Measurement of Absolute Gravity and Deflections of the Vertical at Sea

A. V. Sokolov, A. A. Krasnov, N. V. Kuz’mina, and Yu. F. Stus’

Abstract

Methods to measure absolute gravity and deflections of the vertical on a moving base are presented. The breadboard of integrated gravimetric system is described. The first results of experimental studies confirmed the possibility of high-precision measurement of the absolute values of gravity and deflection of the vertical at sea.

Keywords

Absolute gravity · Deflections of the vertical · Gravity measurements · Integrated gravimetric system

1 Introduction

Knowledge of absolute values of gravity and deflection of the vertical (DOV) is essential for solving a number of problems in geodesy, high-precision inertial navigation and fundamental position, navigation and time support. In water areas, the absolute values of gravity are calculated as a sum of the gravity a priori value measured at an onshore reference station, and of the observed gravity measured with relative gravimeters from marine and air vehicles. The errors in determining the drift and scale of relative gravimeters reduce the accuracy of determining the absolute values of gravity, and the necessity to regularly reference the results of offshore measurements to the onshore absolute value imposes serious operational limitations on the gravity survey procedure. In view of the fact that the geological exploration tasks require only the knowledge of character of gravity anomalies in the survey area, most of modern geophysical works are carried out without precise referencing of measurements to the reference stations, which considerably increases the error of absolute values of gravity measured in water areas.

There is a known technique for the relative gravimeters’ measurements re-calculation to the absolute level, using the global geopotential models (Zheleznyak et al. 2015). However, limited spatial resolution of the global models, as well as their significant errors in the areas with high gravity anomalies can make it impossible to precisely determine the absolute values of gravity using the above technique. At present, there are no commercial devices for measuring the absolute value of gravity from moving vehicles. A number of companies are currently studying and developing such devices (Bidel et al. 2018; Baumann et al. 2012).

Integrating the gravity anomalies according to Vening-Meinesz formulae has been the main method of high-precision determining of DOV in water areas for as long as 100 years (Vening-Meinesz 1928). However, this method is extremely labor-consuming, since it requires accumulation of background gravimetric data for an area that is much larger than the point specified for determining the DOV. Moreover, the error of the absolute value of gravity discussed above is a methodological error of the DOV calculating according to Vening-Meinesz formulae. Also it should be noted that the existing methods of space geodesy do not provide the DOV precisely enough, especially in regions with large gravity anomalies (Koneshov et al. 2013).

A design concept of an integrated gravimetric system for measuring the absolute gravity on a moving base, and

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the first results of its bench tests were discussed at the Symposium TGSMM-2016 (Peshekhonov et al. 2016). Such system is useful to improve accuracy of gravity surveys that were carried out without reference measurements. Further development of the concept resulted in the integrated system construction and incorporation in the equipment for the DOV direct measurement by astrogeodetic method at sea which is essential in inertial navigation (Chatfield 1997).

A breadboard of gyrostabilized zenith telescope was made, and its operation methodology was developed. This paper presents the principles of the integrated system construction, including an absolute gravimeter, a zenith telescope, a system for their gyroscopic stabilization, and receiving equipment of global navigation satellite systems (GNSS). The integrated system is intended for measuring the absolute values of gravity with 1 mGal RMSE and DOV with 1 arcsec RMSE at sea. The system operation methodology is described, and the results of field testing of the system breadboard are discussed.

2 Principles of Measuring the Absolute Values of Gravity and DOV at Sea

Land gravity instruments for high-precision determination of the absolute values of gravity are commercially available and are based on measuring the time and length intervals of a test body fall in vacuum (Vitushkin 2015). Offshore applications of such devices are limited by the effect of inertial accelerations, caused by pitch/roll and orbital motion, on the measuring system of the gravimeter. For this reason, in case of moving vehicles, measurements are taken using relative gravimeters with a gyroscopic system for the sensitive element stabilization in the horizon plane. At the same time, the influence of the vertical component of inertial acceleration is compensated by low-frequency filtering methods involving the external navigation data (Stepanov and Koshaev 2010).

Obviously, absolute measurement of gravity at sea requires the sensitive axis of the absolute gravimeter to be stabilized in the direction of the local vertical with an accuracy of about 15 arcsec, in order to remove the effect of horizontal inertial accelerations. However, due to the effect of vertical inertial acceleration on the absolute gravimeter, the vast majority of its measurements are unreliable, and the methods of frequency filtering cannot be used in absence of a model of the test body motion in the field of inertial accelerations. The solution to this problem was found by integration of the initial data of the absolute and relative gravimeters. The idea of data integration is as follows. Based on the relative gravimeter data, current inertial vertical accelerations are determined, and the absolute gravimeter measurements at which the accelerations were minimal are selected. The resulting measurements of the absolute value of gravity are used for compensating for the errors in the relative gravimeter, caused by drift and nonlinearity of the scale, as well as the measurements referencing to the absolute level (Peshekhonov et al. 2016).

Field digital zenith cameras have been developed and widely used for measuring another important geodetic parameter DOV on the ground (Hirt and Bürki 2002; Tian et al. 2014; Halicioglu et al. 2012; Gerstbach and Pichler 2003). They help to implement the astrogeodetic method of DOV absolute measurement based on determining the direction to the stars located at the zenith, with known equatorial coordinates (right ascension α and declination δ). At that, the equivalence of astronomical coordinates (latitude φ, longitude λ) of the observation point and the equatorial coordinates of the stars is used. This equivalence is due to the validity of the following relations (Torge 2001):

$$\varphi = \delta;$$
$$\lambda = \alpha - \theta,$$

where θ is Greenwich apparent sidereal time.The Helmert, or astronomic, DOV are calculated in accordance with the basic expressions (Jekeli 1999):

$$\xi = \phi - B;$$
$$\eta = (\lambda - L)\cos\phi,$$

where ξ is DOV projection on the meridian plane; η is DOV projection on the prime vertical plane; *B, L* are geodetic coordinates of the observation point (latitude and longitude).As with the absolute gravimeter measuring absolute values of gravity at sea, the zenith telescope obviously needs to be stabilized for measuring DOV on a moving vehicle. However, to ensure the DOV measurement accuracy at the level of few seconds of arc, the required precision of stabilization should be comparable. Even on a slightly oscillating base, it is almost impossible to achieve such precision of stabilization by gyroscopic means only. Therefore, the only solution is to stabilize the telescope's sight axis along the normal to the reference ellipsoid rather than in the direction of the local vertical. The above normal is drawn according to the data from two sources: the zenith telescope itself, and the GNSS receiver (Peshekhonov et al. 1995).

A schematic of a gyrostabilized zenith telescope is shown in Fig. 1. Stabilization motors are controlled by the signals of mismatch between the geodetic coordinates and the astronomical coordinates of the crossing point of the zenith telescope's sight axis with the celestial sphere.

A block diagram of the algorithm for determining the DOV components on a moving base is presented in Fig. 2. The objective of near-zenith stars observation is to record a sequence of frames containing images of the stars, using a TV camera, with the frame record time being simultaneously

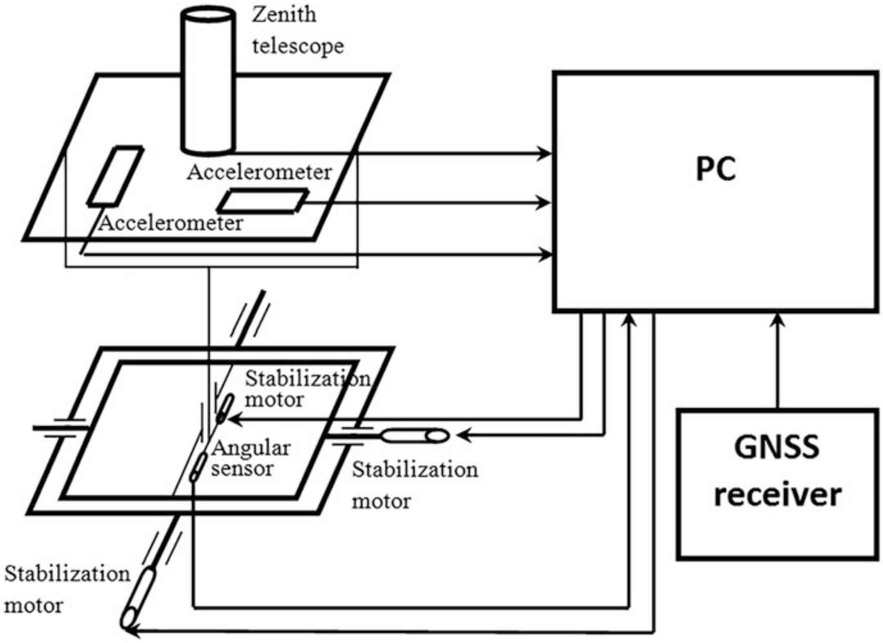

Fig. 1 Schematic of a gyrostabilized zenith telescope

fixed. In each frame, the coordinates of energy centers of the stellar images are determined and then used, along with the star catalog data, for stars identification (Mantsvetov et al. 2006).

As a result of identification, a data set is formed, where the coordinates of stars on the images are matched to the equatorial coordinates of stars from the catalogue. Based on this set, the parameters of transformation between the frame of the TV camera photodetector and the standard frame are calculated; these parameters are used for transforming the coordinates of the photodetector central point into equatorial coordinates and then, taking into account Greenwich apparent sidereal time, into astronomical coordinates. Moreover, the transformation parameters are useful in determining the angle of the photodetector frame rotation relative to the standard frame (azimuth of the TV camera row), which is used for feedback in the azimuth stabilization loop. After that, deviation of the astronomical coordinates of the crossing point of the zenith telescope's axis of sight with the celestial sphere relative to the geodetic vertical is determined. The deviation values are taken into account in the readings of accelerometers, and also used in the stabilization loops. Then linear accelerations are subtracted from the accelerometer readings using GNSS receiver data.

In order to compensate for the tilt of the sight axis relative to the rotation axis of the optronic device, and to prevent the effect of accelerometer bias, observations are carried out in two diametrically opposed positions, with the zenith telescope being turned to 180 degrees. The final values of the DOV components are determined by averaging the accelerometer data obtained in two positions of the zenith telescope.

3 Integrated System Operation Methodology

Combined operation of an absolute gravimeter and a relative one does not suggest any serious changes in the methodology of marine gravity surveys. The gravimeters are placed on a common base onboard a vessel, as close to the vessel's metacenter as possible (Fig. 3). The navigation data, including geographic coordinates, time stamps, and the data from the absolute and relative gravimeters are received to a common laptop which is also used for further post-processing of the data.

The survey starts from taking reference measurements at port, to determine the absolute value of gravity according to the methodology described above, as well as the initial value of the drift of the relative gravimeter. The gravity increments in the survey profiles are measured with the relative gravimeter. If the sea is weak (sea state 0,1,2), it is possible to determine the absolute value of gravity; to do so, the vessel should stay at the specified point of the water area for one to two hours. The survey results are processed in offline mode. Some additional offshore reference points would provide more detailed estimate of the relative gravimeter's drift and reduce the effect of the scale factor error during operations at a significant distance from the reference gravity station.

The zenith telescope is installed on the gyrostabilizer instead of an absolute ballistic gravimeter. In view of the fact that DOV measurements are taken at night and only in case weak sea and clear sky, this circumstance does not impose any significant limitations on the methodology of the integrated system operation during gravity measurements.

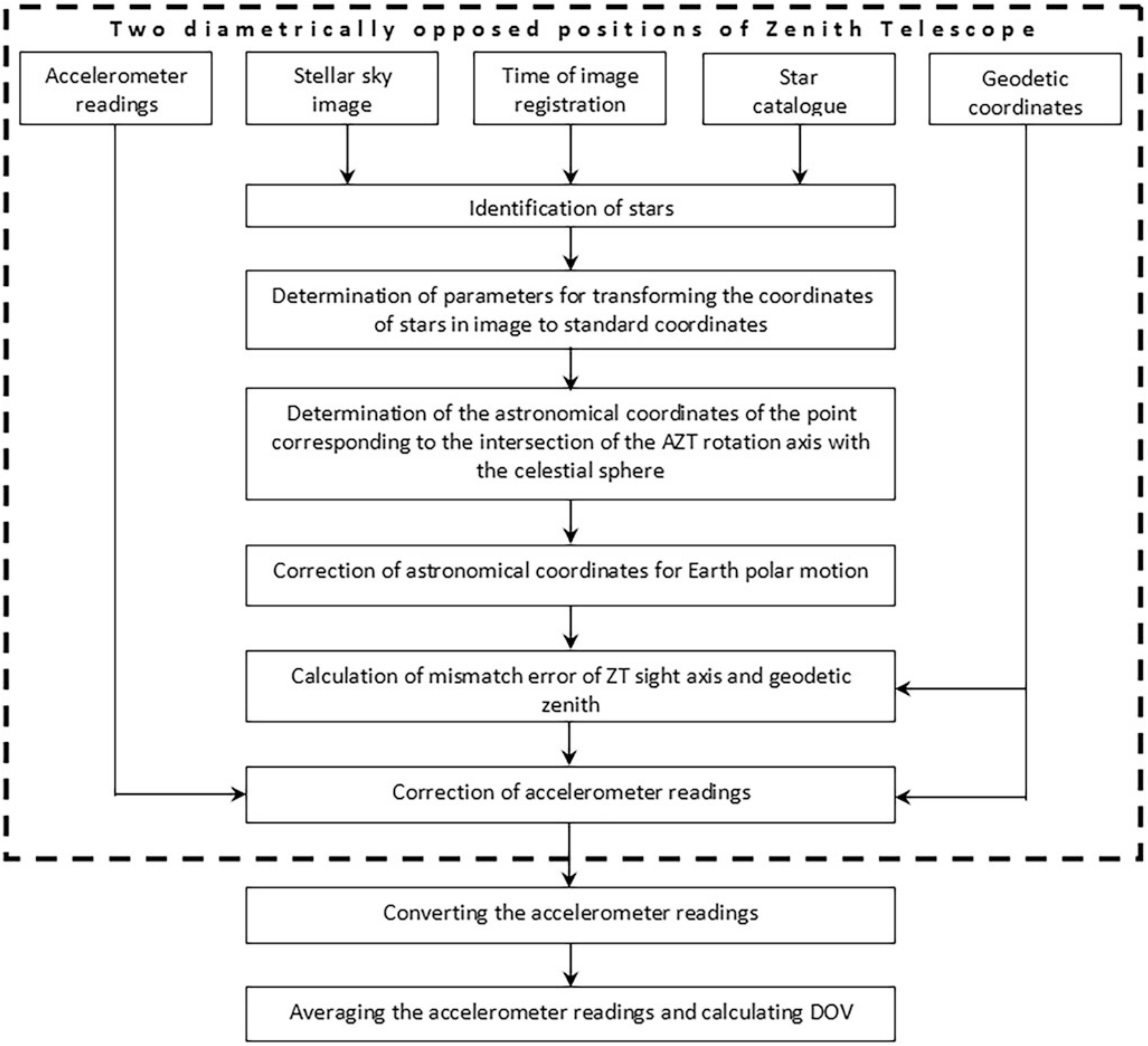

Fig. 2 Block diagram of the algorithm for determining the DOV components on a moving base

4 Integrated System Breadboard

To verify the proposed methods for measuring the absolute values of the gravitational field parameters, a breadboard of the integrated system was assembled and tested. The breadboard composition was based on commercially available equipment.

For continuous measurement of gravity increments, the breadboard included a mobile gravimeter Chekan-AM (Shelf-E model) designed by Concern CSRI Elektropribor, JSC (Krasnov et al. 2014; Evstifeev et al. 2014). This gravimeter is based on a gravity sensor with double quartz elastic system, installed in a two-axis gyrostabilizer. Root-mean-square (RMS) error of gravity increment measurement with the gravimeter Chekan-AM under the action of dynamic disturbances does not exceed 0.4 mGal (Sokolov et al. 2016).

In the breadboard, the absolute value of gravity is measured with a ballistic gravimeter GABL-PM designed for field operation by the Institute of Automation and Electrometry of the Siberian Branch of the RAS (Bunin et al. 2010). RMS error of measurement of the gravity with the gravimeter does not exceed 5 μGal. The dimensions of the gravimeter GABL-PM is 42 × 47 × 93 cm and its weight is 59 kg, which made it possible to install it in the gyrostabilizer commercially manufactured by Concern CSRI Elektropribor,

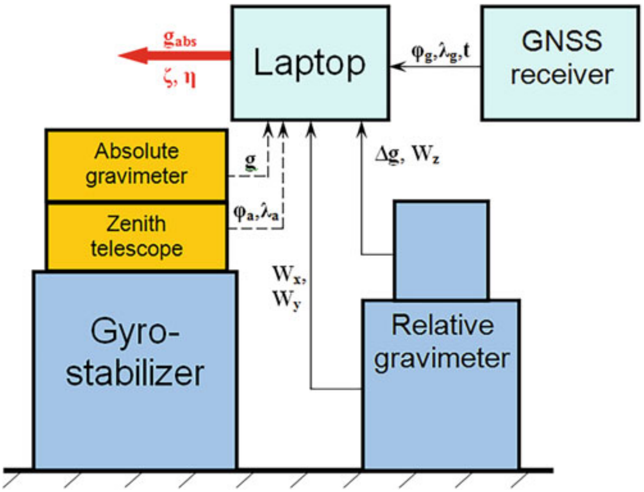

Fig. 3 A schematic of integrated system

JSC. The operating principle and the sensitive elements of this gyrostabilizer are similar to the stabilization system of the gravimeter Chekan-AM, while its weight and size are several times greater, so it could be used for the absolute gravimeter stabilization.

The main elements of the zenith telescope are a catadioptric lens with a focal distance of 2 m, and a specially designed TV camera KT-62 with intrinsic function of automated determination of the coordinates of energy centers on the images of point objects. Such a system of a lens and a camera can determine the position of point objects on the TV camera plane with an accuracy of 1/20 pixel, taking into account the influence of various external factors, which corresponds to 0.1 arcsec. To determine DOV, electronic inclination sensors Zerotronic (accelerometers) with an error of 0.2 arcsec are installed on the zenith telescope base. The error in determination DOV components for such system is less than 0.5″. The zenith telescope has an intrinsic azimuth rotation drive, and due to its configuration it can be installed in the gyrostabilizer instead of the absolute gravimeter.

To determine the geographic coordinates of location and to receive the time stamps, the breadboard included a GNSS receiver Javad of geodetic accuracy grade.

5 Results of the Bench Tests

Bench tests of the gravimetric system breadboard were carried out at the Concern CSRI Elektropribor. The test program included tests on the breadboard system accuracy on a fixed base as well as on dynamic benches of vertical displacements and a sea wave simulator.

The tests of the breadboard instrumental accuracy were carried out on a fixed base during 3 days. The methodology of continuous measurement of the absolute gravity consisted in a series of initial measurements by GABL-PM, continuous measurements of the gravity increments by Chekan-AM, and a series of final measurements by GABL-PM, which were used to refine the drift of the Chekan-AM gravimeter. The measurement results are shown in Fig. 4.

The RMS error of the initial and final measurements taken with the GABL-PM gravimeter was $\sigma_{\mathrm{gabs}} = 0.02$ mGal. After taking into account the drift of the Chekan-AM gravimeter using the GABL-PM gravimeter readings and after the introduction of correction for the lunar-solar tide effects, calculated theoretically, the RMS error of the Chekan-AM gravimeter measurement was $\sigma_{\mathrm{grel}} = 0.03$ mGal. Since the measurements of the gravimeters GABL-PM and Chekan-AM are independent, the instrumental accuracy of continuous measurement of the absolute gravity obtained with the mock-up integrated system can be estimated from the formula:

$$\sigma_{g_{\mathrm{int}}} = \sqrt{\sigma_{g_{abs}}^2 + \sigma_{g_{rel}}^2} = 0.04 mGal.$$

During three nights we put the zenith telescope on the gyrostabilizer and provided measurements outside the test room. The results of DOV measurements are shown in Fig. 5.

Standard deviation of the DOV measurements did not exceed 0.5″. So installation of the zenith telescope on the gyrostabilizer do not affect on the accuracy of the system on the fixed base.

Another aim of the bench tests was to estimate the accuracy of absolute gravity measurements on a weakly oscillating base. We didn't provide dynamic tests of the gyrostabilized zenith telescope because it is impossible to observe stars at the test room.

As can be seen from Fig. 6, the spread in the GABL-PM readings is 200 mGal even with minimum heaving with an amplitude of 0.2 m and a period of 200 s, which additionally confirms the necessity of using both types of gravimeters for occasional determination of absolute gravity aboard a vessel.

The data from the relative gravimeter were used to determine vertical accelerations Wz, which made it possible to choose from a set of discrete gravity measurements of the absolute gravimeter, the measurements that were performed under the best conditions. The criterion for choosing g measurements was the limiting value of vertical accelerations of less than 3 mGal. It took about 2 h to obtain a set of 100 reliable measurements of g at heaving with an amplitude of 0.2 m and a period of 200 s, and the standard deviation of the GABL-PM gravimeter readings was 0.91 mGal. However, as can be seen from Fig. 7, the difference in the mean values of the measurements of the GABL-PM gravimeter before, during and after heaving by modulus was 0.11 mGal,

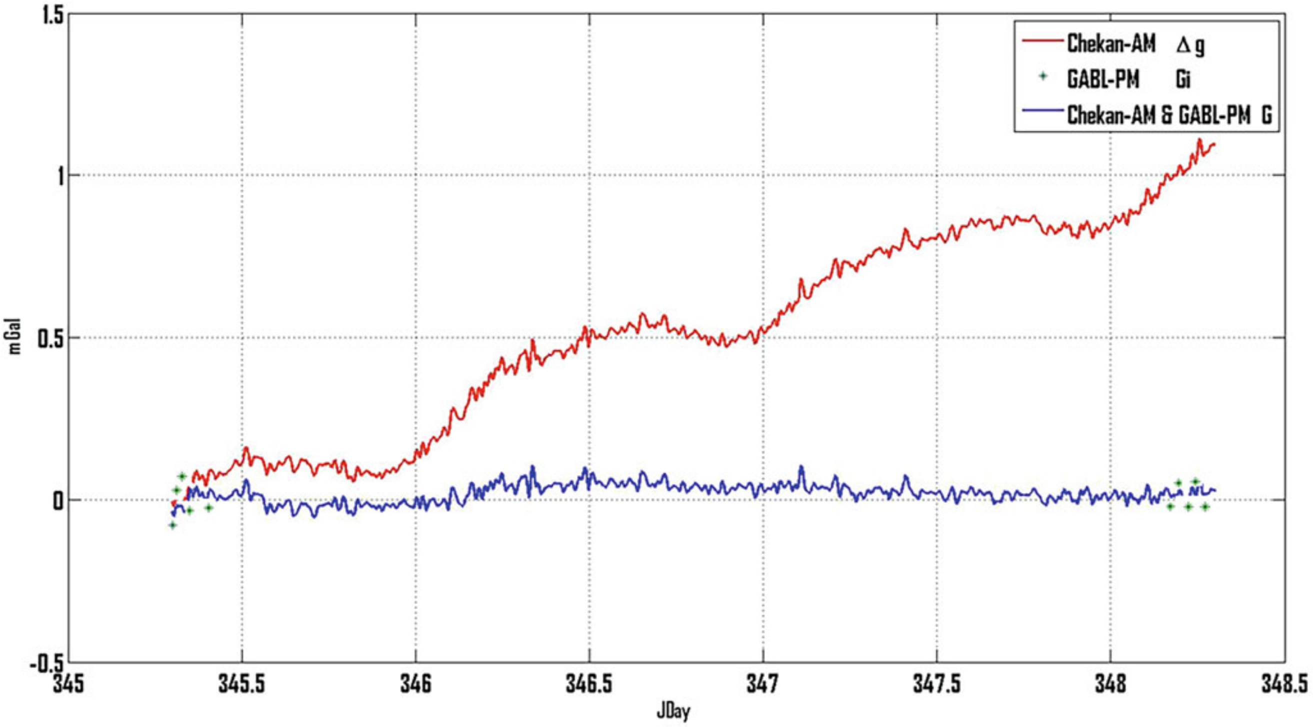

Fig. 4 The results of gravity measurements on a fixed base

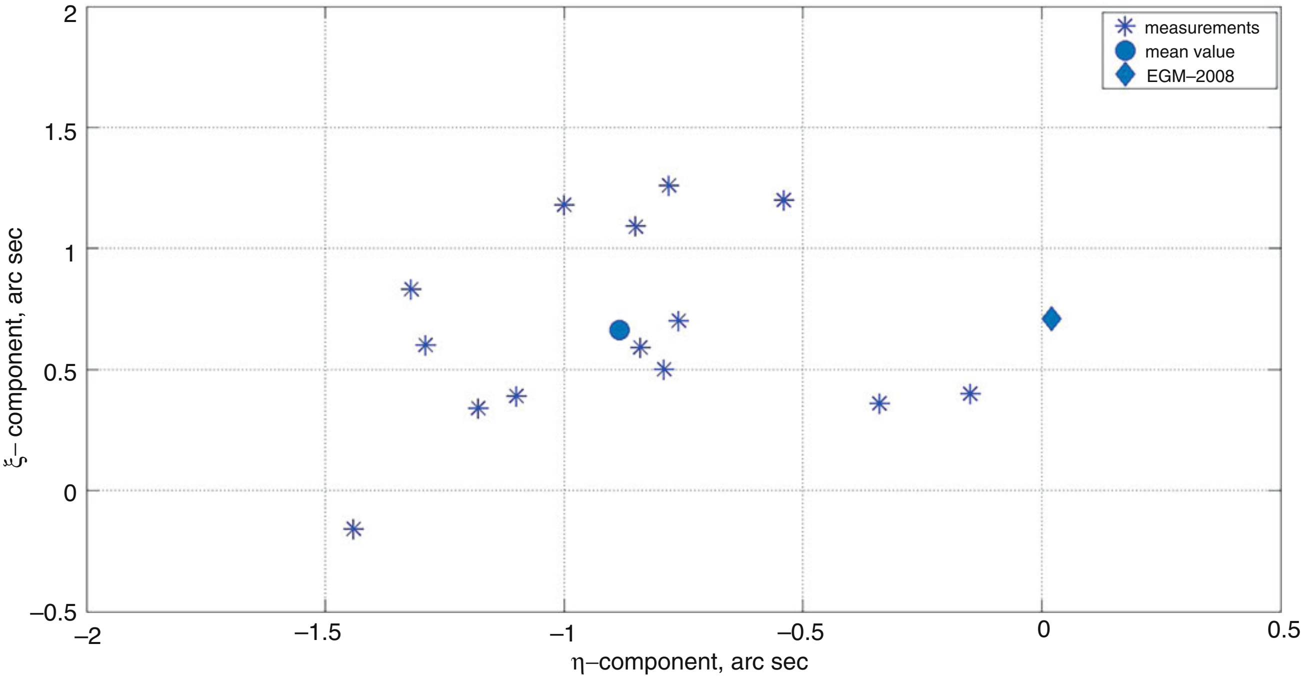

Fig. 5 The results of DOV measurements on a fixed base

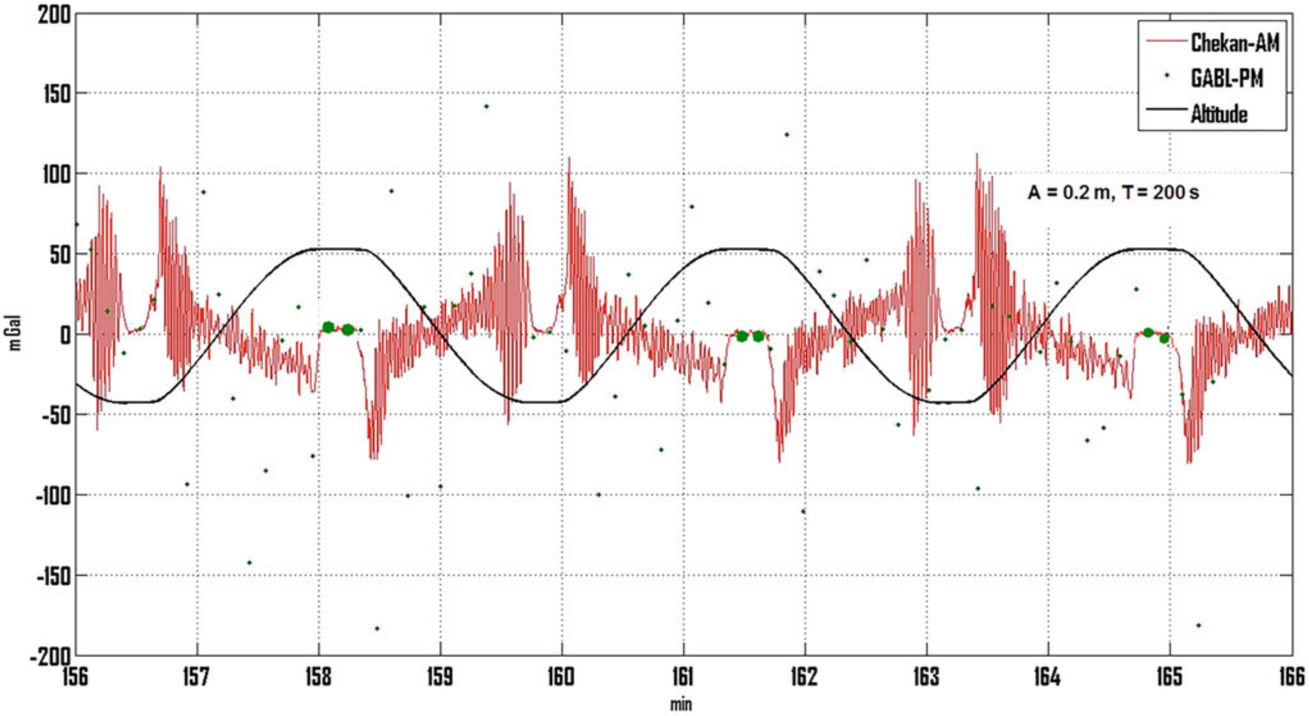

Fig. 6 Measurements of the mock-up gravimetric system on a weakly oscillating base

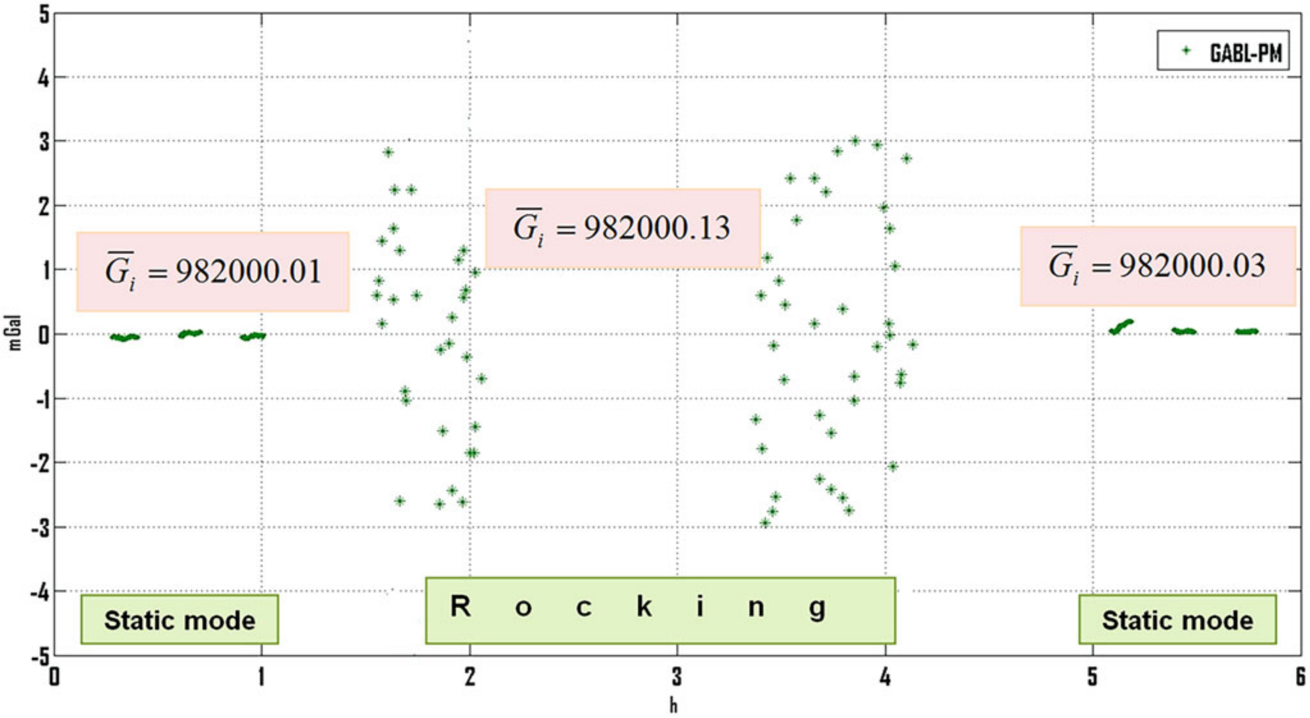

Fig. 7 Measurements results obtained with the absolute gravimeter on a fixed base and a weakly oscillating base

Table 1 Estimation of the breadboard gravimetric system accuracy

		Bench of vertical displacements		Sea-wave simulator	
Test series	Fixed base$\overline{g}$ (σ_g), mGal	Statics$\overline{g}$ (σ_g), mGal	Dynamics$\overline{g}$ (σ_g), mGal	Statics$\overline{g}$ (σ_g), mGal	Dynamics$\overline{g}$ (σ_g), mGal
No. 1	982000.01 (0.04)	982000.02 (0.05)	982000.13 (0.91)	982000.03 (0.05)	982000.11 (0.75)
No. 2	982000.03 (0.04)	982000.01 (0.05)	982000.09 (0.88)	982000.02 (0.05)	982000.12 (0.78)

Fig. 8 System breadboard aboard the vessel

which was the first reliable demonstration of the feasibility of measuring the absolute gravity on a weakly oscillating base.

The final stage of the bench tests was the breadboard testing on the sea-wave simulator, which allows specifying three-component angular motions of a mobile platform with the equipment under test fixed to it. The method for estimating the breadboard accuracy at the sea-wave simulator was identical to that described above for testing at the bench of vertical displacements. The results of two series of mock-up tests on dynamic benches are summarized in Table 1.

From the results of the bench tests it can be seen that imitation of smooth sea waves does not significantly affect the measurements of the absolute gravity with the breadboard gravimetric system. The standard deviation of the heaving measurements was less than 1 mGal, and the difference in the mean values in statics and dynamics did not exceed 0.1 mGal. Based on the positive results of the bench tests, we proceeded to the next stage – the sea trials of the breadboard gravimetric system.

6 Results of the Sea Trials

The system breadboard was tested at Priozersk seaport and in the Ladoga Lake from aboard a vessel with displacement of 120 tons (Fig. 8). The scope of tests included the measurements of the absolute value of gravity and DOV on moored vessel and during the vessel positioning at some points of the water area.

Before installing the absolute gravimeter and the zenith telescope on board, gravity and DOV were measured at the pier on a massive concrete base. These measurements were further used as reference. To account for the difference in altitudes between the location of the gravity measurements on a concrete base and the place where the absolute gravimeter was installed on the vessel, we performed leveling. The difference in the altitudes was 2.1 m. That was taken into account in the further data processing.

The sea tests started from measuring the absolute value of gravity on the vessel moored at the pier. Within 1.5 h, a required data set of 100 reliable measurements taken at the inertial disturbances less than 3 mGal was formed. The difference between the gravity measurements at the pier and aboard the vessel was less than 0.1 mGal (Fig. 9). This result confirmed the possibility of offshore surveys without referencing to onshore gravity stations.

The second stage of the sea tests was verification of gravity measurement accuracy when positioning the vessel at a point of the Ladoga Lake water area. The measurements were taken for 2 h at the sea state 2. The inertial accelerations reached 1.5 Gal, and the vessel pitching/rolling was up to 5°. In spite of significant accelerations (Fig. 10),

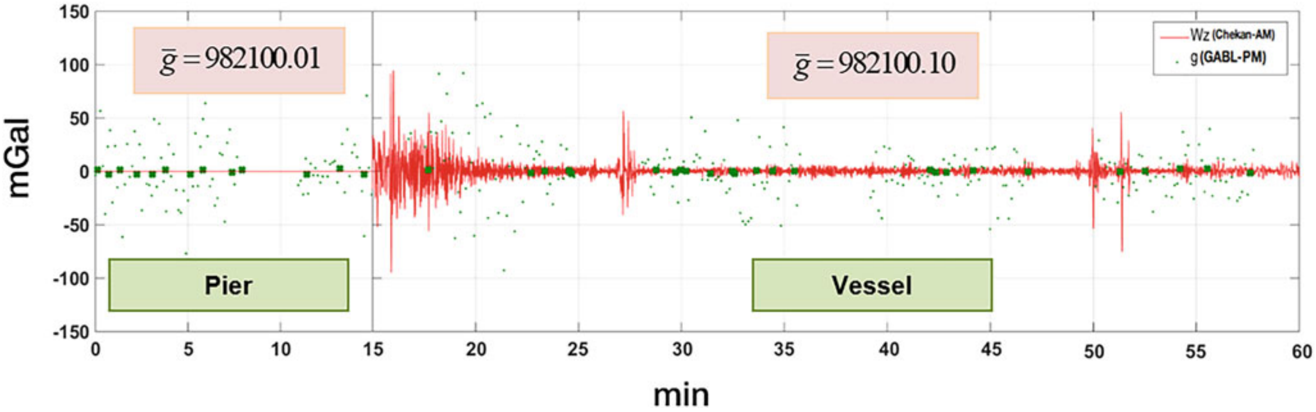

Fig. 9 Breadboard measurements at the pier and aboard the moored vessel

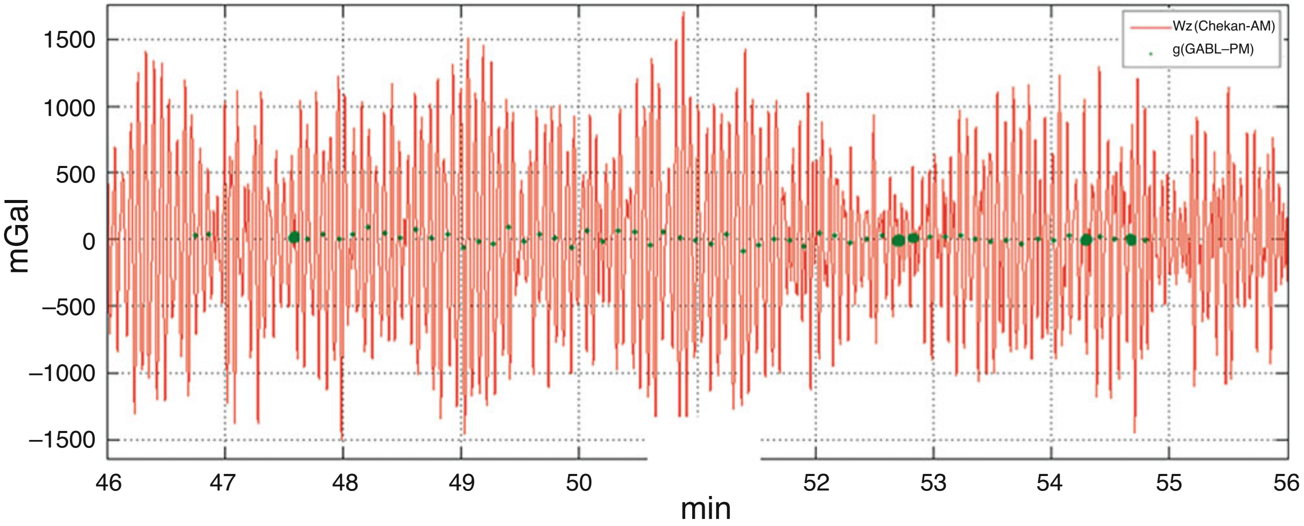

Fig. 10 Gravity measurements at water area point

25 reliable measurements were obtained. The difference of gravity values relative to the pier, calculated by the readings of the absolute and relative gravimeters, was +4.20 and +5.22 mGal, respectively.

The obtained results confirmed the possibility of measuring the absolute value of gravity in real sea conditions at the sea state up to 2 points, using a system comprising the absolute and relative gravimeters.

DOV measurements with the gyrostabilized zenith telescope were carried out in the water area of the Ladoga Lake, at two points located 100 m away from each other, on four nights. The results of the measurements were compared to the known values of DOV according to the global model EGM-2008, since they can be used as a reference in a region with small gravity anomalies and smooth topography (Fig. 11).

The standard deviations of DOV measurements were 0.65″ (ξ-component) and 0.85″ (η-component). The differences with EGM-2008 data were 0.96″ (ξ-component) and 0.36 (η-component). So the results of the field tests demonstrated the possibility of rapid high-precision measurement of the absolute values of DOV in marine conditions, using the astrogeodetic method.

7 Conclusions

The first results of experimental studies confirmed the possibility of high-precision measurement of the absolute values of gravity and deflection of the vertical at sea. The use of an integrated system will improve the quality of geodetic data in regions of the World Ocean with large gravity anomalies.

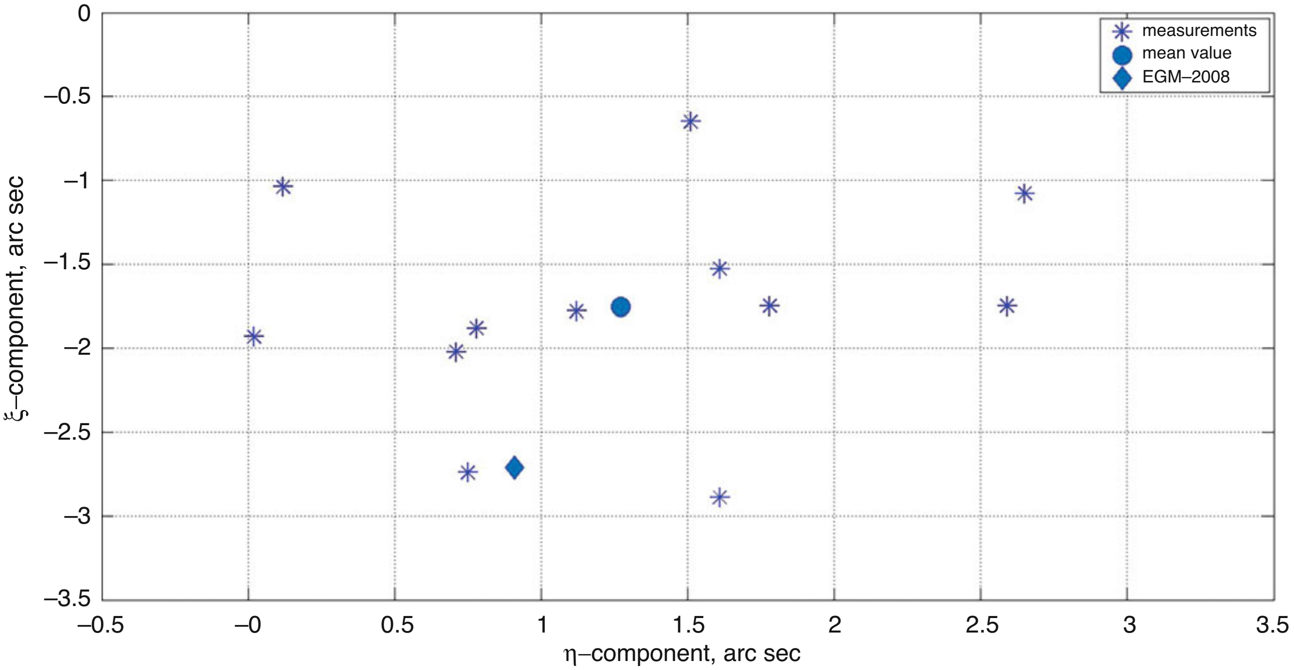

Fig. 11 The results of DOV measurements at water area point

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