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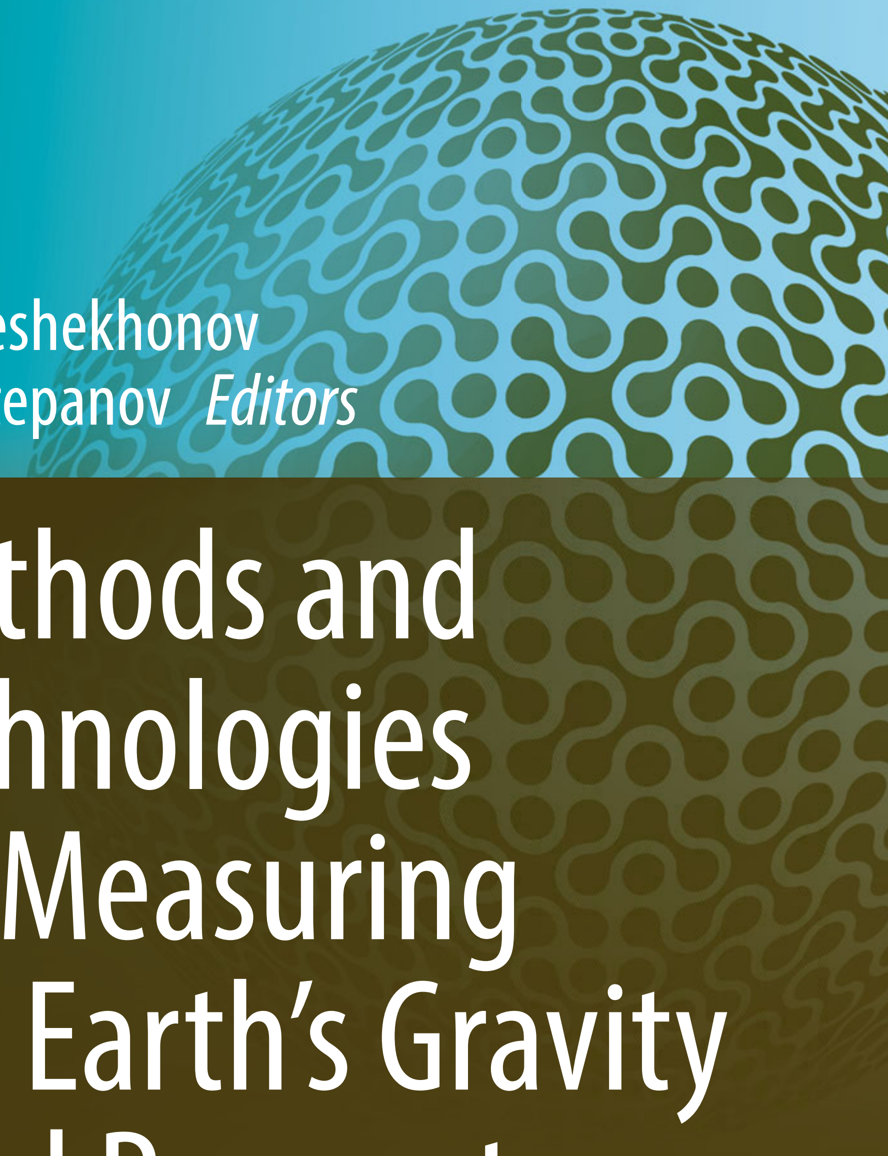

V. G. Peshekhonov
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Methods and Technologies for Measuring the Earth's Gravity Field Parameters

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Editors

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Preface

Knowledge of the Earth's gravity field (EGF) is essential in a wide range of fundamental and applied research areas. They include, for instance, offshore hydrocarbon exploration, for which marine gravimetric surveys are regularly conducted by geophysical companies. The quantum leap in INS/GNSS technology has opened the possibilities for airborne gravimetry along with shipborne surveys. Now the accuracy of airborne gravimetry is about 0.5–1 mGal and higher at a spatial resolution of less than 5–10 km. However, in a variety of problems related to the study of the Earth's figure, high-precision navigation, and geodesy, the requirements for accuracy, spatial resolution, and efficiency of gravimetric surveys are becoming more stringent in recent years. This, in turn, generates a need for improved accuracy of onboard EGF measurements against the background of vertical disturbing accelerations, the magnitude of which is hundreds of thousands times greater than the useful signal.

Recently, marine and airborne gravimetric surveys in remote Arctic regions have assumed a new urgency, which is associated with the studies of the continental shelf. The lack of data on the polar regions also impedes further improvement of the model for the Earth's figure.

To solve the problems of high-precision navigation and geodesy, it is necessary to know the absolute value of the gravity (free-fall) acceleration at the object location. Therefore, high-precision measurement of the total gravity acceleration onboard dynamic vehicles is one of the key challenges in modern gravimetry.

Considerable progress has been made in all the above areas since the late 1980s, but the recent results have not been adequately reported in the literature so far. In this regard, the publication of this monograph on modern methods and technologies for measuring the EGF parameters is particularly relevant.

The book is written by a team of well-known researchers in the field of EGF measurements from prominent Russian organizations, chief designers, and leading developers of widely applied gravimeters. This book provides the most relevant descriptions of designs and principles of operation of modern gravimeters, as well as the data processing methods used. It is neither a training manual nor a methodical guide. Therefore, the book does not claim to be comprehensive or to cover the above topics in full; it is rather a description of the authors' personal experiences in the development and research of methods and technologies for measuring the EGF parameters.

This book is an adapted translation of the Russian book *Sovremennye metody i sredstva izmerenya parametrov gravitatsionnogo polya Zemli* published in 2017 by Concern CSRI Elektropribor, St. Petersburg, Russia.

Compared to the Russian version of the book published in 2017, some changes have been introduced regarding the composition of the sections, reference list, etc. Additional international references have been included, and references to Russian scientific journals have been substituted with the English versions published by Springer and other international publishers. Information about the contributors, including their academic degrees and publications, has also been updated.

The book contains six chapters.

Chapter 1 describes modern equipment used for gravity measurements. It gives an overview of absolute ballistic gravimeters and analyzes the design features of two types of relative gravimeters manufactured in Russia, mobile Chekan-AM gravimeters and airborne/marine GT-2 gravimeters, widely used for onboard gravity measurements.

Chapter 2 analyzes data processing methods for onboard gravity anomaly measurements, implemented in Chekan-AM and GT-2 gravimeters, and discusses various approaches to improving the accuracy of onboard gravity field measurements. In particular, consideration is given to the experience of using optimal and adaptive filtering and smoothing methods, as well as the application of spherical wavelet expansion to combine airborne gravimetry data and global EGF models.

Chapter 3 provides an overview of the methods to determine and calculate deflections of the vertical (DOV) on a moving base. They include the gravimetric method based on gravity anomaly measurements, the astrogeodetic method based on the comparison of astronomical and geodetic coordinates, and the inertial-geodetic method based on high-precision inertial system data. The chapter considers the technologies implementing the DOV determination methods and improving their effectiveness, such as the automated zenith telescope recently developed by Concern CSRI Elektropribor. Improved data processing algorithms enhancing the accuracy of DOV determination methods are also covered.

Chapter 4 focuses on the studies of the gravity field in hard-to-reach areas of the Earth. It discusses the current knowledge of the Arctic gravity field, analyzes the experience of using the Chekan-AM gravimeter in remote areas, and considers the polar versions of GT-2 gravimeters capable of operating in all latitudes.

Chapter 5 presents some advanced methods for studying the Earth's gravity field. Airborne vector gravimetry based on strapdown inertial navigation systems is described. Possible approaches to gravity anomaly determination using this method are addressed. The state and prospects for the development of instruments for onboard measurements of the second derivatives of geopotential are discussed. Basic physical principles of cold-atom gravimeters and the outlook for their further development are also considered.

Chapter 6 deals with the construction of EGF models and their applications. Special attention is given to the estimation of their accuracy. These models are especially important in monitoring the quality of relative measurements (depending on the proper operation of equipment and the physical factors affecting it, such as zero-point drift), map-aided navigation, and estimation of the measurements navigation informativity.

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About the Book

The book provides an overview of the main modern methods and technologies for measuring the Earth's gravity field parameters. It presents a variety of gravity measurement instruments, including ground-based, marine, airborne, and space equipment.

The book addresses data processing methods applied to onboard gravity anomaly measurements. The optimal filtering and smoothing problem is formulated and solved in general form. The problem of structural and parametric identification of the anomaly models and errors of the measuring instruments is formulated. The proposed identification algorithm is described, based on nonlinear filtering methods and actually making the estimation process and algorithms adaptive.

Considerable attention is given to the methods for determining the deflections of the vertical. Their features are covered, and a qualitative comparative analysis is carried out.

The book covers the studies of the Earth's gravity field in remote areas. All-latitude modifications of instruments and software are considered. The results of gravimetric surveys in hard-to-reach regions are presented.

Promising methods for studying the gravity field, including simultaneous determination of the gravity anomaly and deflections of the vertical (vector gravimetry), are described and analyzed. The state of the art in cutting-edge technologies such as gravity gradiometers and cold-atom gravimeters is considered.

Modern models of the Earth's gravity field are compared, and their use in various applied problems such as map-aided navigation is discussed.

The book is written for engineers and researchers in gravimetry-related spheres. It will be also useful to the specialists in development and application of navigation systems, including designers of gravimetric instruments and navigation officers.

Contents

Abbreviations

ABG	Absolute ballistic gravimeter
AI	Atomic interferometer
AZT	Automated zenith telescope
BIPM	International Bureau of Weights and Measures
CCD	Charge-coupled device
CHAMP	Challenging Minisatellite Payload
CID	Control and indication device
CIPM	International Committee of Weights and Measures
CPU	Central processing unit
DOV	Deflections of the vertical
DTG	Dynamically tuned gyroscope
EGF	Earth's gravity field
EGG	Exploration gravity gradiometer
FFA	Free-fall acceleration
FOG	Fiber-optic gyroscope
FTG	Full tensor gradiometer
GA	Gravity anomaly
GES	Gravimeter elastic system
GG	Gravity gradiometer
GNSS	Global Navigation Satellite System
GOCE	Gravity Field and Steady-State Ocean Circulation Explorer
GD	Gravity disturbance
GP	Gyro platform
GRACE	Gravity Recovery and Climate Experiment
GRS	Gravity reference station
GSE	Gravimeter sensing element
IAG	International Association of Geodesy
ICAG	International Comparison of Absolute Gravimeters
IF	Interference fringes
INS	Inertial navigation system
KF	Kalman filter

LHM	Local harmonic modeling
LPF	Low-pass filter
LSM	Least squares method
MOT	Magneto-optical trap
OEC	Optoelectronic converter
OI	Optical interferometer
OSF	Optimal smoothing filter
PDD	Proximate decomposition and decorrelation
PDF	Probability density function
PSD	Power spectral density
SC	Scaling coefficient
SDGP	Second derivatives of the geopotential
SGSF	Suboptimal gravimetric smoothing filter
SIMU	Strapdown inertial measurement unit
SINS	Strapdown inertial navigation system
SWC	Spherical wavelet coefficient
TF	Transfer function
UKF	Unscented Kalman filter
VCT	Vertical component transformation
ZUPT	Zero velocity update

Chapter 1
Instruments for Measuring Gravity

L. Vitushkin, L. Elinson, A. Krasnov, V. G. Peshekhonov, A. Sokolov, Yu. Smoller, and S. Yurist

Abstract This chapter describes technical instrumentation for gravity measurements. Various types of absolute ballistic gravimeters intended for ground-based measurements of the absolute free-fall acceleration are described. The focus is on the most recently used laser-interferometric absolute gravimeters. Regular international comparisons of absolute gravimeters are considered. Applications of ground-based absolute gravimetry using ballistic gravimeters for the national and international geodetic projects such as the Global Geodetic Observing System of the International Association of Geodesy are described. Development and operation of the Russian Chekan and GT-2 series mobile gravimeters are addressed.

Keywords Absolute ballistic gravimeters · International comparisons of absolute gravimeters · Relative gravimeters · Gravimeter Chekan · Gravimeter GT-2A

Introduction

This chapter is devoted to the description of the technical instrumentation for gravity measurement. It contains three sections.

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Section 1.1 describes the principle of operation, structure, and design features of various types of modern absolute ballistic gravimeters (ABG) intended for ground-based measurements of the absolute values of the free-fall acceleration (FFA). The focus is on the most recently used laser-interferometric ABGs, which determine FFA based on measurements—conducted with a laser displacement interferometer—of the travel path of a macroscopic test body (MTB) and the time intervals during its free fall in a gravitational field. The sources of uncertainties in FFA measurements using the ABGs are analyzed. The chapter provides an analysis of the modern metrological assurance system for absolute gravimeters. It is pointed out that, in order to determine ABG metrological characteristics belonging to national metrological institutes, regular international comparisons under the auspices of the International Committee of Weights and Measures and regional international comparisons are held under the authority of regional metrological organizations. The results of these comparisons are briefly described, also given is the information on the international database of absolute FFA measurements, developed by the Institute of Geodesy of the German Federal Agency for Cartography and Geodesy (BKG). Applications of ground-based absolute gravimetry using ABGs for the implementation of national and international projects in modern geodesy such as the Global Geodetic Observing System of the International Association of Geodesy are described. The section points out the current trend of research aimed at determining whether it is possible to carry out absolute FFA measurements using ABGs on moving platforms in marine and airborne gravimetry.

Sections 1.2 **and** 1.3 describe the features of the development and operation of the Russian Chekan series (Sect. 1.2) and GT-2 series (Sect. 1.3) mobile gravimeters. These systems belong to the class of relative gravimeters, i.e., those designed to measure gravity increments. They are widely used for high-precision measurements of the Earth's gravitational field from sea vessels and aircraft, including measurements in hard-to-reach Arctic and Antarctic areas.

Each section provides brief information on the development history of the instruments, describes design features of gravimeter sensing elements along with their block diagrams, and gives a detailed description of the main technical solutions implemented when building the latest versions of gravimeters. Mathematical models of gravity sensors and inertial sensing elements used are provided. The main structural features and the sources of uncertainties of stabilization and correction circuits for gyrostabilized platforms are analyzed.

1.1 Absolute Gravimeters

Absolute measurements of the free-fall acceleration (gravity) are the basis for the determination of the Earth's gravitational field (EGF). In absolute measurements, the measurement result is represented by the absolute FFA value, in contrast to relative measurements, the result of which is represented by the difference between FFA values at the stations where the measurements were taken.

At the initial stages of the development of instruments for measuring the gravitational field, the number of absolute FFA measurements was insignificant, and the uncertainties in measurements were relatively large.

From 1909 to 1971, all gravitational field measurements were performed in the framework of the Potsdam Gravimetric System. At the initial gravimetric site, absolute measurements were taken using reversible pendulums, and their uncertainty was 3 mGal (1 Gal = 1 cm/s^2) (Cook 1965).

IGSN-1971, the gravimetric system that combines gravitational field measurements throughout the world, was adopted by the General Assembly of the International Union of Geodesy and Geophysics in Moscow in 1971, Russia (Resolution 16).

IGSN-71 was originally based on 10 absolute measurements at 8 gravimetric sites with an FFA measurement uncertainty of 1 mGal.

In the 1970s, IGSN-1971 was expanded to 471 sites with 24,000 links measured using relative gravimeters and with 1200 absolute measurements using pendulum gravimeters. The uncertainty in the FFA determination was 0.1 mGal.

In 1986, G. Boedeker and T. Fritzer proposed a new International Absolute Gravity Basestation Network (IAGBN) within which the monitoring of variations in the gravitational field was to be carried out, but the intended set of sites was not implemented.

The emergence of transportable absolute ballistic gravimeters in the 1970s resulted in a significant increase in the accuracy of absolute FFA measurements, increasing their number, and made it possible to build a new global system of absolute gravimetric sites with an uncertainty in measuring absolute FFA values not exceeding 10 μGal.

It should be noted that the modern international database of absolute measurements AGrav developed and supported jointly by the German Federal Agency of Cartography and Geodesy and the International Gravimetric Bureau (BGI) (France) presents the results of more than 3300 absolute measurements by 50 absolute gravimeters with 1100 gravimetric sites (http://agrav.bkg.bund.de).

1.1.1 Types and Designs of Absolute Ballistic Gravimeters

At present, absolute FFA values can be measured by ABGs, in which laser interferometers measure the fall path of an MTB with an optical interferometer reflector attached to it or with cold atom interferometers for which the test objects are the clouds of cold atoms. The term “ballistic” is associated with the type of the free-fall path of the test body in a gravimeter. In such gravimeters, the free motion of the test body in the gravitational field is used, and the FFA is calculated from the measured path and time intervals from the test body ballistic motion equation (Cook 1965).

ABGs use two types of the test body trajectories: symmetric (a rise-and-fall trajectory such that the test body is thrown up and then falls down) and asymmetric (a free-fall trajectory such that the test body falls down freely). An example of a gravimeter with a symmetric trajectory is the device developed by the Italian National Institute of

Metrological Research (INRIM) (Germak et al. 2002). However, most of the modern ABGs have an asymmetric trajectory (please see Niebauer et al. 1995; Arnautov et al. 1974; Vitouchkine and Faller 2002; Vitushkin and Orlov 2014).

Figure 1.1 shows a schematic of a laser-interferometric ABG, which is implemented in various designs of gravimeters with an MTB, where a displacement laser interferometer is used to measure the free-fall trajectory.

At present, the relative uncertainty of the absolute FFA measurements using ABGs is about 10^{-9} (several microgal in absolute units). However, it should be noted that such a measurement uncertainty cannot be obtained in a single throw of the proof mass but is obtained in comparably long series of throws.

ABGs with an MTB normally include:

- a vacuum chamber with a ballistic unit, test body, and a vacuum system;
- a laser interferometer to measure the displacement of the test body in its free motion, passive or active vibration isolation system for the reference reflector, against which the laser interferometer measures the test body displacement;
- a frequency-stabilized laser of the laser interferometer;
- a path and time interval recording system, a reference rubidium frequency oscillator for the path and time interval recording system;

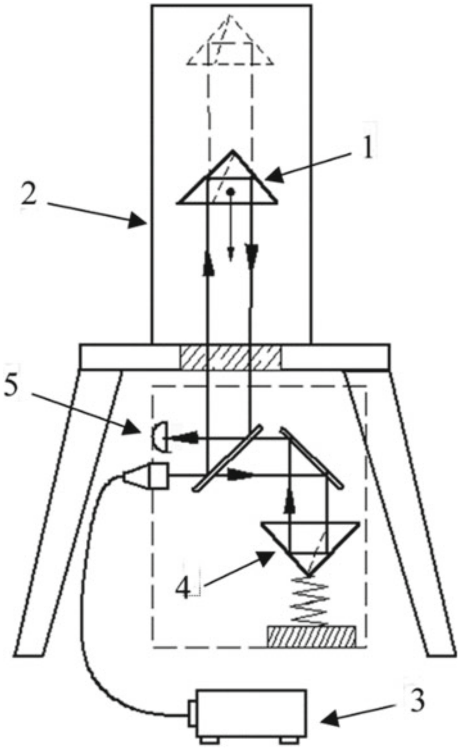

Fig. 1.1 A schematic of a laser-interferometric ABG with a macroscopic test body. *1*—test body with an integrated optical reflector in the measuring arm of the interferometer; *2*—vacuum chamber; *3*—laser; *4*—reflector placed on a vibroprotective (active or passive) suspension in the reference arm of the interferometer; *5*—optical interference signal photoreceiver

- a computer with software for processing the measured data and calculating the measured FFA value with the introduction of necessary instrumental and geophysical corrections;
- additional equipment that ensures ABG functioning.

The test body falls in vacuum chambers to eliminate or reduce air (residual gas) resistance.

In ABGs with an MTB, the laser interferometer measures the displacement of the test body, and the small time interval measuring system measures time intervals.

In ABG designs known, the length of the test body trajectory is from 2 to 50 cm, the time of the test body fall is approximately from 0.02 to 0.32 s.

The vacuum chamber contains a ballistic unit carrying out the entire cycle of the test body motion, including its free motion along a symmetric or asymmetric trajectory and catch of the test body at the end of the trajectory.

In rise-and-fall ABGs, the test body is thrown by a special catapult (for example, see Germak et al. 2002). In almost any design, there is an inevitable effect of mechanical recoil which is the source of undesirable mechanical oscillations of the reference reflector of the laser interferometer, with respect to which the intervals of the path traveled by the test body are measured.

In some free-fall ABGs (for example, in all gravimeters manufactured by Micro-g LaCoste, Inc., USA), in the ballistic unit of the gravimeter, the test body fall is accompanied by a simultaneous motion of the carriage on which the test body rests before the throw and which, having accelerated enough for the test body separation, then moves ahead of the test body during its fall (Niebauer et al. 1994). Such motion of the carriage causes parasitic mechanical excitations.

In the design of the GABL gravimeter of the Institute of Automation and Electrometry of the Siberian Branch of the Russian Academy of Sciences, the test body is held in its initial upper position with an electromagnet and brought to a fall by switching the electromagnet off (Arnautov et al. 1988); there are no mechanical excitations during the test body fall, but the effect of the residual magnetic field remains at the initial segment of the fall path.

In the design of the ABG-VNIIM-1 gravimeter (Vitushkin and Orlov 2011), the test body is held in the initial upper position with a special piezoceramics-based clamp, while there are no mechanical excitations or residual magnetic fields during the free fall of the test body.

The time interval between individual throws in some ABGs with MTB can be quite small: it does not exceed 0.3 s in an eccentric gravimeter (Vitouchkine and Faller 2002).

The equation for the test body motion that does not take into account the vertical gradient of the gravitational field is quite simple:

$$L = L_0 + V_0 T + \frac{gT^2}{2}, \tag{1.1.1}$$

where g is the free-fall acceleration, L is the path interval traveled by the free-falling test body during the time T, L_0 and V_0 are the test body coordinate and speed at the initial moment of time $T = 0$.

If $L_0 = 0$ and $V_0 = 0$, the following measurement equation can be used:

$$g = \frac{2L}{T^2}. \tag{1.1.2}$$

This expression gives simple estimates of the level of measurement uncertainties included in Eq. (1.1.2) path intervals L and time T needed to achieve the relative uncertainty 1×10^{-9} when calculating the absolute value of FFA g. It follows from formula (1.1.2) that the relative uncertainty of path interval measurements should not exceed 1×10^{-9}, and the relative uncertainty in measuring time intervals of the test body fall should not exceed 5×10^{-10}.

These values of uncertainties also define the requirements for the laser radiation wavelength (frequency) uncertainty and for the uncertainty in detecting interference fringes (IF) in the interferometer.

The inhomogeneity of the Earth's gravitational field (the presence of the vertical gradient W_{zz}, i.e., the second derivative of the gravitational potential W in the vertical coordinate z) complicates the equation of motion for a free-falling test body in a gravitational field with a vertical gradient:

$$\ddot{z} = g_{top} + W_{zz}z, \tag{1.1.3}$$

where g_{top} is the FFA at $z = 0$, W_{zz} is the vertical gradient of the gravitational potential W:

$$W_{zz} = \frac{(\partial^2 W)}{\partial z^2}.$$

The approximate solution of Eq. (1.1.3) for $W_{ZZ} \ll 1$ is as follows:

$$z(t) = z_0\left(1 + \frac{t^2}{2}\right) + v_0\left(t + \frac{W_{zz}t^3}{6}\right) + \frac{g_{top}}{2}\left(t^2 + \frac{W_{zz}t^4}{12}\right), \tag{1.1.4}$$

where z_0 and v_0 are the vertical coordinate and speed of the test body at $t = 0$.

In practice, based on Eq. (1.1.4) derived from Eq. (1.1.3), a vertical gradient correction is calculated for the solution of Eq. (1.1.1) when calculating the FFA value measured with an absolute ballistic gravimeter using the least squares method from the "path/time interval" pairs measured during a free fall of the test body.

The vertical gradient is usually measured using a relative gravimeter installed at various heights above the pedestal of the gravimetric site.

The vertical gradient correction is also used in reducing the measured FFA value g_{top} to a specified height above the pedestal. For a more accurate calculation of such a correction, the FFA vertical distribution is measured with a relative gravimeter and approximated by a second-order polynomial.

The reduction of measurement results of various gravimeters with different heights inherent in their designs, where g_{top} is measured, is necessary; in particular, for the analysis of their measurement results during the comparison of absolute gravimeters.

It should be noted that, when measuring the accelerated fall of a test body with an interferometer, the frequency of IF counting rapidly changes from almost zero to several megahertz during the fall in tenths of a second, which requires high-speed recording of such signals with almost linear frequency modulation.

In ABGs, laser interferometers most commonly use helium–neon frequency-stabilized lasers at a wavelength of 633 nm (red region of the visible spectrum) and, more recently, solid-state lasers at a wavelength of 532 nm (for example, see Orlov and Vitushkin 2010).

Solid-state lasers have the following advantages:

(a) a shorter wavelength (which improves the measurement resolution, since the wavelength sets the displacement measurement scale increment: the smaller the increment (scale division), the greater the resolution);
(b) a higher radiation power (which also increases the resolution when measuring displacements due to an increase in the signal-to-noise ratio of the interference signal);
(c) a lower level of frequency noise, i.e., greater frequency stability at short time intervals (which is important when measuring an interference signal with a rapidly changing frequency).

For example, when measuring the free-fall path of a test body with a length of 10 cm (as in the gravimeter described in Vitushkin and Orlov 2014), the path length measuring uncertainty should not exceed 0.1 nm to provide a relative uncertainty of 10^{-9} when measuring the FFA.

In ABGs with an MTB, various versions of two-beam laser interferometers are commonly used (in particular, see Vitushkin et al. 2012). There is also a known case of using a multibeam interferometer in an ABG (Canuteson and Zumberge 1996).

In two-beam interferometers, the length of one of the arms (referred to as the reference arm) is constant; the length of the other measuring arm changes with the motion of the reflector attached to the falling test body. The test body motion is measured with respect to any element in the optical layout (Vitushkin et al. 2012) which represents the origin of a quasi-inertial coordinate system. Such a reference reflector is usually suspended using a passive (usually a long-period seismometer) or active (Niebauer et al. 1994, 1995) vibration isolation system to reduce undesirable vibrations caused by microseismic vibrations of the base.

Over a relatively short time while the test body is falling (tenths of a second), the IF recording system of a laser interferometer records hundreds of thousands of IFs. For example, in the ABG-VNIIM-1 gravimeter, about 350 thousand IFs are recorded within 0.1 s, each of which corresponds to a test body displacement for half the wavelength $\lambda = 532$ nm of the laser radiation $Nd{:}YVO_4/KTP/I_2$ of the laser.

This number of fringes is recorded in groups of scaled fringes (for example, 1024 IFs each) and, together with the recorded time intervals, they are used to calculate the measured FFA value using the least-squares method (LSM). Thus, hundreds of data pairs are used in the calculations with the use of the LSM.

Along with laser-interferometric ABGs with MTBs containing built-in optical reflectors, cold-atom ABGs (Bordé 2002; Peters et al. 2001; Merlet et al. 2009; Gillot et al. 2014) using matter wave interferometry (de Broglie wave interferometry) were developed. The latter are discussed in detail in Sect. 5.3. Cold, i.e. slowed by laser pulses, cesium or rubidium atoms controlled by laser pulses, when absorbing or emitting photons, split or merge while forming equivalents of beam splitters of a classical interferometer, where atomic waves are split or recombine. When propagating in the gravitational field in two arms of an atomic interferometer, atomic waves in one of the arms of the interferometer gain an additional phase shift proportional to the FFA value and the propagation time squared. The interference fringes of such an interferometer can be recorded by measuring the relative population of the states of two recombined atomic beams using induced laser fluorescence.

1.1.2 Sources of Uncertainties and Corrections in Measurements with Absolute Ballistic Gravimeters

When calculating the FFA from measured pairs of path and time intervals, instrumental and geophysical corrections to the measurement results (common to almost all designs of such ABGs) should be introduced in ABGs with an MTB.

Instrumental corrections currently known and common to all types of ABGs include corrections for the following factors:

- deceleration of the test body by residual gases in the vacuum chamber;
- interaction of the falling test body with the gravitational field of the ABG itself;
- interaction of the falling test body with the gradient of the geomagnetic field and the magnetic field of the ion pump (if used in the design);
- effects associated with the finite speed of light;
- diffraction effects during the propagation of a laser beam in the interferometer.

Geophysical corrections are made for the Earth's gravitational tides, the oceanic load and the motion of the Earth's poles.

The following components are taken into account when calculating the total instrumental uncertainty of an ABG:

- uncertainty of the wavelength (frequency) of laser radiation;
- uncertainty of the frequency of the reference rubidium oscillator for the path and time interval measuring system;
- uncertainty due to the choice of the initial and final reference interval of the path from the array of all measured intervals for calculating the FFA using the LSM method;

- uncertainty due to phase delays in electronics;
- uncertainty of the reference height, for which the FFA value is measured;
- uncertainty of the laser beam verticality in the measuring arm of the interferometer;
- uncertainty due to atmospheric pressure variations when determining the correction for the deviation from the nominal value of atmospheric pressure at a gravimetric site;
- uncertainties in the calculation of the above instrumental corrections.

In rise-and-fall ABGs, the influence of such sources of uncertainty as resistance of the residual gas is significantly reduced, and this was used in the initial development of gravimeters when it was impossible to achieve a sufficient degree of vacuum. Later, when ABGs were developed, asymmetric trajectory designs were used, which made it possible to avoid the recoil effect when the test body was thrown up with special catapults.

As examples, we note that the extended (i.e., ensuring a given interval of values with a probability of 95%) total instrumental uncertainty of the ABG-VNIIM-1 gravimeter (Vitushkin and Orlov 2014) and the value of uncertainty reported on the company website for the FG5 gravimeter manufactured by Micro-g LaCoste, Inc., do not exceed 2 μGal. The experimental standard deviation of the measurement result depends on the microseismic conditions at the gravimetric site.

1.1.3 Metrological Assurance of Absolute Gravimeters

ABGs measure the free-fall acceleration. Acceleration is a derivative physical quantity; and an absolute gravimeter should be basically supplied with units of length and time in the respective measurement ranges, which can be done by calibrating the interferometer of the gravimeter with respect to the displacement and the frequency of the laser and the reference frequency oscillator.

In practice, a displacement laser interferometer integrated into an ABG is not calibrated in terms of length unit, like ordinary industrial displacement laser interferometers. Designs of gravimeters with laser interferometers that take measurements in vacuum are not suitable for direct calibration of these interferometers.

The interferometer laser is normally calibrated by frequency (wavelength). However, a unit of length is realized with a laser interferometer rather than with a laser, which is only a source of radiation for the interferometer and generates an infinite traveling electromagnetic wave. Without going into details, it is only worth mentioning that without additional elements (mirrors, photodetectors, etc.), such a wave cannot realize a unit of length in accordance with its definition, i.e. indicate two material points in space between which there is a unit of length or a part of it or two successive positions of a material point as it moves, similar to what, for example, occurs in a gravimeter interferometer that measures the motion of a falling reflector.

As for the calibration of the time interval measurement system, in practice, only the rubidium frequency generator (the reference oscillator for the time interval measurement system) is calibrated by frequency. Such calibration confirms the required level of 5×10^{-10} of the rubidium generator relative frequency uncertainty but not in the entire frequency range of interest. This calibration is normally done at time intervals of tens of minutes, and the question of the metrological characteristics of the measurement system for small (millisecond and microsecond) time intervals for the passage of the above reference path intervals remains open.

Calibration of the laser frequency (wavelength) and the rubidium oscillator frequency is necessary but not sufficient to determine the metrological characteristics of an ABG.

Thus, to determine the metrological characteristics of an ABG when measuring the FFA, it is required to calibrate or verify ABGs using standards in gravimetry as in the case of any other measuring instruments.

ABGs, as well as gravimetric sites and gravimetric networks can be standards in gravimetry. In this case, the FFA values at gravimetric sites and in gravimetric networks should be measured in advance. In some cases, the FFA values at gravimetric sites and in gravimetric networks vary with time as they experience non-tidal changes in the gravitational field.

ABGs, which are, in fact, the measurement standards of the acceleration unit in gravimetry, have the highest metrological characteristics.

Note that a gravimetric site is referred to as the “gravity standard” and an ABG as the “measurement standard in gravimetry” (Vitushkin 2011).

The ABG with the studied metrological characteristics belonging to a National Metrological Institute (NMI) is the officially recognized national primary standard. It is these standards that are involved in the international ABG comparisons organized by the International Committee of Weights and Measures (CIPM) or regional metrological organizations (RMO).

In the Russian Federation, the national primary special standard for the acceleration unit in gravimetry GET190-2011 was created and is used in D. I. Mendeleev All-Russian Research Institute for Metrology (Vitushkin, Orlov 2014).

1.1.4 International Comparisons of Absolute Gravimeters

The first international comparisons of absolute gravimeters were organized following the Recommendation adopted at the XVII General Assembly of the International Union of Geodesy and Geophysics in Canberra (December 1979).

Comparisons of six ABGs built by the International Bureau of Weights and Measures (BIPM), as well as in China, Japan, Russia, and the USA, were organized by the BIPM and the President of Special Research Group 3.40 of the International Association of Geodesy (IAG), associate member of the USSR Academy of Science, Yu. D. Boulanger and conducted in Sèvres (France) in 1980–1981.

Later on, such comparisons were carried out by the BIPM almost every four years. A total of 22 absolute gravimeters were used during the 8th International Comparison of Absolute Gravimeters (ICAG) in 2009.

The organization of ICAGs was improving in the course of time; a technical protocol describing the order of their organization, admission criteria for instruments to participate in comparisons, the procedure for measuring and processing their results, as well as the rules for publishing the results of comparisons were developed and refined. Since 2001, ICAGs have been conducted in accordance with the rules for the organization of comparisons recommended by the international Mutual Recognition Arrangement (MRA) for calibration certificates and measurement results signed by 101 national metrology institutes and organizations responsible for the metrological assurance of any kinds of measurement.

Until 2009, almost all organizations that had ABGs were allowed to participate in the ICAG, and the results of measurements with all gravimeters were used in calculating the result of comparisons (the average FFA values obtained with all gravimeters at gravimetric sites where measurements were taken, the uncertainties of those average values, as well as the degree of equivalence of the gravimeters used which was measured by their deviations from the average values obtained by all gravimeters).

More than 90% of ABGs used in the world are commercial; all of them are produced by one company in the USA. These gravimeters do not have any calibration certificates; therefore, the organizations that had them sought to take part in the ICAG, as well as in comparisons organized in the underground laboratory in Walferdange (Luxembourg) (Jiang et al. 2012) in order to determine metrological characteristics of their instruments.

Due to the increase in the number of ABGs in the world, it will be almost impossible to conduct their simultaneous comparisons in one laboratory in the future; therefore, it is necessary to use a conventional practice in metrology: to recognize national standards and arrange calibrations of ABGs. It should be noted that such a system in the field of absolute gravimetry has not been organized until recently.

In 2009, ICAGs were organized as key comparisons according to the MRA rules (see CIPM MRA-D-05 “Measurement Comparisons in CIPM MRA” at http://www.bipm.org/en/cipm-mra/cipm-mra-documents/), according to which only gravimeters belonging to the NMI are allowed to be compared. As an exception, comparisons of ABGs from other organizations were carried out as pilot studies in parallel with the key comparisons in the BIPM. Meanwhile, only the results of 11 NMI gravimeters were used when calculating the official results of comparisons. These results were published in the official key comparison database on the BIPM website (http://www.kcdb.bipm.org).

The results of pilot studies can be published in scientific journals, but they cannot serve as grounds for issuing calibration certificates. All the results of the ICAG 2009 were published in Jiang et al. (2012).

The increasing IAG requirements for the reliability of absolute measurements of the gravitational field led to the development and adoption of the “Strategy of the Consultative Committee for Mass and Related Quantities and IAG in Metrology in

Absolute Gravimetry" (published in IAG Proceedings of the 2011–2015 (Travaux of the IAG 2011–2015)). The purpose of this document is to draw the attention of geodetic and geophysical communities to the need to develop a system of metrological assurance for absolute gravimeters according to the classical hierarchical procedure with primary standards, calibrations and verifications of ABGs. Various ABG calibration procedures are considered: direct comparison with the primary ABG standard or by measuring the FFA using the gravimeter being calibrated at a gravimetric site where the FFA value was previously measured using the ABG standard, and comparing the measurements using the gravimeter being calibrated with the result obtained with the ABG standard. The highest reliability of this calibration method for the previously measured FFA value can be ensured by continuous monitoring of the FFA time variations using an additional gravitational field measurement tool—a relative superconducting gravimeter (SG) (see an example of using a cryogenic gravimeter during ABG comparisons in Francis et al. 2014). Relative SGs allow for continuous measurements of variations in the gravitational field with a resolution of one hundredth of a microgal over many months and years. SGs are used to measure time variations of the FFA.

1.1.5 Comparisons of Absolute Gravimeters: The Results

A clear understanding of metrological characteristics of modern ABGs is provided by the results of key comparisons organized by the CIPM and key regional comparisons organized by RMOs (EURAMET—Europe RMO, NORAMET—North America RMO, APMP—Asia–Pacific RMO, etc.). The results of the 2009 key ABG comparisons (BIPM) and the 2013 key comparisons (Walferdange), as well as the results of the 2013 key European comparisons (Walferdange) will be presented here.

It should be noted that after ICAG-2009, the BIPM decided to stop the organization of comparisons of absolute gravimeters in the bureau itself because the procedure for organizing comparisons had been well-elaborated and they could now be organized by other NMIs. In 2013, the key ABG comparisons organized by CIPM along with ABG pilot studies took place in the underground laboratory in Walferdange. Comparisons were also held in China in the laboratory of the National Metrology Institute in the Changping campus in 2017.

Figure 1.2 presents the results of key comparisons of CCM.G-K1 ABGs (Jiang et al. 2012; Arias et al. 2012). Note that the reports of all key comparisons are available online in the key comparison database on the BIPM website.

Figure 1.3 shows the results of the key comparisons of CCM.G-K2 ABGs (Francis et al. 2015). Figure 1.4 shows the results of the key European comparisons of ABGs conducted under the authority of the regional metrological organization EURAMET (Francis et al. 2014).

In all the figures, the uncertainty bars represent the extended total uncertainty of each result.

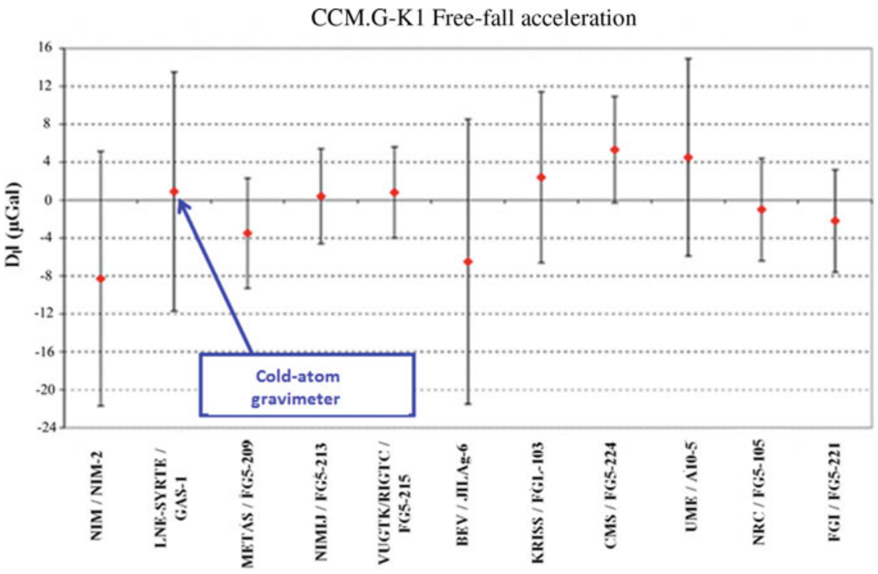

Fig. 1.2 The results of the key comparisons of CCM.G-K1 absolute gravimeters (2009, BIPM, Sèvres, France). The vertical axis shows the deviations from the key comparison reference value (in microgals) for the result of each gravimeter; the horizontal axis shows the type and number of the gravimeter and the organization to which it belongs

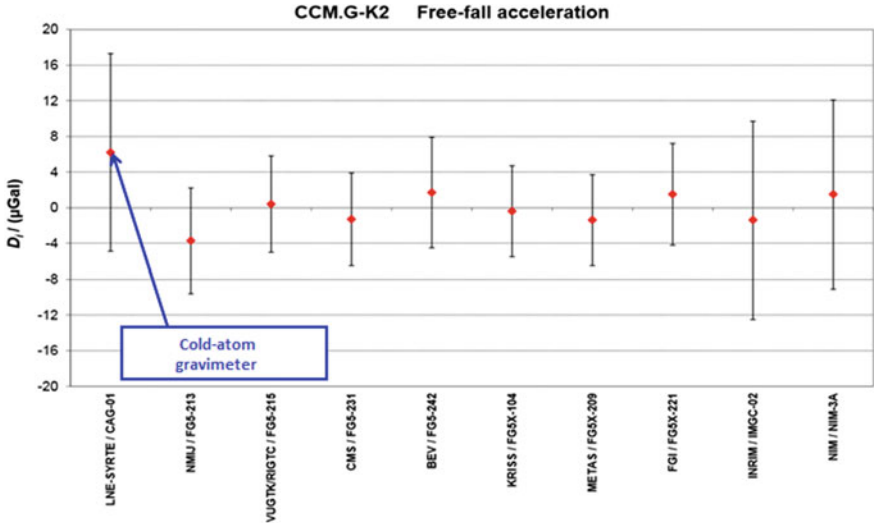

Fig. 1.3 The results of the key comparisons of CCM.G-K2 absolute gravimeters (2013, Walferdange, Luxembourg). The vertical axis shows the deviations from the key comparison reference value in microgals for the result of each gravimeter; the horizontal axis shows the type and number of the gravimeter and the organization to which it belongs

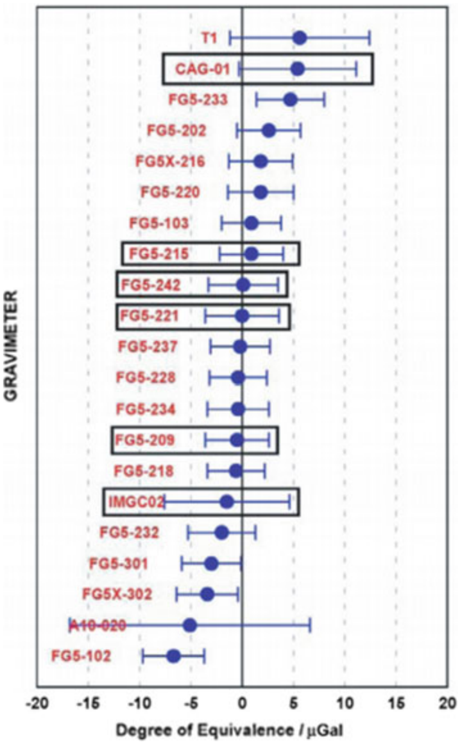

Fig. 1.4 The results of the regional European comparisons of ECAG-2011 absolute gravimeters (2011, Walferdange, Luxembourg). The vertical axis shows the type and number of the gravimeter; the horizontal axis shows the degree of equivalence of the results of each gravimeter in microgals with the reference value of comparisons. The names of the NMI gravimeters used in the key comparisons are shown in frames. The remaining gravimeters were used in pilot studies as part of the general comparison campaign

As can be seen from the figures, the comparisons were carried out mainly for FG5 and A10 gravimeters, both manufactured by Micro-g LaCoste, Inc. There were only three gravimeters from other organizations: the IMGC gravimeter (Italy), the CAG-1 cold atom gravimeter (France), and the T1 gravimeter (China).

Note that the uncertainty of FFA measurements with the use of a cold-atom gravimeter is currently slightly greater than the uncertainty of the best laser-interferometric ABGs with MTB. The A10 gravimeter is designed for field measurements and has a greater uncertainty than the FG5-type gravimeters.

1.1.6 Practical Applications of Absolute Free-Fall Acceleration Measurements

Currently, at least two hundred transportable ABGs are used in the world. Most of them were manufactured by Micro-g LaCoste, Inc.

ABG allows measuring the FFA in any place with no reference to any sites of gravimetric networks. Of course, the accuracy of measurements depends on the level of microseismic conditions at the gravimetric site which determines the random component of the uncertainty.

The emergence of a significant number of such ABGs allowed changing the measuring strategy of gravimetric networks and their use (for example, see Boedecker 2002).

Transportable ABGs made it possible not only to measure the FFA at different gravimetric sites when creating gravimetric networks, but also take repeated measurements to monitor temporal variations of the gravitational field.

The combination of an ABG and an SG allows for almost continuous monitoring of the gravitational field. Starting in 1997, about 30 gravimetric sites on Earth, including the Antarctic Syowa station, conducted monitoring of the gravitational field variations using an ABG and an SG in the framework of the IAG International Global Geodynamic Project. This project has currently been reformed into the permanent IAG IGETS service and continues developing.

Transportable ABGs are used, for example, in hydrogeology for prospecting and monitoring of water reserves, as well as in engineering geology.

Studies are conducted on the possibility of using laser-interferometric ABGs and cold-atom ABGs on moving bases in airborne and marine gravimetry (Baumann et al. 2012; Sokolov et al. 2017).

The concept of joint use of absolute and relative gravimeters installed on a gyro-stabilized platform for marine gravimetry was proposed in the early 2000s. It is not necessary to conduct continuous FFA measurement using ABGs. ABGs can be used for periodic calibration of relative gravimeters when the vessel stops at a pier or on a calm sea. It should be noted that an eccentric-type gravimeter with a short free-fall path of the test body of about 2 cm allowing for 200 drops per minute can be successfully used in airborne and marine gravimetry (Vitouchkine and Faller 2002).

1.1.7 Conclusions

Ground-based absolute gravimetry is finding increasing use for national and international projects in modern geodesy such as the Global Geodetic Observing System of the International Association of Geodesy.

In international comparisons of absolute gravimeters, the uncertainties in measuring absolute FFA values may not exceed 1 μGal at gravimetric sites where many ABGs are compared and a great number of measurement series are carried out (for example, more than 60 12-h series of measurements at 5 gravimetric stations of a gravimetric site in comparisons in BIPM in 2009 (Jiang et al. 2012)). The FFA values and their uncertainties obtained in such comparisons are most reliable. This circumstance, as well as the increasing number of absolute gravimeters, the development of their metrological assurance system, and the distribution of comparisons to other continents (North America, Asia) provided the basis for creating a new global system of absolute gravimetric sites outlined, in particular, in Crossley et al. (2013).

Key comparisons of gravimeters were carried out in Europe; regional comparisons of gravimeters were carried out in North America and China. Gravimetric sites where comparisons are made will be used as the basis for a new global system.

In 2015, the International Association of Geodesy held the 26th General Assembly of the International Union of Geodesy and Geophysics in Prague, where they adopted Resolution 2 "For the Establishment of a Global Absolute Gravity Reference System", specifying the FFA value measurement uncertainty not higher than 10 μGal for the reference sites of the system, i.e., 10 times less than in the IGSN-1971 system.

The development of absolute gravimetry in the Russian Federation requires the development of new ABGs, including field gravimeters and ABGs adapted to measurements on moving bases.

Both types of absolute gravimeters—MTB laser interferometer gravimeters and cold-atom gravimeters—will certainly find their applications; besides, they can be improved to reduce their overall dimensions, increase their reliability and reduce their measurement uncertainty.

1.2 Chekan-Series Relative Gravimeters

For more than 50 years, Concern CSRI Elektropribor has been working on creation of gravimetric systems for measuring gravity from moving carriers. This work started in 1967 with the creation of GAL-M, a gravimeter with a photo-recording system, at the Schmidt Institute of Physics of the Earth under supervision of E.I. Popov. At the same time, the Cheta gyro platform was developed at CSRI Elektropribor for stabilization of this gravimeter on surface ships (Popov 1959). On the basis of these developments, the MGF gravimeter was created and adopted for the Navy supply by order of the Navigation and Oceanography Department of the Russian Ministry of Defense. That was the first Russian gravimetric system intended for marine gravity surveys in the open ocean in 1970–1980.

Cheta-AGG, the first automated marine gravimetric system (chief designer A.D. Bereza) with a specialized digital computer, was created by order of the Navy in 1982 and was produced in series (Zheleznyak and Popov 1982). This system was installed on more than ten research vessels. For many years, it was the main means of route and areal gravity surveys and was used until the beginning of the twenty-first century both on Navy ships and on civilian vessels. Under the World Gravity Survey Program, the Cheta-AGG system was used to take a large amount of measurements in the Atlantic, Indian, and Pacific Oceans, the Black and Barents Seas (Zheleznyak et al. 1983).

The development of the Skalkochnik, the third-generation system (chief designer L.P. Nesenyuk (Pamyati professora L.P. Nesenyuka 2010)), was aimed at improving the performance characteristics through the use of the latest computing aids of the day. It was the first to use a personal computer both for data acquisition and office processing of marine survey results. In 1994, the system passed the Navy tests and was put into operation. Unfortunately, the difficult economic situation in the country at the end of the twentieth century did not allow for full-scale production of the

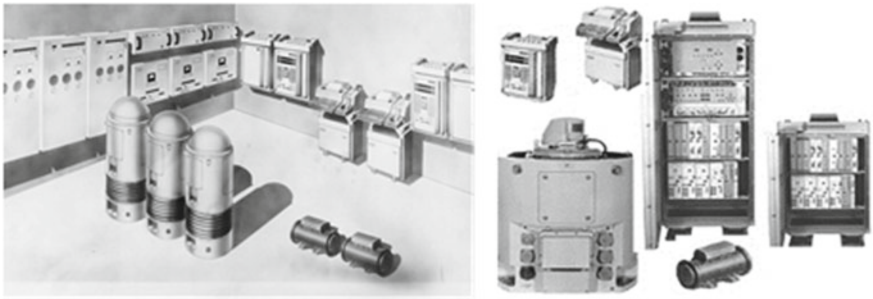

Fig. 1.5 General view of the second- and third-generation systems

Skalochnik system. Only a prototype model was made which was upgraded in 2001 and used by the Navy hydrographic service until 2006 (Nesenyuk and Elinson 1995; Bikeeva et al. 2007). A general view of the Cheta-AGG and Skalochnik systems is shown in Fig. 1.5.

The work on the construction of the fourth-generation system began in the late 1990s, when the Chekan-A prototype system was made in 1998 and its marine tests were carried out in 1999 combined with a commercial marine geophysical survey conducted by the Norwegian company NOPEC (Sokolov et al. 2000). The success in the accomplishment of this work allowed CSRI Elektropribor to fulfill the research on design and development of a mobile gravimeter (chief designer L.S.Elinson). As a result, the fourth-generation Chekan-AM system was developed in 2001 (Sokolov 2003).

Today, the Chekan-AM mobile gravimeter is one of the main instruments used to measure gravity from sea vessels and aircraft (Kovrizhnykh and Shagirov 2013; Atakov et al. 2010; Lygin 2010; Forsberg et al. 2013; Barthelmes et al. 2013; Peshekhonov et al. 2020). More than 50 gravimeters have been manufactured at CSRI Elektropribor and delivered to Russian and international organizations. Table 1.1 shows how the global geophysical equipment market has been developing: from marine surveys abroad to airborne gravity surveys in Russia.

The geography of the gravity surveys carried out with the Chekan-AM mobile gravimeter shown in Fig. 1.6 covers the waters of all oceans and shelf zones in all continents. Chekan-AM has been used in geophysical surveys from the Antarctic to the North Pole (Krasnov et al. 2014a).

In 2013, a new system Shelf-E was developed (chief designer A.V. Sokolov) on the basis of the Chekan-AM mobile gravimeter (Krasnov et al. 2014b). The system has improved accuracy and performance characteristics. Its serial production started in 2015, so that these systems are supposed to replace Chekan-AM mobile gravimeters in the near future. This chapter is devoted to the description of the principle of operation, design features, and technical characteristics of the Chekan-AM and Shelf-E systems.

Table 1.1 Development of the global geophysical equipment market

Country	Years in operation
Marine gravity surveys	
Norway	1999 up to the present
Great Britain	2003–2012
Russia	2005 up to the present
China	2007 up to the present
USA	2008 up to the present
Kazakhstan	2010–2011
Airborne gravity surveys	
Germany	2007 up to the present
Norway	2007–2011
Russia	2007 up to the present

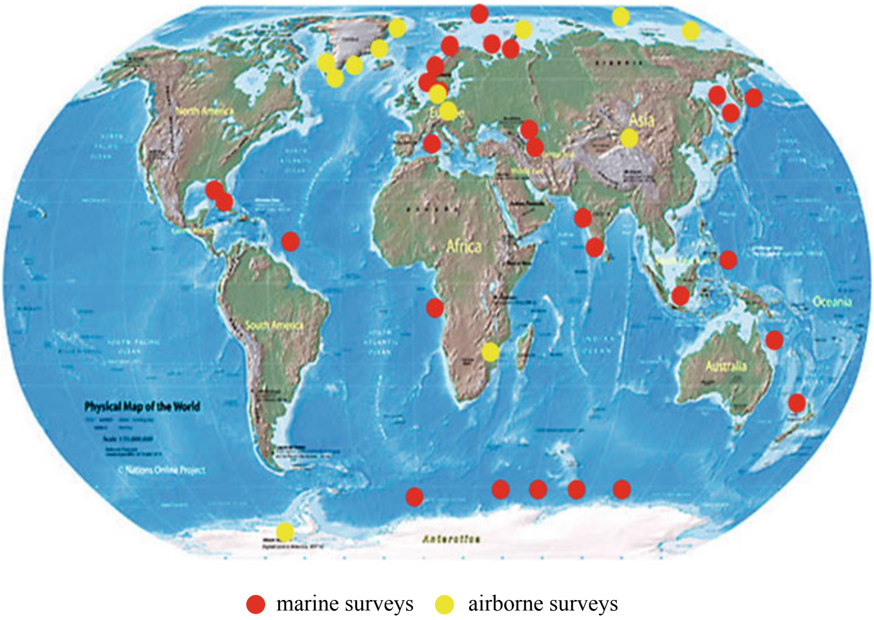

Fig. 1.6 Geography of the gravity surveys carried out with the Chekan-AM mobile gravimeter

1.2.1 Gravimeter Parts

The main distinction of the Chekan-AM mobile gravimeter from the systems of previous generations is its higher accuracy and performance characteristics along with a multifold decrease in its weight and overall dimensions (Blazhnov et al. 2002). The development of electronic components made it possible to combine the