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FUNDAMENTAL PROBLEMS IN METROLOGY

LASER DISPLACEMENT INTERFEROMETERS WITH SUBNANOMETER RESOLUTION IN ABSOLUTE BALLISTIC GRAVIMETERS

L. F. Vitushkin,[1] O. A. Orlov,[1]
A. Germak,[2] and G. D'Agostino[2]

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This is a description of the overall structure of an absolute ballistic gravimeter in which a test object moves freely in a vacuum in the gravitational field. This system is intended for determining the acceleration of gravity using measurements of length and time intervals in the equation of motion of the test object. These intervals are measured by a laser displacement interferometer and a system for precise measurement of time intervals, which are incorporated in the gravimeter. Uncertainties in the measured acceleration of gravity and metrological support of absolute ballistic gravimeters for length and time measurements are discussed.
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Laser displacement interferometers (LDI) are one of the major components of absolute ballistic gravimeters which measure the acceleration of gravity by measuring intervals of length traversed by a test object as it falls freely in a vacuum and the corresponding times.

Absolute ballistic gravimeters are widely used in gravimetry and geodesy and have greatly changed the strategy for measuring the acceleration of gravity [1, 2]. This has been facilitated by the production of an ever increasing number, now more than sixty, of transportable absolute ballistic gravimeters. Absolute ballistic gravimeters are also used in high precision gravitational experiments, as well as in metrology [3] in the search for methods of realizing a new definition of the unit of mass (the kilogram). In these gravimeters, a test object undergoes free fall, so that a definition of the unit of a physical quantity, acceleration, in the area of measurements of the acceleration of gravity by the primary reference method [4–6] is possible. Thus, absolute ballistic gravimeters may become a primary standard for the unit of acceleration in measurements of the acceleration of gravity. By definition, a primary reference method for measurements is a method used to obtain the result of measurements without comparison with a standard for a quantity of the same kind, while a primary standard is a standard based on use of a primary reference method of measurement or created as an artifact chosen by agreement. Then, absolute ballistic gravimeters with relatively low metrological characteristics used in a reference measurement technique can be calibrated with the aid of a primary-standard absolute ballistic gravimeter, i.e., they can be secondary or working standards.

The development and study of absolute ballistic gravimeters, including the uncertainty in measurements of the acceleration of gravity, usually lie beyond the purview of specialists in the area of length measurements and laser displacement interferometry with nano- and subnanometer resolution. Nevertheless, the relative uncertainty in measurements

[1] Mendeleev All-Russia Research Institute of Metrology (VNIIM), St. Petersburg, Russia; e-mail: l.f.vitushkin@vniim.ru.
[2] National Institute of Metrology (INRIM), Turin, Italy.

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of the displacement of a test object falling freely in a vacuum in the LDI of absolute gravimeters should be on the order of 10^{-9}. Attainment of such an accuracy is an extremely complicated task for modern metrology in length and displacement measurements.

For the free fall distances of the test objects of roughly 2.5 to 50 cm required to achieve the required uncertainty of a few microgal (1 Gal = 1 cm/sec^2) when measuring the acceleration of gravity in existing absolute ballistic gravimeters, the uncertainty in the displacement measurements must not exceed 0.025 or 0.5 nm, respectively. Then the count rate for the interference fringes in the laser interferometer of an absolute gravimeter is as high as 6 MHz.

It is natural to assume that the development and study of LDI for absolute gravimeters with these metrological characteristics will be of interest for developers of LDI used in instruments for measuring length and displacements with subnanometer resolution.

Absolute Ballistic Gravimeters: General Description. The acceleration of gravity, g, determined by the resultant of the attractive force of the earth and the centrifugal force caused by the earth's rotation about its axis is found by measuring the parameters of the motion of a test object – its free fall in the gravitational field of the earth. Acceleration is the derivative of a physical quantity, more precisely the second derivative of length with respect to time, and is expressed in units of time and length. The acceleration of gravity is a particular case, measured in these same units.

An equation of motion of a test object in a gravitational field with a constant vertical gravitational gradient W_{zz} based on measured path lengths traversed by the freely falling test object and the corresponding measured time intervals can be used for determining the acceleration of gravity in absolute gravimeters [7]. In a local coordinate system, where the Z axis coincides with the direction of a plumb line, and assuming a small gradient $W_{zz} \ll 1$ sec^{-2} (for a normal geoid, it is on the order of $3 \cdot 10^{-6}$ sec^{-2}), the solution of the z component of the equation of motion of the test object at time t can be written in the form

$$z(t) = z_0(1 + W_{zz}t^2/2) + v_0(t + W_{zz}t^3/6) + (g_{\text{top}}/2)(t^2 + W_{zz}t^4/12), \quad (1)$$

where $z_0 = z(t = 0)$ and $v_0 = v(t = 0)$ are the initial position and velocity of the object, respectively, and g_{top} is the acceleration of gravity for $z = 0$.

A value of W_{zz} is usually obtained by measuring the change in g with height above the base of the gravimetric point with a relative gravimeter. The feasibility of determining W_{zz} by special processing of measurements of the motion of a freely falling test object in an absolute gravimeter has been discussed in Ref. 8.

As noted above, the relative error in measurements of the acceleration of gravity with modern absolute gravimeters is on the order of a few times 10^{-9}, or a few microgal in absolute units. This level of measurement accuracy requires that effects associated with the finite velocity c of light be taken into account. The delay in the time t_i a light wave interacts with a photodetector relative to the time τ_i it interacts with a falling test object is given by

$$\tau_i = t_i - (z_i - z_0)/c,$$

where t_i and z_i are the time and position along the Z axis from Eq. (1).

Two types of trajectories of the freely falling test object are used in absolute gravimeters: symmetric, where the test object is thrown vertically upward and then falls (rise-and-fall trajectory), and asymmetric, where it falls freely (free-fall trajectory). The gravimeter described in Ref. 9 belongs to the first group. Use of a symmetric trajectory makes it possible to compensate or greatly reduce the effect of several sources of error, such as the presence of residual gas in the vacuum chamber, magnetic fields, electrostatic effects, etc. Nevertheless, currently the most widely used gravimeters employ an asymmetric trajectory because of the relative simplicity of this type of motion of the test object and advances in the development of vacuum technology.

The basic parts of an absolute ballistic gravimeter include:

a vacuum vessel with a mechanical system for throwing up and catching the test object in gravimeters with symmetric trajectories or for bringing it to a state of free fall, catching it, and returning it to its initial state in gravimeters with asymmetric trajectories;

a dual beam LDI with a freely moving reflector fastened to the test object in the measurement arm of the interferometer. The reflector in the reference arm of the interferometer is suspended by a passive (usually a long-period seismometer is used) or active vibration isolation system [7, 10]. The motion of the test object is observed with respect to the suspended reference reflector, which forms a quasi-inertial coordinate system. A Fabry–Perot interferometer has been used in an absolute ballistic gravimeter [11];

a frequency stabilized laser as a source of coherent light for the laser interferometer. At present, He–Ne/I_2 lasers with an output wavelength of 633 nm (red light) are most widely used. Their frequency (wavelength) is stabilized with respect to saturated absorption peaks in the hyperfine structure of molecular iodine. Iodine-stabilized solid state Nd:YAG/KTP/I_2 and Nd:YVO_4/KTP/I_2 lasers pumped by laser diodes with wavelengths of 532 nm (green light) have operated successfully in GABL-G [12] and FG5-108 [13] gravimeters, respectively. In these solid state lasers, the respective Nd:YAG and Nd:YVO_4 rods are pumped by light from laser diodes, and the 1064 nm output from these rods is frequency doubled with a KTP crystal;

a frequency reference standard that is stabilized for long time intervals (e.g., a rubidium standard or GPS receiver) for the system to measure time intervals;

control units for absolute ballistic gravimeter systems, programs for controlling the gravimeter systems, measuring the intervals along the path of the test object and the corresponding time intervals, computing the measured value of the acceleration of gravity, and introducing various corrections (in particular, for the tides and the oceanic tidal load).

In existing absolute ballistic gravimeters, mechanical systems of various kinds are used to launch the test object and different optical configurations of the interferometers are used to measure paths ranging from 2.5 (the gravimeter of Ref. 14) to 50 cm (a GABL-G gravimeter) traversed by freely falling test objects.

The seventh and eighth international comparisons of absolute gravimeters, ICAG-2005 and ICAG-2009, held in 2005 and 2009 under the auspices of the BIPM [15], included, respectively, 19 and 21 absolute ballistic gravimeters of different designs. Only two of these used rise-and-fall (symmetric) trajectories; in the others, the test object fell freely. Twelve of the free-fall absolute ballistic gravimeters were commercial gravimeters with various modifications of the Micro-g LaCoste, Inc. (USA), model FG5 using essentially the same optical configurations and mechanisms for actuating the cycle of test object motion, including a free fall path with a length of about 21 cm. Another gravimeter, model FGL from the same company, has a shorter free fall path. Another two free-fall absolute ballistic gravimeters, model MPG developed by the Max Planck Institute (Germany; with a free fall path of about 21 cm) and the model FGC-1 gravimeter with an eccentric drive (fall path about 2.5 cm), were involved in the ICAG-2009 comparisons. The optical configurations of these two absolute ballistic gravimeters are similar to that of the FG5.

Note that the only gravimeter of an entirely new type in the ICAG-2009 comparisons was a cold-atom absolute gravimeter [17] with a different optical configuration from those of the interferometers in absolute ballistic gravimeters with macroscopic test objects.

The Uncertainty in Measuring *g* with an Absolute Ballistic Gravimeter and Metrological Support for it in Measurements of Length and Time. In order to measure the acceleration of gravity with a relative uncertainty of 10^{-9}, the movement of the test object as it falls and the time intervals must be measured with relative uncertainties of no more than $1 \cdot 10^{-9}$ and $5 \cdot 10^{-10}$, respectively.

As pointed out above, absolute ballistic gravimeters are means of measuring the derivative of a physical quantity (velocity) in the specific area of measurements of the acceleration of gravity. In principle, absolute ballistic gravimeters used to derive g from the equations of motion of a test object based on measured intervals of displacement and time must be calibrated in units of length and time (frequency).

In modern absolute ballistic gravimeters, the required uncertainty in long-term measurements of time intervals is provided by a rubidium frequency standard or by GPS receivers which produce a frequency stabilized reference signal at a frequency of 10 or 5 MHz. These frequency standards or GPS receivers can be calibrated for frequency with sufficient accuracy over long time intervals, but measurements of the acceleration of gravity by an absolute gravimeter also require high stability of the frequency over short time intervals.

Depending on the type of gravimeter, the test object falls freely for 0.07 to 0.5 sec. This is necessary to ensure sufficiently high short-term stability of an absolute ballistic gravimeter system for measuring the path (length) intervals and time.

TABLE 1. Absolute Error ΔL in Measurements of the Displacements of a Test Object in an Absolute Ballistic Gravimeter Required to Obtain a Relative error $\Delta L/L = 1 \cdot 10^{-9}$

L, m	ΔL, nm	ΔL in units of wavelengths λ, nm	
		633	532
0.500	0.500	λ/1266	λ/1064
0.200	0.200	λ/3165	λ/2660
0.025	0.025	λ/25320	λ/21280

Calibrating over long time intervals does not directly ensure such a high stability over short time intervals. During free fall or rise and fall of the test object in a gravimeter, the interference fringe counter counts the fringes in groups made up of a previously fixed number of fringes (e.g., in the FG5 gravimeter these groups consist of 1024 or 4000 fringes), with the time to count them ranging from a few milliseconds at the beginning of free fall to a few microseconds at the end. This means that the stability of the system for measuring time intervals during the fall of the test object and the frequency (wavelength) stability of the interferometer laser should be sufficient over these short time intervals; otherwise, the use of a constant wavelength (frequency) of the laser light for calculating the path length from the measured number of interference fringes will introduce error in measurements of the acceleration of gravity. When designing systems for measuring length and time intervals, the possible amplitude and frequency dependent phase delays in the electronic equipment must be kept in mind [7].

Comparative measurements of the frequency stability of He–Ne/I_2 lasers (wavelength 633 nm) and solid-state Nd:YVO_4/KTP/I_2 lasers (wavelength 532 nm) have been made over time intervals from 1 msec to 1 sec [13, 18]. The solid state laser was found to have greater frequency stability than the He–Ne/I_2 laser. The solid state lasers have a significantly higher output power (3–5 mW vs. 0.1–0.15 mW for He–Ne/I_2 lasers), and their lower level of frequency noise over short times is an additional advantage for use in the interferometers of absolute ballistic gravimeters.

The short-term frequency instability of the laser in laser interferometric measurement of displacements has been discussed elsewhere [19].

The path interval covered by a falling test object is measured by counting the interference fringes in the interferometers of absolute ballistic gravimeters and in modern gravimeters is mainly carried out by converting the analog signal from a photodetector into a TTL signal. At the same time, the equipment for fast multichannel signal detection makes it possible to record the analog and TTL signals simultaneously, along with the time intervals. With commercially available means of detection at rates of 100–200 million samples per second, it is possible, for instance, to record more than 600,000 interference fringes simultaneously in analog and TTL forms over an time of 0.2 sec, i.e., along a free fall distance of about 21 cm.

The pairs of measured time and displacement intervals are then used in a least squares calculation of the acceleration of gravity based on the known equation of motion of the test object.

The displacement interferometers in absolute ballistic gravimeters cannot be calibrated in units of length, i.e., by direct comparison of measurements of the displacement of a free falling test object simultaneously using the LDI of an absolute gravimeter and a standard for the unit of length, such as a standard laser interference comparator for measurements of length gauges and calibration of displacement interferometers. This possibility is not provided for in the design of absolute ballistic gravimeters.

In addition, the required error in measurements of displacements in absolute ballistic gravimeters turns out to be smaller than the error of standard interference comparators. Table 1 lists the absolute errors ΔL for different measured length intervals L in absolute gravimeters corresponding to a relative error $\Delta L/L = 1 \cdot 10^{-9}$, expressed in nanometers and in laser wavelengths λ (633 and 532 nm).

In practice, only an integral number of interference fringes is measured in absolute gravimeters, and this often simplifies the problem of dynamic measurement of the displacements of the test object. Nevertheless, Table 1 implies that the required errors ΔL in the displacement measurements are considerably smaller than even for laser interference comparators

TABLE 2. Measurement Uncertainties of Absolute Ballistic Gravimeters Participating in the ICAG-2005 International Comparisons

Gravimeter	Measurement uncertainty, μGal			
	instrumental	depending on point in gravimetric network	experimental mean square deviation	expanded
FG5	2.3	1.1–1.3	0.2–0.7	4.8–5.6
FGC-1	2.3	1.1	1.2–2.2	5.6–6.6
A10-008	5.9	1.1	2.1–3.8	12.4–14.2
JILA	1.8–2.6	1.0–2.1	0.2–0.9	5.0–7.0
IMGC-2	3.8	1.5	1.1–1.3	8.6
GABL-G	5.1	1.1	1.1–1.5	11.6–11.8
TBG	10.0	8.7	7.0–15.0	29.0–40.0

for standards of the unit of length. At present, this also excludes the possibility of direct transfer of the size of the unit of length from a primary standard to a laser interferometer for measuring displacements in an absolute ballistic gravimeter.

In the case of an absolute ballistic gravimeter, usually the only transfer that occurs is that of the sizes of the unit of frequency to a rubidium frequency standard and of the unit of frequency (wavelength) to the laser used in the interferometer of the gravimeter. Calibrations of this sort are necessary, but not sufficient, to calibrate an absolute ballistic gravimeter as a standard (means of measurement) for the unit of a secondary physical quantity, acceleration, in units of length and time (frequency) in the dynamic measurement mode discussed above. The only way of determining the accuracy and uncertainty of measurements of the acceleration of gravity by absolute gravimeters at present is to compare them, i.e., to compare the results of measurements of the acceleration of gravity by the gravimeters to be compared taken over a sufficiently limited time interval on points of a gravimetric network, usually within a laboratory, in accordance with a technical protocol that establishes the order and methods of processing the measurement data, as well as calculating and presenting the results of the comparisons with their uncertainties.

Regular ICAG international comparisons have been made at BIPM almost every four years, beginning in 1980. The results of ICAG-2005, a report at symposium GGEO-2008 of the International Geodesic Association (Chania, Crete), showed that the level of uncertainty in measurements of the acceleration of gravity by the absolute gravimeters participating in the comparisons amounted to a few microgal (or several units of 10^{-9} in relative magnitudes). The constituent uncertainties for the different types of participating absolute ballistic gravimeters are listed in Table 2. The values of the uncertainties were presented, discussed, and agreed upon by all participants in the comparisons in accordance with the Technical Protocol developed subject to the rules for organizing key comparisons at BIPM [20].

The gravimeters involved in the ICAG-2005 comparisons included two from the FG5 series 100 and ten from series 200, two JILA gravimeters, and the FGC-1 (Univ. of Colorado, USA), A10-008 (Micro-g LaCoste Inc., USA), IMGC-2 (Italy), GABL-G (Institute of Automation and Electrometry, Russia), and TBG (Ukraine) gravimeters.

The instrumental errors in the measurements by the absolute gravimeters include the errors inherent in high resolution laser interferometry, as well as some specific errors associated with perturbations in the free motion of a test object in a vacuum chamber, such as drag on the residual gas, nonuniformities in the magnetic field, electrostatic forces, etc. Estimates of the series of errors are given in Refs. 7, 21, and 22. The total instrumental error for the FG5 gravimeter is 1.1 μGal [7], or more than a factor of two smaller than the error indicated in Table 2.

Here we note an important source of error during measurement of the motion of the test object in an absolute ballistic gravimeter by laser displacement interferometry. Laser displacement interferometers are for direct measurement of the displacement of the test object, but also for measuring the optical path of the laser beam in the measurement arm of the interferometer. Random initial rotational velocities of the test object can cause a change in the optical path if its center of gravity

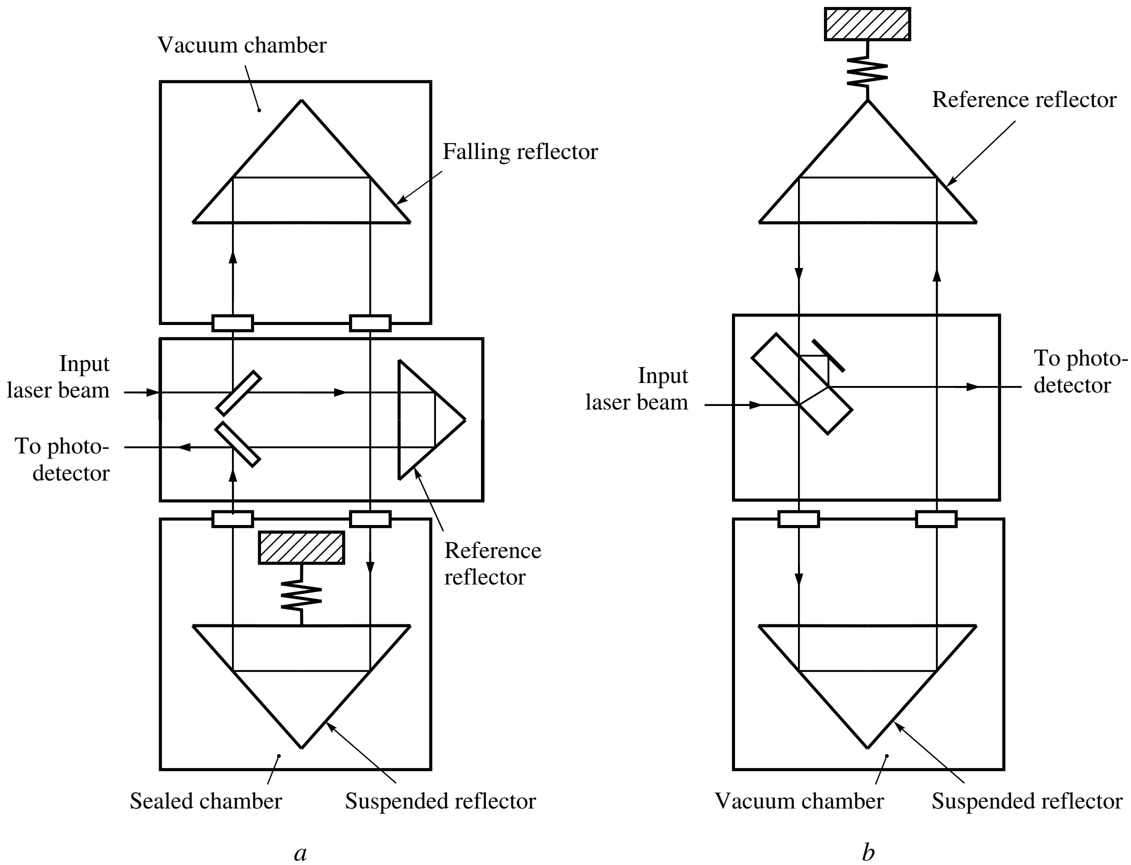

Fig. 1. Optical configurations of the laser displacement interferometers in the free-fall FG5 (*a*) and the rise-and-fall (symmetric) IMGC-2 (*b*) gravimeters.

does not coincide with the optical center of the corner reflector that is usually attached to the test object. The evaluation of these errors in absolute measurements of the acceleration of gravity and methods for matching the center of gravity of the test object to its optical center have been discussed elsewhere [23].

Optical Configurations of Laser Interferometers for Absolute Gravimeters. The optical configurations of dual-beam laser displacement interferometers are basically similar to those used in the free-fall FG5 gravimeter [7] and the rise-and-fall (symmetric) IMGC-2 gravimeter [9] shown in the figure.

The corner reflector mounted in the test object and suspended with passive (a long-period seismometer is often used) or active vibration isolation forms a quasi-inertial reference system, relative to which the displacement of the test object is measured. The freely moving and suspended reflector lie in the measurement arm in both interferometer configurations (see the figure). The main components of the reference arm of the IMGC-2 are integrated into a unit block design, and in the FG5 gravimeters these components are mounted in the interferometer housing.

The verticality of the laser beam in the measurement arm has to be monitored and adjusted with the aid of optical systems in laser displacement interferometers; thus, for example, the two beams (incident on the horizontal surface of a liquid and reflected from it) must coincide.

As the figure shows, in the existing absolute ballistic gravimeter designs the laser beam in the measurement arm of the LDI only propagates partially in the vacuum vessel. A substantial portion of its path lies in the air. Part of the measurement arm, including the reference reflector with its suspension system lie outside the vacuum chamber and is mechanically separated from it. The purpose of this design is to reduce the effect on the reference reflector of vibrations created by the mechanical systems that launch the test object in rise and fall gravimeters or release it into free fall in free-fall absolute ballistic gravimeters.

In interferometers with a relative resolution of displacements at a level of 10^{-9} (in relative units), it is necessary to account for the influence of the gaussian structure of the laser beams and effects related to the limited diameter $2w_0$ of the waist of the laser beam propagating in the interferometer. The influence of the gaussian structure of laser beams on interference measurements is described in [24] and [25] and, as applied to laser displacement interferometers in absolute gravimeters, in [26–28]. In practice, the diameter of the beam waist is restricted because of the need to limit the size and mass of the falling object.

The relative correction $\delta g/g$ to the measured acceleration of gravity is given by [27]

$$\delta g/g = \lambda^2/4\pi^2 w_0^2.$$

In order to keep the correction $\delta g/g$ smaller than $1\cdot10^{-9}$ (about 1 μGal), the radius of the gaussian beam waist should be at least 2.7 or 3.2 mm for λ = 532 and 633 nm, respectively. If w_0 is smaller, then this correction must be introduced.

Conclusion. The increasing need for accurate and reliable absolute measurements of the acceleration of gravity in geophysics, geodesy, gravitational survey work, navigation, and metrology has led to an increased demand for transportable and field absolute ballistic gravimeters, as well as high-precision absolute ballistic gravimeters for use in metrological laboratories and in organizations responsible for primary standards in the area of gravimetry.

In order to satisfy the demand for absolute ballistic gravimeters, it is necessary to develop a new generation of gravimeters that are more reliable and compact than existing equipment. One of the major absolute ballistic gravimeter systems consists of a laser displacement interferometer with subnanometer displacement resolution and rapid counting of interference fringes. High accuracy in dynamic measurements by the laser displacement interferometers in absolute gravimeters requires further serious research on these systems, as well as on the laser displacement interferometers used in metrology for measurement of lengths with nanometer resolution.

The design of the mechanism for launch of the test object (the ballistic system of a gravimeter) must ensure that it moves freely in a way such that the change in the optical path length of the beam in the interferometer as the test object and the attached reflector move will correspond as closely as possible to the motion of its center of gravity in the gravitational field.

The use of solid-state lasers with enhanced frequency stabilization over short time intervals (reduced frequency noise) in gravimeter interferometers makes it possible to reduce the noise level in the interference signal.

Further studies of the sources of error in the laser displacement interferometers of absolute ballistic gravimeters are of great interest in order to improve them and to study the feasibility of calibrating them and optimizing the organization of comparisons.

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