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DEVELOPMENT OF A LOCAL QUASI-GEOID MODEL OF ALMATY CITY USING THE FAST COLLOCATION METHOD

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Abstract. In mountainous regions with pronounced gravity-field heterogeneity and complex topography, global geopotential models fail to deliver the required centimeter-level height consistency, while geometric leveling is economically and technologically demanding. Accordingly, a locally optimized quasigeoid model that reflects regional gravity and topographic features is needed. This study develops a high-accuracy and computationally efficient local quasigeoid using Fast Collocation. The long-wavelength component is taken from XGM2019e_2159, topographic effects are accounted for with the FABDEM DEM, and the short-wavelength signal is reconstructed from 14,061 terrestrial gravity points. The workflow includes rational data screening against ground measurements, covariance-function parameterization accounting for heterogeneity, outlier suppression, and regularization to ensure robustness under sparse coverage. Validation against independent GNSS/leveling benchmarks yields RMSE = 0.055 m and STD = 0.048 m, more than twice as accurate as global solutions EGM2008 and XGM2019e_2159. The resulting model enables stable, high-precision transformation of GNSS ellipsoidal heights to normal heights, contributing to the regional height system and providing a practical basis for engineering-geodetic, land management, and cadastral applications.

Keywords: quasi-geoid, global geopotential model, orthometric height, height anomaly, digital elevation model, Fast Collocation

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АЛМАТЫ ҚАЛАСЫНЫҢ ЖЕРГІЛІКТІ ГЕОИД МОДЕЛІН ЖЫЛДАМ КОЛЛОКАЦИЯ ӘДІСІМЕН ӘЗІРЛЕУ

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Аннотация. Гравитациялық өрістің біркелкі еместігі және күрделі рельефі бар таулы аймақта жаһандық геопотенциалдық модельдер биіктіктердің қажетті сантиметрлік консистенциясын қамтамасыз ете алмайды, ал геометриялық нивелирлеу экономикалық және технологиялық тұрғыдан қымбатқа түседі. Сондықтан аймақтық гравитация өрісі мен топографиялық ерекшеліктерін ескеретін жергілікті квазигеоидты модельді құру өзекті мәселе болып есептеледі. Бұл зерттеудің мақсаты Fast Collocation әдісін пайдалана отырып, жоғары дәлдікпен және есептеу тиімді жергілікті квазигеоидтық модельді жасау. Ұзын толқынды компонент XGM2019e_2159 көмегімен модельденеді, топографиялық әсерлер FABDEM DEM көмегімен есепке алынады. Қысқа толқынды құрамдас 14 061 жердегі гравиметриялық нүктеден қалпына келтірілді. Әдістеме жердегі өлшемдермен сәйкестікке негізделген деректерді ұтымды іріктеуді, әртектілікті ескеретін ковариация функцияларын параметрлеуді, шектен тыс мәндерді басуды және сирек қамту жағдайында орнықтылық үшін регуляризацияны қамтиды. Тәуелсіз ГНСС/нивелирлеу пункттері бойынша валидация RMSE = 0,055 м және STD = 0,048 м нәтижелерін көрсетті, бұл EGM2008 және XGM2019e_2159 сияқты ғаламдық шешімдерден екі еседен астам дәлірек. Алынған модель GNSS эллипсоидтық биіктіктерін нормаль биіктіктерге тұрақты әрі жоғары дәлдікпен түрлендіреді, өңірлік биіктік жүйесін дамытуға үлес қосады және инженерлік-геодезиялық, жерге орналастыру және кадастрлық жұмыстар үшін практикалық негіз болып табылады.

Түйін сөздер: геоид, жаһандық геопотенциал моделі, ортометриялық биіктік, биіктік аномалиясы, цифрлық бедер моделі, Fast Collocation

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РАЗРАБОТКА ЛОКАЛЬНОЙ МОДЕЛИ ГЕОИДА ГОРОДА АЛМАТЫ МЕТОДОМ БЫСТРОЙ КОЛЛОКАЦИИ

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Аннотация. В условиях горного региона с выраженной неоднородностью гравитационного поля и сложным рельефом, глобальные геопотенциальные модели не обеспечивают требуемой сантиметровой согласованности высот, тогда как проведение геометрического нивелирования является экономически и технологически затратной процедурой. В связи с этим актуальной задачей является построение локальной модели квазигеоида, учитывающей региональные особенности гравитационного поля и топографии. Цель данной работы — разработка высокоточной и вычислительно эффективной локальной модели квазигеоида методом быстрой коллокации (Fast Collocation). Долговолновая компонента моделируется на основе модели XGM2019e_2159, топографические эффекты учитываются с использованием цифровой модели рельефа FABDEM, а коротковолновая составляющая восстанавливается по 14 061 наземной гравиметрической точке. Реализация включает рациональный отбор исходных данных по согласованности с наземными измерениями, параметризацию ковариационных функций с учётом неоднородности, а также подавление выбросов и регуляризацию для устойчивости к разреженному покрытию. Валидация по независимым пунктам ГНСС/нивелирования показала RMSE = 0,055 м; STD = 0,048 м, что более чем в два раза превосходит по точности глобальные решения EGM2008 и XGM2019e_2159. Полученная модель обеспечивает устойчивую, высокоточную трансформацию эллипсоидальных высот ГНСС в нормальные, вносит значимый вклад в развитие региональной системы высот, и служит практической основой для инженерно-геодезических, землеустроительных и кадастровых работ.

Ключевые слова: геоид, глобальная модель геопотенциала, ортометрическая высота, аномалия высот, цифровая модель рельефа, быстрая коллокация (Fast Collocation)

Introduction. The development and implementation of a local quasi-geoid model for the Republic of Kazakhstan is a key step toward modernizing the national geodetic and cartographic infrastructure. In practice, the global model EGM2008 is still widely used; while it reliably represents the long-wavelength component, without regional adaptation it does not ensure centimeter-level consistency in mountainous and foothill areas or for high-precision applications. A local quasi-geoid is therefore critical for both applied and scientific tasks, including:

− correct transformation of GNSS ellipsoidal heights to orthometric heights;
− establishment of a unified vertical datum;
− analysis of the gravity field;

− accounting for tectonic motions and deformations;
− maintenance of a modern vertical reference system, etc.

The introduction of a national model will significantly reduce the scope of spirit leveling, lower project costs, and improve the repeatability of results across the country, making its development a priority of state geodetic policy.

Figure 1 shows the study area, bounded by 42.5° – 44° N and 76° – 77.5° E. The inner rectangle denotes the computational domain; the outer frame is a 1° spherical-distance buffer used to provide boundary conditions and robust interpolation during modeling. Almaty Region exhibits substantial gravity anomalies driven by the mountainous terrain of the Trans-Ili Alatau (Zailiysky Alatau). The complex relief, together with the region's active tectonics, complicates the use of global models and traditional leveling methods. The Trans-Ili Alatau, a range of the Tian Shan system, is characterized by high peaks and strong relief contrasts, with elevations reaching up to 5000 m. The study area lies within a zone of high tectonic activity; ongoing geodynamic processes affect the gravity field, generating local anomalies that must be accounted for in quasi-geoid modeling.

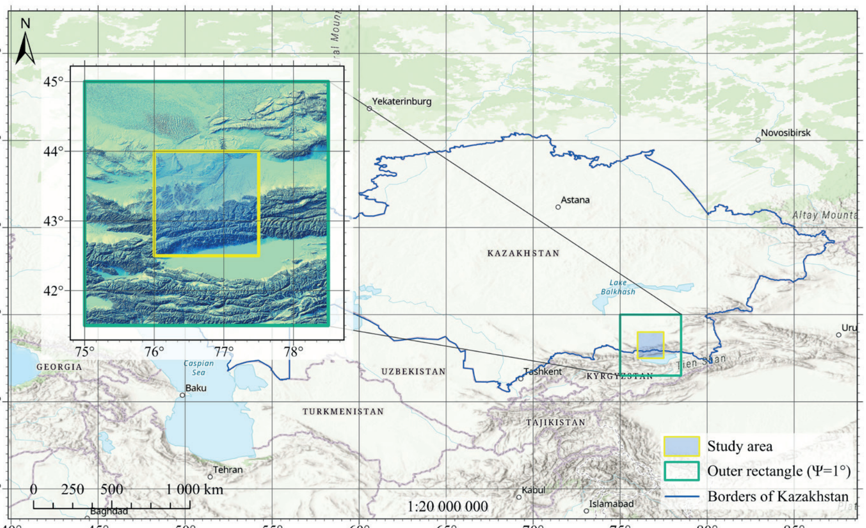


Figure 1 – Boundaries of the study area. Outer buffer at spherical distance Ψ = 1°

A substantial portion of the study region consists of piedmont (foothill) plains, which complicates geoid modeling and requires high-precision computations, especially across transition zones from plains to mountains. The gravity field likewise exhibits variations driven by lateral density contrasts in subsurface rocks. Although global models such as EGM2008 and XGM2019e_2159 provide sufficient accuracy for global purposes, they are not fully suitable for regional applications in rugged terrain (El Shouny et al., 2018). Developing a local geoid model can overcome these limitations, deliver higher accuracy, and in many cases reduce dependence on labor-intensive and costly leveling, thereby significantly lowering the cost of geodetic and cadastral surveys.

One effective approach to quasi-geoid computation is the Least-Squares Collocation (LSC) method. Practical experience shows that, in regions with dense and high-quality gravity coverage, LSC can achieve centimeter-level quasi-geoid accuracy (Szelachowska & Krynski, 2014). Under sparse data conditions, performance is governed by the quality of the covariance modeling and the input datasets (Ramouz et al., 2019).

The LSC method accounts for observations taken at different elevations via a spatial covariance function. A key limitation of LSC, however, is the need to solve systems of equations whose size scales with the number of input data. Given Kazakhstan's vast area, processing such volumes becomes computationally demanding. Numerous techniques have been proposed to optimize LSC for large datasets.

One of the best-known accelerated variants for quasi-geoid modeling is Fast Collocation (FastColl). This approach assumes regularly gridded, homogeneous data, yielding a special structure of the covariance matrix. The autocovariance matrix exhibits Toeplitz symmetry, and each block is itself Toeplitz -i.e., a block Toeplitz with Toeplitz blocks structure. This enables efficient solutions of the collocation problem for large datasets, allowing extensive areas to be treated in a single step without partitioning the data into subsets (Bottoni & Barzaghi, 1993).

Materials. To construct the local quasi-geoid model, the following datasets were use:

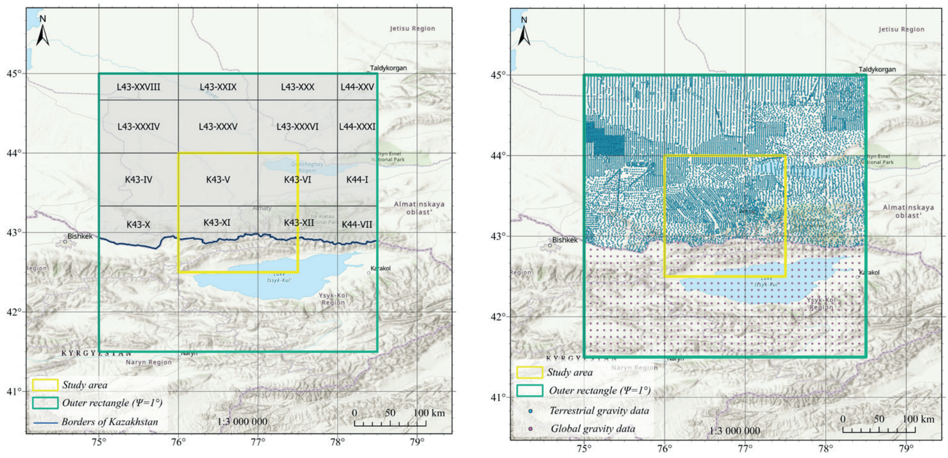
- a combined dataset comprising 14061 terrestrial gravity observation points with gravity-anomaly values together with the global model WGM2012 (shown in Figure 2). The global model is employed to bridge gaps in areas lacking observations;
- GNSS/Leveling data;
- spherical harmonic coefficients of the XGM2019e_2159 global geopotential model;
- the FABDEM digital elevation model.

Additionally, all datasets used in the computations were prepared on a domain expanded by an outer spherical-distance buffer of $\Psi = 1°$ around the study area.

Gravity data. The source dataset for constructing the local geoid model was compiled from a dense network of terrestrial gravity observations in southeastern Kazakhstan. The digital database incorporates scanned Soviet gravimetric maps at scales of 1:200000 (as well as 1:50000 and larger for prospective areas) with Bouguer reduction: a primary layer using a density of 2.67 g/cm³ with terrain correction applied; maps with a density of 2.30 g/cm³ were used only where 2.67 g/cm³ data were unavailable. The catalog contains 14,061 digitized points, providing high spatial detail of the gravity field across the study area; nationwide, approximately 90 % of the territory is covered by 1:200000 surveys conducted with gravimeters SN-3, GAK, and GR-2K.

Scanning was performed at 600 dpi, with georeferencing by intersections of the coordinate grid (Pulkovo 1942, Gauss–Krüger projection) and subsequent transformation to WGS 84 (Pulkovo_1942_To_WGS_1984_16). Quality control included constructing a check surface by Kriging (grid step 250 × 250 m) and comparing the resulting isoanomaly contours with the original maps; anomalous or questionable points were flagged in the database. Georeferencing accuracy requirements were met within 0.1–0.3 mm at the scale of the source map.

The gravity database for the study area was compiled by digitizing 14061 observation points extracted from the following map sheets: L-43-XXVIII, L-43-XXIX, L-43-XXX, L-44-XXV, L-43-XXXIV, L-43-XXXV, L-44-XXXI, K-43-IV, K-43-V, K-43-VI, K-44-I, K-43-X, K-43-XI, K-43-XII, K-44-VII. The selection and spatial coverage of the utilized sheets are shown in Figure 2(a).



a) b)

Figure 2 – a) Cartogram of digitized gravimetric maps at a scale of 1:200000 for the study area. b) Gravity dataset compiled from terrestrial and global sources

To stabilize interpolation in areas with sparse terrestrial data (border sections and regions outside the Republic of Kazakhstan), the dataset was locally supplemented with the global model WGM2012 (5′×5′ grid, 738 points), see Figure 2(b). These data were used locally (on specific sections) and did not replace terrestrial observations.

As a result, for constructing the local quasi-geoid model, a combined gravity database was prepared comprising terrestrial data with a density of 14061 points (≈ 18.0 per 100 km²) and global data on a 5′×5′ grid (738 points).

GNSS/Leveling data. For independent evaluation of the DEM and the constructed quasi-geoid model, as well as for comparison with global models, two GNSS/leveling datasets were used, totaling 49 geodetic control points co-located with second–third-class leveling lines and first-class triangulation nodes. The first dataset consists of 40 points obtained from the open-source QazTRF-23 (ggo.gov.

kz); the second dataset consists of 9 points from the Almaty Geodynamic Polygon (AGP).

Sources and observations.

- 40 points were obtained from the official geoportal "State Geodetic Control" (NIPD) and are part of the national coordinate reference system QazTRF-23. This system comprises points of the Astronomical–Geodetic Network of 1st and 2nd classes; the Geodetic Densification Network of 3rd and 4th classes; as well as the State Leveling Network of classes III and IV, fully covering the territory of the Republic of Kazakhstan (ggo.gov.kz).

- The subset of 9 points belongs to the Almaty Geodynamic Polygon (AGP) - BERE, CHIB, GORN, KARK, KART, KOTU, KURS, PRGD, UZBK - which are first-class triangulation points co-located with a second-class leveling line. Static GNSS observations with dual-frequency receivers were carried out at these points. Session duration was no less than 24 hours with a 30-second sampling rate. Post-processing of the acquired data was performed using GAMIT/GLOBK. The fieldwork minimized ionospheric and tropospheric distortions, and the office processing yielded adjusted point coordinates with high accuracy.

The use of two datasets is due to the need to verify results against benchmark indicators. In this case, the AGP points serve as a high-precision reference for subsequent validation of the local quasi-geoid model. The points are located in the area of the city of Almaty and the adjacent foothills, covering both plain and mountainous sections (Figure 3).

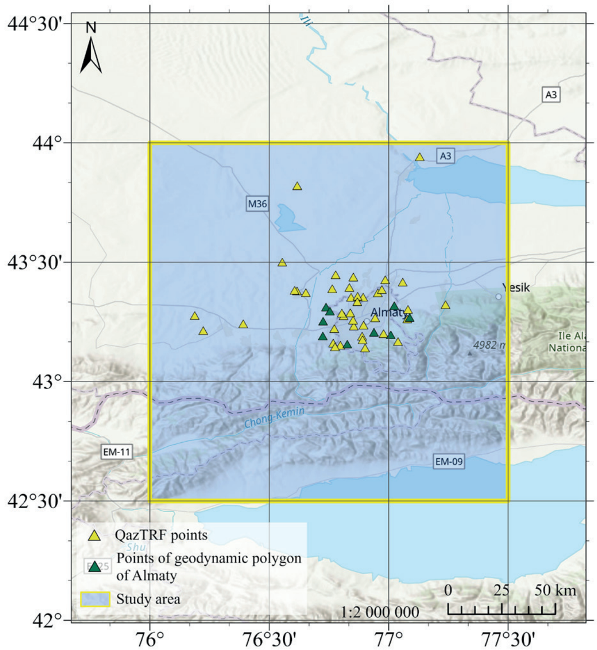


Figure 3 – Spatial distribution of GNSS/leveling benchmarks of II–III order

For each station, geographic coordinates, normal height (BSV-77) and ellipsoidal height (GNSS) are available. The range of normal heights is ≈ 626–1466 m; the range of ellipsoidal heights is ≈ 581–1424 m; he median is ≈ 695 m; The difference $\zeta = h - H$ (pointwise estimate of the quasi-geoid height) varies from ≈ -45.849 m, to ≈ -41.974 m.

Global geopotential models. The assessment and selection of a global geopotential model (GGM) is a critical stage that determines the quality of the long-wavelength component within the remove–restore scheme. Any systematic errors in this component propagate directly into the residual field, affecting the stability of covariance modeling, the correctness of topographic reductions, and the consistency of height systems. Under complex topography and an uneven terrestrial network, a properly chosen GGM reduces biases and spectral leakage.

For selecting the reference GGM, the ICGEM service was used (ICGEM), which provides a catalog and an online calculator of global gravity models, as well as descriptions of model inputs and parameters, thereby facilitating comparative analysis (Liang et al., 2020; Pail, 2023). The evaluation considered five GGMs: SGG-UGM-2 (2020), XGM2019e_2159 (2019), GECO (2015), EIGEN-6C4 (2014), and EGM2008 (2008).

Combining satellite and terrestrial data enables high-quality global models that underpin regional modeling. A classical reference still widely used in Kazakhstan is EGM2008 (complete to degree and order 2190), a combined spherical harmonic model derived by least squares from satellite and ground gravity data (Pavlis et al., 2012). The 2014 model EIGEN-6C4 merged observations from the GOCE, GRACE, and LAGEOS missions with terrestrial gravimetry, improving the long-wavelength component (Förste et al., 2015). The XGM2019e model extended the resolution to 5540 by combining the satellite solution GOCO06s with the NGA terrestrial gravity anomaly grid and supplemental datasets EARTH2014 and DTU13 (Zingerle et al., 2020).

Digital elevation models. The correct choice of a digital elevation model (DEM) is a key factor for the accuracy of a local quasi-geoid model. DEM elevations are involved at several stages at once: the formation of topographic reductions, RTM computations, and downward continuation; any systematic biases or noise in the terrain inevitably propagate into gravity anomalies and, subsequently, into the quasi-geoid surface (Urazaliyev et.al. 2024). In mountainous and foothill areas, DEM errors are amplified by steep slopes and high terrain variability; therefore, under such conditions, the quality requirements for the input DEM are the most stringent (Jalal et al., 2019; Polidori & El Hage, 2020).

To select a suitable model, the following DEMs were used in this study: FABDEM v1.2 (30 m) - the primary DEM for RTM/topographic reductions. A bare-earth product (buildings and vegetation removed), which reduces positive bias in urban/forested areas; independent validation over a complex forested mountain catchment against UAV–LiDAR confirms its suitability for rugged terrain (Marsh et al., 2023); Copernicus GLO-30 (30 m) - reserve/validation and gap filling. Comparisons with ICESat-2 across diverse terrain types indicate high quality and stability relative to alternatives (Li et al., 2022); NASADEM (30 m) - alternative source for sensitivity tests. An updated SRTM with radar calibration, systematic void filling, and auxiliary inputs; used to assess the impact of gap-filling algorithms on RTM (Crippen et al., 2016); MERIT DEM (≈90 m) - sensitivity experiments/hydrologic masking. A hydrologically improved DEM with multiple SRTM/AW3D error corrections, shown to reduce systematics in global tests (Yamazaki et al., 2017); SRTM30 (3″ ≈ 90 m) - a C-band radar DEM from the Shuttle-2000 mission, used as a global comparison reference and for sensitivity tests; for RTM it is limited by its coarser grid and radar artifacts in mountainous areas.

Computational methodology. *Selection of the optimal GGM.* To select the optimal geopotential model, Bouguer anomalies derived from 14061 terrestrial gravity stations were compared. For each station, Bouguer anomaly values were computed using the ICGEM online calculator, followed by comparison with the terrestrial measurements (ICGEM). The following formula was used:

$$\Delta g_B = g_{Ter} - g_{GGM}, \quad (1)$$

where, g_{Ter} is the Bouguer anomaly at terrestrial observation points and g_{GGM} is the Bouguer anomaly from the global geopotential models.

The summary results (RMSE, STD, Min/Max, Mean) are presented in Table 1. Comparative plots for the five GGMs are shown in Figure 5. Based on the criterion of minimizing RMSE (with similar STD values), the GGM optimal for the study area was selected.

Selection of the optimal DEM. The global digital elevation models FABDEM, Copernicus, SRTM30, NASADEM, and MERIT were compared. Normal and ellipsoidal heights were obtained from 49 GNSS/leveling control points shown in Figure 4. For a correct comparison, the models were brought to uniform horizontal and vertical reference systems (geodetic datum WGS84, orthometric heights). Vertical system consistency was enforced using the relation:

$$h_{DEM} = H_{DEM} + N_{GGM}. \quad (2)$$

The geoid heights (N_{GGM}) were obtained from the EGM96 and EGM2008 models using the ICGEM service (Table 1).

Table 1 – Horizontal and vertical reference systems of the DEMs

№	DEM	Horizontal datum	Vertical datum
1	FABDEM	WGS84	EGM2008
2	Copernicus	WGS84	EGM2008

3	NASADEM	WGS84	EGM1996
4	SRTM	WGS84	EGM1996
5	MERIT	WGS84	EGM1996

Next, to compare and analyze the height differences, the additive error model approach was applied:

$$\Delta h = h_{GNSS} - h_{DEM}. \tag{3}$$

The orthometric heights from the DEM at control points with ground surface marks were determined by interpolating the DEM grid at the point coordinates on the WGS 84 ellipsoid.

Quasi-geoid computation. Least-Squares Collocation (LSC) within the Remove–Compute–Restore (RCR) scheme to estimate gravity-field quantities (e.g., height anomalies) with consistent error measures. Global and topographic contributions are first removed so that the residual field is smooth and of low variance; LSC is then performed on residuals, followed by restoration of the removed parts. The observation model after removal is

$$\delta Y = AX + L(T_{res}) + E, \tag{4}$$

where δY are residual observations, A the design matrix, X nuisance parameters, L(·) linear functionals of the residual disturbing potential T_{res}, and E observation errors.

A covariance model is required for LSC. We use the Tscherning–Rapp covariance for the disturbing potential,

$$cov(T_P, T_Q) = a \sum_{i=2}^{N} \left[\frac{R_E^2}{r_P r_Q}\right]^{i+1} \sigma_i^2 P_i(\cos\psi) + \sum_{i=N+1}^{\infty} \left[\frac{R_B^2}{r_P r_Q}\right]^{i+1} \frac{A}{(i-1)(i-2)(i+4)} P_i(\cos\psi), \tag{5}$$

with unknown scale factors α, a and Bjerhammar radius R_B estimated by iterative non-linear adjustment. Let $\bar{C} = \{cov(L_i, L_j) + \sigma_{ij}\}$ be the observation covariance (including noise σ_{ij}). The least-squares estimate and LSC prediction are

$$\hat{X} = (A^T \bar{C}^{-1} A)^{-1} (A^T \bar{C}^{-1} \delta Y), \tag{6}$$

$$\hat{T}_{res}(P) = C_P^T \bar{C}^{-1} (\delta Y - A^T X), \tag{7}$$

$$\hat{\zeta}_{res}(P) = \frac{\hat{T}_{res}(P)}{\gamma}, \tag{8}$$

and the full height anomaly is restored by

$$\hat{\zeta} = \hat{\zeta}_{GGM} + \hat{\zeta}_{RTM} + \hat{\zeta}_{res}. \tag{9}$$

The global signal was removed using XGM2019e_2159 complete to degree 1000, and the topographic signal via RTM computed from FABDEM; results were then restored per (Eq.10) (Shali et al., 2020).

Results and Discussion. *Accuracy Assessment of GGMs.* Selection of the optimal GGM was carried out by comparing the values of the standard deviation and the root mean square error obtained from the differences in Bouguer anomalies. The statistics are given in Table 2.

Table 2 – Statistics of differences in Bouguer anomaly between the GGM and terrestrial stations ($g_{Ter} - g_{GGM}$), mGal

mGal	SGG-UGM-2	XGM2019e_2159	GECO	EIGEN-6C4	EGM2008
Min	-79.185	-79.301	-71.992	-78.387	-76.107
Max	93.819	88.625	99.974	93.441	98.972
Mean	18.291	17.620	18.262	18.256	17.880
STD	10.965	11.322	12.182	10.963	11.419
RMSE	21.326	20.944	21.952	21.295	21.215

The results of comparing the statistical measures obtained from the differences between terrestrial and global data are shown in Figure 4.

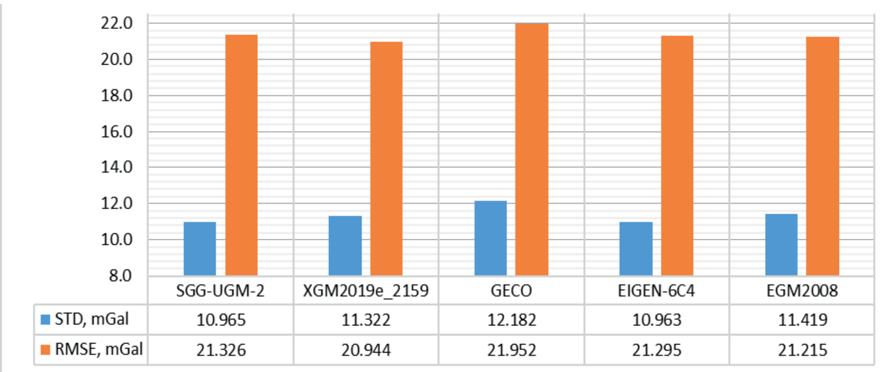


Figure 4 – Comparison chart of standard deviation (STD) and root mean square error (RMSE) between Bouguer anomaly values from various GGMs and terrestrial observations

Within the study area, the best agreement with the terrestrial data was achieved by the XGM2019e_2159 model (STD = 11.322 mGal; RMSE = 20.944 mGal). GECO and EGM2008 exhibit somewhat larger errors; EIGEN-6C4 and SGG-

UGM-2 are similar in quality but inferior in RMSE. Considering these statistics, XGM2019e_2159 was adopted for subsequent computations.

Accuracy Assessment of DEMs. According to formulas (2) and (3), the measured elevations were compared with the values from the DEMs. Table 3 presents the statistics of discrepancies between the heights h_{GNSS} and the reference heights h_{DEM}.

Table 3 – Statistics of differences between h_{GNSS} and h_{DEM}, m

Statistics, m	Fabdem	Copernicus	SRTM30	NasaDem	Merit
min	-3.798	-6.012	-5.366	-6.904	-7.929
max	6.691	5.748	11.685	12.136	24.149
mean	0.937	-0.090	2.333	1.250	0.880
std	2.337	2.526	4.068	4.124	6.226
rmse	2.491	2.496	4.645	4.260	6.211

As seen in Figure 5, within the study area the smallest errors are obtained for FABDEM and Copernicus; the RMSE difference between them is minimal (0.005 m), indicating a comparable level of accuracy. NASADEM and SRTM30 perform worse on both metrics, while MERIT shows the largest deviations.

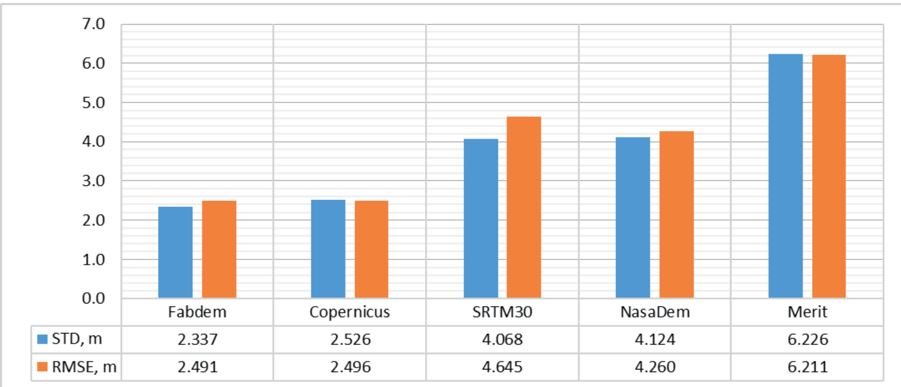


Figure 5 – Plot of statistical parameters (RMSE and STD) of errors across different terrains of the study area

Based on these comparisons, FABDEM was selected as the DEM for computing the quasi-geoid model.

Quasi-geoid computation. Within this study, a quasi-geoid model $N_{FastColl}$ was developed using the spherical harmonic coefficients of the XGM2019e_2159 geopotential model, the FABDEM digital elevation model, and 14061 terrestrial gravity stations, in combination with the WGM2012 model.

The statistics of the residual gravity anomalies are presented in Table 4.

Table 4 – Statistics of residual gravity anomalies, in m

Data	Anomalies	Δg, mGal	Δg^{GGM}, mGal	Δg^{RTM}, mGal	Δg^{ERTM}, mGal
Terrestrial	Mean	-40.390	0.790	1.011	1.451
	STD	55.386	19.233	14.440	8.057
	Min	-150.881	-183.726	-174.611	-57.377
	Max	-40.390	118.965	81.125	60.129
Global	Mean	10.992	-2.521	-0.308	4.352
	STD	89.429	37.419	26.281	21.336
	Min	-147.606	-124.540	-121.544	-85.978
	Max	197.298	101.194	62.025	84.294

As can be seen from table 1, removing the global gravitational and topographic effects from the gravity anomalies substantially smooths the gravity signal. In particular, subtracting the GGM contribution reduces the standard deviation (STD) of the observed (terrestrial) gravity data by approximately 65% (and by about 58% for the global dataset). After removing topographic effects using the RTM technique, the STD is reduced by up to 85% (and by about 76% for the global dataset). The distribution plot of the residual gravity anomalies (Δg_{res}) is shown in Figure 6.

An essential step in achieving an optimal LSC solution is the specification of an appropriate local covariance function that represents the stochastic characteristics of the gravity field in the study area. After removing the global and topographic effects, the residual gravity anomalies were used as input to identify the best-fitting covariance parameters. The empirical covariance was computed from all terrestrial data and fitted with a dedicated covariance model (uniform covariance).

The Tscherning–Rapp TR1974 model was selected to define the analytical covariance function applicable in the LSC procedure.

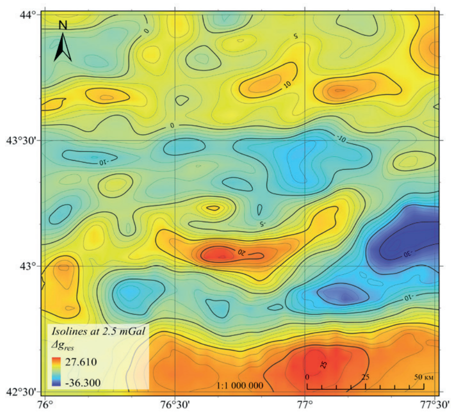


Figure 6 – Residual gravity anomalies after removal of the global gravity model and residual terrain model contributions using XGM2019e_2159 (truncated at degree 1000) and FABDEM, respectively, mGal

This model accounts for the local structure of the Earth's gravity field in the study area by fitting the empirical covariance derived from the residual gravity anomalies. The empirical covariance and the corresponding fitted model were determined by trial-and-error tuning, testing different parameter values and selecting those that make the discrepancies between the LSC predictions and control values smaller and more nearly stationary, as illustrated in Figure 7.

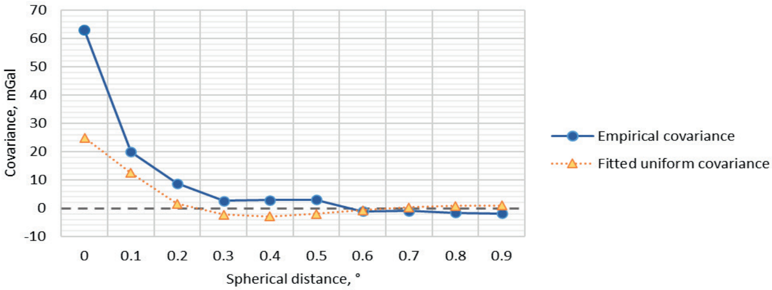


Figure 7 – Empirical covariance and fitted uniform covariance

After specifying the covariance using residual gravity anomalies, the residual height anomalies were computed, the GGM and terrain contributions were then restored, and, finally, the resulting height anomalies were converted to quasi-geoid heights. The quasi-geoid modeled by the FastColl method is shown in Figure 8.

According to Figure 8, which presents the quasi-geoid model for the study area constructed using the Fast Collocation method, the quasi-geoid heights vary from -46.418 m to -36.275 m. The map clearly shows a gradual increase in quasi-geoid height toward the mountainous terrain, consistent with general geophysical patterns in regions with pronounced relief. This variation reflects the influence of mountain masses on the Earth's gravity field, leading to higher quasi-geoid values in those areas.

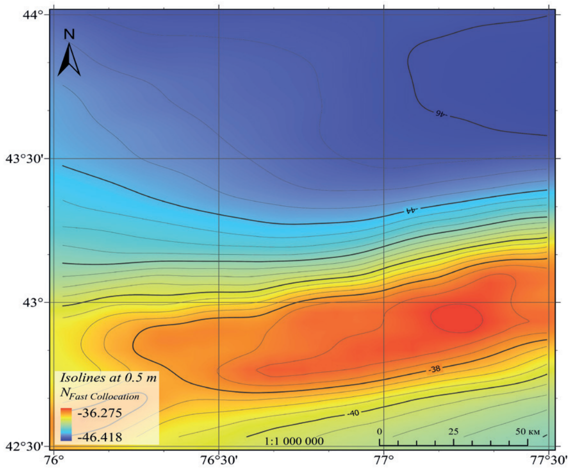


Figure 8 – Quasi-geoid heights from the Fast Collocation method, $N_{FastColl}$, m

The accuracy of the developed models was evaluated by interpolating height anomalies at GNSS/leveling control points. Model errors at the control points were computed as the differences between the height anomalies derived from GNSS/leveling ($\zeta_{quasi\text{-}geoid}$) and those predicted by the model ($\zeta_{GNSS/Lev}$):

$$\Delta\zeta = \zeta_{GNSS/Lev} - \zeta_{model}. \quad (10)$$

Computational accuracy is typically assessed using the standard deviation (STD) and the root-mean-square error (RMSE), which quantify the differences between the gravimetric and geometric models of the quasi-geoid. The comparative results are summarized in Table 5 and Figure 9.

Table 5 – Statistics of differences between height anomalies $\zeta_{GNSS/lev}$ and $\zeta_{Quasi\text{-}geoid.}$

Method	Min, m	Max, m	Mean, m	STD, m	RMSE, m
FastColl	-0.347	0.284	-0.034	0.091	0.096
XGM2019e_2159	-0.444	0.130	-0.168	0.130	0.212
EGM2008	-0.206	0.447	0.104	0.146	0.178

Table 5 presents the comparative statistics between the quasi-geoid model $\zeta_{FastColl}$ and the global models for two datasets (49 points). Figure 9 shows the errors of the three models, indicating the dominance of the local model over the global ones, especially at the 9 AGP points.

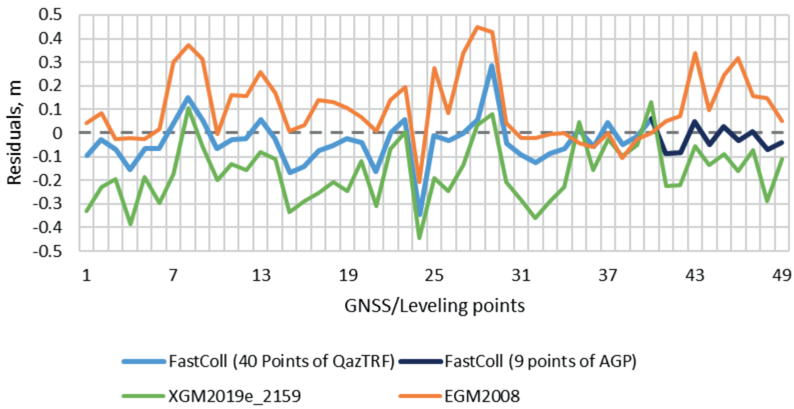


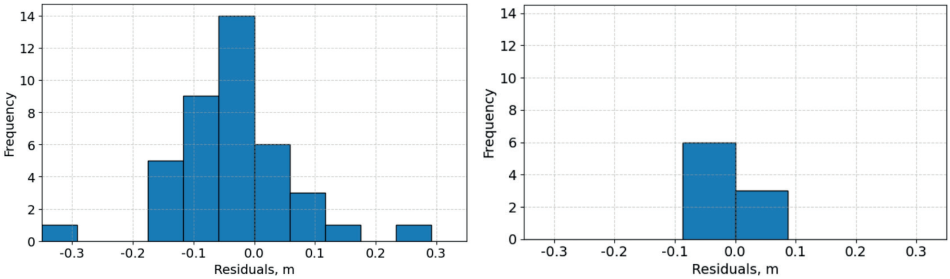
Figure 9 – Residuals of the local FastColl model and global XGM2019e_2159, EGM2008 models

When the accuracy of the two GNSS/leveling groups is considered separately, a clear variation in errors is observed, as shown in Table 6. For the 40 points obtained from the open QazTRF source, the STD and RMSE errors are nearly twice as large as for the 9 AGP points, where high-precision static observations were performed.

Table 6 – Estimation of accuracy on two groups of points ζ(QazTRF) and ζ(AGP)

Method	The data set	Min, m	Max, m	Mean, m	STD, m	RMSE, m
FastColl	QazTRF points	-0.347	0.284	-0.035	0.099	0.104
	AGP points	-0.085	0.048	-0.031	0.048	0.055

The histogram shown in Figure 10 also illustrates the distribution of residuals across stations.



a) b)

Figure 10 – Histogram of residuals of two groups of points: a) 40 points of QazTRF, b) 9 points of geodynamic polygon of Almaty

As seen in Figure 10(a), within the QazTRF group the majority of stations fall within -0.18 m < Residuals < 0.18 m, though some stations reach about ±0.3 m. For the AGP stations, the residuals lie within -0.1 m < Residuals < 0.1 m, as shown in Figure 10(b).

Conclusion. In this study, the methodology of constructing a local quasi-geoid model using the rapid collocation method, adapted to the geophysical conditions of southeastern Kazakhstan, was successfully applied. The proposed approach delivered not only high modeling accuracy but also a substantial reduction in computational cost, which is particularly important when processing large volumes of gravimetric data.

Removal of the global and topographic contributions -based on XGM2019e_2159 (complete to degree 1000) and the FABDEM digital elevation model -significantly reduced the variance of the gravity signal: the standard deviation of the anomalies decreased by up to 85%. Modeling the covariance structure of the residual field with the analytical Tscherning-Rapp function ensured stable estimates and an adequate description of local gravity-field features.

Accuracy of the local quasi-geoid model was assessed by comparing geoid heights obtained at GNSS/leveling control points with those from the GGMs. According to Table 5, the model constructed by the Fast Collocation method yielded, over 49 control points, the following statistics: RMSE = 0.096 m, STD = 0.091 m, and mean = -0.034 m, outperforming the global models. By comparison, EGM2008 and XGM2019e_2159 produced RMSE values of 0.178 m and 0.212 m, respectively. However, the evaluation performed for the two point groups (Table 6) confirms that the quality of the control data has a substantial impact on the final statistics. At the 9 stations where measurements and post-processing were carried out, the results reached RMSE = 0.055 m and STD = 0.048 m, whereas for the 40 stations these values were 0.104 m and 0.099 m, respectively. The large difference between the two datasets indicates the necessity of conducting accuracy assessments using high-quality measurements that can serve as a benchmark. It should be emphasized that the evaluation of geoid model accuracy can be distorted when control data of insufficient quality are used. In such cases, the observed discrepancies may not reflect deficiencies of the model itself but rather the limited reliability of the reference heights. Therefore, a correct validation is only possible when benchmark-quality data, thoroughly processed and quality-controlled, are employed.

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