Determination of the Gravitational Constant Using a BIPM Balance

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***Abstract*—The Newtonian constant of gravitation, G, can be measured with the torsion balance developed at the Bureau International des Poids et Mesures (BIPM), using two methods. In the Cavendish method, the external gravitational torque is obtained from the equilibrium angle of the torsional oscillator and its torsion constant, which itself is determined from the measured period and the calculated moment of inertia. For the servo method, an electrostatic counter torque is applied. The counter torque can be calculated from measurements of the potential differences and the capacitance gradients. The systematic effects entering both measurement methods are very different, leading to a robust combined result. We expect to present a new result at CPEM 2022.**

***Index Terms*—Measurement, measurement techniques, measurement uncertainty, precision measurements, uncertainty.**

I. Introduction

Metrology is the science of measurement, and it earns its trust and place in society by reporting correct results. There is, unfortunately, a persistent black mark that tarnishes the reputation of measurement science. Researchers seem incapable of measuring a consistent value for one of the most basic fundamental constants, the gravitational constant G. Figure 1 shows the reported values for the last forty years. It is evident, at first glance, that the scatter of the measured values is much larger than the typical reported uncertainty.

One problem that ails the situation is that most G experiments are one and done. Typically, a research group spends decades conceiving, building, and conducting a G experiment. Then, after the result is published, the group moves on. A notable exception is the G experiment carried out at the Bureau International des Poids et Mesures (BIPM) that led to a publication in 2001 [1]. It was repeated, albeit with significant upgrades to the apparatus, and a second result was published in 2013 [2]. Both results agree with each other; see the two red data points in Fig. 1.

Unfortunately, the results of the BIPM experiment disagree with all the other published results by at least one standard deviation (of the difference). In light of this discrepancy, it was decided to repeat the measurement at NIST (National Institute of Standards and Technology) using the original apparatus of the 2013 result. The effect of cognitive biases on the experimental result is minimized by performing a blind measurement. The scientists working on the experiment do not know the precise value of the source masses. The NIST mass and force group weighed the source masses but multiplied all weighing results by $(1 + R \times 10^{-6})$, where R is a single, random factor chosen in the interval $[-1000, 1000]$. Note that the values of the test masses (see below) were reported truthfully.

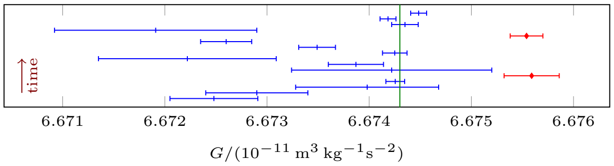

Fig. 1. Measurements of G over the past four decades with the most recent results on top. The two data points on the right, in red, were obtained by researchers at the BIPM. The torsion balance used in the latest result was shipped to NIST in 2015. All error bars are 1-σ. The vertical line is the recommended value by CODATA (Committee on Data of the International Science Council).

II. Description of the measurement

Figure 2 shows the torsion balance that is used in this measurement. The torsion pendulum is formed by four test masses in a circular arrangement with pitch circle radius r on a disk suspended by a torsion strip with torsional stiffness κ. The gravitational interaction between the test masses and four source masses, which are arranged in a circle with a pitch circle radius R on a carousel, is measured in one of two methods described below. For both methods, the source mass assembly is toggled between clockwise (cw) or counterclockwise (ccw) positions with a dwell time of 12 minutes. The bottom of Fig. 2 shows the carousel in the ccw position, i.e., the gravitational torque on the test mass assembly is maximally counterclockwise. In this case, the torque on the mass assembly is

$$N_{\mathrm{ccw}} = G\Gamma \text{ with } \Gamma \approx 35Mm\frac{r^4}{R^5}, \tag{1}$$

where m and M denote the mass of a single test and source mass, respectively. Γ is a mass integration constant, and the above point-mass approximation yields a large fraction of its value. To obtain its precise value, a numerical integration that takes into account all features of the torsion disk needs to be carried out on a personal computer.

A. Cavendish method

In the Cavendish method, the pendulum oscillates freely about its equilibrium position which is altered by the gravitational torque from the source masses. These positions are,

$$\phi_{\mathrm{ccw}} = \phi_o + \frac{\Gamma G}{\kappa} \text{ and } \phi_{\mathrm{cw}} = \phi_o - \frac{\Gamma G}{\kappa}, \tag{2}$$