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NIST MEASUREMENT SERVICES
Three-Terminal Precision Standard Capacitor Calibrations at NIST

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1. INTRODUCTION

We have recently made improvements in capacitance measurements by expanding the frequency range of and lowering the uncertainty assigned to three-terminal (3T) fused-silica and nitrogen gas dielectric standard capacitor calibrations. These improvements are based on the recent frequency response characterization of the NIST primary capacitance maintenance standard from 50 Hz to 20 kHz [1, 2]. The traceability chain from the NIST calculable capacitor to the customer standard capacitor is also shortened and the calibration service automated through the use of a commercial capacitance bridge as a transfer standard between the reference standard and the capacitor under test. This publication describes the revised procedure for 3T capacitance calibrations covered under test services 52130C/52131C, 52140C/52141C, and 52160C/52161C.

The NIST farad representation for 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 only about 0.02 μF/F per year. The standards are calibrated at least once a year indirectly against the calculable capacitor [2] at NIST at a frequency of ≈1592 Hz ($\omega = 10^4$ rad/s), using a 10 pF transportable fused-silica capacitor, C112. This frequency was chosen for a convenient link between the farad and the ohm.

The NIST calculable capacitor is based on the Thompson-Lampard theorem [3]. It is comprised of four parallel, uniform electrodes with very small gaps between them as shown in Fig. 1. The capacitances per unit length, C_a and C_b, between the opposing pairs of electrodes obey the relationship:

$$\exp(-\pi C_a / \varepsilon_o) + \exp(-\pi C_b / \varepsilon_o) = 1,$$

where ε_o is the permittivity of vacuum. When $C_a = C_b = C$, this reduces to

$$C = \frac{\varepsilon_o \ln 2}{\pi},$$

which is a constant that directly links to the defined speed of light. The calculable capacitor provides an absolute determination of capacitance in terms of length only and is the ultimate reference for all impedance measurements in the U.S.

The reference fused-silica standard capacitors of value 100 pF, 10 pF, and 1 pF are calibrated directly against the Farad Bank at 1592 Hz at least once per year to determine the drift of the standards. The frequency dependencies of these capacitance standards have been measured [1, 2] from 50 Hz to 20 kHz using a combination of a 1 pF cross capacitor that has negligible frequency dependence due to electrode surface films and a 10 pF nitrogen gas dielectric capacitor with a very small residual inductance as references. The frequency response curve of a fused-silica standard capacitor is very stable and needs to be re-characterized only infrequently.

The calibrated reference standards are then used in a substitution scheme and measured each time a customer standard is sent to NIST for calibration. The difference between the calibrated value and measured value of the reference at each required frequency is used to correct the measured value of the customer standard. Fig. 2 shows the traceability chain for NIST 3T nitrogen gas and fused-silica standard capacitor calibrations. The calibration procedure will be described in detail below in terms of the reference characterization, reference and customer capacitance measurements, data processing, uncertainty budgets, and report generation.

The 1592 Hz reference point is derived from NIST Calculable Capacitor measurements that are transferred to the Primary 10 pF Bank of standards. The reference standard 1 pF, 10 pF, and 100 pF capacitors are compared directly with the Primary 10 pF Bank at 1592 Hz on a periodic basis at least once per year. The frequency response curve for each reference standard is traceable to a series of measurements on a 1 pF, 9-bar, nitrogen gas cross capacitor, as well as a 10 pF nitrogen gas cylindrical capacitor. References [1] and [2] describe fully the work to characterize fused-silica reference standards across frequencies from 50 Hz to 20 kHz.

2. REFERENCE CHARACTERIZATION

NIST standard reference capacitors of nominal values 100 pF, 10 pF, and 1 pF have been characterized for frequency dependence of the capacitance [1, 2]. Table 1 gives the frequency dependence for the 100 pF, 10 pF, and 1 pF AH11A reference standards used to provide customer calibrations. Figures 3 and 4 show plots of the frequency dependences. These curves show the change in capacitance with respect to the capacitance value at 1592 Hz, as measured against two reference standard capacitors on the NIST four-terminal-pair capacitance bridge. The reference standard capacitors used were a 1 pF cross capacitor, chosen for its negligible frequency dependence at low frequencies, and a 10 pF nitrogen gas capacitor chosen because it has good reference characteristics at higher frequencies [2]. The frequency dependence curves for the fused-silica reference standards have been shown to have stability on the order of one or two parts in 10^8 over a period of many years [3, 4] and so updates are not required frequently. However, normal drift of the reference standards requires periodic calibration at 1592 Hz against the NIST Primary Bank of 10 pF standards. The Primary Bank of standards is calibrated against the NIST Calculable Capacitor approximately once per year. The calibration of all reference standards against the Primary Bank at 1592 Hz is performed no less than once per year. A spot check of the frequency dependence will be performed every ten years to verify the values.

Additionally, errors in the automatic bridge measurements due to bridge loading from the stray capacitances of the measured capacitors must be corrected each calibration for fused-silica standard capacitors. Nitrogen gas standard capacitors are not corrected for bridge loading errors. Fig. 5 shows a schematic diagram of the automatic capacitance bridge measuring a three-terminal standard capacitor. The low-to-high capacitance of the standard capacitor is labeled as C_{LH} and the stray capacitances from the low side of the standard, point B, to ground and from the high side, point A, to ground, are labeled as C_{LG} and C_{HG}, respectively. The effects on bridge measurements at 20 kHz from varying the stray capacitances at points A and B of the reference standards have been measured and are shown for 100 pF calibration reference standard (C272) in Fig. 6. The loading effect curves produced for the automatic capacitance bridge at points A and B using a 10 pF calibration reference standard (C172) are shown in Fig. 7, and those produced using a 1 pF calibration reference standard (C016) are shown in Fig. 8. The increase in capacitance bridge measurement value with increase in stray capacitance is a linear curve for both the high and low sides of the bridge. This effect will change with frequency according to the square of the frequency [1, 2] and so the effect on measured capacitance due to bridge loading will decrease dramatically at lower frequencies. This effect becomes negligible (as can be seen in Tables 2-7 below) at frequencies below a few kilohertz. It is important to note that the bridge is loaded differently for each standard measured. The differences between the stray capacitances of the reference standard and the customer standard at the high and low terminals are the critical quantities for a customer calibration. Customer standards that have stray capacitance values close to the stray capacitance values of the reference standard will have no significant loading corrections.

An example computation of loading correction follows using the 20 kHz bridge loading curve in Fig. 6 for the 100 pF calibration reference standard. The value of reference capacitor C272 with a stray capacitance at the high terminal, point A, adjusted to 3 nF above its normal value of approximately 205 pF, gives a measurement across the high-to-low terminals of 100.01896 pF. Adjusting the stray capacitance to the normal value of 205 pF (zero added stray capacitance) gives a high-to-low capacitance of 100.00269 pF. Normalizing to µF/F of the 100 pF nominal value gives a slope on the loading curve for the high terminal of (189.6 – 26.9 =) 162.7 µF/F per 3 nF, which reduces to 0.0542 µF/F per 1 pF. If the customer standard has a stray capacitance at point A that measures 195 pF, the difference in loading at point A between calibration reference standard C272 and the customer standard is (205 – 195 =) 10 pF, which gives a 20 kHz loading correction at the high terminal (point A) of 0.542 µF/F, compared to the expanded uncertainty of the customer 100 pF at 20 kHz of 2.35 µF/F. Scaling this correction from 20 kHz to 1 kHz, according to a frequency-squared relationship, gives a 1 kHz loading correction at point A of approximately 0.001 µF/F, compared to an expanded uncertainty at 1 kHz of 0.21 µF/F. The bridge loading curve for point B, in Fig. 4, has a smaller slope, producing smaller corrections than for point A. Of course, corrections for both the high terminal (point A) and the low terminal (point B) must be computed to properly correct for the loading effects of the bridge.

The stray capacitances of the reference standards vary little from month to month and therefore, measurements are required only twice per year in order to provide bridge loading corrections for customer fused-silica standard capacitors. For convenience, the stray capacitance measurements on the NIST reference standard as well as the customer standard capacitor are performed at 1 kHz and the correction is computed at the required frequencies from 50 Hz to 20 kHz according to the frequency squared.

3. REFERENCE AND CUSTOMER CAPACITANCE MEASUREMENTS

Capacitance measurements on the reference and customer standard capacitors are performed using the Andeen-Hagerling AH2700A 50 Hz – 20 kHz Ultra-Precision Capacitance Bridge[†]. The bridge is controlled using a personal computer with a software driver and a GPIB interface. Figure 9 shows a photograph of the bridge, controlling laptop, and reference and customer fused-silica standard capacitors.

[†] The identification of a specific commercial product does not imply endorsement by NIST, nor does it imply that the product identified is the best available for a particular purpose.

Since the frequency dependences of the reference standard capacitors have been determined and straightforward measurements can provide corrections for the loading effects of capacitors on the automatic capacitance bridge, the bridge can be used as an effective transfer instrument. Measurements on the reference and customer standards, along with the calibrated values for the reference standards, are used in a substitution procedure. For each customer calibration, five sets of data are taken on different days for all required frequencies over a period of approximately two weeks. At the time of each measurement run, data are taken closely in time on the standard under test and the NIST calibration reference standard of the same nominal value. The only exception to using the same nominal value reference and customer standards is that the 100 pF fused-silica reference standard is used to calibrate 1000 pF nitrogen gas standards, with a corresponding uncertainty component for the 10:1 ratio comparison.

The difference between the measured value of the reference standard and the calibrated value of the reference standard at each frequency is used, along with the loading correction, to determine the calibrated value of the standard under test. So the equation used to produce a calibrated capacitance value for a device under test (DUT) for a single measurement at a single frequency, would be

$$C_{DUTcal} = C_{DUTmeas} + (C_{REFcal} - C_{REFmeas}) + \varepsilon_{Loading} \quad (1)$$

where C_{DUTcal} is the calibrated capacitance of the DUT,

$C_{DUTmeas}$ is the measured value of the DUT,

C_{REFcal} is the value of the reference standard calibrated against the NIST Primary Bank,

$C_{REFmeas}$ is the measured value of the reference standard, and

$\varepsilon_{Loading}$ is the total loading correction for the capacitance bridge with respect to the DUT.

Five such capacitance measurements are performed to produce a reported value for the high accuracy calibrations of fused-silica or nitrogen gas dielectric standard capacitors (NIST test IDs 52130C/52131C and 52140C/52141C). The mean of the five measurements along with the Type A uncertainty and expanded uncertainty are reported in the Report of Calibration for high accuracy tests. Three such measurements are performed to produce a reported value for low accuracy tests on nitrogen gas dielectric standard capacitors (NIST test ID 52160C/52161C). The mean of the three corrected measurements along with the expanded uncertainty are reported in the Report of Calibration for low accuracy tests. Control software is used to automatically perform the measurements and store the results. See reference [7] for definitions of Type A and expanded uncertainties.

The laboratory ambient temperature is maintained at 23.0 ºC. The relative humidity of the laboratory varies seasonally but is held below 50 %. Laboratory ambient temperature and relative humidity are recorded at the time of each customer measurement and the mean value over all measurement sets is given on the Report of Calibration. Customer standards are energized and/or allowed to stabilize within the lab for at least 72 hours prior to measurement. Measurements are not performed if the temperature has varied from the laboratory set point of 23.0 ºC by more than 0.5 ºC or if relative humidity has increased above 50 % within the last 72 hours.

Typical commercial fused-silica standard capacitors provide enclosure temperature control to maintain stability of the standard capacitor. Some older types of standards, however, do not provide a temperature display. Calibration of fused-silica standards without a temperature display requires a standard platinum resistance thermometer (SPRT) to be placed inside the standard capacitor enclosure in order to record the temperature within the standard capacitor at the time of measurement. A resistance thermometry bridge is used to provide such measurements. Enclosure temperature is recorded at the time of each measurement. Mean enclosure temperature and enclosure temperature variation are reported on the Report of Calibration. Figure 10 shows two fused-silica standard capacitor enclosures without enclosure temperature readouts. An SPRT is placed within the right enclosure to record the temperature during measurement. Two standard capacitors are potentially housed within each enclosure. Figure 11 shows a photograph of two fused-silica standard capacitor enclosures that have temperature readouts. Four standard capacitors are potentially housed within each of these enclosures.

Figure 12 shows three 3T nitrogen gas standard capacitors. The upper standard has been placed inside of a foam container in order to reduce handling of the standard and to facilitate temperature stability of the unit. The bridge cable leads are connected to the upper standard and a shorting clip is used to short the outer shields of the high and low terminals of the standard, as some commercial nitrogen gas standards are constructed with the high- and low-terminal shields electrically connected, and some are not connected.

4. DATA PROCESSING

Once all of the measurement data sets have been obtained, they are stored in a spreadsheet file. The corrected values of all capacitance measurements are computed as shown in Eq. (1). The mean values over the five corrected measurements at each frequency are computed. The Type A uncertainty for each frequency is computed as the standard deviation of each group of five corrected measurements. The ambient temperature, relative humidity, and enclosure temperature for the customer standard are averaged over the five measurement runs and are reported, along with the variation in the enclosure temperature. Also, the expanded uncertainty of each capacitance calibration value is computed using a coverage factor of k=2, with the Type A component for a given calibration being the only contributor to the expanded uncertainty that varies from calibration to calibration. The expanded uncertainties reported in this publication are computed such that the Type A uncertainty of a customer standard must increase beyond a specific threshold before the expanded uncertainty must be increased above the normal reported value for that nominal capacitance and frequency.

5. UNCERTAINTY BUDGETS

The uncertainty components contributing to the combined standard uncertainty of a customer calibration for a 3T fused-silica or nitrogen gas standard capacitor are the reference standard uncertainty, the reference standard drift, the Type A uncertainty of the DUT, the drift of the

DUT, the capacitance bridge thermal, mechanical, and linearity components, and the bridge loading component (see Tables 2, 3, 4, 5, 6, and 7). The 1000 pF nitrogen gas standard capacitor calibration uncertainty budget also contains a component for the 10:1 ratio due to using a 100 pF reference standard (see Table 5). Reviewing Eq. (1), there are four terms on the right side of the equation.

$$C_{DUTcal} = C_{DUTmeas} + (C_{REFcal} - C_{REFmeas}) + \varepsilon_{Loading} \quad (1)$$

The component uncertainties are statistically independent and correspond to the terms of Eq. (1) according to:

Term 1: Type A Uncertainty, DUT Drift, and 10:1 Ratio Uncertainty (1000 pF only)
Term 2: Reference Uncertainty and Reference Drift
Term 3: Bridge Thermal, Mechanical, and Linearity
Term 4: Bridge Loading

Since the terms are statistically independent, they can be combined in a root-sum-squared fashion to produce the combined standard uncertainties (not shown in tables). The combined standard uncertainties are used with a coverage factor of k=2 to produce the expanded uncertainties shown in the tables.

Figure 13 shows a short-term stability plot for the 100 pF calibration reference standard. Six measurements across all frequencies from 50 Hz to 20 kHz were performed within 24 hours and are presented. Figure 14 shows the same data from 50 Hz to 1 kHz only. Figure 15 shows a long-term stability plot of the 100 pF calibration reference measurements. The plot contains all bridge measurements of the 100 pF reference standard taken over more than three years. Figure 16 shows the data from Fig. 15 with the average of all capacitance measurement data subrtracted out.

Figures 17, 18, 19, and 20 show the corresponding short-term and long-term stability plots for the 10 pF calibration reference standard as shown in Figs. 13, 14, 15, and 16 for the 100 pF reference. Figures 21, 22, 23, and 24 show the corresponding plots for the 1 pF calibration reference standard. These figures demonstrate stability and repeatability of the capacitance bridge measurements.

Tables 2, 3, and 4 show the uncertainty budgets for the 100 pF, 10 pF, and 1 pF fused-silica standard capacitor calibration services at NIST, provided under test IDs 52130C and 52131C. Tables 5, 6, and 7 show the uncertainty budgets for the 1000 pF, 100 pF, and 10 pF nitrogen gas standard capacitor calibration services at NIST, provided under test IDs 52140C and 52141C. Test IDs 52160C and 52161C are used to provide low accuracy/high uncertainty calibrations for fixed 3T standard capacitors with coaxial connectors. One of the standard types covered under test IDs 52160C and 52161C is the fixed 3T nitrogen gas dielectric standard capacitor that is also calibrated with high accuracy/low uncertainty under test IDs 52140C and 52141C. When test IDs 52160C and 52161C are used to calibrate fixed 3T nitrogen gas dielectric standard capacitors, the expanded uncertainty is always 25 μF/F, for frequencies from 50 Hz to 20 kHz. The only exception is that 35 μF/F is used for the 10 pF standard at a frequency of 20 kHz. A table of the capacitance bridge accuracy for 1 pF, 10 pF, 100 pF, and 1000 pF measurements is included in the Appendix. The expanded uncertainty for all calibrations is the combined standard uncertainty of the calibrated value multiplied by a coverage factor of k=2, consistent with practice recommended by the International Bureau of Weights and Measures (BIPM) [7]. In equation form, this is $U = k\, u_c$, where u_c is the relative combined standard uncertainty for all known sources of error and k is a coverage factor. Consistent with international practice, NIST uses a coverage factor of $k = 2$. The expanded uncertainty is thus given by

$$U = 2\, u_c = 2\sqrt{\sum u_i^{\,2}}\ ,$$

where u_i is the estimated relative standard uncertainty associated with the i^{th} source of error and expressed as an equivalent standard deviation. It is assumed that the probability distribution characterized by the capacitance calibration measurement is approximately normal or Gaussian. A probability interval around the true measurand, Y, within which lies the measurement result, y, is defined such that $y - u_c(y) \leq Y \leq y + u_c(y)$, commonly expressed as $Y = y \pm u_c(y)$, where $u_c(y)$ is the combined standard uncertainty of y. The normal distribution assumption establishes a level of confidence of approximately 68 % that the true measurand is within the uncertainty interval. Applying the coverage factor of k = 2 raises the level of confidence to approximately 95 %, that $Y = y \pm U(y)$, where $U(y)$ is the expanded uncertainty of y, using a coverage factor of $k = 2$ [7].

Summarizing the components listed in Tables 2-7, the reference uncertainties are the combined standard uncertainties produced from calibration of the reference standards with traceability to the NIST Calculable Capacitor. Calibrations of the reference standard capacitors are performed at a minimum of once per year at 1592 Hz with spot checks of the frequency curve being performed once per ten years. The Reference Drift is the short-term drift in the calibrated values of the reference standard. The Type A Uncertainty is a conservative limit determining a typically behaving standard. Any customer standard not performing to within this limit will require a larger uncertainty to be assigned. The DUT drift allows for the drift of the device under test, and is identical in value to the Reference Drift. The Bridge Thermal, Bridge Mechanical, and Bridge Linearity components are taken from the manual of the commercial capacitance bridge used in performing the calibrations [5]. The Bridge Loading component is the uncertainty on the correction for the difference between the bridge loading during measurements of the reference and test standards. Measurement of the stray capacitances of the reference standard capacitors used in computing the bridge loading corrections are performed at least twice yearly. Details of the NIST method of expressing uncertainties can be found in reference [7]. Figures 25, 26, and 27 present plots of the expanded uncertainties (k=2) for NIST calibrations of 100 pF, 10 pF, and 1 pF 3T fused-silica standard capacitors, respectively. Figures 28, 29, and 30 show the corresponding plots for NIST calibrations of 3T nitrogen gas standard capacitors of values 1000 pF, 100 pF, and 10 pF, respectively.

6. CALIBRATION SERVICES

For many years NIST has offered calibrations for 3T fused-silica and nitrogen gas dielectric standard capacitors of values 1 pF, 10 pF, 100 pF, and 1000 pF only at 100 Hz, 400 Hz, and 1000 Hz [7, 8]. Because of the tedious manual bridge measurements required for calibration, multiple measurement points were charged at a rate similar to the fee of the initial calibration point. The fee for having a standard capacitor calibrated at all three frequencies mentioned above was approximately three times the fee for only one frequency. The work done to expand and automate the standard capacitor calibration service has allowed NIST to reduce the fee for the initial point by a factor of more than one third from the previous fee. Moreover, the fee for additional calibration frequencies has been reduced by more than a factor of 15 over the previous fee. The service has expanded from the three frequencies mentioned above to 20 frequencies ranging from 50 Hz to 20 kHz, as shown in the Uncertainty Budget section. Calibration turn-around time is typically estimated at eight weeks for fused-silica standard capacitor calibrations (NIST test IDs 52130C and 52131C). For the nitrogen gas dielectric standard capacitors, NIST also offers a calibration that assesses the effects of physical handling of the standard, under NIST test ID 52150C, recommended only for standards that are used outside of a laboratory setting. When a physical handling test is required in addition to the normal capacitance calibration of a nitrogen gas dielectric standard capacitor, the calibration turn-around time is typically eight weeks (NIST test IDs 52140C, 52141C and 52150C). When no such physical handling test is required, the turn-around time is typically six weeks (NIST test IDs 52140C and 52141C). The turn-around time for the low accuracy calibration of nitrogen gas dielectric standard capacitors is six weeks (NIST test IDs 52160C and 52161C). For more information, visit the NIST Calibration website at http://ts.nist.gov/MeasurementServices/Calibrations and follow the links to Electromagnetic and then to Impedance Measurements.

7. REPORT OF CALIBRATION

The REPORT OF CALIBRATION returned to each standard capacitor calibration customer contains a brief introductory description, a table of test results, a table of test conditions, a signatory line, and a fact sheet describing the measurement service. A sample REPORT OF CALIBRATION for each calibration service (fused-silica standard capacitor, nitrogen gas standard capacitor, and low accuracy nitrogen gas standard capacitor) is included in the Appendix.

All customer standard capacitor calibration information and reports are stored in the Quantum Electrical Metrology Division ISSC. Additionally, all calibration measurement data and spreadsheet data are stored on division computers. Please refer to the division Quality Manuals for information on calibration procedures and equipment maintenance information.

8. REFERENCES

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APPENDICES

A. REPORT OF CALIBRATION for a 100 pF fused-silica standard capacitor under NIST test ID 52130C/52131C
B. REPORT OF CALIBRATION for a 1000 pF nitrogen gas standard capacitor under NIST test ID 52140C/52141C
C. REPORT OF CALIBRATION for a 100 pF nitrogen gas standard capacitor (low accuracy) under NIST test ID 52160C/52161C
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E. Calibration procedure for three-terminal fused-silica standard capacitors
F. Calibration procedure for high-accuracy three-terminal nitrogen gas standard capacitors
G. Calibration procedure for low-accuracy three-terminal nitrogen gas standard capacitors

APPENDIX A

REPORT OF CALIBRATION

Standard Capacitor

Andeen-Hagerling, Inc., Model AH11A
Serial Number 01234
AH1100 Enclosure Serial Number 00068

Submitted by:

XYZ Laboratory
Gaithersburg, MD 20899-8172

This standard capacitor was calibrated between January 31 and March 3, 2006. The measurement conditions are given in Table 1. The results are reported in Table 2. These values are based on at least five independent comparisons of this standard with NIST capacitance standards that are traceable to the SI, as described on the attached fact sheet.

The reported expanded uncertainties are consistent with international practice and are given by $U = 2\,u_c$, where u_c is the relative combined standard uncertainty for all known sources of error and 2 is the coverage factor. The expanded uncertainty contains allowances for short-term drift of the reference and test standards, thermal and mechanical errors of the test standard, and linearity errors and loading errors of the bridge. The expanded uncertainties contain no allowance for long-term drift of the standard under calibration or for the possible effects of transporting the standard between laboratories.

Additional information is given in the attached fact sheet.

Table 1. Test conditions

Date the standard arrived at NIST	January 25, 2006
Condition of the standard upon arrival	No visible damage
NIST SP250 Test Number(s)	52130C, 52131C
Mean Enclosure Temperature	32.2 ºC
Enclosure Temperature Variation	0.4 ºC
Mean ambient temperature during measurements	22.94 ºC ± 0.1 ºC
Mean relative humidity during measurements	33 % ± 5 %

Measurements performed by:

Andrew D. Koffman, Electronics Engineer
Quantum Electrical Metrology Division

For the Director,

Gerald J. FitzPatrick, Group Leader
Quantum Electrical Metrology Division

Table 2. Test results

Frequency (kHz ± 0.01 %)	Capacitance (pF)	Type A Uncertainty (µF/F)	Expanded Uncertainty (µF/F) (k=2)
0.05	100.00032	0.32	1.64
0.08	100.00032	0.20	0.99
0.1	100.00032	0.15	0.77
0.16	100.00033	0.10	0.57
0.2	100.00033	0.08	0.51
0.32	100.000327	0.06	0.41
0.4	100.000326	0.05	0.35
0.6	100.000329	0.04	0.28
0.8	100.000329	0.03	0.24
1.0	100.000330	0.03	0.21
1.6	100.000332	0.03	0.19
2.0	100.000332	0.03	0.20
3.0	100.000332	0.03	0.24
4.0	100.000332	0.04	0.29
6.0	100.000335	0.05	0.40
8.0	100.00035	0.07	0.54
10.0	100.00036	0.10	0.72
12.0	100.00039	0.16	1.08
16.0	100.00042	0.22	1.54
20.0	100.00048	0.34	2.35

Fact Sheet: NIST Measurement of Fused-Silica Dielectric Capacitors

Representation of the Unit of Capacitance

As a result of the absolute measurements of the farad in terms of the units of length and time, the legal unit of capacitance was established at NIST/NBS in 1975 [1], and re-established in 1989 [2]. Since that time, the reported values of capacitance reflect the values assigned to NIST standards used for the maintenance of the legal unit. Since 1989, the difference between the NIST unit, which includes an allowance for possible drift, and the farad is believed to be less than or equal to ± 0.1 part in 10^6.

Fused-Silica Dielectric Standard Capacitors

Three-terminal standard capacitors of fused-silica dielectric are calibrated using an automatic capacitance bridge as a transfer standard. Fused-silica reference standard capacitors that are periodically characterized against NIST 10 pF fused-silica primary standards [3] are measured at all test frequencies immediately prior to measuring the standard under test using the same automatic capacitance bridge. The frequency dependence of the reference standards are determined using the method described in reference [4]. The difference between the measured and characterized values of the reference standard is added to the measured value of the standard under test to produce the calibration value of the standard under test.

The reported value is the mean of the result of five or more measurements with the standard under test connected to the capacitance bridge as a two-terminal-pair admittance [5]. All standard capacitors must be in the calibration laboratory for at least 72 hours prior to measurement. The average ambient temperature of the laboratory is 23.0 ± 1.0 ºC with hourly variations of about 0.1 ºC. The relative humidity in the laboratory varies but does not exceed 50 %.

For standards with an air bath temperature well, the temperature at measurement is taken using a platinum resistance thermometer placed in the well of the bath. The Type B uncertainty of the measured temperatures is estimated to be 0.002 ºC. For best accuracy of measurement for standards with an air bath temperature well, corrections for the capacitance value are required if the temperature of the air bath is changed significantly. If it is not possible to apply corrections for the temperature differences, the magnitude of the errors usually can be estimated from information supplied by the manufacturer, and the uncertainty of the measurement increased accordingly.

Uncertainties

The reported value of capacitance is in terms of the NIST unit of capacitance maintained with a group of stable standards [3]. The reported uncertainty, consistent with practice recommended by the International Bureau of Weights and Measures (BIPM), is the expanded uncertainty, $U = k\,u_c$, where u_c is the relative combined standard uncertainty for all known sources of error and k is a coverage factor. Consistent with international practice, NIST uses a coverage factor of $k = 2$. The expanded uncertainty is thus given by

$$U = 2\,u_c = 2\sqrt{\sum u_i^{\,2}}$$

where u_i is the estimated relative standard uncertainty associated with the i^{th} source of error and expressed as an equivalent standard deviation. One component is an estimated Type A standard uncertainty based on the standard deviation of the mean of five or more individual measurements. The uncertainty contains no allowances for the long-term drift of the standard under calibration or for the possible effects of transporting the standard between laboratories. Details of the NIST method of expressing uncertainties can be found in reference [6].

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[4] Y. Wang, "*Frequency dependence of capacitance standards*," Review of Scientific Instruments, Vol. 74, No. 9, September 2003.

[5] A.M. Thompson, "*The Precise Measurement of Small Capacitances*," IRE Trans. on Instr., Vol. I-7, No. 3 & 4, pp. 245-255, Dec. 1958.

[6] B.N. Taylor and C.E. Kuyatt, "*Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results*," NIST Tech. Note No. 1297, September 1994.

APPENDIX B

REPORT OF CALIBRATION

Standard Capacitor

General Radio Company, Model 1404-A
Serial Number 2316

Submitted by:

NIST
Gaithersburg, MD 20899

This standard capacitor was calibrated between June 29 and July 19, 2006. The measurement conditions are reported in Table 1. The results are given in Table 2. The values are based on at least five independent comparisons of this standard with NIST capacitance standards that are traceable to the SI unit of capacitance, as described on the attached fact sheet.

The reported expanded uncertainties are consistent with international practice and are given by $U = 2\,u_c$, where u_c is the relative combined standard uncertainty for all known sources of error and 2 is the coverage factor. The expanded uncertainty contains allowances for short-term drift of the reference and test standards, thermal and mechanical errors of the test standard, and linearity errors of the bridge. The expanded uncertainties contain no allowance for long-term drift of the standard under calibration, for loading effects of the automatic capacitance bridge, or for the possible effects of transporting the standard between laboratories.

Additional information is given in the attached fact sheet.

Table 1. Test conditions

Date the standards arrived at NIST	June 22, 2006
Condition of the standards upon arrival	No visible damage
NIST SP250 Test Number(s)	52140C, 52141C
Mean ambient temperature during measurements	22.85 ± 0.1 ºC
Mean relative humidity during measurements	32 ± 5 %

Table 2. Test results

Frequency (kHz ± 0.01 %)	Capacitance (pF)	Expanded Uncertainty (µF/F) (k=2)
0.05	1000. 1301	4.5
0.1	1000.1253	3.6
0.4	1000.1162	2.6
1.0	1000.1147	2.2
1.6	1000.1180	2.2

Measurements performed by:

For the Director,

Andrew D. Koffman, Electronics Engineer
Quantum Electrical Metrology Division

Gerald J. FitzPatrick, Group Leader
Quantum Electrical Metrology Division

Test Report No.: 817/275555-06

Reference: 7654321
Date: July 31, 2006
Telephone Contact: 301-975-4221

Fact Sheet: NIST Measurement of Nitrogen Dielectric Standard Capacitors

Representation of the Unit of Capacitance

As a result of the absolute measurements of the farad in terms of the units of length and time, the legal unit of capacitance was established at NIST/NBS in 1975 [1], and re-established in 1989 [2]. Since that time, the reported values of capacitance reflect the values assigned to NIST standards used for the maintenance of the legal unit. Since 1989, the difference between the NIST unit, which includes an allowance for possible drift, and the farad is believed to be less than or equal to ± 0.1 part in 10^6.

Nitrogen Dielectric Standard Capacitors

Three-terminal standard capacitors of nitrogen dielectric are calibrated using an automatic capacitance bridge as a transfer standard. Fused-silica reference standard capacitors with known frequency dependence [3] that are periodically characterized against NIST 10 pF fused-silica primary standards [4] are measured at all test frequencies immediately prior to measuring the standard under test using the automatic capacitance bridge. The difference between the measured and characterized values of the reference standard is added to the measured value of the standard under test to produce the calibration value of the standard under test.

The reported value is the mean of the result of five or more measurements. If the terminals of the standard under test are not two-terminal-pair, connections with negligible impedance are made to make them so [5]. All standard capacitors must be in the calibration laboratory for at least 72 hours prior to measurement. The average ambient temperature of the laboratory is 23.0 ± 1.0 ºC with hourly variations of about 0.1 ºC. The relative humidity in the laboratory varies but calibrations are not performed if the value is above 50 %.

The reported value of capacitance is in terms of the NIST unit of capacitance maintained with a group of stable standards [4]. The expanded uncertainties include allowance for both Type A and Type B uncertainties in the chain of measurements, and are assigned to the capacitance values using a coverage factor k = 2 [6]. The expanded uncertainty is thus given by

$$U = 2\, u_c = 2\sqrt{\sum u_i^{2}}$$

where u_i is the estimated relative standard uncertainty associated with the i^{th} source of error and expressed as an equivalent standard deviation. The uncertainty values do not include any uncertainty components that may be associated with long-term instability, temperature hysteresis, changes due to stresses incurred during shipment, or loading effects of the capacitance bridge.

References

[1] R.D. Cutkosky, "*New NBS Measurements of the Absolute Farad and Ohm*," IEEE Trans. on Instrumentation and Measurements, Vol. IM 23, No. 4, Dec. 1974.

[2] J.Q. Shields, R.F. Dziuba, and H.P. Layer, "*New Realization of the Ohm and Farad Using the NBS Calculable Capacitor*," IEEE Trans. on Instrumentation and Measurements, Vol. IM 38, No. 2, pp. 249-251, Apr. 1989.

[3] Y. Wang, "*Frequency dependence of capacitance standards*," Review of Scientific Instruments, Vol. 74, No. 9, September 2003.

[4] R.D. Cutkosky and L.H. Lee, "*Improved Ten-picofarad Fused Silica Dielectric Capacitor*," Journal of Research NBS, Vol. 69C, No. 3, July & Sept. 1965.

[5] A.M. Thompson, "*The Precise Measurement of Small Capacitances*," IRE Trans. on Instr., Vol. I-7, No. 3 & 4, pp. 245-255, Dec. 1958.

[6] B.N. Taylor and C.E. Kuyatt, "*Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results*," NIST Tech. Note No. 1297, September 1994.

APPENDIX C

REPORT OF CALIBRATION

Standard Capacitor

General Radio Company, Model 1404-B
Serial Number 517

Submitted by:

XYZ Laboratory
Gaithersburg, MD 20899-8172

This standard capacitor was calibrated between March 1 and July 9, 2006. The results are reported in Table 1. The measurement conditions are given in Table 2. The values are based on at least three independent comparisons of this standard with NIST capacitance standards that are traceable to the SI unit of capacitance, as described on the attached Fact Sheet.

The test conditions are summarized in Table 2 and additional information is given in the attached Fact Sheet.

Table 1. Test results

Frequency (kHz ± 0.01 %)	Capacitance (pF)	Expanded Uncertainty (µF/F) (k=2)
0.1	99.9998	25
0.4	99.9995	25
1.0	99.9994	25

Table 2. Test conditions

Date the standard arrived at NIST	February 25, 2006
Condition of the standard upon arrival	No visible damage
NIST SP250 Test Number(s)	52160C, 52161C
Mean ambient temperature during measurements	23.0 ± 1.0 ºC
Mean relative humidity during measurements	33 ± 10 %

Measurements performed by:

Andrew D. Koffman, Electronics Engineer
Quantum Electrical Metrology Division

For the Director,

Gerald J. FitzPatrick, Group Leader, AEM
Quantum Electrical Metrology Division

Fact Sheet: NIST Measurement of Nitrogen Dielectric Standard Capacitors

Representation of the Unit of Capacitance

As a result of the absolute measurements of the farad in terms of the units of length and time, the legal unit of capacitance was established at NIST/NBS in 1975 [1], and re-established in 1989 [2]. Since that time, the reported values of capacitance reflect the values assigned to NIST standards used for the maintenance of the legal unit. Since 1989, the difference between the NIST unit, which includes an allowance for possible drift, and the farad is believed to be less than or equal to ± 0.1 part in 10^6.

Nitrogen Dielectric Standard Capacitors

Three-terminal standard capacitors of nitrogen dielectric are calibrated using an automatic capacitance bridge as a transfer standard. Fused-silica reference standard capacitors that are periodically characterized against NIST 10 pF fused-silica primary standards [3] are measured at all test frequencies immediately prior to measuring the standard under test using the automatic capacitance bridge. The difference between the measured and characterized values of the reference standard is added to the measured value of the standard under test to produce the calibration value of the standard under test.

The reported value is the mean of the result of three or more measurements. If the terminals of the standard under test are not two-terminal-pair, connections with negligible impedance are made to make them so [4]. All standard capacitors must be in the calibration laboratory for at least 72 hours prior to measurement. The average ambient temperature of the laboratory is 23.0 ± 1.0 ºC with hourly variations of about 0.1 ºC. The relative humidity in the laboratory varies but does not exceed 60 %.

The reported value of capacitance is in terms of the NIST unit of capacitance maintained with a group of stable standards [3]. The expanded uncertainties include allowance for both Type A and Type B uncertainties in the chain of measurements. The reported expanded uncertainties are consistent with international practice and are given by $U = 2\,u_c$, where u_c is the relative combined standard uncertainty for all known sources of error and 2 is the coverage factor [5]. The expanded uncertainty contains allowances for short-term drift of the reference and test standards, thermal and mechanical errors of the test standard, and linearity errors of the bridge. The expanded uncertainties contain no allowance for long-term drift of the standard under calibration, for temperature hysteresis, for loading effects of the automatic capacitance bridge, or for changes due to stresses incurred during shipment.

References

[1] R.D. Cutkosky, "*New NBS Measurements of the Absolute Farad and Ohm*," IEEE Trans. on Instrumentation and Measurements, Vol. IM 23, No. 4, Dec. 1974.

[2] J.Q. Shields, R.F. Dziuba, and H.P. Layer, "*New Realization of the Ohm and Farad Using the NBS Calculable Capacitor*," IEEE Trans. on Instrumentation and Measurements, Vol. IM 38, No. 2, pp. 249-251, Apr. 1989.

[3] R.D. Cutkosky and L.H. Lee, "*Improved Ten-picofarad Fused Silica Dielectric Capacitor*," Journal of Research NBS, Vol. 69C, No. 3, July & Sept. 1965.

[4] A.M. Thompson, "*The Precise Measurement of Small Capacitances*," IRE Trans. on Instr., Vol. I-7, No. 3 & 4, pp. 245-255, Dec. 1958.

[5] B.N. Taylor and C.E. Kuyatt, "*Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results*," NIST Tech. Note No. 1297, September 1994.

APPENDIX D

AH2700A Capacitance Bridge Accuracy for 1 pF, 10 pF, 100 pF, and 1000 pF Standards[‡]

Frequency (Hz)	1 pF Bridge Accuracy (µF/F)	10 pF Bridge Accuracy (µF/F)	100 pF Bridge Accuracy (µF/F)	1000 pF Bridge Accuracy (µF/F)
50	62.0	18.8	14.5	14.5
80	30.9	12.4	10.5	10.5
100	23.1	10.5	9.2	9.2
160	13.6	7.9	7.3	7.3
200	11.1	7.1	6.7	6.7
320	8.0	6.0	5.8	5.8
400	7.1	5.6	5.5	5.5
600	6.2	5.3	5.2	5.2
800	5.9	5.2	5.1	5.1
1000	5.8	5.1	5.0	5.0
1600	6.4	5.4	5.2	5.2
2000	7.1	5.6	5.4	5.4
3000	9.2	6.5	5.9	5.9
4000	12.0	7.5	6.5	6.6
6000	19.7	10.1	7.9	8.1
8000	30.2	13.5	9.6	9.9
10000	43.4	17.5	11.4	12.0
12000	59.3	22.1	13.4	14.5
16000	99.2	33.5	18.1	20.3
20000	150.1	47.6	23.6	27.5

[‡] AH2700A specifications obtained from ah2700aSpecCalculator.xls spreadsheet downloaded from Andeen-Hagerling web site www.andeen-hagerling.com.

APPENDIX E

Calibration procedure for three-terminal fused-silica standard capacitors

Arrival of Standards

Standards arrive at the division shipping room. The division shipping specialist documents any issues involving unusual shipping circumstances and transports the standards to the Impedance Calibration Laboratory (ICL). Calibration personnel should coordinate with shipping staff to assure that improper handling during customer packing or shipping is documented and communicated to the customer prior to performing the calibration.

Calibration staff logs standard artifacts into the customer log book in the ICL. Customer name, address, contact name and telephone number, standard model number, standard serial number, NIST test ID number (52130C/52131C), frequencies required for calibration, the date of arrival at NIST, and the date of power-up of the standard, are documented in the customer log book. During the calibration period, the dates of measurement, and the date of report submission are recorded in the customer log book. Any comments pertaining to the calibration, such as whether connectors arrived with the standard or whether any irregularities were noticed upon arrival, requiring customer contact, are also noted in the customer log book. Date of return shipment is documented by the Calibration Coordinator.

Standards are placed at the capacitance calibration workstation in the ICL and powered up for at least 72 hours prior to calibration to allow for temperature stabilization. Standards are not moved during the period of calibration. Laboratory temperature is maintained at 22.9 °C. Stabilization requires that laboratory temperature not vary more than 0.3 °C during the previous 72 hours. Laboratory relative humidity must remain below 50 % in order to perform calibration measurements. Customer standards without BNC connectors require BNC adapters to be fixed on the terminals of the standard.

General Information

Commercial three-terminal (3T) fused-silica standard capacitors are typically housed in a temperature-controlled enclosure to maintain stability of the capacitance. There are two predominant types of fused-silica standard capacitors that are calibrated in the Impedance Calibration Laboratory at NIST. They are an older type of standard without a temperature readout, having values of 10 pF or 100 pF, and a newer type with a built-in temperature readout, having values of 1 pF, 10 pF, or 100 pF. The temperature of the enclosure must be recorded at the time of measurement, regardless of the model. Therefore, the older type of standard requires calibration staff to place a standard platinum resistance thermometer (SPRT) inside the well of the enclosure in order to record the temperature. An automatic resistance thermometry bridge is used to measure the SPRT resistance at the time of measurement on all days when calibration measurements are performed. The resistance value taken from the thermometry bridge is converted into a temperature. The mean and variation of the enclosure temperature, along with the laboratory mean ambient temperature and mean relative humidity are recorded on the Report of Calibration.

Fused-silica standard capacitors can be calibrated at the following frequencies (listed in Hertz): 50, 80, 100, 160, 200, 300, 400, 600, 800, 1000, 1600, 2000, 3000, 4000, 6000, 8000, 10000, 12000, 16000, and 20000.

Reference three-terminal fused-silica standard capacitors with nominal values 100 pF, 10 pF, and 1 pF are calibrated against the NIST primary bank of 10 pF fused-silica standard capacitors at 1592 Hz at least once per year.

Technical Procedures

Calibration of three-terminal fused-silica standard capacitors is performed using an AH2700A automatic capacitance bridge. A calibration consists of the mean of at least five separate capacitance measurements taken on different days over approximately two weeks. Stray capacitance, that is, capacitance across the low-to-ground terminals and high-to-ground terminals of the standard capacitor under test, is also measured one time during the calibration period, to allow for correction of the calibrated value of capacitance.

For each of the five measurements, the standard under test is measured and the NIST reference standard capacitor of the same nominal value is measured on the same work day. The difference between the measured value of the reference standard and the calibrated value of the reference standard is used as a substitutionary correction to the measured value of the standard under test.

To perform a measurement on a standard capacitor, connect the coaxial BNC cables from the AH2700A capacitance bridge controlled by the computer at the capacitance calibration workstation, to the standard capacitor to be measured. Check to be sure the red connector on either end of the cables is fixed to the high terminal of the bridge and of the standard, and the blue connector at either end is fixed to the low terminal of the bridge and of the standard. Open the LabVIEW program library entitled C:\LabVIEW_VIs\ah2700a.llb. Select the VI (virtual instrument) named AH2700A_Cap_Calibration.vi.

This program performs capacitance and loss measurements at the 20 frequencies listed above. Ten measurements are averaged for each frequency. The mean and standard deviation of the measurements at each frequency are shown on the front panel of the VI and are saved in a text file under C:\calibrations\FreqDep\'mmmyy'\c*Model_SerialNumber_MMDDYY_Time*.txt.

On the front panel of the VI, select the nominal value of the standard to be measured, select the model of the standard to be measured, enter the serial number of the standard to be measured, and run the VI. The VI will prompt the user to verify that the name of the file to be saved is satisfactory. Click on the 'OK' button and the program will run over approximately the next 20 minutes. When the customer standard has been measured, repeat the measurement procedure for the NIST reference standard of the same nominal value as the customer standard. Multiple customer values of the same nominal value require only one corresponding measurement of the NIST reference standard.

Enter the data into a spreadsheet file following the templates in the directory C:\calibrations\AHData and store the spreadsheet in the directory C:\calibrations\AHData\FusedSilicaResults\c*Model_Customer_SerialNumber_MMYY*.xls

Once the measurements are completed, the Report of Calibration must be generated. The ISSC is used to generate the reports for all normal calibrations. The ISSC requires a text file containing the exact data for the Test results table of the Report of Calibration (see Appendix A, Table 2). The text files that are input into the ISSC are stored in the directory C:\calibrations\Reports\Fused-silica\ISSCTextFiles*Model_Customer_SerialNumber_MMYY*.txt.

All calibration files are backed up in the group directory G:\adk\calibrations following the same directory and filename patterns as above. This directory is located on a network server and is regularly backed up.

APPENDIX F

Calibration procedure for high-accuracy three-terminal nitrogen gas standard capacitors

Arrival of Standards

Standards arrive at the division shipping room. The division shipping specialist documents any issues involving unusual shipping circumstances and transports the standards to the Impedance Calibration Laboratory (ICL). Calibration personnel should coordinate with shipping staff to assure that improper handling during customer packing or shipping is documented and communicated to the customer prior to performing the calibration.

Calibration staff logs standard artifacts into the customer log book in the ICL. Customer name, address, contact name and telephone number, standard model number, standard serial number, NIST test ID number (52140C/52141C), frequencies required for calibration, the date of arrival at NIST, and the date of arrival at the ICL, are documented in the customer log book. During the calibration period, the dates of measurement, and the date of report submission are recorded in the customer log book. Any comments pertaining to the calibration, such as whether connectors arrived with the standard or whether any irregularities were noticed upon arrival, requiring customer contact, are also noted in the customer log book. Date of return shipment is documented by the Calibration Coordinator.

Standards are placed in a foam insulating container at the capacitance calibration workstation in the ICL for at least 72 hours prior to calibration to allow for temperature stabilization. Standards are not moved during the period of calibration. Laboratory temperature is maintained at 22.9 °C. Stabilization requires that laboratory temperature not vary more than 0.3 °C during the previous 72 hours. Laboratory relative humidity must remain below 50 % in order to perform calibration measurements. Customer standards without BNC connectors require BNC adapters to be fixed on the terminals of the standard.

General Information

Commercial three-terminal (3T) nitrogen gas standard capacitors have a temperature coefficient of capacitance of several parts in 10^6 and are typically not housed in a temperature-controlled enclosure. Therefore, temperature stability of the laboratory is critical to the calibration. There are two predominant types of commercial nitrogen gas standard capacitors that are calibrated in the Impedance Calibration Laboratory at NIST. One type of standard comes with nominal values of 10 pF, 100 pF, or 1000 pF, and the other type has only the nominal value of 1000 pF.

Nitrogen gas standard capacitors can be calibrated at the following frequencies (listed in Hertz): 50, 80, 100, 160, 200, 300, 400, 600, 800, 1000, 1600, 2000, 3000, 4000, 6000, 8000, 10000, 12000, 16000, and 20000.

Reference three-terminal fused-silica standard capacitors with nominal values 100 pF, 10 pF, and 1 pF are calibrated against the NIST primary bank of 10 pF fused-silica standard capacitors at 1592 Hz at least once per year.

Technical Procedures

Calibration of three-terminal nitrogen gas standard capacitors is performed using an AH2700A automatic capacitance bridge. A calibration consists of the mean of at least five separate capacitance measurements taken on different days over approximately two weeks. For each of the five measurements, the standard under test is measured and the NIST reference standard capacitor of the same nominal value (the 100 pF reference is also used for a 1000 pF calibration) is measured on the same work day. The difference between the measured value of the reference standard and the calibrated value of the reference standard is used as a substitutionary correction to the measured value of the standard under test.

To perform a measurement on a standard capacitor, connect the coaxial BNC cables from the AH2700A capacitance bridge controlled by the computer at the capacitance calibration workstation, to the standard capacitor to be measured. Check to be sure the red connector on either end of the cables is fixed to the high terminal of the bridge and of the standard, and the blue connector at either end is fixed to the low terminal of the bridge and of the standard. Open the LabVIEW program library entitled C:\LabVIEW_VIs\ah2700a.llb. Select the VI (virtual instrument) named AH2700A_Cap_Calibration.vi.

This program performs capacitance and loss measurements at the 20 frequencies listed above. Ten measurements are averaged for each frequency. The mean and standard deviation of the measurements at each frequency are shown on the front panel of the VI and are saved in a text file under C:\calibrations\FreqDep\'mmmyy'\c*Model_SerialNumber_MMDDYY_Time*.txt.

On the front panel of the VI, select the nominal value of the standard to be measured, select the model of the standard to be measured, enter the serial number of the standard to be measured, and run the VI. The VI will prompt the user to verify that the name of the file to be saved is satisfactory. Click on the 'OK' button and the program will run over approximately the next 20 minutes. When the customer standard has been measured, repeat the measurement procedure for the NIST reference standard of the same nominal value as the customer standard. Multiple customer values of the same nominal value require only one corresponding measurement of the NIST reference standard.

Enter the data into a spreadsheet file following the templates in the directory C:\calibrations\AHData and store the spreadsheet in the directory C:\calibrations\AHData\GasResults\c*Model_Customer_SerialNumber_MMYY*.xls

Once the measurements are completed, the Report of Calibration must be generated. The ISSC is used to generate the reports for all normal calibrations. The ISSC requires a text file containing the exact data for the Test results table of the Report of Calibration (see Appendix B, Table 2). The text files that are input into the ISSC are stored in the directory C:\calibrations\Reports\Gas\ISSCTextFiles*Model_Customer_SerialNumber_MMYY*.txt. The laboratory mean ambient temperature and mean relative humidity are recorded on the Report of Calibration.

All calibration files are backed up in the group directory G:\adk\calibrations following the same directory and filename patterns as above. This directory is located on a network server and is regularly backed up.

APPENDIX G

Calibration procedure for low-accuracy three-terminal nitrogen gas standard capacitors

Arrival of Standards

Standards arrive at the division shipping room. The division shipping specialist documents any issues involving unusual shipping circumstances and transports the standards to the Impedance Calibration Laboratory (ICL). Calibration personnel should coordinate with shipping staff to assure that improper handling during customer packing or shipping is documented and communicated to the customer prior to performing the calibration.

Calibration staff logs standard artifacts into the customer log book in the ICL. Customer name, address, contact name and telephone number, standard model number, standard serial number, NIST test ID number (52160C/52161C), frequencies required for calibration, the date of arrival at NIST, and the date of arrival at the ICL, are documented in the customer log book. During the calibration period, the dates of measurement, and the date of report submission are recorded in the customer log book. Any comments pertaining to the calibration, such as whether connectors arrived with the standard or whether any irregularities were noticed upon arrival, requiring customer contact, are also noted in the customer log book. Date of return shipment is documented by the Calibration Coordinator.

Standards are placed in a foam insulating container at the capacitance calibration workstation in the ICL for at least 72 hours prior to calibration to allow for temperature stabilization. Standards are not moved during the period of calibration. Laboratory temperature is maintained at 22.9 °C. Stabilization requires that laboratory temperature not vary more than 0.3 °C during the previous 72 hours. Laboratory relative humidity must remain below 50 % in order to perform calibration measurements. Customer standards without BNC connectors require BNC adapters to be fixed on the terminals of the standard.

General Information

Commercial three-terminal (3T) nitrogen gas standard capacitors have a temperature coefficient of capacitance of several parts in 10^6 and are typically not housed in a temperature-controlled enclosure. Therefore, temperature stability of the laboratory is critical to the calibration. There are two predominant types of commercial nitrogen gas standard capacitors that are calibrated in the Impedance Calibration Laboratory at NIST. One type of standard comes with nominal values of 10 pF, 100 pF, or 1000 pF, and the other type has only the nominal value of 1000 pF.

Nitrogen gas standard capacitors can be calibrated at the following frequencies (listed in Hertz): 50, 80, 100, 160, 200, 300, 400, 600, 800, 1000, 1600, 2000, 3000, 4000, 6000, 8000, 10000, 12000, 16000, and 20000.

Reference three-terminal fused-silica standard capacitors with nominal values 100 pF, 10 pF, and 1 pF are calibrated against the NIST primary bank of 10 pF fused-silica standard capacitors at 1592 Hz at least once per year.

Technical Procedures

Low-accuracy calibration of three-terminal nitrogen gas standard capacitors is performed using an AH2700A automatic capacitance bridge. A calibration consists of the mean of at least two separate capacitance measurements taken on different days. For both of the measurements, the standard under test is measured and the NIST reference standard capacitor of the same nominal value (the 100 pF reference is also used for a 1000 pF calibration) is measured on the same work day. The difference between the measured value of the reference standard and the calibrated value of the reference standard is used as a substitutionary correction to the measured value of the standard under test.

To perform a measurement on a standard capacitor, connect the coaxial BNC cables from the AH2700A capacitance bridge controlled by the computer at the capacitance calibration workstation, to the standard capacitor to be measured. Check to be sure the red connector on either end of the cables is fixed to the high terminal of the bridge and of the standard, and the blue connector at either end is fixed to the low terminal of the bridge and of the standard. Open the LabVIEW program library entitled C:\LabVIEW_VIs\ah2700a.llb. Select the VI (virtual instrument) named AH2700A_Cap_Calibration.vi.

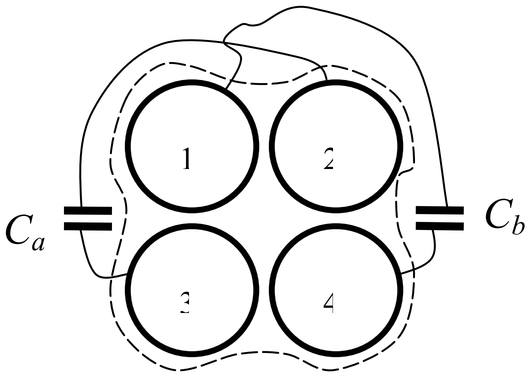
This program performs capacitance and loss measurements at the 20 frequencies listed above. Ten measurements are averaged for each frequency. The mean and standard deviation of the measurements at each frequency are shown on the front panel of the VI and are saved in a text file under C:\calibrations\FreqDep\’mmmyy’\c*Model_SerialNumber_MMDDYY_Time*.txt.

On the front panel of the VI, select the nominal value of the standard to be measured, select the model of the standard to be measured, enter the serial number of the standard to be measured, and run the VI. The VI will prompt the user to verify that the name of the file to be saved is satisfactory. Click on the ‘OK’ button and the program will run over approximately the next 20 minutes. When the customer standard has been measured, repeat the measurement procedure for the NIST reference standard of the same nominal value as the customer standard. Multiple customer values of the same nominal value require only one corresponding measurement of the NIST reference standard.

Enter the data into a spreadsheet file following the templates in the directory C:\calibrations\AHData and store the spreadsheet in the directory C:\calibrations\AHData\25ppmResults\c*Model_Customer_SerialNumber_MMYY*.xls

Once the measurements are completed, the Report of Calibration must be generated. The ISSC is used to generate the reports for all normal calibrations. The ISSC requires a text file containing the exact data for the Test results table of the Report of Calibration (see Appendix B, Table 2). The text files that are input into the ISSC are stored in the directory C:\calibrations\Reports\Gas\ISSCTextFiles*Model_Customer_SerialNumber_MMYY*.txt. The laboratory ambient temperature is reported as 23.0 °C ± 1.0 °C. The mean relative humidity is also recorded on the Report of Calibration.

All calibration files are backed up in the group directory G:\adk\calibrations following the same directory and filename patterns as above. This directory is located on a network server and is regularly backed up.



Fi

g. 1. Four-rod cross capacitor. Dashed line represents a ground shield.

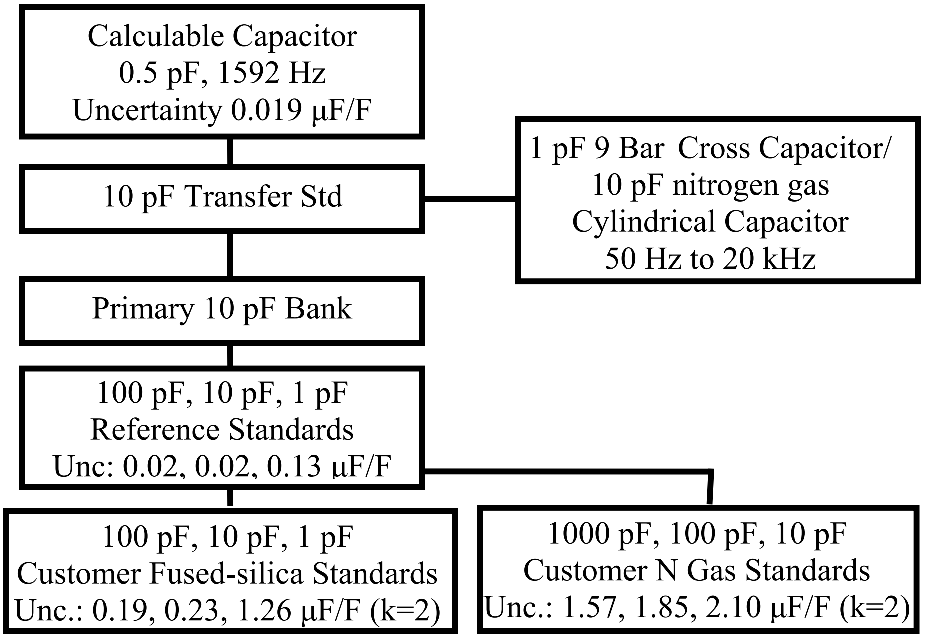


Fig. 2. NIST nitrogen gas and fused-silica standard capacitor traceability chain with 1600 Hz uncertainties.

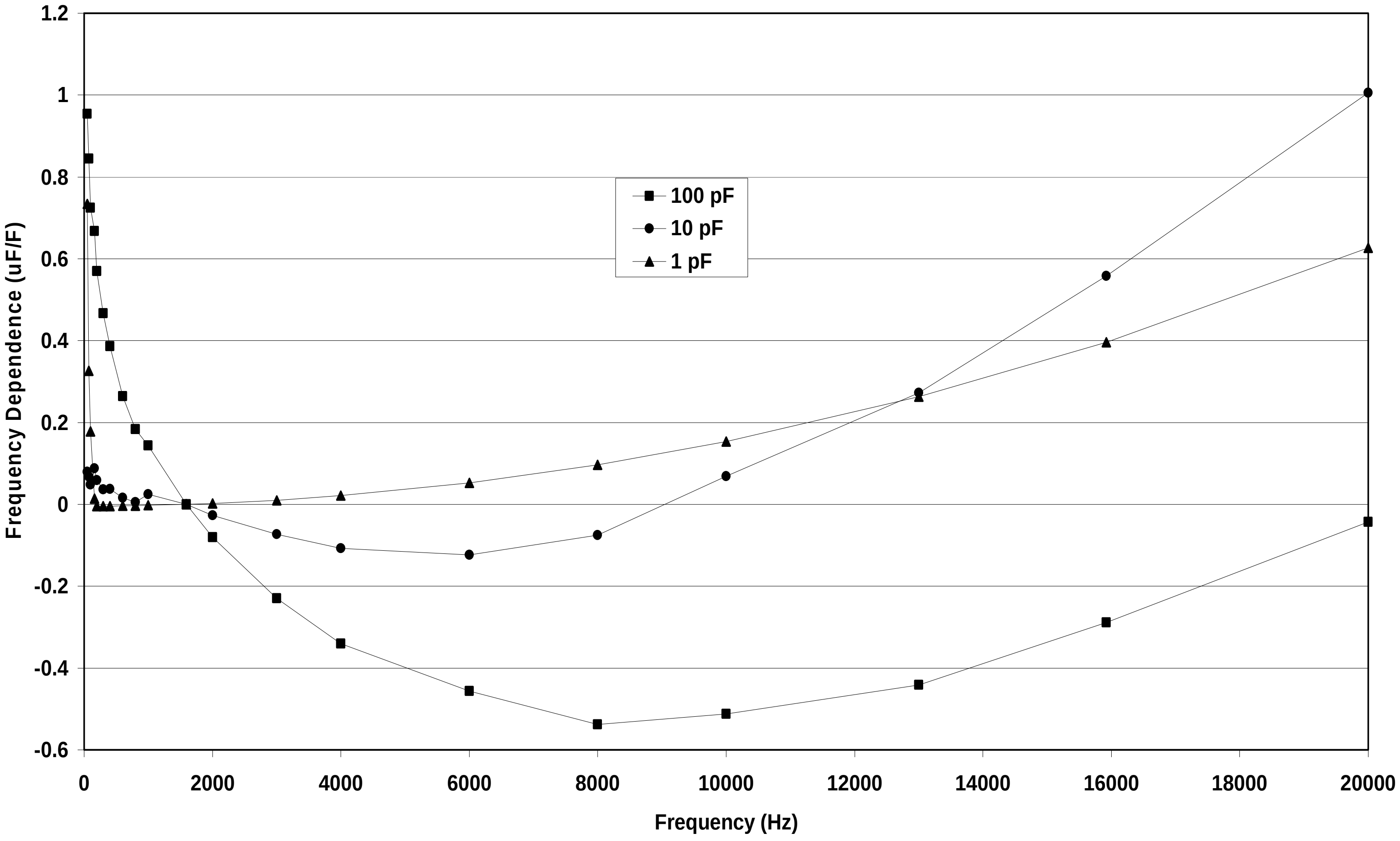


Fig. 3. Frequency dependence of 100 pF, 10 pF, and 1 pF calibration reference standards.

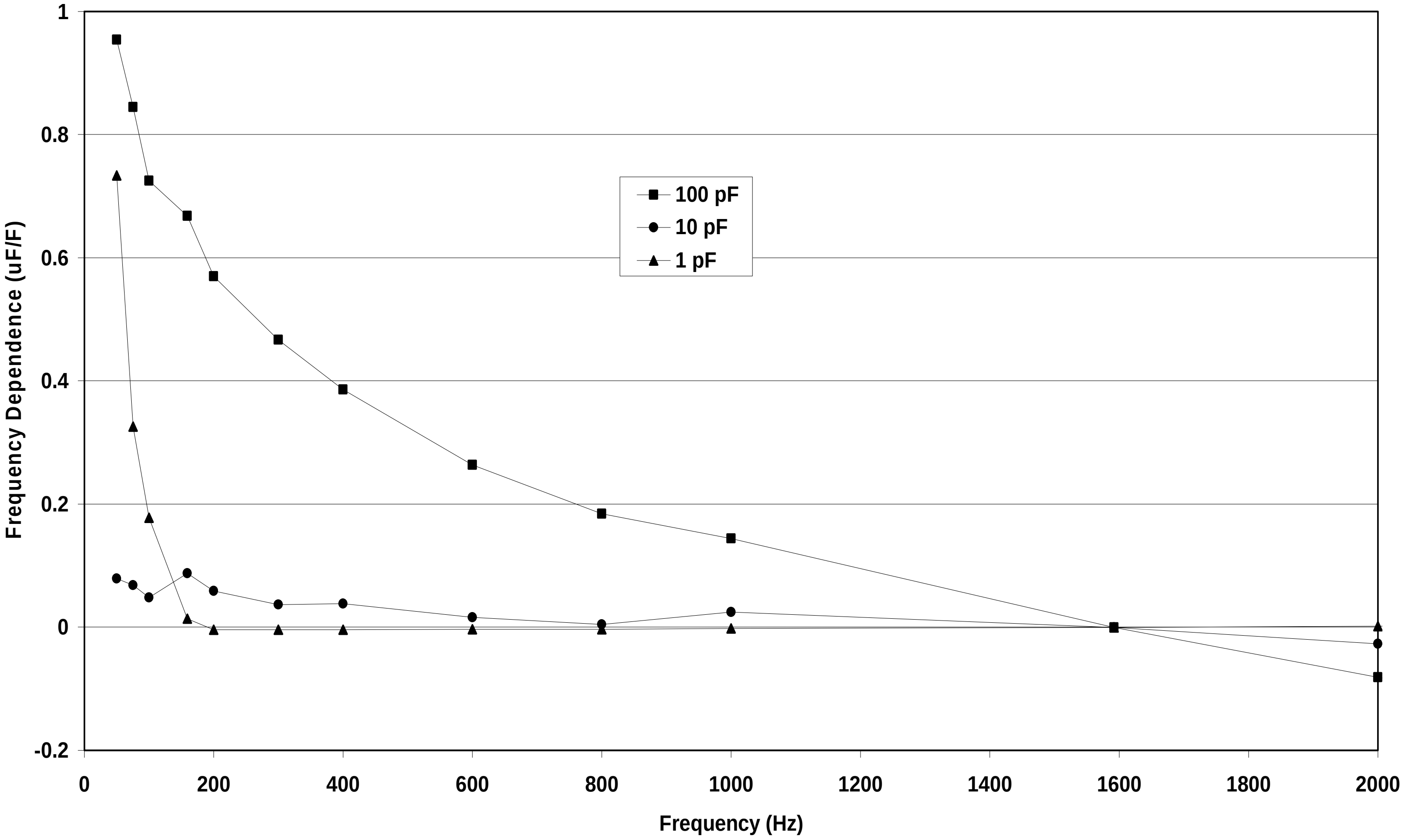


Fig. 4. Low-frequency plot of frequency dependence curves in Fig. 3.

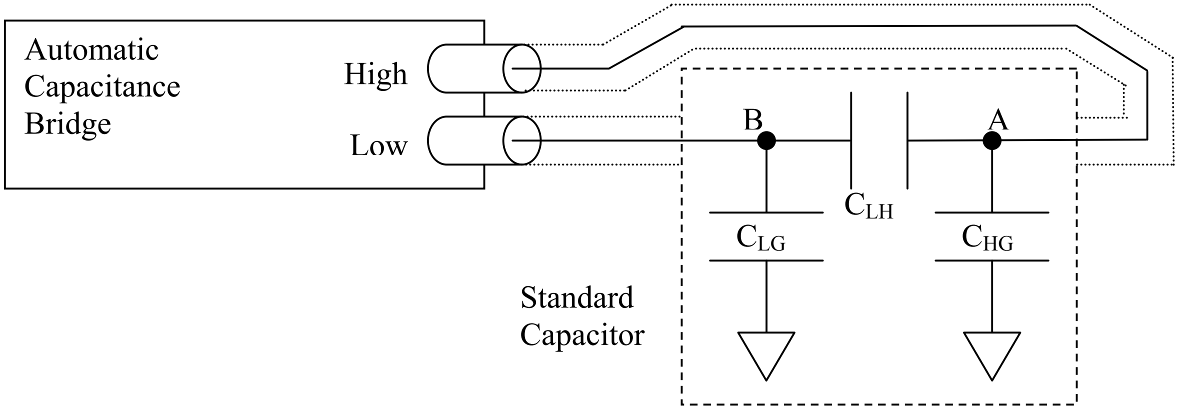


Fig. 5. Measurement of three-terminal standard capacitor using automatic capacitance bridge.

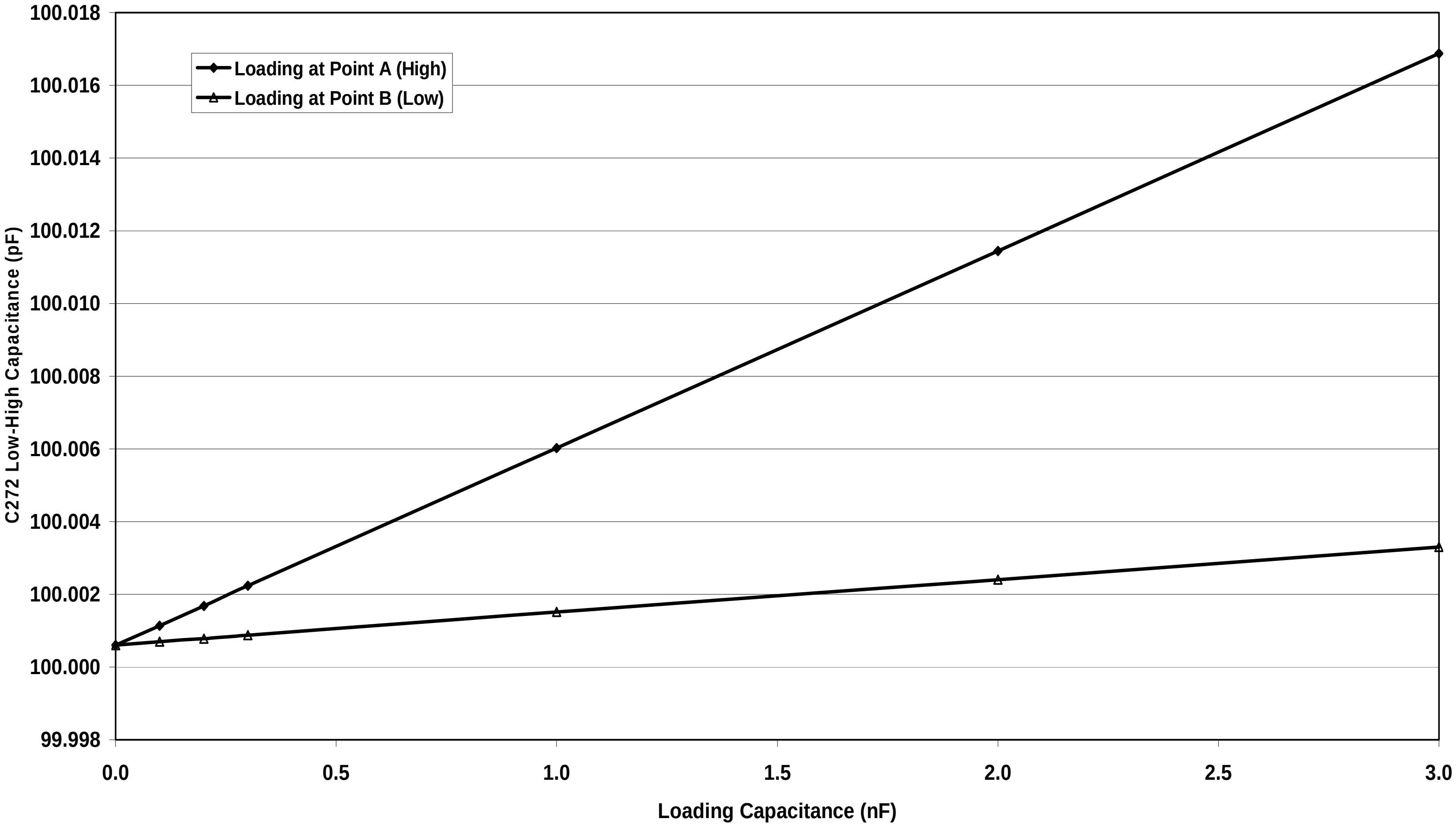


Fig. 6. Bridge loading effects for 100 pF fused-silica reference standard measurements at 20 kHz.

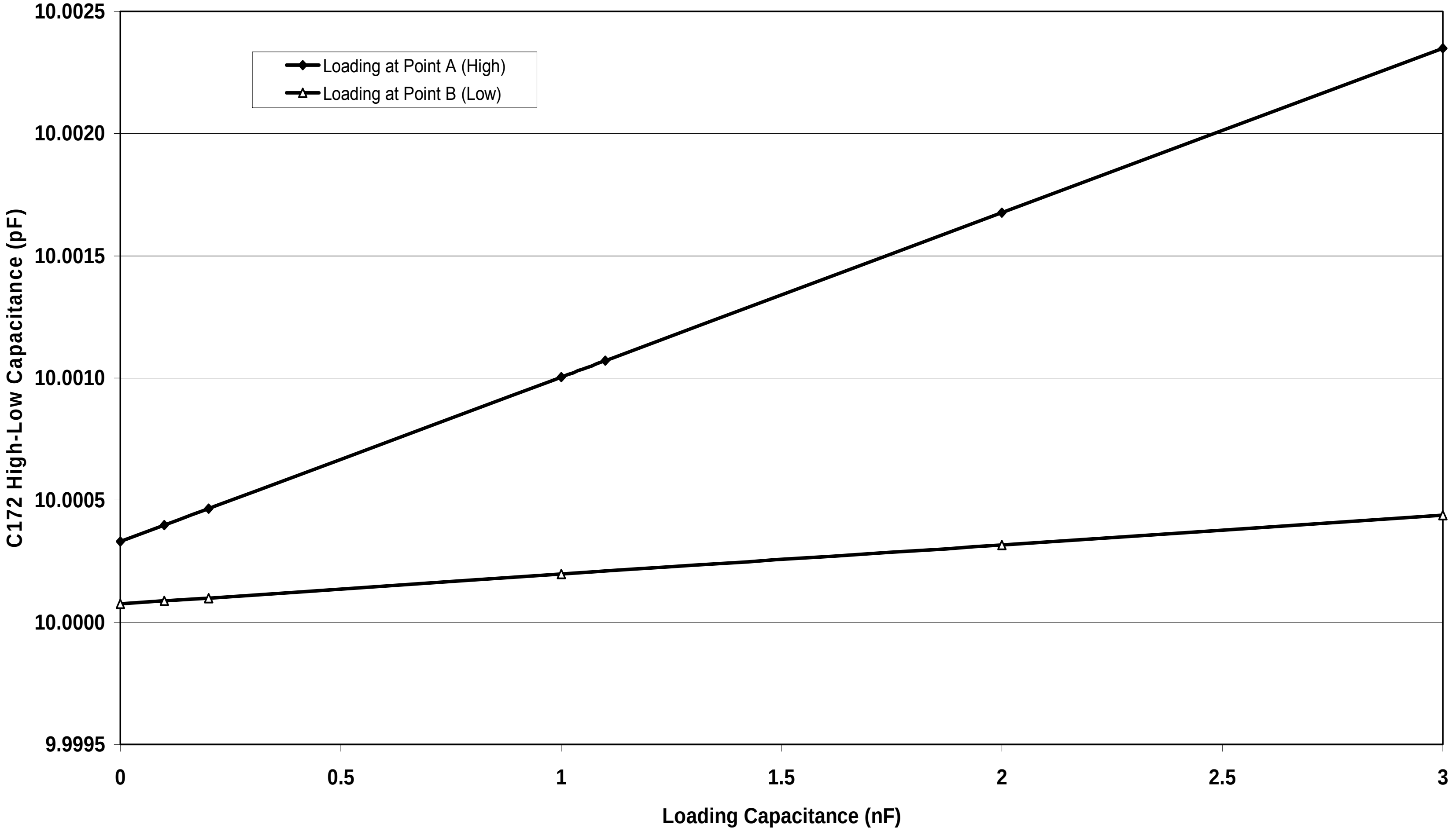


Fig. 7. Bridge loading effects for 10 pF fused-silica reference standard measurements at 20 kHz.

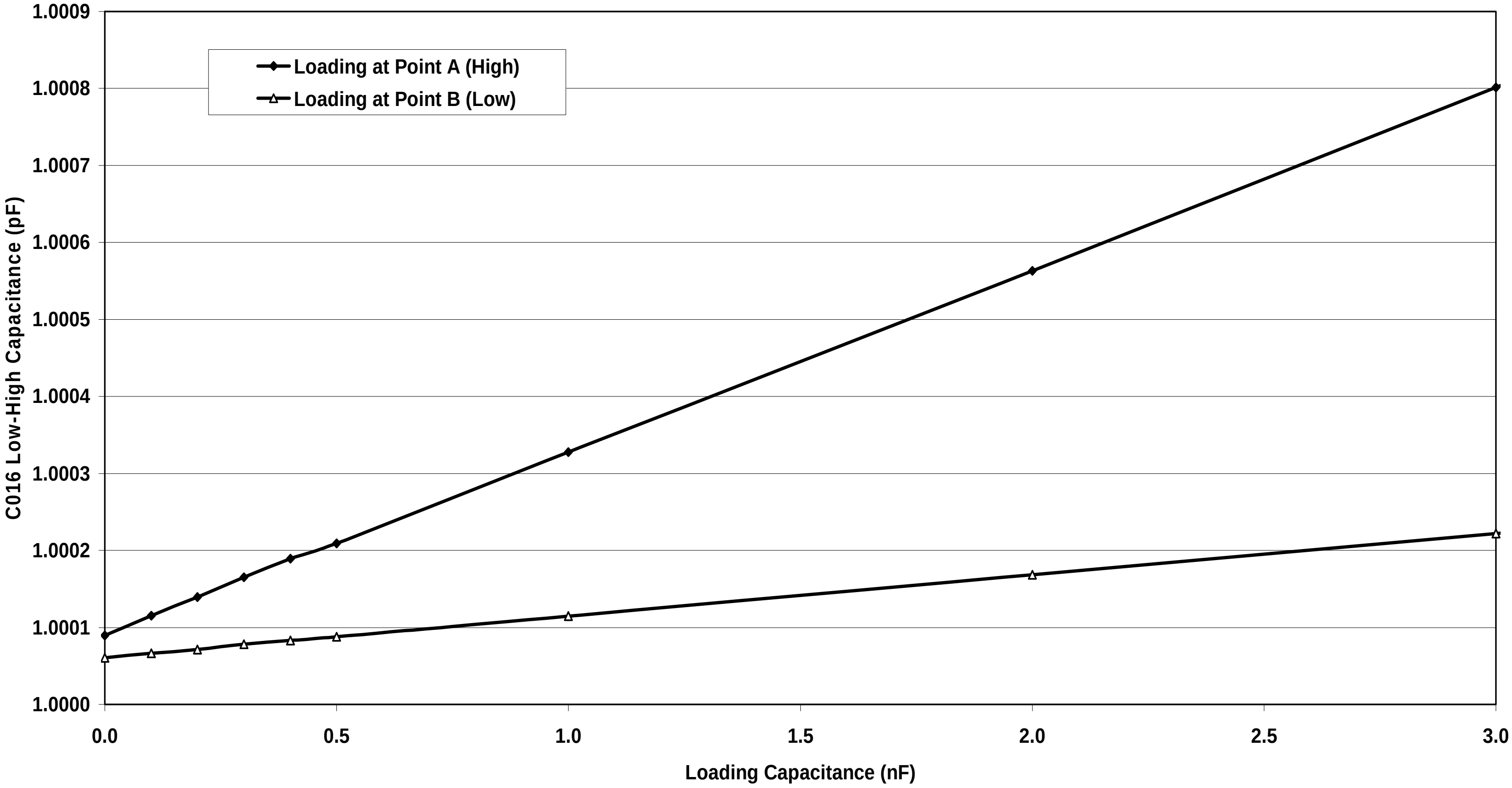


Fig. 8. Bridge loading effects for 1 pF fused-silica reference standard measurements at 20 kHz.

Fig. 9. Photograph of the capacitance bridge, controlling laptop, and reference and customer fused-silica standard capacitors.

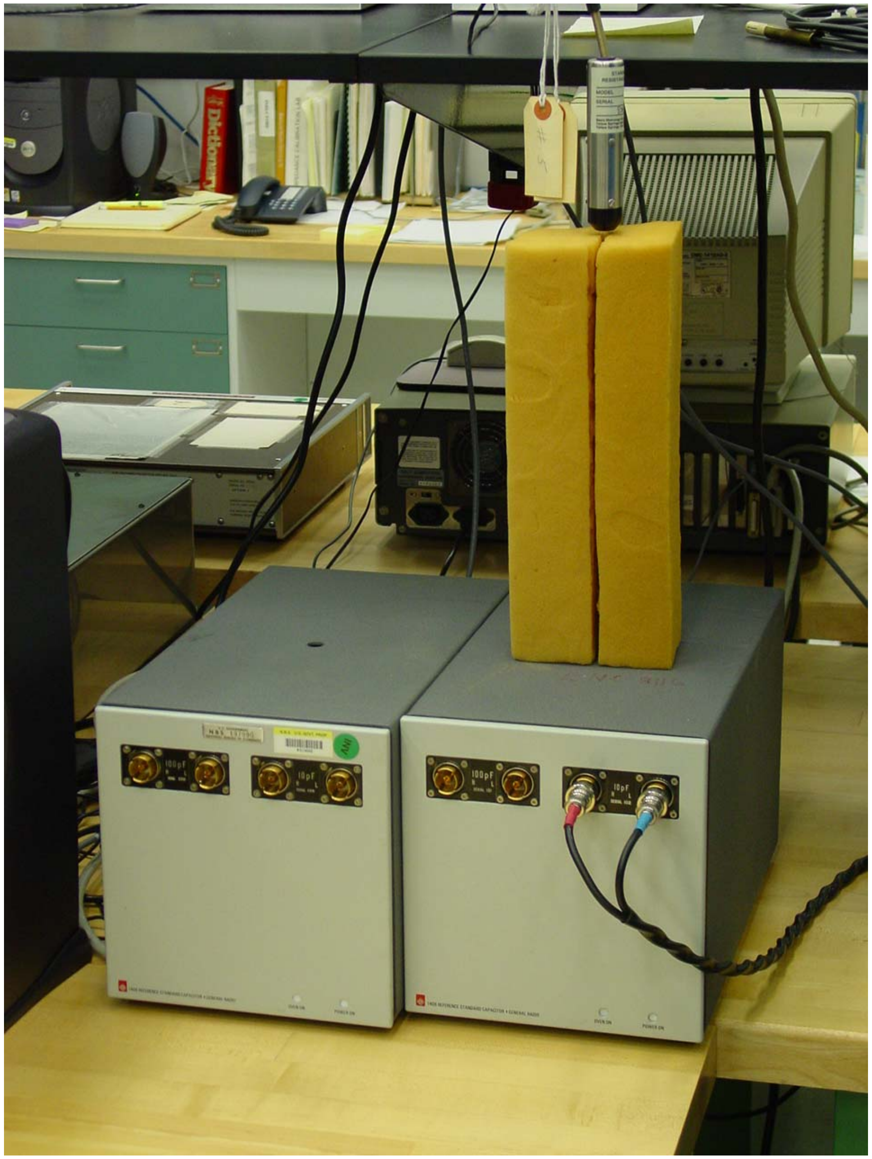


Fig. 10. Photograph of fused-silica standard capacitor enclosures without temperature readouts. Right enclosure contains SPRT.

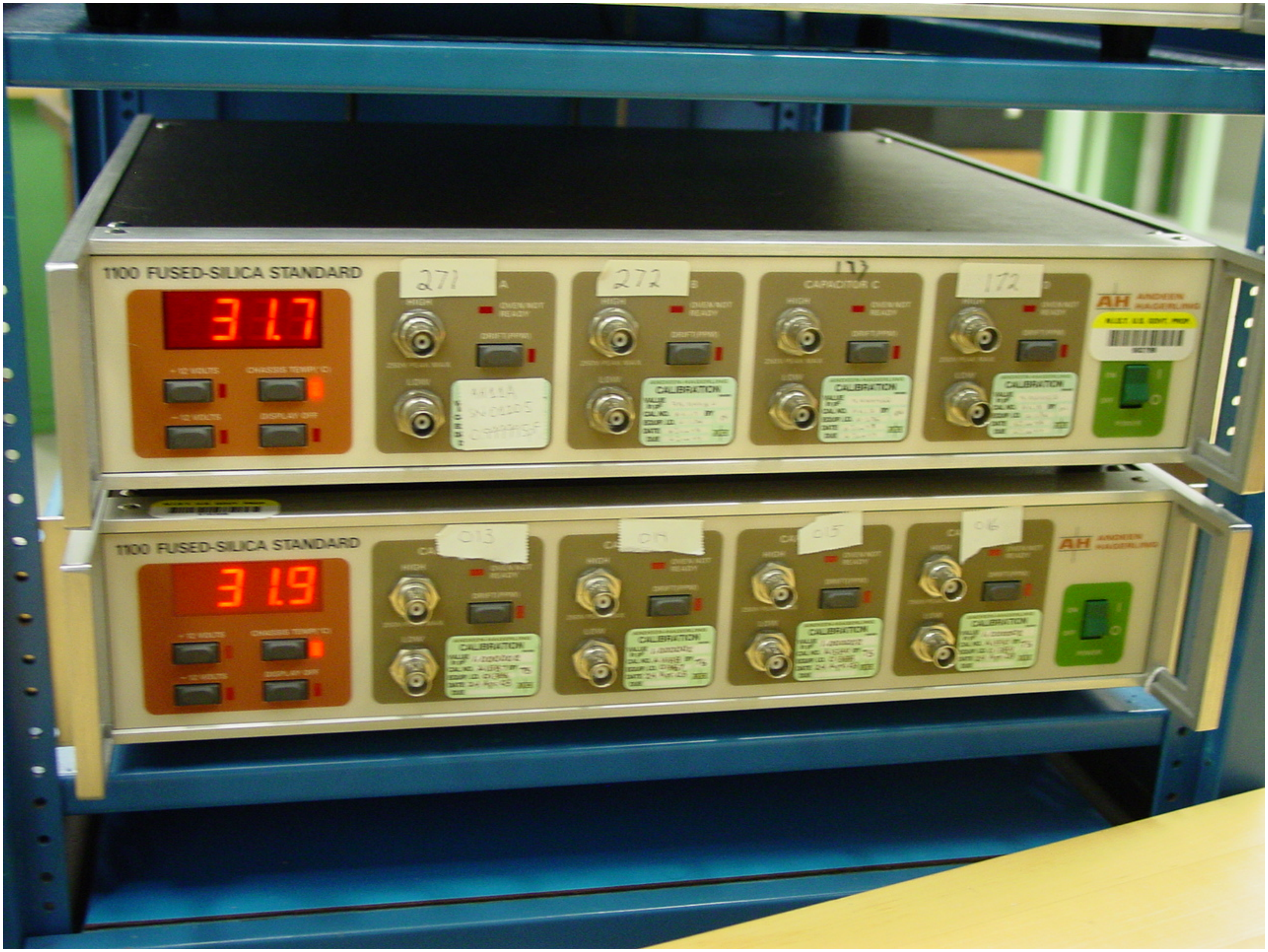


Fig. 11. Photograph of fused-silica standard capacitor enclosures with temperature readouts.

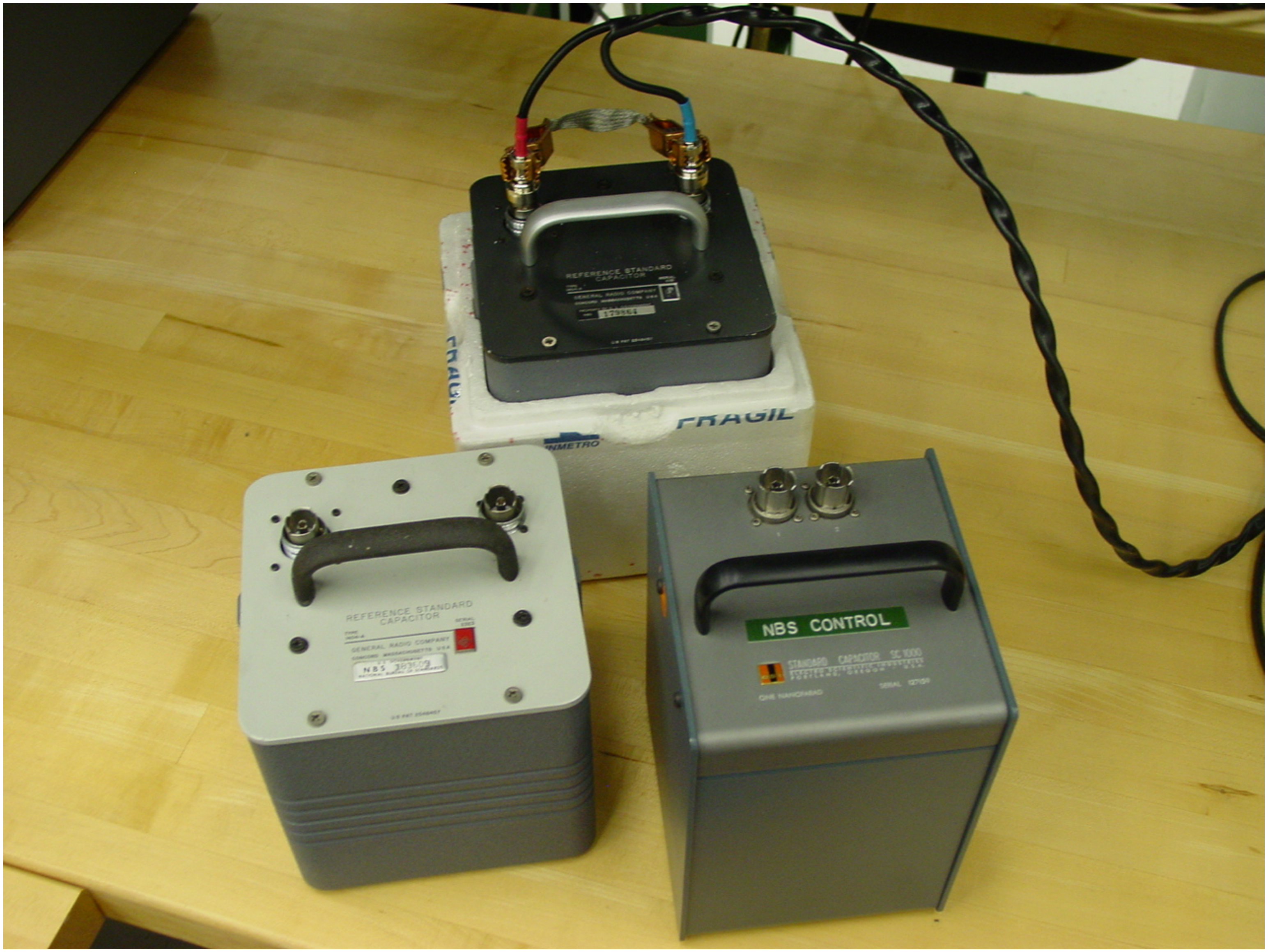


Fig. 12. Photograph of nitrogen gas standard capacitors.

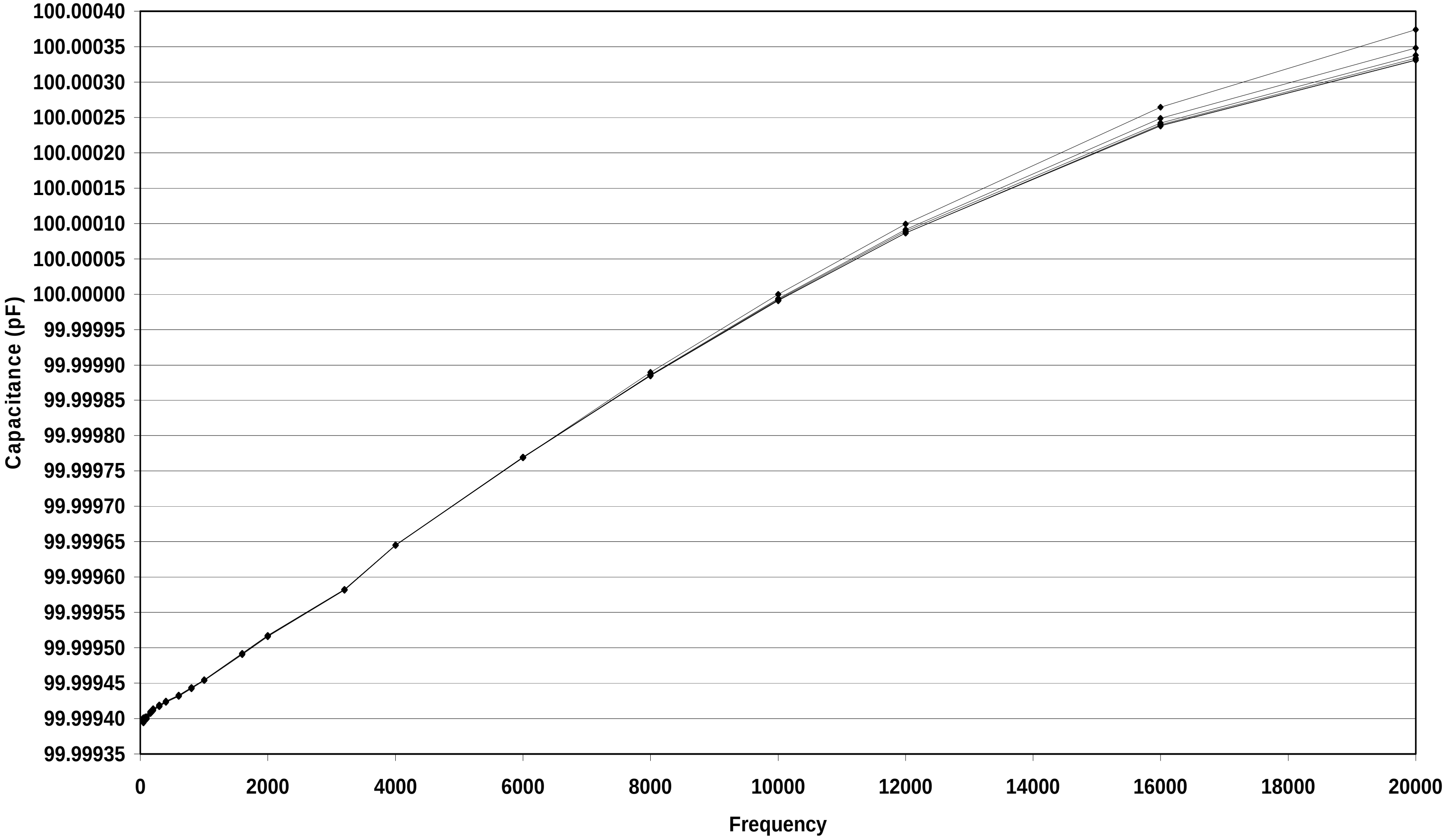


Fig. 13. Short-term stability of 100 pF reference standard (6 bridge measurements taken within 24 hours).

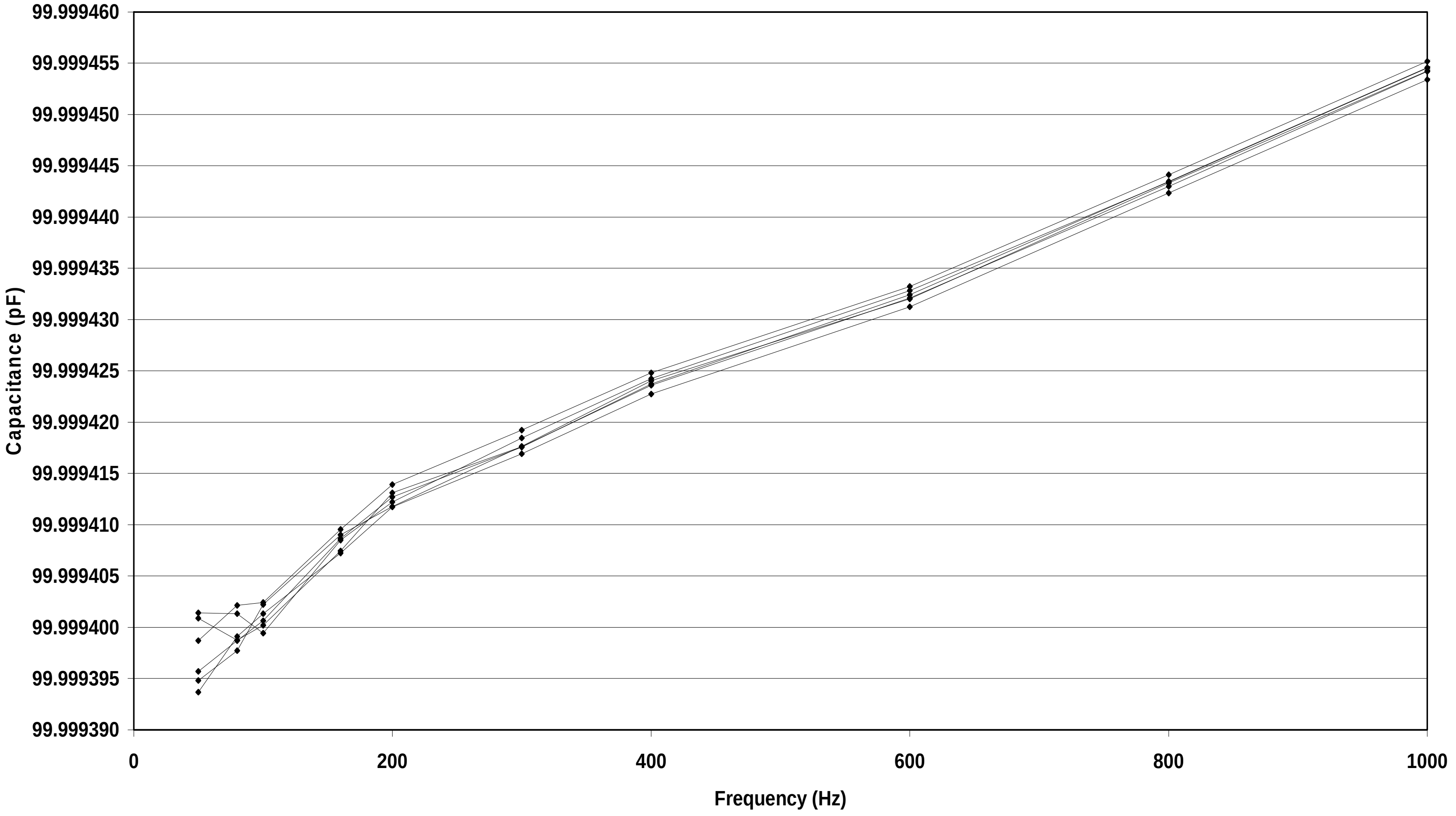


Fig. 14. Low-frequency portion of short-term stability of 100 pF reference standard (Fig. 13).

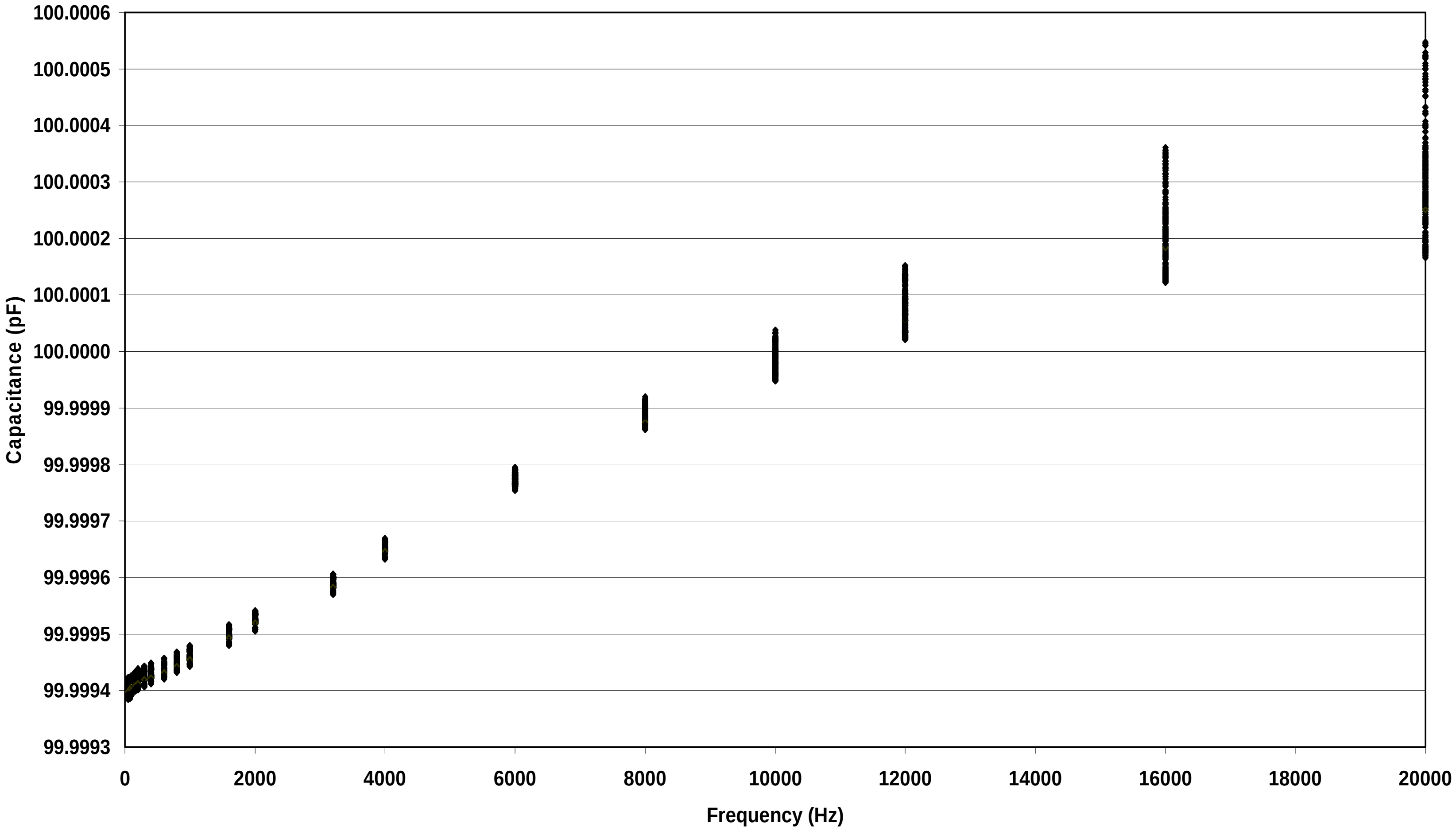


Fig. 15. Long-term stability of 100 pF reference (bridge measurements taken over more than three years).

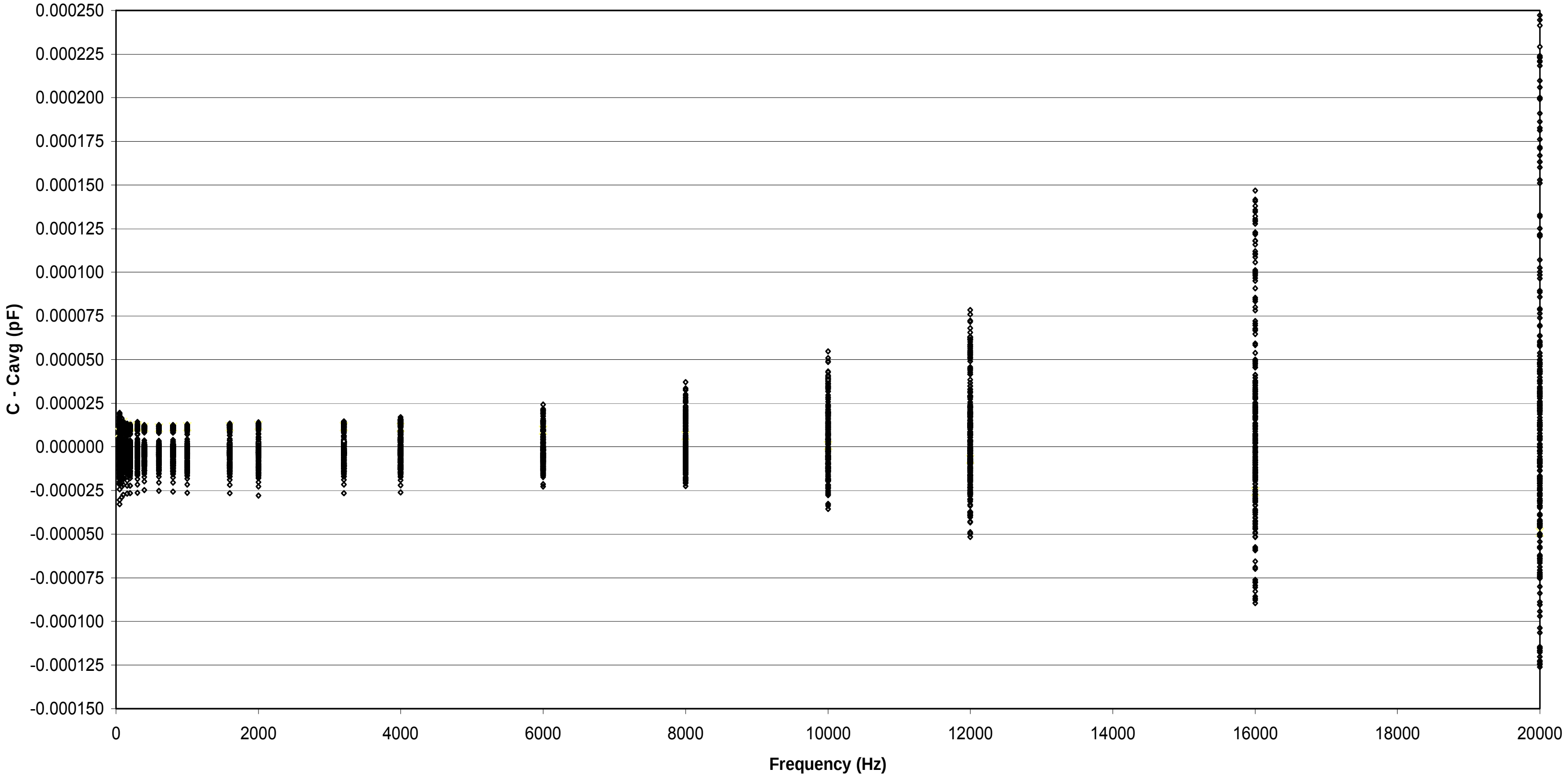


Fig. 16. Normalized long-term stability of 100 pF reference (Figure 15 with average subtracted out).

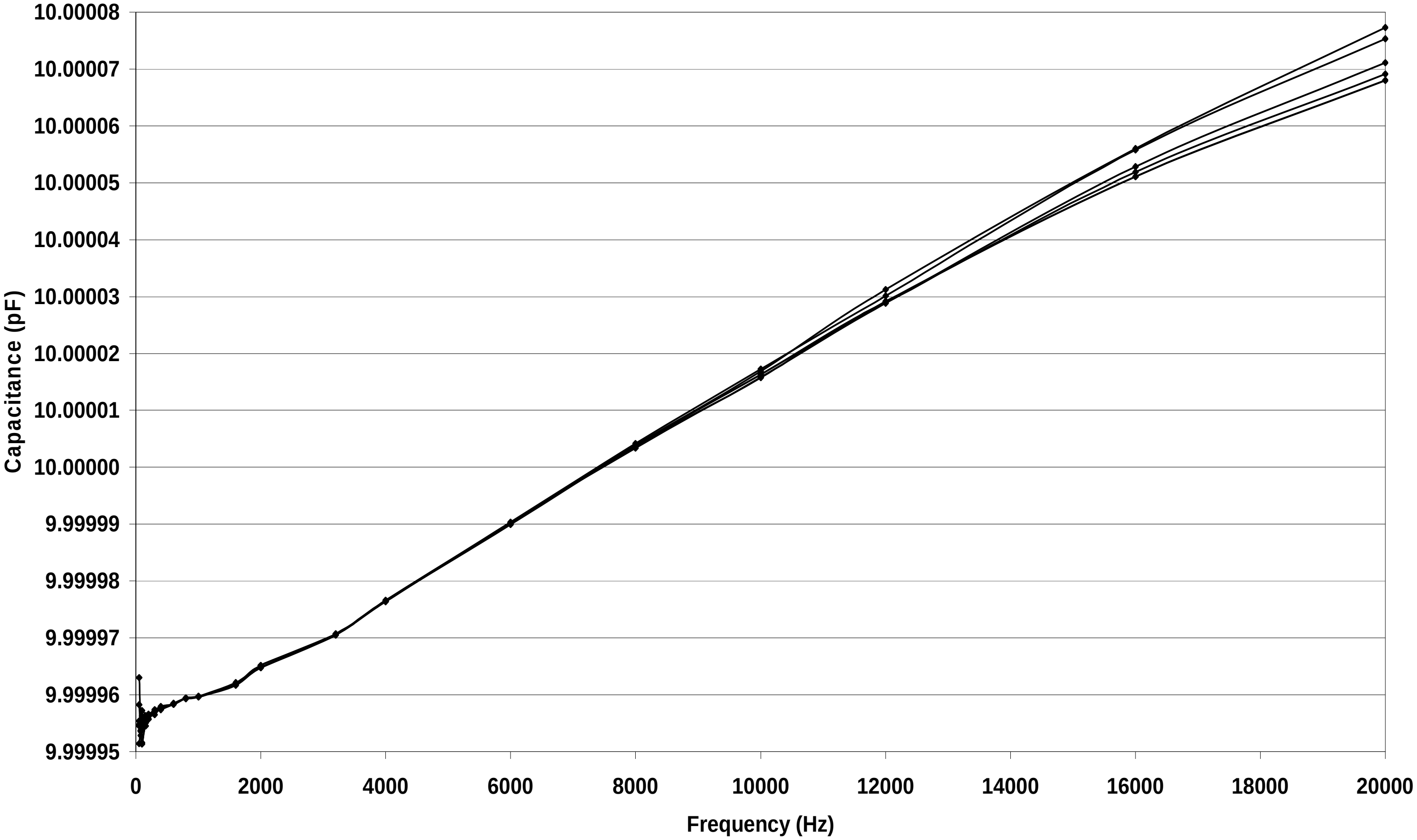


Fig. 17. Short-term stability of 10 pF reference standard (6 bridge measurements taken within 24 hours).

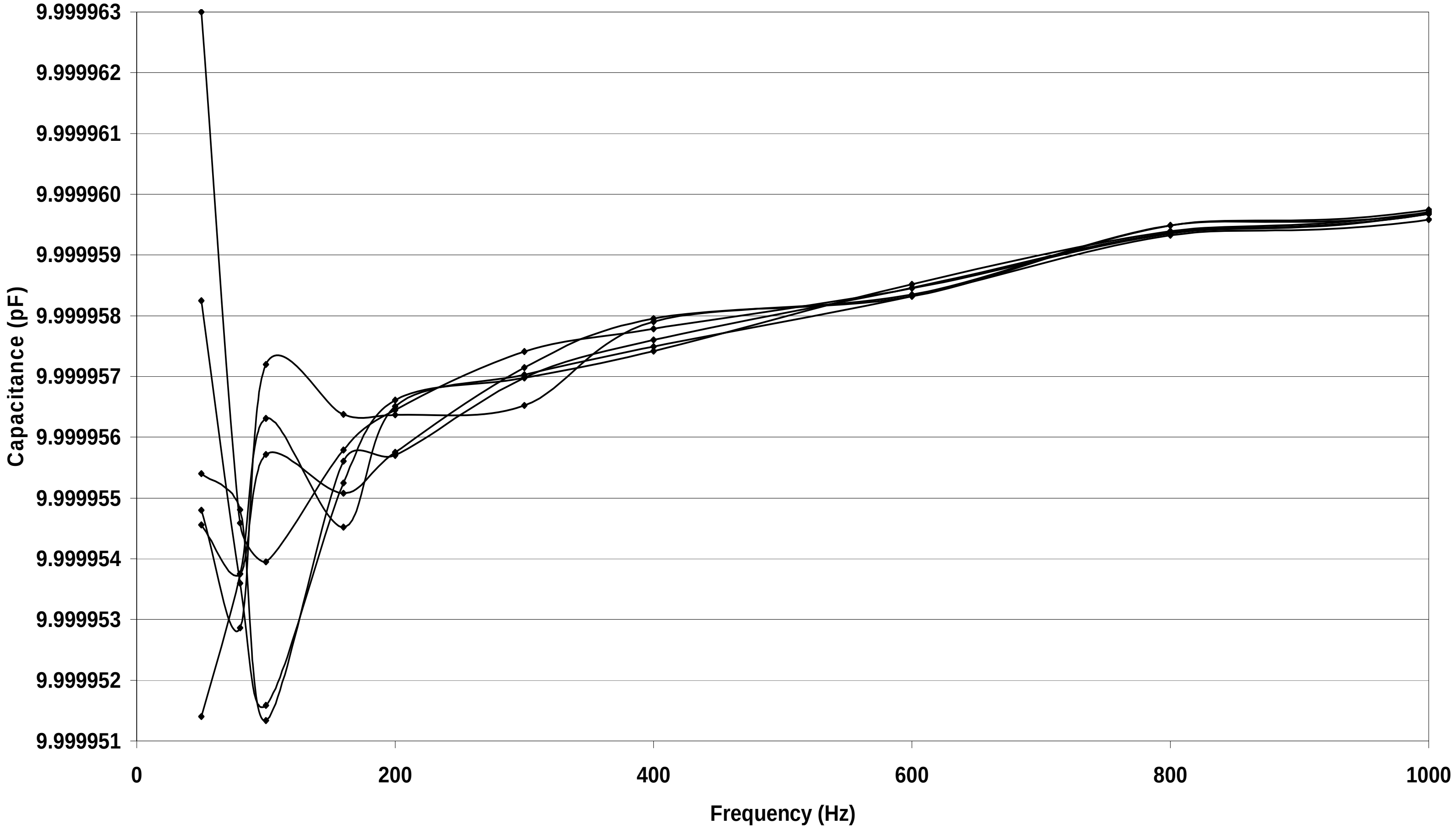


Fig. 18. Low-frequency portion of short-term stability of 10 pF reference standard (Fig. 16).

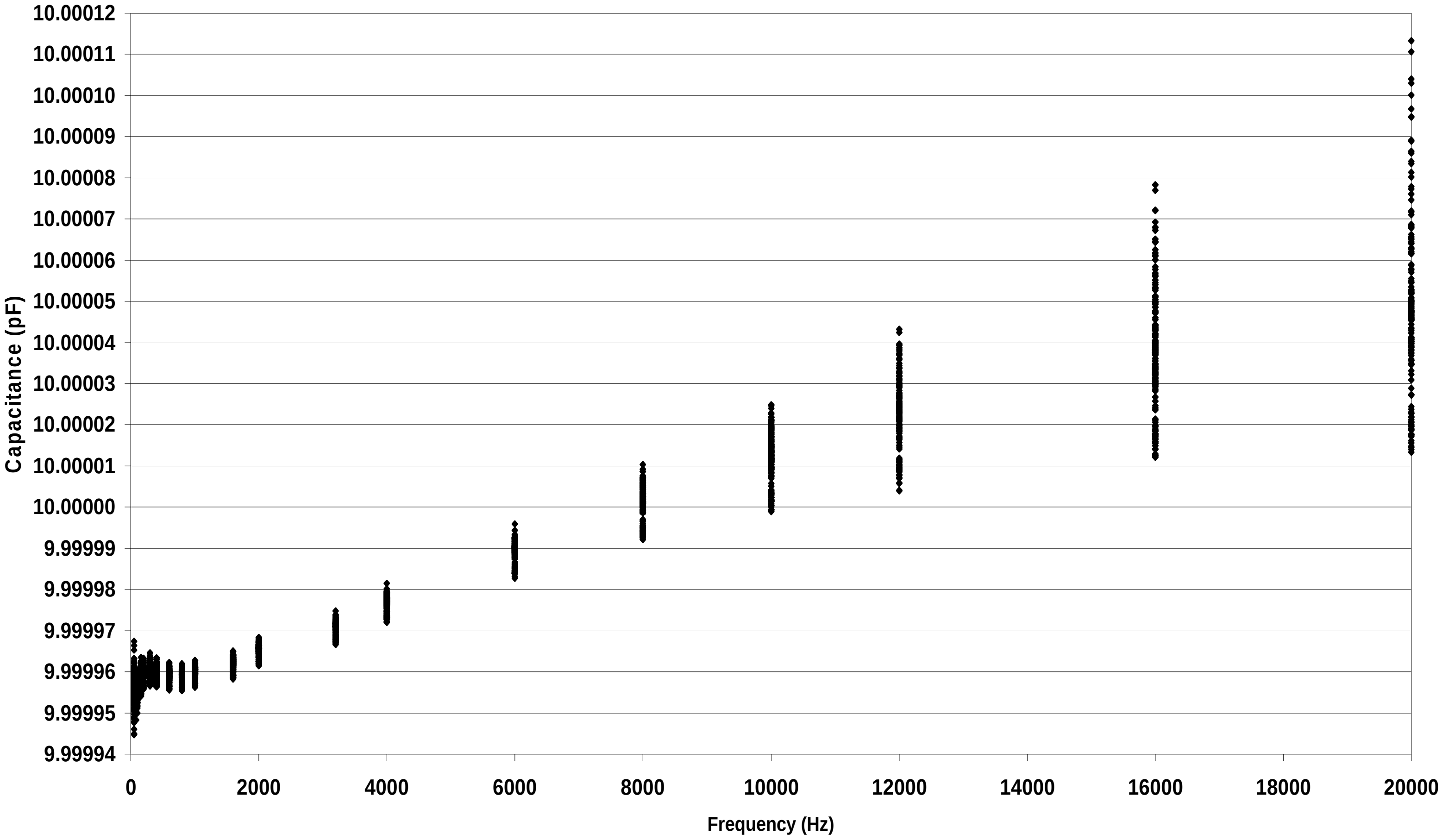


Fig. 19. Long-term stability of 10 pF reference (bridge measurements taken over more than three years).

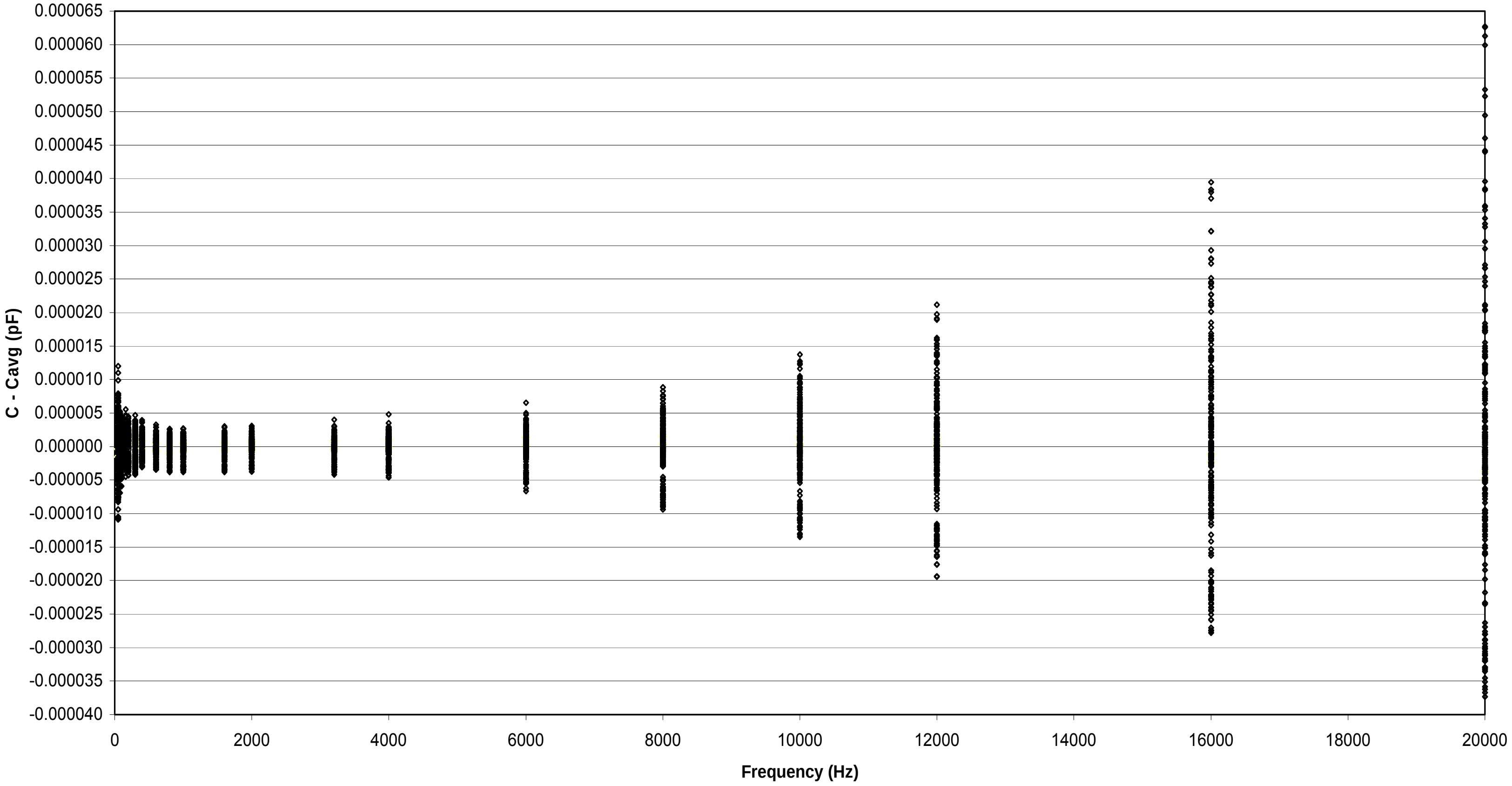


Fig. 20. Normalized long-term stability of 10 pF reference (Figure 19 with average subtracted out).

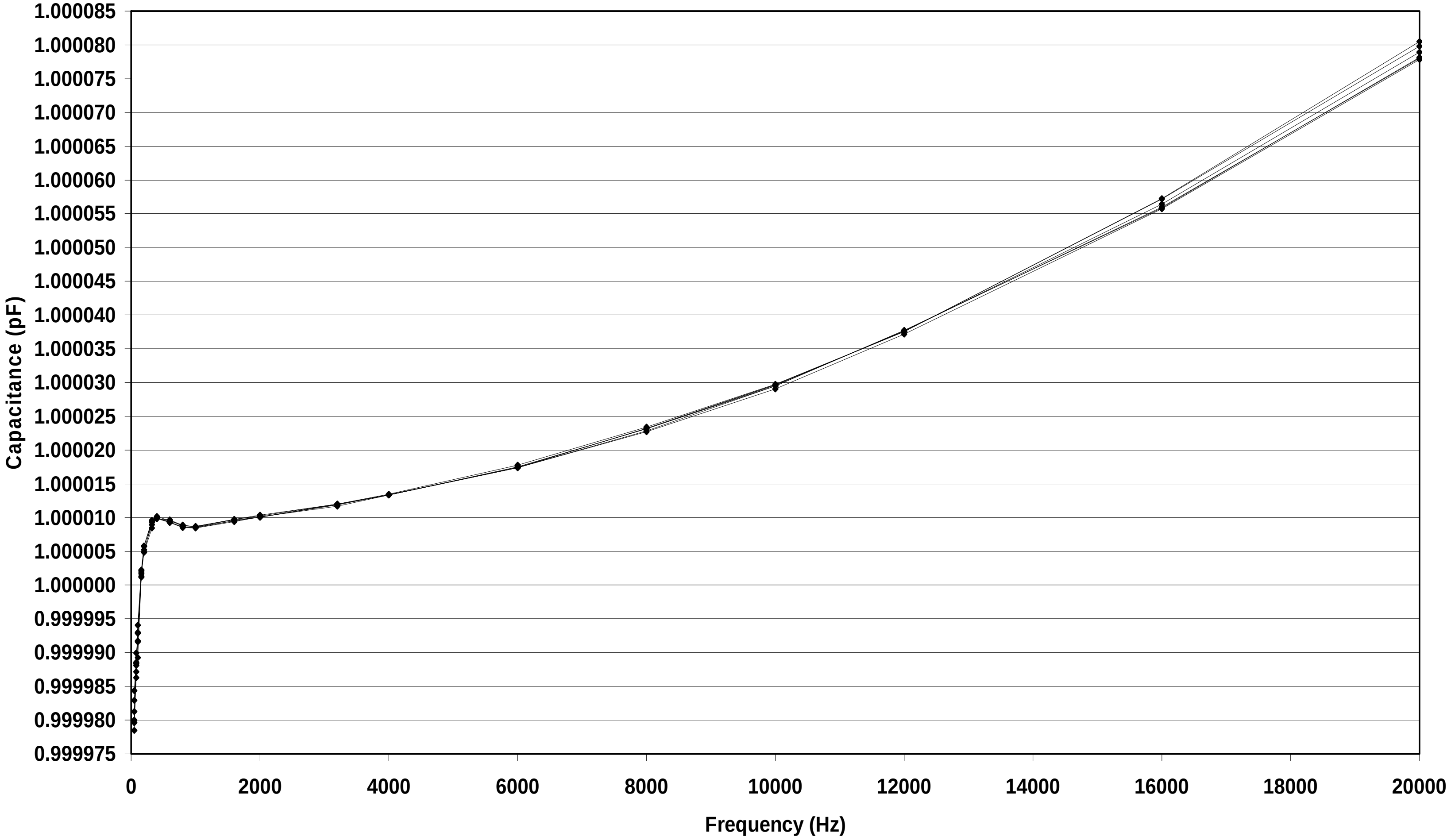


Fig. 21. Short-term stability of 1 pF reference standard (6 bridge measurements taken within 24 hours).

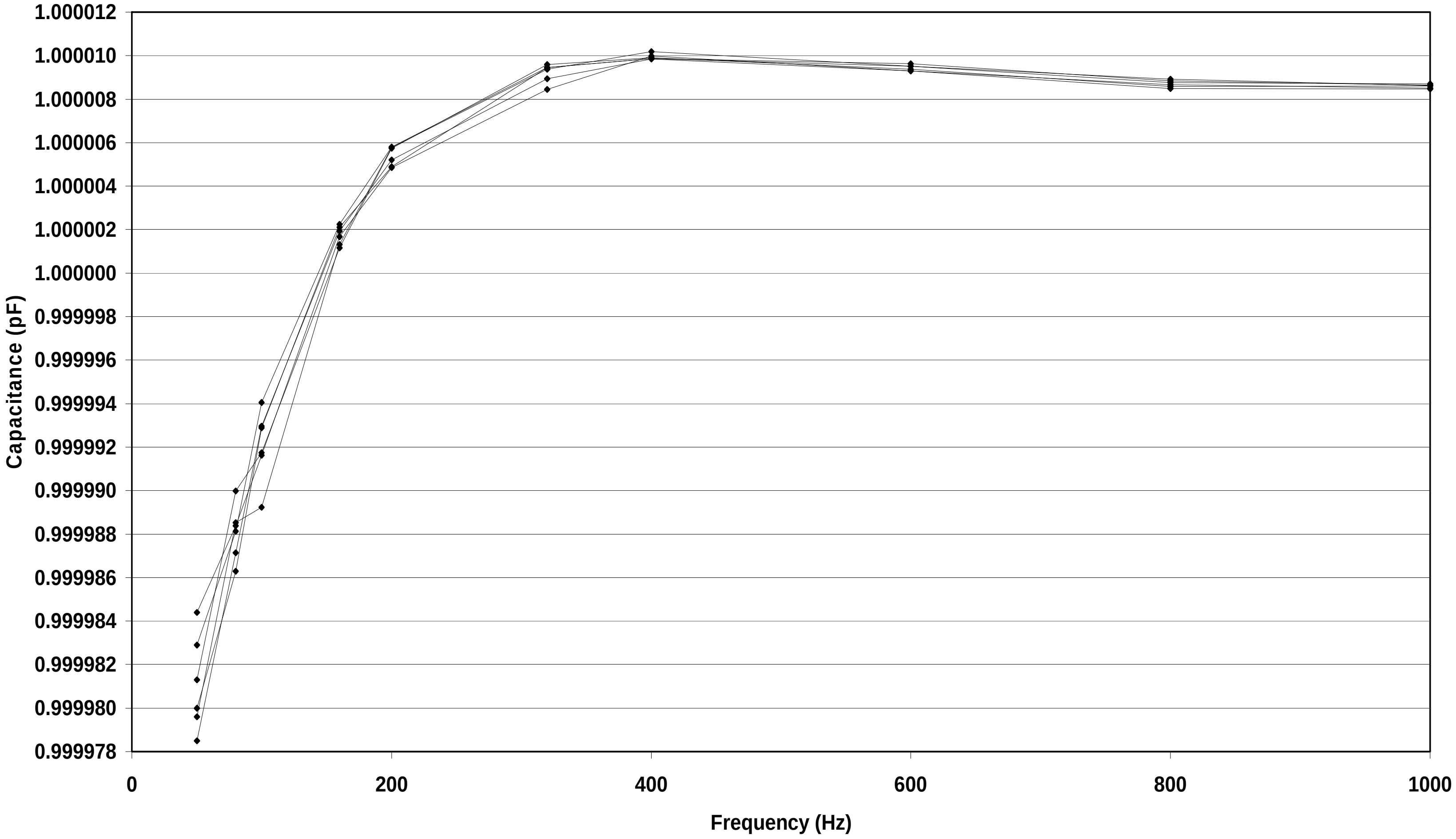


Fig. 22. Low-frequency portion of short-term stability of 1 pF reference standard (Fig. 13).

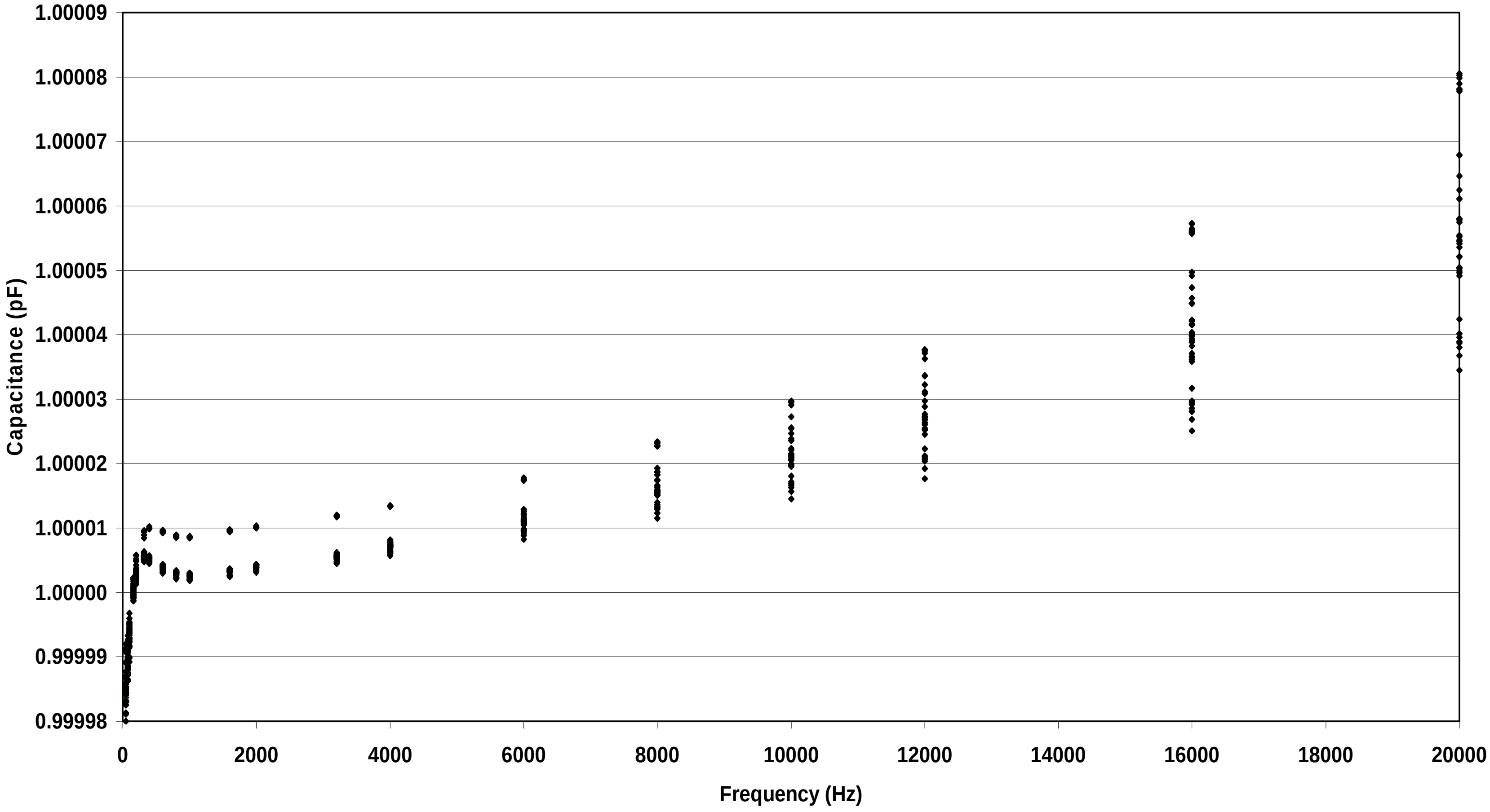


Fig. 23. Long-term stability of 1 pF reference (bridge measurements taken over more than two years).

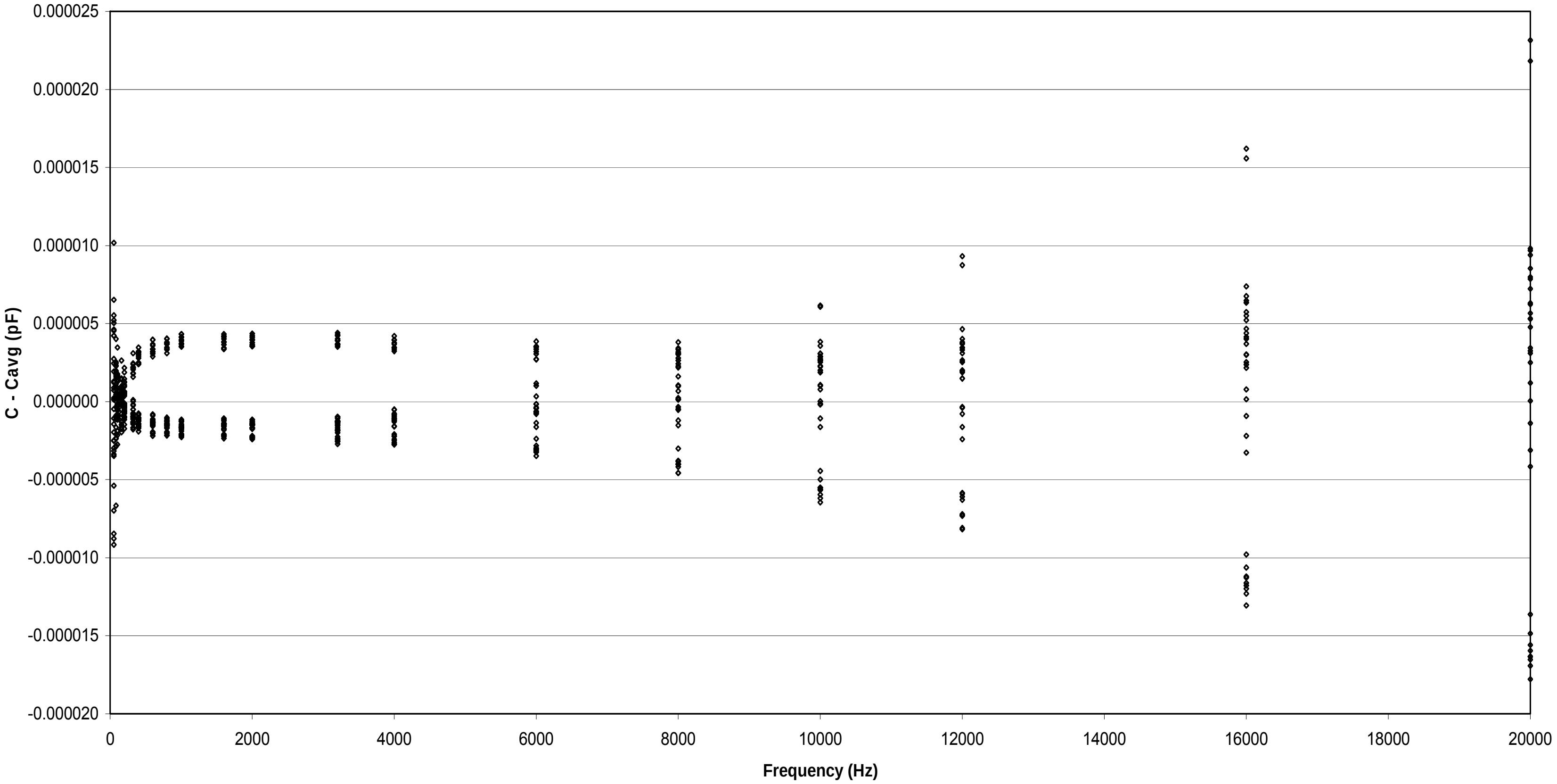


Fig. 24. Normalized long-term stability of 1 pF reference (Figure 23 with average subtracted out).

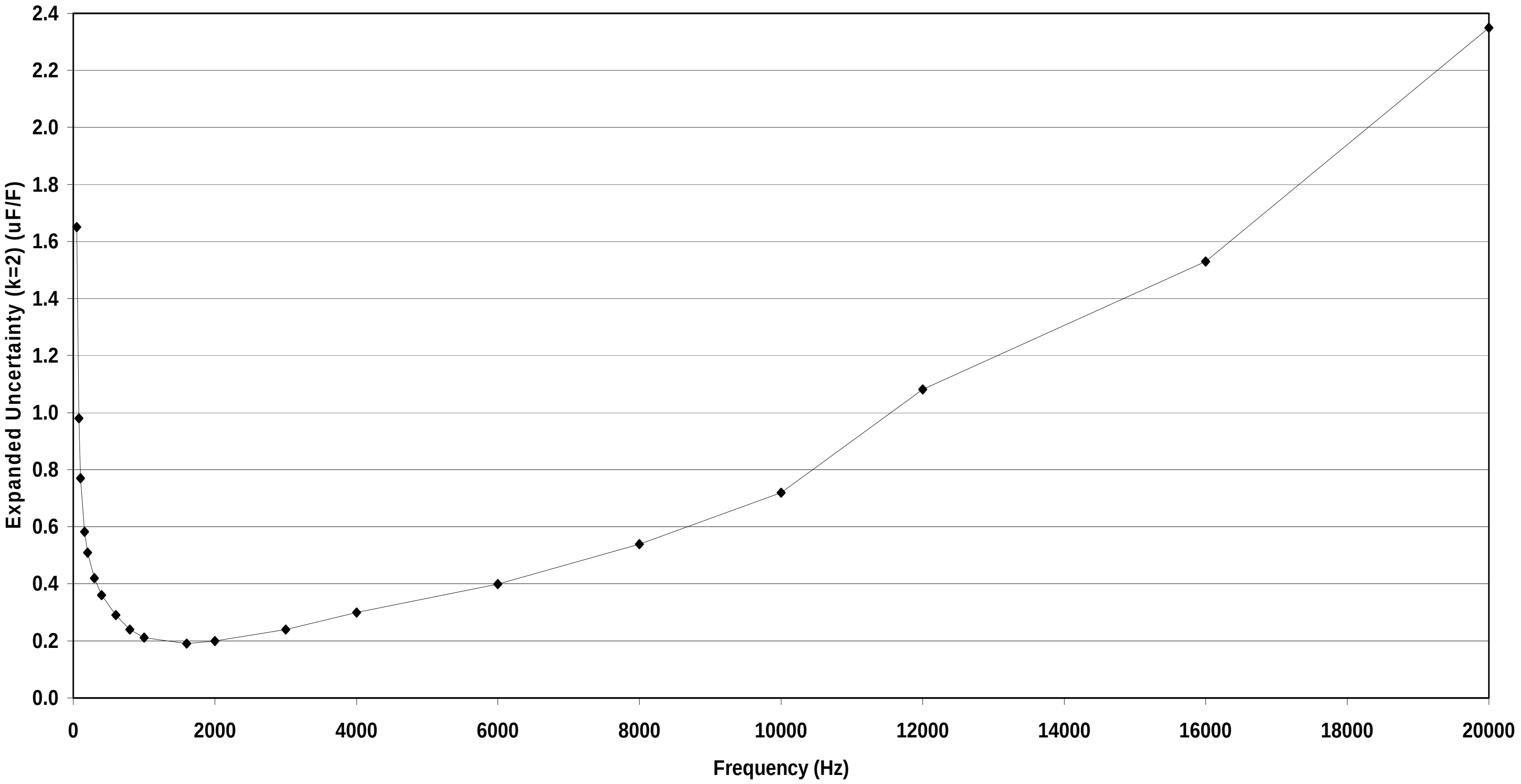


Fig. 25. Expanded uncertainty (k=2) for 100 pF 3T fused-silica standard capacitor calibration.

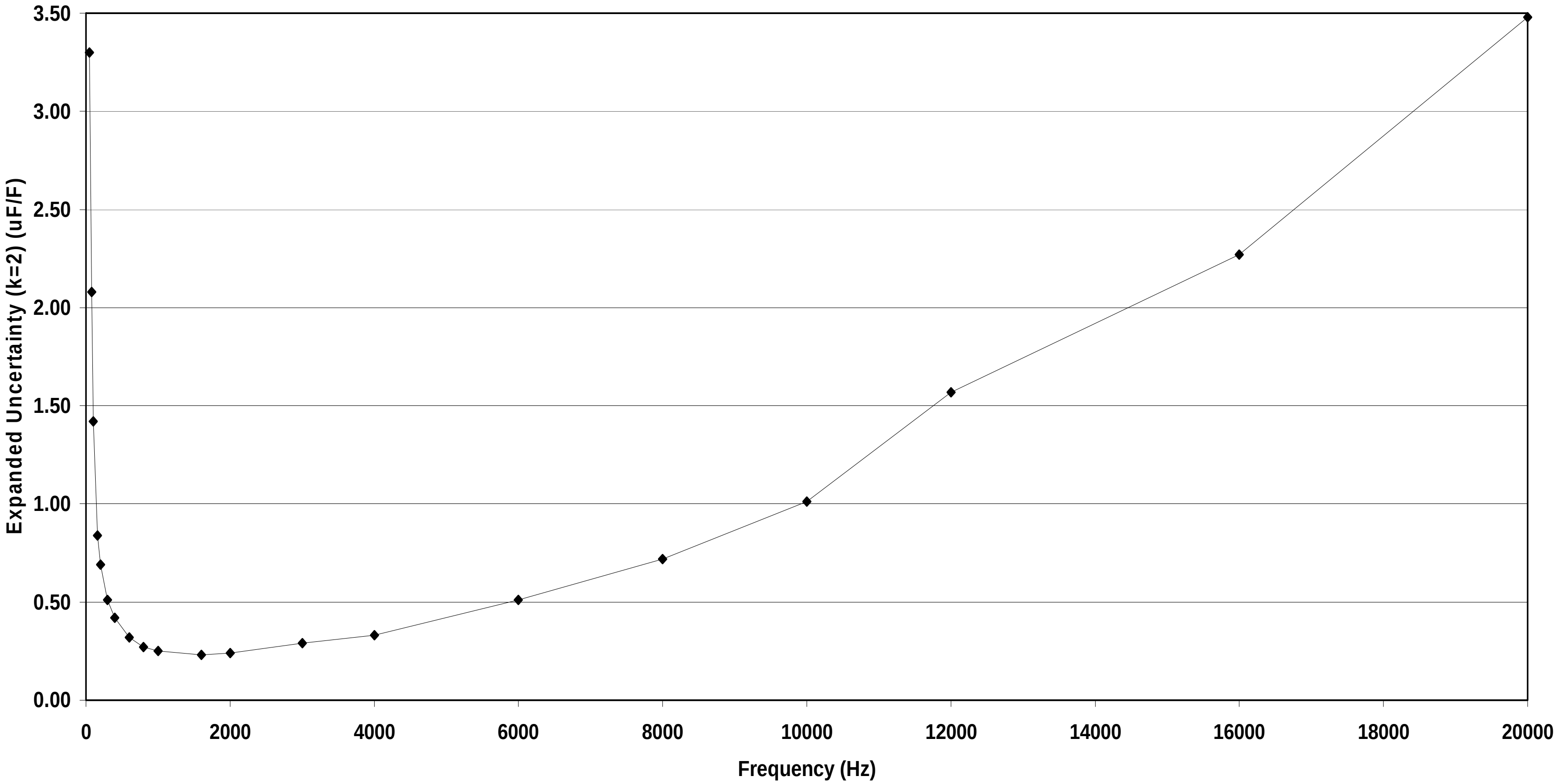


Fig. 26. Expanded uncertainty (k=2) for 10 pF 3T fused-silica standard capacitor calibration.

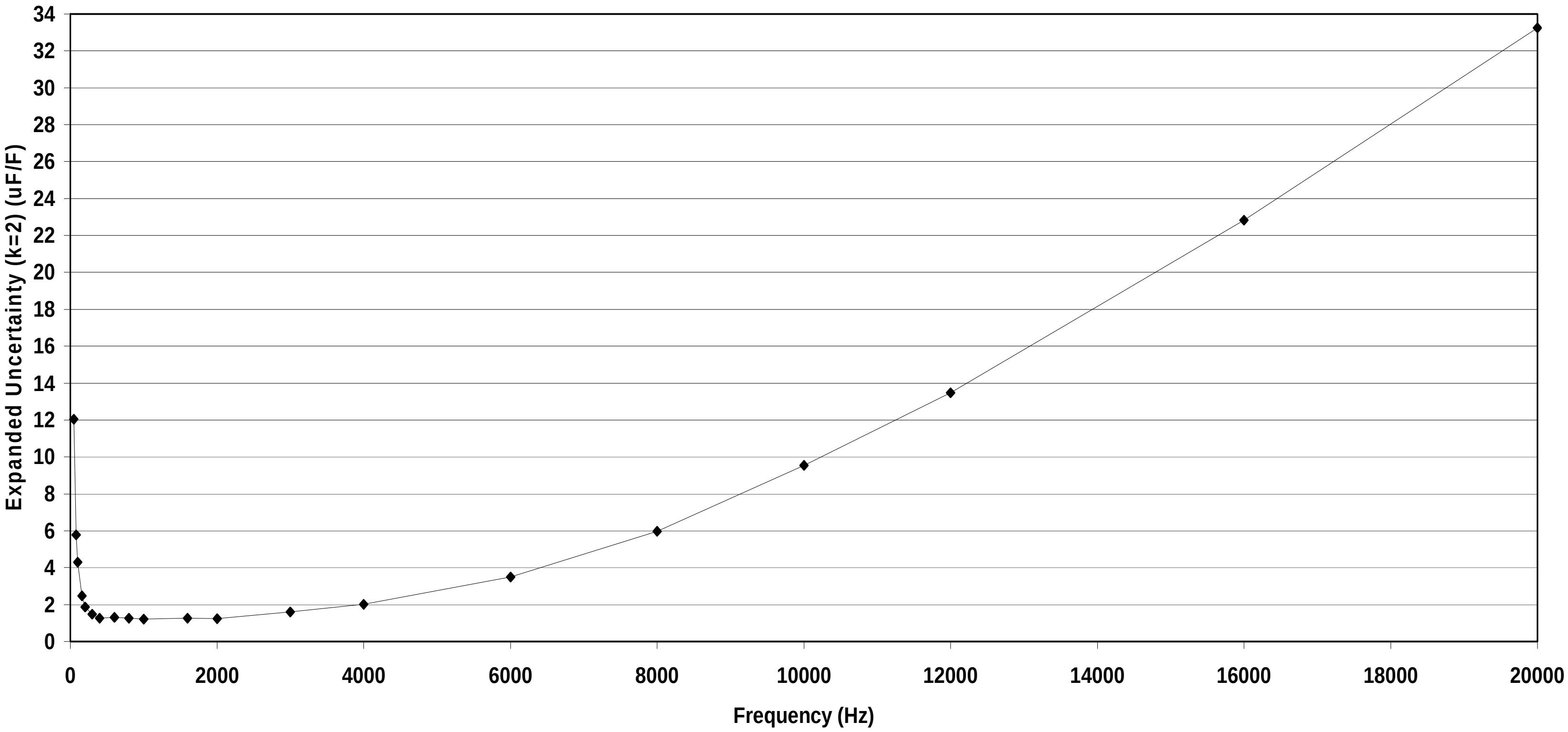


Fig. 27. Expanded uncertainty (k=2) for 1 pF 3T fused-silica standard capacitor calibration.

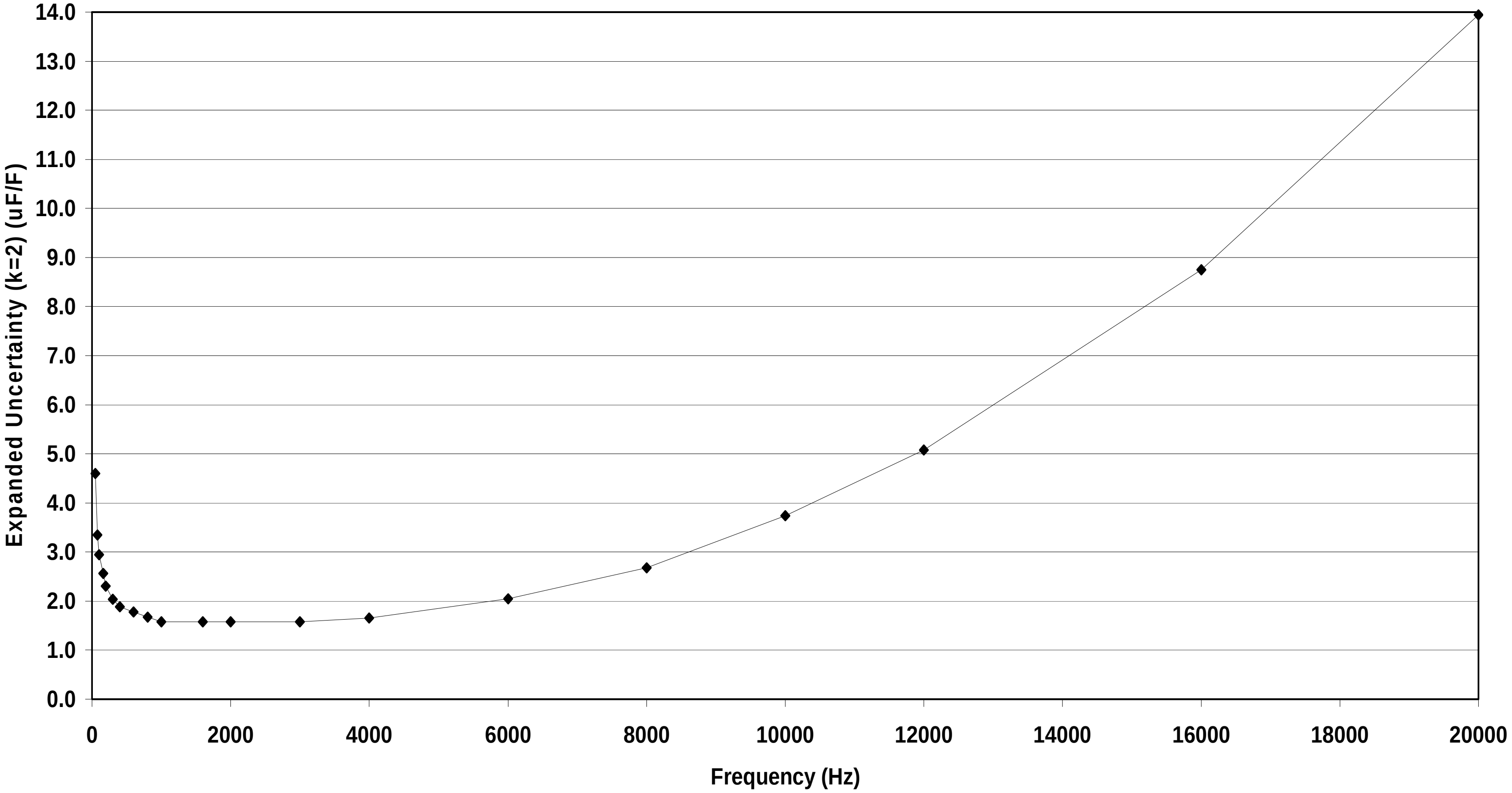


Fig. 28. Expanded uncertainty (k=2) for 1000 pF 3T nitrogen gas standard capacitor calibration.

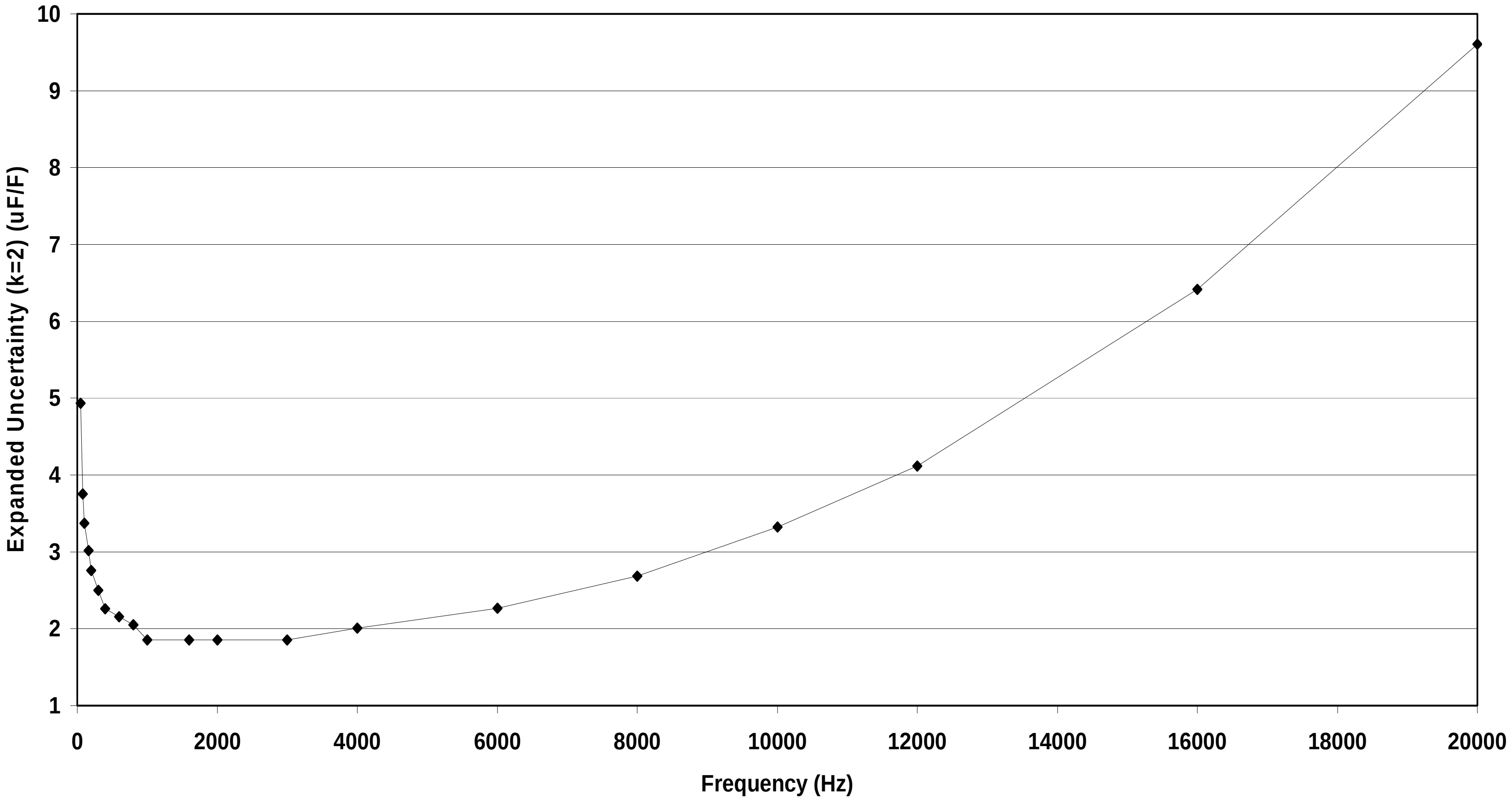


Fig. 29. Expanded uncertainty (k=2) for 100 pF 3T nitrogen gas standard capacitor calibration.

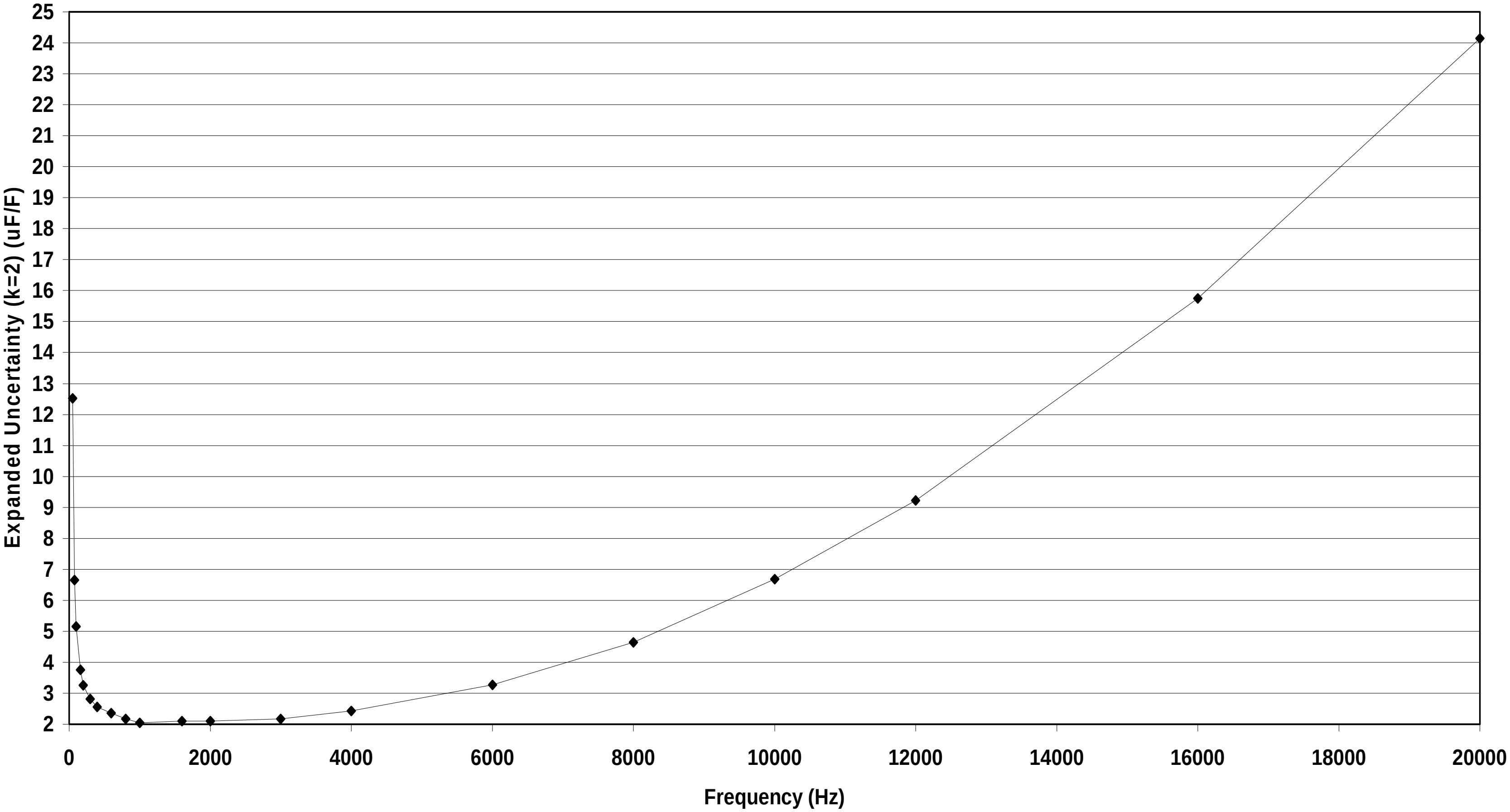


Fig. 30. Expanded uncertainty (k=2) for 10 pF 3T nitrogen gas standard capacitor calibration.

Frequency (Hz)	100 pF Reference (272) Frequency Dependence (μF/F)	10 pF Reference (172) Frequency Dependence (μF/F)	1 pF Reference (016) Frequency Dependence (μF/F)
50	0.08	0.95	0.73
80	0.07	0.85	0.33
100	0.05	0.73	0.18
160	0.09	0.67	0.01
200	0.06	0.57	0.00
300	0.04	0.47	0.00
400	0.04	0.39	0.00
600	0.02	0.26	0.00
800	0.01	0.18	0.00
1000	0.03	0.14	0.00
1600	0.00	0.00	0.00
2000	-0.03	-0.08	0.00
3000	-0.07	-0.23	0.01
4000	-0.11	-0.34	0.02
6000	-0.12	-0.46	0.05
8000	-0.08	-0.54	0.10
10000	0.07	-0.51	0.15
12000	0.27	-0.44	0.26
16000	0.56	-0.29	0.40
20000	1.01	-0.04	0.63

Table 1. Frequency dependence for NIST 100 pF, 10 pF, and 1 pF reference fused-silica standard capacitors.

Frequency (Hz)	Reference Uncertainty C272 (μF/F)	Reference Drift (C272) (μF/F)	Type A Uncertainty (μF/F)	DUT Drift (μF/F)	Bridge Thermal (μF/F)	Bridge Mechanical (μF/F)	Bridge Linearity (μF/F)	Bridge Loading (μF/F)	Expanded Uncertainty (k=2) (μF/F)
50	0.68	0.03	0.32	0.03	0.05	0.05	0.32	0.00	1.65
80	0.39	0.03	0.20	0.03	0.05	0.05	0.20	0.00	0.98
100	0.31	0.03	0.15	0.03	0.05	0.05	0.15	0.00	0.77
160	0.24	0.03	0.1	0.03	0.05	0.05	0.10	0.00	0.58
200	0.21	0.03	0.08	0.03	0.05	0.05	0.08	0.00	0.51
300	0.17	0.03	0.06	0.03	0.05	0.05	0.06	0.00	0.42
400	0.14	0.03	0.05	0.03	0.05	0.05	0.05	0.00	0.36
600	0.10	0.03	0.04	0.03	0.05	0.05	0.04	0.00	0.29
800	0.07	0.03	0.03	0.03	0.05	0.05	0.03	0.00	0.24
1000	0.05	0.03	0.03	0.03	0.05	0.05	0.03	0.00	0.21
1600	0.02	0.03	0.03	0.03	0.05	0.05	0.03	0.01	0.19
2000	0.03	0.03	0.03	0.03	0.05	0.05	0.03	0.01	0.20
3000	0.07	0.03	0.03	0.03	0.05	0.05	0.03	0.02	0.24
4000	0.10	0.03	0.04	0.03	0.05	0.05	0.04	0.04	0.30
6000	0.14	0.03	0.05	0.03	0.05	0.05	0.05	0.09	0.40
8000	0.17	0.03	0.07	0.03	0.05	0.05	0.07	0.16	0.54
10000	0.20	0.03	0.10	0.03	0.05	0.05	0.10	0.25	0.72
12000	0.24	0.03	0.16	0.03	0.05	0.05	0.16	0.42	1.08
16000	0.29	0.03	0.22	0.03	0.05	0.05	0.22	0.63	1.53
20000	0.37	0.03	0.34	0.03	0.05	0.05	0.34	1.00	2.35

Table 2. Uncertainty budget for NIST 100 pF fused-silica standard capacitors.

Frequency (Hz)	Reference Uncertainty C172 (μF/F)	Reference Drift (C172) (μF/F)	Type A Uncertainty (μF/F)	DUT Drift (μF/F)	Bridge Thermal (μF/F)	Bridge Mechanical (μF/F)	Bridge Linearity (μF/F)	Bridge Loading (μF/F)	Expanded Uncertainty (k=2) (μF/F)
50	0.61	0.03	1.08	0.03	0.05	0.05	1.08	0.00	3.30
80	0.38	0.03	0.68	0.03	0.05	0.05	0.68	0.00	2.08
100	0.30	0.03	0.45	0.03	0.05	0.05	0.45	0.00	1.42
160	0.23	0.03	0.24	0.03	0.05	0.05	0.24	0.00	0.84
200	0.21	0.03	0.18	0.03	0.05	0.05	0.18	0.00	0.69
300	0.17	0.03	0.12	0.03	0.05	0.05	0.12	0.00	0.51
400	0.14	0.03	0.09	0.03	0.05	0.05	0.09	0.00	0.42
600	0.10	0.03	0.06	0.03	0.05	0.05	0.06	0.00	0.32
800	0.07	0.03	0.05	0.03	0.05	0.05	0.05	0.00	0.27
1000	0.05	0.03	0.05	0.03	0.05	0.05	0.05	0.00	0.25
1600	0.02	0.03	0.05	0.03	0.05	0.05	0.05	0.01	0.23
2000	0.03	0.03	0.05	0.03	0.05	0.05	0.05	0.01	0.24
3000	0.07	0.03	0.06	0.03	0.05	0.05	0.06	0.02	0.29
4000	0.09	0.03	0.07	0.03	0.05	0.05	0.07	0.04	0.33
6000	0.14	0.03	0.12	0.03	0.05	0.05	0.12	0.09	0.51
8000	0.17	0.03	0.18	0.03	0.05	0.05	0.18	0.16	0.72
10000	0.20	0.03	0.27	0.03	0.05	0.05	0.27	0.25	1.01
12000	0.24	0.03	0.43	0.03	0.05	0.05	0.43	0.42	1.57
16000	0.29	0.03	0.63	0.03	0.05	0.05	0.63	0.63	2.27
20000	0.37	0.03	0.97	0.03	0.05	0.05	0.97	1.00	3.48

Table 3. Uncertainty budget for NIST 10 pF fused-silica standard capacitors.

Frequency (Hz)	Reference Uncertainty C016 (μF/F)	Reference Drift (C016) (μF/F)	Type A Uncertainty (μF/F)	DUT Drift (μF/F)	Bridge Thermal (μF/F)	Bridge Mechanical (μF/F)	Bridge Linearity (μF/F)	Bridge Loading (μF/F)	Expanded Uncertainty (k=2) (μF/F)
50	3.02	0.13	3.31	0.13	0.05	0.05	4.01	0.00	12.04
80	1.36	0.13	1.74	0.13	0.05	0.05	1.85	0.00	5.78
100	0.78	0.13	1.17	0.13	0.05	0.05	1.62	0.00	4.31
160	0.34	0.13	0.74	0.13	0.05	0.05	0.90	0.00	2.47
200	0.25	0.13	0.58	0.13	0.05	0.05	0.66	0.00	1.87
300	0.17	0.13	0.42	0.13	0.05	0.05	0.55	0.00	1.47
400	0.15	0.13	0.30	0.13	0.05	0.05	0.50	0.00	1.26
600	0.14	0.13	0.33	0.13	0.05	0.05	0.51	0.00	1.31
800	0.13	0.13	0.32	0.13	0.05	0.05	0.48	0.00	1.26
1000	0.13	0.13	0.30	0.13	0.05	0.05	0.47	0.01	1.22
1600	0.13	0.13	0.30	0.13	0.05	0.05	0.50	0.01	1.26
2000	0.13	0.13	0.30	0.13	0.05	0.05	0.49	0.02	1.25
3000	0.13	0.13	0.39	0.13	0.05	0.05	0.65	0.05	1.60
4000	0.13	0.13	0.51	0.13	0.05	0.05	0.83	0.08	2.01
6000	0.14	0.13	0.90	0.13	0.05	0.05	1.47	0.18	3.50
8000	0.17	0.13	1.57	0.13	0.05	0.05	2.50	0.32	5.97
10000	0.21	0.13	2.57	0.13	0.05	0.05	3.98	0.50	9.54
12000	0.30	0.13	3.49	0.13	0.05	0.05	5.69	0.85	13.48
16000	0.42	0.13	6.34	0.13	0.05	0.05	9.39	1.27	22.82
20000	0.65	0.13	9.36	0.13	0.05	0.05	13.57	2.00	33.25

Table 4. Uncertainty budget for NIST 1 pF fused-silica standard capacitors.

Frequency (Hz)	Reference Uncertainty C272 (μF/F)	Reference Drift (C272) (μF/F)	10:1 Ratio Uncertainty (μF/F)	Type A Uncertainty (μF/F)	DUT Drift (μF/F)	Bridge Thermal (μF/F)	Bridge Mechanical (μF/F)	Bridge Linearity (μF/F)	Bridge Loading (μF/F)	Expanded Uncertainty (k=2) (μF/F)
50	0.68	0.03	0.10	1.50	0.03	0.05	0.05	1.60	0.00	4.60
80	0.39	0.03	0.10	1.35	0.03	0.05	0.05	0.90	0.00	3.35
100	0.31	0.03	0.10	1.25	0.03	0.05	0.05	0.70	0.00	2.94
160	0.24	0.03	0.10	1.15	0.03	0.05	0.05	0.50	0.00	2.57
200	0.21	0.03	0.10	1.05	0.03	0.05	0.05	0.40	0.00	2.30
300	0.17	0.03	0.10	0.95	0.03	0.05	0.05	0.30	0.00	2.04
400	0.14	0.03	0.10	0.90	0.03	0.05	0.05	0.20	0.00	1.88
600	0.1	0.03	0.10	0.85	0.03	0.05	0.05	0.20	0.00	1.78
800	0.07	0.03	0.10	0.80	0.03	0.05	0.05	0.20	0.00	1.68
1000	0.05	0.03	0.10	0.75	0.03	0.05	0.05	0.20	0.00	1.58
1600	0.02	0.03	0.10	0.75	0.03	0.05	0.05	0.20	0.01	1.57
2000	0.03	0.03	0.10	0.75	0.03	0.05	0.05	0.20	0.01	1.58
3000	0.07	0.03	0.10	0.75	0.03	0.05	0.05	0.20	0.02	1.58
4000	0.1	0.03	0.10	0.75	0.03	0.05	0.05	0.30	0.04	1.65
6000	0.14	0.03	0.10	0.80	0.03	0.05	0.05	0.60	0.09	2.04
8000	0.17	0.03	0.10	0.85	0.03	0.05	0.05	1.00	0.16	2.68
10000	0.2	0.03	0.10	0.90	0.03	0.05	0.05	1.60	0.25	3.74
12000	0.24	0.03	0.10	0.95	0.03	0.05	0.05	2.30	0.42	5.08
16000	0.29	0.03	0.10	1.00	0.03	0.05	0.05	4.20	0.63	8.75
20000	0.37	0.03	0.10	1.10	0.03	0.05	0.05	6.80	1.00	13.94

Table 5. Uncertainty budget for NIST 1000 pF nitrogen gas standard capacitors.

Frequency (Hz)	Reference Uncertainty C272 (μF/F)	Reference Drift (C272) (μF/F)	Type A Uncertainty (μF/F)	DUT Drift (μF/F)	Bridge Thermal (μF/F)	Bridge Mechanical (μF/F)	Bridge Linearity (μF/F)	Bridge Loading (μF/F)	Expanded Uncertainty (k=2) (μF/F)
50	0.68	0.03	1.75	0.03	0.05	0.05	1.60	0.00	4.94
80	0.39	0.03	1.60	0.03	0.05	0.05	0.90	0.00	3.76
100	0.31	0.03	1.50	0.03	0.05	0.05	0.70	0.00	3.37
160	0.24	0.03	1.40	0.03	0.05	0.05	0.50	0.00	3.02
200	0.21	0.03	1.30	0.03	0.05	0.05	0.40	0.00	2.76
300	0.17	0.03	1.20	0.03	0.05	0.05	0.30	0.00	2.50
400	0.14	0.03	1.10	0.03	0.05	0.05	0.20	0.00	2.26
600	0.1	0.03	1.05	0.03	0.05	0.05	0.20	0.00	2.15
800	0.07	0.03	1.00	0.03	0.05	0.05	0.20	0.00	2.05
1000	0.05	0.03	0.90	0.03	0.05	0.05	0.20	0.00	1.85
1600	0.02	0.03	0.90	0.03	0.05	0.05	0.20	0.01	1.85
2000	0.03	0.03	0.90	0.03	0.05	0.05	0.20	0.01	1.85
3000	0.07	0.03	0.90	0.03	0.05	0.05	0.20	0.02	1.86
4000	0.1	0.03	0.95	0.03	0.05	0.05	0.30	0.04	2.01
6000	0.14	0.03	1.00	0.03	0.05	0.05	0.50	0.09	2.27
8000	0.17	0.03	1.05	0.03	0.05	0.05	0.80	0.16	2.69
10000	0.2	0.03	1.10	0.03	0.05	0.05	1.20	0.25	3.32
12000	0.24	0.03	1.20	0.03	0.05	0.05	1.60	0.42	4.12
16000	0.29	0.03	1.40	0.03	0.05	0.05	2.80	0.63	6.41
20000	0.37	0.03	1.60	0.03	0.05	0.05	4.40	1.00	9.60

Table 6. Uncertainty budget for NIST 100 pF nitrogen gas standard capacitors.

Frequency (Hz)	Reference Uncertainty C172 (µF/F)	Reference Drift (C172) (µF/F)	Type A Uncertainty (µF/F)	DUT Drift (µF/F)	Bridge Thermal (µF/F)	Bridge Mechanical (µF/F)	Bridge Linearity (µF/F)	Bridge Loading (µF/F)	Expanded Uncertainty (k=2) (µF/F)
50	0.61	0.03	2.00	0.03	0.05	0.05	5.90	0.00	12.52
80	0.38	0.03	1.75	0.03	0.05	0.05	2.80	0.00	6.65
100	0.3	0.03	1.60	0.03	0.05	0.05	2.00	0.00	5.16
160	0.23	0.03	1.50	0.03	0.05	0.05	1.10	0.00	3.75
200	0.21	0.03	1.40	0.03	0.05	0.05	0.80	0.00	3.26
300	0.17	0.03	1.30	0.03	0.05	0.05	0.50	0.00	2.81
400	0.14	0.03	1.20	0.03	0.05	0.05	0.40	0.00	2.55
600	0.1	0.03	1.13	0.03	0.05	0.05	0.30	0.00	2.35
800	0.07	0.03	1.06	0.03	0.05	0.05	0.20	0.00	2.17
1000	0.05	0.03	1.00	0.03	0.05	0.05	0.20	0.00	2.05
1600	0.02	0.03	1.00	0.03	0.05	0.05	0.30	0.01	2.10
2000	0.03	0.03	1.00	0.03	0.05	0.05	0.30	0.01	2.10
3000	0.07	0.03	1.00	0.03	0.05	0.05	0.40	0.02	2.17
4000	0.09	0.03	1.05	0.03	0.05	0.05	0.60	0.04	2.43
6000	0.14	0.03	1.10	0.03	0.05	0.05	1.20	0.09	3.28
8000	0.17	0.03	1.15	0.03	0.05	0.05	2.00	0.16	4.64
10000	0.2	0.03	1.20	0.03	0.05	0.05	3.10	0.25	6.68
12000	0.24	0.03	1.30	0.03	0.05	0.05	4.40	0.42	9.23
16000	0.29	0.03	1.50	0.03	0.05	0.05	7.70	0.63	15.75
20000	0.37	0.03	1.70	0.03	0.05	0.05	11.90	1.00	24.14

Table 7. Uncertainty budget for NIST 10 pF nitrogen gas standard capacitors.