

Determination of the Planck constant at the National Institute of Standards and Technology

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Abstract—In 2013, a new measurement of the Planck constant h was performed using a watt balance at the National Institute of Standards and Technology (NIST). The value is $h = 6.626\,069\,79(30) \times 10^{-34}$ J s. The relative standard uncertainty of this determination is 45×10^{-9} .

Index Terms—fundamental electrical measurements, watt balance, Planck constant, SI units

I. INTRODUCTION

In a watt balance experiment, the interaction between a coil and a magnetic field is measured in two modes: In velocity mode, the coil is moved vertically through a field, while the induced voltage V and the vertical velocity v is measured. The quotient of voltage to velocity yields the magnetic flux integral Bl . In force mode, a current I is injected into the coil, now at rest, leading to a force that is proportional to the flux integral and the current. This force is compared to the force of a mass m in the gravitational field g , $F = mg$. By combining the results of force and velocity mode, the flux integral cancels, and one obtains

$$\frac{V}{v} = \frac{mg}{I} \implies mgv = VI. \quad (1)$$

The right equation is the so called watt equation that relates mechanical power to electrical power. Since mechanical power is measured in SI units and electrical power is measured in conventional units (subscript 90), the Planck constant can be obtained using

$$h = \frac{\{mgv\}_{\text{SI}}}{\{VI\}_{90}} h_{90}, \quad (2)$$

where $\{mgv\}_{\text{SI}}$ denotes the numerical value of the quantity mechanical power in SI units and $\{VI\}_{90}$ the numerical value of the quantity electrical power in conventional units. Note that in the watt balance experiment the power is always virtual, i.e., the measurements of the two factors (F, v or V, I) in each product are not performed simultaneously.

The quantity m is measured by the mass group at NIST and the local acceleration is measured with an absolute gravimeter nearby the watt balance. The conventional value of the Planck constant is given by [1]

$$h_{90} = \frac{4}{K_{J-90}^2 R_{K-90}} = 6.626\,068\,854 \dots \times 10^{-34} \text{ J s}. \quad (3)$$

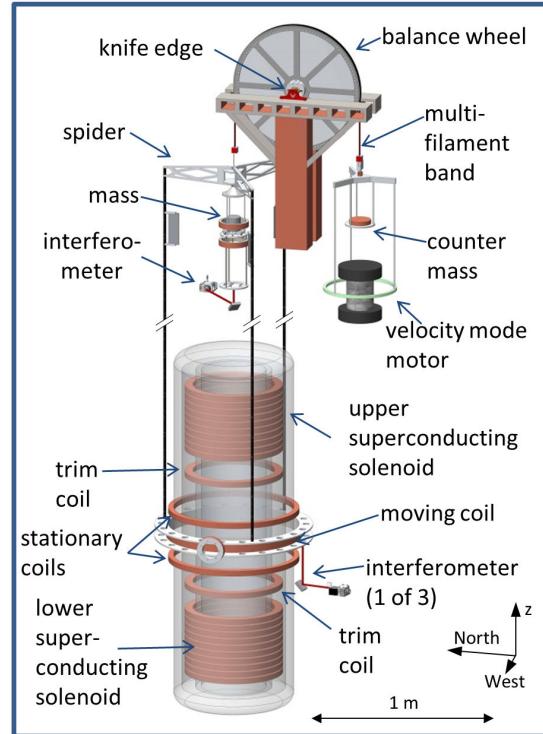


Fig. 1. Drawing of the main components of NIST-3. For clarity, vacuum components are omitted.

II. THE WATT BALANCE, NIST-3

The measurements discussed here were performed with the watt balance, NIST-3. A schematic drawing of this watt balance is shown in Fig. 1. A detailed description of the apparatus can be found in [2]. It should be noted that this watt balance uses superconducting coils to produce the magnetic field.

Before the measurements described below were taken, several improvements were made to the system: The power conditions were improved; the grounding system was changed; the wiring was reorganized; three digital multimeters were replaced; the programmable Josephson voltage standard was upgraded; a new current source was installed [3]; the knife edge

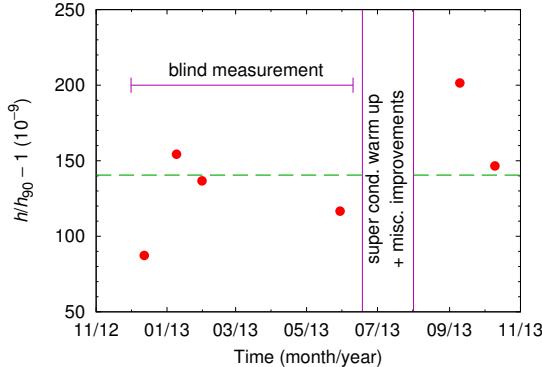


Fig. 2. The results of six measurement campaigns. The first four campaigns were performed blindly. The experimenters did not know the precise value of m .

and the flat was replaced; and the mass, the platinum-iridium prototype K85, was sent to the BIPM for re-calibration.

III. MEASUREMENTS

The result is an average of six measurement campaigns, each lasting between three days and three weeks. Fig. 2 shows the six measurements. The first four campaigns were performed blindly. During these measurements, the true value of m was hidden from the experimenters. The real value of the mass was revealed in June 2013. Thereafter, two additional measurement campaigns were executed. The relative standard deviation of the six observations is 38.4×10^{-9} . Dividing this by $\sqrt{6}$ leads to a relative standard deviation of the mean of 15.7×10^{-9} . In between the six campaigns, measurements to investigate systematic uncertainties were performed.

IV. UNCERTAINTIES

The error budget of the determination of the Planck constant is shown in Table I. All entries are relative standard deviations ($k = 1$). The largest uncertainty is summarized by the term balance mechanics, which contains mechanical effects of the wheel balance that are caused by the knife edge. The knife edge exhibits anelasticity and hysteresis, which can lead to a systematic bias of the data. The second highest contribution in the error budget stems from various misalignments. The category alignment includes error motions of the coil, verticality of interferometer beams, and biases caused by different coil positions in the two states of the substitution weighing in force mode.

V. CONCLUSION

A detailed analysis of the experimental data and their uncertainties yields

$$h = 6.626\ 069\ 79(30) \times 10^{-34} \text{ Js}. \quad (4)$$

The relative standard uncertainty is 45×10^{-9} .

The results is shown in comparison to other results in Fig. 3. This result is relatively higher by 133×10^{-9} than a 2007 measurement with the same instrument [7]. The difference

TABLE I
SOURCES OF UNCERTAINTY IN THIS MEASUREMENT OF h . ALL ENTRIES ARE RELATIVE STANDARD UNCERTAINTIES ($k = 1$)

Source	Type A (10^{-9})	Type B (10^{-9})
Balance mechanics	5.0	21
Alignment	0.0	20
Magnetic field	19.4	0
Electrical	1.5	16.1
Statistical	15.7	0.0
Velocity	0.0	10.6
Mass metrology	0.8	9.6
Local acceleration, g	3.8	6.0
Total	25.7	36.6
A & B combined		44.7

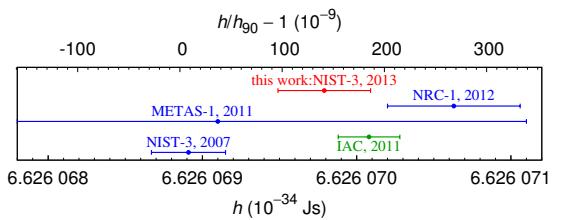


Fig. 3. The result of this work in comparison with other recent determinations of the Planck constant. The labels NRC-1, METAS-1, IAC, and NIST-3 refer to results published in [4], [5], [6], and [7].

corresponds to 2.4 combined standard deviations. No clear reason for this difference has been found so far.

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