The Missing Measurements of the Gravitational Constant

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G measurements are made with torsion balance in "vacuum" to the aim of eliminating the air convection disturbances. Nevertheless, the accuracy of the measured values appears unsatisfying. In 2000 J. Luo and Z. K. Hu first denounced the presence of some unknown systematic error in high vacuum G measurements. In this work a new systematic effect is analyzed which arises in calm air from the non-zero balance of the overall momentum discharged by the air molecules on the test mass. This effect is negligible at vacuum pressures higher than a millibar. However in the interval between the millibar and the nanobar the disturbing force is not negligible and becomes comparable to the gravitational force when the chamber pressure drops to about 10^{-5} bar. At the epoch of Heyl's benchmark measurement at 1–2 millibar (1927), the technology of high vacuum pumps was developed, but this chance was not utilized without declaring the reason. The recent G measurements use high vacuum techniques up to 10^{-10} and 10^{-11} bar, but the effect of the air meatus is not always negligible. We wonder whether the measurements in the interval between the millibar and the nanobar have been made. As a matter of fact, we were not able to find the related papers in the literature. A physical explanation of the denounced unknown systematic error appears useful also in this respect.

1 Introduction

Everyone knows the simple experience of two flat microscopy glasses which cannot be separated from each other when their surfaces touch. Obviously this effect is due to the pressure of the air whose molecules penetrate with difficulty between the corrugations of the polished surfaces generating within the small meatus a considerable air depression. The mean free path of the air molecules at normal pressure is about 10^{-7} metres, that is of the same order of magnitude of the polished surface corrugations. In general, the molecules are not able to freely penetrate within a meatus whose thickness is reduced to about 1 mean free path. When we consider the meatus facing the test mass of a gravitational torsion balance placed in a vacuum chamber, the very little air depression within the meatus originates a disturbing force on the test mass, which adds to the gravitational force. This disturbing force is negligible at normal pressure, but when the pressure within the vacuum chamber is reduced beyond the millibar (for instance to avoid other disturbances due to air convection or to minimize the air friction on the oscillating pendulum) the meatus optical thickness further reduces, so as to attain the above condition about 1 mean free path. It appears opportune to investigate this phenomenon to obtain a semi-quantitative prediction of the disturbing drawing force arising on the gravitational balance. This research takes into account the results of some experimenters which denounced the presence of some unknown systematic effect in the G measurements.

2 Historical background

The torsion balance apparatus was first used by Cavendish in 1798 in a very simple form which permitted him to reach an unexpected accuracy. In the following two centuries the torsion balance was used by several experimenters which substantially improved the technique, but the level of accuracy did not show a dramatic enhancement. Several methods were devised in the XXth century to measure G. In a Conference organized by C. C. Speake and T. J. Quinn [1] at London in 1998 — two centuries after Cavendish — a variety of papers described the methods of measurement and their potential accuracy related to the disturbances and systematic errors. In Table 1 we report the most accurate values presented at the Conference [$G \times 10^{-11}$ kg/m^{3}s^2]:

Author	Method	G	Accur. (ppm)
PTB	torsion balance	6.7154	68
MSL	torsion balance (a)	6.6659	90
MSL	idem (re-evaluation)	6.6742	90
MSL	torsion balance (b)	6.6746	134
BIPM	torsion-streap bal.	6.683	1700
JILA	absolute gravimeter	6.6873	1400
Zurich	beam balance	6.6749	210
Wuppertal	double-pendulum	6.6735	240
Moscow	torsion pendulum	6.6729	75

Table 1: Measurements of G, according to [1].

Among the methods described there are: a torsion balance where the gravitational torque is balanced by an electrostatic torque produced by an electrometer; a torsion-strip balance where the fibre is substituted by a strip; a dynamic method based on a rotating torsion pendulum with angular acceleration feedback; a free fall method where the determination of G depends on changes in acceleration of the falling object, etc. Notwithstanding the technological improvement, up to now the gravitational constant is the less accurately known among the physical constants. The uncertainty has been recognized to depend on various experimental factors. To eliminate the air thermal convection on the test mass, in 1897 K. F. Braun made a torsion balance measurement after extracting the air from the ampule. The level of vacuum obtained with his technique is not known. In 1905 W. Gaede invented the rotary pumps reaching the void level of 10^{-6} bar. Subsequently Gaede developed the molecular drag pumps (1915) using Hg vapour. In 1923 the mercury was substituted by refined or synthetic oil, which enabled to reach void levels around 10^{-9} bar.

In 1927 Heyl [2] made a benchmark measurement with a heavy torsion balance to the aim of establishing a firm value of G. Although the high vacuum technology was available, he adopted a chamber pressure equal to 1–2 millibar. The molecule mean free path at 1 millibar is about 10^{-4} metres, a quantity much smaller than the thickness of the meatus. From our present investigation it appears that the air pressure effect does not alter the accuracy of the classical G measurements performed at pressures higher than some millibars. But this fact was unknown at the epoch. In any case the choice of high vacuum was compelling against the air convection disturbance. After 1958 the development of turbomolecular pumps and the improved molecular drag pumps made available an ultra-high-vacuum up to 10^{-13} bar. Also this spectacular jumping was apparently disregarded by the G experimenters. In 1987 G. T. Gillies published an Index of measurements [3] containing over 200 experiments, which does not report vacuum pressures between the millibar and the nanobar. At the end of ninety the unsatisfying values of G became publicly discussed.

3 First report of a new unknown systematic error

A status of the recent G measurements was published in 2000 by J. Luo and Z. K. Hu [4] in which the presence of some unknown systematic effect was first denounced: "This situation, with a disagreement far in excess to the estimate, suggests the presence of unknown systematic problems".

In 2003 R. Kritzer [5] concluded that "the large spread in G measurements compared to small error estimates, indicates that there are large systematic errors in various results".

Among the last experiments, some of them used new sophisticated methods with technologies coupled to very low pressures within the test chamber. This fact shows a new attention to the problems of possible unknown air effects.

J. H. Gundlach and S. M. Merkowitz [6] made a measurement where a flat pendulum is suspended by a torsion fiber without torque since the accelerated rotation of the attracting masses equals the gravitational acceleration of the pendulum.

To minimize the air dynamic effect, the pressure was lowered to 10^{-7} Torr ($p_0 \approx 10^{-10}$ bar). At this pressure the classical mean free path $l = m/\sigma\,\delta_0$ within a large homogeneous medium is of the order of 1000 metres. Hence within the vacuum chamber the lack of flux homogeneity is everywhere present.

Another accurate measurement was performed in 2002 by M. L. Gershteyn et al. [7] in which the pendulum feels a unique drawing mass fixed at different distances from the test mass. The change of the oscillation period determines G. To minimize the air disturbance, the pressure in the vacuum chamber was lowered to 10^{-6} Pascal (i.e. $p_0 = 10^{-11}$ bar). The reason for such a dramatic lowering is not discussed. The authors revealed the presence of a variation of G with the orientation (regard to the fixed stars) amounting to 0.054%. Incidentally, the anisotropy of G is predicted by the gravitational-inertial theory discussed in [8].

In 2004 a new torsion balance configuration with four attracting spheres located within the vacuum chamber ($p_0 = 1.5\times10^{-10}$ bar) was described by Z. K. Hu and J. Luo [9]. The four masses are aligned and each test mass oscillates between a pair of attracting masses. Each test mass determines with the adjacent spheres a small meatus (estimated about 4 mm) and a large meatus (about 16 mm). During the experiment the authors found the presence of an abnormal period of the torsion pendulum, which resulted independent of the material wire, test mass, torsion beam and could not be explained with external magnetic or electric fields. Adopting a magnetic damper system, the abnormal mode was suppressed, but the variance of the fundamental period of the pendulum introduced an uncertainty as large as 1400 ppm, testifying the presence of a systematic disturbance in determining G.

We applied to this problem the analysis carried out in this paper. From the air density in the vacuum chamber, we calculate the optical thickness of the small meatus and the related air depression, Eq. (5), which substituted in Eq. (7) gives upon the test mass a disturbing force rising up to $F(p_0) \approx 10^{-14}$ Newton, equivalent to about 10^{-4} times the gravitational force, which alters the pendulum period. This fact agrees with the author conclusions [9] that the torsion balance configuration would have an inherent accuracy of about 10 ppm in determining G, but the uncertainty in the fundamental period reduces this accuracy to 1400 ppm.

The presence of an abnormal disturbance was previously described (1998) by Z. K. Hu, J. Luo, X. H. Fu et al. [10] in dealing with the time-of-swing method. They found the presence of "important non-linear effects in the motion of the pendulum itself, independent of any defect in the detector, caused by the finite amplitude of the swing". Their configuration consisted in a torsion balance with heavy masses external to the vacuum chamber, where the pressure was lowered to $p_0 = 2\times10^{-10}$ bar. The test mass, diameter about 19 mm, was suspended within a stainless vacuum tube placed between two heavy masses distant 60 mm apart. Since the test mass oscillates up to 8 mm from the centre of the vacuum tube, the optical thickness of the small meatus can be deduced. The smaller this thickness, the greater the disturbing force $F(p_0)$. Repeating the analysis carried out for the preceding experiment, we found a force $F(p_0)$ which represents a lower fraction of the gravitational force thanks to the heavy attractor masses. Comparing with many measurements made in last decades with high vacuum technology [11–19] we notice that the vacuum pressures (when reported) were not comprised between the millibar and the nanobar. The reasons for this avoidance do not appear to have been discussed.

4 Scattering of molecules upon smooth surfaces

The scattering of gas molecules hitting a smooth surface does not generally follow the optical reflection because that which collide about orthogonally may interact with a few atoms of the lattice. As it happens when two free particles come in collision, these molecules may be scattered randomly. Conversely, the molecules hitting the surface from a nearly parallel direction interact softly with the field of the atomic lattice. In fact these molecules, whose momentum $q = mv$ makes an angle $\alpha = \pi/2$ with the vertical axis, receive from the lattice field a small vertical momentum $\Delta q \approx 2mv\cos\alpha$ which redirects the molecules along a nearly optical reflection. It is usefull to recall that the momentum hv/c of the UV rays (which observe the reflection law) is comparable to the momentum of air molecules at normal temperature.

To resume: after scattering on a smooth surface a fraction of the nearly orthogonal molecules becomes quasi parallel.

As a consequence an isotropic flux ϕ_0 of molecules hitting a smooth surface, after scattering becomes non-isotropic. This condition may be described by the relationship

$$\psi_0(\alpha) \doteq \phi_0 (1 - \Delta_1 \cos\alpha + \Delta_2 \sin\alpha) \qquad (1)$$

where the parameters Δ_1, Δ_2 satisfy the total flux condition $\int_0^{\pi/2} \sin\alpha\, \psi_w(\alpha)\, d\alpha = \phi_0$. Moreover we assume that about χ percent of the nearly orthogonal molecules become quasi-parallel after scattering on the wall. Applying these two conditions one obtains the figures $\Delta_1 \simeq 1.46\chi$, $\Delta_2 \simeq 2\Delta_1/\pi \simeq$ $\simeq 0.928\chi$, where χ may range between 0.10 down to 0,0001 for smoothed glass walls. This physical condition makes easy to understand the molecular flux depression within the meatus around the test mass. This phenomenon becomes particularly evident at low air pressures. For instance when the vacuum pressure is about a millibar, then 99.99% molecules hitting the test mass, Fig. 1, come from scattering with other molecules within the meatus, whereas 0.01% molecules come directly from the scattering on the chamber wall. To feel a sensible flux depression in the meatus it is necessary that the molecules coming from wall-scattering be about a half of the total. Within an air meatus of thickness "s" this happens when the optical thickness $\Sigma s = s\sigma\delta_0/m \simeq 10^7 s\,\delta_0$ equals 1 mean free path, i.e. when the air density equals $\delta_0 \simeq 10^{-7}/s$. For usual torsion balances the critical vacuum pressure which maximizes the flux depression is $p_0 \approx 1\times10^{-5} \div 3\times10^{-5}$ bar.

The old G measurements adopted a torsion balance at atmospheric pressure, so the meatus effect took place between the test mass and the attracting sphere. This happens also to G measurements in vacuum when the heavy masses are comprised within the chamber. But in general the G measurements in vacuum are made with the heavy masses outside the chamber. In this case we define "meatus" the air comprised between the test mass and the adjacent wall of the vacuum chamber (Fig. 1). At pressures higher than some millibars the molecular flux upon the moving mass is highly uniform, so the sum of every momentum discharged by the molecules on the sphere is null for any practical purpose. However, when the pressure in the chamber is further reduced, the molecular flux begins to show a little depression in the meatus. The flux depression in the circular meatus may be expressed along the radial direction x

$$\phi(x) \doteq \phi_m \left(1 + kx^2\right), \qquad (2)$$

where ϕ_m is the minimum figure the flux takes on the meatus centre. Since the flux on the boundary, i.e. $x = L$, is the unperturbed flux ϕ_0, then one gets $\phi_m \left(1 + kL^2\right) = \phi_0$ which shows that k is linked to the flux parameters of the meatus

$$k = (\phi_0/\phi_m - 1)/L^2, \qquad (3)$$

where $L \doteq R\cos\beta$ is the radius of the area of the test mass experiencing the flux depression. The angle β, defined by $\sin\beta = R/(R + s)$ (where R is the radius of the moving mass, s is the minimum thickness of the meatus), plays a fundamental role since it describes (Fig. 1) the "shadow" of the moving mass on the adjacent chamber wall. Choosing spherical co-ordinates with the same axis of the meatus and origin (Fig. 1) in the point B, the monokinetic transport theory gives us the angular flux of incident molecules $\psi_B(\alpha)$ integrating the scattered molecules along the meatus thickness $s(\alpha)$ and adding the flux $\psi_s(\alpha)$ of uncollided molecules scattered on the surface of the moving mass

$$\begin{aligned}\psi_B(\alpha) = \int_0^{s(\alpha)} &\Sigma\,\phi(r)\exp(-\Sigma r)dr + \\ &+ \psi_s(\alpha)\exp\left[-\Sigma s(\alpha)\right],\end{aligned} \qquad (4)$$

where Σ is the air macroscopic cross section, $\Sigma\phi(r)$ is the density of isotropically scattered molecules, $s(\alpha)$ is the meatus thickness along α. This angular flux holds for $\alpha \leqslant \beta$. The above presentation of the problem has only an instructive character denoting the complexity of the problem, because the fluxes $\phi(r)$ and $\psi_s(\alpha)$ are unknown.

5 Calculation of the molecular flux in the meatus

To solve the problem of calculating the molecular flux within the meatus we adopt the principle of superposition of the effects. Let's consider the test sphere surrounded by the air in the vacuum chamber at pressure p_0. To obtain the disturbing force $F(p_0)$ on the test mass we must calculate the flux in the point A of the sphere and in the point C diametrically opposite (Fig. 1). Let's now remove the sphere and substitute an equal volume of air at pressure p_0, so to fill the chamber with the uniform molecular flux ϕ_0. Let's calculate the flux incident on both sides of the point A considering a spherical coordinates system with origin in this point (Fig. 1). The

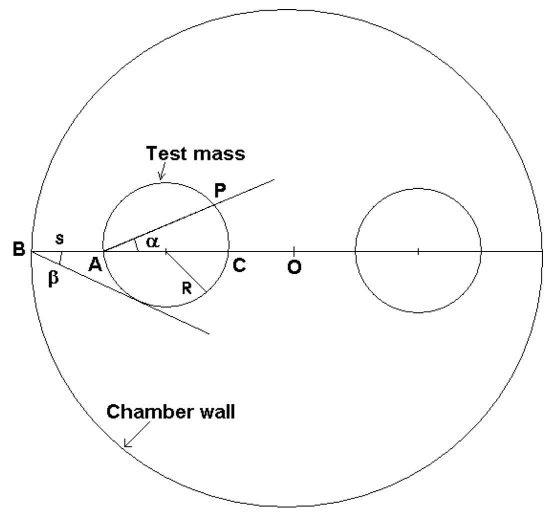

Fig. 1: Schematic drawing of a torsion balance in a vacuum chamber (meatus thickness arbitrarily large).

angular flux on the right-side of the point A is due to the scattering on the molecules within the sphere volume and to the uncollided molecules coming from the surface of the sphere (point P) where there is the uniform flux ϕ_0

$$\psi_A(\alpha) = \int_0^{t(\alpha)} \Sigma\,\phi_0 \exp(-\Sigma r)dr + \phi_0 \exp\left[-\Sigma t(\alpha)\right] \quad (5)$$

where $t(\alpha) = 2R\cos\alpha$ is the distance between the points A and P (Fig. 1) placed on the (virtual) surface of the removed mass. Let's notice that the first term in Eq. (3) represents the flux due to the scattering source occupying the sphere volume. When we cancel this source term (for instance reintroducing the test mass), Eq. (5) gives the flux

$$\psi_{A+}(\alpha) = \phi_0 \exp(-2\Sigma R\cos\alpha). \quad (6)$$

On the left-side of the point A the flux comes from scattering on the air within the meatus and from the uncollided molecules coming from the chamber wall

$$\psi_{A-}(\alpha) = \phi_0\left[1 - \exp(-\Sigma z(\alpha))\right] + \\ + \psi_w(\alpha)\exp(-\Sigma z(\alpha)), \quad (7)$$

where $z(\alpha)$ is the wall distance and $\phi_w(\alpha)$ is the flux scattered on the chamber wall, as defined by Eq. (1). Since in general the size of the chamber is much larger than R, one may assume the distance $z(\alpha) \simeq s/\cos\alpha$. Subtracting the flux $\psi_{A+}(\alpha)$ from $\psi_{A-}(\alpha)$ gives the actual flux on the point A of the test mass

$$\psi_A(\alpha) \simeq \phi_0\left[1 - \exp(-2\Sigma R\cos\alpha)\right] - \\ - \left[\phi_0 - \psi_w(\alpha)\right]\exp(-\Sigma s/\cos\alpha). \quad (8)$$

Now we calculate with the same procedure the incident flux on the point C

$$\psi_C(\alpha) \cong \phi_0\left[1 - \exp(-2\Sigma R\cos\alpha)\right] - \\ - \left[\phi_0 - \psi_w(\alpha)\right]\exp(-\Sigma(s + 2R)/\cos\alpha). \quad (9)$$

The disturbing force on the moving mass is linked to the different pressures on the points A and C due to the momentum discharged by the molecular flux on these points. The molecular flux shows the following difference across the test mass diameter $\phi_C - \phi_A = \phi_0 \int_0^{\pi/2} \sin\alpha\left[\psi_C(\alpha) - \psi_A(\alpha)\right]d\alpha$.

Substituting and putting $w(\alpha) = \psi_w(\alpha)/\phi_0$, one gets the flux difference

$$\Delta\phi_0 = \phi_0 \int_0^{\pi/2} \sin\alpha\left[1 - w(\alpha)\right]\left[\exp(-\Sigma s/\cos\alpha) - \\ - \exp(-\Sigma(s + 2R)/\cos\alpha)\right]d\alpha, \quad (10)$$

which confirms that the flux depression depends on the anisotropy of the flux $\psi_w(\alpha)$ scattered on the wall. Through Eq. (1) we also have $w(\alpha) = 1 - \Delta_1\cos\alpha + \Delta_2\sin\alpha$ which, substituting in the above equation gives the air depression

$$\Delta p_0/p_0 = \Delta\phi_0/\phi_0 = \\ = \Delta_1\Gamma(\Sigma s, \Sigma R) - \Delta_2\Omega(\Sigma s, \Sigma R), \quad (11)$$

where the functions

$$\Gamma(\Sigma s, \Sigma R) = \int_0^{\pi/2} \sin\alpha\cos\alpha\left[\exp(-\Sigma s/\cos\alpha) - \\ - \exp(-\Sigma(s + 2R)/\cos\alpha)\right]d\alpha \quad (12)$$

and

$$\Omega(\Sigma s, \Sigma R) = \int_0^{\pi/2} \sin^2\alpha\left[\exp(-\Sigma s/\cos\alpha) - \\ - \exp(-\Sigma(s + 2R)/\cos\alpha)\right]d\alpha \quad (13)$$

depend on the meatus geometry and on the air density δ_0 in the vacuum chamber. These functions do not appear to have been already tabulated. Fitting functions have been used for calculations, whose accuracy is not completely satisfying.

To give a quantitative idea of the phenomenon, the relative depression $\Delta p_0/p_0$ has been calculated assuming the usual size of a torsion balance, as specified in Table 2. Substituting in Eq. (12) the macroscopic cross section $\Sigma = \sigma\delta_0/m$ for any air density δ_0, one obtains the depressions $\Delta p_0/p_0$ reported in Table 2. Notice the high uniformity of the molecular flux within the meatus at 1 millibar vacuum level.

Conversely, the chamber pressure $p_0 = 10^{-5}$ bar corresponds to a sensible depression $\Delta p_0/p_0 \approx 3.4\times10^{-3}$ which may alter the gravitational force between the gravitational masses.

The disturbing force due to the small depression within the meatus $\Delta p(r) = mv\left[\phi_0 - \phi(r)\right]$ is defined by

$$F = \int_0^L 2\pi r\,\Delta p(r)\,dr, \quad (14)$$

where $L = R\cos\beta$ is the radius of the meatus periphery where $p(L) = p_0$. Substituting the flux distribution given by Eq. (2) one gets the corresponding depression within the meatus

$$p_0 - p(r) = p_0\left[1 - (\phi_m/\phi_0)\left(1 + kr^2\right)\right]. \quad (15)$$

Vacuum pressure p_0 Pascal	Air density δ_0 kg/m^3	Meatus optical width Σs m.f.p.	Flux depression $\Delta\phi_0/\phi_0$	Disturbing force $F(p_0)$ Newton
100	10^{-3}	40	1.4×10^{-22}	3.6×10^{-25}
50	5×10^{-4}	20	1.2×10^{-11}	1.5×10^{-14}
10	10^{-4}	4	2.8×10^{-6}	7.2×10^{-10}
1	10^{-5}	0.4	3.4×10^{-5}	8.4×10^{-10}
0.1	10^{-6}	4×10^{-2}	6.8×10^{-5}	1.7×10^{-10}
10^{-2}	10^{-7}	4×10^{-3}	1.8×10^{-5}	4.5×10^{-12}
10^{-3}	10^{-8}	4×10^{-4}	4.4×10^{-6}	1.1×10^{-13}
10^{-4}	10^{-9}	4×10^{-5}	1.1×10^{-6}	2.8×10^{-15}
10^{-5}	10^{-10}	4×10^{-6}	2.8×10^{-7}	7×10^{-17}
10^{-6}	10^{-11}	4×10^{-7}	8×10^{-8}	2×10^{-18}

Table 2: Calculation of the disturbing force due to the air molecules within the vacuum chamber of a gravitational torsion balance. The assumed geometrical characteristics are: meatus thickness $s = 4$ mm, moving mass radius $R = 5$ mm.

Substituting the expression of k by Eq. (3) one obtains

$$p_0 - p\,(r) = p_0\,[1 - \phi_m/\phi_0]\,\left(1 - r^2/L^2\right) \qquad (16)$$

which, substituted in Eq. (15), gives us the force

$$F(p_0) = (\pi/2)\,p_0 L^2\,(\Delta p_0/p_0) \qquad (17)$$

where the relative depression is given by Eq. (12). Assuming for smoothed chamber walls a value $\xi = 0.001$ we obtain the disturbing force reported in Table 2. One can notice that in the assumed torsion balance apparatus with light test mass ($R = 5$ mm) the disturbing force $F\,(p_0)$ takes a maximum at a pressure $p_0 \approx 2$ Pascal $= 2\times10^{-5}$ bar which makes the optical thickness of the meatus about equal to 1. This maximum is estimated to be comparable to the measured gravitational force F_{gr}. Even taking into account the questionable accuracy of the fitting functions, the values of the disturbing force explain "ad abundantiam" why the region of the intermediate pressures between millibar and nanobar was avoided by the experimenters. Obviously, what is of interest in the measurements is the systematic error due to $F\,(p_0)$. For instance in the Gershteyn's light torsion balance (where F_{gr} may be of the order of 10^{-11} Newton) the measurement was made at a pressure $p_0 = 10^{-11}$ bar (10^{-6} Pascal), so the disturbing force $F\,(p_0)$ gives a negligible systematic error $\epsilon \approx 2\times10^{-7}$.

In the Heyl's heavy balance experiment (where the measured F_{gr} was of the order of 10^{-9} Newton) the disturbing force $F\,(p_0)$ at a pressure $p_0 = 1$ millibar (100 Pascal) gives $\epsilon \approx 10^{-16}$. However the random error due to the air convection was probably around $\epsilon \approx 10^{-4}$, that is much larger than the systematic error due to the vacuum pressure.

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References

1. Speake C.C., Quinn T.J. The gravitational constant: theory and experiment 200 years after Cavendish. *Meas. Sci. Technol.*, 1999, v. 10, 420.
2. Heyl P.R. A determination of the Newtonian constant of gravitation. *Proc. Nat. Acad. Sci.*, 1927, v. 13, 601–605.
3. Gillies G.T. The Newtonian gravitational constant: an index of measurements. *Metrologia*, 1987, v. 24, 1–56.
4. Luo J., Hu Z.K. Status of measurement of the Newtonian gravitational constant. *Class. Quant. Grav.*, 2000, v. 17, 2351–2363.
5. Kritzer R. The gravitational constant. http://www.physics.uni-wuerzburg.de
6. Gundlach J.H., Merkowitz S.M. Mesurement of Newton's constant using a torsion balance with angular acceleration feedback. arXiv: gr-qc/0006043.
7. Gershteyn M.L. et al. Experimental evidence that the gravitational constant varies with orientation. arXiv: physics/0202058.
8. Michelini M. The common physical origin of the gravitational, strong and weak forces. *Apeiron*, 2008, v.15, no. 4, 440.
9. Hu Z.K., Luo J. Progress in determining the gravitational constant with four acttracting masses. *Journal Korean Phys. Soc.*, 2004, v. 45, 128–131.
10. Luo J., Hu Z.K., Fu X.H., Fan S.H., Tang M.X. Determination of the Newtonian constant with a non linear fitting method. *Phys. Rev. D*, 1998, v. 59, 042001.
11. Luther G.G., Towler W.R. Redetermination of the Newtonian *G*. *Phys. Rev. Lett.*, 1981, v. 48, 121–123.
12. Gundlach J.H., Smith G.L., Adelberger E.G. et al. Short-range test of the Equivalence Principle. *Phys. Rev. Lett.*, 1997, v. 78, 2523.
13. Su Y., Heckel B.R., Adelberger H.G., Gundlach J.H. et al. New tests of the universality of free fall. *Phys. Rev. D*, 1994, v. 50, 3614.
14. Sanders A.J., Deeds W.E. Proposed new determination of G and test of Newtonian gravitation. *Phys. Rev. D*, 1991, v. 46, 489.
15. More G.I., Stacey F.D., Tuck G.J. et al. *Phys. Rev. D*, 1991, v. 38, 1023.
16. Karagioz O.V., Izmailov V.P., Gillies V.P. Gravitational constant measurement using a four-position procedure. *Grav. and Cosmol.*, 1998, v. 4, 239.
17. Ritter R.C., Winkler L.I., Gillies G.T. Precision limits of the modern Cavendish device. *Meas. Sci. Technol.*, 1999, v. 10, 499–507.
18. Fitzgerald M.P., Armstrong T.R. The measurement of G using the MSL torsion balance. *Meas. Sci. Technol.*, 1999, v. 10, 439–444.
19. Gundlach J.H. A rotating torsion balance experiment to measure Newton's constant. *Meas. Sci. Technol.*, 1999, v. 10, 454–459.