EXPERIMENTAL NOISE SOURCES IN THE NIST WATT BALANCE

R. L. Steiner, D. B. Newell, and E. R. Williams*
National Institute of Standards and Technology †
Gaithersburg MD 20899-0001 USA

Abstract

The present NIST watt balance has a relative combined standard uncertainty of about 145 nW/W. The final results of this phase of the experiment are presented. Improvements in the Type B (nonstatistical) uncertainty contributions, along with several correction factors and noise sources, are also discussed.

Discussion

Introduction. The present NIST watt balance is the latest successor to a series of "absolute" ampere experiments [1]. The present experiment has been described before [2], and it remains basically the same, although major improvements in the resolution have been achieved. In brief, the experiment consists of two modes of operation. In the first, an induction coil moves vertically at 2 mm/s velocity in a magnetic flux density (B), generating about 1 V. This voltage (U) and velocity (v) are measured to provide a ratio U/v, proportional to the radial magnitude of the flux density. In the second mode, a 10 mA current is applied to the induction coil to balance the force on a kilogram mass standard in the local Earth's gravity. The force (F) and current (I) are measured, providing another ratio, F/I, also proportional to the same B. The 0.1 T magnetic flux density is radially symmetric (to cancel to first order any radial asymmetry in the inductive coil's dimensions) over a cylindrical region 10 cm high and 35 cm in radius from the center line of two opposing superconducting solenoids. The ratio of these two quantities [Eq. 1] eliminates the necessity

$$\frac{\left(F/I\right)}{\left(U/v\right)} = \frac{(F \bullet v)_z}{(UI)} = \frac{P_{mech}}{P_{elec}} \qquad (1)$$

to analyze the exact field geometry and results in a comparison of the calculated mechanical power $(F v) = P_{mech}$ to the calculated electrical power $(U I) = P_{elec}$.

However, this simple summary fails to convey the complexity of managing all of the references and measurements needed to perform the experiment. The Type A relative standard uncertainty for the NIST watt balance has now been reduced to about 50 nW/W. As is commonly the case, Type B (nonstatistical) uncertainties dominate the final combined uncertainty. The major Type B components are listed in Table 1, expressed in units appropriate to the watt determination. We will focus on these type B components and relate some details concerning various procedures.

Analysis. Table 1 is in two sections. The first few sources in the References & Corrections section are the uncertainty in the five basic reference standards which must be maintained to determine the watt as a unit of power: voltage and resistance, or length, frequency (time), and mass. Of these, artifact transfer standards for resistance (traceable via Quantum Hall Effect) and mass (traceable to le Grande Kilogram) imply larger uncertainties. Our gold test mass in particular is subject to wear and surface contamination. The volt involves additional complexity. Voltage measurements are made against a Hg-battery stabilized source, traceable through a Zener reference to an in-lab Josephson array voltage standard. Thermal emfs in the connecting wires are kept within 30 nV. Variations in these and the Zener contribute the major share of the voltage uncertainty.

The other components in this section of the table are corrections that must be measured or estimated from environmental parameters. The refractive index is the largest correction with the largest standard uncertainty, at about (260 ± 0.1) μW/W. It limits our laser interferometry, which is performed in air. We record temperature, pressure,

†Electricity Division, Electronics and Electrical Engineering Laboratory, Technology Administration, U.S. Department of Commerce.

Uncertainty Source	nW/W
References & Corrections	
Mass	30
Resistance	30
Voltage	20
Length	1
Frequency	3
Alignments	20
Gravity	5
Refractive index	100
Mass buoyancy	30
External Effects	
Leakage resistance	10
Knife-edge hysteresis	40
Magnetic flux z-profile fit	50
Magnetic flux drift	20
Balance offset drift	20
RSS value	**136**

Table 1. Type B relative standard uncertainties in the NIST watt experiment.

and humidity to use the Edelin formulae [3] to calculate the refractive index correction. The environmental factors also affect the air buoyancy correction for the force balance mode, equal to about 60 μW/W. Significant reductions in these uncertainties were achieved by reducing temperature gradients near the mass and the lasers from several tenths kelvin to about 20 mK. The values listed in the table are now dominated by uncertainty in our knowledge of the room's air composition, with a smaller contribution from temperatures. The gravity value is regularly determined by a gravimeter in the laboratory. The main uncertainty arises from the comparison transfer to the location of the test mass, a difference of 1.36 μW/W.

The External Effects section of the table lists areas that are influenced by hard-to-control external influences, such as humidity or vibrations. Leakage resistance is limited by variations with seasonal humidity. Knife-edge hysteresis occurs from inelastic deformations in the balance wheel pivot, which relaxes over times related to the duration of the deforming force. Deformations arise when the balance wheel rotates 5° in moving from velocity to force mode, and about 0.04° in each positioning of the mass standard.

The final components in the table generally relate to nonlinear, time-dependent changes of the magnetic field, electrical noise, etc. The relevant times in our procedures are: 1 min between velocities, 5 min between forces, and 1 h between velocity modes that bracket a force mode; a continuous run is typically about 10 points taken at night. Thus, it is difficult to estimate the randomness of short variations which may affect only a few watt points, or whether longer period nonlinear drifts are diurnal events. We've generally reduced the magnetic flux density and the balance offset drifts, but the time dependence in the magnetic flux density z-axis profile is very difficult to assess. This correction varies with changes in oil bath temperature, two secondary current sources, voltmeter offsets, a voltage standard cell, and the liquid helium level. Using a day's average of velocity data (about 250 curves) to calculate a daily correction to the profile has reduced the scatter. Presently, averaging curves with many microwatts equivalent noise, due to vibrations ranging over 0.1 Hz to 30 Hz, mathematically constrains this method.

Conclusions. Work is progressing to reduce the Type B uncertainties in the NIST watt balance, especially the air buoyancy and refractive index. However, the source for these two components, air, can only be significantly reduced in the next generation experiment which will have a vacuum enclosure. Other efforts aim at reducing the Type A and associated Type B uncertainties that depend on the noise and traceability of voltage measurements.

Acknowledgment

The authors would like to thank Z. Jabbour, R. Dziuba and C. Tilford, NIST, for their assistance with mass, resistance, and pressure calibrations respectively.

References

[1] B. P. Kibble, "A Measurement of the Gyromagnetic Ratio of the Proton by the Strong field Method," Atomic Masses and Fundamental Constants, vol. 5, pp. 545-551, J. H. Sanders and A. H. Wapstra, Eds. New York: Plenum, 1976.

[2] R. L. Steiner, A. D. Gillespie, K. Fujii, E. R. Williams, D. B. Newell, A. Picard, G. N. Stenbakken, and P. T. Olsen, "The NIST Watt Balance: Progress Toward Monitoring The Kilogram," IEEE Trans. Instrum. Meas., vol. 46, no. 2, April 1997, pp. 601-604.

[3] K. P. Birch and M. J. Downs, "An Updated Edelin Equation for the Refractive Index of Air," Metrologia, vol. 31, pp. 315-316, 1994.