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MEASUREMENT OF THE GRAVITATIONAL CONSTANT WITH A TORSION BALANCE

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We present results of ten years of measurements of the gravitational constant made using an evacuated torsion balance. We obtained the value G = $(6.6729 \pm 0.0005)\cdot 10^{-11}\ N\cdot m^2\cdot kg^{-2}$. *We have determined the major destabilizing factors accompanying the measurement process and have estimated the contribution from different sources of error.*

Method for Determination of *G*. We present the results of determination of the gravitational constant G using a torsion balance [1-4]. In the gravitational field of a stationary spherical attracting mass, the equation of motion of the balance has the form [5]:

$$d^2\varphi / dt^2 + \omega^2\varphi + GM\,[m_1 L_i (b_1 + b_2) \sin\varphi + m_2 (b_3 + b_4) / 2 \sin\varphi] / J = 0, \tag{1}$$

where $b_1 = L_5/(L_5^2 + L_i^2 - 2L_5L_i\cos\varphi)^{3/2}$;

$$b_3 = (L_i + L_6\cos\varphi)/\left[L_6\left(L_6^2 + L_i^2 + 2L_6L_i\cos\varphi\right)^{1/2}\right];$$

φ is the angle of deviation of the balance rod from the equilibrium position, G is the gravitational constant; M is the difference between the masses of the attracting sphere and the air displaced by it; m_1 is the mass of the weight on the balance rod; m_2 is the mass of the balance rod; L_5, L_6, L_i are the distances from the axis of rotation to the center of mass of the weight on the balance rod, the ends of the balance rod, and the center of mass of the attracting sphere; the subscript i indicates the position of the sphere; b_2 and b_4 are obtained from b_1 and b_3 by changing the sign in front of L_5 and L_6; ω is the cyclic vibrational frequency of the balance in the absence of attracting masses; J is the moment of inertia of the torsion body relative to the vertical axis of rotation.

After expanding the functions of the moments of the attractive forces in a series in odd powers of φ and using the theory of small anharmonic oscillations, for calculating G we obtain a system of difference equations:

$$G_{i,j} = 4\pi J\left(1/T_i^2 - 1/T_j^2\right)/\left[Mm_1\left(b_i - b_j\right)\right], \tag{2}$$

where $b_i = b_{1i} + b_{2i} + b_{3i} + b_{4i}$,

$$b_{1i} = L_iL_5\left(L_i - L_5\right)^{-3}\left\{1 - b_5\left[1 + 9L_iL_5\left(L_i - L_5\right)^{-2}\right] + \right.$$

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TABLE 1

Version number of torsion balance	d_1, mm	d_2, mm	m_1, g	m_2, g	L_5, cm	L_6, cm	g·cm^2	sec/rad^2
1	8	25	0,94200	1,6575	11,8514	11,55	338,397	790
2	6	15	0,94200	1,6575	11,8514	11,55	338,397	100
3	10	25	1,59163	1,6575	11,9102	11,55	525,429	12

TABLE 2

Version number of torsion balance	T, sec	m_3, mg	m_4, mg	m_5, mm	L_7, mm	L_8, mm	L_9, mm	L_{10}, mm	L_{11}, mm	d_3, mm	d_4, mm
1	2077	230	3999,95	996,05	20	221	262	537	150	6,017	1.8
2	3731	171	3972,95	996,05	20	227	261	542	108	6,017	1.8
3	1783	171	5254,00	959,25	20	227	261	542	108	7,165	1 8

Notes to Tables 1 and 2: c_1 **is a coefficient correcting the period in measuring the amplitude of oscillations of the balance (due to the presence of gravitational field gradients);** T **is the oscillation period of the balance;** m_3 **is the mass of the rod attached to the center of the balance rod;** m_4 **is the mass of the torsion body;** m_5 **is the mass of the intermediate body suspended on the auxiliary fiber;** L_{11} **is the length of the rod lowering the frequency of rocking oscillations.**

$$+b_5^2\left[1/3+15L_iL_5\left(L_i-L_5\right)^{-2}+75\left(L_iL_5\right)^2\left(L_i-L_5\right)^{-4}\right]\};$$

$$b_{3i}=b_6\sum_{k=1}^{n}L_iL_6b_7\left(L_i-L_6b_7\right)^{-3}\{1-b_5\left[1+9L_iL_6b_7\times\right.$$

$$\times\left(L_i-L_6b_7\right)^{-2}+b_5^2\left[1/3+15L_iL_6b_7\left(L_i-L_6b_7\right)^{-2}+\right.$$

$$\left.+75\left(L_iL_6b_7\right)^2\left(L_i-L_6b_7\right)^{-4}\right]\};$$

$$b_5=\varphi_{0i}^2/8;\ b_6=m_2/2m_1n;\ b_7=\left(k-1/2\right)/n;$$

The $G_{i,j}$ are the values of the gravitational constant for different combinations of the positions of the mass M; T_i, T_j, φ_{0i}, φ_{0j} are the periods and amplitudes of oscillations of the balance when the center of mass M of the attracting sphere is held in the i-th and j-th positions at distances L_i and L_j from the axis of rotation; b_{2i} and b_{4i} are obtained from b_{1i} and b_{3i} by changing the sign in front of L_5 and L_6, the terms with subscript i are transformed to terms with subscript j by replacing the terms L_i and φ_{0i} by terms L_j and φ_{0j}; n is the natural number closest to ratio L_6/d_4; d_4 is the diameter of the balance rod.

For a symmetric measurement scheme using two identical spherical attracting masses, the value of M in (1) and (2) is doubled. When the attracting mass is shifted along the vertical by the distance h, the square of this value is added to terms of the form

$$L_5^2+L_i^2\pm 2L_iL_5\cos\varphi;\left(L_i\pm L_6\cos\varphi\right)^2;$$

$$\left(L_i\pm L_5\right)^2 \text{ and } \left(L_i\pm L_6b_7\right)^2$$

The moment of inertia of the torsion body J is calculated from the formula

$$J=2m_1L_5^2+0.2m_1d_1^2+m_2\left(L_6^2+0.1875d_2^2\right)/3+J_1,$$

where J_1 is the moment of inertia of the body in the absence of the balance rod.

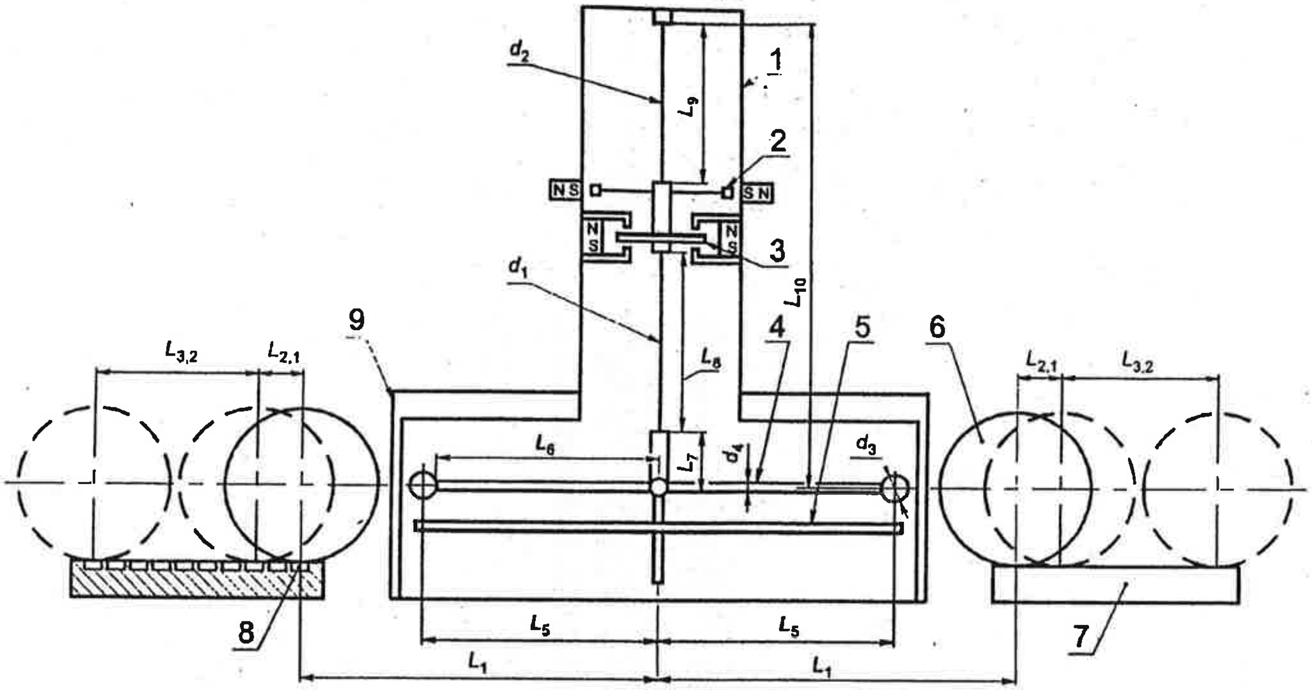

Fig. 1. Schematic of the apparatus for the three-position scheme for holding the attracting masses: *1*) vacuum chamber; *2*) ferromagnetic masses attached to the ends of the balance rod; *3*) aluminum disk; *4*) torsion body of the balance; *5*) copper plate; *6*) spherical attracting mass; *7*) stationary gage; *8*) circular holes; *9*) magnetic shield; d_1, d_2, d_3, d_4 are the diameters of respectively the suspension fiber for the torsion body, the auxiliary suspension fiber, the spherical weights at the ends of the balance rod, and the balance rod; L_7 is the distance from the lower point of suspension to the axis of the balance rod; L_8, L_9 are the lengths of the suspension fibers (the main fiber and the auxiliary fiber); L_{10} is the distance from the upper point of attachment of the auxiliary suspension fiber to the axis of the balance rod.

Design of the Apparatus. The torsion balance, placed in an evacuated chamber *1* (Fig. 1), is equipped with a magnetic damper suspended on a fiber of length L_9 and an assembly for rotating the top point of attachment of the torsion fiber about the axis of rotation. The aluminum disk *3* of the damper is located in the gap between the pole tips of two permanent magnets. The rotation assembly contains the balance rod with two ferromagnetic masses *2* at the ends and two permanent magnets located on the exterior surface of the chamber. Under the torsion body of the balance is placed a circular copper plate *5*, through its central hole passes an aluminum rod of diameter 1 mm, attached at the center of the balance rod. The stainless steel chamber *1* with outer diameter 260 mm, hermetically sealed with a copper gasket, is connected to a NORD-100 magnetic discharge pump. The chamber is surrounded by a magnetic shield *9* made of 79NM Permalloy of thickness 1 mm. The basic and additional parameters of the torsion balance are presented in Tables 1 and 2 respectively. The torsion balance has parasitic degrees of freedom [6], including pendulum oscillations (four degrees of freedom). The eddy currents induced in the aluminum disk *3* damp out the rocking oscillations of the torsion body *4*. The long thin rod connected to the balance rod increases the moment of inertia relative to the axis of the balance rod, lowering the highest frequency of the rocking oscillations. This frequency coming closer to the group of the rest of the three lower frequencies leads to an increase in the effectiveness of damping of the rocking oscillations for all the pendulum degrees of freedom.

The ferromagnetic masses *2*, interacting with the poles of the permanent magnets, make it possible to change the equilibrium position of the torsion body *4* and to hold it in a preset position.

The plate *5* is designed for heat treatment of the suspension fiber of the balance in the vacuum. A high-frequency voltage (on the order of 10 MHz) is supplied to this plate through an input lead. The circuit for the current is closed through a capacity between the plate and the torsion body. This type of annealing ensures practically uniform heating of the fiber over the entire length. Annealing is done with the goal of reducing the drift of the equilibrium position and the damping decrement for the torsion system.

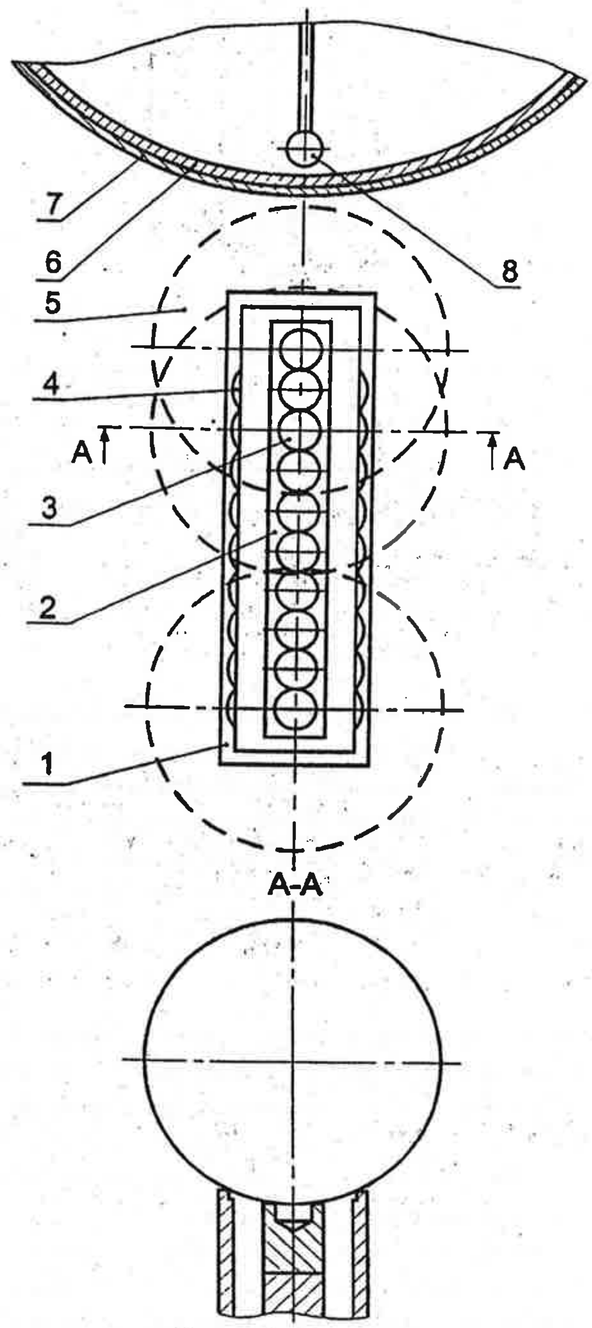

Fig. 2. Schematic of the device for moving and holding the spherical masses: *1*) slotted gage; *2*) stationary gage; *3*) circular holes in the stationary gage; *4*) sectors of circular holes in the slotted gage; *5*) attracting mass; *6*) vacuum chamber wall; *7*) magnetic shield; *8*) spherical weight at the end of the balance rod.

The spherical attracting masses *6* are held in the circular holes *8* of the stationary titanium gages *7* in three or four different positions. In Fig. 2, we illustrate the three-position scheme. The first position is located at the distance L_1 from the axis of rotation, the second position is located at the distance $L_2 = L_1 + L_{2,1}$, the third position is located at the distances $L_3 = L_2 + L_{3,2}$ (Fig. 1). Electric motors with the help of reducing gears, crankshafts, and slotted gages *1* (Fig. 2) with sectors of circular holes *4* move the spherical masses from one hole to the other. The moment the motors are turned on is set by an electronic counter, while the program for moving the spheres and the moment the motors are turned off are set by push-button microswitches. After a movement cycle is completed, the slotted gage is returned to the original position.

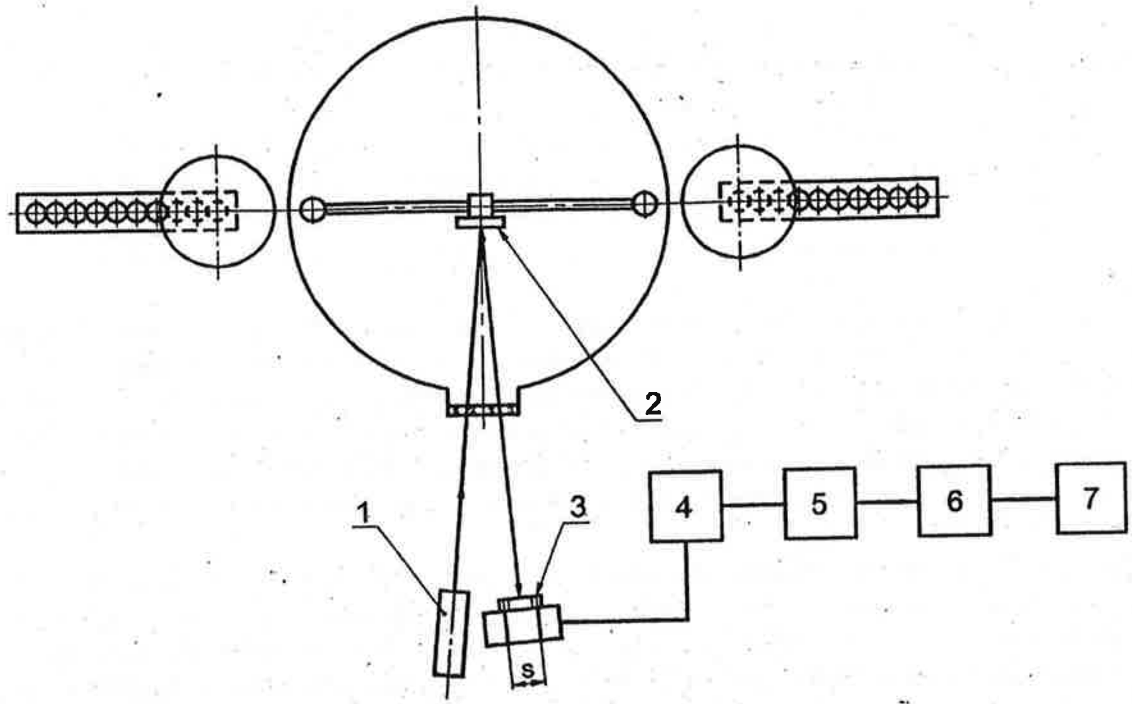

Fig. 3. Schematic of the optoelectronic indicator system: *1*) light source; *2*) reflecting mirror; *3*) photodiodes; *4*) threshold device; *5*) frequency meter; *6*) transcriber; *7*) digital printer.

The optoelectronic system (Fig. 3) includes a light source *1*, a reflecting mirror *2*, two photodiodes *3*, a threshold device *4*, a frequency meter *5*, a transcriber *6*, and a digital printer *7*. This system makes it possible to measure, for each position of the attractive masses, the period and amplitude of the oscillations of the balance. The light source *1* with the help of a miniature incandescent lamp, a condenser, a slit, and an objective forms a vertical band of light which, after reflection from the mirror of the balance attached to the torsion body, passes by the slits mounted in front of two photodiodes. From the photodiodes, the electrical pulses are sent to a comparator, where they are amplified and converted to rectangular pulses. The latter are sent to the frequency meter, which measures the time intervals between the pulses arriving at its input. The measurement results are registered by the transcriber and the digital printer. Between the moments that the electric motors are turned on, eight time intervals are measured. The ratio of these intervals depends on the amplitude of the oscillations and the layout of the photodetectors. With a decrease in amplitude, the short intervals increase while the long intervals decrease. We should note that the first two intervals are distorted by the process of moving the attracting masses, so they are not used in the calculations. Of the six remaining intervals, a group of five intervals is chosen, three long (t_{1i}, t_{3i}, t_5) and two short (t_{2i}, t_{4i}). One short interval is not used; it is found either before the selected group or after it (in the eighth place). The sum of the next four time intervals (one after the other) is equal to the period of the anharmonic oscillations. The five selected intervals make it possible to determine the value of two oscillation periods shifted in time by the quantity t_{1i}. The final values of T_i and φ_{0i} are calculated from the formulas:

$$T_i = 0{,}5\left(t_{1i} + t_{5i}\right) + t_{2i} + t_{3i} + t_{4i},$$

$$\varphi_{0i} = c_3 / \left\{c_2 \sin\left[\pi\left(t_{2i} + t_{4i}\right) / c_2 T_i\right]\right\},$$

where the constant c_2 determines the layout of the photodetectors relative to the zero position (for an asymmetric layout, $c_2 = 1$; for a symmetric layout, $c_2 = 2$); c_3 is a constant of the optical system, used in calculating the balance oscillation amplitude (numerically equal to the ratio of the distance s between the slits in front of the photodetectors to twice the distance L from the photodetectors to the mirror of the balance).

In the absence of noise $t_{5i} < t_{1i}$, and the difference $t_{1i} - t_{5i}$ is proportional to the damping decrement. For an asymmetric layout of the photodetectors, $0.5(t_{1i} + t_{5i}) \approx t_{2i} + t_{3i} + t_{4i}$, and for a symmetric layout $0.5\,(t_{1i} + t_{5i}) \approx t_{3i}$. For

$c_2 = 2$, the measurements can begin with an arbitrary time interval, while for $c_2 = 1$ the process of moving the attracting masses should not be matched with the longest time interval.

Movement of the attracting masses to the next position leads to a change in the period and amplitude of the oscillations of the balance. After the movement is completed and the electric drive is stopped, the presence of the indicated group of five undistorted time intervals makes it possible to determine the periods T_i, T_j and amplitudes φ_{0i}, φ_{0j} of the oscillations (needed for the calculation of G_{ij}), which are shifted due to the process of movement and subsequent change in the relative position of the attracting masses.

Adjustment of the Design Assemblies. After evacuating the balance and annealing the suspension fiber, we adjust the assemblies. Using the rotation assembly, we select the equilibrium position of the balance, monitored by an indicator system. Then we correct the position of the photodetectors. After this, the stationary gages are mounted in a position such that when the attracting mass is moved to a new position, the equilibrium position of the balance is not shifted. Deviation of the masses in a horizontal plane in the direction perpendicular to the equilibrium position is detected with error no greater than 1 μm. Adjustment of the masses in the vertical direction is done before evacuating the balance, with error on the order of 100 μm.

Versions of the Measurement Schemes. Two basic versions are possible. In the first version, we use only one attracting mass. Such a measurement scheme may be called "asymmetric". In the other version, two attracting masses are symmetrically positioned on two sides of the weights on the balance rod. Typically four-inch masses were used. The maximum diameter of the masses was no greater than six inches. For the asymmetric measurement scheme, we used 15 circular holes of diameter 15 mm; in the symmetric scheme the number of holes was reduced down to 10 while the diameter was reduced down to 13 mm. The availability of one or two additional positions for holding the attracting masses allows us to realize the method for measuring the gravitational constant G described in [1], based on smoothing all possible variants of the values of the gravitational constant obtained for different positions of the attracting masses.

Measurement Procedure. During the measurements, the attracting masses are moved by electric motors from one position to the other. When one of the extreme positions is reached, the reverse gear is turned on, providing cyclic motion of the attracting masses. If the program for moving the masses breaks down due to any malfunction, provision is made for emergency shutdown of the electric motor.

Initially the measurements were made using the asymmetric scheme. Then after upgrading the apparatus, the measurements were made using the symmetric scheme. The attracting masses were held either in four or in three positions. First we used a four-position scheme for which the attracting masses were held both at the two extremes and at two intermediate positions. This made it possible, in the case when observing the dependence of the gravitational constant G on the distance R between the interacting masses, to make a more detailed study of the $G(R)$ curve. For realization of the method proposed in [1] and based on strict observance of Newton's law, one intermediate position is sufficient. Then we gave preference to this version, since it allowed us to reduce the measurement error due to the increase in the values of the differences between the reciprocal squares $1/T_i^2 - 1/T_j^2$.

Measurement Results. The measurement results are presented in Table 3. The numbers in the first column indicate the date the measurements began (year, month, day). In the last column, we give the ratio σ/G, where σ is the mean square deviation of the average value of G in the data file. The average value of the ratio σ/G for all the experiments performed (taking into account the weight of each data file, proportional to the number of values of $G_{i,j}$ obtained) is equal to 28. Up to 1986 inclusively, the experiments were done using the asymmetric scheme on balance No. 1, which allowed us to obtain the maximum range of motion for the attracting mass. All the rest of the experiments were done using the symmetric scheme. In 1987, we used balance No. 2, and from 1988 on we used balance No. 3.

The attracting masses were held either in four positions or in three positions. In the experiments, we used a brass mass of diameter 121.98 mm (M = 7975.198 g), a brass mass of diameter 101.6 m (M = 4859.198 g), masses made of 95Kh18 stainless high-carbon tool steel of diameter 152.18 mm (M = 14,083.57 g); in the rest of the experiments we used masses made of ShKh15 steel of diameter 101.60 mm (in experiment 931130, the diameter was 102.24 mm). The measurements were made in a thermostat at a temperature of (23 ± 0.1)°C. When the temperature at the site rose above the indicated level, the thermostat operated in passive mode.

In the experiments performed, we observed time variations in the measured values of G within the range ±0.05%. The nature of these variations suggests that they most likely are connected with the action of microseisms. The presence of a damper made it possible to partially attenuate their effect. Taking into account the weight of each experiment (proportional to

TABLE 3

Data file	Number of measurements	M, g	Distance, cm				$G \cdot 10^{11}$, $N \cdot m^2 \cdot kg^{-2}$	σ/G, 10^{-6}
			L_1	L_2	L_3	L_4		
850419	911	7975,198	19,2115	21,2090	25,2067	47,2110	6,6730	90
850629	527	7975,198	19,5080	21,5055	25,5035	47,5078	6,6730	65
851211	701	7975,198	19,3937	21,3914	25,3889	47,3932	6,6730	64
860325	5050	4287,347	18,5920	20,5901	24,5881	46,5924	6,6730	43
870104	258	4287,347	18,2922	19,6909	22,4901	30,8884	6,6732	140
870303	1064	4859,959	18,3361	19,7361	22,5346	30,9329	6,6729	45
870714	150	4859,959	18,3361	19,7361	22,5346	30,9329	6,6729	90
870722	829	4287,347	18,3387	19,7387	22,5374	30,9357	6,6730	26
870924	57	4859,959	18,3361	22,5346	30,9329	—	6,6729	76
871111	138	4859,959	18,4405	22,6385	31,0368	—	6,6729	45
880802	1046	4859,959	18,5078	19,9072	22,7069	31,1052	6,6727	53
880805	1597	4282,375	18,5069	19,9063	22,7056	31,1039	6,6729	27
890309	2255	4282,375	18,5446	19,9439	22,7433	31,1416	6,6730	23
890606	396	4282,375	18,5469	19,9461	22,7455	31,1438	6,6729	33
890620	880	4282,375	18,5456	21,3438	31,1428	—	6,6727	28
901113	6532	4282,375	18,5458	21,3437	31,1437	—	6,6730	14
930321	4076	4282,375	18,5504	21,3483	31,1498	—	6,6730	20
930622	328	4859,959	18,5507	21,3486	31,1501	—	6,6729	51
931130	3642	4363,761	18,5506	21,3485	31,1500	—	6,6729	25
940705	1690	14083,57	20,8707	23,6690	33,4676	—	6,6728	9
941220	672	14083,57	20,8253	23,6236	33,4222	—	6,6729	13
950206	1105	4282,375	18,3221	21,1197	30,9171	—	6,6729	19
950525	2039	4282,375	18,3231	21,1210	30,9184	—	6,6730	12
950614	142	4859,959	18,3244	21,1223	30,9197	—	6,6730	57
950824	125	4282,375	18,3231	21,1210	30,9184	—	6,6730	26
951019	2641	4282,375	18,3231	21,1210	30,9184	—	6,6727	11

TABLE 4

Influential factor	Probable error	$\Delta G/G$, 10^{-6}
Distance $L_{2,1}$	1 mm	65
Distance $L_{3,2}$	1 mm	6
Moment of inertia J	$2 \cdot 10^{-3}$ $g \cdot cm^2$	6
Masses of weights on balance rod	0,01 mg	< 1
Mass of balance rod	0,01 mg	< 1
Mass of attracting body	20 mg	4
Oscillation amplitude j_0	0,01 %	3
Coefficient c_1	10 %	3
Oscillation period T_i	0,5 msec	10
Shift along vertical h	100 mm	2
Deviation along horizontal from equilibrium line of balance rod	3 mm	< 1
Magnetic coupling	—	< 1
Microseisms	—	40
Total error		78

the ratio G/σ) and the major sources of measurement errors presented in Table 4, we find that the average value of $G = (6.6729 \pm 0.0005) \cdot 10^{-11}$ $N \cdot m^2 \cdot kg^{-2}$.

Versions of the Calculation Procedure. In calculations of $G_{i,j}$, we preliminarily subtracted $\Delta T = c_1(\varphi_j^2 - \varphi_i^2)$ from the higher value of the period (for example, T_i). The constant c_1 is determined experimentally. Introduction of a correction is connected with a change in the oscillation amplitude of the balance when the masses are moved to a new position and the presence of gravitational field gradients in the zone where the torsion body is located.

We used two independent versions of the calculation procedure for the gravitational constant. Mainly after introduction of the correction to the measured values of T_i and T_j, the calculations were done using (2), which can be used for oscillation amplitudes up to 0.07 rad. In the other more complicated, laborious, and less accurate version, we used (1). This version of the calculation procedure is applicable for any oscillation amplitude of the balance. However, its use is complicated by the laborious procedure for calculation of the periods of anharmonic oscillations by determination of the time intervals between

TABLE 5

Subscripts i,j	$G_{i,j} \cdot 10^{11}$, $N \cdot m^2 \cdot kg^2$ for data files:							
	850419		850629		851211		860325	
	from equations							
	(2)	(1)	(2)	(1)	(2)	(1)	(2)	(1)
1,2	6,6731	6,6731	6,6731	6,6731	6,6733	6,6733	6,6720	6,6720
2,1	6,6730	6,6729	6,6726	6,6726	6,6719	6,6719	6,6736	6,6737
1,3	6,6728	6,6728	6,6731	6,6731	6,6731	6,6731	6,6732	6,6732
3,1	6,6730	6,6730	6,6729	6,6729	6,6725	6,6725	6,6726	6,6726
1,4	6,6732	6,6732	6,6732	6,6732	6,6732	6,6732	6,6735	6,6735
4,1	6,6729	6,6728	6,6729	6,6729	6,6727	6,6727	6,6724	6,6724
2,3	6,6722	6,6722	6,6728	6,6728	6,6725	6,6724	6,6748	6,6747
3,2	6,6734	6,6733	6,6726	6,6725	6,6727	6,6727	6,6706	6,6706
2,4	6,6733	6,6732	6,6727	6,6727	6,6727	6,6726	6,6746	6,6746
4,2	6,6727	6,6727	6,6733	6,6733	6,6729	6,6728	6,6710	6,6710
3,4	6,6746	6,6745	6,6720	6,6720	6,6725	6,6725	6,6743	6,6743
4,3	6,6715	6,6714	6,6736	6,6736	6,6727	6,6727	6,6714	6,6713

the zero value of φ by the Runge–Kutta method. In this case, in (1) there are the quantities ω and G, which are not required in calculations using (2). The frequency $\omega = 2\pi/T$ is determined experimentally by measuring the period T of oscillations of the balance in the absence of attracting masses. Comparing the differences between the reciprocal squares $1/T_i^2 - 1/T_j^2$ for the calculated values of the periods of anharmonic oscillations with the experimental values for two positions of the attracting masses and $G\,(1 \pm 0.001)$, using linear interpolation we find the value of G for which the calculated differences coincide with the experimental values. In Table 5, for the example of four experiments done on balance No. 1, we give the results of calculations of $G_{i,j}$ obtained by the two methods indicated above, and the more accurate structure of the data files obtained for the four-position measurement scheme is revealed. Both methods give calculated values which may differ only by one unit in the last (fifth) significant figure. The agreement between values of G for different calculation methods (error $\Delta G/G \leq 1 \cdot 10^{-5}$) suggests both that all the assumptions made in their realization are correct and that there are no systematic errors in the G calculation.

Thus the result obtained matches best the data presented in [2, 3].

We may assume that the major contribution to the error in measuring G comes from the error in measurement of the linear distances between the interacting masses. In our case, it was reduced to the error in determining the distances between the two closest positions of the attracting masses, on the order of 1 μm.

Our accumulated experience probably suggests influence of microseisms on the G measurement results; in this case, their contribution is very hidden and is difficult to predict. The effect of the latter is practically impossible to eliminate. The main method for decreasing the error introduced by microseisms is reduced to designing a highly effective damper. Almost all papers on measurement of G with a torsion balance, including the best known papers [3, 4, 7], were carried out without a damper for the pendulum oscillations. In [2], the presence of a damper promoted reduction of the measurement error. A damper was also used in [8], but the $G(R)$ dependence obtained in that paper most likely indirectly suggests that it was insufficiently effective for the complicated design of the balance which was used. We increased the effectiveness of the damper as a result of the long length of the upper (auxiliary) suspension fiber, which was greater in length than the torsion fiber of the balance, and also the increase in the moment of inertia of the torsion body relative to the axis of the balance rod. Furthermore, cyclic permutation of the attracting masses led to a minimum for all the errors connected with low-frequency drifts of any type. Nevertheless, all the precautions taken proved to be insufficient for complete elimination of the effect of microseisms. Further improvement of the technical characteristics of the damping system is required, a criterion for sufficient effectiveness of which may be in particular the reduction in the amplitude of the time variations in the measured values of G (already mentioned in [9]), down to a level on the order of 0.01%. A decrease in the variations of the measured values of G would make it possible to focus attention on solving the purely metrological problems. In this case, we will be able to more confidently explain the reason for the unsatisfactory convergence of the results of the G measurements obtained both in individual series of measurements [3] and in different papers [4, 7].

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