

## GENERAL PROBLEMS OF METROLOGY AND MEASUREMENT TECHNIQUES

### BUILDING A MODEL OF THE EARTH'S GRAVITY FIELD WITHIN THE CARIBBEAN SEA BASED ON SATELLITE ALTIMETRY DATA

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*The paper systematizes and describes the ways of processing measurement data collected over the past 30 years by altimetry spacecraft using different measurement technologies, as well as having different orbital characteristics. The files of measurement data are described and classified. In addition, a software package using the remove-restore method has been developed for determining the characteristics of the Earth's gravity field and figure via satellite altimetry. On the example of a geologically complex and seismically active region (Caribbean Sea), a model of the gravity field (gravity anomalies) was built and its accuracy characteristics were estimated. The obtained standard deviation of gravity anomalies from the EGM2008 global model does not exceed 4 mGal in the open sea and 14 mGal in the coastal zone, which corresponds to the international level. The interactive digital gravity model of the world ocean is currently used to solve the applied problems of geophysics and geology, specifically for the prediction of oil and gas occurrence.*

**Keywords:** altimetry, Earth's gravity anomalies, Earth's gravity field, remote sensing, geoid model.

**Introduction.** The most important task undertaken by modern geology, geodesy, and geophysics involves studying the deep structure of the world ocean using data on the Earth's gravity field (EGF) and the Earth's magnetic field [1]. For example, geodesy uses gravity anomalies to determine the figure of the Earth, specifically the geoid (the equipotential surface of the EGF, which most closely corresponds to the average sea level), while geophysics uses them to determine changes in mass density and, therefore, the geological structure of the Earth's interior for a wide range of applications.

Gravity anomalies reveal variations in rock density, with the amplitude of the anomaly proportional to the contrast between the density and thickness of the anomalous body. Short-wavelength gravity anomalies (less than 250 km) generally correlate with crustal structures, while long-wavelength gravity anomalies (over 1000 km) correlate with lateral variations in the mantle density. In 1989, Martin Kane and Richard Godson demonstrated that long-wavelength gravity highs are correlated with high seismic velocities in the mantle, whereas gravity lows correspond to low velocities [2].

Due to the vastness of the territory, the inaccessibility of most parts of the world ocean, the severe weather conditions for conducting research, as well as associated great financial costs, it is virtually impossible to accomplish the specified tasks on the world ocean scale (specifically in the polar regions) [3, 4].

Given that highly accurate and detailed EGF data for almost the entire area of the world ocean is available, information obtained from the Earth's gravity and magnetic fields can be used to study the tectosphere across the entire world ocean area. Such an opportunity arose after the launches of geodetic spacecraft equipped with an altimeter, providing a qualitatively new type of data [4–7].

Satellite altimetry missions have become an important tool for obtaining regional and global marine EGF data due to high resolution and data availability [8]. Satellite-derived EGF data, along with advanced geophysical methodologies, help to create a clear picture of the Earth's geological features. A large number of geological features, such as seafloor spreading ridges, pre-Cenozoic basement fault systems, and the distribution of sedimentary basins, can be identified through the interpretation of gravity anomalies and other data.

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In 2017, the Russian Metrological Institute of Technical Physics and Radio Engineering (VNIIFTRI) initiated a large-scale processing of satellite altimetry data in order to build a high-precision marine EGF model [9], as well as to determine deflections of the plumb line, gravity anomalies, and geoid heights.

The implementation of satellite altimetry is based on

$$ssh = N + \zeta + e ,$$

where *ssh* is the sea surface height; *N* is the geoid height;  $\zeta$  is the sea surface topography; *e* is the errors.

According to [10], the following factors affecting the accuracy of altimetry measurements are distinguished: instrumental (technical), ionospheric, tropospheric, geophysical, and procedural.

The study aims to assess the capabilities of modern multi-satellite altimetry in terms of creating accurate global or regional marine geoid and EGF models, as well as build and determine the accuracy characteristics of an EGF model representing a geologically complex and seismically active region, specifically the Caribbean Sea area.

**Software Package for Determining EGF Characteristics and the Earth's Figure via Satellite Altimetry.** A software package for determining the characteristics of the Earth's gravity field and figure was developed in MATLAB environment to comprise four modules:

- collection and preliminary processing of measurement data;
- determination of Earth rotation parameters and the orbits of Earth's satellites (as integral elements in solving any problem using satellite geodesy methods);
- calculations of EGF characteristics (gravity anomalies; deflections of the plumb line) and the figure of the Earth (geoid heights). The mathematical tools are presented in [9];
- generation of output data in the form of an interactive map (Fig. 1a).

**Examined Region.** Located between latitudes 9° and 22° N and longitudes 89° and 60° W, the Caribbean Sea forms the sub-oceanic basin of the western Atlantic Ocean. Its area is " ... approximately 2,753,000 km<sup>2</sup>. To the south it is bounded by the coasts of Venezuela, Colombia, and Panama; to the west by Costa Rica, Nicaragua, Honduras, Guatemala, Belize, and the Yucatán Peninsula of Mexico; to the north by the Greater Antilles islands of Cuba, Hispaniola, Jamaica, and Puerto Rico; and to the east by the north-south chain of the Lesser Antilles, consisting of the island arc that extends from the Virgin Islands in the northeast to Trinidad..."<sup>1</sup>

**Altimetry Data.** Several types of altimetry measurement data are distinguished: operational, interim, and final.

*Operational data* (operational geophysical data records, OGDRs) are generated every 3–9 h after receiving information from the satellite. Since the time in which OGDRs become available to users is too short to accurately calculate the orbital altitude using data from navigation and tracking systems, these data use only orbital altitude prediction.

*Interim Data.* During the next 1–2 weeks, the orbital altitude is refined using onboard navigation equipment, as well as the radial error component calculated according to the intersection points (orbital altitude equalization). At this stage interim data are generated (interim geophysical data records, IGDRs). In this case, the error in estimating the orbital altitude is much smaller, which already enables reliable use of IGDR for studying sea and ocean level variations.

*Final Data.* After refining the orbital altitude using data from land navigation systems and the Global Navigation Satellite System (GNSS), the accuracy of orbit calculations significantly increases. Thus, the calculations yield the final data (geophysical data records, GDRs). This increases the accuracy of sea surface height calculations while allowing the use of satellite altimetry to solve geodetic as well as oceanological problems [11].

Measurement data from altimetric missions are provided by PO.DAAC,<sup>2</sup> AVISO,<sup>3</sup> NOAA,<sup>4</sup> OpenADB,<sup>5</sup> etc.

**Calculation Method and Construction Results.** The marine gravity field provides the main source of data for modeling the geoid and the geological structure of continental shelves. In order to calculate marine gravity anomalies as per satellite altimetry data, the results of measuring either sea surface slope (gradients) or marine geoid height are used (i.e., *ssh* values adjusted to factor in the mean dynamic topography).

<sup>1</sup>Britannica, available at: <https://www.britannica.com> (accessed: Nov. 25, 2022).

<sup>2</sup>Physical Oceanography Distributed Active Archive Center (USA), available at: <https://podaac.jpl.nasa.gov> (accessed: Nov. 25, 2022).

<sup>3</sup>Database of satellite-derived oceanographic data (France), available at: <http://www.aviso.oceanobs.com> (accessed: Nov. 25, 2022).

<sup>4</sup>National Centers for Environmental Information (USA), available at: <https://www.nodc.noaa.gov> (accessed: Nov. 25, 2022).

<sup>5</sup>Open Altimeter Database (Germany), available at: <https://openadb.dfgi.tum.de> (accessed: Nov. 25, 2022).

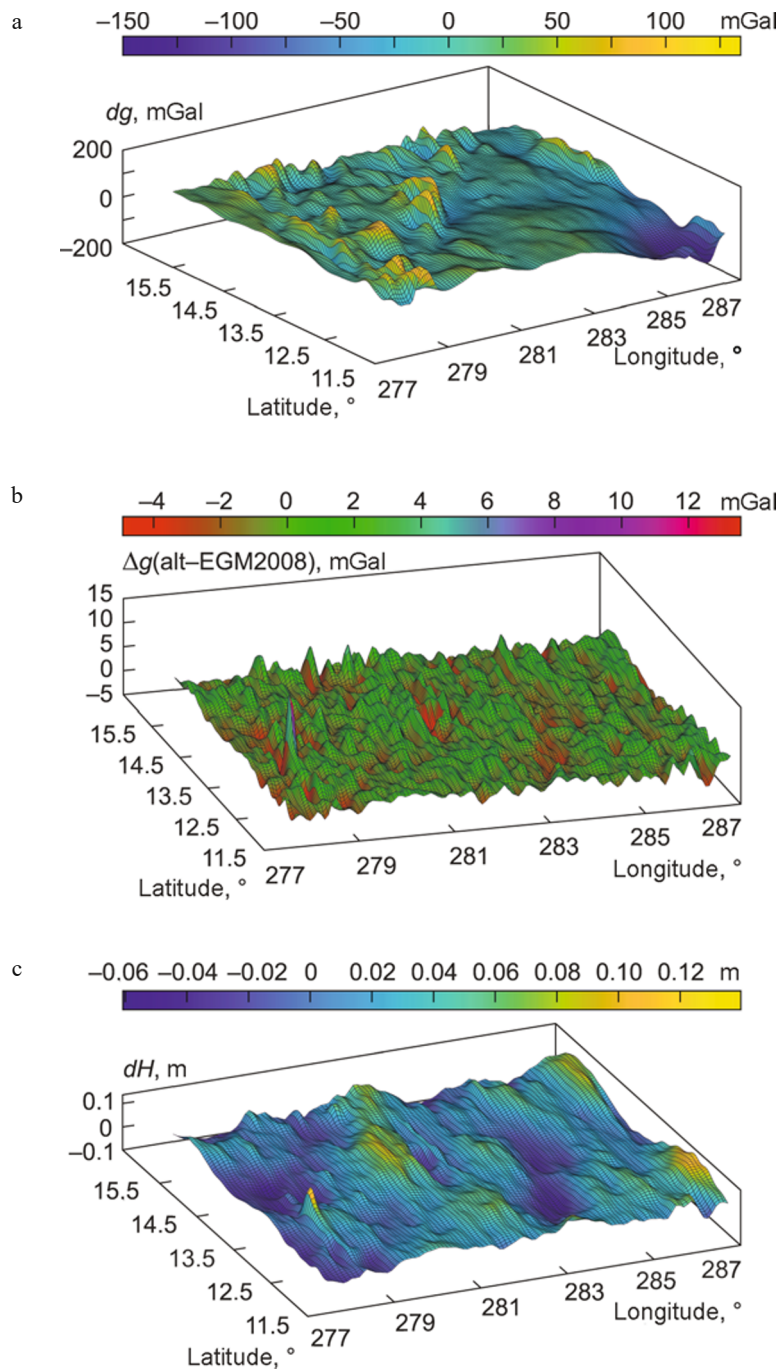


Fig. 1. Interactive digital models of EGF anomalies in the Caribbean Sea (a), deviation of the altimetric model of EGF anomalies (b) and the geoid model (c) from the EGM2008 global model;  $dg$ , gravity anomalies as per altimetry data;  $\Delta g(\text{alt-EGM2008})$ ,  $dH$ , deviation of the calculated gravity anomalies and built (altimetric) geoid model from the EGM2008 global model, respectively.

For the conversion of altimeter measurements into gravity anomalies, one of the three methods is commonly used: inverse Stokes formula using marine geoid heights; inverse Vening–Meinesz formula using sea surface slopes; integration of Laplace's equation [12–15]. All three approaches use the remove–restore method, which applies a global geopotential model during the transformation of geoid heights or slopes into gravity anomalies/perturbations (according to the fast Fourier transform [16]). Algorithms for constructing a grid of marine gravity field models are presented in [5].

The remove–restore method was used to calculate and construct interactive digital models of the marine geoid and EGF anomalies in the Caribbean Sea area (as a capability demonstration of the developed software package for determining the characteristics of the Earth's gravity field and figure). Here, the EGM2008 global model was used as a reference. The construction results are shown in the figure (digital maps of EGF anomalies; deviations of determined anomalies and geoid heights from the international EGM2008 model).

The standard deviation of gravity anomalies (in the Caribbean Sea area) from the EGM2008 model does not exceed 4 mGal in the open sea and 14 mGal in the coastal zone, while the deviation of geoid heights from the model values amounts to several centimeters (see Fig. 1c). The observed anomalous values within the range of 6–10 mGal (see Fig. 1b) are attributed to altimetry measurements in the coastal zone of Providencia Island (coordinates: 13°20'56" N, 81°22'29" W).

**Discussion.** Data on the EGF in the world ocean area are available from various sources, such as gravimeters aboard ships (ships and submarines) and aircraft, land gravimeters, and altimetry measurements. These sources of measurement data complement each other, providing an excellent opportunity to obtain additional EGF data, which is the only way to create a truly global EGF, including the polar regions.

Airborne gravimetry is a rapid and cost-effective method of local and regional gravity mapping, whose advantages include uniform and continuous coverage of land and sea, as well as the possibility to cover remote and inaccessible areas [17, 18].

Shipboard gravity measurements offer one of the most accurate sources of EGF data in water areas; however, the cost of measuring EGF parameters through shipboard means is high; in addition, the ship requires a minimum water surface height (to implement the method). Airborne and marine gravimeters are used to directly observe gravity; they can also be employed to determine any shifts in the altimetric gravity field.

As a rule, global altimetric gravity fields are very accurate in the open ocean (less than 4 mGal) [3]; however, in coastal and polar regions, the measurement error increases. Gravity recovery in coastal regions are particularly problematic; however, the greatest improvement (in determining EGF characteristics) can be achieved through targeted actions to enhance the accuracy of sea surface height measurements, as well as to develop new methods, models, and algorithms for processing measurement data.

The EGF derived from altimetry observations can be combined with aircraft and/or marine gravimetric observations by applying the least-squares collocation. The expression for determining EGF anomalies is as follows:

$$\Delta g = (C_{\Delta g h} C_{\Delta g \Delta g}) \begin{pmatrix} C_{hh} + D_h & C_{h\Delta g'} \\ C_{\Delta g' h} & C_{\Delta g' \Delta g'} + D_{\Delta g'} \end{pmatrix}^{-1} \begin{pmatrix} h \\ \Delta g' \end{pmatrix},$$

where  $C_{hh}$ ,  $C_{\Delta g h}$ ,  $C_{\Delta g \Delta g}$ ,  $D_h$ , and  $D_{\Delta g'}$  are the covariance matrices;  $h$  is the residual geoid height;  $\Delta g'$  is the gravity anomalies (according to altimetry and/or shipboard data).

**Conclusion.** VNIIFTRI developed a software package for determining the characteristics of the Earth's gravity field and figure via satellite altimetry in the world ocean area. The standard deviation of gravity anomalies from the EGM2008 model does not exceed 4 mGal in the open sea and 14 mGal in the coastal zone, which corresponds to the international level. The experimental interactive digital gravity model of the world ocean area built by the present authors is currently used to solve applied problems of geophysics and geology. For example, prediction of oil and gas occurrence (according to the parameters of the Earth's gravity and magnetic fields) using the analogy/comparison method (the task was first formulated by Arkhangel'skii and Fedynskii, while the patterns identified by them still constitute the fundamental criteria in the geological interpretation of gravity anomaly maps) [19, 20]. The achieved accuracy characteristics of the EGF allow portable AI-enabled equipment to be developed in the near future for a preliminary prediction of oil and gas occurrence in the world ocean area using altimetry measurements.

**Conflict of interest.** The authors declare no conflict of interest.

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