Absolute Determination of the Ampere

Just before the outbreak of World War II, the International Committee on Weights and Measures (CIPM) began to consider moving from the existing international system of units to a so-called absolute system, the predecessor to the SI. In their first post-war meeting in October of 1946, the CIPM resolved to make that change on January 1, 1948. The decision was driven in large part by the results of a study by the National Bureau of Standards of absolute electrical experiments around the world (including our own), and recommendations for the ratios of the international electrical units to their absolute counterparts. These recommendations were based on averages of the results of determinations made in the United States and other countries. In this study, NBS contributed two results relevant to the determination of the ohm ratio and one determination of the ampere ratio. Since no absolute volt determination had been made, the volt ratio was computed from those of the ohm and ampere.

The paper *An Absolute Determination of the Ampere, using Helical and Spiral Coils* [1] gives one of the two NBS values that went into the 1948 redefinition of the ampere. It describes in detail the radically modified fixed and moving coils of the current balance; the measurements made on the coil dimensions; computations of their fields and interactions; and the force measurements relating current through a coil to the values of the national reference resistors and voltage standards of the time.

The final recommended value of the absolute ampere was constructed as the average of the results of three experiments, one from the National Physical aboratory and two from NBS [1,2]. This evaluation also stood with that of the absolute ohm to provide the internationally accepted volt representation until 1969, when improved measurements and the use of the Josephson effect to determine the volt unit made a further change practical.

H. L. Curtis and R. W. Curtis published an earlier paper, *An Absolute Determination of the Ampere* [3], in 1934. This measurement used a Rayleigh current balance, in which the electromagnetic force between concentric coils is balanced by the gravitational force on a mass. By 1944, three absolute-ampere and three absolute-ohm experiments had been completed at the Bureau [4], and similarly accurate absolute determinations of the ampere and ohm were available from Britain.

Improved absolute measurements of current were in some ways more difficult than those of the ohm, and they proceeded by smaller steps. Before World War II, at about the same time that the moving-coil current balance was being used to determine the ohm, H. L. Curtis and R. W. Curtis had started to prepare a balance of a special design for the absolute ampere determination. In 1958 R. L. Driscoll reported results from this Pellat balance [5]. The mechanical measurement was of the torque on a small coil, with axis at right angle to the magnetic field of a large horizontal solenoid. When the current passing through the small coil was reversed, it produced a force that could be balanced by a mass of about 1.48 g placed on the balance arm. The large stationary coil was wound on a fused-silica form, and the balance beam was equipped with knife-edges and supports machined from natural agate. The effect of the measured dimensions of the small coil on the computed mutual inductance was the largest contribution to the uncertainty, which totaled about 8 μA/A. Also contributing to the uncertainty were the determination of the balancing mass and the of the acceleration due to gravity.

As soon as possible after completing the Pellat balance measurement, Driscoll and Cutkosky [6] repeated the 1934 Rayleigh current-balance determination of the ampere using the original apparatus. The results of these two experiments, 1 NBS ampere = $(1.000\,013 \pm 0.000\,008)$ absolute amperes by the Pellat method, and 1 NBS ampere = $(1.000\,008 \pm 0.000\,006)$ absolute amperes by the current balance, were in good agreement. This gave an overall relative uncertainty in the ampere at NBS of about 5 μA/A at that time (1958) and verified that the ratio of emf to resistance of the maintained standards had been constant to within about one part in 10^5 since 1942.

Absolute experimental determinations of units are now known as SI realizations, and the uncertainty of the SI values of the electrical units are limited by the uncertainty of their realizations in terms of the kilogram, meter, and second. Results from the calculable capacitor experiment and other determinations of the fine-structure constant recently have been combined analytically [7] to yield a value of the von Klitzing constant R_K with a relative standard uncertainty of 4×10^{-9}. The Josephson constant K_J is based both on its direct measurement by voltage balances and by combining R_K with a value of the Planck constant, the latter obtained by realizing the watt in a special way. This realization of the SI watt is achieved by the moving-coil watt balance, which is a modern version of the absolute ampere experiment.

The NIST watt balance has been designed to measure the ratio of mechanical to electrical power, linking the artifact kilogram, the meter, and the second to the practical realizations of the ohm and the volt derived from the quantum Hall effect (QHE) and the Josephson effect, respectively. The first results from the NIST watt experiment, sometimes called an ampere experiment, were published in 1989 [8], giving a relative standard uncertainty for K_J of 6.7×10^{-7}. That experiment was a prototype for the next version in which the magnetic field was increased a factor of 50 using a superconducting magnet, resulting in similar increases in the force and voltage. During the next decade many improvements were made [9,10]. In 1998 the latest results were published [11] by E. R. Williams, R. L. Steiner, D. B. Newell, and P. T. Olsen. That work, which used a NIST calculable capacitor measurement of R_K, reports that $K_J = 483\,597.892$ GHz/V with a relative standard uncertainty of 4.4×10^{-8}. This is the most accurate measurement of the Josephson constant to date.

The experiment is automated and runs nightly and over holidays to reduce vibrations. Recent measurements recorded 989 values of the SI watt over a 4-month period. The total uncertainty is dominated by Type B uncertainty components, that is, components that have to be evaluated by means other than statistical analysis of repeated measurements. Of the possible Type B error sources that contribute to the uncertainty, the three largest components arise from the following: (1) the index of refraction of air; (2) the present alignment procedures; and (3) residual knife-edge hysteresis effects during force measurements. Using the data discussed above, Williams *et al.* [11] obtained a relative standard uncertainty of 0.087 μW/W.

By connecting the macroscopic unit of mass (the kilogram) to quantum standards based on the Josephson and quantum Hall effects, this result provides a significant improvement in the Josephson constant as well as many other constants. For example, recent measurements of the Plank constant h can be derived directly from this work with a relative standard uncertainty of 8.7×10^{-8}.

The NIST watt experiment is being completely rebuilt to reduce the uncertainty by a factor of ten, with a goal of less than 10 nW/W relative standard uncertainty. At that level of measurement uncertainty, the watt-balance experiment becomes a very good means of monitoring the mass artifact that is used in the weighings. The present definition of the unit of mass in the SI is based on the International Prototype of the Kilogram, which is a cylinder of platinum-iridium housed at the BIPM in France. The Prototype and a set of duplicate standards of mass accumulate contaminants on their surfaces, and must be cleaned to achieve fractional changes over the long term of less than 10^{-8} per year. Since the kilogram is the last SI base unit defined in terms of a material artifact, a quantum standard of mass founded on electrical measurements would complete the modern trend of removing all artifacts from the definitions of SI units.

The largest uncertainties in the NIST watt experiment of the 1990s arose from operating in air, which required that the changing air buoyancy and refractive index be calculated from many readings of pressure, temperature, and humidity sensors. Almost every part of the balance assembly is being rebuilt to operate inside a specially constructed vacuum system consisting of two chambers, schematically represented in Fig. 1. The upper chamber houses the balance section, and a toroid-shaped chamber houses the inductive coils, located 3 m below and centered about the liquid helium cryostat containing the superconducting magnet.

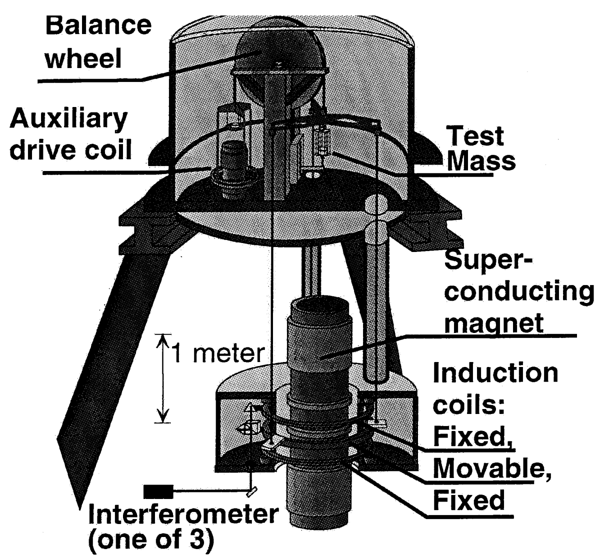

Fig. 1. Schematic representation of the electronic kilogram apparatus. The vacuum chamber and support tripod are shown in cut-away view.

Prepared by E. R. Williams, R. E. Elmquist, N. B. Belecki, and J. F. Mayo-Wells based on excerpts from the paper The Ampere and Electrical Units [12], *authored by members of the Electricity Division.*

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