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Research paper
Doi 10.61892/STP202601005O
ISSN 2566-4484

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EFFECTS OF EPOCH HARMONIZATION ON TERRESTRIAL AND GOCO-DERIVED HEIGHT ANOMALIES: CASE STUDY IN SERBIA

Abstract:

Terrestrial height anomalies are compared with anomalies derived from Global Geopotential Models (GGMs) developed within the GOCO initiative. The analysis examines the influence of epoch differences on geometric heights. Terrestrial anomalies are determined from ellipsoidal heights obtained by GNSS and from precise levelling data. Ellipsoidal heights from 2005 are adjusted to the reference epoch 2025 using a velocity field derived from the European Permanent Network. The results indicate regional subsidence of about −1 mm per year. After temporal harmonization, root-mean-square of differences between terrestrially determined anomalies and those derived from GGMs is approximately 0.21 m for satellite-only models and 0.11 m for combined GGM.

Keywords: height anomalies, Global Geopotential Models, GOCO, GNSS, levelling

УСКЛАЂИВАЊЕ ЕПОХА У АНАЛИЗИ ТЕРЕСТРИЧКИХ И GOCO АНОМАЛИЈА ВИСИНА: СТУДИЈА СЛУЧАЈА НА ТЕРИТОРИЈИ СРБИЈЕ

Сажетак:

Терестричке аномалије висина упоређене су са аномалијама добијеним из глобалних геопотенцијалних модела (GGM) развијених у оквиру иницијативе GOCO. Анализира се утицај разлика епоха на геометријске висине. Терестричке аномалије одређене су на основу елипсоидних висина добијених применом GNSS и података нивелмана. Елипсоидне висине из 2005. године прилагођене су референтној епохи 2025 коришћењем поља брзина изведеног из Европске перманентне мреже. Резултати указују на регионално слегање тла од око −1 mm годишње. Након временске хармонизације, средња квадратна грешка разлика између терестрички одређених аномалија и аномалија изведених из GGM износи приближно 0.21 m за сателитске моделе и 0.11 m за комбиноване GGM.

Кључне речи: аномалије висина, глобални геопотенцијални модели, GOCO, GNSS, нивелман

1. INTRODUCTION

Height anomalies serve as a critical link between geometric positioning obtained from Global Navigation Satellite System (GNSS) and physical heights defined by the Earth's gravity field. These anomalies are essential for geoid and quasigeoid determination, height system realization and unification, and the interpretation of long-wavelength geodynamic processes [1], [2]. The development of modern satellite gravity missions has enabled the derivation of height anomalies from Global Geopotential Models (GGMs) that are independent of terrestrial gravity observations, thereby facilitating systematic comparisons between satellite-based and ground-based geodetic data. The Gravity Observation Combination (GOCO) initiative has developed a consistent series of GGMs by rigorously combining satellite gravity observations from missions such as GRACE [3], Gravity Recovery and Climate Experiment Follow-On (GRACE-FO), Gravity field and steady-state Ocean Circulation Explorer (GOCE), Challenging Minisatellite Payload (CHAMP) [4], and Satellite Laser Ranging (SLR) [1], [5], [6], [7], [8]. These models comprise both satellite-only solutions, which rely exclusively on spaceborne observations, and combined solutions that incorporate terrestrial gravimetry and satellite altimetry data [2]. In this paper, the term “GOCO-derived” refers to height anomalies computed from GOCO gravity field models, while “terrestrial height anomalies” denote anomalies obtained from GNSS and levelling data. Satellite-only GOCO models are particularly appropriate for unbiased comparisons with terrestrial height anomalies because they do not include local ground gravity information that could mask systematic discrepancies.

Alongside advances in satellite gravity field modelling, national geodetic infrastructures have experienced substantial modernization. In Serbia, the implementation of GNSS-based spatial reference networks (SREF and AGROS) aligned with the European Terrestrial Reference System 1989 (ETRS89), combined with high-precision levelling networks and a national quasigeoid model, establishes a robust framework for determining terrestrial height anomalies with well-defined accuracy and internal consistency [9]. These datasets provide a reliable foundation for regional validation and interpretation of satellite-derived height anomalies. A direct comparison between terrestrial and satellite-derived height anomalies poses significant challenges. Terrestrial height data are frequently obtained from historic levelling campaigns, whereas GNSS-based geometric heights are derived from much later epochs. Over several decades, even minor vertical crustal motions, typically a few millimeters per year, can accumulate to centimeter-level height changes, which are comparable to the height anomaly differences analyzed in this research [10], [11]. Neglecting temporal inconsistencies may result in differences that reflect unmodeled vertical motion rather than genuine inconsistencies in gravity field models. Despite this, many regional validations of satellite-derived or satellite-only global gravity field models implicitly assume epoch-consistent terrestrial height data. In contrast, the potential impact of multi-decadal epoch mismatches on height anomaly comparisons is rarely quantified. As a result, systematic differences caused by long-term vertical crustal motion may be misinterpreted as deficiencies of gravity field models rather than as artifacts of temporal inconsistency. This challenge is especially pertinent in intraplate regions such as Serbia, where vertical crustal motion is typically slow and spatially coherent, yet becomes significant over extended time periods.

Modern terrestrial reference frame realizations explicitly model long-term station behavior and establish the theoretical foundation for interpreting GNSS-derived vertical motion in a physically meaningful manner [12]. At the European level, these principles are implemented within the framework of the European Reference Frame Sub-Commission (EUREF) of the International Association of Geodesy (IAG) through the EUREF Permanent Network (EPN), which provides long-term solutions facilitating the derivation of regional vertical velocity fields [13], [14]. Recent GNSS-based regional velocity models, such as the Adjusted EPN-Derived (AEPND) vertical velocity field, provide a practical approach to harmonize geometric heights across epochs and to isolate long-term vertical trends [14]. The implications of these velocity fields for datum definition and vertical motion analysis have been examined in detail by Erkoç and Doğan [15]. When integrated with historical normal heights from national levelling networks, these models enable the construction of epoch-consistent terrestrial height anomalies suitable for comparison with satellite-based GGMs. This study aims to analyze the differences between terrestrial height anomalies and those derived from GOCO global geopotential models, using Serbia as a regional case study. Terrestrial height anomalies are determined by integrating GNSS-derived ellipsoidal heights, national levelling data, and the Serbian national quasigeoid model, while explicitly accounting for long-term vertical crustal motion through GNSS-derived velocity modelling [9], [14]. These terrestrial anomalies are compared with height anomalies calculated from a set of GOCO satellite-only models and the combined GOCO05c model to assess their consistency and identify systematic spatial patterns. Instead of attributing the observed differences solely to model errors, this study examines them within the frameworks of reference frame realization, height system definition, temporal consistency, and regional vertical crustal motion. This approach seeks to clarify the conditions necessary for meaningful comparison between satellite-derived and terrestrial height anomalies and to demonstrate the significance of epoch-consistent terrestrial data for regional evaluation of modern GGMs.

2. AVAILABLE DATA

This analysis utilizes both terrestrial geodetic observations and satellite-derived gravity field data. The terrestrial dataset comprises discrete height anomaly values obtained from GNSS observations, precise levelling, and the national quasigeoid model, all referenced to Serbia's official spatial and vertical frameworks. These datasets offer physically consistent and rigorously controlled reference quantities for regional analysis. Concurrently, height anomalies from the GOCO GGMs are used to represent satellite-based gravity field information across various spectral resolutions. The following subsections detail the terrestrial datasets and the selected GOCO GGMs, focusing on their reference systems, accuracy, internal consistency, and appropriateness for comparative analysis.

2.1. TERRESTRIAL DATA

At 1001 locations across Serbia, discrete terrestrial height anomaly values were determined by combining GNSS-derived ellipsoidal heights and normal heights from the national levelling network. All points are expressed in the official spatial reference framework and their heights were determined in relation with vertical reference framework of Serbia, established over many years through the long-term development of a geodetic network. Figure 1 illustrates the spatial coverage of the GNSS and levelling points forming the terrestrial dataset. To interpret the results correctly, it is important to explain the reference networks behind these values and discuss the quality and consistency of the data. The development of geodetic reference networks in Serbia spans more than 1.5 centuries and reflects the gradual transition from classical terrestrial surveying techniques to modern satellite-based positioning systems. A comprehensive historical overview of this development is provided by Odalović et al. [9], who describe the evolution of trigonometric, levelling, astro-geodetic, and GNSS-based networks established in Serbia from the mid-19th century to the present day. For many years, classical trigonometric and levelling networks were the main tools for horizontal and vertical positioning. However, differences in their creation, incomplete adjustments, and maintenance issues made them less suitable for today's high-precision needs. The arrival of GNSS technology in the 1990s changed this, enabling a unified, geocentric reference frame that aligns with European and global standards. This led to modern networks aligned with the ETRS89, making them compatible with European geodetic systems [9]. The spatial coordinates for the points in this study were determined using GNSS observations linked to the Serbian Reference Frame (SREF) and the Active Geodetic Reference Network of Serbia (AGROS). SREF is a passive GNSS-based reference network set up between 1998 and 2003. It includes 838 stable points spread across Serbia, with about 10 km between each. The network was built using static GNSS observations and adjusted using seven fixed stations from the Yugoslav Reference Frame (YUREF) which is related with the EUREF. The coordinates are based on ETRS89, with an estimated accuracy of about 6 mm for horizontal position and 10 mm for ellipsoidal height [9]. AGROS is the active part of Serbia's national reference framework. It is a network of permanent GNSS stations that has been running since 2005 and supports both real-time and post-processed positioning. AGROS stations are linked to the EPN, ensuring consistency with European reference frames. The network supports positioning using Real-Time Kinematic (RTK), Virtual Reference Station (VRS), and post-processing, achieving centimeter-level accuracy in both horizontal and vertical measurements under normal conditions [9]. In this study, GNSS coordinates for benchmarks from the Second High Precision Levelling Network were determined by linking the observations to SREF and/or AGROS. This ensures that all spatial coordinates use a modern, unified, and geocentric reference frame consistent with ETRS89. The vertical data in this study come from Serbia's national levelling networks, particularly the Second High-Precision Levelling Network. Over time, several major levelling networks have been developed in Serbia. The Second Levelling Network of Yugoslavia, established in the early 1970s, was a major step forward in accuracy and methodology [9].

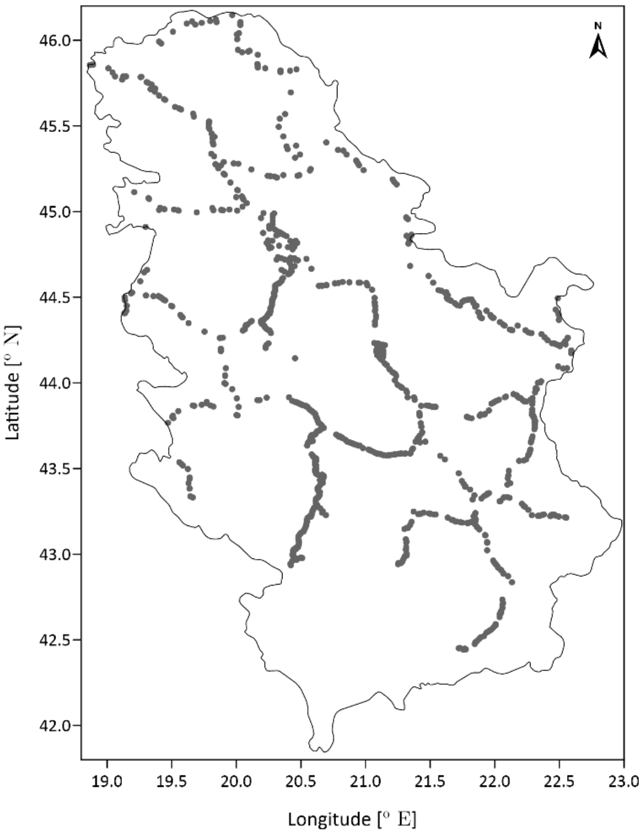

Figure 1. Spatial distribution of GNSS/levelling points used in the analysis across the territory of Serbia (figure created by authors).

Normal heights from this network form Serbia's official physical height system. These heights were determined using precise geometric levelling and are linked to the national vertical datum. Although later political and institutional changes halted the full official use of this network, its data remain public and widely used in research due to their high quality [9]. For GNSS applications, ellipsoidal heights need to be converted to normal heights using a geoid or quasigeoid model. In Serbia, the development of a national quasigeoid began in the early 2000s, using gravimetric data, a detailed digital terrain model, and GNSS/levelling points. The first official quasigeoid model was completed in 2011, enabling GNSS ellipsoidal heights to be converted to normal heights with an accuracy of a few centimeters across the country [9]. In this study, the normal heights of SREF points and levelling benchmarks are considered physically stable reference values within a physical height reference system, not implying the absence of crustal motion. This is methodologically sound because an equipotential surface defines normal heights and represents a physical height system, unlike ellipsoidal heights, which only show geometric positions in space. The discrete values in this analysis come from two independent but consistent data sources:

1. GNSS-determined ellipsoidal coordinates of benchmarks from the Second High Precision Levelling Network, tied to SREF and/or AGROS.
2. Normal heights of SREF points and levelling benchmarks, determined by precise levelling and transformed into ellipsoidal heights using the national quasigeoid model.

The quality of these discrete values depends on the quality of the reference networks. Spatial coordinates from SREF and AGROS are accurate to within millimeters or centimeters. Normal heights from the Second Levelling Network are also accurate to a few millimeters or centimeters, depending on the relevant network quality [9]. Care was taken to keep the spatial and vertical data fully consistent. Incompatible reference frames or height systems were not mixed. All coordinates use ETRS89, and all heights are given as normal heights in the national vertical datum. This ensures the discrete values form a coherent dataset for later numerical and geophysical analysis.

2.2. GOCO GLOBAL GEOPOTENTIAL MODELS

The GOCO initiative produces a consistent series of global geopotential models based on complementary satellite gravity observations, with some models further augmented by terrestrial and/or altimetric data. This study compares terrestrial height anomalies with those derived from various GOCO models. These models are categorized as either (i) satellite-only solutions, which rely exclusively on satellite observations, or (ii) combined solutions, which integrate satellite data with terrestrial gravimetry and/or satellite altimetry. The satellite missions and observation types considered include GRACE [3], GRACE-FO (the follow-on mission) [16], GOCE [17], CHAMP [4], kinematic orbit solutions from multiple low Earth orbiters (LEOs), and SLR [18]. GOCE satellite gravity gradiometry measurements are referred to as SGG.

2.2.1. MODEL GOCO01S

GOCO01s is the first published result of the GOCO initiative and belongs to the satellite-only class. It was produced by combining measurements from GRACE and GOCE without incorporating terrestrial gravimetry or satellite altimetry, which makes the model fully independent of ground-based gravity information and therefore suitable for unbiased comparisons with terrestrial height anomalies [1]. The model was generated by combining full normal equations derived independently from both satellite missions. GRACE inter-satellite K-band range-rate observations and precise orbit determination dominate the low- and medium-degree part of the spherical harmonic spectrum, while GOCE SGG observations strengthen the solution in the medium- to high-degree spectral range. GOCO01s is resolved up to degree and order 224 [1]. To ensure numerical stability at high degrees, Kaula-type regularization was applied beyond degree 170. This approach does not introduce an external gravity field model as prior information. Instead, it constrains the high-degree coefficients according to the expected spectral decay, thereby stabilizing the solution when satellite-only data become less reliable. The stochastic characteristics of GOCE gradiometer observations were addressed using Autoregressive Moving Average (ARMA) filtering to account for frequency-dependent noise, and Variance Component Estimation (VCE) was employed to determine the statistically consistent relative weighting of GRACE and GOCE normal equations [1]. Validation against independent global gravity field models and regional GNSS/levelling data demonstrates that the combined satellite solution surpasses GRACE-only and GOCE-only solutions across most of the spectrum, with notable improvements in the intermediate band (approximately degrees 100–150), which is significant for geoid and quasigeoid height applications [1]. In this study, GOCO01s is used as a first-generation satellite-only reference model to identify systematic differences between satellite-based and terrestrial gravity information.

2.2.2. MODEL GOCO02S

GOCO02s, a second-generation satellite-only model, extends both the observation period and the range of contributing satellite data types beyond those used in GOCO01S, while remaining entirely independent of terrestrial gravimetry and altimetry. The model is constructed by combining full normal equations from several satellite missions, including long-term GRACE observations, an extended GOCE data period, and additional data from SLR and CHAMP. This expanded observation base enhances the determination of low- and medium-degree coefficients and yields a more consistent spectral solution than GOCO01s [6]. GOCO02s is resolved to the degree and order 250. Kaula-type regularization is applied beyond degree 180, and VCE-based weighting, along with observation-level stochastic modeling, are used to generate realistic formal error estimates and improved signal-to-noise characteristics [6]. Comparisons with independent GNSS/levelling data, particularly in well-surveyed European regions, reveal reduced geoid height discrepancies relative to GOCO01s, demonstrating the advantages of the extended GOCE data span and the inclusion of additional satellite observations [6].

2.2.3. MODEL GOCO03S

GOCO03S, the third generation of GOCO satellite-only models, continues the approach of enhancing spectral consistency by extending mission observation periods and refining stochastic modeling, while maintaining independence from terrestrial and altimetric gravity data [7]. GOCO03s integrates full normal equations from long-term GRACE observations, an expanded set of GOCE SGG measurements, SLR, and CHAMP. Compared to GOCO02s, the GOCE observation period is extended by approximately 18 months, thereby strengthening the medium- and high-degree spectral domains. SLR data improve the determination of the lowest degrees, particularly degree 2, which is essential for global consistency [7]. The model is resolved up to degree and order 250, with Kaula-type regularization applied beyond degree 180. A key methodological feature is the focus on realistic formal error estimates: non-white noise is addressed at the observation level, VCE determines relative weighting, and no post-hoc calibration factors are used [7]. GNSS/levelling comparisons show further reductions in geoid height discrepancies relative to GOCO02s, supporting the adoption of GOCO03s as a mature satellite-only reference before using high-resolution combined solutions.

2.2.4. MODEL GOCO05S

GOCO05s represents a significant advancement in the GOCO satellite-only series, incorporating a substantially extended and reprocessed set of satellite observations and fully utilizing the complete GOCE mission alongside long-term GRACE data [19]. The model is constructed from a rigorous combination of full normal equations, with primary contributions from GRACE and GOCE (processed using the time-wise approach), and is further supported by SLR and kinematic orbit data from additional LEO satellites to enhance the lowest degrees. GOCO05s is resolved to a degree and order 280, marking a notable increase in spatial resolution compared to GOCO03S. The combination employs observation-level stochastic modeling and VCE-based relative weighting to maximize the complementary spectral strengths of the input data sets [1], [19]. GOCO05s remains independent of terrestrial gravity and altimetry data, establishing it as a high-quality satellite-only benchmark. External validation, including orbit analyses and GNSS/levelling comparisons, demonstrates improvements over previous GOCO satellite-only models, particularly in the medium-wavelength domain relevant for geoid and quasigeoid determination [19].

2.2.5. MODEL GOCO05C

GOCO05c is a high-resolution combined gravity field model that integrates satellite mission data with terrestrial and altimetric gravity information within a rigorous combination framework. Unlike the satellite-only GOCO-s models, GOCO05c merges the satellite-only reference model GOCO05s with a global set of gravity anomalies from terrestrial gravimetry and satellite altimetry, thereby reducing omission errors and enhancing spatial detail, especially over continental regions [2]. The model is resolved up to degree and order 720. A key methodological feature is the use of full normal equation systems at full resolution, which enables regionally varying stochastic models that account for the heterogeneous quality of terrestrial and altimetric data worldwide. VCE-based weighting allows the spectral transition from satellite-dominated to ground-data-dominated content to vary regionally, typically between degrees 140 and 240 [2]. To achieve global completeness and numerical stability, GOCO05c incorporates fill-in data for regions with limited observations. This approach reduces omission error and supports geodetic applications such as geoid determination and height system unification. However, it also means that GOCO05c is not recommended for detailed geophysical interpretation in areas where fill-in data predominate [2]. Extensive validation through GNSS/levelling comparisons, orbit tests, and mean dynamic topography computations demonstrates that GOCO05c attains accuracy comparable to or exceeding that of other contemporary high-resolution models, while remaining largely independent of Earth Gravitational Model 2008 (EGM2008) except for minimal regularization at the highest degree [2]. Within this study, GOCO05c is used as a combined model suitable for direct comparison with terrestrial height anomalies at higher spatial resolutions.

2.2.6. MODEL GOCO06S

GOCO06s is a satellite-only global gravity field model that advances the GOCO concept by incorporating an unprecedented volume and diversity of satellite observations. The model is based on a rigorous combination of full normal equations derived from approximately 1.16 billion observations collected by 19 satellites. The data sources include GOCE SGG observations - GOCE time-wise solution, release 6 (TIM6), GRACE satellite-to-satellite tracking data from ITSG-Grace2018s, kinematic orbits from multiple LEO missions (such as Swarm A/B/C [20], TerraSAR-X and TanDEM-X [21], CHAMP, GRACE, and GOCE), and SLR observations to a wide range of geodetic satellites (including LAGEOS-1/2, Starlette, Stella, AJISAI, LARES, LARETS, Etalon-1/2, and BLITS) [5], [8], [18]. GOCO06s is resolved up to degree and order 300 and incorporates secular and annual temporal variations up to degree and order 120. VCE is used to determine the relative weighting among the data sources. To address the GOCE polar gap, Kaula regularization is applied beyond degree and order 150. The model is provided in the zero-tide system with fully normalized coefficients and formal error information [8]. For the comparison with terrestrial height anomalies, GOCO06s serves as an advanced satellite-only reference, offering improved robustness at low and medium degrees due to the expanded kinematic orbit and SLR data.

2.2.7. MODEL GOCO2025S

GOCO2025s is the latest satellite-only model in the GOCO series and represents a new generation of global gravity field modeling that leverages modern satellite missions and advanced measurement techniques. The model is resolved up to degree and order 300 and includes constrained secular, annual, and semi-annual variations up to degree and order 200. GOCO2025s is based on satellite data collected from 2002 to 2024 and integrates GOCE SGG observations (TIM6), GRACE and GRACE-FO data (including both K-band range-rate and Laser Ranging Interferometer measurements), kinematic orbit information from a wide range of LEO missions (such as Swarm

[20], multiple Sentinel satellites [22], TerraSAR-X, TanDEM-X [21], and others), and extensive SLR observations referenced to International Terrestrial Reference Frame (ITRF2020) [23]. The combination is obtained using the full normal equations, with VCE determining the relative weights. Temporal variations are regularized using isotropic noise models and treated separately over land and oceans, enhancing the consistency of time-dependent coefficients. GOCO2025s is distributed with spherical harmonic coefficients and formal uncertainties, along with accompanying normal equation products for advanced uncertainty analyses and transparent handling of non-tidal atmosphere and ocean contributions already included in the model [23]. In this study, GOCO2025s serves as the highest-level satellite-only benchmark for evaluating agreement with terrestrial height anomalies.

2.2.8. COMPARATIVE OVERVIEW OF GOCO SATELLITE-ONLY MODELS (GOCO01S–GOCO2025S) AND THE DISTINCT ROLE OF THE COMBINED MODEL GOCO05C

The GOCO satellite-only (s) models form a consistent family of global gravity field solutions derived exclusively from satellite observations. These models are processed through rigorous combinations of the full normal equations with variance-component-based weighting. GOCO01s, as the first-generation solution, establishes the baseline by combining GRACE and early GOCE data, resolved up to degree and order 224, and demonstrates the core GOCO methodology in a purely satellite-only context [1]. GOCO02s and GOCO03s provide successive refinements by extending the GOCE time span and incorporating additional satellite tracking data, such as SLR and CHAMP. These models increase the maximum resolution to degree and order 250 and emphasize realistic stochastic modeling and formal error characterization at the observation level [6], [7]. GOCO05s represents a significant advancement within the satellite-only branch by utilizing the complete GOCE mission period alongside long-term GRACE observations and further strengthening the low-degree spectrum with complementary tracking data. It is resolved up to degree and order 280 and is widely recognized as a high-quality satellite-only reference for geodetic applications [19]. GOCO06s advances the satellite-only concept by integrating a greater volume and diversity of satellite observations, including extensive kinematic orbits from multiple LEO missions and an expanded SLR data set, while maintaining a strict satellite-only approach. GOCO06s is resolved to degree and order 300 and incorporates secular and annual temporal variations up to degree and order 120. Kaula-type regularization is applied beyond degree and order 150 to address the GOCE polar gap, resulting in improved robustness and reduced noise, particularly at low and medium degrees that are critical for global consistency [8]. GOCO2025s is the most recent state-of-the-art satellite-only solution, also resolved to degree and order 300, but based on the longest observation window (2002–2024). It incorporates modern measurement technologies, most notably GRACE-FO Laser Ranging Interferometer observations, along with an expanded set of LEO kinematic orbits and SLR targets. GOCO2025s also estimates constrained secular, annual, and semi-annual temporal variations up to degree and order 200, supported by refined regularization strategies and transparent auxiliary products, including normal equations and non-tidal atmosphere and ocean mass signals [23]. Unlike the s-series, GOCO05c is not a satellite-only model. It is a combined (c) solution that integrates the satellite-only reference GOCO05s with global gravity anomalies derived from terrestrial gravimetry and satellite altimetry. This integration uses full normal equations at full resolution, up to degree and order 720, and applies regionally varying stochastic models to address the heterogeneous quality of ground and altimetric data worldwide [2]. As a result, GOCO05c is expected to capture shorter-wavelength gravity signals relevant for high-resolution height anomaly applications. However, it also inherits limitations related to uneven global ground-data coverage and the presence of fill-in data regions, which require careful interpretation depending on the study area [2]. In comparative analyses against terrestrial height anomalies, the s models provide an internally consistent satellite-only benchmark hierarchy (from GOCO01s to GOCO2025s). In contrast, the c model represents a fundamentally different class of solution due to its explicit inclusion of ground and altimetric gravity information.

3. NUMERICAL RESEARCH

All numerical analyses were conducted in the zero-tide system to maintain consistency among terrestrial observations, global geopotential models, and the adopted normal gravity field. Normal gravity quantities were calculated with respect to the Geodetic Reference System 1980 (GRS80) reference ellipsoid, which serves as the standard geometric and physical reference for both terrestrial and GOCO-derived height anomalies. Ellipsoidal heights used in the calculation of terrestrial height anomalies were obtained from GNSS observations at GNSS–levelling points, with an accuracy of approximately 1–2 cm, as specified by the Republic Geodetic Authority [24]. These ellipsoidal heights represent the geometric component of terrestrial height anomalies and provide reliable information at long and medium wavelengths for regional comparisons. Height anomalies derived from global geopotential models were computed using the full spectral content of each model, up to their respective maximum spherical harmonic degree and order. The satellite-only models were evaluated up to degree and order 224 (GOCO01s), 250 (GOCO02s and GOCO03s), 280 (GOCO05s), and 300 (GOCO06s and GOCO2025s). The combined model GOCO05c was evaluated up to degree and order 720. No additional spectral truncation or filtering was applied, which enabled each model to express its maximum spatial resolution and long-wavelength signal content. All terrestrial and GOCO-derived height anomalies were evaluated at identical point locations and within a consistent reference-system realization. The numerical procedure was structured to minimize methodological biases and to ensure that observed differences between terrestrial and model-derived height anomalies primarily reflect the effects of spectral resolution, model composition, and temporal harmonization, rather than inconsistencies in reference systems or numerical implementation.

3.1. DETERMINATION OF HEIGHT ANOMALIES USING GOCO GLOBAL GEOPOTENTIAL MODELS

The determination of height anomalies using GGMs in this study follows the classical framework of physical geodesy. It employs the methodology previously used to *evaluate and tailor global geopotential models for gravity field determination in Serbia* [25]. In this work, the procedure is limited to the determination of height anomalies from GOCO models, with no regional modification of model coefficients. In physical geodesy, the Earth's gravity potential W is represented as the sum of the normal potential U of the reference ellipsoid and the disturbing potential T [26], [27]:

$$W = U + T. \tag{1}$$

When the normal potential is properly defined, height anomalies can be determined as functionals of the disturbing potential [28]. For any point P located on the physical surface of the Earth, the height anomaly ζ is determined by Bruns' formula [26], [29]:

$$\zeta(P) = \frac{T(P)}{\gamma(Q)}, \tag{2}$$

where $T(P)$ denotes the disturbing potential at the point, and $\gamma(Q)$ is the normal gravity evaluated at the corresponding point on the telluroid, defined by the condition $U(Q) = W(P)$. In practical applications, $\gamma(Q)$ is computed using the ellipsoidal latitude of the point P and the normal height H^N. Normal gravity on the reference ellipsoid is determined using the Somigliana formula, while normal gravity at the telluroid is obtained by accounting for the height dependence along the ellipsoidal normal [26], [27]. The gravitational potential V associated with a selected GOCO global geopotential model is represented by a fully normalized spherical harmonic expansion [1], [2]:

$$V(r, \varphi, \lambda) = \frac{GM}{r} \sum_{n=0}^{N} \left(\frac{a}{r}\right)^n \sum_{m=0}^{n} \overline{P}_{nm}(\sin\varphi)(\overline{C}_{nm} \cos m\lambda + \overline{S}_{nm} \sin m\lambda), \tag{3}$$

where r is the geocentric radius, φ and λ are geocentric latitude and longitude, GM is the Earth's gravitational constant of the model, a is the reference radius, $\overline{C}_{nm}$ and $\overline{S}_{nm}$ are the fully normalized spherical harmonic coefficients, and $\overline{P}_{nm}$ are the associated Legendre functions. The normal potential U of the reference ellipsoid is represented analogously using the ellipsoidal constants and coefficients [27]. The disturbing potential is then determined as [27]

$$T(P) = V(P) - V_U(P). \tag{4}$$

Following Molodensky's concept, the height anomaly represents the distance along the ellipsoidal normal between the point on the physical surface and the corresponding point on the telluroid, at which the normal potential equals the actual potential at the physical surface of the Earth [28].

3.2. TERRESTRIAL HEIGHT ANOMALIES AND TEMPORAL HARMONIZATION USING THE AEPND MODEL

In modern geodetic and geophysical studies, long-term vertical stability represents a fundamental prerequisite for the correct interpretation of spatial and temporal variations of physical quantities. Even small vertical crustal motions, typically on the order of millimeters per year, may accumulate to several centimeters over multi-decadal time spans, becoming significant for height reference systems, deformation analysis, and regional geodynamic interpretation [10], [11]. The reliable interpretation of such small signals requires careful treatment of reference frames, height systems, and temporal consistency. Contemporary terrestrial reference frame realizations explicitly model long-term station behavior and provide the necessary framework for interpreting GNSS-derived vertical motion in a physically meaningful way [12]. At the European scale, these concepts are operationally implemented through the EPN, whose long-term multi-year solutions form the basis for regional velocity modeling [13]. The determination of terrestrial height anomalies in this study is based on height data referring to two distinct epochs and height systems:

- Epoch 1971: normal heights H^{N}_{1971} derived from national precise levelling networks,
- Epoch 2005: GNSS-derived ellipsoidal heights h_{2005}, determined within a modern geocentric reference frame.

The use of historic normal heights is consistent with geodetic practice in Serbia, where repeated levelling campaigns provide the primary long-term record of vertical behavior [24]. Normal heights are physical heights defined with respect to an equipotential surface and realized within the national vertical datum. As such, they represent stable physical reference quantities rather than kinematic observables. A direct combination of these quantities yields a mixed-epoch observable:

$$\zeta^{2005} = h_{2005} - H^{N}_{1971}. \tag{5}$$

This quantity does not represent a height anomaly at a single epoch. Instead, it combines geometric information from the epoch 2005 with a physical height datum established in 1971. Consequently, explicit treatment of temporal consistency is required before further interpretation. In the present analysis, the normal heights H^{N}_{1971} are treated as fixed reference quantities and are not propagated in time. This methodological choice is justified because GNSS-derived vertical velocity models describe the temporal evolution of the geometric position of points in space. In contrast, normal heights are defined with respect to an equipotential surface and represent a physical reference rather than a kinematic quantity. Applying GNSS-based vertical corrections directly to normal heights would therefore be physically inconsistent. Throughout the analysis, the normal heights from 1971 serve as a stable physical reference against which geometric height changes are evaluated. Temporal harmonization of the geometric component is achieved by vertically propagating the GNSS-derived ellipsoidal heights using the Adjusted EPN-Derived (AEPND) vertical velocity model, version v2023.0. The AEPND model provides a spatially continuous field of secular vertical velocities derived from long-term GNSS observations within the EPN framework [14]. The derivation of such regional velocity fields relies on rigorous modelling of GNSS time series, including the treatment of colored noise and seasonal signals, which predominantly affect the vertical component [11], [30]. As a result, the AEPND model captures long-wavelength, regionally coherent deformation patterns that are consistent with European-scale GNSS analyses and ground motion services [31], [32]. GNSS observations are available only for the epoch 2005. In order to obtain epoch-consistent geometric quantities, the ellipsoidal heights are vertically propagated to the reference epoch 2025 according to

$$h^{Model}_{2025} = h_{2005} + V_{up} \cdot \Delta t\,, \tag{6}$$

where V_{up} denotes the AEPND vertical velocity (mm/year), and Δt = 20 years corresponds to the interval between 2005 and 2025. This operation represents a model-based extrapolation of the regional secular trend and does not imply the existence of direct GNSS observations at the reference epoch. The conceptual validity of such extrapolation in the context of datum definition and vertical velocity fields has been discussed in detail by Erkoç and Doğan [15]. Using the vertically transported ellipsoidal heights, an epoch-consistent terrestrial height anomaly is defined as

$$\zeta^{2025} = h^{Model}_{2025} - H^{N}_{1971}. \tag{7}$$

This quantity represents a height anomaly referenced to the 1971 normal height system and geometrically consistent with the reference epoch 2025. It constitutes the primary terrestrial observable used for subsequent spatial and statistical analyses and for comparison with height anomalies derived from GOCO GGMs. The construction of such anomalies implicitly assumes spatial smoothness of the underlying regional vertical signal. Comparable results obtained from combined GNSS and InSAR analyses of vertical crustal movements have been demonstrated in recent regional studies [33]. Similar assumptions are inherent in spatial interpolation and regional modelling techniques commonly applied in geodetic analyses of long-wavelength deformation [34], [35]. The epoch-consistent terrestrial height anomalies defined above therefore provide a physically meaningful and temporally harmonized reference against which GOCO-derived height anomalies are evaluated in the subsequent analysis.

4. RESULTS

The analysis compares vertically harmonized terrestrial height anomalies, height anomalies from GOCO global geopotential models, and their differences. Tables 1 to 4 summarize the results, showing the magnitude of long-term vertical motion, the consistency of terrestrial anomalies, and the agreement between terrestrial and satellite-derived height anomalies. Table 1 shows the main statistical features of the AEPND-derived vertical velocity field in the study area. The vertical velocities range from −2.50 to −0.15 mm per year, with an average of −1.06 mm per year and a standard deviation of 0.60 mm per year. These numbers show a consistent pattern of subsidence across the region. Over 20 years, from the GNSS observation in 2005 to the reference in 2025, the total vertical displacement ranges from −0.050 m to −0.003 m, with an average of −0.021 m and a standard deviation of 0.012 m. While the annual velocities are small, their long-term effects accumulate to several centimeters (Table 1), comparable to the differences observed between terrestrial and satellite-derived height anomalies (Table 4). This shows that aligning geometric heights over time is important for accurate comparison.

Table 1. Basic statistical parameters of vertical point displacements derived from the AEPND model

Parameter	Minimum	Maximum	Average	Standard deviation
V_{up} [mm/year]	-2.50	-0.15	-1.06	0.60
Displacement for 20 years [m]	-0.050	-0.003	-0.021	0.012

Table 2 shows the statistical details of the epoch-consistent terrestrial height anomalies. These anomalies range from 42.314 m to 46.381 m, with an average of 44.620 m and a standard deviation of 0.856 m. The small range of values suggests that height anomalies change smoothly across the study area and that the combined GNSS, levelling, and quasigeoid-based terrestrial data are internally consistent after temporal harmonization. The size and spread of these anomalies match what are expected for regional height anomalies in southeastern Europe and offer a reliable reference for comparing satellite-derived results.

Table 2. Basic statistical parameters of terrestrial height anomalies derived from measurements ($\zeta^{2025} = h_{2025}^{Model} - H_{1971}^{N}$)

Parameter	Minimum	Maximum	Average	Standard deviation
ζ [m]	42.314	46.381	44.620	0.856

Table 3. Basic statistical parameters of height anomalies derived from GOCO GGMs

Model		Minimum	Maximum	Average	Standard deviation
GOCO01s	[m]	42.465	46.573	44.581	0.829
GOCO02s		42.408	46.555	44.577	0.856
GOCO03s		42.339	46.599	44.582	0.869
GOCO05s		42.467	46.678	44.620	0.860
GOCO06s		42.314	46.631	44.605	0.880
GOCO2025s		42.293	46.617	44.605	0.879
GOCO05c		42.275	46.144	44.577	0.883

Table 3 shows the main statistical features of height anomalies from the selected GOCO global geopotential models. For the satellite-only GOCO models (GOCO01s to GOCO2025s), minimum values range from 42.293 m to 42.467 m, and maximum values range from 46.555 m to 46.678 m. The mean values are very similar across all satellite-only models, ranging from 44.577 to 44.620 m. Standard deviations are between 0.829 m and 0.880 m, which is similar to the spread seen in the terrestrial anomalies. The combined model GOCO05c has a similar mean value (44.577 m), with obviously different maximum value, and a similar standard deviation (0.883 m). The close match in mean values and spread between terrestrial anomalies and those from the GOCO models suggests that both datasets reflect the same long-wavelength gravity field signal at the regional level.

Table 4 shows the statistics of the differences $\Delta\zeta^{2025} = \zeta^{GOCO} - \zeta^{2025}$. For satellite-only models, the minimum differences are between −81.5 cm and −52.5 cm, and the maximum differences are between 56.0 cm and 71.1 cm. The mean differences are small, ranging from −4.4 cm to −0.1 cm, suggesting no significant systematic bias between terrestrial and satellite-derived anomalies. The spread of the differences, measured by standard deviation and root-mean-square (RMS), changes with each model generation. Earlier satellite-only models (GOCO01s to GOCO03s) have RMS values between 25.0 cm and 28.2 cm. Newer satellite-only models (GOCO05s, GOCO06s, and GOCO2025s) have lower RMS values, around 21.5 to 23.4 cm. This improvement demonstrates greater consistency with terrestrial data, thanks to longer observation periods and improved use of satellite data.

The combined model GOCO05c behaves differently. Its differences are within a smaller range (−31.3 cm to 20.9 cm), with a standard deviation of 9.8 cm and an RMS of 10.7 cm. This much better agreement is due to the addition of terrestrial and altimetric gravity data, which reduces omission errors at shorter wavelengths and improves regional consistency. Figures 2 and 3 illustrate the spatial distributions of differences between the epoch-consistent terrestrial height anomalies and the corresponding height anomalies derived from the GOCO2025s satellite-only model and the combined GOCO05c model, respectively. The small mean values, ranging from a few millimeters to several centimeters, indicate no significant systematic bias between the epoch-harmonized terrestrial height anomalies and the GOCO-derived anomalies at the regional scale.

Table 4. Basic statistical parameters of differences $\Delta\zeta^{2025} = \zeta^{GOCO} - \zeta^{2025}$

Model		**Minimum**	**Maximum**	**Average**	**Standard deviation**	**RMS**
GOCO01s	**[m]**	-0.558	0.578	-0.039	0.247	0.250
GOCO02s		-0.763	0.560	-0.044	0.271	0.275
GOCO03s		-0.815	0.618	-0.038	0.280	0.282
GOCO05s		-0.694	0.711	-0.001	0.234	0.234
GOCO06s		-0.529	0.651	-0.016	0.215	0.215
GOCO2025s		-0.525	0.641	-0.016	0.215	0.215
GOCO05c		-0.313	0.209	-0.043	0.098	0.107

In summary, the results show that temporally harmonized terrestrial height anomalies match well with height anomalies from modern GOCO satellite-only models at the regional level. On average, the mean values of the harmonized terrestrial height anomalies show better agreement with the GOCO models by 2.1 cm, with a standard deviation of 0.2 cm. The steady decrease in RMS of differences from earlier to more recent satellite-only models shows that satellite gravity field solutions have improved over time. The much smaller differences seen with the combined GOCO05c model show how adding terrestrial gravity data makes a significant difference and sets it apart from models that use only satellite data. These results offer a solid basis for the interpretation and discussion in the next section.

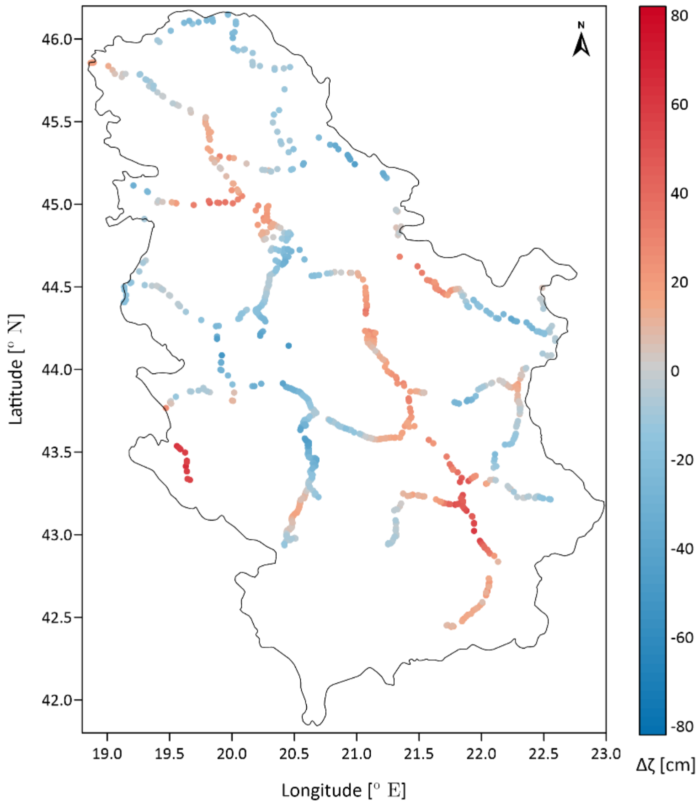

Figure 2. Spatial distribution of differences between epoch-consistent terrestrial height anomalies and height anomalies derived from the GOCO2025s model (figure created by authors).

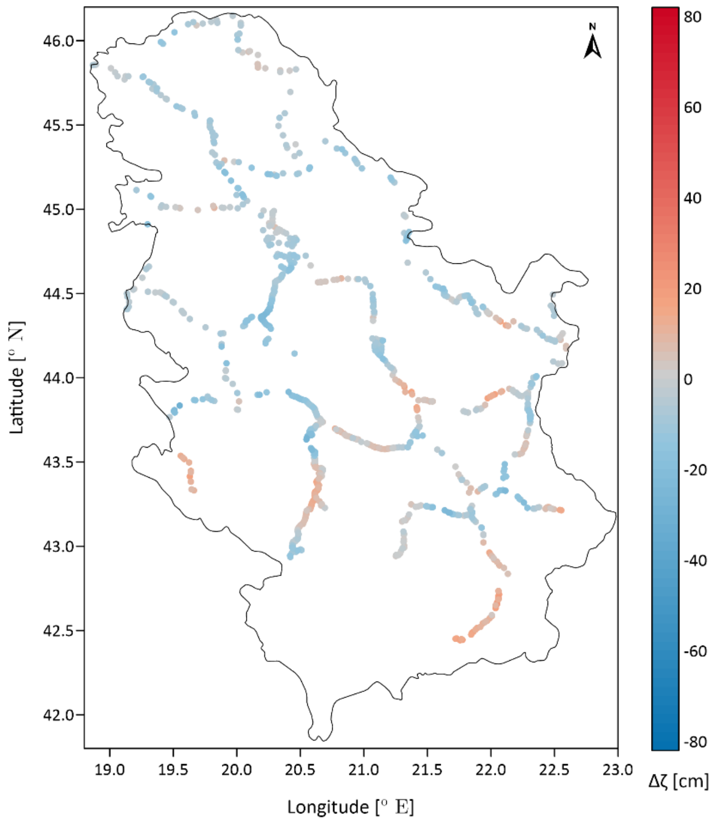

Figure 3. Spatial distribution of differences between epoch-consistent terrestrial height anomalies and height anomalies derived from the GOCO05c model (figure created by authors).

5. DISCUSSION

The results show that terrestrial and satellite-based height anomalies agree well when temporal effects are accounted for. Even small long-term vertical crustal movements, like the subsidence rates of about −1 mm per year from the AEPND velocity model, add up to several centimeters over decades. These changes are of similar magnitude to the regional height-anomaly differences studied here, suggesting that failing to correct for epoch differences can significantly affect comparisons. The chosen temporal harmonization method, which adjusts GNSS-based ellipsoidal heights to a common reference time while preserving historic normal heights as fixed reference points, is methodologically sound. After this adjustment, terrestrial height anomalies show smooth spatial patterns and stable statistics, much like those from modern GOCO gravity field models. The close match in average values shows that both terrestrial and satellite data capture the main long-wavelength part of the regional gravity field. There is a clear improvement in the agreement between terrestrial height anomalies and satellite-only GOCO models, moving from early versions (GOCO01s–GOCO03s) to newer ones (GOCO05s, GOCO06s, and GOCO2025s). This progress comes from longer observation epoch, better background models, and more tracking data, like kinematic orbits and SLR. On the other hand, the combined GOCO05c model shows much lower variation and RMS differences compared to terrestrial anomalies. This better match is mainly due to its higher spectral resolution and the use of both terrestrial gravimetry and satellite altimetry data, which help reduce errors and improve regional agreement. Even though the combined model matches the numbers better, this does not necessarily mean it is better for geophysical interpretation. Combined gravity field models use terrestrial gravity data of varying quality and coverage, which can sometimes mask systematic differences when used for independent checks. As a result, while combined models work well for practical geodetic tasks such as height system realization and unification, satellite-only models remain essential for unbiased geophysical studies and for independently verifying terrestrial data.

6. CONCLUSIONS

This study shows that to compare terrestrial and satellite-derived height anomalies accurately; terrestrial data must be consistent over time. Even small vertical crustal movements, measured in millimeters per year, accumulate over decades and become significant relative to regional height anomalies. Aligning GNSS-derived ellipsoidal heights over time with vertical velocity models and using historical normal heights as fixed reference points is an effective and reliable method. Once harmonized, terrestrial height anomalies show stable statistics and spatial patterns that match those from modern GOCO gravity field models. The match between terrestrial anomalies and satellite-only GOCO models improves with each new model generation, indicating progress in satellite gravity measurements and data processing. While the combined GOCO05c model exhibits smaller differences due to its higher resolution and use of terrestrial gravity data, satellite-only models remain important for unbiased geophysical analysis. In summary, the differences seen between terrestrial and satellite-derived height anomalies are not just due to problems with global gravity field models. They result from a mix of factors, including how reference frames are set, how height systems are defined, timing issues, and long-term vertical crustal movement. The approach in this study offers a strong way to validate GGMs at the regional level. It can be applied in other areas where both old levelling data and modern GNSS measurements are available.

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