Optimizing the Use of Commercial Capacitance Bridges in Fused-Silica Standard Capacitor Calibrations at NIST

Speaker: Andrew Koffman
National Institute of Standards and Technology*
100 Bureau Drive, MS 8172
Gaithersburg, MD 20899-8172
E-mail: andrew.koffman@nist.gov
Phone: (301) 975-4518; FAX: (301) 926-3972

Authors: Yicheng Wang and Scott Shields
National Institute of Standards and Technology

Abstract
Commercial capacitance bridges are used as accurate transfer standards in the calibration of fused-silica capacitors. Tedious manual bridge measurements are still the basis for transferring the unit of capacitance from the calculable capacitor, which realizes the farad, to the U.S. representation of the farad, which is a bank of 10 pF fused-silica standards. However, additional manual measurements are no longer used to disseminate the farad to the customer.

Staff in the Quantum Electrical Metrology Division at the National Institute of Standards and Technology (NIST) have developed procedures using commercial capacitance bridges to expand the frequency range of calibrations offered for fused-silica standards while decreasing the combined standard uncertainties well below the 1 μF/F level across a large range of audio frequencies. Previously, normal calibration services for three-terminal capacitance standards were offered only at 100 Hz, 400 Hz, and 1 kHz. The expanded service provides calibrations at numerous frequencies from 50 Hz to 20 kHz. Moreover, the cost of the test service has decreased drastically with the initial point for a single standard dropping by over one third and additional calibration points for the same standard decreasing by a factor of over 15.

This paper will briefly describe the calibration procedure, the uncertainty budgets, and the details of the calibration service.

1 CALIBRATION PROCEDURE

The NIST calibration procedure for fused-silica standard capacitors can be described in terms of the reference characterization, reference and customer measurements, data processing, and report generation. Fig. 1 shows the traceability chain for NIST fused-silica standard capacitor calibrations. The 1592 Hz reference point is derived from NIST Calculable Capacitor measurements that are transferred to the primary bank of 10 pF standards. The frequency response curve for each reference standard comes from a series of measurements on a 1 pF, 9 bar nitrogen cross capacitor as well as a 10 pF nitrogen cylindrical capacitor. Reference [1] describes

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* Electronics and Electrical Engineering Laboratory, Technology Administration, U.S. Department of Commerce. Contribution of the U.S. Government.

fully the work to characterize fused-silica reference standards across frequencies from 50 Hz to 20 kHz.

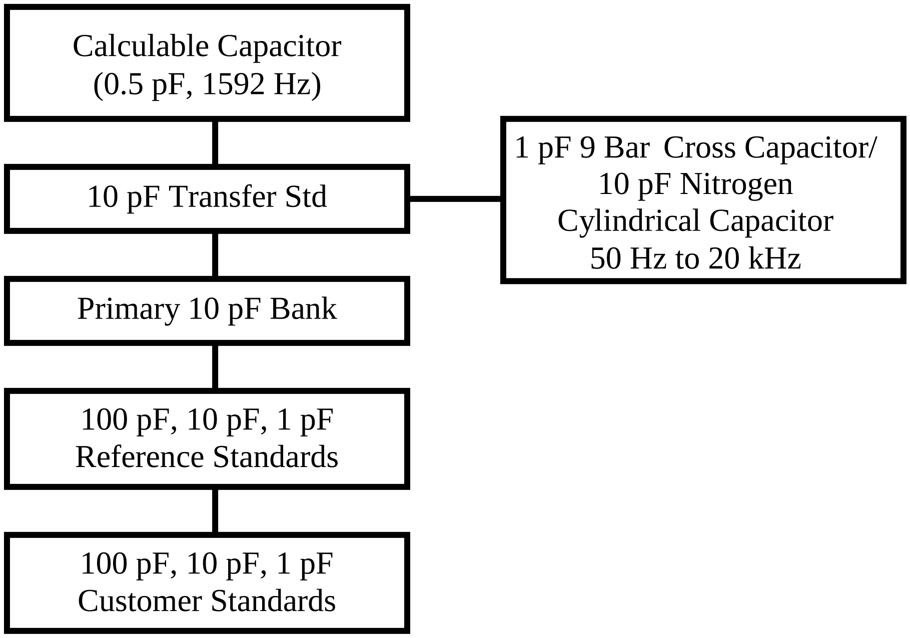

Figure 1. NIST fused-silica standard capacitor traceability chain.

1.1 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]. 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 several years [2, 3] and so updates are not frequently required. 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 approximately every six months. Additionally, errors in the automatic bridge measurements due to bridge loading from the stray capacitances of the measured capacitors must be corrected for each calibration. Fig. 2 shows a schematic diagram of the automatic capacitance bridge measuring a three-terminal standard capacitor. The capacitance value of the standard capacitor is labeled as C_{LH} and the stray capacitances from the low side of the standard (B) to ground and from the high side (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 for 100 pF reference C272 and are shown in Fig. 3. The curves are similar for measurements using a 10 pF reference standard. 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] and so the effect on measured capacitance due to bridge loading will increase at higher frequencies. This effect becomes negligible (as can be seen in the uncertainties listed below) at frequencies less than a few kilohertz. It is important to note that the bridge is loaded differently for each standard measured. The loading characteristics of the bridge with respect to the reference standards are updated periodically so that during a calibration, only the loading error of the bridge due to the customer standard must be measured.

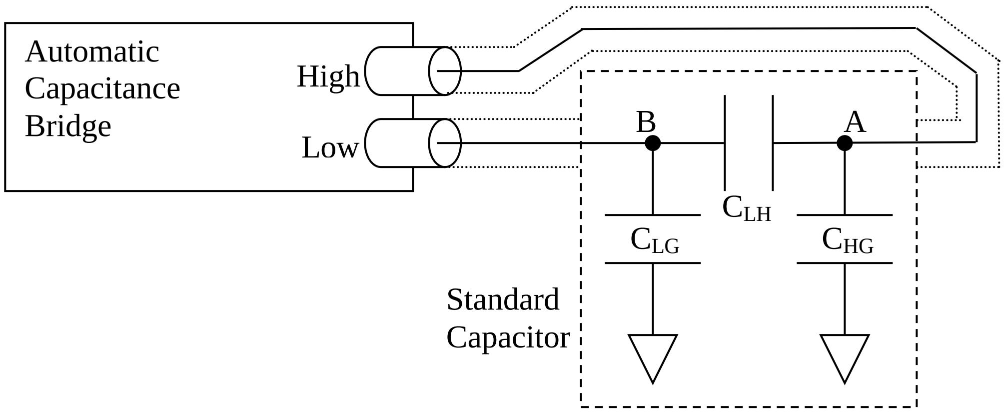

Figure 2. Measurement of three-terminal standard capacitor using automatic capacitance bridge.

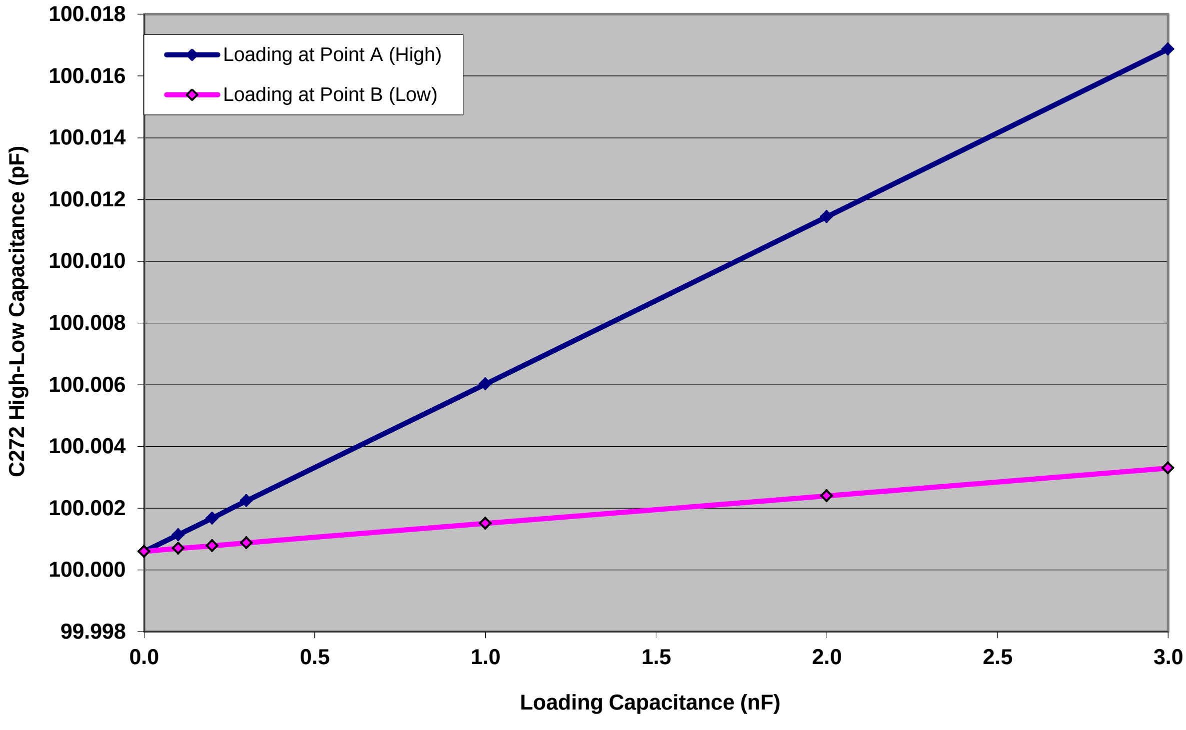

Figure 3. Effects of loading on automatic capacitance bridge measurements.

1.2 Reference and Customer Capacitance Measurements

Once the correction factors have been determined, the automatic capacitance bridge can be used as an effective transfer instrument by measuring the reference and customer standards using a substitution procedure. For each customer calibration, five sets of data are taken 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 reference standard of the same nominal value. The vector of differences between the measured values of the reference standard and the periodically obtained calibrated values of the reference standard is used, along with the loading correction, as a correction factor to determine the calibrated value of the standard under test. In equation form, the calibrated value for a device under test (DUT) at one frequency is

$$C_{DUTCal} = C_{DUTMeas} + (C_{\mathrm{Re}\,fCal} - C_{\mathrm{Re}\,fMeas}) + \varepsilon_{Loading},$$

where $C_{DUTMeas}$ is the measured value of the device under test, $C_{\mathrm{Re}\,fCal}$ is the previously-determined calibrated reference value, $C_{\mathrm{Re}\,fMeas}$ is the measured value of the reference standard, and $\varepsilon_{Loading}$ is the bridge loading error.

Control software is used to automatically perform the measurements and store the results. The laboratory temperature is maintained at 23.0 ± 1.0ºC. The relative humidity of the laboratory varies seasonally but is held below 50 percent. Ambient temperature, relative humidity, and enclosure temperature are recorded at the time of each customer measurement and the average values over all measurement sets are reported. Customer standards are energized for at least 72 hours prior to measurement and measurements are not performed if the temperature has varied from 23.0 ± 1.0ºC or if relative humidity has increased above 50 percent within the last 72 hours.

1.3 Data Processing

Once all of the data sets have been obtained, they are corrected for the various error factors. The difference between the value of the reference standard obtained from calibration against the primary bank of 10 pF standards is subtracted from the measured value of the reference standard for each of the five measurement runs. The bridge loading corrections are then applied and the data are averaged over the five measurement runs to obtain the calibrated value for the standard under test. The standard deviation for each frequency is determined over all measurement runs and reported as the Type A uncertainty. The ambient temperature, relative humidity, and chassis temperature are also averaged over the five measurement runs for reporting.

2 UNCERTAINTY BUDGETS

Tables 1 and 2 show the new uncertainty budgets for the 100 pF and 10 pF fused-silica standard capacitor calibration services at NIST. The Expanded Uncertainty for each frequency 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). The reference uncertainties are the combined standard uncertainties produced from calibration of the reference standards with traceability to the NIST Calculable Capacitor. The Reference Drift is the short-term drift in the calibrated values of the reference standard. The

Type A Uncertainty is a conservative limit describing the behavior of a typical standard. Any standard not performing to within this stability limit will require a larger uncertainty to be assigned. The DUT and reference drift components were determined empirically for the specific types of fused-silica standards used. The DUT Thermal and DUT Mechanical components are taken from the standard specifications [4][*]. The Bridge Linearity component is taken from the manual of the commercial capacitance bridge used in performing the calibrations [5]. The Bridge Loading component is the correction for the difference between the bridge loading during measurements of the reference and test standards. Details of the NIST method of expressing uncertainties can be found in reference [6]. The 1 pF uncertainty budget has not yet been completed at the time of this publication.

Table 1. Uncertainty budget for NIST 100 pF fused-silica standard capacitor calibrations.

Frequency (Hz)	Reference Uncertainty C272 (μF/F)	Reference Drift (C272) (μF/F)	Type A Uncertainty (μF/F)	DUT Drift (μF/F)	DUT Thermal (μF/F)	DUT 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	1.64
80	0.39	0.03	0.20	0.03	0.05	0.05	0.20	0.00	0.99
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	0.57
200	0.21	0.03	0.08	0.03	0.05	0.05	0.08	0.00	0.51
320	0.17	0.03	0.06	0.03	0.05	0.05	0.06	0.00	0.41
400	0.14	0.03	0.05	0.03	0.05	0.05	0.05	0.00	0.35
600	0.10	0.03	0.04	0.03	0.05	0.05	0.04	0.00	0.28
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	0.29
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	1.54
20000	0.37	0.03	0.34	0.03	0.05	0.05	0.34	1.00	2.35

3 CALIBRATION SERVICE

For many years NIST has offered calibrations for three-terminal fused-silica standard capacitors of values 100 pF, 10 pF, and 1 pF only at 100 Hz, 400 Hz, and 1000 Hz. 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

[*] 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.

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 100 pF and 10 pF service has already 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.

Work to characterize the 1 pF reference standards at frequencies from 50 Hz to 20 kHz continues and should be completed for the conference. The uncertainty budget for the 1 pF calibration will be presented at that time.

Please contact the authors to inquire about NIST calibration of standard capacitors.

Table 2. Uncertainty budget for NIST 10 pF fused-silica standard capacitor calibrations.

Frequency (Hz)	Reference Uncertainty C172 (μF/F)	Reference Drift (C172) (μF/F)	Type A Uncertainty (μF/F)	DUT Drift (μF/F)	DUT Thermal (μF/F)	DUT Mechanical (μF/F)	Bridge Linearity (μF/F)	Bridge Loading (μF/F)	Expanded Uncertainty (k=2) (μF/F)
50	0.61	0.03	1.28	0.04	0.05	0.05	1.28	0.00	3.81
80	0.38	0.03	0.68	0.04	0.05	0.05	0.68	0.00	2.07
100	0.30	0.03	0.45	0.04	0.05	0.05	0.45	0.00	1.42
160	0.23	0.03	0.24	0.04	0.05	0.05	0.24	0.00	0.85
200	0.21	0.03	0.18	0.04	0.05	0.05	0.18	0.00	0.69
320	0.17	0.03	0.12	0.04	0.05	0.05	0.12	0.00	0.50
400	0.14	0.03	0.09	0.04	0.05	0.05	0.09	0.00	0.41
600	0.10	0.03	0.06	0.04	0.05	0.05	0.06	0.00	0.32
800	0.07	0.03	0.05	0.04	0.05	0.05	0.05	0.00	0.27
1000	0.05	0.03	0.05	0.04	0.05	0.05	0.05	0.00	0.24
1600	0.02	0.03	0.05	0.04	0.05	0.05	0.05	0.01	0.22
2000	0.03	0.03	0.05	0.04	0.05	0.05	0.05	0.01	0.23
3000	0.07	0.03	0.06	0.04	0.05	0.05	0.06	0.02	0.28
4000	0.09	0.03	0.07	0.04	0.05	0.05	0.07	0.04	0.34
6000	0.14	0.03	0.12	0.04	0.05	0.05	0.12	0.09	0.50
8000	0.17	0.03	0.18	0.04	0.05	0.05	0.18	0.16	0.72
10000	0.20	0.03	0.27	0.04	0.05	0.05	0.27	0.25	1.00
12000	0.24	0.03	0.43	0.04	0.05	0.05	0.43	0.42	1.56
16000	0.29	0.03	0.63	0.04	0.05	0.05	0.63	0.63	2.26
20000	0.37	0.03	0.97	0.04	0.05	0.05	0.97	1.00	3.48

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