



Assessment of topographically influenced gravity-height gradients and plumb line curvature at Sümela Monastery (Türkiye)

Mehmet Tütüncü^{1,2} · Nazan Yılmaz²

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Abstract

Accurate estimation of gravity-height gradient and plumb line curvature is fundamental for gravity field modeling, geoid determination, and high-precision geodetic applications, especially in mountainous regions. This study presents an integrated computational framework combining terrestrial gravity observations, precise leveling, GNSS measurements, and Global Geopotential Models (GGMs) to estimate and compare gravity-height gradient and plumb line curvature in the rugged terrain surrounding Sümela Monastery. Simultaneous gravity and leveling surveys were conducted during two observation periods to compute actual and normal gradient, level surface curvature, and plumb line curvature. Additionally, twelve GGMs obtained from the ICGEM service were used to derive the same parameters through spherical harmonic expansions. A comprehensive statistical evaluation, including minimum, maximum, mean, standard deviation, and RMSE, was performed to assess the consistency between terrestrial and model-based results. The results show that normal gradient and level surface curvature from GGMs generally agree well with terrestrial data, whereas larger discrepancies occur in actual gradient and plumb line curvature in areas with steep topographic gradients. CHAMP-based models demonstrate comparatively better consistency in representing plumb line curvature. The proposed framework confirms the reliability of global models at regional scales while emphasizing the importance of terrestrial data in complex topographic environments.

Keywords Gravity-height gradient · Plumb line curvature · Global geopotential models · Terrestrial gravity measurements

Introduction

For the reduction of gravity values to the geoid, the gravity gradient must be known. The vertical gravity gradient (VGG) represents the correlation between gravity and height (Simav et al. 2021). It is computed as the ratio of

the gravity differences observed at different elevations to the corresponding height difference. As the vertical variation of the Earth's gravity field, the VGG, together with the curvature of the plumb line which enables precise determination of the vertical direction and the gravity effect on the Earth's surface, plays a critical role in modeling the internal structure of the Earth, geoid determination, precise leveling studies, and solving problems of physical geodesy. The vertical gradient depends not only on the latitude and elevation of a point, but also more importantly on the surrounding topography and geological structure (Hunt et al. 2002). In Hungary, the non-linearity of the vertical gravity gradient was investigated by performing 3–4 series of gravity measurements at different heights using three different gravimeters. The VGG values were estimated using linear and quadratic adjustments, and the results obtained from different approaches were compared (Csapó and Völgyesi 2004). In Sós-kút, Hungary, VGG values were computed using a Digital Elevation Model

Mehmet Tütüncü and Nazan Yılmaz contributed equally to this work.

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✉ Mehmet Tütüncü
mehmettutuncu@gumushane.edu.tr
Nazan Yılmaz
n_berber@ktu.edu.tr

¹ Department of Land Registry and Cadastre, Gümüşhane Üniversitesi, Gümüşhane 29600, Türkiye

² Department of Geomatics Engineering, Karadeniz Technical University, Trabzon 61080, Türkiye

(DEM) and the prism integration method (Rózsa and Tóth 2005). In a study conducted in the Rocky Mountains of Canada, the mean gravity gradient was used for gravity reduction. The effects of mass density distribution in the topography, the shape of the Earth, and the variation of the gravity gradient with depth on the mean gravity gradient were examined. The mean gravity gradient along the plumb line within the topography was expressed through an analytical formulation (Tenzer and Ellmann 2009). In Poland, it was demonstrated that the use of the normal VGG in absolute gravity reduction, particularly in mountainous regions, may lead to errors exceeding 100 μGal per meter (Dykowski 2012). In Türkiye, the vertical gravity gradient was determined using a tripod approximately one meter in height and two Scintrex Autograv CG-5 instruments. For each relative gravimeter, gravity differences were observed ten times, and the VGG corresponding to a one-meter height difference was derived (Dogan et al. 2013). In Croatia, relative gravity measurements conducted at two absolute gravity stations at different epochs were combined with absolute gravity observations through the determination of the VGG (Repanić et al. 2015). On Tenerife Island in Spain, VGG values were obtained using a high-resolution DEM. The modeled values were found to differ by up to 60% from the normal gradient. It was emphasized that, particularly in microgravimetric surveys in volcanic areas, the use of modeled VGG values is essential. The software Toposk was employed for VGG modeling by incorporating topographic effects into the normal vertical gravity gradient (Zahorec et al. 2015). In another study conducted around the Teide volcano in Italy, modeled and measured VGG values showed good agreement in flat areas, whereas significant discrepancies were observed in steep topography (Zahorec et al. 2016). A study carried out in Slovenia and Serbia demonstrated that the vertical gravity gradient can be modeled using only the normal gravity field and digital terrain models, without additional gravity measurements or global geopotential models. The differences between modeled and observed VGG values were shown to depend strongly on the resolution of the terrain model, with high-resolution models providing significantly more accurate results (Odalovic et al. 2022). In a more recent study around the Teide volcano, while a constant normal gradient value ($-308.6 \mu\text{Gal/m}$) was used at locations where measurements were not available, this approach was found to cause errors of up to 90%, particularly in mountainous and volcanic areas. Therefore, a local VGG estimation method based on the modeling of topographic effects was proposed (Zahorec et al. 2024).

Novelty and contribution of the study

Previous studies on vertical gravity gradient (VGG) determination have generally been based on prototype setups with limited height differences of approximately 1–2 m and have typically relied solely on gravity observations, implicitly assuming an idealized vertical profile. In contrast, the present study was conducted in the steep and rugged topography surrounding the Sümela Monastery in the Eastern Black Sea Region of Türkiye, where relative gravity measurements were performed simultaneously with precise leveling observations in a challenging field environment. The study area covers an approximately 1 km long profile with a total elevation difference of about 210 m. Field campaigns were carried out in October 2023 and October 2024 at 115 and 106 stations, respectively, enabling dense and continuous vertical sampling across the entire elevation range. At each station, gravity and precise leveling measurements were collected simultaneously, providing a more realistic representation of vertical gravity variations in complex terrain compared to discrete multi-level approaches used in previous studies. In addition, GNSS observations were employed to determine station coordinates, and gravity-height gradient was derived from the combined dataset. Normal gravity gradients, level surface curvature, and plumb line curvature were also computed. Furthermore, twelve global geopotential models obtained from the ICGEM service were used to derive the same parameters, and the results were statistically evaluated and compared with field-based estimates. Overall, this study extends previous research by integrating dense in-situ measurements with geodetic and global gravity field models, offering a higher-resolution and more realistic assessment of vertical gravity variations in mountainous terrain. This integrated approach represents a clear methodological advancement in gravity-height gradient studies.

Data sets

All simultaneous gravity and leveling measurements, together with the GNSS observations conducted within the scope of this study, were carried out along a predefined profile located in the vicinity of the Sumela Monastery in the Maçka district of Trabzon Province, Türkiye, in two separate observation periods. The study area is characterized by steep and rugged topography, with a profile length of approximately 1 km and a mean elevation of about 1200 m. The Google Earth image of the measurement profile and its corresponding geographic coordinates are presented in

Fig. 1. All measurements were collected within a region bounded by latitudes $40^{\circ}41'19.74'' < \varphi < 40^{\circ}41'29.54''$ and longitudes $39^{\circ}39'29.62'' < \lambda < 39^{\circ}39'37.91''$. The field campaigns were conducted in two separate observation periods during October 2023 and October 2024.

Simultaneous gravity and leveling measurements

Along the measurement profile, 115 stations were established in October 2023 and 106 stations in October 2024, at which simultaneous gravity and leveling observations were carried out Fig. 2. Gravity measurements were performed using a Scintrex CG-5 Autograv gravimeter with a reading precision of $1 \mu\text{Gal}$. At each station, the gravimeter was operated for a duration of three minutes. For each minute, the final recorded value was taken as the average of the corresponding 60-second observation interval. The standard deviation values between the three repeated measurements at each station were examined and found to be a maximum of $15 \mu\text{gal}$. Daily drift correction was calculated linearly using morning and evening rotations to the main reference points. Tidal correction was performed in real-time using an algorithm employed by the instrument's internal software. Regarding temperature effects, sufficient stabilization time was provided to allow the instrument to adapt to ambient conditions during measurements, direct sunlight exposure was avoided, and sudden temperature changes were prevented. Thanks to its internal temperature control system, the Scintrex CG-5 gravimeter maintains a constant sensor temperature, significantly reducing temperature-related systematic effects. Any potential residual effects were considered within the scope of drift correction. Leveling observations were conducted using a Topcon DL-501 digital level. In the precise leveling application, the BFFB (backward-forward-forward-backward) observation method, commonly employed in high-precision leveling surveys, was adopted. Three readings were taken at each station, and



Fig. 2 Simultaneous gravity and leveling measurements

their arithmetic mean was considered as the final value. The instrumental precision is $\pm 10 \text{ mm}$ in the horizontal direction and $\pm 1 \text{ mm}$ in the vertical direction.

GNSS measurements

During the simultaneous gravity and leveling measurements along the survey profile, the gravity stations were first monumented, and their coordinates were subsequently determined in real time using the Network-RTK technique. The coordinates of the gravity stations were obtained with a CHCNAV i93 Visual IMU-RTK GNSS receiver, utilizing the TUSAGA-Aktif (CORS-TR) reference station network.

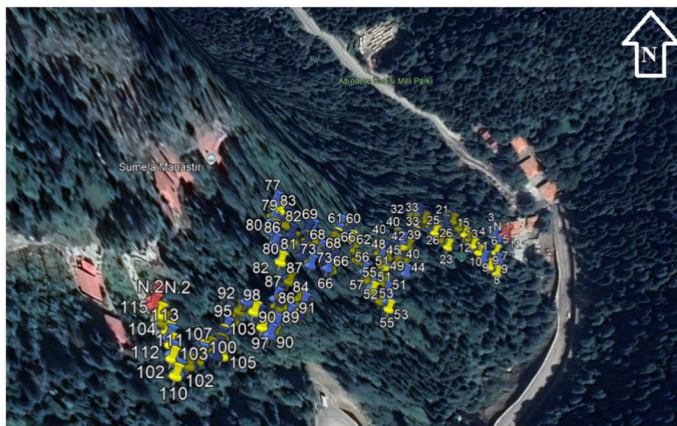
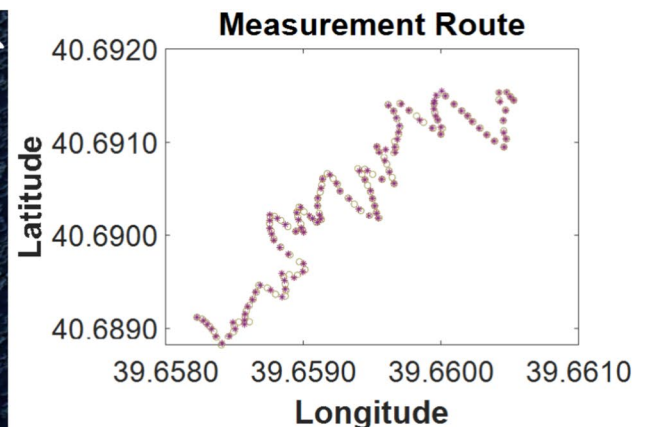


Fig. 1 Measurement route



The positioning accuracy achieved was approximately ± 10 mm in the horizontal component and ± 15 mm in the vertical component.

Global geopotential models

In geodetic studies, global geopotential models derived from low Earth orbit satellite missions such as CHAMP, GRACE, and GOCE—based on the Earth's gravity field information (Barthelmes 2013)—are made publicly available through the ICGEM (International Centre for Global Earth Models) web portal. In the selection of the models, criteria such as the year of release, data source, regional compatibility, and the maximum degree of the global spherical harmonic expansion were taken into consideration. In this study, twelve global geopotential models (GGMs) obtained from the ICGEM service were selected in order to evaluate and compare the performance of different satellite-based and combined satellite–terrestrial gravity field solutions over the study area. The use of multiple models enables a systematic assessment of how different mission types and combination strategies represent the gravity field in complex mountainous terrain. This approach provides a more comprehensive evaluation of the consistency and variability of global models rather than relying on a single solution. Information on the global geopotential models selected for this study and obtained from the ICGEM database is presented in Table 1. For the purposes of this study, gravity field data corresponding to

the selected models were retrieved from the ICGEM portal. Subsequently, using the heights derived from precise leveling measurements and the geographic coordinates obtained from GNSS observations, the vertical gravity gradient values, level surface curvatures, and plumb line curvature values associated with the respective models were computed.

Methods

In this study, a computational framework was developed for the integrated estimation of the vertical gravity gradient (VGG), level surface curvature, and plumb line curvature using both terrestrial observations and global geopotential models (GGMs). The workflow consists of four main stages:

1. terrestrial data acquisition,
2. geometric and gravimetric parameter computation,
3. model-based gravity field derivation,
4. statistical comparison and validation.

The adopted framework enables a consistent evaluation of gravity field parameters under complex topographic conditions.

Terrestrial determination of gravity-height gradient

A body resting on the Earth's surface is subjected to the resultant of gravitational attraction and centrifugal force. Gravitational attraction is the force exerted on bodies due to the Earth's mass, whereas the centrifugal force arises from the Earth's rotation about its axis. The vector sum of these two forces is defined as gravity. The gravity potential is expressed as the sum of the gravitational and centrifugal potentials:

$$W = V + \Phi = G \iiint \frac{\rho}{l} dv + \frac{1}{2} \omega^2 (x^2 + y^2) \quad (1)$$

where V denotes the gravitational potential and Φ represents the centrifugal potential. The gradient vector of the gravity potential is given by:

$$g = \text{grad}W = \left(\frac{\partial W}{\partial x}, \frac{\partial W}{\partial y}, \frac{\partial W}{\partial z} \right) \quad g_x = \frac{\partial W}{\partial x}, \quad g_y = \frac{\partial W}{\partial y}, \quad g_z = \frac{\partial W}{\partial z} \quad (2)$$

where g is the gravity vector and g_x , g_y , and g_z are its components (Heiskanen and Moritz 1967). The normal gravity value on the reference ellipsoid can be computed using Somigliana's formula:

$$\gamma_0 = \gamma_{ekv} \frac{1 + k \sin^2 \varphi}{\sqrt{1 - e^2 \sin^2 \varphi}} \quad (3)$$

Table 1 Information on global geopotential models obtained from the ICGEM website

Models	Year	Degree	Data	Reference
AIUB-CHAMP01S	2007	70	S(Champ)	Prange et al. (2009)
EIGEN-CHAMP05S	2010	150	S(Champ)	Flechtner et al. (2010)
ULux_CHAMP2013s	2013	120	S(Champ)	Weigelt et al. (2013)
ITU_GRACE16	2016	180	S(Grace)	Akyilmaz et al. (2016)
Tongji-Grace02k	2018	180	S(Grace)	Chen et al. (2018)
ITSG-Grace2018s	2019	200	S(Grace)	Mayer-Gürr et al. (2018)
IGGT_R1	2017	240	S(Goce)	Lu et al. (2018)
GO_CONS_GCF_2_TIM_R6	2019	300	S(Goce)	Brockmann et al. (2021)
GOSG02S	2023	300	S(Goce)	Xu et al. (2023)
ITU_GGC16	2016	280	S(Goce), S(Grace)	Akyilmaz et al. (2016)
IGGT_R1C	2018	240	S(Goce), S(Grace)	Lu et al. (2018)
WHU-SWPU-GOGR2022S	2023	300	S(Goce), S(Grace)	Zhao et al. (2023)

where γ_{ekv} is the normal gravity at the equator, φ is the ellipsoidal latitude, k is the normal gravity constant, and e^2 is the first eccentricity squared of the reference ellipsoid. The vertical gravity gradient ($\Delta g/\Delta H$) (Akdoğan et al. 2024) was computed based on simultaneous gravity and precise leveling measurements using:

$$W_{zz}(h_i) = \frac{g(h_1) - g(h_2)}{\Delta h} \quad (4)$$

where $g(h_i)$ is the gravity value at the measurement level, $g(h_0)$ is the gravity at the reference height, Δh is the height difference between stations, and $W_{zz}(h_i)$ represents the gravity-height gradient ($\Delta g/\Delta h$) (Heiskanen and Moritz 1967). The traditional unit of gravity gradient is the Eötvös (E) unit, defined as $1E = 10^{-9} s^{-2} = 0.1 \mu\text{Gal}/m$ (Hunt et al. 2002).

Computation of level surface and plumb line curvature

Using Bruns' equation, which relates gravity-height gradient to the mean curvature of the level surface, the level surface curvatures were determined as follows (Heiskanen and Moritz 1967; Vermeer 2020):

$$\frac{\partial g}{\partial H} = -2gJ + 4\pi G\rho - 2\omega^2 \quad (5)$$

where $\partial g/\partial H$ is gravity-height gradient, g is the gravity value, G is the universal gravitational constant, ρ is the mean density of the Earth, and ω is the angular velocity of the Earth's rotation. The curvature of the plumb line is defined by Heiskanen and Moritz (1967):

$$K = \sqrt{\kappa_1^2 + \kappa_2^2} = \frac{1}{g} \sqrt{W_{xz}^2 + W_{yz}^2} \quad (6)$$

where

$$\kappa_1 = -\frac{1}{g} \frac{\partial g}{\partial x}, \kappa_2 = -\frac{1}{g} \frac{\partial g}{\partial y} \quad (7)$$

Calculation of plumb line deflection componentss

The quantities obtained from gravity measurements are converted into the η and ξ components of the deflection of the vertical by means of the Vening–Meinesz integral presented in Eq. 8.

$$\begin{pmatrix} \eta \\ \xi \end{pmatrix} = \frac{1}{4\pi\gamma} \iint_{\sigma} \Delta g \frac{ds(\psi)}{d\psi} \begin{pmatrix} \sin \alpha \\ \cos \alpha \end{pmatrix} d\sigma \quad (8)$$

Here, η and ξ denote the east–west and north–south components of the deflection of the vertical, respectively; γ denotes the normal gravity value; Δg denotes the gravity anomaly; $\frac{ds(\psi)}{d\psi}$ denotes the Vening–Meinesz function, defined as the derivative of the Stokes function with respect to the spherical distance ψ (10); α denotes the azimuth angle; and $d\sigma$ denotes the surface element.

$$\begin{aligned} \frac{ds(\psi)}{d\psi} = & -\frac{\cos(\psi/2)}{2 \sin^2(\psi/2)} + 8 \sin \psi - 6 \cos\left(\frac{\psi}{2}\right) \\ & - 3 \frac{1 - \sin(\psi/2)}{\sin \psi} + 3 \sin \psi \ln \left[\sin\left(\frac{\psi}{2}\right) + \sin^2\left(\frac{\psi}{2}\right) \right] \end{aligned} \quad (9)$$

The azimuth angle α in Eq. 10 is determined by the following equation:

$$\tan \alpha = \frac{\cos \varphi' \sin(\lambda' - \lambda)}{\cos \varphi \sin \varphi' - \sin \varphi \cos \varphi' \cos(\lambda' - \lambda)} \quad (10)$$

Global geopotential model-based computations

Twelve global geopotential models (GGMs) were selected from the ICGEM service. For each model, gravity field quantities were derived using spherical harmonic expansions up to their maximum degree and order. Geographic coordinates obtained from GNSS measurements were uploaded to the “user-defined points” user interface on the ICGEM website. Subsequently, gravity and normal gravity values for the selected models were downloaded from the platform. Using the GNSS-derived coordinates and leveling-based heights of the stations, the following parameters were computed for each GGM using the MATLAB program:

- Gravity-height gradient
- Normal gravity gradient
- Level surface curvature
- Plumb line curvature

This ensured a direct and consistent comparison between terrestrial and model-derived results.

Statistical evaluation and model performance analysis

To assess the agreement between terrestrial measurements and GGM-derived values, the following statistical indicators were computed:

- Minimum and maximum differences
- Mean deviation
- Standard deviation
- Root Mean Square Error (RMSE)

This evaluation was performed separately for both observation periods, allowing temporal consistency analysis. Model performance was interpreted in terms of sensitivity to topographic variability and gravity field complexity.

Results and analysis

Comparisons between first-period terrestrial measurements

Simultaneous gravity and leveling measurements conducted during two independent observation periods enabled the assessment of temporal consistency of the derived gravity field parameters. Within the study area, gravity measurements were carried out using a relative gravimeter at 115 stations during the first observation period and at 106 stations during the second period. Height differences were determined from the leveling observations conducted simultaneously with the gravity measurements. Following the analysis of the gravity and leveling data, the terrestrial and normal gravity-height gradient values, as well as the level surface curvatures and plumb line curvature values, were computed for both observation periods. For the statistical evaluation of the differences between the terrestrial measurements obtained in the first and second periods, the minimum, maximum, mean, standard deviation, and root mean square error (RMSE) values are presented in Table 2.

The wide minimum–maximum range of the terrestrial gravity-height gradient values and the relatively high RMSE indicate a pronounced variability between the two observation periods Fig. 3. This finding demonstrates that

the gravity-height gradient is highly sensitive to local topography, mass distribution, and measurement conditions. The positive mean value suggests that systematically higher values may have been obtained in one of the periods. The mean of the normal gravity-height gradient differences being close to zero indicates the absence of a significant systematic discrepancy between the two periods. This result implies that the normal gravity field, computed solely as a function of latitude and height, exhibits a more stable temporal behavior. The small magnitude of the level surface curvature differences suggests that no systematic shift occurred between the two observation periods. This indicates that the geometry of the level surfaces remained generally stable over time. In contrast, the plumb line curvature exhibits greater variability when compared to the level surface curvature. This may be attributed to the higher sensitivity of the plumb line direction to local irregularities in the gravity field and mass distribution. The negative mean value points to the possibility of a small but directionally consistent difference between the two periods.

Comparisons between first-period terrestrial measurements and global geopotential models

Gravity-height gradient

The differences between the gravity-height gradient values obtained in this observation period and the corresponding gravity-height gradient values derived from the global models were computed. The statistical results of these differences are presented in Table 3, while the graphical representation illustrating their relationship is shown in Fig. 4.

The gravity-height gradient difference statistics within the study area indicate that, in regions characterized by steep topographic gradients, the global models do not fully agree with the terrestrial measurements.

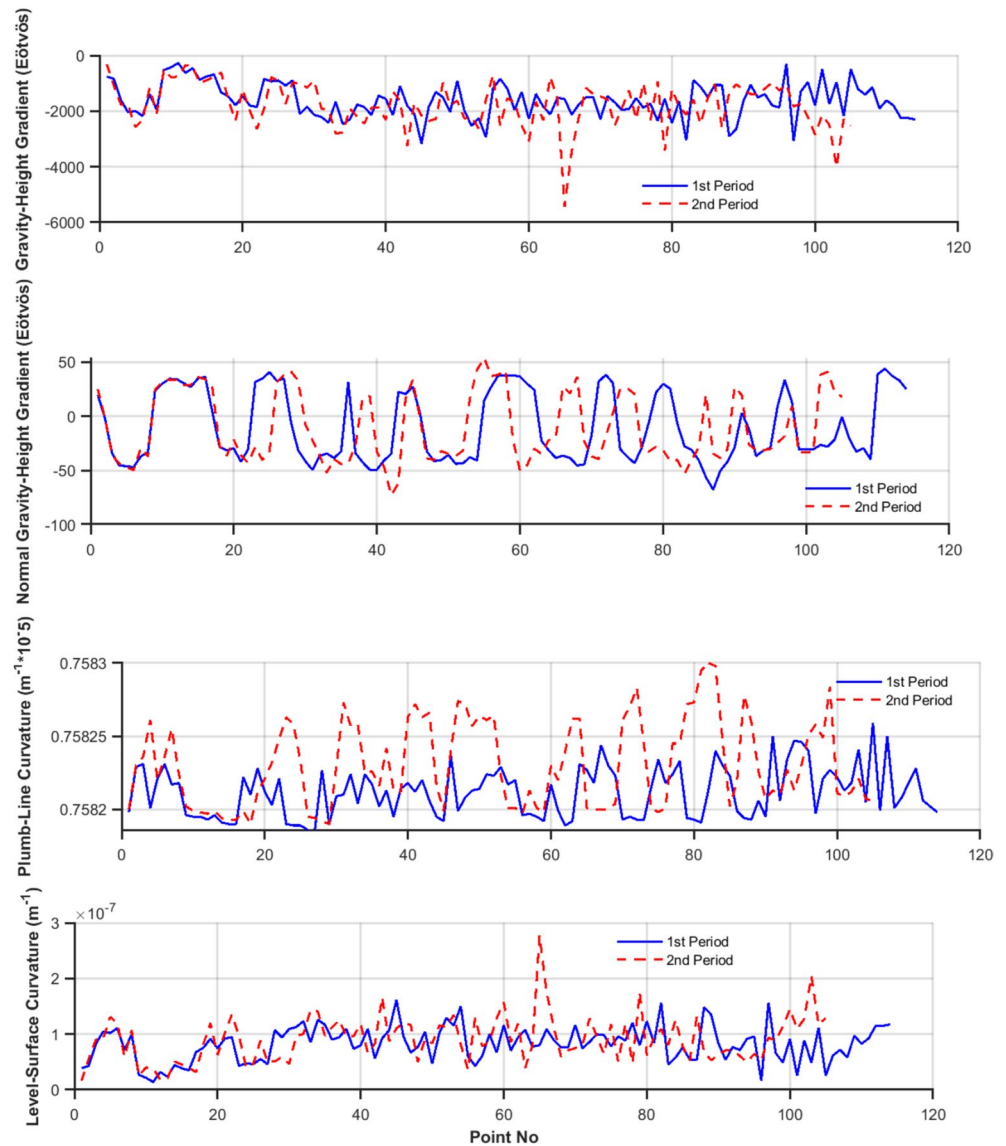
Normal gravity-height gradient

The differences between the normal gravity-height gradient values obtained for this observation period and the corresponding normal gravity-height gradient values derived from the models were computed. The statistical results of these differences are presented in Table 4, while the graphical representation illustrating their relationship is shown in Fig. 5.

No systematic bias is observed between the terrestrial normal gravity-height gradient values and those derived from the global geopotential models. All models exhibit a comparable level of accuracy and demonstrate a consistent and stable agreement with the terrestrial data. This outcome is expected and physically meaningful, as the normal gravity field is defined by

Table 2 Statistical information on the differences between the first and second periods

Parameter	Min.	Max.	Mean	Std. Dev.	RMSE
Actual Vertical Gravity Gradient (VGG) (Eötvös)	−1965.240	3785.679	158.242	882.136	892.434
Normal Vertical Gravity Gradient (VGG) (Eötvös)	−83.433	86.754	−1.240	38.312	38.149
Curvature of level surface ($\text{m}^{-1} \times 10^{-8}$)	−21.7	10.8	−0.708	4.87	4.90
Curvature of plumb line ($\text{m}^{-1} \times 10^{-5}$)	−10.5	4.02	−1.87	3.24	3.73

Fig. 3 Relationships between Periods 1 and 2**Table 3** Statistical information on the differences between the gravity-height gradient values derived from terrestrial measurements and those obtained from the global models

Model	Min. (Eötvös)	Max. (Eötvös)	Mean (Eötvös)	Std. Dev. (Eötvös)	RMSE (Eötvös)
AIUB-CHAMP01S	-1325.093	4209.533	1481.818	797.687	1681.222
EIGEN-CHAMP05S	-1313.525	4224.041	1480.286	799.311	1680.637
ULux_CHAMP2013s	-1303.895	4228.978	1474.679	800.661	1676.339
ITU_GRACE16	-1281.346	4273.867	1487.130	804.661	1689.188
Tongji-Grace02k	-1289.847	4252.133	1477.910	803.047	1680.311
ITSG-Grace2018s	-1282.800	4259.823	1477.051	804.285	1680.142
IGGT_R1	-1257.289	4298.161	1479.039	808.966	1684.114
GO_CONS_GCF_2_TIM_R6	-1270.107	4282.605	1481.950	806.706	1685.598
GOSG02S	-1266.419	4284.732	1479.750	807.387	1683.988
ITU_GGC16	-1265.153	4286.491	1479.377	807.607	1683.765
IGGT_R1C	-1258.911	4291.128	1475.785	808.704	1681.133
WHU-SWPU-GOGR2022S	-1266.425	4284.725	1479.751	807.386	1683.988

Fig. 4 Relationship between the gravity-height gradient values derived from terrestrial measurements and those computed from the global geopotential models

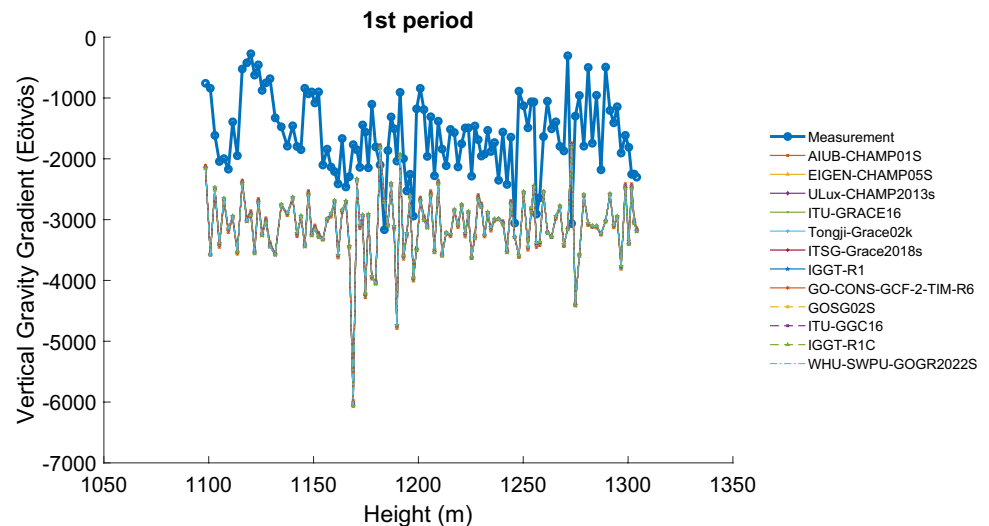


Table 4 Statistical information on the differences between the normal gravity-height gradient values derived from terrestrial measurements and those obtained from the global models

Model	Min.	Max.	Mean	Std. Dev.	RMSE
	(Eötvös)	(Eötvös)	(Eötvös)	(Eötvös)	(Eötvös)
AIUB-CHAMP01S	-0.603	0.446	0.002	0.221	0.220
EIGEN-CHAMP05S	-0.603	0.446	0.002	0.221	0.220
ULux-CHAMP2013s	-0.603	0.446	0.002	0.221	0.220
ITU-GRACE16	-0.603	0.446	0.002	0.221	0.220
Tongji-Grace02k	-0.603	0.446	0.002	0.221	0.220
ITSG-Grace2018s	-0.603	0.446	0.002	0.221	0.220
IGGT_R1	-0.603	0.446	0.002	0.221	0.220
GO-CONS-GCF-2-TIM-R6	-0.603	0.446	0.002	0.221	0.220
GOSG02S	-0.603	0.446	0.002	0.221	0.220
ITU-GGC16	-0.603	0.446	0.002	0.221	0.220
IGGT_R1C	-0.603	0.446	0.002	0.221	0.220
WHU-SWPU-GOGR2022S	-0.603	0.446	0.002	0.221	0.220

a reference ellipsoid and depends only on latitude and height, not on the specific Global Geopotential Model (GGM). Therefore, all models inherently yield the same normal gravity-height gradient values when computed consistently using the same reference system. The observed agreement up to three decimal places is not a computational artifact, but rather a direct consequence of the definition of normal gravity and its independence from the detailed spectral content of GGMs.

Level surface curvature

The differences between the level surface curvature values obtained for this observation period and the corresponding level surface curvature values derived from the models were computed. The statistical results of these differences are presented in Table 5, while the graphical representation illustrating their relationship is shown in Fig. 6.

No significant systematic difference is observed between the level surface curvature values derived from the terrestrial measurements and those computed from the global geopotential models. All models demonstrate a comparable level of accuracy and exhibit a stable and consistent agreement with the terrestrial results.

Plumb line curvature

The differences between the plumb line curvature values obtained for this observation period and the corresponding plumb line curvature values derived from the models were computed. The statistical results of these differences are presented in Table 6, while the graphical representation illustrating their relationship is shown in Fig. 7.

CHAMP-based models have produced results that are more consistent with the terrestrial data. In contrast, the ITU-GRACE16 model exhibits a comparatively lower level of agreement than the other models. A certain systematic discrepancy is observed between the terrestrial plumb line curvature values and those derived from the global models. While the CHAMP-based models demonstrate a higher degree of consistency with the terrestrial measurements, the level of deviation tends to increase in some GRACE-based and combined models.

Fig. 5 Relationship between the normal gravity-height gradient values derived from terrestrial measurements and those computed from the global geopotential models

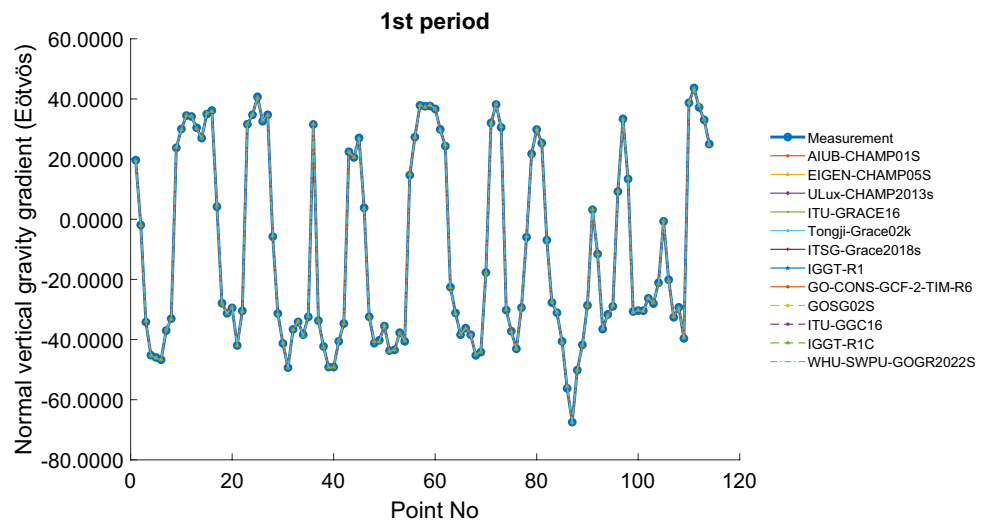


Table 5 Statistical information on the differences between the level surface curvature values derived from terrestrial measurements and those obtained from the global models

Model	Min.	Max.	Mean	Std. Dev.	RMSE
AIUB-CHAMP01S	0.8870	3.050	1.581	0.284	0.283
EIGEN-CHAMP05S	0.8930	3.057	1.581	0.284	0.283
ULux-CHAMP2013s	0.8980	3.060	1.578	0.283	0.283
ITU-GRACE16	0.9090	3.082	1.581	0.284	0.283
Tongji-Grace02k	0.9050	3.071	1.579	0.284	0.283
ITSG-Grace2018s	0.9080	3.075	1.579	0.284	0.283
IGGT_R1	0.9210	3.095	1.580	0.284	0.283
GO-CONS-GCF-2-TIM-R6	0.9150	3.087	1.581	0.284	0.283
GOSG02S	0.9170	3.088	1.580	0.284	0.283
ITU-GGC16	0.9170	3.089	1.580	0.284	0.283
IGGT_R1C	0.9210	3.091	1.578	0.284	0.283
WHU-SWPU-GOGR2022S	0.9170	3.088	1.580	0.284	0.283

All values are expressed in 10^{-7} m^{-1}

Table 6 Statistical information on the differences between the plumb line curvature values derived from terrestrial measurements and those obtained from the global models

Model	Min.	Max.	Mean	Std. Dev.	RMSE
AIUB-CHAMP01S	-8.998	-0.002	-2.307	2.020	3.060
EIGEN-CHAMP05S	-8.003	-0.004	-2.574	1.671	3.065
ULux-CHAMP2013s	-8.709	-0.002	-2.385	1.902	3.045
ITU-GRACE16	-13.850	3.912	-1.006	4.685	4.771
Tongji-Grace02k	-10.670	0.787	-1.859	2.838	3.382
ITSG-Grace2018s	-11.420	1.502	-1.658	3.253	3.638
IGGT_R1	-11.980	2.053	-1.509	3.570	3.862
GO-CONS-GCF-2-TIM-R6	-12.870	2.935	-1.270	4.094	4.270
GOSG02S	-12.880	2.943	-1.267	4.100	4.274
ITU-GGC16	-12.600	2.663	-1.343	3.932	4.138
IGGT_R1C	-11.960	2.035	-1.513	3.561	3.855
WHU-SWPU-GOGR2022S	-12.880	2.942	-1.268	4.099	4.273

All values are expressed in 10^{-5} m^{-1}

Fig. 6 Statistical information on the differences between the level surface curvature values derived from terrestrial measurements and those obtained from the global models

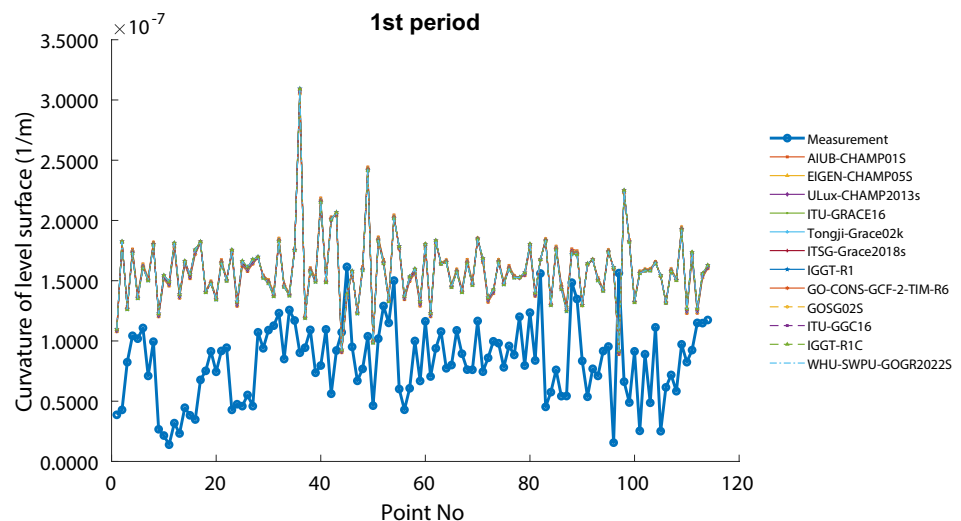
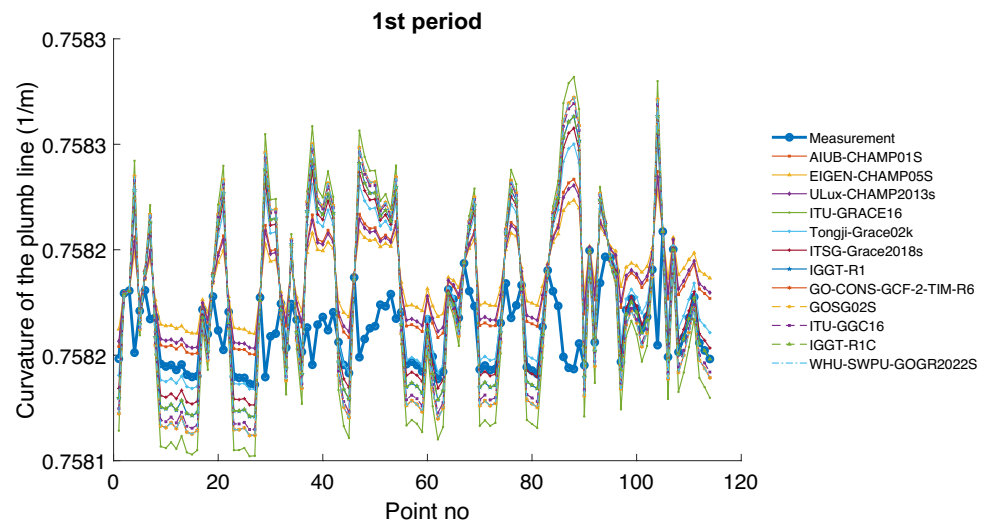


Fig. 7 Relationship between the plumb line curvature values derived from terrestrial measurements and those computed from the global geopotential models



Comparisons between second-period terrestrial measurements and global geopotential models

Gravity-height gradient

The differences between the gravity-height gradient values obtained for this observation period and the corresponding the gravity-height gradient values derived from the models were computed. The statistical results of these differences are presented in Table 7, while the graphical representation illustrating their relationship is shown in Fig. 8.

Although the lowest RMSE value among the models is observed for the ULux_CHAMP2013s model, the differences do not indicate a statistically meaningful superiority in terms of the overall trend.

Normal gravity-height gradient

The differences between the normal VGG values obtained for this observation period and the corresponding normal the gravity-height gradient values derived from the models were computed. The statistical results of these differences

are presented in Table 8, while the graphical representation illustrating their relationship is shown in Fig. 9.

A noticeable systematic difference is observed between the terrestrial normal the gravity-height gradient values and those derived from the global models. However, all models exhibit similar error characteristics and demonstrate comparable performance levels. The observed similarity in RMSE values (approximately 1676–1689 Eötvös for Period 1) arises primarily from the limited spatial resolution of the Global Geopotential Models (GGMs). Specifically, at the latitude of the study area (40.69°), the half-wavelength resolution corresponding to the maximum spherical harmonic degree ($N_{max} = 300$) of the highest-degree models utilized here is approximately $\lambda/2 = \pi \cdot R/N_{max} \approx 20000/300 \approx 67$ km. This satellite-derived spatial scale is roughly four orders of magnitude larger than our localized profile length (1 km) and the terrestrial inter-station spacing (5–10 m). Consequently, the high-frequency gravity-height variations induced by the steep and rugged topography of the Altındere Valley occur at spatial wavelengths that are far too short to be captured by these models, mathematically explaining why their individual RMSE responses cluster so tightly around identical baselines.

Table 7 Statistical information on the differences between the gravity-height gradient values derived from terrestrial measurements and those obtained from the global models

Model	Min. (Eötvös)	Max. (Eötvös)	Mean (Eötvös)	Std. Dev. (Eötvös)	RMSE (Eötvös)
AIUB-CHAMP01S	-3988.202	4094.614	1326.681	1281.698	1840.431
EIGEN-CHAMP05S	-4010.680	4079.663	1325.145	1281.921	1839.478
ULux_CHAMP2013s	-4024.152	4061.577	1319.193	1282.062	1835.293
ITU_GRACE16	-4057.254	4073.127	1331.461	1286.703	1847.330
Tongji-Grace02k	-4047.916	4056.796	1322.361	1283.808	1838.778
ITSG-Grace2018s	-4057.337	4050.808	1321.297	1284.631	1838.582
IGGT_R1	-4104.952	4040.201	1323.297	1286.902	1841.592
GO_CONS_GCF_2_TIM_R6	-4075.901	4052.606	1326.038	1287.032	1843.652
GOSG02S	-4082.103	4044.816	1323.753	1287.063	1842.031
ITU_GGC16	-4085.940	4041.739	1323.440	1286.915	1841.703
IGGT_R1C	-4099.878	4038.869	1319.877	1286.546	1838.888
WHU-SWPU-GOGR2022S	-4082.093	4044.823	1323.754	1287.063	1842.031

Fig. 8 Relationship between the terrestrial measurements and the gravity-height gradient values computed from global geopotential models for the second observation period

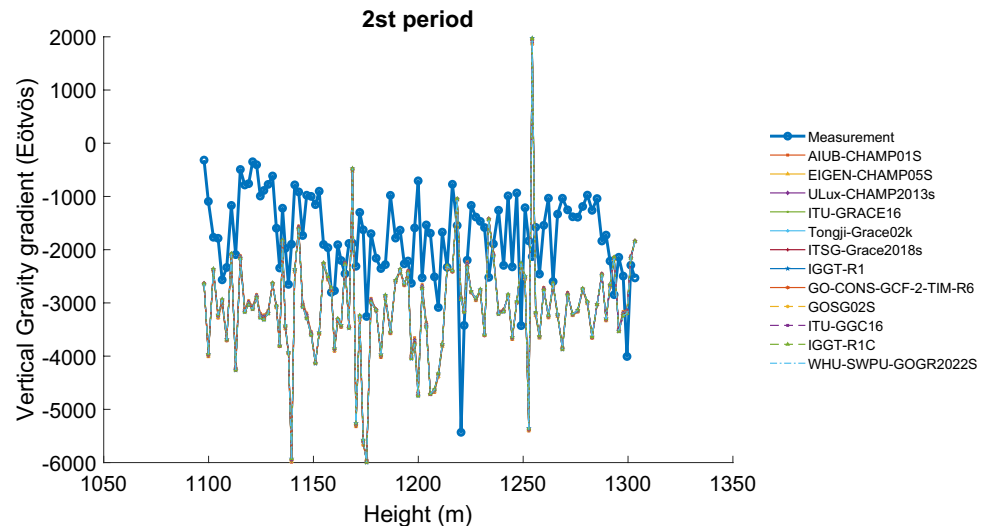


Table 8 Statistical information on the differences between the normal the gravity-height gradient values derived from terrestrial measurements and those obtained from the global models

Model	Min. (Eötvös)	Max. (Eötvös)	Mean (Eötvös)	Std. Dev. (Eötvös)	RMSE (Eötvös)
AIUB-CHAMP01S	-84.762	62.796	0.301	26.208	26.084
EIGEN-CHAMP05S	-84.762	62.796	0.301	26.208	26.084
ULux-CHAMP2013s	-84.762	62.796	0.301	26.208	26.084
ITU-GRACE16	-84.762	62.796	0.301	26.208	26.084
Tongji-Grace02k	-84.762	62.796	0.301	26.208	26.084
ITSG-Grace2018s	-84.762	62.796	0.301	26.208	26.084
IGGT_R1	-84.762	62.796	0.301	26.208	26.084
GO_CONS-GCF-2-TIM-R6	-84.762	62.796	0.301	26.208	26.084
GOSG02S	-84.762	62.796	0.301	26.208	26.084
ITU-GGC16	-84.762	62.796	0.301	26.208	26.084
IGGT_R1C	-84.762	62.796	0.301	26.208	26.084
WHU-SWPU-GOGR2022S	-84.762	62.796	0.301	26.208	26.084

Level surface curvature

The differences between the level surface curvature values obtained for this observation period and the corresponding level surface curvature values derived from the models were computed. The statistical results of these differences are presented in Table 9, while the graphical representation illustrating their relationship is shown in Fig. 10.

The results obtained for the second observation period indicate that the differences between the level surface curvature values derived from terrestrial measurements and those computed from the global geopotential models are of similar magnitude and exhibit low dispersion across all models. This finding suggests that no distinct superiority can be attributed to any specific model and that, overall, the models demonstrate a consistent performance in agreement with the terrestrial data.

Plumb line curvature

The differences between the plumb line curvature values obtained for this observation period and the corresponding plumb line curvature values derived from the models were computed. Table 10 presents the statistical results of the differences, while Fig. 11 illustrates their graphical relationship.

The Tongji-Grace02k and ITSG-Grace2018s models exhibit the highest level of agreement with the terrestrial data, as indicated by their lowest RMSE values. In contrast, comparatively larger deviations are observed in the EIGEN-CHAMP05S and ITU-GRACE16 models.

Discussion and conclusion

In this study, simultaneous gravity and GNSS/leveling measurements were conducted in a mountainous and rugged area surrounding the Sümela Monastery in Trabzon Province to determine the actual gravity-height gradient. Based on these observations, the gravity-height gradient, normal gradient, level surface curvature, and plumb line curvature values were computed and subsequently

Fig. 9 Relationship between the normal VGG values derived from terrestrial measurements and those computed from the global geopotential models

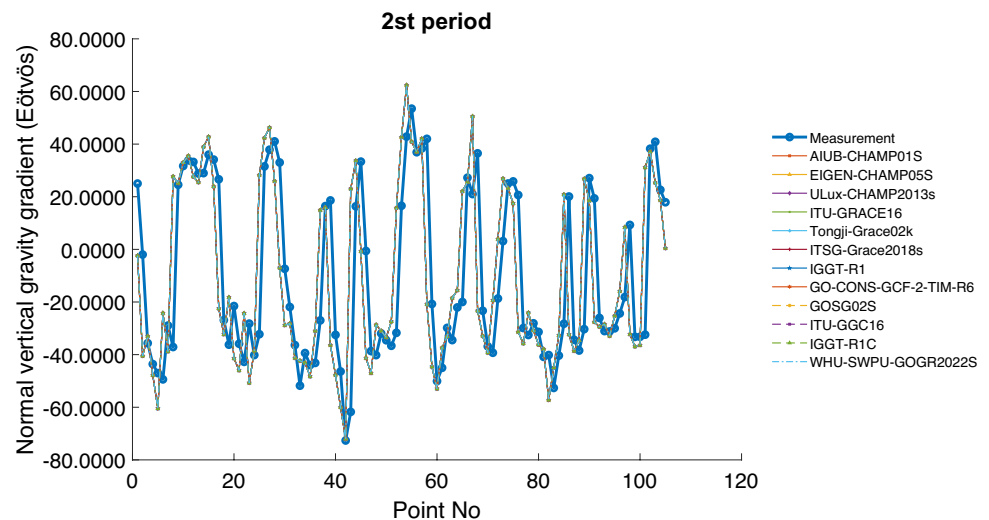


Table 9 Statistical information on the differences between the level surface curvature values

Model	Min.	Max.	Mean	Std. Dev.	RMSE
AIUB-CHAMP01S	-2.089	2.035	-0.677	0.654	0.939
EIGEN-CHAMP05S	-2.082	2.046	-0.676	0.654	0.939
ULux-CHAMP2013s	-2.072	2.053	-0.673	0.654	0.937
ITU-GRACE16	-2.078	2.070	-0.679	0.657	0.943
Tongji-Grace02k	-2.070	2.065	-0.675	0.655	0.938
ITSG-Grace2018s	-2.067	2.070	-0.674	0.655	0.938
IGGT-R1	-2.061	2.095	-0.675	0.657	0.939
GO-CONS-GCF-2-TIM-R6	-2.068	2.080	-0.676	0.657	0.941
GOSG02S	-2.064	2.083	-0.675	0.657	0.940
ITU-GGC16	-2.062	2.085	-0.675	0.657	0.940
IGGT-R1C	-2.061	2.092	-0.674	0.656	0.938
WHU-SWPU-GOGR2022S	-2.064	2.083	-0.675	0.657	0.940

All values are expressed in 10^{-7} m^{-1}

compared with those derived from global geopotential models. Gravity-height gradient parameter is considered a highly sensitive indicator for describing variations in the gravity field, particularly in mountainous regions. Gravity-height gradient results also reveal that the models generally exhibit a high level of consistency and similarity. The observed differences are largely attributed to topographic complexity and resolution discrepancies; nevertheless, the models are found to be generally successful in representing the regional gravity field. These findings demonstrate that global geopotential models operate in agreement with terrestrial data and can be reliably employed in regional applications. The level surface curvature results indicate that the models produce generally comparable outcomes and are capable of reliably representing the geometric characteristics of level surfaces at the regional scale, thereby demonstrating strong

Fig. 10 Relationship between the level surface curvature values derived from terrestrial measurements and those computed from the global geopotential models

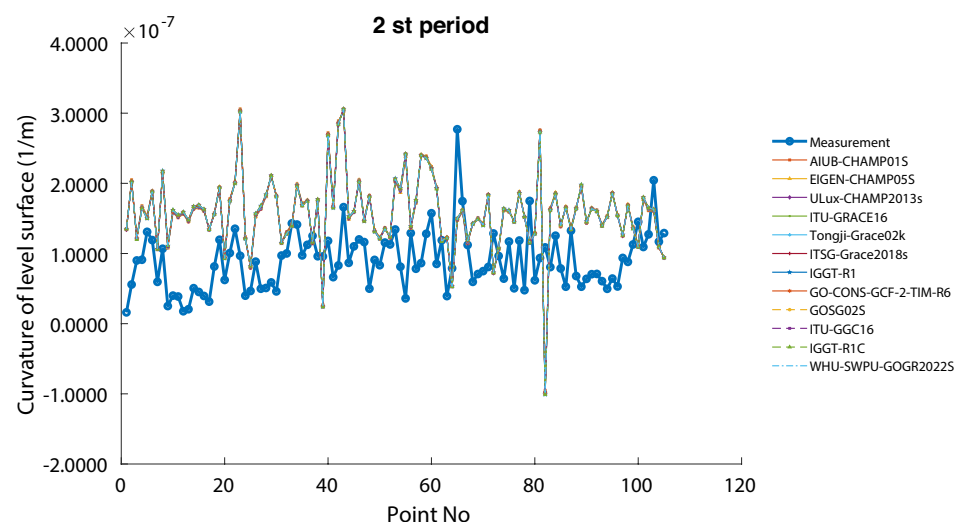


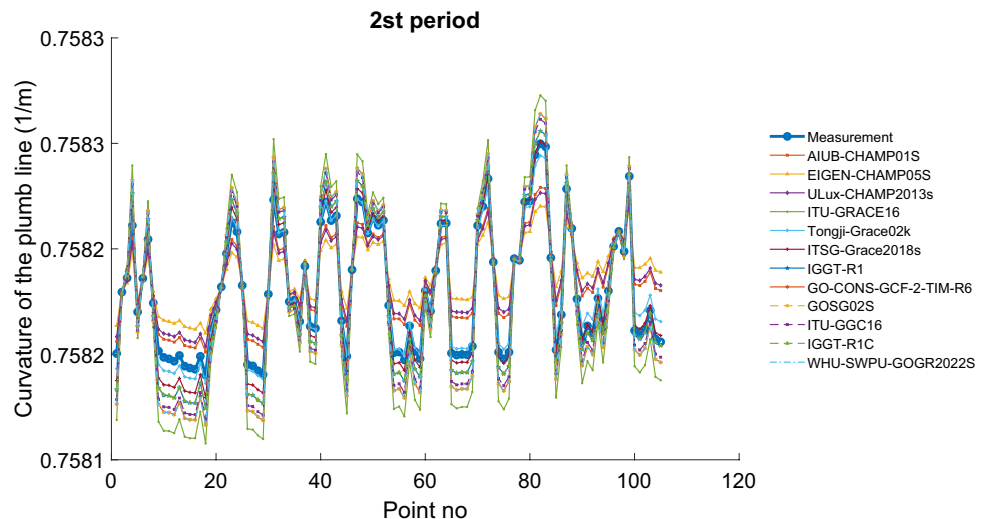
Table 10 Statistical information on the differences between the plumb line curvature values

Model	Min.	Max.	Mean	Std. Dev.	RMSE
AIUB-CHAMP01S	-2.433	2.064	-0.453	1.109	1.193
EIGEN-CHAMP05S	-3.305	2.958	-0.695	1.665	1.797
ULux_CHAMP2013s	-2.683	2.324	-0.523	1.269	1.368
ITU_GRACE16	-2.873	3.479	0.729	1.797	1.931
Tongji-Grace02k	-9.660	0.707	-0.461	0.369	0.370
ITSG-Grace2018s	-1.120	1.301	0.137	0.503	0.519
IGGT_R1	-1.514	1.798	0.272	0.763	0.806
GO_CONS_GCF_2_TIM_R6	-2.146	2.596	0.489	1.244	1.331
GOSG02S	-2.151	2.603	0.491	1.248	1.336
ITU_GGC16	-1.951	2.349	0.422	1.092	1.166
IGGT_R1C	-1.501	1.782	0.268	0.754	0.797
WHU-SWPU-GOGR2022S	-2.151	2.602	0.491	1.248	1.335

All values are expressed in 10^{-5} m^{-1}

performance in terms of geodetic accuracy. The plumb line curvature results show that regional topographic effects lead to limited discrepancies in certain models. While the global geopotential models reliably reflect the overall trend of the plumb line curvature components, the findings suggest that, in areas characterized by pronounced topographic variation, model accuracy can be enhanced through the support of terrestrial data. The observed performance reversal of CHAMP- and GRACE-based models between Period 1 and Period 2 is interpreted primarily as a sampling artefact rather than a reflection of the models'

spectral resolutions. Theoretically, GRACE-only static models (e.g., Tongji-Grace02k up to degree/order 180 and ITSG-Grace2018s up to degree/order 200) resolve higher spherical-harmonic degrees than CHAMP-only models (e.g., AIUB-CHAMP01S up to degree/order 70 and ULux_CHAMP2013s up to degree/order 120), meaning that they extend to shorter wavelengths (higher frequencies) rather than longer ones. Therefore, the slight shift in model performance is attributed mainly to the 8% reduction in the number of terrestrial stations (from 115 to 106) and the consequent spatial redistribution of the stations along the profile between the two measurement periods. Furthermore, at the highly localized scale of the present study, the numerical differences among the satellite-only GGMs are generally small and remain below the noise level of the terrestrial comparisons. The implementation of this study in a mountainous and steep terrain provided an opportunity to test the methodological approach and to characterize the nonlinear distribution of gravity gradient values. In this respect, the study serves as a reference not only for Türkiye but also for other regions worldwide exhibiting similar morphological characteristics. Its application in a topographically distinctive area clearly demonstrates the flexibility and applicability limits of the existing methodologies. Furthermore, the challenging field conditions enabled the development of a methodological framework that can serve as a reference for other areas with comparable topographic settings.

Fig. 11 Relationship between the plumb line curvature values derived from terrestrial measurements and those computed from the global geopotential models

Author Contributions M.T. conceived the study, performed the field measurements, and conducted the data analysis. N.Y. contributed to data interpretation and statistical evaluation. M.T. drafted the manuscript. All authors reviewed and approved the final manuscript.

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Data Availability The Global Geopotential Models (GGMs) used in this study are publicly available from the International Centre for Global Earth Models (ICGEM) service (<https://icgem.gfz-potsdam.de>).

Declarations

Competing interests The authors declare no competing interests.

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