

New Realization of the Ohm and Farad Using the NBS Calculable Capacitor

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Abstract—Results of a new realization of the ohm and farad using the NBS calculable capacitor and associated apparatus are reported. The results show that both the NBS representation of the ohm and the NBS representation of the farad are changing with time, Ω_{NBS} at the rate of -0.054 ppm/year and F_{NBS} at the rate of 0.010 ppm/year. The realization of the ohm is of particular significance at this time because of its role in assigning an SI value to the quantized Hall resistance. The estimated uncertainty of the ohm realization is 0.022 ppm (1σ) while the estimated uncertainty of the farad realization is 0.014 ppm (1σ).

I. INTRODUCTION

THE NBS REPRESENTATION of the ohm Ω_{NBS} is based on the mean resistance of five Thomas-type wire-wound resistors maintained in a 25°C oil bath at NBS Gaithersburg, MD. Similarly, the NBS representation of the farad F_{NBS} is based on the mean capacitance of four fused-silica capacitors in a comparable oil bath. By means of the United States calibration hierarchy, measurements of resistance, capacitance, and inductance made throughout the country are generally traceable to these representations.

Realization of the ohm and farad is necessary for two distinct reasons: first, to determine Ω_{NBS} and F_{NBS} in SI units, thereby ensuring that measurements based on these electrical quantities are consistent with the SI, the unit system used throughout the world; second, to determine in SI units a number of fundamental physical constants of importance to both physics and electrical metrology. These include the fine-structure constant α , the quantized Hall resistance $R_H = h/e^2$, and the Josephson frequency to voltage quotient $E_J = 2e/h$ (h is the Planck constant, e is the elementary charge). Indeed, it is likely that starting January 1, 1990, representations of the ohm worldwide will be based on a conventional value of R_H and representations of the volt will be based on a new conventional value of E_J , both consistent with the SI. These values are to be derived from the data available by June 15, 1988 [1].

In order to contribute to the pool of data, NBS, like other national standards laboratories, is carrying out experiments to determine R_H and E_J . Realizing the ohm by means of the NBS calculable capacitor is an important

part of the NBS effort. This paper describes our measurements and gives our latest results.

II. AC MEASUREMENTS

The measurement sequence used in the 1974 ohm and farad determinations [2] has been retained in the present NBS measurements. A 0.5-pF calculable cross-capacitor is used to measure a transportable 10-pF reference capacitor which is carried to the laboratory containing the NBS bank of 10-pF fused silica reference capacitors. A $10:1$ bridge is used in two stages to measure two 1000-pF capacitors which are in turn used as two arms of a special frequency-dependent bridge for measuring two $100\text{-k}\Omega$ resistors. A $100:1$ bridge is used to compare each of the two $100\text{-k}\Omega$ resistors with a $1000\text{-}\Omega$ transportable resistor, R311, which is carried to the laboratory containing the NBS bank of $1\text{-}\Omega$ resistors where the dc stepdown is made. The ac-dc difference of R311 is determined by means of a special $1000\text{-}\Omega$ coaxial resistor of negligible ac-dc difference. All ac measurements are carried out at $\omega = 10^4$ rad/s ≈ 1592 Hz.

The calculable capacitor [2], the ac bridges [3] and standards [4], the ac-dc resistance standard [5], and the equipment used to measure transformer ratios [6], [7] and voltage dependencies [8] remain basically the same as in the 1974 measurements. The calculable capacitor was partially disassembled in order to realign the electrical and optical axes, clean the optical flats, install larger diameter PTFE rings on the guard tubes, check for microphonic coupling errors [9], and measure the distributed inductances and capacitances used to calculate frequency corrections.

Residual gas in the calculable capacitor has been reduced to a negligible level by the installation of a turbomolecular pump. All of the ac voltage sources and some of the preamplifiers and phase-sensitive detectors are new. An automated data acquisition system is now used in the comparison of the calculable capacitor with the 10-pF reference capacitor, resulting in a standard deviation of 0.003 ppm for the random scatter in one complete measurement requiring about one hour.

III. DC MEASUREMENTS

Relative to the 1974 measurements the most significant reduction in uncertainty is in the dc stepdown. To relate the $1000\text{-}\Omega$ transportable resistor R311 to the reference

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bank of 1- Ω resistors, measurements at 1, 100, and 1000 Ω are necessary using three different measurement systems. NBS-built Hamon-type resistance transfer standards [10] are used to provide accurate 1:100 and 1:10 resistance ratios to extend the 1- Ω reference bank to the 100- Ω level, and then to the 1000- Ω level. All of the resistance standards used in the scaling process to measure resistor R311 are measured *in situ*, immersed in specially designed circular oil baths with temperature maintained at $(25.000 \pm 0.002)^\circ\text{C}$.

An automated direct-current comparator system [11] is used to compare the five 1- Ω resistors in the reference bank to Hamon transfer standard H10A containing ten 10- Ω coils configured in the parallel mode. The resistance coils for Hamon H10A are individually sealed in brass cans filled with silicone heat-sink compound and terminated with mercury-wetted contacts. The connectors for the parallel configuration consist of (a) low-resistance amalgamated copper shorting bars for the current terminations, and (b) one of two fixtures having fan resistances of either 1 or 10 Ω for the potential terminations. A second Hamon standard of similar design but different construction is used as a check standard for scaling from 1 to 100 Ω .

The measurements at 100 Ω are made using an automated direct-current comparator system similar in design, construction, and operation to the 1- Ω system. Hamon H10A in its series mode is compared to a guarded Hamon standard H1kA containing ten 1000- Ω elements in its parallel configuration. The card-type resistance elements for H1kA are sealed in a thick-walled aluminum box filled with silicone fluid. The resistor terminations are British Post Office (BPO) connectors. A second Hamon standard containing ten 100- Ω resistors is used as a check standard for scaling from 100 to 1000 Ω .

Resistor comparisons at the 1000- Ω level are made using a guarded, resistance-ratio bridge. The adjustable part of the bridge is a modified direct-reading, double-ratio set. With this bridge the individual resistance sections of Hamon H1kA are compared to the 1000- Ω transportable resistor R311. Alternatively, Hamon H1kA can be compared to resistor R311 by first measuring the series-parallel combination of its first nine coils, and then measuring its tenth coil individually.

A set of three measured values is obtained for resistor R311 over a period of three consecutive days. Each day's measurement procedure consists of scaling from 1 to 1000 Ω and then back down to 1 Ω . The total uncertainty in assigning a value to resistor R311 in terms of the NBS 1- Ω reference bank is 0.010 ppm, the root-sum-square of the individual uncertainties listed in Table III. (Throughout this paper, all uncertainties are one standard deviation estimates.)

IV. INTERFEROMETER

The optical apparatus used to illuminate the capacitor interferometer has undergone complete renovation since the last series of measurements made in the early 1970's.

TABLE I
UNCERTAINTIES IN THE MEASUREMENT OF F_{NBS} IN SI UNITS

	one standard deviation
	estimate (ppm)
Type A (random)	0.003
Geometrical imperfections in the calculable capacitor	0.007
Laser/interferometer misalignment	0.003
Frequency (loading) corrections	0.004
Microphonic coupling	0.005
Voltage dependence	0.005
Drift between calibrations/failure to close	0.006
Transformer ratio measurement	0.002
Bridge linearity and phase adjustment	0.003
Detector uncertainties	0.002
Coaxial choke effectiveness	0.001
Temperature corrections for 10 pF capacitors	0.002
RSS	0.014

The Fabry-Perot (flat plate) interferometer is illuminated by a mode-stabilized He-Ne local oscillator whose wavelength is stable to within a few hundred kilohertz over the course of a measurement. Because this laser is not stabilized to a well-defined wavelength and may drift several megahertz per day, its frequency is continuously compared to an iodine stabilized laser whose wavelength is accurate to about three parts in 10^{10} and is stable to several parts in 10^{13} [12]. The lasers are compared by measuring the frequency of the heterodyne signal using a high-speed photo detector, electronic amplification, and a digital frequency counter. The frequency comparison contributes no significant error to the laser calibration.

The interferometer cavity is isolated from the working laser by using an acousto-optic modulator which shifts the frequency of the incident beam by 90 MHz and any light reflected back from the interferometer system by an additional 90 MHz. Because of the narrow bandwidth of the laser cavity, the return light, shifted from the incident light by 180 MHz, is no longer resonant in the laser cavity and is not coupled to the laser modes. No frequency pulling of the working laser wavelength due to back reflections from the interferometer or the beam steering optics could be detected. The uncertainty due to imperfect laser/interferometer alignment (Table I) was determined empirically by making comparative capacitance measurements after repeatedly misaligning the cavity and the beam steering optics and then realigning the system.

The laser beam diameter is expanded so that it fills the interferometer mirrors, and the entire transmitted beam is used to illuminate the photodetector so there is no beam truncation error. An integrating servo system locks the interferometer to the local oscillator with an accuracy of 1×10^{-3} of the interferometer transmission width and contributes negligible error to the determination of capacitance.

TABLE II
UNCERTAINTIES IN THE MEASUREMENTS RELATING THE NBS BANK OF 10-pF
CAPACITORS TO THE TRANSPORTABLE 1000-Ω RESISTOR

	one standard deviation estimate (ppm)
Type A (random)	0.004
Transformer ratio measurements	0.005
Voltage dependence measurements	0.005
Bridge linearity and phase adjustment	0.006
AC/DC difference of transportable 1000 Ω resistor	0.005
Quadrature bridge harmonics	0.003
Drift between calibrations/failure to close	0.006
Coaxial choke effectiveness	0.002
Auxiliary adjustments on four-terminal-pair bridges	0.002
Detector uncertainties	0.003
RSS	0.014

TABLE III
UNCERTAINTIES IN THE STEPDOWN FROM THE TRANSPORTABLE 1000-Ω
RESISTOR TO THE NBS BANK OF 1-Ω RESISTORS

	one standard deviation estimate (ppm)
Type A (random)	0.006
Temperature dependence of standards	0.003
Pressure dependence of standards	0.002
Loading effects of standards	0.003
Leakage effects of Hamon standards	0.003
Series-parallel connections of Hamon standards	0.004
Linearity of detector systems	0.003
Drift between calibrations/failure to close	0.003
RSS	0.010

V. RESULTS

The results of the measurements are

$$\underline{\Omega}_{\text{NBS}} = [1 - (1.594 \pm 0.022) \times 10^{-6}] \Omega \quad (1)$$

$$F_{\text{NBS}} = [1 + (0.143 \pm 0.014) \times 10^{-6}] F \quad (2)$$

where the mean date of each is May 17, 1988 and the uncertainties are one standard deviation estimates representing the root-sum-square of the appropriate uncertainties listed in Tables I–III.

Using the results of the last NBS ohm realization [2] which had a mean date of December 2, 1973, we find that $\underline{\Omega}_{\text{NBS}}$ has changed by (-0.775 ± 0.035) ppm and the average rate of change of $\underline{\Omega}_{\text{NBS}}$ is (-0.0536 ± 0.0024) ppm/year. This is in good agreement with the result (-0.0529 ± 0.0040) ppm/year obtained from measurements of the quantized Hall resistance [13] in terms of $\underline{\Omega}_{\text{NBS}}$ which have been made on a regular basis since August 1983. Of more importance, the quantized Hall resistance measurements [13] can be used with (1) to cal-

culate an SI value for the quantized Hall resistance. This calculation and other fundamental constant calculations using (1) are described in another paper [14]. Suffice it to say here that on the mean date May 17, 1988

$$R_H = 25\,812.8[1 + (1.874 \pm 0.012) \times 10^{-6}] \underline{\Omega}_{\text{NBS}}$$

which, in combination with (1), yields

$$\begin{aligned} R_H &= 25\,812.8[1 + (0.280 \pm 0.024) \times 10^{-6}] \Omega \\ &= (25\,812.807\,23 \pm 0.000\,61) \Omega \end{aligned}$$

where the correlation between the $\underline{\Omega}_{\text{NBS}}$ and R_H measurements due to the fact that some uncertainties are common to both has been taken into account.

Noting that F_{NBS} was adjusted to coincide with the SI value following the last NBS farad realization [2], we find that F_{NBS} has changed by (0.143 ± 0.016) ppm and the average rate of change of F_{NBS} is (0.0099 ± 0.0011) ppm/year.

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REFERENCES

- [1] P. Giacomo, "News from the BIPM," *Metrologia*, vol. 24, pp. 45–51, 1987.
- [2] R. D. Cutkosky, "New NBS measurements of the absolute farad and ohm," *IEEE Trans. Instrum. Meas.*, vol. IM-23, pp. 305–309, Dec. 1974.
- [3] R. D. Cutkosky, "Techniques for comparing four-terminal-pair admittance standards," *J. Res. Nat. Bur. Stand.*, vol. 74C, pp. 63–78, July–Dec. 1970.
- [4] R. D. Cutkosky and L. H. Lee, "Improved ten-picofarad fused silica dielectric capacitor," *J. Res. Nat. Bur. Stand.*, vol. 69C, pp. 173–179, July–Sept. 1965.
- [5] R. J. Haddad, "A resistor calculable from dc to $\omega = 10^5$ rad/s," M.S. thesis, School Eng. Appl. Sci., George Washington Univ., Apr. 1969.
- [6] R. D. Cutkosky and J. Q. Shields, "The precision measurement of transformer ratios," *IRE Trans. Instrum.*, vol. I-9, pp. 243–250, Sept. 1960.
- [7] J. Q. Shields, "Measurement of four-pair admittances with two-pair bridges," *IEEE Trans. Instrum. Meas.*, vol. IM-23, pp. 345–352, Dec. 1974.
- [8] J. Q. Shields, "Voltage dependence of precision air capacitors," *J. Res. Nat. Bur. Stand.*, vol. 69C, pp. 265–274, Oct.–Dec. 1965.
- [9] J. Q. Shields, "Absolute measurement of loss angle using a toroidal cross capacitor," *IEEE Trans. Instrum. Meas.*, vol. IM-27, pp. 464–466, Dec. 1978.
- [10] B. V. Hamon, "A 100 Ω build-up resistor for the calibration of standard resistors," *J. Sci. Instrum.*, vol. 31, pp. 450–453, Dec. 1954.
- [11] K. R. Baker and R. F. Dziuba, "Automated NBS 1-Ω measurement system," *IEEE Trans. Instrum. Meas.*, vol. IM-32, pp. 154–158, Mar. 1983.
- [12] H. P. Leyer, "A portable iodine-stabilized helium–neon laser," *IEEE Trans. Instrum. Meas.*, vol. IM-29, pp. 358–361, Dec. 1980.
- [13] M. E. Cage, R. F. Dziuba, C. T. Van Degrift, and D. Y. Yu, "Determination of the time dependence of $\underline{\Omega}_{\text{NBS}}$ using the quantized Hall resistance," pp. 263–269, this issue.
- [14] M. E. Cage *et al.*, "NBS determination of the fine-structure constant, and of the quantized Hall resistance and Josephson frequency to voltage quotient in SI units," pp. 284–289, this issue.