A Measurement of the NBS Electrical Watt in SI Units

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Abstract—We have measured the NBS electric watt in SI units to be: \( \frac{W_{\text{NBS}}}{W} = K_N = 1 - (16.69 \pm 1.33) \text{ ppm} \). The uncertainty of 1.33 ppm has the significance of a standard deviation and includes our best estimate of random and known or suspected systematic uncertainties. The mean time of the measurement is May 15, 1988. Combined with the recent measurement of the NBS ohm in SI units: \( \frac{\Omega_{\text{NBS}}}{\Omega} = K_\Omega = 1 - (1.593 \pm 0.022) \text{ ppm} \), this leads to a Josephson frequency/voltage quotient of \( E_N = E_0 [1 + (7.94 \pm 0.67) \text{ ppm}] \) where \( E_0 = 483 \text{ 594 GHz/V} \).

I. INTRODUCTION

IN THE International System of Units (SI), the electrical units are defined in such a way that the electrical unit of power, the volt-ampere, is identical to the mechanical unit of power, the newton-meter/second, and each of these units is a watt. In the laboratory representation of the electrical units, or “laboratory system of units,” where the volt is defined by the Josephson effect and the ohm by the quantum Hall effect (or by reference to an artifact resistance standard), the units of electrical and mechanical power are not necessarily equivalent. Our experiment compares the NBS laboratory electrical watt to the mechanical, SI watt. It is, in effect, an electrical realization of the SI watt. In spirit, this experiment is very much like a realization of the ampere, and its relationship to more traditional ampere realizations or absolute ampere experiments, has been described earlier [1]. The measurement is based on an idea first proposed by Kibble [2].

II. THEORY

Consider the circuit of Fig. 1(a). Two coils carry currents \( I_1 \) and \( I_2 \). The vertical, \( z \)-component of the force between them, \( F_z \), is given by the derivative of the mutual inductance: \( F_z = I_1 I_2 \frac{dM_{12}}{dz} \). This vertical force can be compared to a gravitational force \( mg \) using a balance. Now consider the same two coils in Fig. 1(b), where coil 2 is open-circuit and a voltmeter measures the EMF generated across it as it is moved along \( z \) with respect to coil 1. The generated EMF is given by: \( \mathcal{E} = I_1 \frac{dM_{12}}{dt} \). Combining the expressions for \( F_z \) and \( \mathcal{E} \), we have

\[
F_z v = I_2 \mathcal{E}
\]

where \( v = \frac{dz}{dt} \). This simply expresses the equivalence of mechanical and electrical power, all quantities being expressed in SI units.

To express the electrical quantities in our laboratory units we define \( K_N = A_{\text{NBS}}/A \), the ratio of the NBS and SI units of current. \( K_N \) and \( K_W \) are defined in a similar way. Taking \( I_{\text{NBS}} \) to mean the current measured in NBS units, and similarly for \( I_{\text{NBS}} \), we have \( I_2 = I_{\text{NBS}} K_N \), and \( \mathcal{E} = K_N \mathcal{E}_{\text{NBS}} \). Substituting these expressions in (1) we have

\[
K_N = \frac{K_a K_V}{I_{\text{NBS}} \mathcal{E}_{\text{NBS}}}
\]

(2)

If \( K_N \) is separately measured, as in an absolute ohm experiment, we can obtain \( K_a \) and \( K_V \) from \( K_N \):

\[
K_N = \frac{K_N K_V}{K_a}
\]

(3)

Since \( K_V = E_{0,\text{NBS}}/(2e/h) \) where \( E_{0,\text{NBS}} = 483 \text{ 593.420 GHz/V} \), a determination of \( K_V \) determines \( 2e/h \) in SI units.

Because it is difficult in practice to measure accurately an instantaneous velocity or voltage, we do not use (2) directly to determine \( K_W \). Instead, we use an integral form of (2), obtained by integrating the expression for the generated EMF over time and the expression for the force over distance. Experimentally, we realize these integrals by: a) measuring the EMF as a function of time while moving coil 2, and b) measuring the current required in

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coil 2 to maintain a constant force between the coils for various static positions of coil 2. It can be shown that $K_W$ is given by

$$K_W = \frac{mg}{I_0} \int_{z_1}^{z_2} \left[ I_0 / I(z) \right] dz,$$

(4)

Here $\varepsilon_{\text{NBS}}(t)$ is the generated voltage when the moveable coil is moved along some path in the field of the fixed coil; $mg$ is the fixed gravitational force against which the magnetic force is balanced. $I(z)$ is the current in the moveable coil needed to create that magnetic force at a position $z$. The current $I_0$ is $I(z_0)$, where $z_0$ is some arbitrary reference point where $I(z)$ is measured. The quantity $\left[ I_0 / I(z) \right] dz$ is called the force integral and is a quantity which depends only on the geometry of the coils and on the path of integration, but not on the current in the coils. Equation (4) requires that the current in the fixed coil (i.e., the field coil) and the geometry of all the coils remain constant between the time that $\varepsilon_{\text{NBS}}(t)$ is measured and $I_0$ are measured. Furthermore, the path of the moveable coil in the time integral and in the distance integral (i.e., the force integral) must be identical. Finally, the integral $\int F_z dz$ (to which $mg[I_0/I(z)] dz$ is equivalent) must account for all of the mechanical work done in moving the coil from $z_1$ to $z_2$; that is, either the displacements $dx$ and $dy$ must be zero along the chosen path or the force components $F_x$ and $F_y$ must be zero.

III. Apparatus

The apparatus used to make the measurements required in (4) has been described in some detail previously [1]. Here we will review the apparatus only very briefly. The apparatus is shown schematically in Fig. 2. Coil C is the moveable, suspended coil which is equivalent to coil 2 in Fig. 1. The fixed field coils B, above and below the suspended coil, are equivalent to coil 1 in Fig. 1. In the experiment reported here, these B coils are wound with copper wire and cooled by being immersed in a circulating oil bath. We also have available a superconducting version of coils B which produces a field two orders of magnitude larger than the present coils, and which will be used in future measurements [3].

The suspended coil C is attached to the “balance wheel” A through the spider E. The spider also supports a pan for the standard masses. Wheel A is an aluminum disc with a knife edge at its center. A band consisting of 40 fine wires hangs from the wheel on both sides. As the wheel rotates, it acts like a pulley, raising or lowering the suspended coil. The advantage of this arrangement, compared to hanging the coil from one arm of a conventional beam balance, is that the translation of the coil is almost perfectly vertical, helping to satisfy the requirement for validity of (4) that there be no horizontal displacements.

Coils G along with permanent magnets F provide the means by which the balance wheel is made to rotate. A servo feedback to these drive coils controls the motion of the suspended coil for the generation of the EMF $E$. The position of the suspended coil is measured with a laser interferometer. Servo feedback to the suspended coil maintains this position while we measure the current in the suspended coil required to balance the force $mg$.

For more details concerning the apparatus, the reader is referred to [1]. Among the significant changes since that wiring is that the suspended coil now is wound in three separate concentric sections with a total of 2355 turns of copper wire. The suspended coil has a total resistance of 480 $\Omega$. Reversing a current of 50 mA through this coil changes the magnetic force by about the equivalent force produced by a mass of 105 g. Gold or brass 105-g mass standards are used to measure the force. We also have used a 70-g mass standard, reversing 33 mA through the coil. The 50- or 33-mA current is passed through a 20- or 30-$\Omega$ resistor which allows comparison of the voltage against our working 1-V voltage standard. The 20- or 30-$\Omega$ resistor is also used to generate 20 or 30 mV as a reference for the generated EMF when the coil moves. Use of the same 20- or 30-$\Omega$ resistor for these two functions eliminates the need for precise calibration of these resistors. Furthermore, the 20-$\Omega$ resistor is made of two 10-$\Omega$ resistors and alternate use of these 10-$\Omega$ resistors to generate the 10-mV reference eliminates the need for their calibration. These changes, along with complete automation of the measurement, have allowed us to achieve a substantial improvement in precision over that reported previously.
The measurement of $K_m$ is divided into three phases, corresponding to three key measurable quantities in (4). In the first phase, the suspended coil moves under servo control so as to generate a nearly constant EMF. Data accumulated during this "voltage" phase is used to compute the time integral of the voltage. In the second, or "force" phase, we measure the current $I_1$ which balances the force $mg$ at a specific position of the suspended coil. These two measurement phases are repeated many times in succession. At a different time, often separated from the first two phases by several days, we perform the third phase or "force integral" measurement. This is accomplished by comparing the current needed to balance $mg$ at many z-positions of the suspended coil.

All of the measurements use a 1-mA current source to supply working voltage references. This current source, which can be reversed with a ramped reversing switch, supplies 10-, 20-, 30-Ω, and 1-kΩ resistors, producing 10-, 20-, 30-mV, and 1-V references. These working voltage references, produced from stable resistors, are used throughout the measurement. The current source is calibrated by comparing the 1-V reference to a Zener voltage standard which is periodically calibrated against the NBS volt and by calibrating the 1-kΩ resistor in terms of QNBs. Note that the 10-, 20-, and, 30-Ω resistors need not be precisely calibrated (see discussion at the end of the previous section).

In the voltage phase of the measurement the EMF generated by the moving coil is servoed to be nominally equal to the 10-, 20-, or, 30-mV reference. At 20-mV, this produces a velocity of about 2 mm/s. When the moving coil position, as measured by the laser interferometer, reaches selected positions along the vertical path, the computer is triggered to perform measurements of the error voltage (difference between the reference voltage and the generated voltage) and of the time from a 1-MHz clock. The triggerings occur at rates up to 400 Hz for the 20-mV reference level and at somewhat lower rates for the other levels, limited by the data-taking speed of the computer.

With a perfect servo, the error voltage would be zero, as the velocity is adjusted to produce a constant EMF. In reality, there is a typical error on the order of a microvolt. In principle, even with such an error voltage, a correct measurement of the EMF and the times should lead to the correct time integral of the voltage in (4). Unfortunately, because of the time constant of the linear amplifier used to detect the error voltage, we do not have the true instantaneous generated EMF at the time data points are acquired. To correct for this in the calculation of the time integral, we have digitally filtered the measured time points with the same time constant measured for the linear amplifier.

The total path length over which we collect data is 7.6 cm. Up to 15 000 points are recorded during a traversal. After each such traversal the current source is reversed, reversing the reference voltage. Under servo control, this reverses the direction of travel of the suspended coil, and another measurement is taken going in the opposite direction. Some computation of the time integral of the generated EMF, including digital filtering of the time data, is performed during the period when the coil turns around for another traversal. The compressed data is stored for later analysis. The integral is taken over a path whose length is 5.9 cm (370 000 interferometer fringes of $\lambda/4$ for $\lambda = 633$ nm). The time interval for the voltage integral is about 30 s when the generated EMF is 20 mV. A set of 10 traversals in each direction is measured, which, with the time for turning around, requires between 18 and 36 min, depending on the chosen reference voltage. To eliminate the effect of drift and of zero offsets, we interpolate the voltage integral obtained for two up (down) traversals to the time of a down (up) traversal and compute the up/down difference in voltage integrals. Typical scatter in such differences over a set of traversals is a bit less than 1 ppm.

During the force phase the suspended coil position is servoed to a fixed location by feeding back the interferometer measurement as a current to the coil. This current is measured with the standard mass alternately on or off the pan connected to the spider from which the coil is hung. A force measurement typically consists of eight reversals where the mass is lowered onto or raised from the suspended pan. For each positioning of the mass, the coil current is measured by passing it through a 20- or 30-Ω resistor and comparing the voltage drop to the 1-V reference. The balance is arranged so that when the mass is lifted or replaced the current in the coil must reverse in order to maintain the servo position. Current is measured for about 2 min in each mass position. Including the time for raising and lowering the mass and stabilizing the servo, the elapsed time for force measurements is about 25 min. To eliminate the effect of drift and zero offsets we interpolate between two measurements with the mass off (on) to the time of a measurement with the mass on (off) to obtain the on/off current difference. The scatter in such differences, made over 25 min, is considerably less than 1 ppm for most measurements.

On a typical day of taking data, we obtain 10–16 pairs of voltage and force measurements, at the rate of about one pair per hour, including the time required to automatically reconfigure the apparatus when changing from voltage to force and vice versa.

The final phase of the measurement, the determination of the "force profile," is very similar to the force measurements described above. Here, we simply make repeated force measurements, but at various positions of the suspended coil. To eliminate the effect of drifts, we continually measure the reversal current at the reference position used in the force phase. Thus we obtain the ratio of the reversal current at various positions, $I(z)$, to the current at the reference position, $I_0$. The measurements are repeated at different positions continuously for several
days. The ratios obtained are fit to a polynomial and analytically integrated over the same interval used for the voltage integral.

In order to minimize the influence of choosing a particular set of endpoints for the integration interval, we calculated the voltage integral for 20-50 overlapping regions with different sets of endpoints. The endpoints of the fixed-length intervals used were changed by about a third of the total distance used in the analysis. From each voltage integral, and the appropriate force integrals for each interval, we obtain a value of $K_w$. To reduce the noise and to eliminate effects which contribute at the endpoints of the integral, such as variations in the velocity which might be due to servo errors, we averaged these with equal weight. (This process tends to weight measurements of voltage and time taken near the ends of the analyzed region less than those in the central region, since the integrated region always included one or two centimeters of the region nearest the center.)

V. RESULTS AND DISCUSSION

Fig. 3 shows a histogram of 191 values of $K_w$ obtained over a period of approximately one month. Each value contributing to the histogram is obtained as follows: from the values of two successive voltage integrals, typically taken an hour apart, we interpolate a voltage integral at the mean time of the intervening weighing measurement and calculate a $K_w$ from the actual weighing and the interpolated voltage integral. Similarly, we interpolate between two successive weighings to the time of a voltage integral measurement and obtain a $K_w$ from those values. The values in the histogram are averages of two successive values of $K_w$, one from two voltage integrals and a weighing, and one from two weighings and a voltage integral. The next two values of $K_w$ so obtained are used to produce another point on the histogram. Each point, therefore, contains information from two weighings and two voltage integrals, corresponding to approximately two hours of elapsed time. While some of the same information is used in adjacent points, they are nearly independent. The standard deviation of all the values of $K_w$ obtained is 1.1 ppm.

The interpolation process described above is supposed to account for variations in the current or geometry of the fixed field coils between voltage and force measurements. Fig. 4 shows the voltage and force measurements themselves during the course of a typical day. The fact that they follow the same pattern of variation is good evidence that the experiment is in control and operating as expected.

Fig. 5 shows the results of a typical measurement of the force profile, along with the polynomial fit to the measured points. A similar profile can be obtained by integrating the voltage data over appropriately small time intervals. Because of the short time intervals, such a profile is noisier than the directly measured force profile, but it has the same shape, as expected.

For the final analysis, we have divided the data by days and averaged the various days together with equal weighting. The standard deviation of 13 days of data is 0.80 ppm. The fact that the standard deviation of 13 days is not much reduced from the standard deviation of 191 individual points suggests that day-to-day scatter is not purely statistical, but hides some systematic error possibly related to conditions which change from one day to the next. Because of this, we felt it was prudent to average the days together without weighting them either according to the time spent taking data on a given day or according
to the variance of a given day’s data. For a discussion of the statistical treatment of data with differences between groups of measurements, see [4].

The mean of 13 days of data taken over a period of approximately the month of May 1988 was $K_{w} = 1 + \delta_{w}$, where $\delta_{w} = -16.69$ ppm. If we had taken the mean of all the results in the histogram (equivalent to weighting each day according to the amount of data taken on that day) we would get a $\delta_{w}$ of 0.12-ppm lower. The voltage generated in the voltage-velocity part of the measurement was nominally 10, 20, or 30 mV. The velocity in turn also varied as the voltage. If we consider the data obtained at each of these voltages separately, we obtain $\delta_{w} = -16.96, -16.51$, and -16.74 ppm for 10, 20, and 30 mV, respectively. The standard deviation as estimated from these three values is 0.23 ppm.

Data was actually taken on 17 days during May, but four of these sets were discarded. Those four were the ones in which the voltage for the voltage-velocity part was sampled at rates of -100 and 50 Hz. We kept only that 10-mV data sampled at -200 Hz. The reason for discarding that data is as follows: both the velocity and the voltage measured during the voltage-velocity phase are modulated at about 30 Hz with an amplitude as high as 2 percent of the velocity and 0.1 percent of the voltage. This modulation is thought to be the result of mechanical vibrations of the building which couple into the balance. Computer simulations of the acquisition of data from such a modulated source indicate that when the sampling rate is too low, a significant error (at the parts per million level) can result from the inability to accurately integrate the modulated voltage signal. For 20-mV data, the percent modulation is smaller, and simulations show the effect to be much smaller. We find experimentally that the value of $K_{w}$ obtained at 10 mV depends on the sampling rate, while at 20 mV it does not. We, therefore, eliminate the questionable 10-mV data taken at the low sampling rate. Had we included that data, we would have $\delta_{w} = -16.94$ ppm. It was all the 10-mV data by itself gives $\delta_{w} = -17.41$, while if we eliminate all the 10-mV data, the 20- and 30-mV data give $\delta_{w} = -16.60$ ppm. Considering the results of the simulations and the observed variation with sampling rate, we feel justified in discarding the slow 10-mV data. However, we do consider the effect of the sampling rate in assigning the final uncertainty.

The voltages used to compute the voltage integral are measured with a low noise dc linear amplifier and sampled using an A/D converter. The amplifier has a frequency response which effectively filters the voltage appearing at its input. Roughly speaking, this filtering corresponds to a time constant of about 50 ms. As discussed above, to correct this, we digitally apply the measured filter function of the null detector to the time data. The result quoted is for data so filtered. Comparing the filtered data with unfiltered data where the raw times are used to calculate the voltage integral, we find that for unfiltered data $\delta_{w} = -15.88$ ppm, a 0.75-ppm difference from the filtered data. The difference is greater for higher velocity data. Computer simulations of the data indicate that filtering is the proper way to handle the data, so we have used only filtered data.

Table I shows our one standard deviation uncertainty estimates for $K_{w}$.

1) Statistical and Undiscovered Systematics: The entry of 0.80 ppm is the day-to-day standard deviation of the 13 days used in the determination. While we might reduce this by $\sqrt{13}$ to 0.22 ppm, the suggestion that the data are not statistically and that there may be some undiscovered systematics (such as a remaining error due to insufficient sampling rate, for example) leads us to use the full day-to-day standard deviation.

2) Analysis: The entry of 0.6 ppm refers to uncertainties arising from shifts found to arise in $K_{w}$ when different data analyses are used, including filtering of time data and averaging of voltage data before integrating.

3) Different Force Profiles: This represents uncertainties which were estimated by deliberately changing the configuration of the fixed coils or by using different parts of the total path of the moveable coil to determine $K_{w}$. Shifts in $K_{w}$ from such changes lead to an uncertainty of 0.5 ppm.

4) Polynomial Representation of the Force Profile: The force profile is measured at a large number of points and fit with a polynomial of order 4-6. The statistical uncertainty of the fit and the changes in the integral with the order of the polynomial fit contribute 0.42 ppm.

5) Gain of Detector: The gain of the dc linear amplifier used in voltage measurements and in current measurements during weighing is important because the mea-

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**Table I: Estimated One Standard Deviation Uncertainties**

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measurements are always somewhat off null. Uncertainties in this calibration contribute 0.36 ppm.

6) Effect of Vibrations: Mechanical vibrations are responsible for the observed 30-Hz modulation, which, when added to simulated data, leads to errors. We can also deliberately apply vibrations which are seen to shift $K_\varphi$. The size of these shifts for large applied vibrations leads us to assign 0.3-ppm uncertainty associated with the actual vibrations. The equipment necessary to cool the large electromagnet is one source which produces mechanical and acoustic vibrations. This noise source is a source of uncertainty in the measurement which will be eliminated with the superconducting magnet.

7) Effect of Different Velocities: Choice of different generated voltages in the voltage phase leads to different velocities. Because of the finite time response of the detector and the servo system, this might lead to errors. We assign 0.2 ppm-uncertainty based on the scatter between results obtained at different velocities.

8) Verticality: The interferometric measurements of position of the moveable coil must be made along a vertical line to correspond to the direction in which forces can be measured by the balance. The error in setting the interferometer path to vertical contributes 0.1 ppm.

9) Standards: The total effect of uncertainties in the various calibrations and standardizations is 0.3 ppm, which reflects not only the basic calibration uncertainty but also uncertainties in corrections applied to the calibrations. Volt transfer includes the accuracy of the calibration of our Zener reference against the NBS volt and the drift between calibrations. "Current calibrations" refers to errors in establishing our working standard of voltage against which the weighing currents and the generated voltages are measured. Laser wavelength uncertainties include errors in the refractive index of air due to uncertainty in temperature, pressure, humidity, and CO$_2$ content of the local atmosphere. Resistor calibration includes uncertainty in the drift of the resistor compared to the NBS ohm. Mass calibration includes uncertainties in the buoyancy corrections due to measurement of the parameters of the local atmosphere. Gravity uncertainty includes uncertainties in the absolute gravimeter measurement at a reference site, transfer to the experimental site, and tidal variations in the gravitational acceleration.

We have considered other sources such as leakage resistances, frequency standard errors, and the influence of nonvertical forces; and have concluded that all such identified errors are significantly less than 0.1 ppm and so do not need to be considered in our uncertainty estimate. We should point out that the evaluation of our most significant errors is limited by the day-to-day fluctuations in measurement. We expect that the accumulation of a significantly larger set of data will allow most errors to be reduced.

Furthermore, use of the superconducting field coils will increase the fixed magnetic field by two orders of magnitude. This will allow the force and the generated voltage to be increased substantially, reducing most of the largest errors by about an order of magnitude.

The final result for our present measurement of the NBS watt in SI units is

$$W_{\text{NBS}} = K_w = 1 - (16.69 \pm 1.33) \times 10^{-6}.$$  
(May 15, 1988)

The uncertainty of 1.33 ppm has the significance of a standard deviation and includes our best estimate of random and known or suspected systematic uncertainty. The mean time of the measurement is May 15, 1988, and refers to the NBS volt and ohm as of that date. Combined with the measurement of May 17, 1988 of the NBS ohm in SI units which implies $\Omega_{\text{NBS}}/\Omega = K_\varphi = 1 - (1.593 \pm 0.022)$ ppm, this leads to a Josephson frequency/voltage quotient of

$$E_j = E_0 [1 + (7.94 \pm 0.67) \text{ ppm}]$$

where $E_0 = 483.594 \text{ GHz}/V$.

A comparison of the current experimental values of $E_j$ are given in Fig. 6. Direct force measurements are contributions from CSIRO (Australia), U. Zagreb (Yugoslavia), NPL (U.K.), and this paper NBS (U.S.). Values of derived $E_j$ are from the Faraday: NBS F (U.S.); from high and low field gamma-p: NIM (PRC), NPL high NBS low, ASMW (DDR); and the derivation resulting from Avogadro's number: NBS $N_A$ (U.S.) and PTB, $N_A$ (FRG).

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