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ASSESSMENT OF DIGITAL ELEVATION MODELS ACCURACY FOR LOCAL GEOID MODELING

One of the critical factors influencing the accuracy of a local geoid model is the quality of the digital elevation model (DEM). A properly selected high-resolution DEM can significantly mitigate errors in geoid modeling, gravity anomaly processing, and topography and downward continuation correction.

Purpose. Evaluating the accuracy of five global DEMs obtained from open sources to identify the most suitable model for creating a local geoid.

Methodology. The vertical accuracy of the DEMs was assessed by comparing the heights between the DEM and control points across different types of terrain. The reference values are based on 344 ground benchmarks, where GNSS observations were performed with subsequent adjustment of coordinates and heights. The accuracy analysis involved calculating statistical indicators of the height differences between the GNSS data and the DEM data.

Findings. The standard deviation assessment showed favorable values for the COPERNICUS and ALOS DEMs, followed by SRTM, ASTER, and ETOPO. In the mean absolute error calculations for mountainous areas, the ALOS model performed best, followed by COPERNICUS, SRTM, ASTER, and ETOPO. For other types of terrain, COPERNICUS demonstrated the best results in mean absolute error.

Originality. This study distinguishes itself through the incorporation of advanced high-resolution DEMs, such as GLO30, providing a modern and thorough evaluation of DEM accuracy specifically for Kazakhstan. What is new is a detailed analysis of the impact of terrain features (plain, hilly, mountainous) on modeling accuracy. This approach advances beyond previous assessments, delivering new and significant insights into the performance of contemporary DEMs.

Practice value. The practical value of the results obtained consists in issuing recommendations regarding the possibility of using the studied DEM for the regions of Kazakhstan which differ among themselves in terms of landscape characteristics. The findings indicate that COPERNICUS and ALOS DEMs are highly suitable for precise geoid modeling in southern Kazakhstan. These models can significantly improve the accuracy of local geoid models, benefiting applications in geospatial science and engineering.

Keywords: *digital terrain model, geoid, accuracy assessment, ASTER, ALOS, ETOPO, SRTM, COPERNICUS*

Introduction. The modernization of the state geodetic support system in Kazakhstan involves establishing a geocentric coordinate system. Transitioning to this new geocentric coordinate system requires the development of leveling and gravimetric networks. International experience indicates that the advancement of state geodetic networks, particularly regarding the vertical datum, necessitates the creation of a local geoid. Developing a high-precision geoid model for the country is of significant scientific and practical value, and is also economically advantageous, as it facilitates the replacement of costly, labor-intensive geometric leveling with more affordable GNSS methods. This issue is especially pertinent for Kazakhstan, as the country currently lacks a national geoid that meets the accuracy standards of geometric leveling.

The quality of the generated geoid is directly contingent upon the initial data used [1]. The complex geographic relief features (including plains, highlands, lowlands, plateaus, and hills) and the extensive territory characteristic of the country necessitate a thorough assessment of the quality of the data employed.

A primary source of errors in geoid modeling, gravity anomaly processing, and the incorporation of corrections for topography and downward analytic continuation (DWC) is the quality of the digital elevation model (DEM) [2].

Consequently, the selection and evaluation of global DEMs is a critical issue. DEM quality assessment can be conducted both with and without ground data. External assessments utilize reference data for comparison, whereas internal assessments examine the intrinsic properties and errors of the data [3].

Currently, there are numerous global and regional digital elevation models (DEMs) available in the public domain. Notable among them are SRTM, ASTER, and ETOPO1 [3, 4], which are frequently employed in geoid model computation. However, in recent years, new models such as ALOS [5] and Copernicus have been released but have not yet been evaluated in the context of Kazakhstan [6, 7]. Selecting an inappropriate DEM can introduce inaccuracies in gravity anomalies, interpolation of Bouguer gravity anomalies, and propagate errors into the geoid model through topographic and downward continuation corrections when applying the Stokes formula [8]. DEMs are known to be susceptible to various types of errors, and the accuracy of elevations can vary based on the geographic location of the study area. Given the integral role of DEMs in multiple stages of the geoid modeling process, it is common practice worldwide to assess the quality and impact of new high-resolution models.

The objective of this study is to identify the most suitable DEM for geoid modelling, which necessitates meticulous comparison and analysis. The study involves comparing the height differences between the DEMs and GNSS observations. Five DEMs were selected for evaluation: AW3D30, ASTGTM003, ETOPO1, SRTM30, and GLO30. The reference points consist of control points where GNSS measurements were performed in static mode, followed by the adjustment of coordinates and elevations.

Research area. The territory in the southern part of Kazakhstan (Turkestan region), defined by the coordinates 40°N <

φ < 6°30’N and 65°30’E < λ < 71°30’E, where φ denotes latitude and λ denotes longitude (Fig. 1), was selected as the test site.

The area of this region is approximately 116.280 km². The selection of this site as a test area is justified by its diverse landscape: the northern part features the Betpak-Dala desert, while the Hungry Steppe (Myrzazhol) is located in the south. The central part is dominated by the Karatau range, with Mount Bessaz reaching an elevation of 2,176 meters. The southeastern part includes the western edge of the Talas Alatau and the Karzhantau (2,824 m) and Ugamsky ridges, with the highest point being Sairam Peak at 4,238 meters [9].

Literature review. The distribution of raw DEM data and its random, systematic, and gross errors can significantly impact the reliability of analysis results [10, 11]. The global validation of freely available DEMs has been extensively documented. For instance, AW3D30 reports a root mean square error (RMSE) of 5 meters [12–14], while ASTER’s RMSE ranges from 5 to 25 meters [15], and SRTM has an RMSE reported to be less than 16 meters [16]. Despite these global validations, numerous researchers have also evaluated DEMs in local contexts. One of the most common methods for assessing DEM accuracy is using control points to calculate RMSE [17]. Global Navigation Satellite System (GNSS) ground control points (GCP) data have been utilized to evaluate the horizontal and vertical accuracy of ASTER, SRTM, and AW3D30. In Cameroon, these DEMs exhibited RMSEs of 16.7 meters for AW3D30, 20.4 meters for ASTER, and 13.2 meters for SRTM. The influence of land cover and slope on the vertical accuracy of DEMs has also been analyzed. Patel, et al. (2016) used GNSS control points to evaluate various open-source DEMs, with assessments in India showing RMSEs of 12.62 meters and 17.76 meters for ASTER and SRTM, respectively [18, 19]. Additional studies have confirmed that SRTM generally offers higher accuracy than ASTER [20, 21].

Various investigations have examined the accuracy of DEMs across different topographies. Hu, et al. [22] evaluated ASTER, SRTM, and AW3D30 in China, finding that the accuracy of all three DEMs exceeded 11.7 meters in hilly areas. Rexer & Hirt [23] reported RMSEs of 9.4 meters for ASTER and 6.8 meters for SRTM in hilly areas, mountainous areas. Hladik & Albert [24] used GNSS control points to assess the accuracy of salt marsh maps extracted from LiDAR data. Another method for error evaluation involves comparing reconstructed contour lines from both control points and DEMs [21]. Plotting the slope from control points and the DEM and comparing them is another estimation method frequently used to evaluate DEM accuracy [20, 25, 26].

Digital Elevation Models. To determine the optimal model for geoid modeling in the Turkestan region, the following digital elevation models (DEMs) were evaluated: AW3D30, ASTGTM003, ETOPO1, SRTM30, and GLO30 (Fig. 2).

The *ALOS World 3D (AW3D30)* Digital Elevation Model (DEM) is constructed using stereoscopic imagery from the Advanced Land Observing Satellite (ALOS) via its Panchromatic Remote-sensing Instruments for Stereo Mapping (PRISM). The process involves capturing three-angle (forward, nadir, backward) stereo images, which are then processed using photogrammetry to derive elevation data. This data is refined through filtering, interpolation, and void-filling to ensure consistency and accuracy before being mosaicked into a global DEM [27–29].

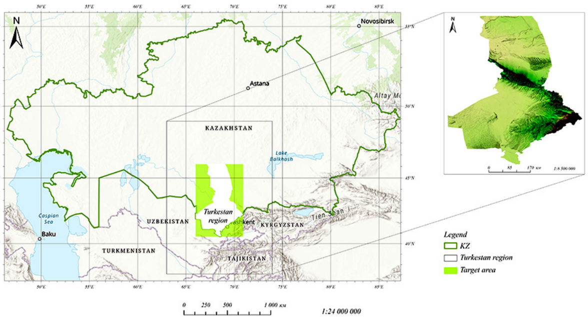


Fig. 1. Research area

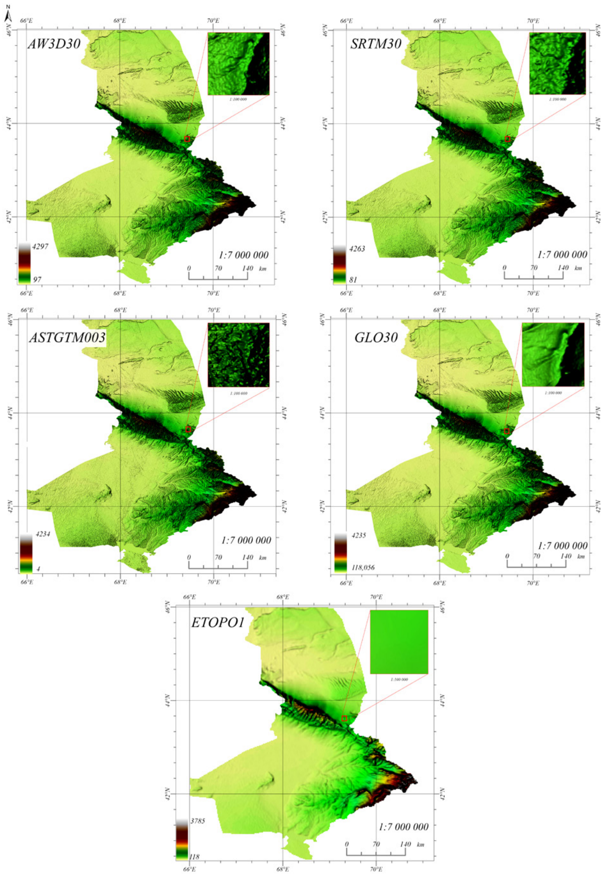


Fig. 2. Visualization of DEM models of the Turkestan region with the resolution view

Accuracy Indicators:

1. Horizontal Resolution: 30 meters.
2. Vertical Accuracy: 5 to 10 meters, varying with terrain.
3. Global Coverage: Between latitudes 82°N and 82°S.

AW3D30 is noted for its superior accuracy compared to other global DEMs like SRTM and ASTER, making it a reliable choice for detailed geospatial analysis.

The *ASTER Global Digital Elevation Model (ASTGTM003)* is constructed using stereoscopic imagery from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) aboard NASA’s Terra satellite. The process involves capturing near-infrared images from two telescopes at different angles (nadir and backward), enabling the generation of 3D elevation data through photogrammetric techniques. The data is processed to remove anomalies, fill voids, and integrate additional datasets, resulting in a global DEM [5].

Accuracy Indicators:

1. Horizontal Resolution: 30 meters (1 arc second).
2. Vertical Accuracy: 10 to 25 meters, depending on terrain complexity.
3. Global Coverage: Between latitudes 83°N and 83°S.

ASTGTM003 is widely used for its broad coverage and reasonable accuracy, particularly in regions where other DEMs may be less effective. Its continuous updates and integration of water body data enhance its reliability for various geospatial applications.

The *ETOPO1* Global Digital Elevation Model (DEM) is constructed by integrating a variety of data sources, including satellite radar data, shipborne sonar, and land topography datasets. Developed by NOAA’s National Geophysical Data

Center (NGDC), ETOPO1 combines these diverse datasets to produce a comprehensive global DEM that includes both land elevation and ocean bathymetry. The model is available in two versions: Ice Surface (including ice sheet topography) and Bedrock (underlying terrain) [32].

Accuracy Indicators:

1. Horizontal Resolution: 1 arc minute (~1.8 kilometers).
2. Vertical Accuracy: Generally, around 10 meters on land, with variable accuracy for bathymetric data depending on the data source.
3. Global Coverage: Complete global coverage, including land, ice, and ocean floor topography.

ETOPO1 is valued for its extensive coverage and integration of both terrestrial and marine elevation data, making it a key resource for studies requiring detailed topographic and bathymetric information.

The *SRTM30* (Shuttle Radar Topography Mission) Digital Elevation Model (DEM) is constructed using radar interferometry, which was employed during the Shuttle Radar Topography Mission in February 2000. The mission utilized dual radar antennas aboard the Space Shuttle Endeavour to capture high-resolution elevation data by measuring the phase difference between radar signals reflected from the Earth's surface. The collected data were processed to generate a global DEM [5].

Accuracy Indicators:

1. Horizontal Resolution: 3 arc seconds (~90 meters).
2. Vertical Accuracy: Approximately 16 meters, though this can vary depending on terrain and region.
3. Global Coverage: Between latitudes 60°N and 56°S.

SRTM30 is widely used due to its consistent coverage and reasonably high accuracy, particularly in low and mid-latitude regions. It has become a standard dataset for various geospatial and environmental applications, particularly in regions where higher-resolution DEMs are unavailable.

The GLO-30 Digital Elevation Model (DEM) is part of the Copernicus DEM, developed using data from the TanDEM-X mission, which involved two radar satellites flying in close formation to collect interferometric synthetic aperture radar (InSAR) data. The GLO-30 variant specifically provides global elevation data at a 30-meter resolution. The data undergoes extensive processing, including noise filtering, void filling, and smoothing, to produce a high-quality, consistent DEM [34].

Accuracy Indicators:

1. Horizontal Resolution: 1 arc second (~30 meters).
2. Vertical Accuracy: Ranges from 4 to 12 meters, depending on the terrain and region.
3. Global Coverage: Complete global coverage between latitudes 90°N and 90°S.

GLO-30 is highly regarded for its fine resolution and accuracy, making it suitable for a wide range of applications, from environmental monitoring to infrastructure planning. The dataset's consistency and global availability enhance its utility for detailed geospatial analysis.

Ground control data. To evaluate the accuracy of the DEM for the research area, Global Navigation Satellite System (GNSS) measurements were conducted. Reference heights for the control points were determined through extended statistical GNSS observations at ground reference points. The adjustment of the coordinates and heights resulted in a standard deviation ranging from 0.0010 to 0.017 meters horizontally and from 0.003 to 0.034 meters vertically.

For an accurate assessment of the Digital Elevation Model (DEM), the target area was divided into three distinct parts based on the topography variation: flat terrain, hilly terrain, and mountainous terrain (Figs. 3, 4).

The total number of control points was 344 (Fig. 4), of which:

- mountainous terrain – 32 points, the height ranges from 89.65 to 396.741 m;
- hilly terrain – 105 points, the height ranges from 400.535 to 791.187 m;

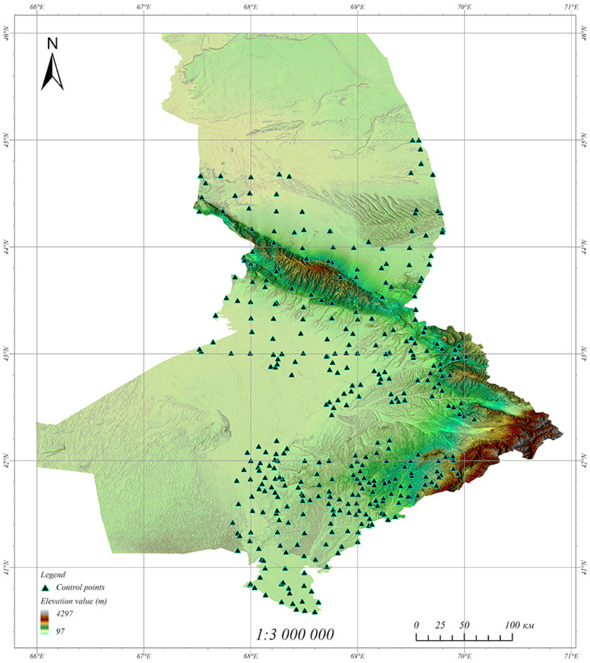
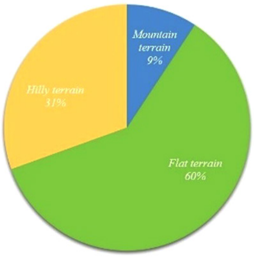


Fig. 3. Location of control points on the territory of the research area



Location	Points	Min height (m)	Max height (m)
flat terrain	**207**	89.65	396.74
hilly terrain	**105**	400.53	791.18
mountain area	**32**	825.03	2002.43
	344		

Fig. 4. The percentage of points belonging to a certain type of relief

- flat terrain – 207 points, the height ranges from 825.034 to 2,002.432 m.

Elevation variations in the target area were categorized based on the number of points and the terrain differences.

The classification of control points revealed that a majority of points are located on flat terrain (60.2 %), followed by hilly regions (30.5 %), and a smaller proportion in mountainous terrain (9.3 %).

Comparison of coordinate systems. The reference surface for the Digital Elevation Model (DEM) is the WGS84 ellipsoid. Heights are calculated relative to mean sea level (normal height, H) by applying height anomalies (N) derived from the EGM96 and EGM2008 geoid models (Table 1).

The Global Navigation Satellite Systems (GNSS) inherently calculates heights based on the WGS84 vertical datum [35, 36]. To compare GNSS/WGS84 height reference data (geodetic heights, h) with DEM, it is necessary to perform a vertical datum transformation, also known as datum matching. For this comparison, GNSS-based height points were transformed to ellipsoidal heights through geoid correction, ensuring consistency with the corresponding DEMs [37].

The relationship between the geodetic height (h), the normal height (H), and the height anomaly (N) at each given point was determined using the following expression

$$h = H + N.$$

In this study, the height anomalies values were calculated according to the EGM96 and EGM2008 models using the online service of the International Centre for Global

Table 1

DEM coordinate systems

No.	DEM	Horizontal data	Vertical data
1	AW3D30	WGS 84	WGS 84
2	ASTGTM003	WGS 84	EGM 96
3	SRTM30	WGS 84	EGM 96
4	ETOPO1	WGS 84	MSL
5	GLO-30	WGS 84	EGM 2008

Earth Models (International Centre for Global Earth Models (ICGEM)).

Methods for quality assessment. There are two main approaches to calculating the difference between the topographic surface and the DEM:

1. Interpolation of the DEM surface heights at given points of the topographic surface with known GNSS elevations.
2. Interpolation of the topographic surface heights at the grid nodes of the DEM elevation matrix.

In this study, the first approach was adopted to calculate the height difference. The elevation marks of the DEM surfaces at given points with known elevations of the Earth's surface were calculated by interpolating the model's elevation matrix using the coordinates of the points on the WGS-84 ellipsoid [1].

As part of the statistical data processing, an additive error model was used to analyze the differences in the heights obtained using the DEM (h_{DEM}) and the actual relief height (h_{GNSS}).

$$\Delta h = h_{DEM} - h_{GNSS}.$$

The primary indicators of the model's accuracy were:

- standard deviation estimate

$$STD_{\Delta H} = \frac{1}{n}\sum_{i=1}^{n}\Delta h_i;$$

- root mean square error (RMSE)

$$RMSE_{\Delta \acute{\imath}} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\Delta h_i^2};$$

- mean absolute error (MAE)

$$MEA_{\Delta \acute{\imath}} = \frac{1}{n}\sum_{i=1}^{n}\left|\Delta h_i\right|;$$

- minimum ($R_{\min}$) and maximum ($R_{\max}$) values of the height differences.

All the given formulas assume that the errors are normally distributed.

Results and discussion. Statistical indicators of vertical accuracy assessment revealed that GNSS measurements showed the strongest correlation with the GLO-30 model. This was followed in descending order of accuracy by the ASTGTM003, AW3D30, SRTM30, and ETOPO1 models (Table 2).

To compare the resolutions of the DEMs, two visualization methods were employed: hypsometry and hillshading (Fig. 5).

Hypsometry assigns a gray level to a range of elevations, creating a continuous grayscale that represents the vertical amplitude from the lowest point (black) to the highest point (white). Hillshading involves illuminating the ground surface with a virtual light source.

Statistical analysis of the errors between the actual relief height and the DEM (Table 3) was conducted for flat, hilly, and mountainous terrain within the experimental zone.

The standard deviation estimation indicated favorable values for the GLO30 and AW3D30 DEMs, with values of 1.232 and 2.092 m for flat terrain, 1.848 and 2.013 m for hilly terrain, and 2.224 and 1.657 m for mountainous terrain. These were followed by the SRTM30, ASTGTM003, and ETOPO1 models. In the mean absolute error calculations for mountainous terrain, the AW3D30 model exhibited the best performance with a value of 1.447 m, followed by GLO30, SRTM30, ASTGTM003, and ETOPO1. For other terrain types, the GLO30 model showed superior results with mean absolute error values of 0.866 m for flat terrain and 1.500 m for hilly terrain. The root mean square error also demonstrated higher accuracy for the AW3D30 model in mountainous regions, with a value of 1.631 m, while for flat terrains this value was 1.122 m, and for hilly terrains, it was 2.100 m, highlighting the GLO30 model's superiority.

Due to the high error values reflected in Table 3 and insufficient resolution as shown in Fig. 5, the ETOPO1 data were not considered for further analysis.

Based on the error statistics parameters at various locations within the experimental area, 384 points from each DEM were visualized in graphs to assess the quality of the obtained DEMs (Fig. 6).

The upward trend lines in the graphs indicate that ASTGTM003 and SRTM30 exhibit significant fluctuations, whereas AW3D30 demonstrates more stable behavior. The substantial variation in the elevations of some control points across different DEM surfaces suggests that steep slopes, gorges, and complex mountain slope aspects significantly impact the accuracy of the DEMs. Statistical analysis reveals that GLO30 exhibits the smallest fluctuation.

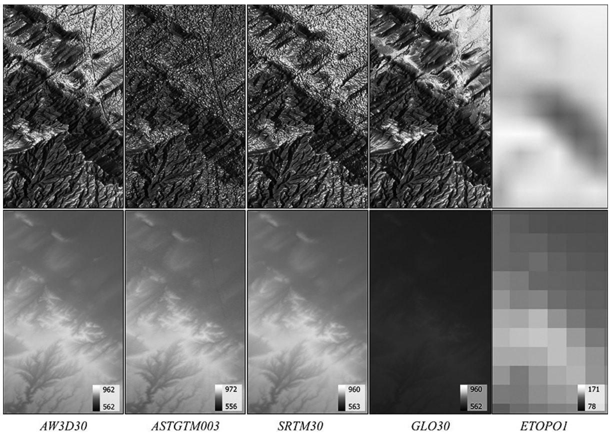
The differences between GLO-30 and AW3D30 DEMs across different terrain types are partly due to the different technologies and methodologies used to generate them. Signal acquisition and processing play a key role in generating surface models. Despite the efforts made to correct for inaccuracies, modeling mountainous regions remains a challenge for both radar and optical surveys. Radar surveys in such areas often result in data gaps requiring void-filling algorithms, while photogrammetric processing can introduce artifacts due to correlation errors. In urban areas, AW3D30 is inferior to GLO-30, likely due to interpolation of the photogrammetric point cloud without prior filtering of structures and vegetation [38].

Conclusions. The evaluation of the selected digital elevation models (ASTGTM003, AW3D30, ETOPO1, SRTM30, GLO30) was conducted by comparing the differences between the control points (384) and their height values interpolated from the DEM data of the studied sources. According to the results of calculating the height difference between the DEM and the reference points (Table 4), it is evident that GLO30 and AW3D30 yield better results than ASTER, SRTM30, and ETOPO1. Diagrams (Fig. 6) provide a detailed explanation by summarizing the relationship between the study results. The standard deviation ($STD_{\Delta H}$), mean absolute error ($MEA_{\Delta H}$), and root mean square error ($RMSE_{\Delta H}$) for the five different DEMs, presented in Table 4, indicate that GLO30 and AW3D30 DEMs are more suitable models compared to SRTM30 and ASTGTM003. The comparison line plot of

Table 2

Difference in heights between control points and DEM

Statistics	$STD_{\Delta H}$, m	$RMSE_{\Delta H}$, m	$MEA_{\Delta H}$, m	$R_{\min}$, m	$R_{\max}$, m
GNSS/ ASTGTM003	5.202	6.102	4.357	–46.363	11.609
GNSS/AW3D30	2.035	2.067	1.673	–5.780	7.050
GNSS/ETOPO1	37.847	43.508	35.560	–257.38	141.57
GNSS/SRTM30	3.201	4.163	3.009	–17.970	4.106
GNSS/GLO30	1.574	1.633	1.122	–8.068	2.904



AW3D30 ASTGTM003 SRTM30 GLO30 ETOPO1

Fig. 5. Comparison of hillshade (*top*) *and hypsometry* (*bottom*) *for estimating DEM resolution* (*1:200,000*), *m*

Table 3

Parameters of error statistics in different locations of the experimental zone

Slope	Statistics	ASTGTM003	AW3D30	ETOPO1	SRTM30	GLO30
Flat land	R, m	5.621	2.122	35.107	3.316	1.232
	$R_{\max}$, m	11.145	7.050	69.538	3.585	2.473
	$R_{\min}$, m	–18.512	–5.713	–10.483	–10.477	–6.075
	STD, m	4.587	2.092	11.386	2.525	1.225
	MEA, m	4.315	1.724	33.468	2.480	0.866
Hilly area	R, m	7.140	2.046	37.852	5.368	2.100
	$R_{\max}$, m	11.609	5.339	115.455	4.106	2.647
	$R_{\min}$, m	–46.363	–5.780	–86.062	–17.970	–7.617
	STD, m	6.439	2.013	36.186	4.071	1.848
	MEA, m	4.366	1.625	29.259	3.909	1.500
Mountainous area	R, m	5.899	1.631	91.637	5.241	2.413
	$R_{\max}$, m	8.634	3.395	141.572	3.349	2.904
	$R_{\min}$, m	–14.978	–2.789	–257.389	–12.618	–8.068
	STD, m	5.214	1.657	86.361	3.764	2.224
	MEA, m	4.641	1.447	72.052	4.056	1.817

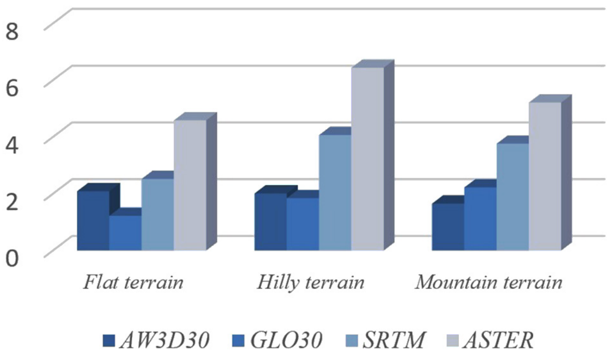


Fig. 6. Standard deviations of DEMs by locality

control points (384) with DEMs (Fig. 6) further shows that GLO30 is more suitable for flat and hilly terrain, while AW3D30 is better suited for mountainous terrain. Based on the study results, it can be concluded that GLO30 and AW3D30 are more suitable models for this experimental area.

The analysis of digital elevation models demonstrates that GLO30 and AW3D30 are the most suitable for constructing a geoid model among all the considered DEMs, due to their higher resolution and the most accurate matches to the reference elevation data.

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Оцінка точності цифрових моделей рельєфу для моделювання локальних геоїдів

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Одним із найважливіших факторів, що впливають на точність локальної моделі геоїда, є якість цифрової моделі рельєфу (ЦМР). Правильно підібрана ЦМР із високою роздільною здатністю може значно зменшити помилки при моделюванні геоїда, обробці гравітаційних аномалій і корекції рельєфу та низхідного простягання.

Мета. Оцінка точності п›яти глобальних ЦМР, отриманих із відкритих джерел, для визначення найбільш придатної моделі для створення локального геоїда.

Методика. Вертикальна точність матриць висот оцінювалася шляхом порівняння висот між матрицею висот і контрольними точками на різних типах місцевості. Реперні значення базуються на 344 наземних опорних точках, де були проведені GNSS спостереження з подальшим коригуванням координат і висот. Аналіз точності включав розрахунок статистичних показників різниці висот між даними GNSS і даними ЦМР.

Результати. Оцінка середньоквадратичного відхилення показала сприятливі значення для ЦМР COPERNICUS і ALOS, за ними йдуть SRTM, ASTER та ETOPO. У розрахунках середньої абсолютної похибки для гірських районів найкраще себе зарекомендувала модель ALOS, за нею йдуть COPERNICUS, SRTM, ASTER та ETOPO. Для інших типів місцевості найкращі результати за середньою абсолютною похибкою продемонструвала модель COPERNICUS.

Наукова новизна. Це дослідження вирізняється тим, що у ньому використані сучасні ЦМР із високою роздільною здатністю, такі як GLO30, що забезпечує сучасну й ретельну оцінку точності ЦМР спеціально для Казахстану. Новим є детальний аналіз впливу особливостей рельєфу місцевості (рівнинний, пагорбовий, гірський) на точність моделювання. Цей підхід виходить за рамки попередніх оцінок, надаючи нове й важливе розуміння продуктивності сучасних ЦМР.

Практична значимість. Практична цінність отриманих результатів полягає у винесенні рекомендацій щодо можливості використання досліджуваних ЦМР для регіонів Казахстану, що різняться між собою за ландшафтними характеристиками. Отримані результати показують, що ЦМР COPERNICUS і ALOS дуже добре підходять для точного моделювання геоїдів на півдні Казахстану. Ці моделі можуть значно підвищити точність локальних моделей геоїдів, що сприятиме застосуванню в геопросторовій науці та інженерії.

Ключові слова: *цифрова модель рельєфу, геоїд, оцінка точності, ASTER, ALOS, ETOPO, SRTM, COPERNICUS*

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