First mass measurements with the NIST-4 watt balance

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***Abstract*—In the past four years, we have constructed a new watt balance at the National Institute of Standards and Technology (NIST), with the goal to realize the unit of mass after the redefinition of the International System of Units, expected to occur in 2018. The new watt balance has been operational since the fall of 2015 and we describe our first measurements with it.**

***Index Terms*—fundamental electrical measurements, watt balance, Planck constant, SI units, mass metrology, revised SI**

I. INTRODUCTION

The mass of an unkown object can be determined with a watt balance using precision measurements of current, voltage, local acceleration, and coil velocity [1]. The measurements are performed in two modes. In the force mode, the weight of an artifact is counteracted by an electromagnetic force produced by a coil in a magnetic field. This force balance is given by

$$mg = IBl, \tag{1}$$

where I denotes the current in the coil, B the magnetic flux density and l the length of the wire. The product of B and l is called the flux integral. While the current and the local gravitational acceleration can be measured with high precision, a dedicated separate measurement is necessary to obtain the flux integral. In the velocity mode, the coil is moved vertically through the magnetic field which leads to an induced electromotive force (EMF) in the coil. The coil velocity and the EMF are measured simultaneously and the flux integral can be obtained by

$$Bl = \frac{V}{v}. \tag{2}$$

Applying this result in the equation for the force mode allows one to solve for the mass of the object,

$$m = \frac{IV}{gv}. \tag{3}$$

By using modern quantum electrical standards, a programmable Josephson Voltage System and a Quantum Hall Resistor, the electrical measurements can be derived from the Planck constant and two frequencies.

II. A BRIEF OVERVIEW OF NIST-4

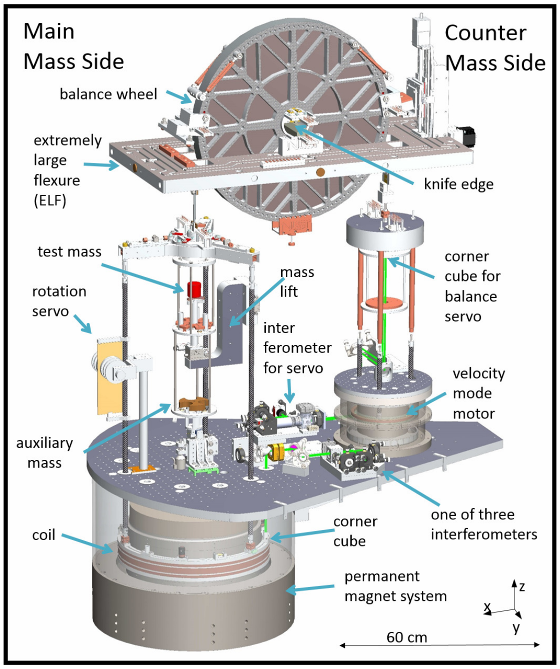

Fig. 1. Drawing of the main components of NIST-4. For clarity, vacuum components and part providing structural support have been omitted. Only one rotation servo and only one interferometer is shown. Three of each are present in the apparatus.

The watt balance descibed here and shown in Fig. 1 is the fourth watt balance built at the National Institute of Standards and Technology (NIST) [2]. Like its predecessors [3], it uses a balance wheel supported by a knife edge for two functions: (1) translating the coil vertically through the magnetic field and (2) balancing the electromagnetic force against the weight. A rather significant change to the previous NIST watt balances is the source of the magnetic field: NIST-4 employs a permanent magnet system, consisting of two large Samarium Cobalt disks and a soft iron yoke. With a field strength of $B = 0.55\,\mathrm{T}$ a total flux integral of $709.5\,\mathrm{Tm}$ is reached. The dependence of the flux integral on coil position is shown in Fig. 2.

Three heterodyne interferometers operating at 532 nm are employed to measure the coil's position and velocity. The interferometer's beat note is 2 MHz plus a Doppler shift of 1.8 kHz that is incurred by the vertical coil velocity, about 1 mm/s. Time interval analyzers are used to measure the beat note using a GPS referenced oscillator as a time base. Three hollow corner cube mirrors are attached on the coil spaced 120 degrees apart. The three interferometer readings are mathematically combined to obtain the vertical position

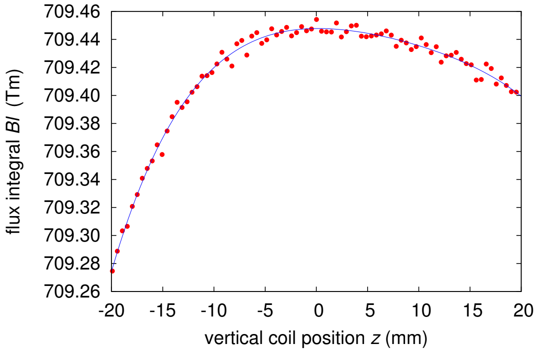

Fig. 2. A typical measurement of the flux integral in velocity mode. The blue line is a polynomial fit of sixth order to the data. The weighing position is at $z = 0$.

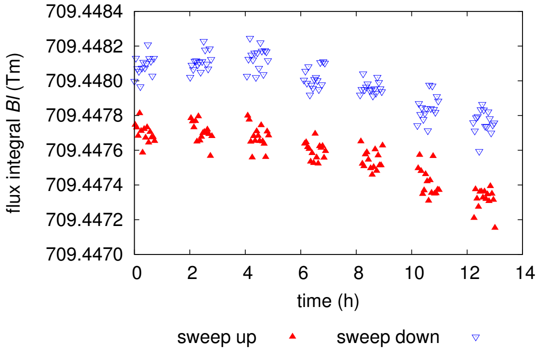

Fig. 3. Measurements of the flux integral in velocity mode, $Bl(z = 0)$, as a funtion of time during one measurement run. The blue squares/ red circles are obtained during a downward/upward sweep of the coil. The difference between up and down sweeps is due to thermal voltages. For further data analysis an up and down data point is averaged together, eliminating the thermal voltage.

of the coils' center and the rotational angle around the two orthogonal horizontal axes. To measure the EMF we use three high precision voltmeters that are connected in parallel. This voltmeter set is connected in series to the coil and the programmable Josephson voltage system.

In force mode, the circuit consists of a current source the coil and a 100 Ohm resistor in series. The current in the coil is measured using the voltag drop across the resistor. This voltage drop is largely compensated with the programmable Josephson voltage standard. The remaining voltage is measured with the voltmeter set.

The servo signal for the balance is derived from a fourth interferometer. Its measurement arm terminates on a corner cube mirror mounted on the counter mass side. In force mode, the output of the balance servo is directed to a current source that is connected to the coil. In velocity mode, the servo controls the current to a smaller coil on the counter mass side. This smaller coil together with a small magnet system form the velocity mode motor. It is capable of producing a force that is equivalent to about 40 g.

A mass lift is used to load the test mass onto the mass pan which is located on the main mass side. Two types of weighings are performed, mass off and mass on. In the former/latter the coil produces aproximately 5 N downard/upward force to keep the wheel balanced. In velocity mode an additional mass, the so called auxiliary mass is added on to the main mass side. This 0.5 kg mass keeps the wheel balanced, without applying electromagnetic force. Adding an auxiliary mass, instead of removing a counter mass as was done in NIST-3 while transitioning to the velocity mode, keeps the load on the knife edge constant, resulting in a notably improved knife edge performance.

III. MEASUREMENTS

A measurement run typically lasts between 12 hours and 24 hours. The two modes are interleaved, starting with the velocity mode. In velocity mode, the coil is swept up and down 15 times each, see Fig. 3. In force mode 17 interleaved measurements are performed, nine with the mass on and eight with the mass off.

Figure 4 shows the result of a data run. From each force mode, a value for the mass is obtained using a fixed value of the Planck constant. The error bars give the standard deviation of 15 differences of three consecutive force mode measurements. The flux integral was calculated using a linear fit to the values obtained in the velocity mode measurements obtained immediately before and after the force mode measurement. The data is very consistent and has a low statistical uncertainty.

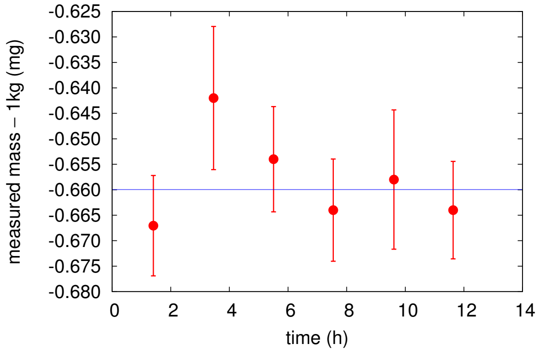

Fig. 4. Mass measurements in a typical data run. The data obtained in each force mode is collated into one point. The error bar gives the standard deviation of the 15 differences measured in each force mode measurement.

IV. OUTLOOK

We are currently working on a detailed uncertainty analysis of the NIST-4 watt balance. We will present a new value for the Planck constant with measurement uncertainty at the conference.

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