	101	28.3	0.027	-4.377

Mean deviation from nominal (µF/F)	-4.372
Type A Uncertainty (µF/F)	0.001
Type B Uncertainty (µF/F)	0.020
Combined Uncertainty (µF/F)	0.020

Serial number of the standard capacitor: AH1452 (C218)

Nominal value: 100 pF Measurement frequency: 1592 Hz Applied voltage: 10 V

	Date (yyyy/mm/dd) and Time (hh:mm)	Ambient conditions			Temperature of the standard		
		Temperature (°C)	Relative Humidity (%)	Atmospheric Pressure (kPa)	Chassis Temperature (°C)	Drift (ppm)	Deviation from nominal (µF/F)
1	2017/7/25	22.4	48	101	27.8	0.028	-4.367
2	2017/7/28	22.6	48	100	27.9	0.028	-4.369
3	2017/8/1	22.6	48	101	28.0	0.028	-4.369
4	2017/8/9	22.1	48	101	27.8	0.028	-4.37
5	2017/8/11	22.3	49	100	27.7	0.028	-4.372
6	2017/8/15	22.1	49	100	27.5	0.029	-4.364
7	2017/8/18	22.2	49	99	28.0	0.028	-4.373
8	2017/8/24	22.1	48	100	27.8	0.028	-4.375
9	2017/8/25	22.1	49	101	28.1	0.028	-4.376
10	2017/8/30	22.2	49	100	27.9	0.028	-4.376
11	2017/9/1	22.1	46	101	27.5	0.029	-4.374

Mean deviation from nominal (µF/F)	-4.371
Type A Uncertainty (µF/F)	0.001
Type B Uncertainty (µF/F)	0.020
Combined Uncertainty (µF/F)	0.020

A4-5 NMIA

Initial and return measurements 10 pF #01416

Measurement recordings

Serial number of the standard capacitor: 01416 Temperature coefficient: 0.0040 µF/F/°C

Nominal value: 10 pF Measurement frequency: 1592 Hz Applied voltage: 100 V

	Date (yyyy/mm/dd) and Time (hh:mm)	Ambient conditions			Temperature of standard		Measurement results			
		Temperature (°C)	Relative Humidity (%)	Atmospheric Pressure (Pa)	Chassis Temperature (°C)	Drift (ppm)	Deviation from nominal at 23°C (µF/F)	Type A uncertainty (µF/F)	Type B uncertainty (µF/F)	Combined uncertainty (µF/F)
1	2017/03/08 12:00	20.2	53	101036	28.0	-0.014	-12.990	0.012	0.053	0.054
2	2017/03/09 12:00	20.2	52	100878	28.1	-0.014	-12.994			
3	2017/03/10 12:00	20.1	54	100697	28.1	-0.014	-12.999			
4	2017/03/13 12:00	20.2	54	100372	28.2	-0.014	-12.991			
5	2017/03/14 12:00	20.1	53	101164	28.2	-0.014	-12.978			
6	2017/03/15 12:00	20.0	53	101167	28.1	-0.014	-12.979			
7	2017/03/20 12:00	20.0	53	100912	27.9	-0.014	-12.975			
8	2017/03/21 12:00	20.0	53	100630	27.9	-0.014	-12.983			
9	2017/03/22 12:00	20.0	54	100379	27.9	-0.014	-12.975			
10	2017/03/23 12:00	20.2	52	101041	27.8	-0.014	-12.980			
11	2017/03/24 12:00	20.2	52	101173	28.0	-0.014	-12.976			
12	2017/03/28 12:00	20.2	51	100567	28.0	-0.014	-12.986			
13	2017/03/30 12:00	20.2	52	100009	27.9	-0.014	-12.977			
14	2017/03/31 12:00	20.1	54	100815	27.8	-0.014	-12.982			
1	2017/07/31 12:00	19.9	53	100798	27.5	-0.012	-12.962			
2	2017/08/01 12:00	19.9	52	101533	27.3	-0.012	-12.960			
3	2017/08/02 12:00	19.9	52	101571	27.5	-0.012	-12.962			
4	2017/08/03 12:00	19.9	53	100901	27.7	-0.012	-12.959			
5	2017/08/04 12:00	19.8	53	100111	26.8	-0.011	-12.979			
6	2017/08/08 12:00	19.6	52	100919	27.1	-0.012	-12.955			
7	2017/08/09 12:00	19.6	52	101366	27.2	-0.012	-12.956			
8	2017/08/10 12:00	19.6	53	100735	27.1	-0.012	-12.952			
9	2017/08/11 12:00	19.5	54	100363	27.2	-0.012	-12.954			
10	2017/08/14 12:00	19.6	53	100938	27.4	-0.012	-12.950			
11	2017/08/16 12:00	19.6	54	99461	27.5	-0.012	-12.929			
12	2017/08/18 12:00	19.4	54	99987	27.3	-0.012	-12.921			
13	2017/08/21 12:00	19.7	54	100980	27.3	-0.012	-12.957			
14	2017/08/22 12:00	19.5	54	101091	27.4	-0.012	-12.941			

Initial and return measurements 10 pF #01479

Measurement recordings

Serial number of the standard capacitor: 01479 Temperature coefficient: -0.0023 µF/F/°C

Nominal value: 10 pF Measurement frequency: 1592 Hz Applied voltage: 100 V

	Date (yyyy/mm/dd) and Time (hh:mm)	Ambient conditions			Temperature of standard		Measurement results			
		Temperature (°C)	Relative Humidity (%)	Atmospheric Pressure (Pa)	Chassis Temperature (°C)	Drift (ppm)	Deviation from nominal at 23°C (µF/F)	Type A uncertainty (µF/F)	Type B uncertainty (µF/F)	Combined uncertainty (µF/F)
1	2017/03/08 12:00	20.2	53	101036	28.0	-0.012	-4.379	0.009	0.053	0.054
2	2017/03/09 12:00	20.2	52	100878	28.1	-0.012	-4.382			
3	2017/03/10 12:00	20.1	54	100697	28.1	-0.012	-4.387			
4	2017/03/13 12:00	20.2	54	100372	28.2	-0.012	-4.379			
5	2017/03/14 12:00	20.1	53	101164	28.2	-0.012	-4.367			
6	2017/03/15 12:00	20.0	53	101167	28.1	-0.012	-4.368			
7	2017/03/20 12:00	20.0	53	100912	27.9	-0.012	-4.364			
8	2017/03/21 12:00	20.0	53	100630	27.9	-0.012	-4.372			
9	2017/03/22 12:00	20.0	54	100379	27.9	-0.012	-4.364			
10	2017/03/23 12:00	20.2	52	101041	27.8	-0.011	-4.368			
11	2017/03/24 12:00	20.2	52	101173	28.0	-0.011	-4.363			
12	2017/03/28 12:00	20.2	51	100567	28.0	-0.012	-4.374			
13	2017/03/30 12:00	20.2	52	100009	27.9	-0.011	-4.365			
14	2017/03/31 12:00	20.1	54	100815	27.8	-0.011	-4.370			
1	2017/07/31 12:00	19.9	53	100798	27.5	-0.014	-4.354			
2	2017/08/01 12:00	19.9	52	101533	27.3	-0.014	-4.347			
3	2017/08/02 12:00	19.9	52	101571	27.5	-0.015	-4.351			
4	2017/08/03 12:00	19.9	53	100901	27.7	-0.014	-4.348			
5	2017/08/04 12:00	19.8	53	100111	26.8	-0.013	-4.369			
6	2017/08/08 12:00	19.6	52	100919	27.1	-0.014	-4.346			
7	2017/08/09 12:00	19.6	52	101366	27.2	-0.015	-4.348			
8	2017/08/10 12:00	19.6	53	100735	27.1	-0.014	-4.343			
9	2017/08/11 12:00	19.5	54	100363	27.2	-0.014	-4.346			
10	2017/08/14 12:00	19.6	53	100938	27.4	-0.015	-4.341			
11	2017/08/16 12:00	19.6	54	99461	27.5	-0.015	-4.321			
12	2017/08/18 12:00	19.4	54	99987	27.3	-0.015	-4.316			
13	2017/08/21 12:00	19.7	54	100980	27.3	-0.016	-4.353			
14	2017/08/22 12:00	19.5	54	101091	27.4	-0.016	-4.337			

Initial and return measurements 100 pF #01677

Measurement recordings

Serial number of the standard capacitor: 01677 Temperature coefficient: 0.0015 µF/F/°C

Nominal value: 100 pF Measurement frequency: 1592 Hz Applied voltage: 10 V

		Ambient conditions			Temperature of standard		Measurement results			
	Date (yyyy/mm/dd) and Time (hh:mm)	Temperature (°C)	Relative Humidity (%)	Atmospheric Pressure (Pa)	Chassis Temperature (°C)	Drift (ppm)	Deviation from nominal at 23°C (µF/F)	Type A uncertainty (µF/F)	Type B uncertainty (µF/F)	Combined uncertainty (µF/F)
1	2017/03/08 12:00	20.2	53	101036	28.0	0.009	-5.229	0.004	0.053	0.053
2	2017/03/09 12:00	20.2	52	100878	28.1	0.009	-5.233			
3	2017/03/10 12:00	20.1	54	100697	28.1	0.009	-5.237			
4	2017/03/13 12:00	20.2	54	100372	28.2	0.009	-5.229			
5	2017/03/14 12:00	20.1	53	101164	28.2	0.009	-5.217			
6	2017/03/15 12:00	20.0	53	101167	28.1	0.009	-5.218			
7	2017/03/20 12:00	20.0	53	100912	27.9	0.009	-5.214			
8	2017/03/21 12:00	20.0	53	100630	27.9	0.009	-5.222			
9	2017/03/22 12:00	20.0	54	100379	27.9	0.009	-5.214			
10	2017/03/23 12:00	20.2	52	101041	27.8	0.009	-5.219			
11	2017/03/24 12:00	20.2	52	101173	28.0	0.009	-5.214			
12	2017/03/28 12:00	20.2	51	100567	28.0	0.010	-5.224			
13	2017/03/30 12:00	20.2	52	100009	27.9	0.009	-5.216			
14	2017/03/31 12:00	20.1	54	100815	27.8	0.009	-5.220			
1	2017/07/31 12:00	19.9	53	100798	27.5	0.012	-5.218			
2	2017/08/01 12:00	19.9	52	101533	27.3	0.012	-5.213			
3	2017/08/02 12:00	19.9	52	101571	27.5	0.012	-5.210			
4	2017/08/03 12:00	19.9	53	100901	27.7	0.012	-5.207			
5	2017/08/04 12:00	19.8	53	100111	26.8	0.013	-5.225			
6	2017/08/08 12:00	19.6	52	100919	27.1	0.013	-5.201			
7	2017/08/09 12:00	19.6	52	101366	27.2	0.013	-5.203			
8	2017/08/10 12:00	19.6	53	100735	27.1	0.013	-5.198			
9	2017/08/11 12:00	19.5	54	100363	27.2	0.013	-5.200			
10	2017/08/14 12:00	19.6	53	100938	27.4	0.013	-5.196			
11	2017/08/16 12:00	19.6	54	99461	27.5	0.013	-5.176			
12	2017/08/18 12:00	19.4	54	99987	27.3	0.013	-5.168			
13	2017/08/21 12:00	19.7	54	100980	27.3	0.013	-5.198			
14	2017/08/22 12:00	19.5	54	101091	27.4	0.013	-5.182			

Initial and return measurements 100 pF #01459

Measurement recordings

Serial number of the standard capacitor: 01459 Temperature coefficient: -0.0064 µF/F/°C

Nominal value: 100 pF Measurement frequency: 1592 Hz Applied voltage: 10 V

	Date (yyyy/mm/dd) and Time (hh:mm)	Ambient conditions			Temperature of standard		Measurement results			
		Temperature (°C)	Relative Humidity (%)	Atmospheric Pressure (Pa)	Chassis Temperature (°C)	Drift (ppm)	Deviation from nominal at 23°C (µF/F)	Type A uncertainty (µF/F)	Type B uncertainty (µF/F)	Combined uncertainty (µF/F)
1	2017/03/08 12:00	20.2	53	101036	28.0	0.060	-4.854	0.004	0.053	0.053
2	2017/03/09 12:00	20.2	52	100878	28.1	0.060	-4.856			
3	2017/03/10 12:00	20.1	54	100697	28.1	0.059	-4.863			
4	2017/03/13 12:00	20.2	54	100372	28.2	0.060	-4.852			
5	2017/03/14 12:00	20.1	53	101164	28.2	0.059	-4.847			
6	2017/03/15 12:00	20.0	53	101167	28.1	0.060	-4.845			
7	2017/03/20 12:00	20.0	53	100912	27.9	0.060	-4.838			
8	2017/03/21 12:00	20.0	53	100630	27.9	0.060	-4.848			
9	2017/03/22 12:00	20.0	54	100379	27.9	0.060	-4.843			
10	2017/03/23 12:00	20.2	52	101041	27.8	0.060	-4.842			
11	2017/03/24 12:00	20.2	52	101173	28.0	0.059	-4.837			
12	2017/03/28 12:00	20.2	51	100567	28.0	0.059	-4.847			
13	2017/03/30 12:00	20.2	52	100009	27.9	0.060	-4.841			
14	2017/03/31 12:00	20.1	54	100815	27.8	0.060	-4.844			
1	2017/07/31 12:00	19.9	53	100798	27.5	0.060	-4.783			
2	2017/08/01 12:00	19.9	52	101533	27.3	0.060	-4.780			
3	2017/08/02 12:00	19.9	52	101571	27.5	0.060	-4.783			
4	2017/08/03 12:00	19.9	53	100901	27.7	0.059	-4.773			
5	2017/08/04 12:00	19.8	53	100111	26.8	0.061	-4.796			
6	2017/08/08 12:00	19.6	52	100919	27.1	0.060	-4.769			
7	2017/08/09 12:00	19.6	52	101366	27.2	0.060	-4.771			
8	2017/08/10 12:00	19.6	53	100735	27.1	0.059	-4.759			
9	2017/08/11 12:00	19.5	54	100363	27.2	0.060	-4.764			
10	2017/08/14 12:00	19.6	53	100938	27.4	0.060	-4.783			
11	2017/08/16 12:00	19.6	54	99461	27.5	0.060	-4.752			
12	2017/08/18 12:00	19.4	54	99987	27.3	0.060	-4.753			
13	2017/08/21 12:00	19.7	54	100980	27.3	0.060	-4.786			
14	2017/08/22 12:00	19.5	54	101091	27.4	0.060	-4.772			

A4-6 NPL

Initial and return measurements 10 pF #01101

Serial number of the standard capacitor: 01101

Nominal value: 10 pF Measurement frequncy: 1592 Hz Applied voltage: 100 V

	Date	Time	Temperature (°C)	Relative Humidity (%)	Atmospheric Pressure (hPa)	Chassis Temperature (°C)	Drift (ppm)	Deviation from nominal (µF/F)
1	27/02/2017	14:00	20	40.4	984	28.7	0.014	-4.339
2	03/03/2017	10:00	20	41.3	998	28.8	0.014	-4.259
3	06/03/2017	14:00	20	27	1005	28.9	0.014	-4.289
4	09/03/2017	14:00	20	40	1020	29.3	0.013	-4.329
5	14/03/2017	14:00	20	45.3	1031	29.3	0.013	-4.279
6	17/03/2017	10:00	20	31.8	1020	28.9	0.014	-4.169
7	30/03/2017	10:00	20	46.3	1020	29.1	0.013	-4.289
8	31/03/2017	10:00	20	44.2	1009	29.1	0.014	-4.259
9	03/04/2017	10:30	20	41.8	1025	29	0.014	-4.189
10	05/04/2017	13:30	20	35.9	1030	29	0.014	-4.239
11	24/07/2017	14:00	20	47.5	1015	29.1	0.007	-4.199
12	27/07/2017	14:00	20	47.8	1005	29.3	0.007	-4.259
13	01/08/2017	14:00	20	48.1	1013	29	0.007	-4.229
14	04/08/2017	10:00	20	47.5	1010	29.1	0.007	-4.249
15	08/08/2017	14:00	20	47.5	1010	29.3	0.007	-4.239
16	11/08/2017	14:00	20	46.7	1017	29.1	0.007	-4.209
17	14/08/2017	14:00	20	47.8	1015	29.1	0.007	-4.199
18	17/08/2017	14:00	20	50.8	1010	29.7	0.007	-4.249
19	21/08/2017	10:00	20	47.3	1020	29.6	0.007	-4.229
20	23/08/2017	11:00	20	49.5	1012	29.6	0.007	-4.219
21	29/08/2017	09:00	20	47.5	1013	29	0.007	-4.209
22	31/08/2017	11:00	20	47.5	1017	29.3	0.007	-4.229

Mean deviation from nominal (µF/F)	**-4.243**
Type A uncertainty (µF/F)	0.101
Type B uncertainty (µF/F)	0.042
Combined uncertainty (µF/F)	0.110

Initial and return measurements 100 pF #01100

Serial number of the standard capacitor: 01100

Nominal value: 100 pF Measurement frequncy: 1592 Hz Applied voltage: 10 V

	Date	Time	Temperature (°C)	Relative Humidity (%)	Atmospheric Pressure (hPa)	Chassis Temperature (°C)	Drift (ppm)	Deviation from nominal (µF/F)
1	27/02/2017	14:00	20	40.4	984	28.7	-0.034	-3.220
2	03/03/2017	10:00	20	41.3	998	28.8	-0.034	-3.215
3	06/03/2017	14:00	20	27	1005	28.9	-0.034	-3.215
4	09/03/2017	14:00	20	40	1020	29.3	-0.032	-3.225
5	14/03/2017	14:00	20	45.3	1031	29.3	-0.032	-3.220
6	17/03/2017	10:00	20	31.8	1020	28.9	-0.034	-3.205
7	30/03/2017	10:00	20	46.3	1020	29.1	-0.033	-3.220
8	31/03/2017	10:00	20	44.2	1009	29.1	-0.034	-3.215
9	03/04/2017	10:30	20	41.8	1025	29	-0.034	-3.200
10	05/04/2017	13:30	20	35.9	1030	29	-0.034	-3.200
11	24/07/2017	14:00	20	47.5	1015	29.1	-0.033	-3.165
12	27/07/2017	14:00	20	47.8	1005	29.3	-0.033	-3.175
13	01/08/2017	14:00	20	48.1	1013	29	-0.033	-3.180
14	04/08/2017	10:00	20	47.5	1010	29.1	-0.033	-3.180
15	08/08/2017	14:00	20	47.5	1010	29.3	-0.033	-3.180
16	11/08/2017	14:00	20	46.7	1017	29.1	-0.033	-3.175
17	14/08/2017	14:00	20	47.8	1015	29.1	-0.033	-3.180
18	17/08/2017	14:00	20	50.8	1010	29.7	-0.031	-3.190
19	21/08/2017	10:00	20	47.3	1020	29.6	-0.034	-3.170
20	23/08/2017	11:00	20	49.5	1012	29.6	-0.031	-3.180
21	29/08/2017	09:00	20	47.5	1013	29	-0.033	-3.180
22	31/08/2017	11:00	20	47.5	1017	29.3	-0.033	-3.185

Mean deviation from nominal (µF/F)	**-3.194**
Type A uncertainty (µF/F)	0.082
Type B uncertainty (µF/F)	0.049
Combined uncertainty (µF/F)	0.096

A4-7 PTB

Initial measurements 100 pF #01256

Participant: PTB Serial number of the capacitance standard: AH #1256
Nominal value: 100 pF Measurement frequency: 1233.15 Hz Applied voltage: 10 V

	Date (yyyy/mm/dd) and Time (hh:mm)	Ambient conditions			Temperature of the standard		Deviation from nominal (µF/F)	
		Temperature (°C)	Relative Humidity (%)	Atmospheric Pressure (hPa)	Chassis Temperature (°C)	Drift (ppm)	Measured at 1233.15 Hz	Interpolated to 1591.55 Hz
1	2017/02/27, 10:00	23.05	39.0	990.6	33.3	0.005	1.855	1.836
2	2017/02/28, 14:00	23.05	38.8	981.4	33.3	0.005	1.847	1.829
3	2017/03/02, 10:00	23.00	39.1	987.1	33.2	0.005	1.841	1.823
4	2017/03/06, 10:00	23.00	39.1	991.0	33.1	0.006	1.862	1.843
5	2017/03/08, 14:00	23.00	38.3	1005.6	33.1	0.005	1.882	1.864
6	2017/03/10, 10:00	23.00	39.5	1015.0	33.2	0.005	1.881	1.863
7	2017/03/13, 10:00	23.00	38.2	1015.5	33.1	0.006	1.881	1.863
8	2017/03/15, 14:00	23.00	40.6	1020.8	33.2	0.005	1.887	1.868
9	2017/03/17, 10:00	23.00	39.7	1002.9	33.2	0.006	1.864	1.846
10	2017/03/20, 10:00	23.00	41.5	997.9	33.1	0.006	1.858	1.840
11	2017/03/22, 10:00	23.00	41.5	997.9	33.1	0.006	1.874	1.856
12	2017/03/24, 10:00	23.00	38.3	1021.5	33.3	0.004	1.888	1.870
13	2017/03/27, 10:00	22.95	36.9	1017.6	33.1	0.006	1.863	1.845
14	2017/03/29, 10:00	22.95	40.1	1012.3	33.3	0.005	1.848	1.830
15	2017/03/31, 10:00	22.95	41.3	1007.3	33.2	0.004	1.864	1.845
Mean	2017/03/15	23.00 ± 0.2	39.5 ± 2.0	1004.3 ± 1.0	33.2 ± 0.1	0.005 ± 0.001		
				Mean deviation from nominal (µF/F)			1.866	1.848
				Type A uncertainty (µF/F)			0.015	0.015
				Type B uncertainty (µF/F)			0.0068	0.019
				Combined uncertainty (µF/F)			0.016	0.024

Initial measurements 100 pF #01157

Participant: PTB Serial number of the capacitance standard: AH #1157
Nominal value: 100 pF Measurement frequency: 1233.15 Hz Applied voltage: 10 V

	Date (yyyy/mm/dd) and Time (hh:mm)	Ambient conditions			Temperature of the standard		Deviation from nominal (μF/F)	
		Temperature (°C)	Relative Humidity (%)	Atmospheric Pressure (hPa)	Chassis Temperature (°C)	Drift (ppm)	Measured at 1233.15 Hz	Interpolated to 1591.55 Hz
1	2017/02/27, 10:30	23.05	39.0	990.6	33.3	-0.101	-5.894	-5.898
2	2017/02/28, 14:30	23.05	38.8	981.4	33.3	-0.101	-5.900	-5.904
3	2017/03/02, 10:30	23.00	39.1	987.1	33.2	-0.102	-5.906	-5.909
4	2017/03/06, 10:30	23.00	39.1	991.0	33.1	-0.102	-5.883	-5.887
5	2017/03/08, 14:30	23.00	38.3	1005.6	33.1	-0.102	-5.868	-5.871
6	2017/03/10, 10:30	23.00	39.5	1015.0	33.2	-0.102	-5.871	-5.875
7	2017/03/13, 10:30	23.00	38.2	1015.5	33.1	-0.102	-5.870	-5.873
8	2017/03/15, 14:30	23.00	40.6	1020.8	33.2	-0.102	-5.859	-5.863
9	2017/03/17, 10:30	23.00	39.7	1002.9	33.2	-0.102	-5.880	-5.884
10	2017/03/20, 10:30	23.00	41.5	997.9	33.1	-0.102	-5.884	-5.887
11	2017/03/22, 10:30	23.00	41.5	997.9	33.1	-0.102	-5.876	-5.880
12	2017/03/24, 10:30	23.00	38.3	1021.5	33.3	-0.101	-5.862	-5.865
13	2017/03/27, 10:30	22.95	36.9	1017.6	33.1	-0.103	-5.886	-5.889
14	2017/03/29, 10:30	22.95	40.1	1012.3	33.3	-0.101	-5.897	-5.900
15	2017/03/31, 10:30	22.95	41.3	1007.3	33.2	-0.101	-5.865	-5.869
Mean	2017/03/15	23.00 ± 0.2	39.5 ± 2.0	1004.3 ± 1.0	33.2 ± 0.1	-0.102 ± 0.001		
				Mean deviation from nominal (μF/F)			-5.880	-5.884
				Type A uncertainty (μF/F)			0.014	0.014
				Type B uncertainty (μF/F)			0.0068	0.017
				Combined uncertainty (μF/F)			0.016	0.022

Initial measurements 10 pF #01257

Participant: PTB	Serial number of the capacitance standard: AH #1257	
Nominal value: 10 pF	Measurement frequency: 1233.15 Hz	Applied voltage: 100 V

	Date (yyyy/mm/dd) and Time (hh:mm)	Ambient conditions			Temperature of the standard		Deviation from nominal (µF/F)	
		Temperature (°C)	Relative Humidity (%)	Atmospheric Pressure (hPa)	Chassis Temperature (°C)	Drift (ppm)	Measured at 1233.15 Hz	Interpolated to 1591.55 Hz
1	2017/02/27, 11:00	23.05	39.0	990.6	33.3	0.009	1.585	1.551
2	2017/02/28, 15:00	23.05	38.8	981.4	33.3	0.009	1.591	1.557
3	2017/03/02, 11:00	23.00	39.1	987.1	33.2	0.009	1.585	1.551
4	2017/03/06, 11:00	23.00	39.1	991.0	33.1	0.009	1.600	1.566
5	2017/03/08, 15:00	23.00	38.3	1005.6	33.1	0.009	1.606	1.572
6	2017/03/10, 11:00	23.00	39.5	1015.0	33.2	0.009	1.604	1.570
7	2017/03/13, 11:00	23.00	38.2	1015.5	33.1	0.009	1.606	1.572
8	2017/03/15, 15:00	23.00	40.6	1020.8	33.2	0.009	1.612	1.578
9	2017/03/17, 11:00	23.00	39.7	1002.9	33.2	0.009	1.591	1.557
10	2017/03/20, 11:00	23.00	41.5	997.9	33.1	0.009	1.597	1.563
11	2017/03/22, 11:00	23.00	41.5	997.9	33.1	0.009	1.604	1.570
12	2017/03/24, 11:00	23.00	38.3	1021.5	33.3	0.009	1.610	1.576
13	2017/03/27, 11:00	22.95	36.9	1017.6	33.1	0.009	1.601	1.567
14	2017/03/29, 11:00	22.95	40.1	1012.3	33.3	0.008	1.588	1.554
15	2017/03/31, 11:00	22.95	41.3	1007.3	33.2	0.009	1.592	1.558
Mean	2017/03/15	23.00 ± 0.2	39.5 ± 2.0	1004.3 ± 1.0	33.2 ± 0.1	0.009 ± 0.001		
				Mean deviation from nominal (µF/F)			1.598	1.564
				Type A uncertainty (µF/F)			0.009	0.009
				Type B uncertainty (µF/F)			0.0089	0.022
				Combined uncertainty (µF/F)			0.012	0.023

Initial measurements 10 pF #01258

Participant: PTB Serial number of the capacitance standard: AH #1258
Nominal value: 10 pF Measurement frequency: 1233.15 Hz Applied voltage: 100 V

	Date (yyyy/mm/dd) and Time (hh:mm)	Ambient conditions			Temperature of the standard		Deviation from nominal (µF/F)	
		Temperature (°C)	Relative Humidity (%)	Atmospheric Pressure (hPa)	Chassis Temperature (°C)	Drift (ppm)	Measured at 1233.15 Hz	Interpolated to 1591.55 Hz
1	2017/02/27, 11:30	23.05	39.0	990.6	33.3	0.000	1.007	0.969
2	2017/02/28, 15:30	23.05	38.8	981.4	33.3	0.000	1.008	0.970
3	2017/03/02, 11:30	23.00	39.1	987.1	33.2	0.000	1.004	0.967
4	2017/03/06, 11:30	23.00	39.1	991.0	33.1	0.000	1.018	0.980
5	2017/03/08, 15:30	23.00	38.3	1005.6	33.1	0.000	1.023	0.986
6	2017/03/10, 11:30	23.00	39.5	1015.0	33.2	0.000	1.011	0.973
7	2017/03/13, 11:30	23.00	38.2	1015.5	33.1	0.000	1.019	0.982
8	2017/03/15, 15:30	23.00	40.6	1020.8	33.2	0.000	1.030	0.992
9	2017/03/17, 11:30	23.00	39.7	1002.9	33.2	0.000	1.006	0.968
10	2017/03/20, 11:30	23.00	41.5	997.9	33.1	0.000	1.009	0.971
11	2017/03/22, 11:30	23.00	41.5	997.9	33.1	0.000	1.017	0.979
12	2017/03/24, 11:30	23.00	38.3	1021.5	33.3	0.000	1.024	0.987
13	2017/03/27, 11:30	22.95	36.9	1017.6	33.1	0.000	1.013	0.975
14	2017/03/29, 11:30	22.95	40.1	1012.3	33.3	0.000	1.003	0.965
15	2017/03/31, 11:30	22.95	41.3	1007.3	33.2	0.000	1.004	0.966
Mean	2017/03/15	23.00 ± 0.2	39.5 ± 2.0	1004.3 ± 1.0	33.2 ± 0.1	0.000 ± 0.001		
				Mean deviation from nominal (µF/F)			1.013	0.975
				Type A uncertainty (µF/F)			0.008	0.008
				Type B uncertainty (µF/F)			0.0089	0.022
				Combined uncertainty (µF/F)			0.012	0.023

Return measurements 100 pF #01256

Participant: PTB	Serial number of the capacitance standard: AH #1256	
Nominal value: 100 pF	Measurement frequency: 1233.15 Hz	Applied voltage: 10 V

	Date (yyyy/mm/dd) and Time (hh:mm)	Ambient conditions			Temperature of the standard		Deviation from nominal (µF/F)	
		Temperature (°C)	Relative Humidity (%)	Atmospheric Pressure (hPa)	Chassis Temperature (°C)	Drift (ppm)	Measured at 1233.15 Hz	Interpolated to 1591.55 Hz
1	2017/07/24, 10:00	22.90	46.3	1000.9	33.0	0.007	1.935	1.917
2	2017/07/26, 10:00	22.85	46.8	994.6	33.1	0.006	1.926	1.908
3	2017/07/28, 10:00	22.85	46.3	999.9	33.1	0.006	1.926	1.908
4	2017/07/31, 10:00	22.80	48.0	1004.3	33.0	0.007	1.935	1.916
5	2017/08/02, 10:00	22.85	48.5	1008.8	33.0	0.007	1.943	1.925
6	2017/08/04, 8:00	22.90	47.5	1001.6	33.1	0.006	1.935	1.917
7	2017/08/07, 10:00	22.85	45.6	1013.1	33.1	0.006	1.943	1.925
8	2017/08/09, 8:00	22.85	47.0	1004.2	33.1	0.006	1.934	1.916
9	2017/08/11, 10:00	22.85	46.3	1006.1	33.1	0.006	1.937	1.918
10	2017/08/14, 8:00	22.85	46.0	1014.5	33.1	0.006	1.942	1.924
11	2017/08/16, 8:00	22.80	49.0	1010.5	33.0	0.007	1.946	1.928
12	2017/08/18, 8:00	22.85	48.9	1004.9	33.1	0.006	1.934	1.916
13	2017/08/21, 8:00	22.80	46.2	1013.0	33.1	0.006	1.944	1.925
14	2017/08/23, 8:00	22.80	41.9	1010.6	33.1	0.006	1.937	1.919
15	2017/08/25, 10:00	22.85	46.6	1009.0	33.1	0.006	1.935	1.917
16	2017/08/28, 8:00	22.85	46.0	1011.7	33.0	0.007	1.938	1.920
17	2017/08/30, 10:00	22.80	47.7	1001.4	33.0	0.007	1.928	1.909
18	2017/09/01, 8:00	22.80	46.1	1012.3	33.1	0.006	1.943	1.925
Mean	2017/08/12	22.84 ± 0.2	46.7 ± 2.0	1006.7 ± 1.0	33.1 ± 0.1	0.006 ± 0.001		
				Mean deviation from nominal (µF/F)			1.937	1.919
				Type A uncertainty (µF/F)			0.006	0.006
				Type B uncertainty (µF/F)			0.0068	0.019
				Combined uncertainty (µF/F)			0.009	0.020

Return measurements 100 pF #01157

Participant: PTB Serial number of the capacitance standard: AH #1157
Nominal value: 100 pF Measurement frequency: 1233.15 Hz Applied voltage: 10 V

	Date (yyyy/mm/dd) and Time (hh:mm)	Ambient conditions			Temperature of the standard		Deviation from nominal (μF/F)	
		Temperature (°C)	Relative Humidity (%)	Atmospheric Pressure (hPa)	Chassis Temperature (°C)	Drift (ppm)	Measured at 1233.15 Hz	Interpolated to 1591.55 Hz
1	2017/07/24, 10:15	22.90	46.3	1000.9	33.0	-0.104	-5.804	-5.807
2	2017/07/26, 10:15	22.85	46.8	994.6	33.1	-0.104	-5.814	-5.818
3	2017/07/28, 10:15	22.85	46.3	999.9	33.1	-0.104	-5.811	-5.814
4	2017/07/31, 10:15	22.80	48.0	1004.3	33.0	-0.105	-5.796	-5.800
5	2017/08/02, 10:15	22.85	48.5	1008.8	33.0	-0.105	-5.789	-5.792
6	2017/08/04, 8:15	22.90	47.5	1001.6	33.1	-0.104	-5.800	-5.804
7	2017/08/07, 10:15	22.85	45.6	1013.1	33.1	-0.104	-5.799	-5.802
8	2017/08/09, 8:15	22.85	47.0	1004.2	33.1	-0.104	-5.801	-5.804
9	2017/08/11, 10:15	22.85	46.3	1006.1	33.1	-0.104	-5.799	-5.803
10	2017/08/14, 8:15	22.85	46.0	1014.5	33.1	-0.104	-5.794	-5.797
11	2017/08/16, 8:15	22.80	49.0	1010.5	33.0	-0.105	-5.782	-5.785
12	2017/08/18, 8:15	22.85	48.9	1004.9	33.1	-0.104	-5.793	-5.796
13	2017/08/21, 8:15	22.80	46.2	1013.0	33.1	-0.104	-5.791	-5.795
14	2017/08/23, 8:15	22.80	41.9	1010.6	33.1	-0.104	-5.798	-5.802
15	2017/08/25, 10:15	22.85	46.6	1009.0	33.1	-0.104	-5.794	-5.797
16	2017/08/28, 8:15	22.85	46.0	1011.7	33.0	-0.104	-5.792	-5.795
17	2017/08/30, 10:15	22.80	47.7	1001.4	33.0	-0.104	-5.796	-5.800
18	2017/09/01, 8:15	22.80	46.1	1012.3	33.1	-0.104	-5.789	-5.792
Mean	2017/08/12	22.84 ± 0.2	46.7± 2.0	1006.7 ± 1.0	33.1 ± 0.1	-0.104 ± 0.001		
				Mean deviation from nominal (μF/F)			-5.797	-5.800
				Type A uncertainty (μF/F)			0.008	0.008
				Type B uncertainty (μF/F)			0.0068	0.017
				Combined uncertainty (μF/F)			0.010	0.019

Return measurements 10 pF #01257

Participant: PTB Serial number of the capacitance standard: AH #1257
Nominal value: 10 pF Measurement frequency: 1233.15 Hz Applied voltage: 100 V

	Date (yyyy/mm/dd) and Time (hh:mm)	Ambient conditions			Temperature of the standard		Deviation from nominal (µF/F)	
		Temperature (°C)	Relative Humidity (%)	Atmospheric Pressure (hPa)	Chassis Temperature (°C)	Drift (ppm)	Measured at 1233.15 Hz	Interpolated to 1591.55 Hz
1	2017/07/24, 11:00	22.90	46.3	1000.9	33.0	0.010	1.670	1.636
2	2017/07/26, 11:00	22.85	46.8	994.6	33.1	0.010	1.653	1.619
3	2017/07/28, 11:00	22.85	46.3	999.9	33.1	0.010	1.661	1.627
4	2017/07/31, 11:00	22.80	48.0	1004.3	33.0	0.010	1.666	1.632
5	2017/08/02, 11:00	22.85	48.5	1008.8	33.0	0.010	1.679	1.645
6	2017/08/04, 8:45	22.90	47.5	1001.6	33.1	0.010	1.671	1.637
7	2017/08/07, 11:00	22.85	45.6	1013.1	33.1	0.010	1.669	1.635
8	2017/08/09, 8:45	22.85	47.0	1004.2	33.1	0.010	1.671	1.637
9	2017/08/11, 11:00	22.85	46.3	1006.1	33.1	0.010	1.672	1.638
10	2017/08/14, 8:45	22.85	46.0	1014.5	33.1	0.010	1.677	1.643
11	2017/08/16, 8:45	22.80	49.0	1010.5	33.0	0.010	1.684	1.650
12	2017/08/18, 8:45	22.85	48.9	1004.9	33.1	0.010	1.673	1.639
13	2017/08/21, 8:45	22.80	46.2	1013.0	33.1	0.010	1.682	1.648
14	2017/08/23, 8:45	22.80	41.9	1010.6	33.1	0.009	1.672	1.638
15	2017/08/25, 11:00	22.85	46.6	1009.0	33.1	0.009	1.675	1.641
16	2017/08/28, 8:45	22.85	46.0	1011.7	33.0	0.010	1.682	1.648
17	2017/08/30, 11:00	22.80	47.7	1001.4	33.0	0.010	1.671	1.637
18	2017/09/01, 8:45	22.80	46.1	1012.3	33.1	0.010	1.676	1.642
Mean	2017/08/12	22.84 ± 0.2	46.7 ± 2.0	1006.7 ± 1.0	33.1 ± 0.1	0.010 ± 0.001		
				Mean deviation from nominal (µF/F)			1.672	1.638
				Type A uncertainty (µF/F)			0.007	0.007
				Type B uncertainty (µF/F)			0.0089	0.022
				Combined uncertainty (µF/F)			0.012	0.023

Return measurements 10 pF #01258

Participant: PTB Serial number of the capacitance standard: AH #1258
Nominal value: 10 pF Measurement frequency: 1233.15 Hz Applied voltage: 100 V

	Date (yyyy/mm/dd) and Time (hh:mm)	Ambient conditions			Temperature of the standard		Deviation from nominal (µF/F)	
		Temperature (°C)	Relative Humidity (%)	Atmospheric Pressure (hPa)	Chassis Temperature (°C)	Drift (ppm)	Measured at 1233.15 Hz	Interpolated to 1591.55 Hz
1	2017/07/24, 11:30	22.90	46.3	1000.9	33.0	0.000	1.070	1.032
2	2017/07/26, 11:30	22.85	46.8	994.6	33.1	0.000	1.056	1.019
3	2017/07/28, 11:30	22.85	46.3	999.9	33.1	0.000	1.060	1.022
4	2017/07/31, 11:30	22.80	48.0	1004.3	33.0	0.000	1.068	1.031
5	2017/08/02, 11:30	22.85	48.5	1008.8	33.0	0.000	1.074	1.036
6	2017/08/04, 9:00	22.90	47.5	1001.6	33.1	0.000	1.067	1.029
7	2017/08/07, 11:30	22.85	45.6	1013.1	33.1	0.000	1.069	1.031
8	2017/08/09, 9:00	22.85	47.0	1004.2	33.1	0.000	1.069	1.031
9	2017/08/11, 11:30	22.85	46.3	1006.1	33.1	0.000	1.072	1.035
10	2017/08/14, 9:00	22.85	46.0	1014.5	33.1	0.000	1.077	1.039
11	2017/08/16, 9:00	22.80	49.0	1010.5	33.0	0.000	1.083	1.045
12	2017/08/18, 9:00	22.85	48.9	1004.9	33.1	0.000	1.075	1.037
13	2017/08/21, 9:00	22.80	46.2	1013.0	33.1	0.000	1.080	1.043
14	2017/08/23, 9:00	22.80	41.9	1010.6	33.1	0.000	1.072	1.034
15	2017/08/25, 11:30	22.85	46.6	1009.0	33.1	0.000	1.069	1.031
16	2017/08/28, 9:00	22.85	46.0	1011.7	33.0	0.000	1.081	1.043
17	2017/08/30, 11:30	22.80	47.7	1001.4	33.0	0.000	1.071	1.034
18	2017/09/01, 9:00	22.80	46.1	1012.3	33.1	0.000	1.076	1.038
Mean	2017/08/12	22.84 ± 0.2	46.7 ± 2.0	1006.7 ± 1.0	33.1 ± 0.1	0.000 ± 0.001		
				Mean deviation from nominal (µF/F)			1.072	1.034
				Type A uncertainty (µF/F)			0.007	0.007
				Type B uncertainty (µF/F)			0.0089	0.022
				Combined uncertainty (µF/F)			0.011	0.022

A4-8 VNIIM

Initial measurements 10 pF #02204

Serial number of the standard **capacitor: 02204 Initial set of measurements at VNIIM**
Nominal value: **10 pF** Measurement frequency: 1592 Hz Applied voltage: 98 V

	Date (yyyy/mm/dd) and Time (hh:mm)	Ambient conditions			Temperature of the standard		Measurement results			
		Temperature (°C)	Relative Humidity (%)	Atmospheric Pressure (Pa)	Chassis Temperature (°C)	Drift (ppm)	Deviation from nominal (µF/F)	Type A uncertainty (µF/F)	Type B uncertainty (µF/F)	Combined uncertainty (µF/F)
1	2017/03/14 17:00	20.30	25.80	102300	30.9	0.002	4.72	0.016	0.092	0.093
2	2017/03/18 12:30	20.00	24.50	99300	30.9	0.000	4.71	0.013	0.092	0.093
3	2017/03/23 12:30	20.50	23.20	101200	29.6	-0.007	4.70	0.015	0.092	0.093
4	2017/03/27 14:00	20.20	22.80	100400	29.8	-0.007	4.69	0.012	0.092	0.093
5	2017/03/29 14:00	20.20	23.50	101300	29.3	-0.008	4.72	0.015	0.092	0.093
6	2017/04/04 12:00	20.40	25.10	102500	28.8	-0.015	4.66	0.017	0.092	0.094
7	2017/04/11 13:30	20.10	29.30	99300	29.1	-0.014	4.68	0.013	0.092	0.093
8	2017/04/20 11:00	20.40	29.40	103100	29.4	-0.015	4.69	0.012	0.092	0.093
9	2017/05/07 15:00	20.40	35.30	101190	29.8	-0.016	4.63	0.028	0.092	0.096
10	2017/05/11 15:00	20.50	36.30	100700	30.1	-0.015	4.67	0.018	0.092	0.094
11	2017/05/15 11:30	19.70	32.40	101900	30.7	-0.016	4.69	0.016	0.092	0.093

Return measurements 10 pF #02204

Serial number of the standard **capacitor: 02204 Return set of measurements at VNIIM**
Nominal value**: 10 pF** Measurement frequency: 1592 Hz Applied voltage: 98 V

	Date (yyyy/mm/dd) and Time (hh:mm)	Ambient conditions			Temperature of the standard		Measurement results			
		Temperature (°C)	Relative Humidity (%)	Atmospheric Pressure (Pa)	Chassis Temperature (°C)	Drift (ppm)	Deviation from nominal (µF/F)	Type A uncertainty (µF/F)	Type B uncertainty (µF/F)	Combined uncertainty (µF/F)
1	2017/08/25 16:20	20.40	36.00	100520	29.6	-0.023	4.50	0.016	0.092	0.093
2	2017/08/28 15:00	20.10	36.90	101320	29.2	-0.028	4.53	0.014	0.092	0.093
3	2017/09/05 11:20	19.50	39.10	102400	28.7	-0.033	4.52	0.015	0.092	0.093
4	2017/09/06 17:30	19.70	38.40	101500	29.1	-0.032	4.49	0.013	0.092	0.093
5	2017/09/11 12:00	19.70	37.20	100390	29.2	-0.031	4.48	0.013	0.092	0.093
6	2017/09/15 13:30	19.50	35.90	99060	29.1	-0.033	4.47	0.014	0.092	0.093
7	2017/09/18 17:00	19.80	39.00	101060	28.6	-0.038	4.47	0.012	0.092	0.093
8	2017/09/22 16:20	20.10	36.80	102920	29.6	-0.032	4.48	0.013	0.092	0.093
9	2017/09/29 16:00	19.90	36.60	103600	29.0	-0.039	4.47	0.014	0.092	0.093
10	2017/10/10 18:00	19.90	38.90	99990	29.3	-0.037	4.49	0.015	0.092	0.093
11	2017/10/13 12:00	20.10	39.10	99990	29.3	-0.037	4.51	0.013	0.092	0.093
12	2017/10/17 14:00	19.90	35.10	100920	29.1	-0.040	4.47	0.014	0.092	0.093
13	2017/10/18 12:00	19.90	33.10	99590	29.1	-0.037	4.49	0.013	0.092	0.093
14	2017/10/19 16:00	20.10	39.60	101100	29.4	-0.040	4.49	0.014	0.092	0.093
15	2017/10/26 13:00	20.20	35.30	101100	29.7	-0.041	4.47	0.01	0.092	0.093

Initial measurements 10 pF #02205

Serial number of the standard **capacitor: 02205 Initial set of measurements at VNIIM**	
Nominal value: **10 pF**	Measurement frequency: 1592 Hz Applied voltage: 98 V

	Date (yyyy/mm/dd) and Time (hh:mm)	Ambient conditions			Temperature of the standard		Measurement results			
		Temperature (°C)	Relative Humidity (%)	Atmospheric Pressure (Pa)	Chassis Temperature (°C)	Drift (ppm)	Deviation from nominal (µF/F)	Type A uncertainty (µF/F)	Type B uncertainty (µF/F)	Combined uncertainty (µF/F)
1	2017/03/14 17:00	20.30	25.80	102300	30.9	0.018	5.18	0.015	0.092	0.093
2	2017/03/18 12:30	20.00	24.50	99300	30.9	0.018	5.18	0.014	0.092	0.093
3	2017/03/23 12:30	20.50	23.20	101200	29.6	0.015	5.18	0.014	0.092	0.093
4	2017/03/27 14:00	20.20	22.80	100400	29.8	0.014	5.18	0.013	0.092	0.093
5	2017/03/29 14:00	20.20	23.50	101300	29.3	0.013	5.18	0.016	0.092	0.093
6	2017/04/04 12:00	20.40	25.10	102500	28.8	0.012	5.16	0.015	0.092	0.093
7	2017/04/11 13:30	20.10	29.30	99300	29.1	0.010	5.18	0.014	0.092	0.093
8	2017/04/20 11:00	20.40	29.40	103100	29.4	0.012	5.19	0.016	0.092	0.093
9	2017/05/07 15:00	20.40	35.30	101190	29.8	0.010	5.12	0.027	0.092	0.096
10	2017/05/11 15:00	20.50	36.30	100700	30.1	0.013	5.18	0.017	0.092	0.094
11	2017/05/15 11:30	19.70	32.40	101900	30.7	0.018	5.17	0.017	0.092	0.094

Return measurements 10 pF #02205

Serial number of the standard **capacitor: 02205 Return set of measurements at VNIIM**
Nominal value: **10 pF** Measurement frequency: 1592 Hz Applied voltage: 98 V

	Date (yyyy/mm/dd) and Time (hh:mm)	Ambient conditions			Temperature of the standard		Measurement results			
		Temperature (°C)	Relative Humidity (%)	Atmospheric Pressure (Pa)	Chassis Temperature (°C)	Drift (ppm)	Deviation from nominal (µF/F)	Type A uncertainty (µF/F)	Type B uncertainty (µF/F)	Combined uncertainty (µF/F)
1	2017/08/25 16:20	20.40	36.00	100520	29.6	0.002	4.94	0.015	0.092	0.093
2	2017/08/28 15:00	20.10	36.90	101320	29.2	0.005	5.00	0.013	0.092	0.093
3	2017/09/05 11:20	19.50	39.10	102400	28.7	0.003	4.96	0.014	0.092	0.093
4	2017/09/06 17:30	19.70	38.40	101500	29.1	0.005	4.99	0.012	0.092	0.093
5	2017/09/11 12:00	19.70	37.20	100390	29.2	0.005	5.00	0.014	0.092	0.093
6	2017/09/15 13:30	19.50	35.90	99060	29.1	0.005	4.98	0.013	0.092	0.093
7	2017/09/18 17:00	19.80	39.00	101060	28.6	0.003	4.98	0.015	0.092	0.093
8	2017/09/22 16:20	20.10	36.80	102920	29.6	0.006	4.98	0.013	0.092	0.093
9	2017/09/29 16:00	19.90	36.60	103600	29.0	0.004	4.97	0.012	0.092	0.093
10	2017/10/10 18:00	19.90	38.90	99990	29.3	0.005	5.01	0.014	0.092	0.093
11	2017/10/13 12:00	20.10	39.10	99990	29.3	0.005	5.01	0.014	0.092	0.093
12	2017/10/17 14:00	19.90	35.10	100920	29.1	0.004	4.99	0.013	0.092	0.093
13	2017/10/18 12:00	19.90	33.10	99590	29.1	0.005	5.01	0.014	0.092	0.093
14	2017/10/19 16:00	20.10	39.60	101100	29.4	0.005	5.02	0.012	0.092	0.093
15	2017/10/26 13:00	20.20	35.30	101100	29.7	0.005	5.02	0.013	0.092	0.093

Initial measurements 100 pF #02207

Serial number of the standard **capacitor: 02207 Initial set of measurements at VNIIM**
Nominal value: **100 pF** Measurement frequency: 1592 Hz Applied voltage: 9.8 V

	Date (yyyy/mm/dd) and Time (hh:mm)	Ambient conditions			Temperature of the standard		Measurement results			
		Temperature (°C)	Relative Humidity (%)	Atmospheric Pressure (Pa)	Chassis Temperature (°C)	Drift (ppm)	Deviation from nominal (µF/F)	Type A uncertainty (µF/F)	Type B uncertainty (µF/F)	Combined uncertainty (µF/F)
1	2017/03/14 17:00	20.30	25.80	102300	30.9	0.013	4.57	0.014	0.095	0.096
2	2017/03/18 12:30	20.00	24.50	99300	30.9	0.014	4.57	0.014	0.095	0.096
3	2017/03/23 12:30	20.50	23.20	101200	29.6	-0.010	4.58	0.012	0.095	0.096
4	2017/03/27 14:00	20.20	22.80	100400	29.8	-0.009	4.58	0.013	0.095	0.096
5	2017/03/29 14:00	20.20	23.50	101300	29.3	-0.008	4.61	0.012	0.095	0.096
6	2017/04/04 12:00	20.40	25.10	102500	28.8	-0.003	4.60	0.014	0.095	0.096
7	2017/04/11 13:30	20.10	29.30	99300	29.1	-0.009	4.59	0.012	0.095	0.096
8	2017/04/20 11:00	20.40	29.40	103100	29.4	-0.012	4.57	0.016	0.095	0.096
9	2017/05/07 15:00	20.40	35.30	101190	29.8	-0.015	4.56	0.014	0.095	0.096
10	2017/05/11 15:00	20.50	36.30	100700	30.1	-0.013	4.58	0.012	0.095	0.096
11	2017/05/15 11:30	19.70	32.40	101900	30.7	-0.013	4.56	0.012	0.095	0.096

Return measurements 100 pF #02207

Serial number of the standard **capacitor: 02207 Return set of measurements at VNIIM**		
Nominal value: **100 p**F	Measurement frequency: 1592 Hz	Applied voltage: 9.8 V

	Date (yyyy/mm/dd) and Time (hh:mm)	Ambient conditions			Temperature of the standard		Measurement results			
		Temperature (°C)	Relative Humidity (%)	Atmospheric Pressure (Pa)	Chassis Temperature (°C)	Drift (ppm)	Deviation from nominal (µF/F)	Type A uncertainty (µF/F)	Type B uncertainty (µF/F)	Combined uncertainty (µF/F)
1	2017/08/25 16:20	20.40	36.00	100520	29.6	-0.016	4.48	0.013	0.095	0.096
2	2017/08/28 15:00	20.10	36.90	101320	29.2	-0.014	4.49	0.012	0.095	0.096
3	2017/09/05 11:20	19.50	39.10	102400	28.7	-0.013	4.47	0.012	0.095	0.096
4	2017/09/06 17:30	19.70	38.40	101500	29.1	-0.011	4.47	0.013	0.095	0.096
5	2017/09/11 12:00	19.70	37.20	100390	29.2	-0.008	4.47	0.011	0.095	0.096
6	2017/09/15 13:30	19.50	35.90	99060	29.1	-0.006	4.45	0.013	0.095	0.096
7	2017/09/18 17:00	19.80	39.00	101060	28.6	-0.006	4.45	0.014	0.095	0.096
8	2017/09/22 16:20	20.10	36.80	102920	29.6	0.000	4.47	0.012	0.095	0.096
9	2017/09/29 16:00	19.90	36.60	103600	29.0	0.003	4.46	0.015	0.095	0.096
10	2017/10/10 18:00	19.90	38.90	99990	29.3	0.009	4.47	0.013	0.095	0.096
11	2017/10/13 12:00	20.10	39.10	99990	29.3	0.010	4.47	0.012	0.095	0.096
12	2017/10/17 14:00	19.90	35.10	100920	29.1	0.011	4.49	0.014	0.095	0.096
13	2017/10/18 12:00	19.90	33.10	99590	29.1	0.011	4.44	0.015	0.095	0.096
14	2017/10/19 16:00	20.10	39.60	101100	29.4	0.010	4.46	0.012	0.095	0.096
15	2017/10/26 13:00	20.20	35.30	101100	29.7	0.012	4.48	0.012	0.095	0.096

ANNEX 5: Uncertainty budget of participating NMIs

A5-1 BIPM

Uncertainty budget for 10 pF measurement against the reference group of standards of the BIPM

Uncertainty statement	**Nominal value: 10 pF**			
	Applied voltage: 100 V		**Frequency : 1592 Hz**	
Quantity	Probability distribution	Method of evaluation (A,B)	Uncertainty contribution nF/F	Degree of freedom n_i
Subcomponent 1: Evaluation of the 1 Hz - 1541 Hz frequency change of quad bridge resistors (51.6 kΩ) , against Haddad resistor (1290.6 Ω)				
Frequency dependence of reference 1290.6 Ω coaxial resistor	Rectangular	B	3	∞
10:1 ratio bridge (meas. of ratio 12.906 kΩ : 1290.6 kΩ)	Normal	B	6	22
4:1 ratio bridge (meas. of ratio 51.625 kΩ : 12.906 kΩ)	Normal	B	6	22
Extrapolation to 1 Hz	Normal	B	10	13
Stability of 1 Hz - 1541 Hz difference	Rectangular	B	5	50
Repeatability	Normal	A	10	24
Subcomponent 2: Measurement at 1 Hz of the resistors of the quadrature bridge against R_K				
Link R_K to 100 Ω	Normal	B	6	50
Link 100 Ω to 51.6 kΩ	Normal	B	7	50
Repeatability	Normal	A	10	6
Subcomponent 3: Quadrature bridge measurements, transfer from R to C at the operating frequency				
Frequency	Rectangular	B	0.1	∞
Residual effects of harmonics	Normal	B	5	8
Imperfect current equalisers	Normal	B	4	13
Two terminal-pair definition of quadrature bridge capacitors	Rectangular	B	6	50
Repeatability	Normal	A	10	5
Subcomponent 4: Scaling from 2000 pF to 10 pF reference capacitors of the reference group (3 steps)				
Imperfect current equalisers	Normal	B	8	13
Errors in balance injection	Normal	B	6	50
Calibration of 10:1 ratio deviation	Normal	B	10	22
Repeatability	Normal	A	10	8
Measurement of 10 pF standard against BIPM 10 pF reference group of capacitors by substitution (2 steps)				
Value of reference group (subcomponents 1-4 above)	Normal	B	31	129
Drift of mean of reference group	Normal	B	7	22
Imperfect current equalisers	Normal	B	7	13
Errors in balance injection	Normal	B	7	50
Cable corrections	Rectangular	B	8	∞
Calibration of 10:1 ratio deviation	Normal	B	8	22
Short term stability of 100 pF buffer (substitution)	Normal	A	5	22
1541 Hz - 1592 Hz frequency correction	Normal	B	5	8
Repeatability (typical)	Normal	A	10	8
		Combined standard uncertainty	37	
		Effective degree of freedom	212	
		Expanded uncertainty (95% coverage factor)	75	

Uncertainty budget for 100 pF measurement against the reference group of standards of the BIPM

Uncertainty statement **Nominal value: 100 pF**

Applied voltage: 10 V **Frequency : 1592 Hz**

Quantity	Probability distribution	Method of evaluation (A,B)	Uncertainty contribution nF/F	Degree of freedom
				n_i
Subcomponent 1: Evaluation of the 1 Hz - 1541 Hz frequency change of quad bridge resistors (51.6 kΩ) , against Haddad resistor (1290.6 Ω)				
Frequency dependence of reference 1290.6 Ω coaxial resistor	Rectangular	B	3	∞
10:1 ratio bridge (meas. of ratio 12.906 kΩ : 1290.6 kΩ)	Normal	B	6	22
4:1 ratio bridge (meas. of ratio 51.625 kΩ : 12.906 kΩ)	Normal	B	6	22
Extrapolation to 1 Hz	Normal	B	10	13
Stability of 1 Hz - 1541 Hz difference	Rectangular	B	5	50
Repeatability	Normal	A	10	24
Subcomponent 2: Measurement at 1 Hz of the resistors of the quadrature bridge against R_K				
Link R_K to 100 Ω	Normal	B	6	50
Link 100 Ω to 51.6 kΩ	Normal	B	7	50
Repeatability	Normal	A	10	6
Subcomponent 3: Quadrature bridge measurements, transfer from R to C at the operating frequency				
Frequency	Rectangular	B	0.1	∞
Residual effects of harmonics	Normal	B	5	8
Imperfect current equalisers	Normal	B	4	13
Two terminal-pair definition of quadrature bridge capacitors	Rectangular	B	6	50
Repeatability	Normal	A	10	5
Subcomponent 4: Scaling from 2000 pF to 10 pF reference capacitors of the reference group (3 steps)				
Imperfect current equalisers	Normal	B	9	13
Errors in balance injection	Normal	B	6	50
Calibration of 10:1 ratio deviation	Normal	B	10	22
Repeatability	Normal	A	10	8
Measurement of 100 pF standard against BIPM 10 pF reference group of capacitors (1 steps)				
Value of reference group (subcomponents 1-4 above)	Normal	B	31	130
Drift of mean of reference group	Normal	B	5	22
Imperfect current equalisers	Normal	B	5	13
Errors in balance injection	Normal	B	5	50
Cable corrections	Rectangular	B	8	∞
Calibration of 10:1 ratio deviation	Normal	B	5	22
1541 Hz - 1592 Hz frequency correction	Normal	B	8	8
Repeatability (typical)	Normal	A	10	8
Combined standard uncertainty			36	
Effective degree of freedom			185	
Expanded uncertainty (95% coverage factor)			72	

In the following tables is reported the type A uncertainty (repeatability of measurement) for each of the standards measured at the BIPM. These components were taken into account for the calculation of the combined standard uncertainty of the measurements carried out by the BIPM.

	10 pF standards	
	Capacitance standard s/n	Type A uncertainty after correction from drift nF/F
METAS	1191	16
	1300	7
NIM	1606	5
	1682	-
NIST	1423	8
	1424	9
NMIA	1416	6
	1479	6
NPL	1101	4
	1186	-
PTB	1257	8
	1258	7
VNIIM	2204	17
	2205	9
BIPM	1227	11
	1310	9

	100 pF standards	
	Capacitance standard s/n	Type A uncertainty after correction from drift nF/F
METAS	1188	8
	1189	11
NIM	1596	3
	2090	6
NIST	1442	2
	1452	3
NMIA	1677	4
	1459	7
NPL	1100	10
	1185	-
PTB	1157	9
	1256	12
VNIIM	2207	18
BIPM	1225	6
	1642	5

A5-2 METAS

The relative deviation of the capacitance from its nominal value can be expressed by

$$\alpha_{100\,\mathrm{pF}} = -\frac{1}{2}\left\{\alpha_{G1} + \alpha_{G2} + \alpha_{Q} + \alpha_{c}\right\} + \frac{\alpha_{S1} + \alpha_{S2}}{2} + \alpha_{S3} - 2 \cdot \alpha_{10} + 2 \cdot \left(\alpha_{c}^{b} - \alpha_{c}^{t}\right)$$

for the 100 pF capacitance standard and

$$\alpha_{10\,\mathrm{pF}} = -\frac{1}{2}\left\{\alpha_{G1} + \alpha_{G2} + \alpha_{Q} + \alpha_{c}\right\} + \frac{\alpha_{S1} + \alpha_{S2}}{2} + \alpha_{S3} + \alpha_{S4} - 3 \cdot \alpha_{10} + 2 \cdot \left(\alpha_{c}^{b} - \alpha_{c}^{t}\right) + \left(\alpha_{c}'^{b} - \alpha_{c}'^{t}\right)$$

for the 10 pF capacitance standards.

The different parameters are:

α_{G1}, α_{G2} : are the relative deviation of the calculable resistances (G1 and G2) from the nominal value $\left(R_{K-90}/_{2}\right)$ at the frequency of 1233 Hz.

α_{Q} : is the in-phase component of the main balance of the quadrature bridge.

α_{c} : is the cable correction for the quadrature bridge

α_{S1} : is the in-phase balance of the 10 nF(A) -1 nF comparison

α_{S2} : is the in-phase balance of the 10 nF(B) -1 nF comparison

α_{S3} : is the in-phase balance of the 1 nF -100 pF comparison

α_{S4} : is the in-phase balance of the 100 pF -10 pF comparison

α_{10} : is the error of the 10:-1 ratio transformer

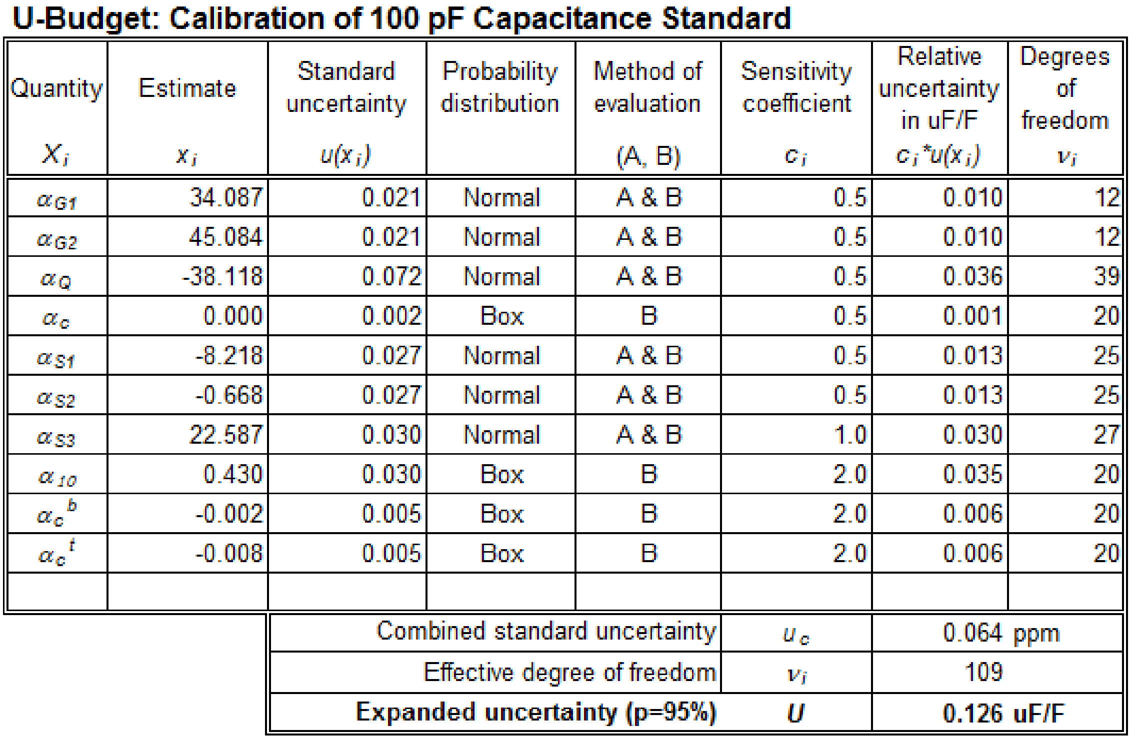
α_{c}^{t} : is the 4TP cable correction for the top standard of the 10:-1 comparison

α_{c}^{b} : is the 4TP cable correction for the bottom standard of the 10:-1 comparison

$\alpha_{c}'^{t}$: is the 3TP cable correction for the top standard of the 10:-1 comparison

$\alpha_{c}'^{b}$: is the 3TP cable correction for the bottom standard of the 10:-1 comparison

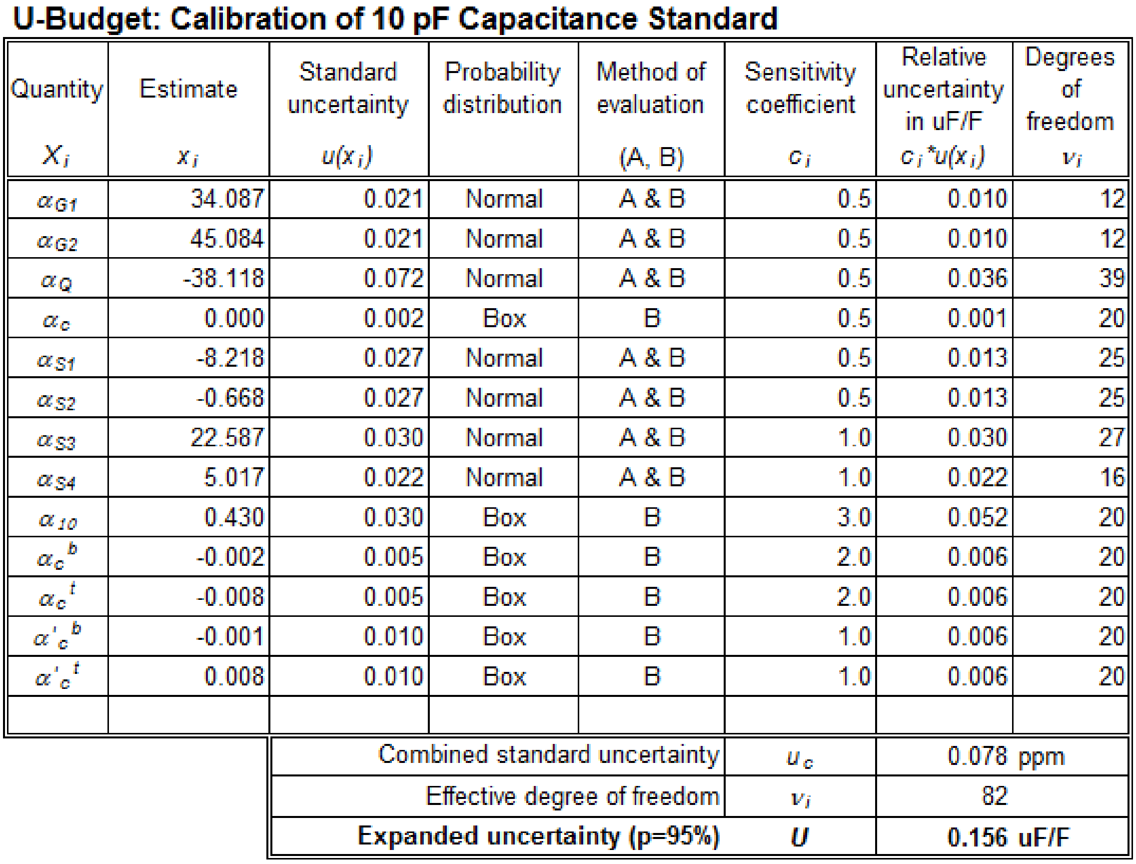
Uncertainties associated with these different parameters are reported in the following tables.



U-Budget: Calibration of 100 pF Capacitance Standard

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Method of evaluation (A, B)	Sensitivity coefficient c_i	Relative uncertainty in uF/F $c_i{}^*u(x_i)$	Degrees of freedom ν_i
α_{G1}	34.087	0.021	Normal	A & B	0.5	0.010	12
α_{G2}	45.084	0.021	Normal	A & B	0.5	0.010	12
α_Q	-38.118	0.072	Normal	A & B	0.5	0.036	39
α_c	0.000	0.002	Box	B	0.5	0.001	20
α_{S1}	-8.218	0.027	Normal	A & B	0.5	0.013	25
α_{S2}	-0.668	0.027	Normal	A & B	0.5	0.013	25
α_{S3}	22.587	0.030	Normal	A & B	1.0	0.030	27
α_{10}	0.430	0.030	Box	B	2.0	0.035	20
$\alpha_c{}^b$	-0.002	0.005	Box	B	2.0	0.006	20
$\alpha_c{}^t$	-0.008	0.005	Box	B	2.0	0.006	20

Combined standard uncertainty	u_c	0.064 ppm
Effective degree of freedom	ν_i	109
Expanded uncertainty (p=95%)	***U***	**0.126 uF/F**



U-Budget: Calibration of 10 pF Capacitance Standard

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Method of evaluation (A, B)	Sensitivity coefficient c_i	Relative uncertainty in uF/F $c_i{}^*u(x_i)$	Degrees of freedom ν_i
α_{G1}	34.087	0.021	Normal	A & B	0.5	0.010	12
α_{G2}	45.084	0.021	Normal	A & B	0.5	0.010	12
α_Q	-38.118	0.072	Normal	A & B	0.5	0.036	39
α_c	0.000	0.002	Box	B	0.5	0.001	20
α_{S1}	-8.218	0.027	Normal	A & B	0.5	0.013	25
α_{S2}	-0.668	0.027	Normal	A & B	0.5	0.013	25
α_{S3}	22.587	0.030	Normal	A & B	1.0	0.030	27
α_{S4}	5.017	0.022	Normal	A & B	1.0	0.022	16
α_{10}	0.430	0.030	Box	B	3.0	0.052	20
$\alpha_c{}^b$	-0.002	0.005	Box	B	2.0	0.006	20
$\alpha_c{}^t$	-0.008	0.005	Box	B	2.0	0.006	20
$\alpha'_c{}^b$	-0.001	0.010	Box	B	1.0	0.006	20
$\alpha'_c{}^t$	0.008	0.010	Box	B	1.0	0.006	20

Combined standard uncertainty	u_c	0.078 ppm
Effective degree of freedom	ν_i	82
Expanded uncertainty (p=95%)	***U***	**0.156 uF/F**

U-Budget: α_{G1} and α_{G2} at 1233 Hz

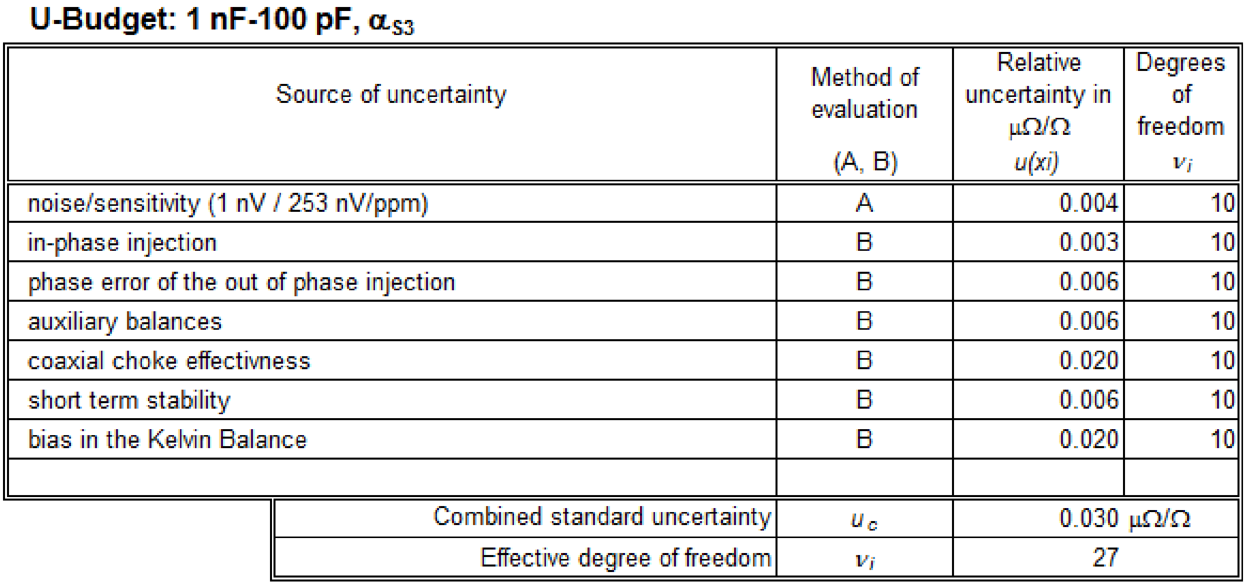
Source of uncertainty	Method of evaluation (A, B)	Relative uncertainty in µΩ/Ω $u(xi)$	Degrees of freedom ν_i
Type A and B uncertainty of the CCC measurement	A & B	0.005	20
Determination of the mean value at mean time	A	0.002	18
Frequency dependence between DC and 1233 Hz	B	0.020	10
Combined standard uncertainty	u_c	0.021 µΩ/Ω	
Effective degree of freedom	ν_i	12	

U-Budget: α_Q

Source of uncertainty	Method of evaluation (A, B)	Relative uncertainty in µΩ/Ω $u(xi)$	Degrees of freedom ν_i
Type A (1 nV after 100 sec)	A	0.042	10
Accuracy on the C_{in}/C_{Nom} ratio	A & B	0.029	18
Frequency accuracy	A	0.016	10
Auxiliary balances	B	0.020	5
Intermodulation distortion	B	0.010	10
Coaxial current inequalities	B	0.010	10
Detector offset	B	0.042	10
Combined standard uncertainty	u_c	0.072 µΩ/Ω	
Effective degree of freedom	ν_i	39	

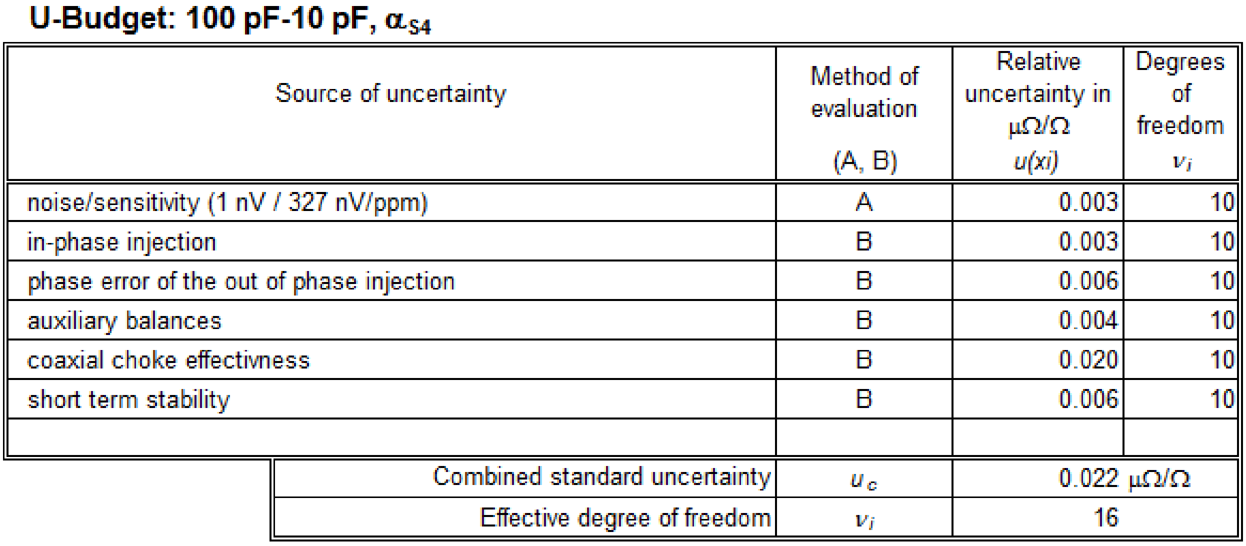
U-Budget: 10 nF-1 nF, α_{S1} and α_{S2}

Source of uncertainty	Method of evaluation (A, B)	Relative uncertainty in µΩ/Ω $u(xi)$	Degrees of freedom ν_i
noise/sensitivity (1 nV / 70 nV/ppm)	A	0.014	10
in-phase injection	B	0.003	10
phase error of the out of phase injection	B	0.006	10
auxiliary balances	B	0.006	10
coaxial choke effectivness	B	0.002	10
short term stability	B	0.006	10
voltage coefficient of the 10 nF capacitance standard	B	0.020	10
Combined standard uncertainty	u_c	0.027 µΩ/Ω	
Effective degree of freedom	ν_i	25	



U-Budget: 1 nF-100 pF, α_{S3}

Source of uncertainty	Method of evaluation (A, B)	Relative uncertainty in µΩ/Ω $u(xi)$	Degrees of freedom ν_i
noise/sensitivity (1 nV / 253 nV/ppm)	A	0.004	10
in-phase injection	B	0.003	10
phase error of the out of phase injection	B	0.006	10
auxiliary balances	B	0.006	10
coaxial choke effectivness	B	0.020	10
short term stability	B	0.006	10
bias in the Kelvin Balance	B	0.020	10
Combined standard uncertainty	u_c	0.030 µΩ/Ω	
Effective degree of freedom	ν_i	27	



U-Budget: 100 pF-10 pF, α_{S4}

Source of uncertainty	Method of evaluation (A, B)	Relative uncertainty in µΩ/Ω $u(xi)$	Degrees of freedom ν_i
noise/sensitivity (1 nV / 327 nV/ppm)	A	0.003	10
in-phase injection	B	0.003	10
phase error of the out of phase injection	B	0.006	10
auxiliary balances	B	0.004	10
coaxial choke effectivness	B	0.020	10
short term stability	B	0.006	10
Combined standard uncertainty	u_c	0.022 µΩ/Ω	
Effective degree of freedom	ν_i	16	

A5-3 NIM

Statement for the Initial series of measurements - Standard #01606

Uncertainty statement of AH#1606 (2017/03)

Nominal capacitance value : 10 pF Frequency: 1592Hz Voltage: 100V

Quantity / X_i	Estimate / x_i	Standard uncertainty / $u(x_i)$ (µF/F)	Probability distribution	Method of evaluation (A,B)	Sensitivity coefficient / c_i	Contribution to relative standard uncertainty / $u_i(C_x)$ (µF/F)	Degrees of freedom / ν_i
Calculable capacitor	-	0.0093	Normal	B	1	0.0093	5.7
Laser displace measurement	-	0.0054	Normal	B	1	0.0054	4.2
Bridge ratio correction	-	0.003	Normal	B	2	0.006	34.3
Bridge balance Injection	-	0.001	Normal	B	2	0.002	8
Detector uncertainty	-	0.002	Rect.	B	2	0.004	infinite
Two port definition	-	0.002	Rect.	B	2	0.004	infinite
Potential drop at residual wire	-	0.002	Rect.	B	2	0.004	infinite
Leads correction	-0.012 µF/F	0.002	Rect.	B	1	0.002	infinite
Voltage coefficient	-	0.010	Normal	B	1	0.010	2
Temperature coefficient	-	0.003	Normal	B	1	0.003	8
Repeated meas. of 10 pF	0.096 µF/F	0.0035	Normal	A	1	0.0035	9

Measured value / C_x :	10.00000096
Total type A uncertainty (µF/F)	0.0035
Total type B uncertainty (µF/F)	0.0178
Combined standard uncertainty / $u_c(C_x)$:	0.018
Effective degrees of freedom / ν_{eff} :	16.4
Expanded uncertainty (95% coverage factor)	0.038

Statement for the Return series of measurements - Standard #01606

Uncertainty statement of AH#1606 (2017/08)

Nominal capacitance value : 10 pF Frequency: 1592Hz Voltage: 100V

Quantity / X_i	Estimate / x_i	Standard uncertainty / $u(x_i)$ (µF/F)	Probability distribution	Method of evaluation (A,B)	Sensitivity coefficient / c_i	Contribution to relative standard uncertainty / $u_i(C_x)$ (µF/F)	Degrees of freedom / ν_i
Calculable capacitor	-	0.0093	Normal	B	1	0.0093	5.7
Laser displace measurement	-	0.0054	Normal	B	1	0.0054	4.2
Bridge ratio correction	-	0.003	Normal	B	2	0.006	34.3
Bridge balance Injection	-	0.001	Normal	B	2	0.002	8
Detector uncertainty	-	0.002	Rect.	B	2	0.004	infinite
Two port definition	-	0.002	Rect.	B	2	0.004	infinite
Potential drop at residual wire	-	0.002	Rect.	B	2	0.004	infinite
Leads correction	-0.012 µF/F	0.002	Rect.	B	1	0.002	infinite
Voltage coefficient	-	0.010	Normal	B	1	0.010	2
Temperature coefficient	-	0.003	Normal	B	1	0.003	8
Repeated meas. of 10 pF	0.070 µF/F	0.0042	Normal	A	1	0.0042	9

Measured value / C_x :	10.00000070
Total type A uncertainty (µF/F)	0.0042
Total type B uncertainty (µF/F)	0.0178
Combined standard uncertainty / $u_c(C_x)$:	0.018
Effective degrees of freedom / ν_{eff} :	16.9
Expanded uncertainty (95% coverage factor)	0.039

Statement for the Initial series of measurements - Standard #01596

Uncertainty statement of AH#1596 (2017/03)

Nominal capacitance value : 100 pF Frequency: 1592Hz Voltage: 10V

Quantity / X_i	Estimate / x_i	Standard uncertainty / $u(x_i)$ (µF/F)	Probability distribution	Method of evaluation (A,B)	Sensitivity coefficient / c_i	Contribution to relative standard uncertainty / $u_i(C_x)$ (µF/F)	Degrees of freedom / ν_i
Calculable capacitor	-	0.0093	Normal	B	1	0.0093	5.7
Laser displace measurement	-	0.0054	Normal	B	1	0.0054	4.2
Bridge ratio correction	-	0.003	Normal	B	3	0.009	34.3
Bridge balance Injection	-	0.001	Normal	B	3	0.003	8
Detector uncertainty	-	0.002	Rect.	B	3	0.006	infinite
Two port definition	-	0.002	Rect.	B	3	0.006	infinite
Potential drop at residual wire	-	0.002	Rect.	B	3	0.006	infinite
Leads correction	-0.021 µF/F	0.002	Rect.	B	1	0.002	infinite
Voltage coefficient	-	0.010	Normal	B	1	0.010	2
Temperature coefficient	-	0.003	Normal	B	1	0.003	8
Repeated meas. of 100 pF	0.064 µF/F	0.0047	Normal	A	1	0.0047	9

Measured value / C_x :	100.0000064
Total type A uncertainty (µF/F)	0.0047
Total type B uncertainty (µF/F)	0.021
Combined standard uncertainty / $u_c(C_x)$:	0.021
Effective degrees of freedom / ν_{eff} :	29.7
Expanded uncertainty (95% coverage factor)	0.043

NOTE: Uncertainty statement of the 100 pF standard #01596 has been revised by NIM after the issue of the first version of draft A (reduction from 2 to 1 of the value of the sensitivity coefficient applied to the voltage correction). This revision had the effect to reduce the combined uncertainty by about 6 ppb.

Statement for the Return series of measurements - Standard #01596

Uncertainty statement of AH#1596 (2017/08)

Nominal capacitance value : 100 pF Frequency: 1592Hz Voltage: 10V

Quantity / X_i	Estimate / x_i	Standard uncertainty / $u(x_i)$ (µF/F)	Probability distribution	Method of evaluation (A,B)	Sensitivity coefficient / c_i	Contribution to relative standard uncertainty / $u_i(C_x)$ (µF/F)	Degrees of freedom / ν_i
Calculable capacitor	-	0.0093	Normal	B	1	0.0093	5.7
Laser displace measurement	-	0.0054	Normal	B	1	0.0054	4.2
Bridge ratio correction	-	0.003	Normal	B	3	0.009	34.3
Bridge balance Injection	-	0.001	Normal	B	3	0.003	8
Detector uncertainty	-	0.002	Rect.	B	3	0.006	infinite
Two port definition	-	0.002	Rect.	B	3	0.006	infinite
Potential drop at residual wire	-	0.002	Rect.	B	3	0.006	infinite
Leads correction	-0.021 µF/F	0.002	Rect.	B	1	0.002	infinite
Voltage coefficient	-	0.010	Normal	B	1	0.010	2
Temperature coefficient	-	0.003	Normal	B	1	0.003	8
Repeated meas. of 100 pF	0.027 µF/F	0.0034	Normal	A	1	0.0034	9

Measured value / C_x :	100.0000027
Total type A uncertainty (µF/F)	0.0034
Total type B uncertainty (µF/F)	0.021
Combined standard uncertainty / $u_c(C_x)$:	0.021
Effective degrees of freedom / ν_{eff} :	28.5
Expanded uncertainty (95% coverage factor)	0.043

NOTE: Uncertainty statement of the 100 pF standard #01596 has been revised by NIM after the issue of the first version of draft A (reduction from 2 to 1 of the value of the sensitivity coefficient applied to the voltage correction). This revision had the effect to reduce the combined uncertainty by about 6 ppb.

Statement for the Initial series of measurements - Standard #02090

Uncertainty statement of AH#2090 (2017/03)

Nominal capacitance value : 100 pF Frequency: 1592Hz Voltage: 10V

Quantity / X_i	Estimate / x_i	Standard uncertainty / $u(x_i)$ (µF/F)	Probability distribution	Method of evaluation (A,B)	Sensitivity coefficient / c_i	Contribution to relative standard uncertainty / $u_i(C_x)$ (µF/F)	Degrees of freedom / ν_i
Calculable capacitor	-	0.0093	Normal	B	1	0.0093	5.7
Laser displace measurement	-	0.0054	Normal	B	1	0.0054	4.2
Bridge ratio correction	-	0.003	Normal	B	3	0.009	34.3
Bridge balance Injection	-	0.001	Normal	B	3	0.003	8
Detector uncertainty	-	0.002	Rect.	B	3	0.006	infinite
Two port definition	-	0.002	Rect.	B	3	0.006	infinite
Potential drop at residual wire	-	0.002	Rect.	B	3	0.006	infinite
Leads correction	-0.021 µF/F	0.002	Rect.	B	1	0.002	infinite
Voltage coefficient	-	0.010	Normal	B	1	0.010	2
Temperature coefficient	-	0.003	Normal	B	1	0.003	8
Repeated meas. of 100 pF	0.170 µF/F	0.011	Normal	A	1	0.011	9

Measured value / C_x :	100.0000170
Total type A uncertainty (µF/F)	0.011
Total type B uncertainty (µF/F)	0.021
Combined standard uncertainty / $u_c(C_x)$:	0.023
Effective degrees of freedom / ν_{eff} :	35.9
Expanded uncertainty (95% coverage factor)	0.047

NOTE: Uncertainty statement of the 100 pF standard #02090 has been revised by NIM after the issue of the first version of draft A (reduction from 2 to 1 of the value of the sensitivity coefficient applied to the voltage correction). This revision had the effect to reduce the combined uncertainty by about 6 ppb.

Statement for the Return series of measurements - Standard #02090

Uncertainty statement of AH#2090 (2017/08)

Nominal capacitance value : 100 pF Frequency: 1592Hz Voltage: 10V

Quantity / X_i	Estimate / x_i	Standard uncertainty / $u(x_i)$ (µF/F)	Probability distribution	Method of evaluation (A,B)	Sensitivity coefficient / c_i	Contribution to relative standard uncertainty / $u_i(C_x)$ (µF/F)	Degrees of freedom / ν_i
Calculable capacitor	-	0.0093	Normal	B	1	0.0093	5.7
Laser displace measurement	-	0.0054	Normal	B	1	0.0054	4.2
Bridge ratio correction	-	0.003	Normal	B	3	0.009	34.3
Bridge balance Injection	-	0.001	Normal	B	3	0.003	8
Detector uncertainty	-	0.002	Rect.	B	3	0.006	infinite
Two port definition	-	0.002	Rect.	B	3	0.006	infinite
Potential drop at residual wire	-	0.002	Rect.	B	3	0.006	infinite
Leads correction	-0.021 µF/F	0.002	Rect.	B	1	0.002	infinite
Voltage coefficient	-	0.010	Normal	B	1	0.010	2
Temperature coefficient	-	0.003	Normal	B	1	0.003	8
Repeated meas. of 100 pF	0.150 µF/F	0.004	Normal	A	1	0.004	9
Measured value / C_x :		100.0000150					
Total type A uncertainty (µF/F)		0.004					
Total type B uncertainty (µF/F)		0.021					
Combined standard uncertainty / $u_c(C_x)$:		0.021					
Effective degrees of freedom / ν_{eff} :		29.0					
Expanded uncertainty (95% coverage factor)		0.043					

NOTE: Uncertainty statement of the 100 pF standard #02090 has been revised by NIM after the issue of the first version of draft A (reduction from 2 to 1 of the value of the sensitivity coefficient applied to the voltage correction). This revision had the effect to reduce the combined uncertainty by about 6 ppb.

A5-4 NIST

Uncertainty statement for C143

Nominal capacitance value : 10 pF Frequency: 1592 Hz Voltage: 100 V

Quantity / X_i	Estimate / x_i (µF/F)	Standard uncertainty / $u(x_i)$ (µF/F)	Probability distribution	Method of evaluation (A,B)	Sensitivity coefficient / c_i (F/F)	Contribution to relative standard uncertainty / $u_i(C_x)$ (µF/F)	Degrees of freedom / ν_i
Repeatability	0	0.001	normal	A	1	0.001	100
Reference 10 pF (C112) measured with calculable capacitor	6.002	0.019	normal	B	1	0.019	∞
Drift of C112	0	0.002	normal	B	1	0.002	30
Error of loading correction	0	0.002	rect	B	1	0.002	4
Error of substitution method	0	0.001	normal	B	1	0.001	∞
Error due to ambient conditions	0	0.002	normal	B	1	0.002	∞

Measurand value / C_x :	-4.865
Total type A uncertainty (µF/F)	0.001
Total type B uncertainty (µF/F)	0.020
Combined standard uncertainty / $u_c(C_x)$:	0.020
Effective degrees of freedom / ν_{eff} :	237
Expanded uncertainty (95% coverage factor)	0.04

Uncertainty statement for C144

Nominal capacitance value : 10 pF Frequency: 1592 Hz Voltage: 100 V

Quantity / X_i	Estimate / x_i (µF/F)	Standard uncertainty / $u(x_i)$ (µF/F)	Probability distribution	Method of evaluation (A,B)	Sensitivity coefficient / c_i (F/F)	Contribution to relative standard uncertainty / $u_i(C_x)$ (µF/F)	Degrees of freedom / ν_i
Repeatability	0	0.001	normal	A	1	0.001	100
Reference 10 pF (C112) measured with calculable capacitor	6.002	0.019	normal	B	1	0.019	∞
Drift of C112	0	0.002	normal	B	1	0.002	30
Error of loading correction	0	0.002	rect	B	1	0.002	4
Error of substitution method	0	0.001	normal	B	1	0.001	∞
Error due to ambient conditions	0	0.002	normal	B	1	0.002	∞

Measurand value / C_x :	-4.780
Total type A uncertainty (µF/F)	0.001
Total type B uncertainty (µF/F)	0.020
Combined standard uncertainty / $u_c(C_x)$:	0.020
Effective degrees of freedom / ν_{eff} :	237
Expanded uncertainty (95% coverage factor)	0.04

Uncertainty statement for C218

Nominal capacitance value : 100 pF Frequency: 1592 Hz Voltage: 10 V

Quantity / X_i	Estimate / x_i (µF/F)	Standard uncertainty / $u(x_i)$ (µF/F)	Probability distribution	Method of evaluation (A,B)	Sensitivity coefficient / c_i (F/F)	Contribution to relative standard uncertainty / $u_i(C_x)$ (µF/F)	Degrees of freedom / ν_i
Repeatability	0	0.001	normal	A	1	0.001	100
Reference 10 pF (C112) measured with calculable capacitor	6.002	0.019	normal	B	1	0.019	∞
Drift of C112	0	0.002	normal	B	1	0.002	30
Error of loading correction	0	0.002	rect	B	1	0.002	4
Error of 10:1 transformer bridge	0.023	0.005	rect	B	1	0.005	10
Error due to ambient conditions	0	0.002	normal	B	1	0.002	∞

Measurand value / C_x :	-4.372
Total type A uncertainty (µF/F)	0.001
Total type B uncertainty (µF/F)	0.020
Combined standard uncertainty / $u_c(C_x)$:	0.020
Effective degrees of freedom / ν_{eff} :	211
Expanded uncertainty (95% coverage factor)	0.04

Uncertainty statement for C219

Nominal capacitance value : 100 pF Frequency: 1592 Hz Voltage: 10 V

Quantity / X_i	Estimate / x_i (µF/F)	Standard uncertainty / $u(x_i)$ (µF/F)	Probability distribution	Method of evaluation (A,B)	Sensitivity coefficient / c_i (F/F)	Contribution to relative standard uncertainty / $u_i(C_x)$ (µF/F)	Degrees of freedom / ν_i
Repeatability	0	0.001	normal	A	1	0.001	100
Reference 10 pF (C112) measured with calculable capacitor	6.002	0.019	normal	B	1	0.019	∞
Drift of C112	0	0.002	normal	B	1	0.002	30
Error of loading correction	0	0.002	rect	B	1	0.002	4
Error of 10:1 transformer bridge	0.023	0.005	rect	B	1	0.005	10
Error due to ambient conditions	0	0.002	normal	B	1	0.002	∞

Measurand value / C_x :	-4.724
Total type A uncertainty (µF/F)	0.001
Total type B uncertainty (µF/F)	0.020
Combined standard uncertainty / $u_c(C_x)$:	0.020
Effective degrees of freedom / ν_{eff} :	211
Expanded uncertainty (95% coverage factor)	0.04

A5-5 NMIA

Uncertainty statement for SN 01416

Uncertainty statement

Serial number of the standard capacitor: 01416
Nominal value: 10 pF Measurement frequency: 1592 Hz Applied voltage: 100 V

Quantity	Estimate	Standard uncertainty	Probability distribution (A/B)	Sensitivity coefficient	Contribution to relative standard uncertainty	Degrees of freedom
X_i	x_i	$u(x_i)$		c_i	$u_i(C_x)$	ν_i
Calculable capacitor measurements	-	0.0013 fringe	Normal/A	3 µF/F/fringe	0.004 µF/F	7
Calculable capacitor	-	0.034 µF/F	Normal/B	1	0.034 µF/F	7.76
Bridge resolution	-	0.003 µF/F	Rectangular/B	2.35	0.007 µF/F	Infinite
Accuracy of two-port definition	-	0.001 µF/F	Normal/B	1	0.001 µF/F	3
Bridge balance injection	-	0.001 µF/F	Normal/B	1	0.001 µF/F	3
Calibration of 10:1 ratio	-	0.003 µF/F	Normal/B	1	0.003 µF/F	211
Bridge voltage coefficient: 5I to C½	-	0.001 µF/F	Normal/B	1	0.001 µF/F	5
Voltage coefficient 5I	-	0.008 µF/F	Normal/B	0.99	0.008 µF/F	5
5I interpolation / extrapolation	-	0.039 µF/F	Normal/B	1	0.039 µF/F	60
Leads correction	-0.031 µF/F	0.002 µF/F	Rectangular/B	1	0.002 µF/F	infinite
Temperature	-	0.16 °C	Normal/B	0.004 µF/F/°C	0.001 µF/F	9368
Temperature correction	0.012 µF/F/°C	0.004 µF/F/°C	Normal/A	3 °C	0.012 µF/F	5
Combined standard uncertainty / u_c					0.054 µF/F	
Effective degree of freedom / ν_{eff}					42	

Uncertainty statement for SN 01479

Uncertainty statement

Serial number of the standard capacitor: 01479
Nominal value: 10 pF Measurement frequency: 1592 Hz Applied voltage: 100 V

Quantity	Estimate	Standard uncertainty	Probability distribution (A/B)	Sensitivity coefficient	Contribution to relative standard uncertainty	Degrees of freedom
X_i	x_i	$u(x_i)$		c_i	$u_i(C_x)$	ν_i
Calculable capacitor measurements	-	0.0013 fringe	Normal/A	3 µF/F/fringe	0.004 µF/F	7
Calculable capacitor	-	0.034 µF/F	Normal/B	1	0.034 µF/F	7.76
Bridge resolution	-	0.003 µF/F	Rectangular/B	2.35	0.007 µF/F	Infinite
Accuracy of two-port definition	-	0.001 µF/F	Normal/B	1	0.001 µF/F	3
Bridge balance injection	-	0.001 µF/F	Normal/B	1	0.001 µF/F	3
Calibration of 10:1 ratio	-	0.003 µF/F	Normal/B	1	0.003 µF/F	211
Bridge voltage coefficient: 5I to C½	-	0.001 µF/F	Normal/B	1	0.001 µF/F	5
Voltage coefficient 5I	-	0.008 µF/F	Normal/B	0.99	0.008 µF/F	5
5I interpolation / extrapolation	-	0.039 µF/F	Normal/B	1	0.039 µF/F	60
Leads correction	-0.031 µF/F	0.002 µF/F	Rectangular/B	1	0.002 µF/F	infinite
Temperature	-	0.16 °C	Normal/B	0.002 µF/F/°C	0.000 µF/F	9368
Temperature correction	-0.007 µF/F/°C	0.003 µF/F/°C	Normal/A	3 °C	0.008 µF/F	5
Combined standard uncertainty / u_c					0.054 µF/F	
Effective degree of freedom / ν_{eff}					40	

Uncertainty statement for SN 01677

Uncertainty statement

Serial number of the standard capacitor: 01677
Nominal value: 100 pF Measurement frequency: 1592 Hz Applied voltage: 10 V

Quantity	Estimate	Standard uncertainty	Probability distribution (A/B)	Sensitivity coefficient	Contribution to relative standard uncertainty	Degrees of freedom
X_i	x_i	$u(x_i)$		c_i	$u_i(C_x)$	ν_i
Calculable capacitor measurements	-	0.0013 fringe	Normal/A	3 µF/F/fringe	0.004 µF/F	7
Calculable capacitor	-	0.034 µF/F	Normal/B	1	0.034 µF/F	7.76
Bridge resolution	-	0.003 µF/F	Rectangular/B	2.55	0.007 µF/F	Infinite
Accuracy of two-port definition	-	0.001 µF/F	Normal/B	1	0.001 µF/F	3
Bridge balance injection	-	0.001 µF/F	Normal/B	2	0.002 µF/F	3
Calibration of 10:1 ratio	-	0.003 µF/F	Normal/B	2	0.006 µF/F	211
Bridge voltage coefficient: 5I to C½	-	0.001 µF/F	Normal/B	1	0.001 µF/F	5
Voltage coefficient 5I	-	0.008 µF/F	Normal/B	0.99	0.008 µF/F	5
5I interpolation / extrapolation	-	0.039 µF/F	Normal/B	1	0.039 µF/F	60
Leads correction	-0.046 µF/F	0.002 µF/F	Rectangular/B	1	0.002 µF/F	infinite
Temperature	-	0.16 °C	Normal/B	0.002 µF/F/°C	0.000 µF/F	9368
Temperature correction	0.005 µF/F/°C	0.001 µF/F/°C	Normal/A	3 °C	0.002 µF/F	5
Combined standard uncertainty / u_c					0.053 µF/F	
Effective degree of freedom / ν_{eff}					40	

Uncertainty statement for SN 01459

Uncertainty statement

Serial number of the standard capacitor: 01459
Nominal value: 100 pF Measurement frequency: 1592 Hz Applied voltage: 10 V

Quantity	Estimate	Standard uncertainty	Probability distribution (A/B)	Sensitivity coefficient	Contribution to relative standard uncertainty	Degrees of freedom
X_i	x_i	$u(x_i)$		c_i	$u_i(C_x)$	ν_i
Calculable capacitor measurements	-	0.0013 fringe	Normal/A	3 µF/F/fringe	0.004 µF/F	7
Calculable capacitor	-	0.034 µF/F	Normal/B	1	0.034 µF/F	7.76
Bridge resolution	-	0.003 µF/F	Rectangular/B	2.55	0.007 µF/F	Infinite
Accuracy of two-port definition	-	0.001 µF/F	Normal/B	1	0.001 µF/F	3
Bridge balance injection	-	0.001 µF/F	Normal/B	2	0.002 µF/F	3
Calibration of 10:1 ratio	-	0.003 µF/F	Normal/B	2	0.006 µF/F	211
Bridge voltage coefficient: 5I to C½	-	0.001 µF/F	Normal/B	1	0.001 µF/F	5
Voltage coefficient 5I	-	0.008 µF/F	Normal/B	0.99	0.008 µF/F	5
5I interpolation / extrapolation	-	0.039 µF/F	Normal/B	1	0.039 µF/F	60
Leads correction	-0.046 µF/F	0.002 µF/F	Rectangular/B	1	0.002 µF/F	infinite
Temperature	-	0.16 °C	Normal/B	0.006 µF/F/°C	0.001 µF/F	9368
Temperature correction	-0.020 µF/F/°C	0.001 µF/F/°C	Normal/A	3 °C	0.002 µF/F	5
Combined standard uncertainty / u_c					0.053 µF/F	
Effective degree of freedom / ν_{eff}					40	

A5-6 NPL

Uncertainty Budget

The uncertainty budget for the two NPL capacitors have been reported as instructed by the protocol document in table form - see Appendix B.

The total expanded uncertainties are **0.238 μF/F for 10 pF**, and **0.226 μF/F for 100 pF.** The 1σ uncertainty of the traceability chain was estimated in ref. [1] to be 0.041 ppm. During the course of this comparison 6 traceability measurements were performed, and the scatter of the resulting values of QC1 (1 nF), QC2 (1 nF) and 143 (100 pF) were found not to be consistent with this uncertainty. Analysis of the AC bridge balance settings strongly suggests a source of randomness is present in the 100:1 equal-power resistance bridge although the problem has not yet been identified. An additional type A uncertainty term of 0.08 μF/F has been added to the uncertainty budget, based on a rectangular distribution fitted around the upper and lower limits of the 6 values from the traceability measurements. A rectangular distribution is appropriate because the problem is not sufficiently well understood to justify a normal distribution. Instability in the current transformer ratio used in the 100:1 bridge contributes to scatter in the values of the traceability capacitors. Consequently this instability is not accounted for separately in the breakdown of the type B uncertainty of the 100:1 bridge. The resulting final uncertainty budget is considerably larger than that presented in [1] but it is an accurate representation of our confidence in the measurements at the time of the comparison.

Additional comments on the uncertainty budget:

- The 100 pF (S/N 01100) capacitor was measured at 100 V. Its value at 10 V is reported after applying a voltage co-efficient correction. The voltage correction was (0.06 ± 0.03) μF/F, estimated from 1:1 measurements against 100 pF S/N 143, which has a known voltage coefficient. For the 100 pF capacitor, the uncertainty in the voltage co-efficient is the second largest component in the uncertainty budget after the 0.08 μF/F type A component associated with the traceability bridges.

- To simplify the data analysis, temperature corrections were not applied for the NPL standard capacitors. Instead, an additional component was added to the uncertainty budget to cover the maximum range of temperature recorded for the standards during the measurement campaign. This resulted in negligible increase to the overall uncertainty for both the AH 10 pF and AH 100 pF capacitors.

- Values of the 10 pF capacitor measured at NPL before the shipment to BIPM exhibited anomalous scatter. The type A uncertainty of the this capacitor was estimated from a rectangular distribution fitted around the upper and lower limits of its measured value before the transfer. This yielded a contribution of 0.049 μF/F, which is the second largest term in the uncertainty budget for 10 pF.

- The number of degrees of freedom, as calculated using the Welch-Satterwaite equation, is relatively small (8 in the case of 100 pF). This is because the largest term in the uncertainty budget is evaluated as a type A contribution from only 6 traceability measurements of the NPL standards. Consequently the expanded uncertainty is obtained from the standard uncertainty by multiplying by a factor >2, obtained from t-distribution tables.

- The small type B uncertainty terms associated with the AC/DC transfer resistor, 100:1 equal-power resistance bridge, quadrature bridge and 10:1 bridge, were taken from [1]. These terms capture cable effects, IVD linearity, 10:1 transformer ratio correction etc.
  There is no evidence that they have changed since the publication of [1].

References

[1] S A Awan, R G Jones and B P Kibble 2003 Metrologia **40** 264-270.

Uncertainty statement for S/N 01101

Nominal capacitance value : 10 pF Frequency: 1.592 kHz Voltage: 100 V

Quantity / X_i	Estimate / x_i	Standard uncertainty / $u(x_i)$	Probability distribution	Method of evaluation (A,B)	Sensitivity coefficient / c_i	Contribution to relative standard uncertainty / $u_i(C_x)$ (µF/F)	Degrees of freedom / ν_i
AC/DC transfer resistor (CCCs)	1 kΩ	0.023 µΩ/Ω	Rectangular	B	1	0.023	∞
AC resistors (100:1 bridge)	100 kΩ	0.019 µΩ/Ω	Rectangular	B	1	0.019	∞
Known capacitors (quad bridge)	1 nF	0.018 µΩ/Ω	Rectangular	B	1	0.018	∞
Known capacitors (quad bridge)	1 nF	0.08 fF	Rectangular	A	1	0.08	5
Known capacitors (10:1 bridge)	100 pF	0.014 µF/F	Rectangular	B	1	0.014	∞
Temp. variation of NPL 100 pF Std.	0 K	0.0011 K	Rectangular	A	127 (µF/F) /K	0.038	21
Temp Correction of S/N 01101	0.005 (uF/F)/K	0.0029 (µF/F)/K	Rectangular	B	3 K	0.009	∞
Volt. Correction of 100 pF	0 (uF/F)/V	0.0001 (µF/F)/V	Rectangular	B	90 V	0.009	∞
Unknown capacitor (10:1 bridge)	10 pF	0.014 µF/F	Rectangular	B	1	0.014	∞
Unknown capacitor (10:1 bridge)	10 pF	0.049	Rectangular	A	1	0.049	21

Measurand value / C_x :	9.99995757 pF	
Total type A uncertainty (µF/F)	0.1012	
Total type B uncertainty (µF/F)	0.0420	
Combined standard uncertainty / $u_c(C_x)$:	0.1096	µF/F
Effective degrees of freedom / ν_{eff} :	16	
Expanded uncertainty (95% coverage factor)	**0.238**	From t-distribution, *k* = 2.17 for 16 degrees of freedom

N.B. Rows highlighted in green, associated with the 100:1 equal power resistance bridge, quadrature bridge and 10:1 capacitance bridge, are further broken down in three additional uncertainty tables.

Uncertainty statement for S/N 01100

Nominal capacitance value : 100 pF Frequency: 1.592 kHz Voltage: 10 V

Quantity / X_i	Estimate / x_i	Standard uncertainty / $u(x_i)$	Probability distribution	Method of evaluation (A,B)	Sensitivity coefficient / c_i	Contribution to relative standard uncertainty / $u_i(C_x)$ (μF/F)	Degrees of freedom / ν_i
AC/DC transfer resistor (CCCs)	1 kΩ	0.023 μΩ/Ω	Rectangular	B	1	0.023	∞
AC resistors (100:1 bridge)	100 kΩ	0.019 μΩ/Ω	Rectangular	B	1	0.019	∞
Known capacitors (quad bridge)	1 nF	0.018 μΩ/Ω	Rectangular	B	1	0.018	∞
Known capacitors (quad bridge)	1 nF	0.08 fF	Rectangular	A	1	0.08	5
Temp. variation of NPL 1nF Std.	0 K	0.0021K	Rectangular	A	12 (μF/F) /K	0.007	21
Temp. correction of S/N 01100	0.005 (uF/F)/K	0.0029 (μF/F)/K	Rectangular	B	3 K	0.009	∞
Unknown capacitors (10:1 bridge)	100 pF	0.014 μF/F	Rectangular	B	1	0.014	∞
Voltage correction of unknown	0.0007 (uF/F)/V	0.00033 (μF/F)/V	Rectangular	B	90 V	0.03	∞
Unknown capacitor (10:1 bridge)	100 pF	0.017	Rectangular	A	1	0.017	21

Measurand value / C_x :	99.9996806 pF	
Total type A uncertainty (μF/F)	0.08209	
Total type B uncertainty (μF/F)	0.04890	
Combined standard uncertainty / $u_c(C_x)$:	0.09555	μF/F
Effective degrees of freedom / ν_{eff} :	8	Rounded down from 8.3
Expanded uncertainty (95% coverage factor)	**0.226**	From t-distribution, *k* = 2.37 for 8 degrees of freedom

N.B. Rows highlighted in green, associated with the 100:1 equal power resistance bridge, quadrature bridge and 10:1 capacitance bridge, are further broken down in three additional uncertainty tables.

Uncertainties for 100:1 equal-power resistance bridge taken from [1] Awan, Kibble and Jones, Metrologia vol. 40, 264 (2003)

Quantity / X_i	Estimate / x_i	Standard uncertainty / $u(x_i)$	Probability distribution	Method of evaluation (A,B)	Sensitivity coefficient / c_i	Contribution to relative standard uncertainty / $u_i(C_x)$ (µF/F)	Degrees of freedom / ν_i
Current transformer ratio	$10(1-0.465 \times 10^{-6})$	1.40×10^{-8}	Rectangular	B	1	0.014	∞
Bridge Network corrections	0	1.00×10^{-8}	Rectangular	B	1	0.01	∞
Voltage transformer ratio	$10(1-0.323 \times 10^{-6})$	6.00×10^{-9}	Rectangular	B	1	0.006	∞
Temperature Drift corrections	0	6.00×10^{-9}	Rectangular	B	1	0.006	∞
Total type A uncertainty (µF/F)		0					
Total type B uncertainty (µF/F)		0.019					
Combined standard uncertainty / $u_c(C_x)$:		0.019					

Uncertainties for Quadrature bridge taken from [1] Awan, Kibble and Jones, Metrologia vol. 40, 264 (2003)

Quantity / X_i	Estimate / x_i	Standard uncertainty / $u(x_i)$	Probability distribution	Method of evaluation (A,B)	Sensitivity coefficient / c_i	Contribution to relative standard uncertainty / $u_i(C_x)$ (µF/F)	Degrees of freedom / ν_i
Frequency	1591.54878 Hz	0.014 µHz/Hz	Rectangular	B	1	0.014	∞
Bridge Network corrections	0	5.00x10^{-9}	Rectangular	B	1	0.005	∞
Harmonic rejection	0	1.00x10^{-8}	Rectangular	B	1	0.01	∞
Temperature Drift corrections	0	4.00x10^{-9}	Rectangular	B	1	0.004	∞
Total type A uncertainty (µF/F)		0					
Total type B uncertainty (µF/F)		0.018					
Combined standard uncertainty / $u_c(C_x)$:		0.018					

Uncertainties for 10:1 Capacitance bridge taken from [1] Awan, Kibble and Jones, Metrologia vol. 40, 264 (2003)

Quantity / X_i	Estimate / x_i	Standard uncertainty / $u(x_i)$	Probability distribution	Method of evaluation (A,B)	Sensitivity coefficient / c_i	Contribution to relative standard uncertainty / $u_i(C_x)$ (µF/F)	Degrees of freedom / ν_i
Bridge Network corrections	0	$1.00\mathrm{x}10^{-8}$	Rectangular	B	1	0.01	∞
Voltage Transformer ratio	$10(1+0.323\mathrm{x}10^{-6})$	$6.00\mathrm{x}10^{-9}$	Rectangular	B	1	0.006	∞
Injection IVD linearity correction	0	$5.00\mathrm{x}10^{-5}$	Rectangular	B	0.0001	0.005	∞
Temperature Drift corrections	0	$6.00\mathrm{x}10^{-9}$	Rectangular	B	1	0.006	∞
Total type A uncertainty (µF/F)		0					
Total type B uncertainty (µF/F)		0.014					
Combined standard uncertainty / $u_c(C_x)$:		0.014					

A5-7 PTB

Nominal capacitance value: 100 pF **Frequency: 1233.15 Hz** **Voltage: 10 V**

Quantity X_i	Estimate x_i (µF/F)	Standard uncertainty $u(x_i)$ (nF/F)	Probability distribution	Sensitivity coefficient	Contribution to standard uncertainty (nF/F)	Type	Degree of freedom ν_i
Quadrature bridge deviation Δ_Q	-54.0	2.45	normal	0.5	1.23	A	36
		6.03			3.02	B	44
10 nF:1 nF deviation Δ_1	-12.7	2.59	normal	-0.5	1.30	A	6.4
		2.23			1.12	B	15
10 nF:1 nF deviation Δ_2	-23.7	2.59	normal	-0.5	1.30	A	6.4
		2.23			1.12	B	15
1 nF:100 pF deviation Δ_3	-11.6, -3.8	1.16	normal	-1	1.16	A	69
		2.40			2.40	B	∞
10:1 deviation δ	0.4	1.8	normal	-2	3.6	B	8.6
linear voltage dependence of δ, δ calibrated at 37 V instead of 5.5 V [1]	$\leq 5\cdot10^{-9}$/100 V	1.6	rectangular	-2	1.8	B	∞
unintended magnetisation of 10:1 ratio transformer		$\leq$ 3.0	rectangular	2	3.5	B	∞
transfer instability of 10 nF standards		2.3	normal	1	2.3	A	∞
transfer instability of 1 nF standard		1.0	normal	1	1.0	A	∞
temperature instability of AH 100 pF standards		2.8	normal	1	2.8	A	∞

Total type A uncertainty: 4.51 nF/F

Total type B uncertainty: 6.77 nF/F

Combined standard uncertainty u_C: 8.14 nF/F
Effective degree of freedom ν_{eff}: 193
Expanded uncertainty: 16.3 nF/F

---

[1] (1 V + 10 V + 100 V)/3 = 37 V and (1 V + 10 V)/2 = 5.5 V

Nominal capacitance value: 10 pF **Frequency: 1233.15 Hz** **Voltage: 100 V**

Quantity X_i	**Estimate x_i (µF/F)**	**Standard uncertainty $u(x_i)$ (nF/F)**	**Probability distribution**	**Sensitivity coefficient**	**Contribution to standard uncertainty (nF/F)**	**Type**	**Degree of freedom ν_i**
Quadrature bridge deviation Δ_Q	-54.0	2.45	normal	0.5	1.23	A	36
		6.03			3.02	B	44
10 nF:1 nF deviation Δ_1	-12.7	2.59	normal	-0.5	1.30	A	6.4
		2.23			1.12	B	15
10 nF:1 nF deviation Δ_2	-23.7	2.59	normal	-0.5	1.30	A	6.4
		2.23			1.12	B	15
1 nF:100 pF deviation Δ_3	-11.6, -3.8	1.16	normal	-1	1.16	A	69
		2.40			2.40	B	∞
100 pF:10 pF deviation Δ_4	<1	1.18	normal	-1	1.18	A	53
		2.35			2.35	B	∞
10:1 deviation δ (calibrated at 37 V [2])	0.4	1.8	normal	-3	5.4	B	8.6
unintended magnetisation of ratio transformer		≤ 3.0	rectangular	3	5.2	B	∞
transfer instability of 10 nF standards		2.3	normal	1	2.3	A	∞
transfer instability of 1 nF standard		1.0	normal	1	1.0	A	∞
transfer instability of AH 100 pF standards		2.8	normal	1	2.8	A	∞
temperature instability of AH 10 pF standards		2.8	normal	1	2.8	A	∞

Total type A uncertainty: 5.44 nF/F

Total type B uncertainty: 8.89 nF/F

Combined standard uncertainty u_C: 10.4 nF/F
Effective degree of freedom ν_{eff}: 115
Expanded uncertainty: 20.9 nF/F

---

[2] Under this condition, the effect of a possible weak linear voltage dependence cancels because (1 V + 10 V + 100 V)/3 = 37 V.

Nominal capacitance ratio: 100 pF:10 pF	**Frequency: 1233.15 Hz**	**Voltage: 100 V:10 V**

Quantity X_i	**Estimate x_i (µF/F)**	**Standard uncertainty $u(x_i)$ (nF/F)**	**Probability distribution**	**Sensitivity coefficient**	**Contribution to standard uncertainty (nF/F)**	**type**	**Degree of freedom ν_i**
100 pF:10 pF deviation Δ_4	<1	1.18	normal	-1	1.18	A	53
		2.35			2.35	B	∞
10:1 deviation δ	0.4	1.8	normal	-1	1.8	B	
linear voltage dependence of δ, δ calibrated at 37 V instead of 100 V	$\leq 5 \cdot 10^{-9}$/100 V	3.2	rectangular	-1	1.8	B	∞
unintended magnetisation of ratio transformer		≤ 3.0	rectangular	1	1.7	B	∞
temperature instability of 100 pF standards		2.8	normal	1	2.8	A	∞
temperature instability of 10 pF standards		2.8	normal	1	2.8	A	∞

Total type A uncertainty: 4.13 nF/F
Total type B uncertainty: 3.86 nF/F
Combined standard uncertainty u_C: 5.65 nF/F Effective degree of freedom ν_{eff}: ∞ Expanded uncertainty: 11.3 nF/F

Uncertainty of Δ_Q of the quadrature bridge at 1233 Hz

Source		distribution	uncertainty, sensitivity coefficient	uncertainty (k = 1) (10^{-9})	type	ν
detector noise		normal	6.6 nV at τ = 120 s forward and reverse at sens = 1.2 µV/10^{-6} (U = 100 mV)	2.0	A	4
detector offset		normal	< 3 nV at sens = 1.2 µV/10^{-6}	2.5	B	4
main in-phase injection		normal		0.3	B	4
frequency		normal	$\Delta\omega/\omega < 4 \cdot 10^{-11}$	0.08	B	4
ac QHR		normal		4.0	B	∞
phase error of quadrature injection		rectangular		0.4	B	∞
residual imbalance of auxiliary balances	Wagner	rectangular	4 dials	1.0	A	∞
	current sources	rectangular	4 dials	1.0	A	∞
	twin-T	rectangular	5 dials	0.04	A	∞
harmonic distortion		normal		≤ 2.0	B	4
lead correction		normal		1.4	B	4
equaliser evaluation		normal	$55 \cdot 10^{-9}$ x 5%	2.8	B	4

total uncertainty (k = 1) and effective degree of freedom	**type A**	**2.45**		**36**
	type B	**6.03**		**44**
	combined	**6.50**		**52**

Uncertainty of $\Delta_{1,2}$, Δ_3 and Δ_4 of the 10:1 ratio bridge at 1233 Hz

The different 10:1 ratios are colour-coded: $\Delta_{1,2}$ **(10 nF:1 nF)**, Δ_3 **(1nF:100 pF)** und Δ_4 **(100 pF:10 pF)**. Uncertainty **c**ontributions quoted in black equally apply to all 10:1 ratios.

Source		Distribution	Uncertainty, sensitivity	Uncertainty (k = 1) (10^{-9})	type	ν
detector noise		normal	U_{Det} = 7.9 nV, τ = 120 s, U = 1.0 V, sens = 3.48 µV / 10^{-6}	2.3	A	4
			U_{Det} = 9.8 nV, τ = 90 s, U = 10 V, sens = 17.3 µV / 10^{-6}	0.57	A	4
			U_{Det} = 16 nV, τ = 60 s, U = 100 V, sens = 28.1 µV / 10^{-6}	0.57	A	4
in-phase injection IVD		normal	$\Delta D_P/D_P = 1.9\cdot10^{-5}$, $D_P = 24\cdot10^{-6}$	0.45	B	∞
			$D_P \leq 10\cdot10^{-6}$	0.19	B	∞
			$D_P \leq 10\cdot10^{-6}$	0.19	B	∞
phase error of quadrature IVD		rectangular	$80\cdot10^{-6} \times 6.2$ µV/V	0.50	B	∞
cable corrections		rectangular	sensitivity = 1	0.17	B	∞
phase shifter		normal	$\Delta\varphi/\varphi \leq 4\cdot10^{-5}$, $D_Q = 40\cdot10^{-6}$	1.6	B	4
			$\Delta\varphi/\varphi \leq 4\cdot10^{-5}$, $D_Q < 3\cdot10^{-6}$	0.12	B	4
			$\Delta\varphi/\varphi \leq 4\cdot10^{-5}$, $D_Q < 3\cdot10^{-6}$	0.12	B	4
residual imbalance of auxiliary balances	current source 1	rectangular	0.3	0.3	A	∞
			0.1	0.1	A	∞
			0.2	0.2	A	∞
	current source 2	rectangular	0.3	0.3	A	∞
			0.1	0.1	A	∞
			0.1	0.1	A	∞
	Kelvin	rectangular	0.5	0.5	A	∞
			0.1	0.1	A	∞
			0.1	0.1	A	∞
	Wagner	rectangular	1.0	1.0	A	∞

evaluation of equalisers	normal	sensitivity = 1		1.2 2.0 2.0	B B B	∞
detector offset	normal	≤ 2.5 nV		0.7	B	∞
		≤ 20 nV		1.2	B	∞
		≤ 30 nV		1.1	B	∞
		total uncertainty (*k* = 1) and effective degree of freedom:	**type A**	**2.59** **1.16** **1.18**		6.4 69.6 72.7
			type B	**2.23** **2.40** **2.35**		15.1 ∞ ∞
			combined	**3.42** **2.67** **2.63**		15.8 ∞ ∞

A5-8 VNIIM

Uncertainty statement						
Nominal capacitance value : **10 pF**			Frequency : 1592 Hz		Voltage : 98 V	
Quantity / X_i	Estimate / x_i (mention unit)	Standard uncertainty / $u(x_i)$ (mention unit)	Probability distribution	Sensitivity coefficient / c_i (mention unit)	Contribution to relative standard uncertainty / $u_i(C_x)$ (µF/F)	Degrees of freedom / ν_i
1. Capacitance measurement (type A)	10 pF	0.01 µF/F	Normal	1	0.01	9
2. Uncertainty of the reference value – group standard mean value derived from VNIIM cross capacitor (type B)	9.9999 142 pF	0.08 µF/F	Normal	1	0.08	200
3. Uncertainty of the reference standard during measurement (type B)	0	0.02 µF/F	Normal	1	0.02	16
4. Uncertainty components relative to the measuring bridge (type B):						
- ratio	1.00000000	0.02 µF/F	Rectangular	1	0.02	13
- bridge voltage coefficient	0	0.02 µF/F	Rectangular	1	0.02	17
- bridge loading coefficient	0	0.008 µF/F	Rectangular	1	0.008	22
- nonlinearity of variable capacitor	0	0.01 µF/F	Rectangular	1	0.01	6
- quadrature component effect (α in β)	0	0.025 µF/F	Rectangular	1	0.025	9
- detector noise	0	0.01 µF/F	Normal	1	0.01	6
Measurand value / C_x : 10 pF						
Combined standard uncertainty / $u_c(C_x)$: 0.093 µF/F						
Effective degrees of freedom / ν_{eff} : 36						

Uncertainty statement

Nominal capacitance value : **100 pF** Frequency : 1592 Hz Voltage : 9.8 V

Quantity / X_i	Estimate / x_i (mention unit)	Standard uncertainty / $u(x_i)$ (mention unit)	Probability distribution	Sensitivity coefficient / c_i (mention unit)	Contribution to relative standard uncertainty / $u_i(C_x)$ (µF/F)	Degrees of freedom / ν_i
1. Capacitance measurement (type A)	100 pF	0.01 µF/F	Normal	1	0.01	9
2. Uncertainty of the reference value – group standard mean value derived from VNIIM cross capacitor (type B)	9.9999 142 pF	0.08 µF/F	Normal	1	0.08	200
3. Uncertainty of the reference standard during measurement (type B)	0	0.02 µF/F	Normal	1	0.02	16
4. Uncertainty components relative to the measuring bridge (type B):						
- ratio	10.0000034	0.11 µF/F	Rectangular	1	0.11	13
- dependence of ratio on applied voltage	0	0.02 µF/F	Rectangular	1	0.02	17
- dependence of ratio on capacitive load	0	0.008 µF/F	Rectangular	1	0.008	22
- nonlinearity of variable capacitor	0	0.01 µF/F	Rectangular	1	0.01	6
- quadrature component effect (α in β)	0	0.025 µF/F	Rectangular	1	0.025	9
- detector noise	0	0.01 µF/F	Normal	1	0.01	6

Measurand value / C_x : 100 pF

Combined standard uncertainty / $u_c(C_x)$: 0.145

Effective degrees of freedom / ν_{eff} : 36

NOTE: Uncertainty statement of the 100 pF standard #02207 have been revised by VNIIM after the issue of the first version of draft A (increase of the uncertainty component on the 10:1 ratio). This revision had the effect to increase the combined uncertainty by about 55 ppb.

ANNEX 6: General conditions of measurement

Institute	**BIPM**	**METAS**	**NIM**	**NIST**
Measurand = 2 TP capacitance value at the input terminals of the AH capacitors	*Yes*	*Yes*	*Yes*	*Yes*
Reported capacitance values corrected from cable effect	*Yes*	*Yes*	*Yes*	*Yes*
Temperature of measurement	*see table below*	*23.3 ± 0.5 °C*	*20 ± 0.5 °C - temperature dependence evaluated and value reported at 23 ± 0.5 °C*	*22 ± 0.5 °C - uncertainty component to cover deviation from protocol*
Humidity range during measurement period	*see table below*	*40 ± 10 %*	*50 ± 10 %*	*45 ± 10 %*
Pressure range during measurement period	*see table below*	*956 ± 12 hPa*	*1008 ± 7 hPa*	*1003 ± 10 hPa*
Applied voltage	*100 V for 10 pF*	*100 V for 10 pF*	*100 V for 10 pF*	*100 V for 10 pF*
	10 V for 100 pF	*10 V for 100 pF*	*10 V for 100 pF*	*10 V for 100 pF*
Frequency	*1592 Hz*	*1233 Hz interpolated to 1592 Hz by the BIPM*	*1592 Hz*	*1592 Hz*
Traceability from a calculable capacitor or from last R_K CODATA adjustment	*Last R_K CODATA adjustment*	*Last R_K CODATA adjustment*	*Calculable capacitor*	*Calculable capacitor*
Local mains voltage	*230 V / 50 Hz*	*230 V / 50 Hz*	*220 V / 50 Hz*	*120 V / 60 Hz*

Institute	**NMIA**	**NPL**	**PTB**	**VNIIM**
Measurand = 2 TP capacitance value at the input terminals of the AH capacitors	*Yes*	*Yes*	*Yes*	*Yes*
Reported capacitance values corrected from cable effect	*Yes*	*Yes*	*Yes*	*Yes*
Temperature of measurement	*19.9 ± 0.4 °C - value reported at 23 °C*	*20.0 °C corrected for 23°C*	*23.0 ± 0.2 °C*	*20.1 ± 0.5 °C - corrected for 23°C by the pilot*
Humidity range during measurement period	*53 ± 2 %*	*44 ± 12 %*	*39.5 ± 2 %*	*30 ± 10 %*
Pressure range during measurement period	*1008 ± 10 hPa*	*1014 ± 24 hPa*	*1004 ± 1 hPa*	*1013 ± 23 hPa*
Applied voltage	*100 V for 10 pF*	*100 V for 10 pF*	*100 V for 10 pF*	*98 V for 10 pF*
	10 V for 100 pF	*100 V for 100 pF corrected for 10 V*	*10 V for 100 pF*	*9.8 V for 100 pF*
Frequency	*1592 Hz*	*1592 Hz*	*1233.15 Hz interpolated to 1591.55 Hz*	*1592 Hz*
Traceability from a calculable capacitor or from last R_K CODATA adjustment	*Calculable capacitor*	*Last R_K CODATA adjustment*	*Last R_K CODATA adjustment*	*Calculable capacitor*
Local mains voltage	*230 V / 50 Hz*	*230 V / 50 Hz*	*230 V / 50 Hz*	*230 V / 50 Hz*

Ambient conditions during measurement at the BIPM

	Mean ambient temperature (°C)	Mean atmospheric pressure (hPa)	Mean relative humidity (%)
BIPM vs METAS	23.3 ± 0.1	1007 ± 15	49 ± 8
BIPM vs NIM	23.4 ± 0.2	1007 ± 16	50 ± 9
BIPM vs NIST	23.3 ± 0.2	1008 ± 16	49 ± 6
BIPM vs NMIA	23.3 ± 0.2	1007 ± 14	49 ± 7
BIPM vs NPL	23.3 ± 0.2	1007 ± 16	50 ± 8
BIPM vs PTB	23.3 ± 0.2	1007 ± 15	49 ± 8
BIPM vs VNIIM	23.3 ± 0.3	1006 ± 14	52 ± 9