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Accuracy Assessment of Sentinel-3 Satellite Altimetry in the Coastal Areas of the Azov Sea

Sofya V. Protsenko✉, **Elena A. Protsenko**, **Anton V. Kharchenko**

Taganrog Institute named after A.P. Chekhov (branch) of RSUE (RINH), Taganrog, Russian Federation

✉ rab55555@rambler.ru

Abstract

Introduction. The Azov Sea is a shallow semi-enclosed sea where satellite altimetry (SA) faces challenges in ensuring accurate sea level measurements. This study focuses on verifying Sentinel-3 altimetry data in the coastal areas of the Azov Sea using observational platform data and a three-dimensional hydrodynamic model.

Materials and Methods. The study is based on a comparison of sea surface heights (SSH) obtained from the Sentinel-3 radar altimeter with tide gauge data and modelling results. A three-dimensional hydrodynamic model, adapted to the conditions of the Azov Sea, was used, along with satellite data processed considering atmospheric and tidal corrections.

Results. The root mean square error (RMSE) between satellite-derived and reference data was found to be 85 mm. The analysis demonstrated that Sentinel-3 Doppler altimetry in SAR mode provides higher accuracy compared to traditional altimetry, particularly in coastal areas.

Discussion and Conclusion. The assessment of Sentinel-3 data confirms their reliability in modeling water levels in the Azov Sea. The comparative analysis methodology proposed in this study enables the identification of systematic errors in satellite data and facilitates their integration with modelling and in situ observations. The study confirms the effectiveness of Sentinel-3 data in determining sea levels in complex coastal conditions. The developed methodology can be applied to other coastal areas to assess satellite altimetry performance.

Keywords: satellite altimetry, Sentinel-3, Azov Sea, sea level variations, hydrodynamic modeling, three-dimensional hydrodynamic model, satellite data verification

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Оригинальное теоретическое исследование

Оценка точности спутниковой альтиметрии Sentinel-3 в прибрежных районах Азовского моря

С.В. Проценко✉, **Е.А. Проценко**, **А.В. Харченко**

Таганрогский институт имени А.П. Чехова (филиал) РГЭУ (РИНХ), г. Таганрог, Российская Федерация

✉ rab55555@rambler.ru

Аннотация

Введение. Азовское море является мелководным полузамкнутым морем, где спутниковая альтиметрия (SA) сталкивается с трудностями в обеспечении точности измерений уровня моря. Рассматривается верификация данных альтиметрии спутника Sentinel-3 в прибрежных районах Азовского моря с использованием данных платформ наблюдений и трехмерной гидродинамической модели.

Материалы и методы. Исследование основано на сравнении высот поверхности моря (SSH), полученных с радиовысотомера Sentinel-3, с данными мареографов и результатами моделирования. Использована трехмерная гидродинамическая модель, адаптированная к условиям Азовского моря, а также спутниковые данные, обработанные с учетом атмосферных и приливных поправок.

Результаты исследования. Среднеквадратичная ошибка (RMSE) между спутниковыми и эталонными данными составила 85 мм. Анализ показал, что доплеровская альтиметрия Sentinel-3 в SAR-режиме обеспечивает более высокую точность по сравнению с традиционной альтиметрией, особенно в прибрежной зоне.

Обсуждение и заключение. Оценка данных Sentinel-3 демонстрирует их надежность в моделировании уровня воды в Азовском море. Методика сравнительного анализа, предложенная в работе, позволяет учитывать систематические ошибки спутниковых данных и использовать их в сочетании с моделированием и натурными наблюдениями. Исследование подтверждает эффективность данных Sentinel-3 в определении уровня моря в сложных прибрежных условиях. Разработанная методика может быть применена в других прибрежных районах для оценки характеристик спутниковой альтиметрии.

Ключевые слова: спутниковая альтиметрия, Sentinel-3, Азовское море, колебания уровня моря, гидродинамическое моделирование, трехмерная гидродинамическая модель, верификация спутниковых данных

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Introduction. The Azov Sea is a shallow semi-enclosed body of water characterized by low salinity, significant seasonal fluctuations in water levels, and intense river discharge. These factors significantly affect the dynamics of water masses and necessitate precise tools for monitoring sea level changes. In recent decades, remote sensing has become one of the key methods for studying marine and coastal processes. In particular, satellite altimetry (SA) enables continuous observation of sea level variations on a global scale.

One of the modern tools for satellite monitoring is the Sentinel-3A satellite, launched by the European Space Agency (ESA) in 2016 as part of the Copernicus program. It is equipped with a synthetic aperture radar (SAR) altimeter, which significantly improves the spatial resolution of data compared to traditional altimetry. However, the application of satellite altimetry methods in coastal zones presents significant challenges due to the influence of the coastline, wave heterogeneity, seabed topography variations, and land-induced interference. This makes the verification of Sentinel-3 data particularly relevant in complex marine areas such as the Azov Sea.

Previous studies have shown that while satellite altimetric data achieve high accuracy in open ocean waters, their precision may decrease in coastal areas due to signal reflections, meteorological effects, and water mass dynamics. Therefore, it is crucial to assess the accuracy of Sentinel-3 data under the specific conditions of the Azov Sea, where shallow depths and the influence of river discharge and seasonal changes significantly affect sea levels [1].

This study conducts a comprehensive verification of Sentinel-3 satellite altimetry data by comparing them with in situ tide gauge measurements installed in the Azov Sea, as well as with numerical modeling results obtained using a three-dimensional hydrodynamic model. The objective of the study is to determine the accuracy of satellite data and analyze their applicability for monitoring sea level in coastal conditions.

To achieve this, the following tasks were carried out:

– collection and processing of Sentinel-3 satellite altimetry data;

– adaptation and application of a three-dimensional hydrodynamic model to calculate sea surface height;

– analysis of discrepancies between satellite, model-based, and in situ data;

– determination of root mean square error (RMSE) and evaluation of the reliability of satellite data for monitoring the Azov Sea.

Thus, this study aims to expand the capabilities of satellite altimetry in coastal areas and enhance methods for evaluating Sentinel-3 data under the complex hydrodynamic conditions of the Azov Sea.

Materials and Methods

Satellite Altimetry Data. Satellite altimetry (SA) is a remote sensing method for measuring sea level based on the use of a radar altimeter, which emits an electromagnetic pulse and records the time it takes to return after reflecting off the water surface. This method enables global measurements of sea surface height (SSH) and provides valuable data for analyzing water level variations in both coastal and open sea areas.

The Sentinel-3 satellite (Fig. 1), launched by the European Space Agency (ESA) as part of the Copernicus program, is equipped with the SRAL (Synthetic Aperture Radar Altimeter), which operates in two modes:

– Low Resolution Mode (LRM) — traditional altimetry with relatively low spatial resolution;

– Synthetic Aperture Radar (SAR) Mode — a synthetic aperture mode that provides enhanced resolution and more accurate sea level measurements, particularly in coastal areas.

Fig. 1. Artistic depiction of Sentinel-3 [2]

This study analyzes data obtained in SAR mode, which minimizes signal reflections from land and improves measurement accuracy under complex hydrodynamic conditions.

The Sentinel-3 satellite follows a sun-synchronous orbit at an altitude of 814 km with an inclination of 98.6°, ensuring global coverage with a repeat cycle of 27 days over the same region (when combined with Sentinel-3B, the repeat period is reduced to 13.5 days) (Fig. 2). The SRAL radar altimeter operates in the Ku/C bands and transmits pulses at a frequency of 1 kHz, allowing sea level measurements with a temporal resolution of 20 Hz (i. e., approximately one measurement every 350 meters along the satellite's track) (Fig. 3) [2].

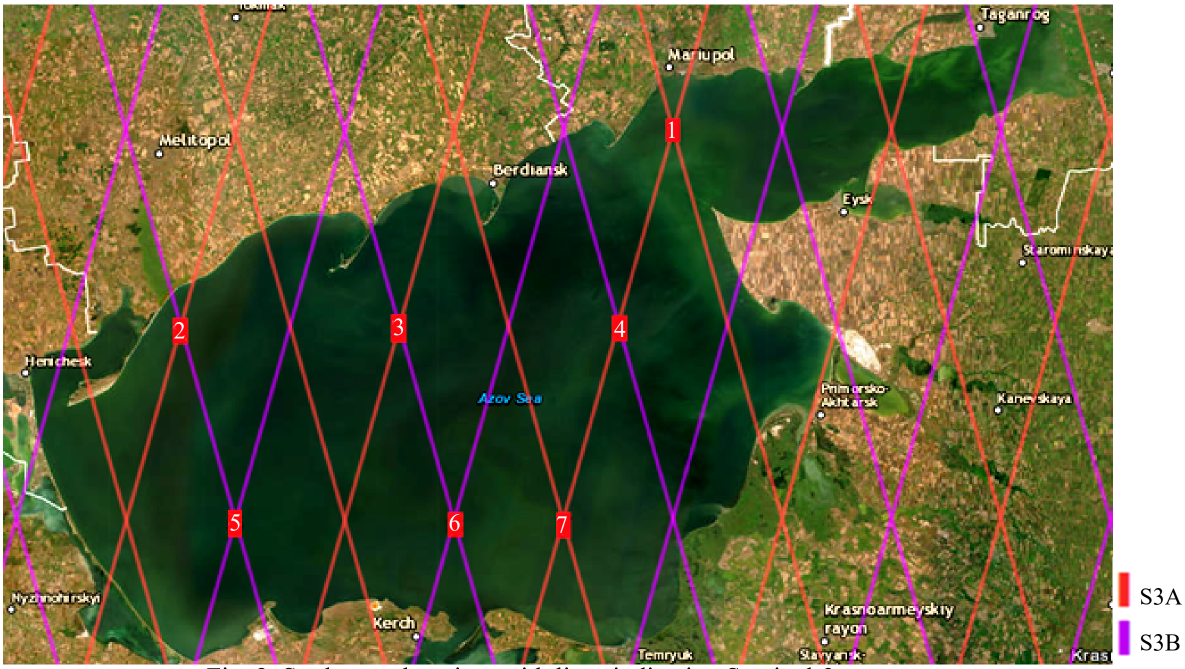

Fig. 2. Study area location, with lines indicating Sentinel-3 passes

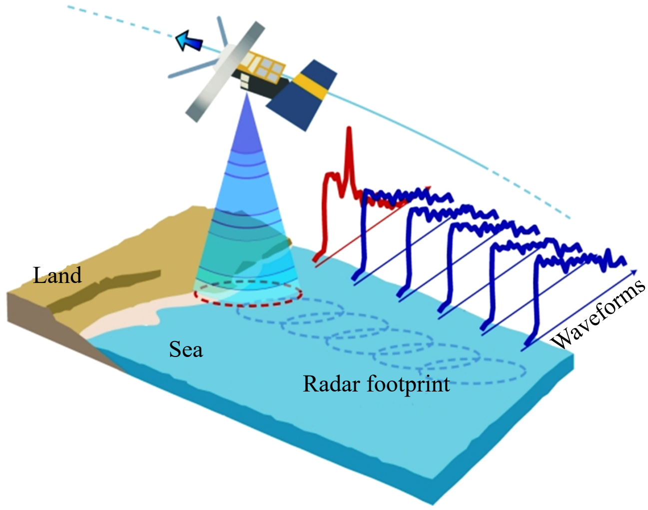

Fig. 3. Changes in signal shape (red) as the satellite altimeter approaches the coastline and enters the radar coverage zone [2]

The altimeter onboard the satellite transmits microwave radiation at two frequencies toward the sea surface and records the time required for the signal to return to the satellite. The initial distance $R(\lambda, \phi, t)$ at a specific coordinate and time t is corrected for atmospheric effects and instrumental errors. The corrected distance R_c is calculated using the formula [3]:

$$R_{corr}(\lambda, \phi, t) = R(\lambda, \phi, t) - C_r,$$

where the corrections C_r, applied to the satellite range include:

– sea state bias correction, which accounts for the influence of waves on radar signal reflection;

– polar tide correction, which compensates for changes in the Earth's shape due to mass movements in polar regions;

– solid Earth tide correction, which considers the deformation of the Earth's crust caused by the gravitational pull of the Moon and the Sun;

– ionospheric correction, which adjusts for the effect of electron density in the ionosphere on radio wave propagation;

– dry and wet tropospheric corrections, which account for the refraction of radio waves in the atmosphere due to the presence of water vapor and other gases.

These corrections are essential to minimize systematic errors and ensure high-precision satellite sea level measurements.

After applying all necessary corrections, the sea surface height determined from satellite data is calculated as follows:

$$SSH_{SA}(\lambda, \phi, t) = h_{sat}(\lambda, \phi, t) - R_{corr}(\lambda, \phi, t),$$

where $SSH_{SA}(\lambda, \phi, t)$ — sea surface height determined from satellite altimetry data; $h_{sat}(\lambda, \phi, t)$ — satellite altitude above the reference ellipsoid; $R_{corr}(\lambda, \phi, t)$ — corrected distance from the satellite to the water surface [4–5].

The verification of Sentinel-3 satellite altimetry data is performed by comparing the sea surface heights obtained from the altimeter SSH_{SA}, with reference data, including measurements from observation platforms in the Azov Sea SSH_{TG} and results from numerical modeling based on a three-dimensional hydrodynamic model SSH_{HDM}.

In this study, Sentinel-3 *SSH* products obtained from the official Copernicus Data Hub [6] were used. The data were downloaded in NetCDF format and underwent preprocessing, which included:

– selecting Sentinel-3 orbital segments passing over the Azov Sea;

– filtering and removing noisy data with anomalous values;

– interpolating to align with the coordinates of tide gauges and the hydrodynamic model..

To verify the accuracy of Sentinel-3 measurements, *SSH* data were compared with reference measurements from:

1. Ground-based observation platforms (tide gauges) – sea level height data from the Unified State Information System on the Situation in the World Ocean (ESIMO).

2. Numerical modeling – sea surface height data obtained using a three-dimensional hydrodynamic model (the model description is provided in the next section).

The accuracy assessment of the data was conducted by calculating the root mean square error (RMSE) between *SSH* values derived from satellite data and tide gauge observations, as well as analyzing the standard deviation (STD) between Sentinel-3 data and numerical modeling results.

Observation Platforms in the Azov Sea. For the verification of Sentinel-3 satellite altimetry data in the coastal zone of the Azov Sea, data from seven observation platforms registered in the Unified State Information System on the Situation in the World Ocean (ESIMO) were used (Fig. 4). These platforms are tide gauge stations equipped with high-precision measuring instruments, enabling real-time sea level recording and providing long-term observation series [7].

Fig. 4. Observation platforms in the Azov Sea

Tide gauges installed at various locations across the Azov Sea continuously record sea level fluctuations. These stations are strategically positioned near key hydrodynamic nodes where wave action, wind surges, and river discharge effects are most pronounced. This placement ensures the collection of representative data on sea level dynamics across different regions of the Azov Sea.

Coastal tide gauges are used to measure and continuously record fluctuations in the sea level of the Azov Sea. The sea surface height $SSH_{TG}(\lambda_{TG}, \phi_{TG}, t)$ based on tide gauge data can be determined as follows:
where $H_{TG}(t)$ — sea level measured by the tide gauge relative to the zero level of the national vertical reference system.

For a proper comparison with satellite data, tide gauges were used, located at varying distances from the shore: from deep-water areas to shallow zones influenced by the shoreline. This distribution allows for the assessment of the accuracy of Sentinel-3 altimetric data depending on the distance from the shore, the identification of the impact of coastal effects on satellite measurements, and consideration of the local hydrodynamic features of the Sea of Azov when analyzing discrepancies in the data. The locations of the tide gauge stations are shown in Fig. 2, with the coordinates of each observation platform marked.

The tide gauge data were standardized to a common reference system for accurate comparison with satellite altimetry and hydrodynamic modeling data. The processing included:

– harmonic analysis of tidal and set-up oscillations of the sea level;

– filtering of high-frequency fluctuations caused by local hydrodynamic processes (e. g., short-term wind effects);

– adjustment of data to a reference level aligned with the geoid used in satellite measurements;

– interpolation of time series to match Sentinel-3 satellite passes.

Additionally, an analysis of statistical characteristics of the measured data was performed, including the mean value, standard deviation (STD), and range of sea level fluctuations for each station.

A spatially inhomogeneous three-dimensional mathematical model of wave hydrodynamics in a shallow water body. The governing equations of the wave hydrodynamics model are [8–12]:

– the equation of motion (Navier-Stokes):

$$
\begin{aligned}
u'_t + uu'_x + vu'_y + wu'_z &= -\frac{1}{\rho}P'_x + \left(\mu u'_x\right)'_x + \left(\mu u'_y\right)'_y + \left(\nu u'_z\right)'_z, \\
v'_t + uv'_x + vv'_y + wv'_z &= -\frac{1}{\rho}P'_y + \left(\mu v'_x\right)'_x + \left(\mu v'_y\right)'_y + \left(\nu v'_z\right)'_z, \\
w'_t + uw'_x + vw'_y + ww'_z &= -\frac{1}{\rho}P'_z + \left(\mu w'_x\right)'_x + \left(\mu w'_y\right)'_y + \left(\nu w'_z\right)'_z + g;
\end{aligned}
\tag{1}
$$

– the continuity equation in the case of variable density:

$$
\rho'_t + \left(\rho u\right)'_x + \left(\rho v\right)'_y + \left(\rho w\right)'_z = 0,
\tag{2}
$$

where $V=\{u,v,w\}$ is the velocity vector; P is the pressure; ρ is the density; μ, ν are the horizontal and vertical components of the turbulent exchange coefficient; g is the acceleration due to gravity.

The system of equations (1)–(2) is considered with the following boundary conditions:

– at the inlet:

$$
u(x,y,z,t) = u(t), \quad v(x,y,z,t) = v(t), \quad P'_n(x,y,z,t) = 0, \quad V'_n(x,y,z,t) = 0,
$$

– on the lateral boundary (shore and bottom):

$$
\rho\mu(u')_n(x,y,z,t) = -\tau_x(t),\ \rho\mu(v')_n(x,y,z,t) = -\tau_y(t),
$$
$$
V_n(x,y,z,t) = 0,\ P'_n(x,y,z,t) = 0,
$$

– on the upper boundary:

$$\rho\mu(u')_n(x,y,z,t) = -\tau_x(t),\ \rho\mu(v')_n(x,y,z,t) = -\tau_y(t),$$

$$w(x,y,t) = -\omega - P_t' / \rho g,\ P_n'(x,y,t) = 0, \qquad (3)$$

where ω is the intensity of liquid evaporation; τ_x, τ_y are the tangential stress components.

Tangential stress components for the free surface are given by $\{\tau_x, \tau_y\} = \rho_a Cd_s |\vec{w}| \{w_x, w_y\}$, where $Cd_s = 0.0026$ is the wind velocity relative to the water, ρ_a is the air density; Cd_s is the dimensionless surface drag coefficient, which depends on wind speed and is considered in the range of 0.0016–0.0032.

Tangential stress components for the bottom, accounting for water movement, can be written as $\{\tau_x, \tau_y\} = \rho Cd_b |V| \{u, v\}$, $Cd_s = gn^2 / h^{1/3}$, where $n = 0.04$ is the roughness group coefficient in the Manning formula (0.025–0.2); $h = H + \eta$ is the depth of the water body; H — is the depth to the undisturbed surface; η is the free surface elevation relative to the geoid (sea level).

The data from the hydrodynamic model on sea level $H_{HDM}(\lambda, \phi, t)$ relative to the geoid will be used in the form of:

$$SSH_{HDM}(\lambda,\phi,t) = H_{HDM}(\lambda,\phi,t) + N(\lambda,\phi).$$

The displacement between the tide gauge data and the three-dimensional wave hydrodynamics model can be determined at a nearby tide gauge location at time t:

$$B_{TG/HDM}(t) = SSH_{TG}(\lambda_{TG}, \phi_{TG}, t) - SSH_{HDM}(\lambda_{TG}, \phi_{TG}, t).$$

The displacement is introduced for each corresponding node of the grid cell in the discrete hydrodynamic model during the computation of SSH_{HD}:

$$SSH_{HDMcorr}(\lambda,\phi,t) = SSH_{HDM}(\lambda,\phi,t) \cdot B_{TG/HDM}(t).$$

To account for the systematic error $SSH_{diff}(\lambda, \phi, t)$ between the satellite data and the hydrodynamic model, the following is introduced:

$$SSH_{diff}(\lambda,\phi,t) = SSH_{SA}(\lambda,\phi,t) - SSH_{HDMcorr}(\lambda,\phi,t).$$

The effectiveness of the Sentinel-3 SRAL altimeter was assessed in the coastal zone of the Sea of Azov. Remote sensing data were obtained from the official Copernicus data center in the standard NetCDF format [1]. Based on these data, SSH_{HDM} was calculated. Observation series from 7 coastal tide gauges were used to calculate $SSH_{TG}(\lambda_{TG}, \phi_{TG}, t)$ [2]. The three-dimensional spatially inhomogeneous model of wave hydrodynamics in shallow water, which includes three equations of motion, was used to obtain $SSH_{HDM}(\lambda, \phi, t)$ [3].

Results

Comparative analysis of Sentinel-3 satellite altimetry data, tide gauge observations, and hydrodynamic modelling. To assess the accuracy of Sentinel-3 satellite data, it was compared with in situ measurements from tide gauges located in the Sea of Azov, as well as with the results of numerical simulations performed using a three-dimensional hydrodynamic model. The analysis is based on the calculation of statistical characteristics of the differences between measured and computed sea surface height values, considering the spatial and temporal alignment of the data.

The study covers the year 2024, during which the satellite passes of Sentinel-3A and Sentinel-3B over the Sea of Azov were analyzed. SAR-mode altimetry products were used, providing higher accuracy compared to traditional methods. For each satellite pass, points of intersection with the tide gauges and the hydrodynamic model grid were identified.

For verification, the following data were used:

– tide gauge data (seven stations), recorded in the Unified Interagency Federal Information System (ESIMO);
– Sentinel-3 SSH satellite measurements, obtained from the Copernicus data center;
– results of a three-dimensional hydrodynamic model, adapted for the conditions of the Sea of Azov.

To quantitatively assess the discrepancies between the SSH values obtained by different methods, the following were calculated:

– Root Mean Square Error (RMSE) — the scatter of satellite data relative to tide gauge and model values;
– Mean Bias (Bias) — the magnitude of the systematic error;
– Standard Deviation (STD) — the degree of scatter of the values.

The results of the calculations showed that the overall RMSE between the Sentinel-3 data and the tide gauges was 85 mm. The mean bias between the satellite data and the tide gauges does not exceed 2–3 cm, indicating the absence of significant systematic deviation. The STD ranged from 6 to 9 cm, depending on the specific satellite pass and its distance from the shore.

Table 1 presents statistical data on the difference in SSH measurements. The overall difference across all fourteen passes was 85 mm.

Table 1

Data on the difference in SSH measurements

Points	Sentinel-3 Passes	RMSE, mm	Distance from the point to the shore, km	Distance from the point to the platform, km
1	653 S3A	78	16.3	2.3
	270 S3A	106		
2	42 S3A	109	11.6	2.4
	425 S3B	84		
3	539 S3B	43	36.2	2.1
	156 S3A	115		
4	270 S3A	68	48.6	3.2
	653 S3B	102		
5	156 S3B	87	37.8	2.7
	425 S3B	110		
6	270 S3B	63	33.9	3.2
	539 S3B	75		
7	539 S3A	79	28.3	4.4
	270S3A	68		

To assess the impact of coastal effects on the accuracy of Sentinel-3 altimetry, an analysis of the dependence of discrepancies on the distance of the measurement point from the shore was conducted. In deep-water areas (>20 km from the shore), the measurement accuracy is maximal: RMSE does not exceed 6–7 cm, and STD ranges from 5 to 8 cm. In areas 10–20 km from the shore, the errors increase: RMSE reaches 7–9 cm, and STD ranges from 6 to 9 cm. In shallow coastal zones (<10 km from the shore), the accuracy of satellite data deteriorates due to reflection effects and the influence of dynamic processes in the surf zone. In these areas, RMSE reaches 10–12 cm, and STD ranges from 9 to 12 cm. Thus, Sentinel-3 data in SAR mode demonstrate high accuracy in open waters but require correction when analyzing coastal areas.

The three-dimensional hydrodynamic model used in the study allowed for the calculation of SSH with high spatial and temporal resolution, providing an additional means of assessing the accuracy of satellite altimetry. The analysis showed that the average discrepancy between the model and satellite SSH data is 4–6 cm, confirming the high accuracy of the model. In areas with intense river runoff (e. g., the mouths of the Don and Kuban rivers), discrepancies increase to 8–10 cm due to variations in water density and currents. In deep-water areas of the Sea of Azov, model data align with satellite data within ±5 cm, further confirming their reliability.

Discussion and Conclusion. Sentinel-3 satellite altimetry in SAR mode demonstrates high measurement accuracy in the open waters of the Sea of Azov but is subject to errors in coastal areas (<10 km from the shore). The root mean square error (RMSE) between satellite and tide gauge data is 85 mm, which aligns with the current level of altimetry methods. The hydrodynamic model showed good agreement with Sentinel-3 data (average discrepancy of 4–6 cm), confirming the possibility of jointly using numerical modeling and satellite data. To further improve the accuracy of satellite altimetry in coastal areas, adaptive data filtering and correction algorithms should be applied. Therefore, the results of the study confirm the effectiveness of using Sentinel-3 data for sea level monitoring in the Sea of Azov and underscore the need for continued improvement of satellite measurement correction methods in the coastal zone.

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About the Authors:

Sofia V. Protsenko, Candidate of Physical and Mathematical Sciences, Associate Professor of the Department of Mathematics, Research Fellow, A.P. Chekhov Taganrog Institute (branch) Rostov State University of Economics (48, Initiative St., Taganrog, 347936, Russian Federation), ORCID, SPIN-code, rab5555@rambler.ru

Elena A. Protsenko, Candidate of Physical and Mathematical Sciences, Associate Professor of the Department of Mathematics, Leading Research Fellow, A.P. Chekhov Taganrog Institute (branch) Rostov State University of Economics (48, Initiative St., Taganrog, 347936, Russian Federation), ORCID, SPIN-code, eapros@rambler.ru

Anton V. Kharchenko, Research Fellow at the Taganrog Institute of A.P. Chekhov (branch) of the Rostov State Economic University (48, Initiative St., Taganrog, 347936, Russian Federation), kharch_91@rambler.ru

Contributions of the authors:

S.V. Protsenko: concept development; scientific guidance.

E.A. Protsenko: data management; annotation, data cleaning, and maintaining data integrity; software development; visualization.

A.V. Kharchenko: conducting research; methodology development; result validation.

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Об авторах:

Проценко Софья Владимировна, кандидат физико-математических наук, доцент кафедры математики, научный сотрудник, Таганрогский институт им. А.П. Чехова (филиал) Ростовского государственного экономического университета (347936, Российская Федерация, г. Таганрог, ул. Инициативная, 48), ORCID, SPIN-код, rab5555@rambler.ru

Проценко Елена Анатольевна, кандидат физико-математических наук, доцент кафедры математики, ведущий научный сотрудник, Таганрогский институт им. А.П. Чехова (филиал) Ростовского государственного экономического университета (347936, Российская Федерация, г. Таганрог, ул. Инициативная, 48), ORCID, SPIN-код, eapros@rambler.ru

Харченко Антон Владимирович, научный сотрудник Таганрогского института им. А.П. Чехова (филиал) Ростовского государственного экономического университета (347936, Российская Федерация, г. Таганрог, ул. Инициативная, 48), kharch_91@rambler.ru

Заявленный вклад авторов:

С.В. Проценко: разработка концепции; научное руководство.

Е.А. Проценко: курирование данных; деятельность по аннотированию, очистке данных и поддержанию их целостности; разработка программного обеспечения; визуализация.

А.В. Харченко: проведение исследования; разработка методологии; валидация результатов.

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