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The Newtonian Gravitational Constant: Modern Status of Measurement and the New CODATA Value

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Abstract—Measurements of G, the Newtonian constant of gravitation, in laboratory experiments have a more than two hundred years' history. Although the accuracy of the best modern experimental measurements of G reaches 15–40 ppm, the scatter of the measured values is large enough, and the knowledge of the absolute value of G is still rather poor. The results of the G measurements which were used for CODATA adjustments, as well as the CODATA values, are reviewed in the paper.

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1. INTRODUCTION

The Newtonian gravitational constant G, together with Planck's constant $\hbar$ and the speed of light c, are fundamental constants of nature. While the absolute values of the fundamental constants such as c and $\hbar$ are known with high accuracy, the situation with the gravitational constant G is absolutely different. Due to the weakness and non-shieldability of the gravitational interaction, the accuracy of experimental determination of G is substantially below accuracy that of other fundamental constants.

The first experiment to measure the force of gravity between masses in the laboratory has been performed by Henry Cavendish (1731–1810), outstanding English scientist (Fig. 1), in 1797–98, hundred years later after Newton's discovery of the law of gravitation.

The instrument constructed by Cavendish was a torsion balance made of a 1.8 m wooden rod suspended from a wire, with a 51 mm diameter, 0.73 kg lead sphere attached to each end. Two 300 mm and 158 kg lead balls were located near the smaller balls, about 230 mm away, and held in place with a separate suspension system (Fig. 2). The experiment measured the faint gravitational attraction between the small balls and the larger ones. Their mutual attraction caused the torsion balance to rotate, twisting the wire supporting the rod. The rod stopped rotating when it reached an angle where the twisting force of the wire balanced the combined gravitational force of attraction between the large and small lead spheres. By measuring the angle of the rod, and knowing the twisting force (torque) of the wire for a given angle, Cavendish was able to determine the force between the pairs of masses. Since the gravitational force of the Earth on the small ball could be measured directly by weighing it, the ratio of the two forces allowed the density of the Earth to be calculated using Newton's law of gravity [1].

Cavendish expressed his result in terms of the density of the Earth. The formulation of Newtonian gravity in terms of a gravitational constant did not

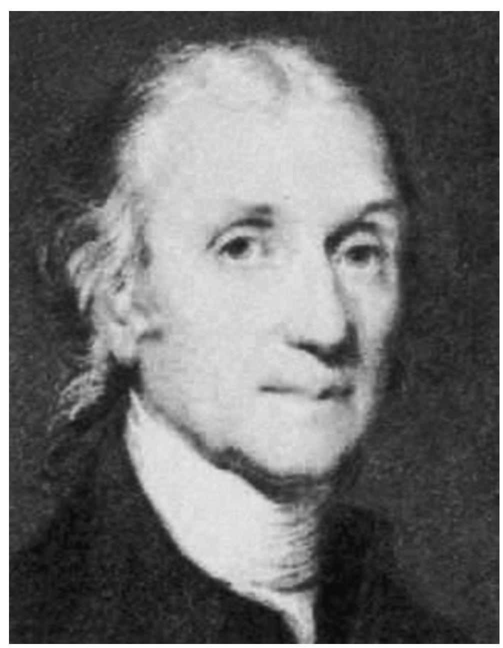

Fig. 1. Sir Henry Cavendish (1731–1810), outstanding English scientist.

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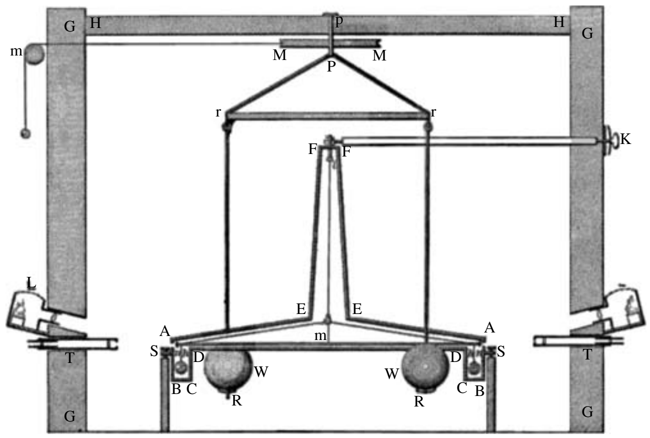

Fig. 2. Vertical section drawing of Cavendish's torsion balance instrument including the building in which it was housed. The large balls were hung from a frame, so they could be rotated into a position next to the small balls by a pulley from outside (from [1]).

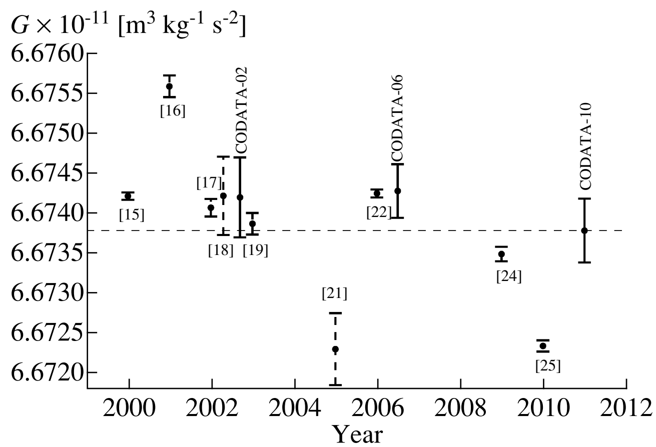

Fig. 3. The results of the best world experiments for G measurement the CODATA values. The horizontal dash line is the CODATA-2010 value.

become standard until long after Cavendish's time. Indeed, one of the first references to G was made in 1873, 75 years after Cavendish's work. After converting to the SI units, Cavendish's value for the Earth's density, (5.448 ± 0.033) g cm^{-3}, gives $G = (6.67 \pm 0.07) \times 10^{-11}$ m^3 kg^{-1} s^{-2} with a relative uncertainty of 10^4 ppm, which differs by only 1% from the currently accepted value.

The modern experimental installations for measurement of the gravitational constant are complicated devices, designed on a high technology level, but the main part of their majority is also a horizontal torsion balance. After 2000, several new results on measurement of G with a relative uncertainty less than 50 ppm have been published. Table 1 summarizes various results of G measurements which were used for CODATA adjustments, as well as CODATA values. The results after 2000 are also compared graphically in Fig. 3.

2. CODATA VALUES OF THE GRAVITATIONAL CONSTANT

The Task Group on Fundamental Constants of the Committee on Data for Science and Technology (CODATA) was established in 1969 to periodically provide the scientific and technological communities with a self-consistent set of internationally recommended values of the basic constants and conversion factors of physics and chemistry based on all relevant data available at a given point in time.

The first set of recommended values of the constants provided by CODATA was published in 1973 [3]. The recommended value of the Newtonian gravitation constant $G = (6.6720 \pm 0.0041) \times 10^{-11}$ m^3 kg^{-1} s^{-2} (615 ppm) was mainly based

The best world experiments for G measurement and the CODATA values

Authors, year of publication		$G \times 10^{-11}$, $m^3\,kg^{-1}\,s^{-2}$	$STD \times 10^{-11}$, $m^3\,kg^{-1}\,s^{-2}$	ppm
a. Heil and Chrzanowski, 1942	[2]	6.6720	0.0041	615
CODATA 1973	[3]	6.6720	0.0041	615
b. Rose, Beams, et al., 1969	[5]	6.6740	0.0030	450
c. Ponticis, 1972	[6]	6.6714	0.0006	90
d. Sagitov, Milyukov, et al., 1979	[7]	6.6745	0.0008	120
e. Luther and Towler, 1982	[8]	6.6726	0.0005	75
CODATA 1986	[4]	6.67259	0.00085	128
f. Michaelis, et al., 1995	[9]	6.7154	0.0006	90
g. Karagioz, Izmailov, 1996	[10]	6.6729	0.0005	75
h. Bagley and Luther, 1997	[11]	6.6740	0.0007	105
CODATA 1998	[14]	6.673	0.010	1500
i. Jun Luo, et al., 1999	[12]	6.6699	0.0007	105
j. Fitzgerald and Armstrong, 1999	[13]	6.6742	0.0007	105
k. Gundlach and Merkowich, 2000	[15]	6.674215	0.000092	14
l. Quinn, Speake et all., 2001	[16]	6.67559	0.00027	41
m. Schlamminger et all., 2002	[17]	6.67407	0.00022	33
n. Kleinevoß, 2002	[18]	6.67422	0.00098	150
o. Armstrong and Fitzgerald, 2003	[19]	6.67387	0.00027	41
CODATA 2002	[20]	6.6742	0.0010	150
q. Hu, Guo, and Luo, 2005	[21]	6.6723	0.0009	130
r. Schlamminger et all., 2006	[22]	6.67425	0.00010	16
CODATA 2006	[23]	6.67428	0.00067	100
s. Jun Luo, et al., 2009	[24]	6.67349	0.00018	26
t. Parks and J. E. Faller, 2010	[26]	6.67234	0.00014	21
CODATA 2010	[27]	6.67384	0.00080	120

on the Heil and Chrzanowski results obtained in 1942 [2]. The next CODATA adjustment of the fundamental physical constants was made in 1986 [4]. By this time, several new results of measurements of G had been reported [5–8]. For some reasons, CODATA recommended value of the gravitational constant was based on the Luther and Towler result [8], but with an arbitrarily doubled uncertainty, what reflects the fact, that, historically, G measurements were difficult to carry out: $G = (6.67259 \pm 0.00085) \times 10^{-11}\ m^3\,kg^{-1}\,s^{-2}$ (128 ppm).

During the 90s of the last century, a large enough number of laboratory experiments for G measurement were done with a relative accuracy about 100 ppm and less [9–13]. Nevertheless, the discrepancies between the values of the gravitational constant obtained in these experiments remained large enough. In particular, the value $G = 6.7146$ obtained in the Physikalish-Technische Bundesanstalt, PTB (Germany) [9] was more than by 40 standard deviations (i.e., more than by 5000 ppm) above the G value recommended by CODATA in 1986. As a result of such a scatter of G values, CODATA had to significantly increase the uncertainty and recommended in 1998 the value $G = (6.673 \pm 0.010) \times 10^{-11}\ m^3\,kg^{-1}\,s^{-2}$ [14], with a relative uncertainty of 1500 ppm. I.e., the "uncertainty of knowledge" of G has increased by almost a factor of 10!

In the next years (2000–2002) five new results, four of them with relative errors less than 50 ppm, were published. These are the experiments of the University of Washington, (UWash, USA) with a relative error of 14 ppm [15], of Bureau International des Poids et Measures, (BIPM, France) with a relative error of 41 ppm [16], of the University of Zurich, (UZur, Switzerland) with a relative error of 33 ppm [17], of the University of Wuppertal (UWup, Germany) with a relative error of 150 ppm [18], and of the Measurement Standards Laboratory, (MSL, New Zealand) with an uncertainty of 40 ppm (the final result was reported in 2003 [19]). Although the situation with G substantially improved since the 1998 adjustment, these new results were not in complete agreement, as can be seen from the table and Fig. 3. These new G values are not crossed inside confidential intervals. Based on weighted means of the results obtained after 1998, all of which are around $G = 6.6742 \times 10^{-11}$ m^3 kg^{-1} s^{-2}, as well as their uncertainties and a relatively poor agreement of the data, CODATA has taken as the 2002 recommended value $G = (6.6742 \pm 0.0010) \times 10^{-11}$ m^3 kg^{-1} s^{-2} with relative uncertainty of 150 ppm [20].

During the next 4 years, no new competitive independent results for G became available, only two revisions of the existing results were made by the researchers involved in the original work. One of the two results that changed was from the Huazhong University of Science and Technology (HUST, China) [21], and the other was from the University of Zurich [22]. The basement for the 2006 adjustment was the same as in 2002 with the exception of these two revised results. The overall agreement of the eight values of G in the Table (items g, h, k, l, n, o, q, r) has somewhat improved since the 2002 adjustment, but the situation is still far from being satisfactory.

Based on the fact that all eight values of G pointed out in the Table are credible, and that the two results with the smallest uncertainties, UWash–2000 and UZur–2006, are highly consistent with one another, the value of G recommended by CODATA in 2006 is equal to $G = (6.67428 \pm 0.00067) \times 10^{-11}$ m^3 kg^{-1} s^{-2} with a relative error of 100 ppm [23].

It seemed that the situation with the absolute value of G had been finally stabilized and we got the "true value" of G. But that value is being challenged by the results of two different experiments realized in HUST and in Sandia National Laboratories (SNL, USA). The Chinese researchers, led by Academician Jun Luo, emplyed, as usual, a torsion balance to measure the gravitational forces between the balance and test masses. They obtained a value of 6.67349×10^{-11} m^3 kg^{-1} s^{-2}, with an uncertainty of 26 ppm [24, 25], about three standard deviations below the CODATA-2006 value. James Faller and Harold Parks at Sandia National Laboratories used a laser interferometer to measure the displacement of pendulum bobs by various masses. Their result (6.67234×10^{-11} m^3 kg^{-1} s^{-2}, with an uncertainty of 21 ppm [25]) is by enormous 10 standard deviations lower than CODATA-2006 value.

In June 2011, CODATA introduced a new value of G based on the whiting mean of all data available at the end of 2010: $G = (6.67384 \pm 0.00080) \times 10^{-11}$ m^3 kg^{-1} s^{-2} with a relative error of 120 ppm [26]. The new results pulled down the value of G as compared to 2006, and the final uncertainty has become larger.

3. THE EFFECT OF ANELASTICITY

It is difficult to explain such an inconsistency in the results of measurements of the gravitational constant, especially, the conflict of the new results with the previous ones. Bearing in the mind only the statistical errors of the measurements, one could expect much smaller disagreements among them, probably no more than a couple of standard deviations. Apparently, such experiments are not free from systematic errors. Obvious systematic errors are connected with absolute measurements of three physical quantities: the dimensions and density distributions of the interacting bodies, and the frequency of torsion oscillations. The experimenters always tried to minimize possible errors associated with these absolute measurements. Not such an obvious bias in the measurements of the gravitational constant could be caused by anelastic properties of the suspension wire of the torsion balance. The first who drew attention to this problem with respect to measurements of the gravitational constant was Kusuaki Kuroda in 1995 [27]. Let us consider this effect.

The Newtonian gravitational constant G, determined in the time-of-swing method, is calculated using the equation

$$G = \frac{I(w_n^2 - w_f^2) - (k_n - k_f)}{C_{gn} - C_{gf}} = \frac{I\Delta(w^2)}{\Delta C_g}, \qquad (1)$$

where I is the moment of inertia of the torsion balance, w is the frequency of torsion oscillations, and C_g is the coefficient determined by the density distributions of the torsion balance and the source masses and distances between them; w and C_g are measured for "near" (n) and "far" (f) positions of the source masses. This calculation supposes an ideal torsion wire, whose spring "constant" k is constant, and consequently $(k_n - k_f) = 0$. The accuracy of such

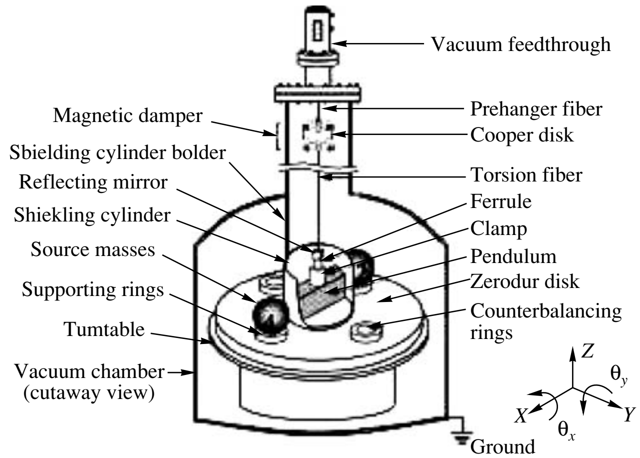

Fig. 4. Schematic view of the pendulum system used to measure G by the time-of-swing method. The coordinate axes in the laboratory frame are also shown (from [23]).

an experiment depends on the constancy of the spring constant of the torsion wire.

In general, the losses of a low-dissipation mechanical oscillator at very low frequencies are described by a complex spring constant with a constant imaginary part [28]. A consequence of such an anelastic model of solid materials is that not only the dissipation but also the elasticity is frequency-dependent. Due to the anelasticity effect, the spring constant of the torsion wire in the general case can be frequency-dependent. In this case, some additional term appears in the expression (1) for G, which determines the value of the relative systematic error

$$G = \frac{I(w_n^2 - w_f^2) - (k_n - k_f)}{C_{gn} - C_{gf}} = \frac{I\Delta(w^2)}{\Delta C_g}\left[1 - \frac{\Delta k}{I\Delta(w^2)}\right], \quad (2)$$

and the measured value of the gravitational constant becomes overestimated. Kuroda has shown that a systematic error due to the effect of anelasticity is inversely proportional to the quality factor of the torsion wire Q, i.e., $\Delta G/G \approx 1/\pi Q$.

4. A BRIEF REVIEW OF MODERN EXPERIMENTS

In all experiments for measuring the absolute value of G performed after 2000, a special attention was paid to the anelastic properties of the torsion wire since this effect determines the largest systematic error. To overcome this problem there are a few ways.

4.1. Correcting the Measured Value of G

If the traditional time-of-swing method using a torsion balance on a tungsten wire is realized in the experiment, this systematic error can reach a significant value. Such a classical scheme was used in the HUST experiment [24]. The pendulum was a gold-coated rectangular quartz block with the dimensions of 91 mm × 26 mm × 12 mm and a mass of 63 g. The pendulum was suspended by an 890 mm long, 25μm diameter annealed and thoriated tungsten fiber linked with a cylindrical aluminum clamp, which was adhered centrically on the pendulum. The upper end of the fiber was connected to a magnetic damper, which was used to suppress simple pendulum motions. Two stainless steel spheres with a diameter of 57 mm and a mass of 778 g were used as source masses and were placed on a turntable. The torsion pendulum, the source masses, and the turntable were all located inside a high-vacuum chamber. The oscillation of the pendulum was monitored by an optical lever, and the output signal was sampled at a rate of 2 Hz (Fig. 4).

The frequency dependence of the spring constant of the tungsten fiber used in the HUST experiment had been directly measured by employing two disk pendulums with different moments of inertia. The ratio of the moments of inertia of the two pendulums is determined precisely by a quartz fiber with $Q \approx 3.36 \times 10^5$, whose anelastic effect is negligible. The experimental result indicates that the torsion spring constant of the tungsten fiber depends on the oscillation frequency. This contributes a bias in G measurements up to $\Delta G/G = (211.80 \pm 18.69)$ ppm [30]. The value of the gravitational constant was corrected by an amount of -211 ppm. The observed result is slightly larger than the upward bias predicted by Kuroda. In the HUST measurements of G, the

Q-factor of the main torsion fiber is ≈ 1700, and $\Delta G/G \approx 1/\pi Q \approx 187$ ppm.

This systematic error has been calculated for the old SAI MSU experiment. Measurements of the gravitational constant had been done in four series of experiments between March 1975 and January 1978. The G value which was published in 1979 [7] had been calculated as a mean value of 43 measurements of G and was equal to $G = (6.6745 \pm 0.0008) \times 10^{-11}$ m^3 kg^{-1} s^{-2}. In each experiment, six parameters of torsion oscillations had been determined. These were the amplitude A, the frequency ω, the time constant τ, the phase φ and the linear drift coefficients B and C. It should be noted that the torsion frequencies had been determined with high relative accuracies: 3×10^{-7} and 3×10^{-6} for the near and far positions of the source masses. This gave a contribution to the error budget of the gravitational constant at the level of 3 ppm, i.e, at a level that meets the requirements of the best modern experiments. An estimate of the time constant was also calculated as the mean value of all τ values measured in all experiments, $\tau_0 = (9.41 \pm 0.77) \times 10^5$ s. In addition, a series of experiments were performed in the absence of the source masses to determine the eigenfrequency of the torsion balance, $\omega_0 = (2.70953 \pm 0.00001) \times 10^{-3}$ s^{-1}.

Accordingly, the quality factor of the torsion balance in the SAI experiment had been calculated: $Q = \omega_0\tau_0 = 2500 \pm 200$, $\Delta Q/Q \approx \Delta\tau_0/\tau \approx 0.08$.

The systematic error due to the "Kuroda effect" is $\Delta G/G = -124$ ppm. The corrected value of the gravitational constant is equal to $G = (6.6736 \pm 0.0008) \times 10^{-11}$ m^3 kg^{-1} s^{-2} and is consistent with the HUST result within one standard deviation.

4.2. Compensating the Twist of the Torsion Wire

Such schemes were realized in the experiments of the University of Washington [15], Bureau International des Poids et Measures [16] and the Measurement Standards Laboratory [19].

The heart of the UWash apparatus is a torsion balance (a gold-coated Pyrex glass plate, 76 mm $\times$ 42 mm $\times$ 1.5 mm, suspended on a tungsten fiber, 41.5 cm $\times$ 17 μm) placed on a turntable located between a set of 8 kg attractor spheres (Fig. 5). The turntable is first rotated at a constant rate, so that the pendulum experiences a sinusoidal torque due to the gravitational interaction with the attractor masses. A feedback is then turned on that changes the rotation rate so as to minimize the torsion fiber twist. The resulting angular acceleration of the turntable is equal to the gravitational angular acceleration of the torsion balance. Since the torsion fiber does not experience any appreciable deflection, this technique is independent of many torsion fiber properties including anelasticity. The applied technique also greatly reduces several other sources of possible systematic uncertainties: a flat plate pendulum minimizes the sensitivity due to the pendulum density distribution; a continuous attractor rotation reduces the background noise.

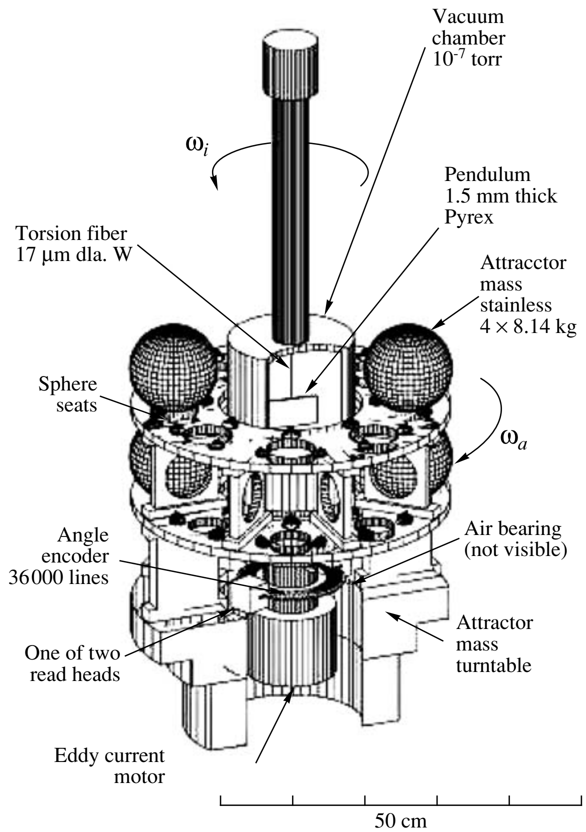

Fig. 5. Cut-away of the apparatus (from [15]).

The BIPM torsion balance has a four-mass configuration (four right-circular cylinders with masses of 1.2 kg are mounted on the torsion balance disk) to give a much reduced sensitivity to external gravitational fields. The torsion strip, 160 mm $\times$ 2.5 mm $\times$ 30 μm, gives a much improved stability with practically no dependence on the material properties of the strip. The scheme of the experiment, which involves also four cylindrical source masses with a weight of 12 kg, mounted symmetrically to the torsion balance disk (Fig. 6), allows for three possible methods of operation, (a) electrostatic servo control, (b) free deflection (the Cavendish method), and (c) a change in the period of free oscillation. The result presented in [16] is based only on (a) and (b).

In the servo-controlled method, the gravitational torque of the source masses is balanced by an electrostatic torque acting directly on the test masses. The

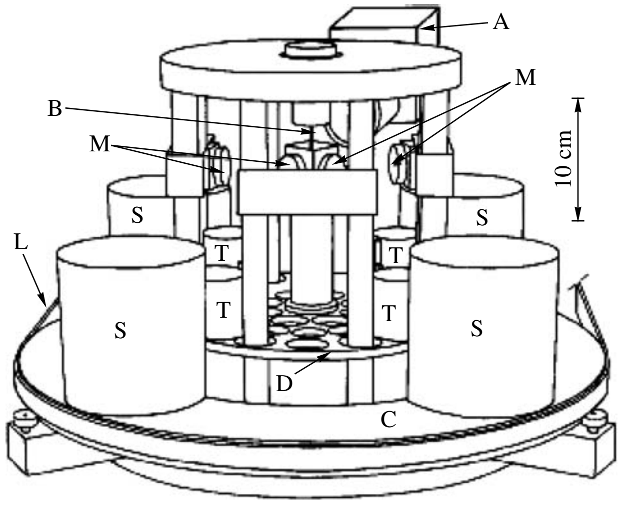

Fig. 6. Outline of the apparatus: **T**, test masses; **S**, source masses; **D**, torsion balance disk; **B**, torsion strip; **C**, carousel; **L**, drive belt; **M**, mirrors for sixfold multiplying optics; **A**, autocollimator (from [16]).

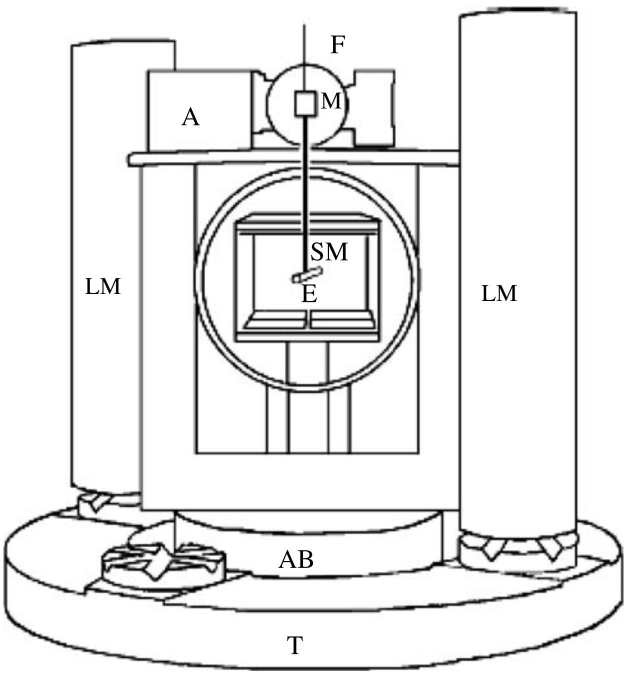

Fig. 7. A schematic diagram of the MSL torsion balance. **SM**, small mass; **LM**, large masses; **T**, turntable; **A**, autocollimator; **F**, fiber; **AB**, air bearing; **E**, electrometer; **M**, mirror (from [19]).

control of the balance is accomplished by applying ac voltages at a frequency of 1 kHz between the test masses themselves and a pair of thin vertical cylindrical copper electrodes placed about 1 mm from the masses.

The MSL experimental scheme uses two large cylindrical masses ($\sim$27 kg each) to produce a gravitational attraction on a $\sim$500 g cylindrical small mass (the torsion balance) made of copper. The small mass is suspended from a $\sim$1 m long tungsten fiber with a rectangular cross section of 300 μm $\times$ 17 μm, so that it is free to rotate in response to the gravitational attraction of the large masses. This rotation is detected by an autocollimator viewing a mirror attached to the small mass. The signal from the autocollimator goes to a feedback control system to generate a voltage applied to an electrometer. This produces an electrostatic force on the small mass that compensates the gravitational attraction so that the fiber is not required to twist (Fig. 7).

4.3. Replacing the Torsion Balance with a Beam Balance or a Simple Pendulum

The idea of high-precision weighting of the test masses in the proximity of moving changing field masses with the help of a beam balance was realized in the UZur experiments [17, 22]. The experimental setup consists of two nearly identical 1.1 kg tests masses (TM) hanging on long wires of different lengths. The test masses are alternately weighed on a beam balance in the presence of two movable field masses (FM) weighing 7.5 t each. The position of the FMs relative to the TMs affects the measured weights. The geometry is such that when the FM are in the position labelled "together", the weight of the upper TM is increased while that of the lower TM is decreased. The opposite change in the TM weights occurs when the FMs are in the position labelled "apart". One measures the difference of TM weights first with one position of the FMs and then with the other. The difference between the TM weight differences for the two FM positions is the gravitational signal (Fig. 8).

The simple pendulum method was used in the SNL experiment [26]. A schematic of the apparatus is shown in Fig. 9. A Fabry-Perot interferometer measures the spacing between two pendulum bobs with respect to a suspension-point-located reference cavity. The pendulum bobs were attached to the supporting bar of a reference cavity by a four-wire suspension. The bobs are made of oxygen-free copper and have a mass of 780 g. The pendulum length is 72 cm, and the spacing between the bob centers is 34 cm. When the four 120 kg tungsten source masses (which are floated on air bearings) are moved from one position to another, the horizontal gravitational force on each pendulum bob changes, giving rise to a change in the pendulum bob separation. Magnets below the pendulum bobs damp the swinging motion of the pendulums, so that the static deflection due to the gravitational pull of the source masses can be measured. The gravitational signal is changed when

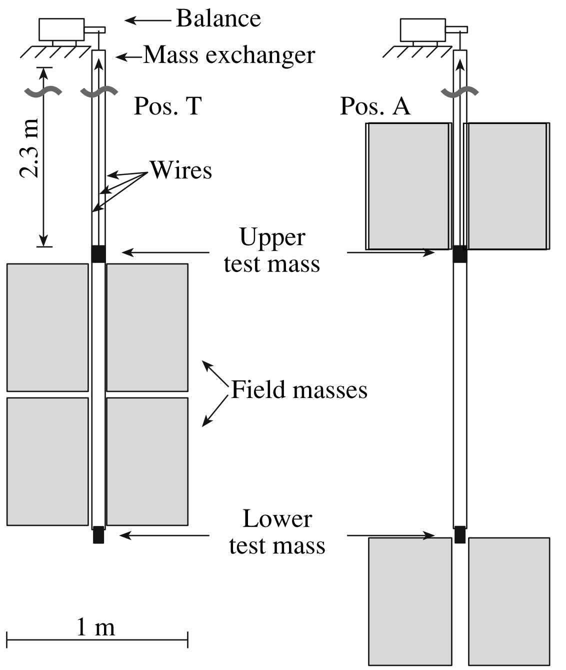

Fig. 8. The principle of the experiment. The two field masses are shown in the two positions together (T) and apart (A) used for the measurements (from [17]).

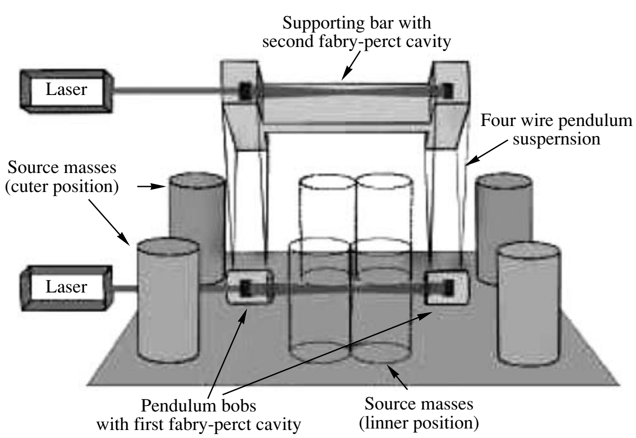

Fig. 9. A schematic of the apparatus (from [27]).

the source masses are moved between the inner and outer positions several times (with the source masses pausing at each position for 80 s). The 125 MHz change in the beat frequency between the laser locked to the pendulum cavity and the laser locked to the reference cavity corresponds to a 90 nm change in the pendulum bobs' separation.

4.4. Using a Torsion Fiber with High Q-Factor

As was mentioned above, the scheme of the BIPM experiment allowed for three possible methods of operation, one of them is the Cavendish method. In the Cavendish method, the torsion balance is moved in response to movements of the source masses. At equilibrium, the applied gravitational torque is balanced by the suspension stiffness. The torsion strip used in the experiment is made from a Cu-1.8%Be dispersion-hardened alloy. The anelasticity in the suspension is much reduced due to the high mechanical Q of the system (3×10^5).

In the new HUST experiment, planned for realization in the nearest future, it is supposed to use the traditional time-of-swing method, but with a quartz torsion wire. In this case, the effect of anelasticity can be reduced by 1 or 2 orders of magnitude.

5. CONCLUSION

Since Cavendish's first laboratory measurement over 200 years ago, the reduction in G uncertainty has been only two orders of magnitude. The progress in the measurement of G occurs slowly enough: the error value decreases by approximately a factor of 10 per century, and the knowledge of the absolute value of G is still rather poor. Moreover, since 1986, i.e., for 25 years, the accuracy of the GODATA recommended value has practically not changed. We have seen that different kinds of systematic errors can reach considerable magnitudes and greatly distort the absolute value of the gravitational constant. That is why it is so important to reduce the systematic errors in each experiment and to measure G in a variety of ways. Nevertheless we would like to conclude this paper by the words of James Faller: "Big G is the Mt. Everest of precision measurement science, and it should be climbed".

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