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Absolute Ballistic Gravimeters

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Abstract—Operating principle of modern ballistic gravimeters is based on the measurement of motion parameters of a macroscopic test body or a cloud of cold atoms in the gravity field and calculation of free-fall acceleration using the measured motion parameters from the test body motion equation. There are about 200 transportable ballistic gravimeters in the world, the best of which feature uncertainty of a few units of 10^{-8} ms^{-2}. Metrological assurance system for absolute gravimeters is being developed. Improvements in absolute gravimeters will allow their use on moving platforms.

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INTRODUCTION

Currently absolute ballistic gravimeters (ABGs) are the most accurate devices used for ground measurements of the free-fall (gravity) acceleration. In ABGs, reference measurement procedure [1] of free-fall acceleration (FFA) is applied, where free motion of the test body (TB) is realized in the gravity field in a local frame on the rotating Earth. The TB is a macroscopic body with embedded optical reflector, or a cloud of cold atoms.

If the first case, length and time intervals of macroscopic TB fall are measured by laser displacement interferometer and time interval measurement system. FFA is calculated from the measured length and time intervals using the known motion equation of the TB freely moving in the gravity field.

In the second case the atoms controlled by the laser form matter wave interferometers (atom interferometers), and the phase shifts of these matter waves due to their motion in gravity field are measured to receive FFA value (see for example [2–5]).

The word *ballistic* in the term *absolute ballistic gravimeter* means that the TB in absolute gravimeter follows a ballistic trajectory.

Relative uncertainty of FFA measurement by modern ABGs is a few units of 10^{-9}. In absolute values for FFA ground values it makes a few units of 10^{-8} m s^{-2} or a few microgals (Gal is a widely used off-system acceleration unit, 1 Gal = 1 cm s^{-2}).

Ground absolute gravimetry is applied in Earth sciences such as geodesy and geophysics, geology, geologic exploration, technical geology, Earth gravitational models for global satellite navigation systems, military science, gravimetric support of navigation systems, research focusing on the consideration of gravity field effect, metrology. Currently one of the most important applications of absolute gravimetry in metrology is FFA measurement during the experiments on Planck constant measurement and providing a new definition of the kilogram unit of mass using watt or joule balance [6].

In a major project of International Association of Geodesy (IAG) on Global Geodetic Observing System (GGOS, see for example [7]) the target uncertainty of FFA absolute measurements is defined to be 1 μGal.

At least 150 ABGs with macroscopic test bodies are used in the world for absolute FFA measurements. Most of them are commercial devices manufactured by an American company. A number of absolute gravimeters are under development in universities, National metrology institutes, and commercial companies. These are mainly experimental models. Gravimeters on cold atoms are also developed (see for example [2–5] and http://www.muquans.com/). Further we'll focus on ABGs with macroscopic TB.

In conclusion of this section, we mention several review papers [8-11] covering the development of technology of FFA absolute ballistic measurements.

GENERAL ABG DESIGN

With the required relative uncertainty of FFA measurement of the order of 1×10^{-9}, ABG systems should provide measurement of length intervals with the same relative uncertainty, and measurement of time intervals, with relative uncertainty of max 5×10^{-10}. With system approach to gravimeter design, these requirements should be taken into consideration in development of all its components.

An ABG with macroscopic TB usually includes

- ballistic unit, which realizes TB free motion;
- vacuum chamber for the ballistic unit;

- support table for arrangement and adjustment of the position of vacuum chamber with ballistic unit;
- laser displacement interferometer measuring the length intervals of TB free motion;
- passive or active vibration isolation suspension of reference optical reflector;
- frequency-stabilized laser of laser interferometer;
- system measuring the time intervals required for TB to pass the relevant length intervals;
- computer with the software controlling ABG systems, computing the measured FFA value from the measured length and time intervals using the equation of TB free motion, and calculating geophysical corrections (such as correction for gravity tides) and other types of corrections (such as gravitational self-attraction correction, correction for finite speed of light);
- auxiliary equipment including vacuum system for the vacuum camera.

Technical implementations of these systems differ with different ABGs. Further some implementations are described.

BALLISTIC UNITS

ABG ballistic unit is an electromechanical system realizing all TB motion cycles including its free fall inside the vacuum chamber and setting TB to the initial position for the drop.

In modern ABGs, two types of free motion are used: throwing TB vertically up and its motion following the symmetrical trajectory up and down (rise-and-fall gravimeters) or free fall from the initial position (free fall gravimeters).

Gravimeters with symmetrical TB trajectory were developed to eliminate the effect that the resistance of residual gas in vacuum chamber provides on TB motion, because this effect is eliminated or significantly reduced with symmetrical trajectory. Currently gravimeters with symmetrical TB trajectories are being developed in Istituto Nazionale di Ricerca Metrologica, Italy (INRIM, former IMGC) [12].

In the course of technical development, as the length of TB free fall decreased, which was conditioned by the progress in laser displacement interferometers, lasers, and vacuum technology, the designers converted to gravimeters with nonsymmetrical TB trajectories. Ballistic units of such gravimeters had one more advantage: there was no need in the system for suppressing the impact excitation after catapult action throwing the TB in gravimeters with symmetrical trajectory.

There exist different designs of ballistic units for ABGs with nonsymmetrical trajectory. In the most popular gravimeters such as FG5 by Micro-g LaCoste, Ltd (USA), before the drop the TB is set in top point on the trajectory on a cart, which at first moves with vertically down acceleration so that the TB separates from the cart and starts the free fall. During TB free fall the cart controlled by a special system moves at a certain distance in front of TB and at the end of the length (about 21 cm) smoothly slows down to gently catch the TB [11, 13]. The disadvantage of the design is the constant motion of the cart in ballistic unit during TB free fall, which excites mechanical microvibrations of the whole unit. Even introduction of the updated mechanically balanced design FG5X failed to completely exclude the microvibrations. Complete drop cycle in FG5-type gravimeters is max 10 s long.

In various modifications of GABL-type gravimeters developed by Automation and Electrometry Institute (Siberian branch of the Russian Academy of Sciences), TB with the embedded element made of nonretentive material is at first kept in the top initial point by electromagnet system, and then starts to fall after deenergizing [14]. The drawback of this design is the presence of residual magnetic field of electromagnet, which does not disappear instantly after electromagnet deenergizing, and the presence of residual magnetic field in nonretentive TB element, due to which TB at the beginning moves not quite freely, rather, it interacts with electromagnet residual field and with geomagnetic field.

These drawbacks have been eliminated or reduced in the ballistic unit of ABG-VNIIM-1 gravimeter developed by Mendeleyev Research Institute for Metrology [15, 16]. Here, the TB with a vertical thin rod attached to its top is kept in initial top position of fall trajectory by a special catcher. The piezoelectric catcher releases the TB without exciting microvibrations, and the TB freely falls. At the bottom the body is caught by a special trap and moved to its initial top position by a cart. The fall length in ABG-VNIIM-1 is about 10 cm. Complete drop cycle is max 10 s.

We should also note a gravimeter design with an cam-driven ballistic unit providing 200 single drops a minute with 2 cm freefall length [17].

LASERS AND LASER DISPLACEMENT INTERFEROMETERS

Another important system of any ABG is a laser displacement interferometer measuring the freefall intervals with relative uncertainty of 1×10^{-9}. Therefore, for a freefall length of about 20 cm (FG5 type gravimeters) the absolute uncertainty should not exceed 0.2 nm, and for eccentric gravimeters, 0.02 nm. It is a rather complicated problem, actually belonging to subnanometrology. The situation is somehow simplified by the fact than only integer numbers of interference fringes are counted in ABGs.

Existing ABGs mostly use double-beam laser interferometers [11, 12, 15, 19] with optical scheme of Michelson or Jamin interferometer type. An example of implementing an optical scheme of Fabri-Perot interferometer is also known [20].

633 nm (red) frequency-stabilized HeNe lasers (for example, [12]) and 532 nm (green) diode-pumped solid-state lasers (for example, [15]) are mostly used as lasers for laser displacement interferometers. 532 nm solid-state lasers feature greater radiative power, shorter lasing wavelength, and lower frequency noise as compared with gas HeNe laser.

Vibroisolation of Interferometer Reference Reflector

Interferometer reference reflector should implement the origin of quasiinertial reference frame with respect to which TB freefall intervals are measured. The reflector should be stable in space, which is provided by using active or passive vibration isolation systems.

All ABGs by Micro-g LaCoste, Ltd use the active system of reflector vibration isolation [11, 13]. Some other gravimeter developers also apply these systems. In other gravimeters, passive vibration isolation is used, usually realized by long-period seismometers.

Length and Time Interval Measurement Systems

Different recording systems are used based on high-speed ADC. For example, two-channel ADC NI 5112 and NI 5114 are applied [15, 21].

By the example of ABG-VNIIM-1 gravimeter [15], estimate the number of interference fringes recorded during the TB 10 cm free fall, and count frequency at 532 nm laser wavelength. During 0.14 s fall, the count frequency changes from near-zero at the beginning to over 5 ÌHz at the end, and the number of recorded fringes exceeds 360000. Interference fringes are usually counted in groups (of 1000 fringes for example). Thus, about 360 groups of interference fringes (length intervals) and corresponding time intervals should be registered in a single TB drop in ABG-VNIIM-1 gravimeter.

METROLOGICAL CHARACTERISTICS AND COMPARISONS OF ABSOLUTE GRAVIMETERS

The following components should be included in evaluation of systematic instrumental uncertainty of ABG with macroscopic TB (see for example [11, 15]):

- uncertainty in the measurement of laser wavelength;
- uncertainty in the measurement of Rb standard frequency;
- uncertainty in calculation of correction for TB deceleration by residual gas in vacuum chamber;
- uncertainty in the measurement of reference height about the foundation of the gravity site to which the measured FFA value refers;
- uncertainty in the calculation of diffraction effect;
- uncertainty in the calculation of correction for gravitational self attraction of test body by the gravimeter;
- uncertainty in the calculation of correction for the interaction between the falling TB and nonhomogenous magnetic field;
- uncertainty in the adjustment of the verticality of laser beam;
- uncertainty in the calculation of correction for the atmospheric pressure;
- uncertainty in the calculation of correction for the finite speed of light;
- uncertainty due to tolerances in the fabrication of optical elements;
- uncertainty due to the selection of the initial and final scaled fringes;
- uncertainty due to phase delays in the system of detecting and recording of interference fringes.

Total instrumental uncertainty of ABG-VNIIM-1 is 2 μGal. The stated total instrumental uncertainty of commercial FG5 gravimeters is 2 μGal, too.

Random component of uncertainty of FFA measurement by absolute gravimeters depends on microseismic environment at the gravimetric site.

ABG measures the free-fall acceleration. Acceleration is a derived unit, therefore, ABG should be calibrated in length and time units.

Normally only the frequencies of the laser and reference clock used for the time interval measurement system of ABG (usually Rb clock or GPS/GLONASS receiver) are calibrated. This is necessary but not sufficient for the gravimeter calibration [22]. It should be borne in mind that the laser does not realize the unit of length and its calibration in frequency (wavelength) does not provide the calibration of gravimeter laser interferometer in units of length. The unit of length is realized by the laser displacement interferometer.

Rb clock is calibrated on the time intervals of tens of minutes, which does not confirm the required metrological characteristics of time interval measurement system over the intervals of 0.1 s order, i.e., freefall time in a single drop.

To define ABG metrological characteristics, comparisons of FFA measurements by ABGs are organized. Comparisons are conducted in one gravimetric site according to the agreed technical protocols defining the measurement procedure, method of calculating the comparison results, and representation procedure.

The first International Comparison of FFA measurement results by five absolute gravimeters was conducted in 1981 at the International Bureau of Weights and Measures (BIPM) (Sèvres, France). Till 2009, BIPM and IAG have organized eight international comparisons at BIPM. Further, international comparisons were organized in other countries (Luxembourg, USA, China). Currently, gravimeter comparisons are organized according to metrological community rules

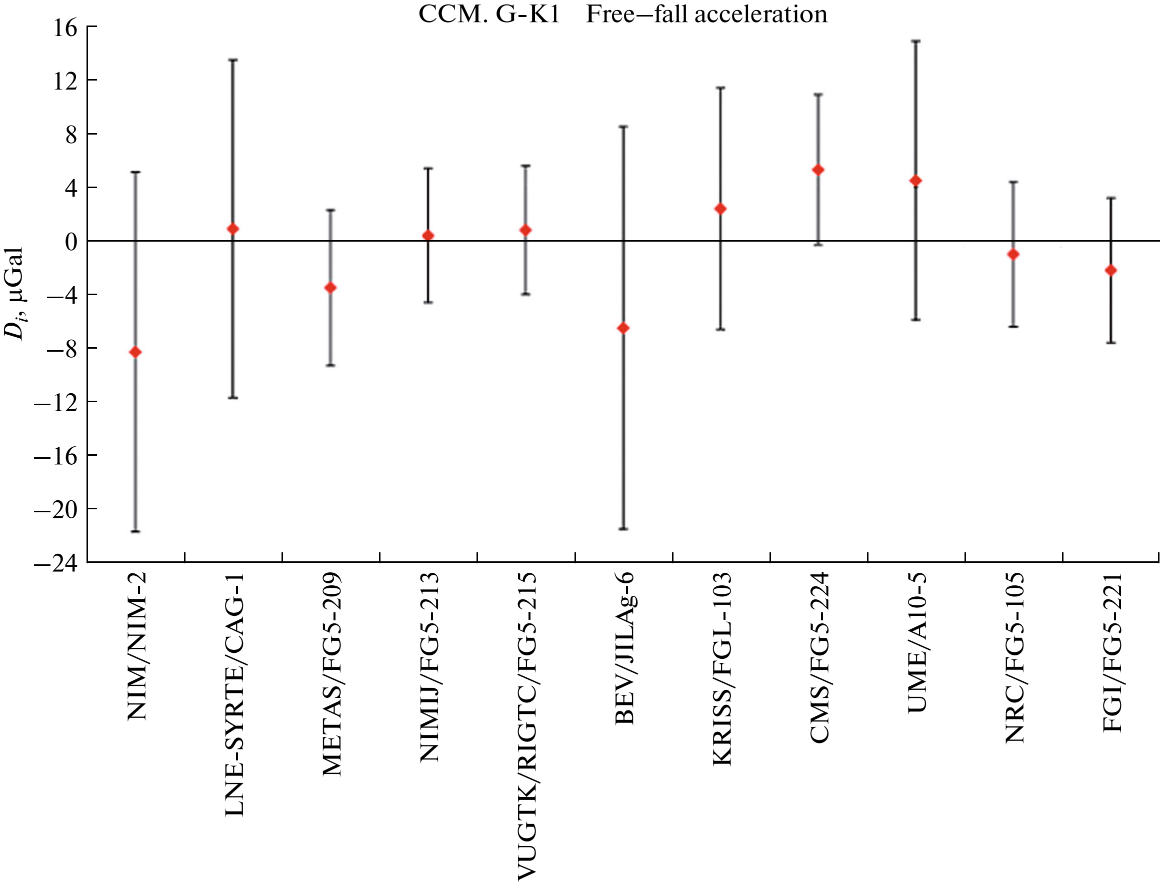

Fig. 1. Results from key comparisons of absolute gravimeters CCM.G-K1 (2009, BIPM, Sèvres, France).

defined by Mutual Recognition Arrangement (see the documents including the comparison guide at BIPM website http://www.bipm.org/en/cipm-mra/cipm-mra-documents/).

Metrological comparisons of absolute gravimeters (key comparisons) are a means of establishing the equivalence of national standards. Absolute gravimeters recognized as national primary standards in gravimetry are the standards of acceleration unit in FFA measurement.

The Strategy of Consultative Committee on Mass and IAG on metrology in absolute gravimetry adopted by the metrological and geodetic communities proposes the implementation of traditional metrological hierarchical structure based on the primary standard and subordinate secondary and working standards and measurement instruments – absolute gravimeters to be calibrated using the measurement standards.

It should be mentioned that the absolute ballistic gravimeter ABG-VNIIM-1 is the part of the Primary special measurement standard GET 190-2011 of acceleration unit in gravimetry [16]. In this measurement standard the ABG-VNIIM-1 realizes the acceleration unit in gravimetry (in the measurement of FFA), and the transfer of the unit (calibration) is performed at the gravimetry site “Lomonosov-1” in Lomonosov branch of VNIIM.

The results of key comparisons of absolute gravimeters – national standards are presented in BIPM Key Comparison Data Base (KCDB) (http://kcdb.bipm.org/, enter “free fall acceleration” in “search comparisons” line).

Results from Key comparisons of absolute gravimeters in 2009 and 2013 are presented in Figs. 1 and 2. On horizontal axis, the titles of national metrology institutes participating in the comparisons and the gravimeter names are indicated. On vertical axis, deviations of each result from key comparison reference value (KCRV), being the FFA value calculated using the measurements of all gravimeters at the gravimetric site during the comparison are indicated. In 2009 comparison, 11 ABGs have performed 96 12-hour measurement series at five gravimetric stations of BIPM gravimetric site [24]. Total uncertainties of all gravimeters at confidence level 95% are shown by vertical lines coming out of points denoting the measurement result.

Results for cold atom gravimeter CAG-01 by French national metrology institute LNE-SYRTE are presented in Figs. 1 and 2. The demonstrated compar-

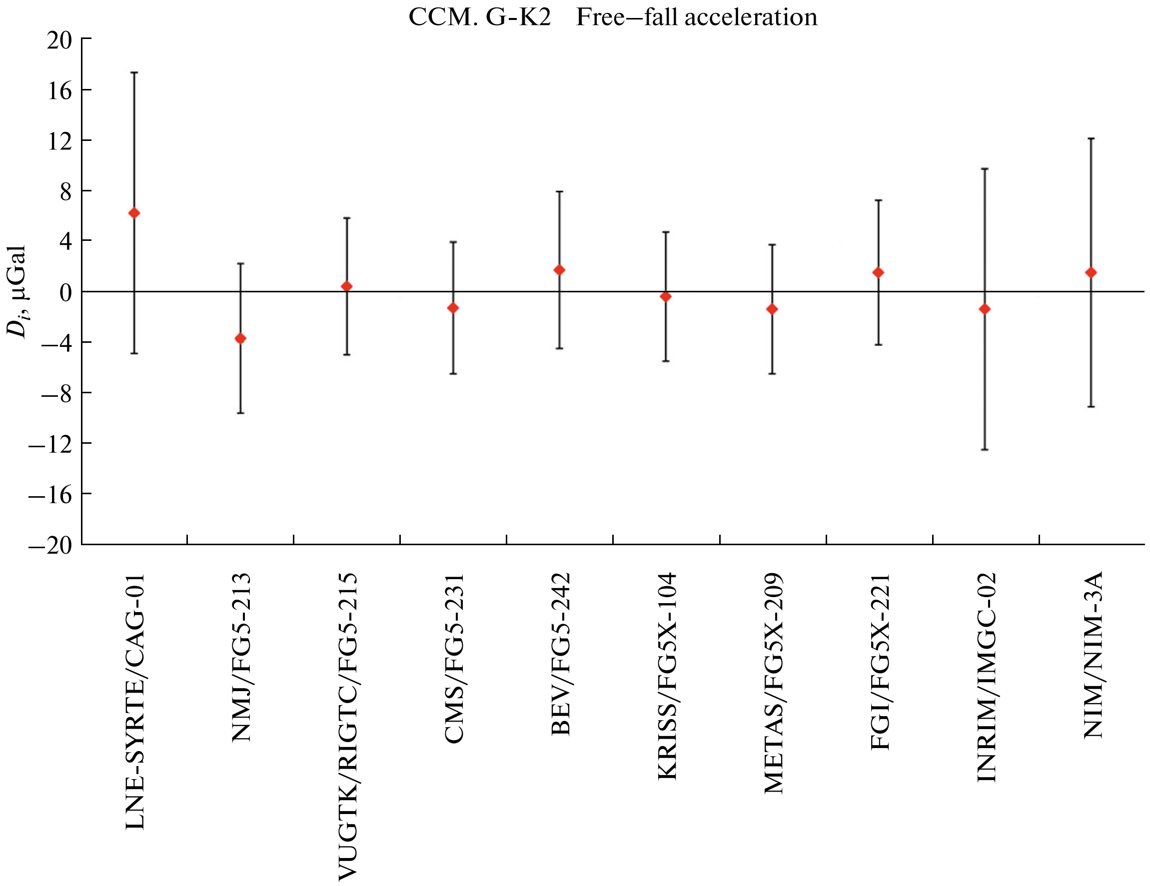

Fig. 2. Results from key comparisons of absolute gravimeters CCM.G-K2 (2013, Walferdange, Luxembourg) [25].

ison results reflect real uncertainties of the best existing ABGs. It should be noted that key comparison reference values, i.e., measured FFA at gravimetric sites, are determined accurate to about 1 μGal.

Extending the gravimetric network for international key comparisons to all continents (now being organized and going to be organized in Europe, Asia, and North America) combined with continuous monitoring of time variations of gravity field at these sites using superconducting gravimeters with a resolution of several tens of nanoGal creates perspectives for establishing a new global network of absolute gravimetric sites with FFA determination uncertainty of max 10 μGal, which is an order of magnitude better than featured by existing international gravimetric network IGSN-71 [25].

CONCLUSIONS

In recent decades, the number of transportable gravimeters (mostly produced by foreign companies) has considerably increased, and uncertainty of FFA determination by the best gravimeters has decreased to several microgals. It made possible to conduct a lot of high precision FFA measurements not merely for single FFA determination at individual sites of fundamental gravimetric networks but also for rather frequent repeated measurements and observations of time variations of gravity field.

An obvious advantage of absolute gravimeters is the absence of zero drift (high repeatability and reproducibility of measurement results). The metrological assurance system of absolute gravimeters is being developed based on national primary standards of acceleration unit in gravimetry (absolute gravimeters) and on calibration system of working absolute gravimeters, along with organization of their key comparisons.

The possibilities are opened for establishing a new global network of reference absolute gravimetric sites with FFA determination uncertainty at least an order of magnitude less than in the existing international gravimetric network IGSN-71.

Both types of absolute gravimeter – ABGs with macroscopic test bodies and ABGs on cold atoms – are constantly improving and will find their application spheres. There are perspectives for their downsizing, improving reliability and reproducibility of results.

The currently obtained ABG characteristics and perspectives for their improvement let us hope for the development of absolute gravimeters for mobile measurements in airborne and marine gravimetry.

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