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The First High-Precision Gravity Survey in the North Pole Region

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Abstract—The experience with conducting a marine gravity survey onboard a surface vessel under complicated ice conditions at high latitude is described. In 2014, a high-precision marine gravity survey with two modifications of the Chekan-AM gravimeter was carried out in the North Pole region. The measurements were conducted during two months from aboard the Akademik Fedorov research vessel on a given grid with a total length of 10000 km of the routes. As a result, 70000 gravity points at Arctic latitudes including the region of the geographical North Pole itself are acquired. In this paper, we discuss the methodical aspects of conducting the survey and present the accuracy estimates of the gravity measurements. The comparison of the obtained results with the Earth's gravity models demonstrates the absence of systematic errors and the higher spatial resolution of the measurements with the Chekan-AM gravimeters.

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Recently, studying the Earth's gravity field (EGF), particularly in hard-to-reach regions, has become increasingly topical (Drobyshev, 2009a; 2009b; 2011; Krasnov and Sokolov, 2009; Krasnov et al., 2011). As of now, airborne gravimetry is the most common and promising method for these purposes; however, its lower spatial resolution makes it inferior to the standard marine survey. Hence, conducting a high-precision route marine gravity survey onboard a vessel in the conditions of High North is certainly topical from the geophysical and geodetic standpoints.

In 2014, such a survey was carried out for the first time in the central part of the Arctic Ocean as part of the works on assessing the oil and gas potential of the continental shelf beyond the 200-mile exclusive economic zone of the Russian Federation.

GRAVIMETRIC INSTRUMENTS USED IN THE SURVEY

The gravity measurements were conducted with two instrumental complexes of similar type, Chekan-AM and Shelf-E, designed and manufactured by TSNII Elektropribor (Blazhnov et al., 2002; Krasnov et al., 2014a). All the gravimetric sensors designed by TSNII ELEKTROPRIBOR have sensitive elements in the form of different modifications of a heavily damped double quartz elastic system of the torsion-type developed at the Schmidt Institute of Physics of the Earth of the Russian Academy of Sciences (Zheleznyak and Popov, 1988; Krasnov et al., 2014). The angular position of the pendulums of the quartz elastic system is picked up by the optical electronic convertor in the autocollimation mode of operation. The quartz elastic system of the gravimeter and the optoelectronic convertor are placed in a specialized thermostat.

The gravity sensor is installed into the biaxial gyrostabilized platform which keeps its sensitive axis vertical (along the plumb line). The gearless servodrive system ensures guiding the motion of a gyroscope by the rings of the gyroplatform. In each of the two identical channels of the servosystem, on the gyro angular position signal, the microcontroller guides the control to the torque motor installed on the corresponding axis of the gyrostabilizer. The exterior view of the gravimeter and its main components are shown in Fig. 1.

The gyroscope's rotation axes are driven to the horizon plane according to the signals from the accelerometers which are fed to the microcontroller guiding the precession motion of the gyros. The microcontrollers can be adjusted in accordance with the external information (velocity, course, and coordinates) for eliminating the errors due to the vessel's maneuvering (Krasnov et al., 2009).

The mobile Shelf-E gravimeter is delivered with a notebook computer with preinstalled software including the following programs:

—a program package for data acquisition and real-time preprocessing;

Fig. 1. The exterior view of the Chekan-AM gravimeter (Shelf-E modification).

—programs for diagnosing the components of the system;

—a program package for the field control and complete processing of the observations.

The SeaGrav program for data acquisition and real-time preprocessing implements the following procedures:

—receiving the output information from the gravity sensor, gyrostabilizing system, and thermostabilizing system of the gravimeter;

—receiving the navigational information from GPS receiver and synchronization of the gravimeter data;

—linearizing the scale of the gravity sensor;

—smoothing the gravimeter output data by low-pass digital filtering;

—introducing the zero drift correction;

—calculating the gravity increment relative to the value at the initial reference gravity point;

—storing the initial data with a sampling frequency of 10 Hz on the hard drive.

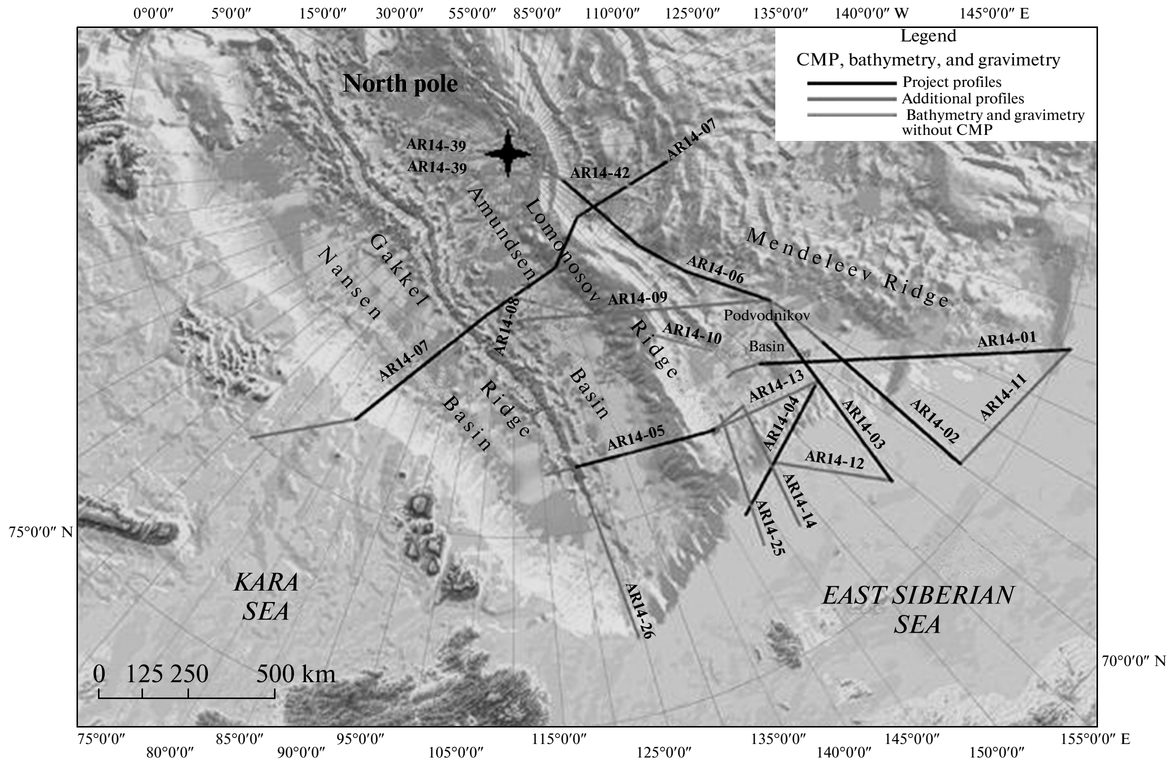

Fig. 2. The schematic layout of the profiles of the marine gravity survey.

The software for the field control and full-scale data processing of the Chekan-AM instrument includes the entire set of procedures from analyzing the reference observations to estimating the quality of the measurements by the intrinsic convergence and independent control (Krasnov et al., 2009).

The results of survey processing can be exported for further processing and geophysical interpretation in different formats. This is primarily the interdepartmental MVF78 format, which is regulated by the Guidelines of the marine gravity survey, as well as the text format *XYZ*, which is suitable for uploading into most of the modern geophysical data processing packages.

METHODICAL FEATURES OF GRAVITY MEASUREMENTS AT HIGH LATITUDES

The surface marine gravity survey that was carried out in the Arctic Ocean was a concomitant method and was conducted together with the seismic prospecting and bathymetry on a common grid of the profiles.

The gravimeters were installed aboard the Akademin Fedorov research vessel in the stateroom of the geophysical observatory, which is closest to the metacentre of the vessel.

Data processing was carried out with the use of the information from the files in the international data exchange format P1/90, which contain navigational (latitude, longitude) and bathymetric (sea depth) information with a step of 50 or 25 m, depending on the mode of operation of the compressed air sources of the seismic measurements.

The spatial coverage of the survey was the Arctic Ocean; Podvodnikov Basin; Vil'kitskogo Trough; Amundsen, Nansen, and Makarov basins; and the external margins of the Laptev and East Siberian sea shelves. The total area of the survey region was 350000 km^2. The schematic layout of the survey profiles is shown in Fig. 2.

One of the characteristic features of the hydrological regime of the Arctic basin is associated with the ice cover which persists all the year round and is in permanent motion.

The ice conditions overall were favorable for the solution of the tasks of the expedition. The works were predominantly carried out in the first-year ice with a thickness of at most 1.5–2.0 m with an ice concentration of 9/10. However, on some routes, mainly in the near-polar regions, the first-year ice contained the inclusions of old ice with a concentration of up to 3 m and a thickness of 2.5 to 4 m.

Considering these complicated ice conditions in the study region and the global experience of the recent studies in the Arctic Ocean, we conducted the measurements in the two-vessel mode. The Yamal ice breaker cut the channel and the Akademik Fedorov with enhanced ice reinforcement followed the channel and conducted the survey.

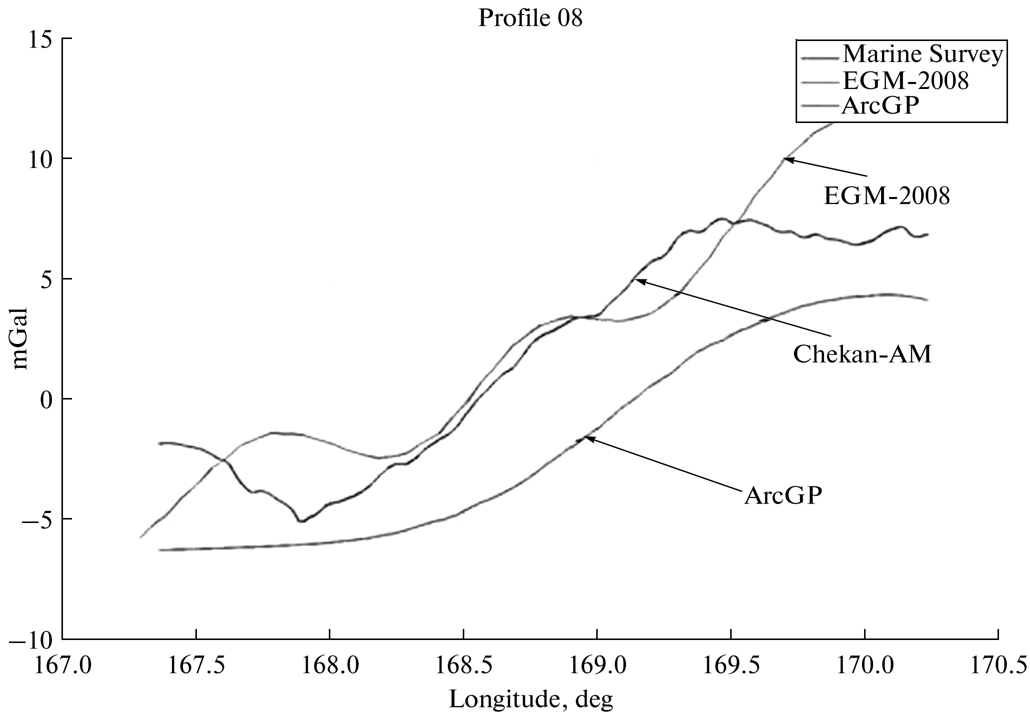

Fig. 3. The comparison of the results of the marine gravity survey with the data of the Earth gravity model for the profile AR1409-08.

A particular feature of the surface marine gravity survey was the work in an ice field whose thickness in the near-polar regions reached 4 m. In these conditions, the Akademik Fedorov vessel was not able to move continuously and uniformly and had to stop in the ice and wait until the Yamal ice breaker chipped the ice. For example, ice chipping was carried out 21 times on the route along profile 39 with a length of 182 km and 32 times on the route along profile 42 with a length of 265 km, which corresponds to one stop every 8–9 km of the survey. In these conditions, the vessel repeated the routes along the profiles.

Of the 10 200 line km of the survey, 7500 line km were carried out in the compacted ice with an ice concentration of 10, and only 2700 line km were surveyed in relatively ice-free water. The average vessel speed was 3.8 knots when in ice (with a minimal velocity of 2.1 knots) and 5.1 knots when in open water.

THE RESULTS OF THE GRAVITY SURVEY

As a result of the conducted combined survey, 36 gravimetric profiles were obtained and a catalog of the gravity points with 71 179 independent measurements was compiled. The accuracy of the measurements was evaluated by the main criterion of the root mean square (RMS) error at the intersections of the routes, which was 0.28 mGal for the Shelf-E gravimeter and 0.72 mGal for the Chekan-AM gravimeter. These values comply with the accuracy of the present-day high-precision marine surveys.

Due to the placement of two gravimeters aboard, we obtained an additional criterion for evaluating the quality of the measurements by the difference between the readings by the two instruments. The RMS error of the inter-instrumental difference was 0.79 mGal, which again testifies to the high instrumental accuracy of the gravimeters. The comparison of the graphs of the depths and the free-air and Bouguer gravity anomalies demonstrates their high correlation. The processing of the entire survey data enabled the identification of the EGF anomalies with a spatial resolution of less than 1 km and amplitude of 1–5 mGal, which could only be measured from aboard the surface marine vessel.

This argument is supported by the comparison of the results of the survey with the values of EGF anomalies estimated from the global EGM2008 model and the Arctic with the use of the data of the Arctic gravimetric project, which are represented for the discussed research area by the results of the airborne gravity survey of 1999 (Forsberg and Kenyon, 2005; Pavlis et al., 2008).

It can be seen that, besides the significantly higher spatial resolution, the marine measurements are free of the systematic bias of the airborne survey (ArcGP) and additional shift of the local maxima in the calculated model (EGM2008).

CONCLUSIONS

The results of the marine gravity survey carried out in the region of the geographical North Pole support the evident priority of this method in studying the high-frequency component of EGF anomalies. The nonuniform motion of the vessel in ice, associated with the complicated ice conditions, barely affects the accuracy of the EGF measurements. The software and instrumental capabilities of the Chekan-AM gravimeter make it suitable for application at the Arctic latitudes up to the geographical pole of the Earth without a reduction in the instrumental accuracy.

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