

RESEARCH ARTICLE

DETERMINATION OF ORTHOMETRIC HEIGHTS OF POINTS USING GLOBAL NAVIGATION SATELLITE SYSTEM (GNSS) AND GLOBAL GEOID MODELS FOR ABIOLA AJIMOBİ TECHNICAL UNIVERSITY

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ABSTRACT

The determination of orthometric heights with high precision is vital for geospatial analysis, engineering design, and modern infrastructure planning. While spirit levelling technique is accurate, it is labor-intensive and less practical for large areas or difficult terrain. This study adopts a GNSS-based approach at Abiola Ajimobi Technical University (AATU), integrating multiple global geoid models to enhance vertical accuracy. A dual-frequency DGPS receiver, linked to a CORS network, was used to obtain ellipsoidal heights from 300 stochastically and randomly distributed points. Five gravimetric geoid models; EGM2008, EIGEN-6C4, GECO, SGG-UGM-2, and XGM2019e, were applied to compute geoid undulations and convert ellipsoidal heights to orthometric heights. Data processing involved QGIS for spatial mapping, statistical software for accuracy checks, and online geoid computation tools for verification. Quality control steps included outlier detection, cross-model comparisons, and heatmap analysis of deviations. Results showed that EGM2008 and XGM2019e had the closest agreement, while SGG-UGM 2 recorded larger discrepancies, highlighting the importance of model selection for local geophysical conditions. The workflow demonstrates that GNSS with appropriate geoid models can reliably deliver engineering grade orthometric heights, offering a replicable, efficient, and precise method for infrastructure development and geodetic modernization in developing regions.

KEYWORDS

Orthometric heights, EGM2008, EIGEN-6C4, GECO, SGG-UGM-2, XGM201, GNSS

1. INTRODUCTION

The measurement of heights, a pursuit woven into the fabric of human civilization, has transitioned from the rudimentary tools of antiquity to the sophisticated satellite-based systems of today, embodying a relentless drive to comprehend and shape the physical world. Within the domain of geospatial science, orthometric heights; elevations precisely gauged relative to the geoid, an equipotential surface approximating mean sea level, stand as a linchpin for a vast array of practical applications. These heights, far from mere abstractions, are indispensable for the precise engineering of infrastructure, ensuring that roads traverse landscapes efficiently, buildings rest on stable foundations, and drainage systems channel water away from populated zones. At Abiola Ajimobi Technical University (AATU), situated in the heart of Oyo State, Nigeria, the need for such elevation data emerges as a pressing imperative, as the institution seeks to expand its campus to meet the demands of a burgeoning academic community. Yet, the traditional method of spirit levelling, long revered for its precision, has its shortcomings in this context, encumbered by its slow pace and resource-heavy nature (Oluoyori and Ono, 2015).

Historically, surveyors wielding levelling rods and optical instruments traversed terrains with painstaking diligence, establishing height differences point by point; a method that, while effective in confined settings, falters when applied to expansive or obstructed landscapes like AATU's campus (Abdulrahman and Kamarudin, 2022). The advent of Global Navigation Satellite Systems (GNSS) has heralded a transformative era, offering a leap forward in efficiency and scalability. Encompassing

systems such as the United States' GPS, Russia's GLONASS, and Europe's Galileo, GNSS employs constellations of satellites to deliver three-dimensional coordinates, latitude, longitude, and ellipsoidal height, with unprecedented speed. However, these ellipsoidal heights, referenced to a mathematical ellipsoid rather than the geoid, require conversion to orthometric heights through geoid models like EGM2008, a process that has garnered global attention (Odera, 2018).

The scholarly landscape brims with evidence of GNSS's prowess. In Kenya, researchers achieved sub-decimeter accuracy using EGM2008, validating its superiority over EGM96 while in Ghana, similar efforts underscored its robustness in tropical climates akin to Nigeria's (Dzidefo and Issaka, 2019; Kemboi and Odera, 2018). Turkish studies refined GNSS techniques in urban settings, achieving 3-5 cm precision despite multipath challenges (Yilmaz and Turgut, 2018; Soycan and Soycan, 2012). In Egypt, GNSS paired with global geopotential models supported infrastructure needs and in Poland, integration with GRACE data pushed accuracy to 2-3 cm (Kryncki & Rogowski, 2014; El-Ashqer and El-Sagheer, 2020). Coastal applications in Korea and the U.S. further refined GNSS conversions, offering standardized guidelines. Even real time kinematic approaches in Dubai showcased centimeter-level precision collectively painting a picture of GNSS as a versatile tool (Park and Nerem, 2020; Smith and Roman, 2001; Nahavandchi and Soltanpour, 2006).

In Nigeria, this technological shift resonates deeply. Urban planning in Ibadan, near AATU, has embraced GNSS for orthometric heights while Lagos refined local geoid models for similar ends (Oluoyori and Ono, 2015; Eteje and Oduyebo, 2018; Akinlolu and Olorunfemi, 2021). Ondo State's

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GNSS leveling Akure's campus mapping and Southwestern Nigeria's height control efforts highlight its growing adoption (Herbert and Olatunji, 2021; Fajuyigbe and Balogun, 2019; Oluwadare and Okeke, 2023). Northern Nigeria's engineering surveys and coastal differential further attest to its versatility (Abdulrahman and Kamarudin, 2022). Yet challenges persist; sparse gravity data limits geoid accuracy, and campus settings introduce signal interference, necessitating localized solutions (Tata and Olatunji, 2021).

AATU exemplifies this nexus of opportunity and need. Named for a forward-thinking leader, the university aspires to expand its facilities; lecture halls, hostels, and roads to accommodate a rising student body amid Nigeria's educational boom (Adejare and Opaluwa, 2020). Traditional leveling, with its high cost and logistical demands, falters here, as studies across Nigeria affirm (Badejo et al., 2017). GNSS, particularly GPS, offers a lifeline, capturing heights across AATU's diverse terrain, open fields, pathways, and emerging structures; far more efficiently (Park and Nerem, 2020). The resulting orthometric heights, derived via EGM2008, promise to guide infrastructure with precision unattainable by outdated methods (Milbert and Smith, 1999).

This study thus stands at a confluence of global innovation and local necessity. By leveraging GPS within GNSS, it seeks to establish a height framework for AATU, supporting immediate campus needs while contributing to Nigeria's geospatial evolution (Oluwadare & Okeke, 2023). The cited works from regional applications provide a robust scaffold, positioning AATU as a proving ground for satellite-based surveying in an educational context where technical advancement is both a goal and a necessity (Fajuyigbe and Balogun, 2019; Tata and Olatunji, 2021).

2. MATERIALS AND METHODS

At the core of the data acquisition process was a dual-frequency Differential GNSS (DGPS) receiver, a high-precision surveying instrument capable of tracking multiple GNSS constellations (GPS, GLONASS, Galileo, and BeiDou). In this study, the DGPS receiver was employed in rover mode, wherein it was physically transported to 300 pre-selected sampling points across the Abiola Ajimobi Technical University (AATU) campus. These points were chosen using a stochastic-random sampling method, allowing for broad spatial coverage and unbiased data acquisition. The rover collected raw ellipsoidal heights and transmitted or stored observational data for real-time or post-processed corrections.

To enable differential correction and improve the accuracy of positional data, the DGPS receiver was paired with data from a Continuously Operating Reference Station (CORS). For this research, the NIGNET-AABT CORS station was selected, strategically located within proximity to the study area at approximate coordinates of Latitude 7.3799° N and Longitude 3.9470° E. This station is managed by the Office of the Surveyor General of the Federation (OSGoF) and forms part of the Nigerian GNSS Reference Network (NIGNET), a nationwide infrastructure designed to support scientific, cadastral, and engineering applications.

To obtain the geoid height (also referred to as geoid undulation or geoid separation), the study adopted five high-resolution global gravity field models, consistent with prior scholarly precedents including (Tata and Olatunji, 2021). The selected models were Earth Gravitational Model 2008 (EGM2008), EIGEN-6C4, GECO (Gravity field and steady-state Ocean Circulation Explorer/GRACE combined model), SGG-UGM-2 (Satellite Gravity Gradiometry-University of Graz Model 2) and XGM2019e (Experimental Gravity Model 2019 enhanced). These models were chosen for their wide acceptance, recent updates, and compatibility with geodetic applications at both regional and global scales.

QGIS, a free and open-source geographic information system, served as the central platform for spatial data processing, geodetic transformation, and visualization. Its flexible plugin architecture and robust computational capacity made it ideal for handling geospatial datasets derived from GNSS field campaigns. In this study, QGIS was used to import GNSS-derived point data in CSV and ESRI Shapefile formats, integrate global digital geoid models (EGM2008, EIGEN-6C4, GECO, SGG-UGM-2, and XGM2019e) in GeoTIFF formats for the computation of geoid undulations, perform raster-vector overlay analyses to derive orthometric heights using equation 1, generate graduated symbol maps, contour maps, and 3D terrain models to illustrate variations in elevation across the campus terrain and visualize geoid induced discrepancies and spatial error propagation patterns.

$$H = h - N \tag{1}$$

Where: *H* = Orthometric Height (m); *h* = Ellipsoidal Height from GNSS observation (m); *N* = Geoid Undulation from geoid model (m)

To support the generation of high-resolution surface models, Surfer was employed. This specialized software for geospatial visualization and gridding was particularly effective for modeling geoid undulation surfaces and orthometric height fields in three dimensions.

2.1 Study Area Description

Abiola Ajimobi Technical University (AATU) is situated in the southwestern region of Nigeria, specifically within the Ibadan metropolis of Oyo State. The university occupies a vast and topographically diverse landmass in a peri-urban setting that is progressively transforming due to infrastructural expansion and urban sprawl. Strategically located between latitudes 7°14' and 7°15' N and longitudes 3°55' and 3°56' E, AATU lies within the humid tropical climatic zone, characterized by a bimodal rainfall pattern and well-defined wet and dry seasons. These climatic and geographic attributes significantly influence both natural terrain variability and anthropogenic development within the campus and its surroundings.

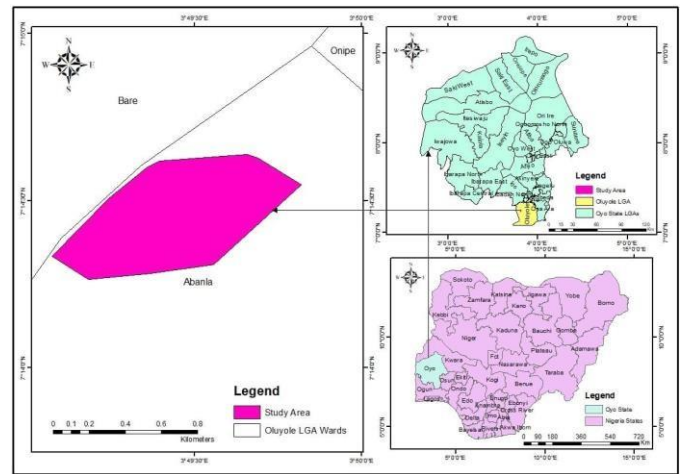


Figure 1: Locational map of the study area.

2.2 Data Processing

The transformation of raw field observations into scientifically valid and usable elevation data constituted a critical stage of this study. This stage involved the meticulous extraction of ellipsoidal heights, retrieval and integration of geoid undulations (N) from multiple global geopotential models, and the eventual derivation of orthometric heights using established geodetic formulas. Each step in this workflow was guided by international best practices, robust computational tools, and a commitment to achieving geospatial accuracy commensurate with modern surveying and geodesy standards.

2.2.1 Extraction of Ellipsoidal Heights from GNSS Observations

The ellipsoidal heights (h) were extracted directly from the GNSS data recorded by the dual-frequency DGPS receiver in rover mode, which was used to survey 300 strategically sampled points across the Abiola Ajimobi Technical University (AATU) campus. Each observation session, as previously stated, was designed to last between 5 to 15 minutes depending on satellite geometry, signal quality, and local obstructions.

2.2.2 Computation of orthometric heights

Orthometric height (H) is defined as the height of a point above the geoid, the mean sea level equipotential surface. Following standard geodetic principles, orthometric heights were derived using Equation 1.

For each of the 300 surveyed points, this equation was computed separately for each of the five geoid models. This resulted in five sets of orthometric height datasets, each corresponding to a unique geopotential model. The calculations were initially performed in Microsoft Excel, where a master spreadsheet was developed to automate the subtraction operation across all entries. Statistical quality checks were performed using functions such as STDEV.P, AVERAGE, and SQRT(SUMSQR(...)) to compute parameters like mean height difference, standard deviation, and RMSE between models.

Subsequently, the computed orthometric height datasets were imported into QGIS for spatial analysis and visualization. Attribute tables were updated with height differentials between geoid models to examine the spatial variability of orthometric height determinations over the AATU campus. To systematically investigate differences between the models, pairwise comparisons were carried out, with EGM2008 selected as the baseline reference due to its widespread adoption in geodetic practice and

extensive validation in global studies. For each of the other four models, residuals were computed as:

$$\Delta H = H_{model} - H_{EGM2008} \tag{2}$$

3. RESULTS AND DISCUSSION

3.1 Spatial distribution of sample points

The 300 observation points were spread across all accessible quadrants of the AATU main campus, including academic buildings, administrative blocks, student residential areas, road networks, open fields, and infrastructural corridors. This spatial diversity was designed to test how well each geoid model performs across varying micro-terrain types and possible gravitational anomalies.

Spatial Distribution of GNSS Data Collection Points at AATU

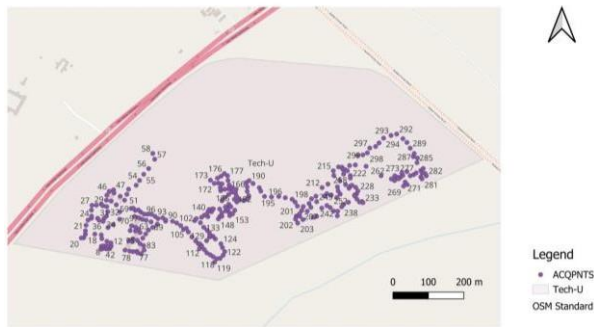


Figure 2: AATU GNSS Observation Vector Map

Figure 2 presents the spatial distribution of GNSS observation points

Table 1: Comparative Analysis between Geoid Models

Model	Mean Difference (m)	Minimum Deviation (m)	Maximum Deviation (m)	Standard Deviation (m)
EIGEN-6C4	0.082655555	0.0821946	0.0833058	0.000298419
GECO	0.145838152	0.1452902	0.1465046	0.000357616
SGG-UGM-2	0.078111847	0.0773455	0.0790488	0.000503148
XGM2019e	0.110349642	0.1092343	0.1118847	0.000780369

3.3 Residuals

Figure 3 presents the residual distribution for four geoid models; EIGEN, GECO, SGG, and XGM, computed against observed GNSS-levelling data. The residuals represent the magnitude of discrepancies between the modelled and observed geoid heights, expressed in metres.

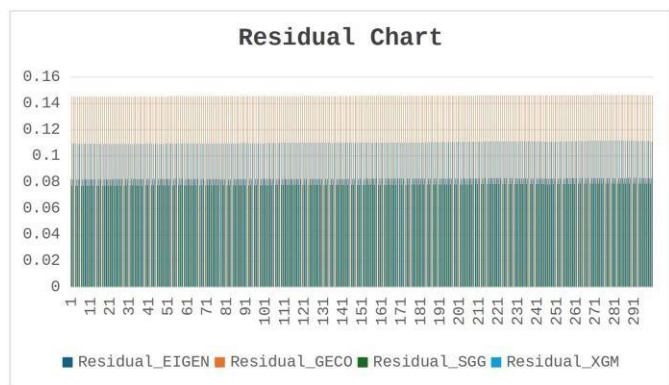


Figure 3: Residual Chart

Across the observation set, Residual consistently exhibits the highest residual magnitudes (~0.11–0.14 m), suggesting comparatively lower agreement with the GNSS-levelling reference. Residual_GECO and Residual_SGG follow closely, showing residuals in the ~0.08–0.11 m range. Residual_EIGEN consistently records the smallest residuals (~0.07–0.08 m), indicating the strongest fit to the reference data among the evaluated models. The generally stable residual values across the indices imply that model performance does not fluctuate significantly with location in the study area. However, the clear ranking in magnitude demonstrates measurable differences in model accuracy, with EIGEN being the most reliable and XGM the least accurate for the dataset

across the Abiola Ajimobi Technical University (AATU) campus. A total of 300 points were randomly sampled to ensure comprehensive spatial coverage. These points form the core dataset for ellipsoidal height acquisition using dual-frequency DGPS. The map serves to contextualize the survey area, illustrating the geographical extent of GNSS data collection, and visually supports the representativeness and dispersion of the sampled locations. This spatial representation is critical for subsequent height transformation analysis using various geoid models.

3.2 Comparative Analysis of Orthometric Heights Derived from Different Geoid Models

The comparative analysis as shown in table 1 focuses on evaluating the orthometric heights obtained from the five geoid models; EGM2008, EIGEN-6C4, GECO, SGG-UGM-2, and XGM2019e, applied to the GNSS-derived ellipsoidal heights collected across the study area. This analysis is critical to understanding not only the variations in height values across models but also the degree of agreement or divergence between them, which has implications for their practical application in local surveying and engineering projects.

The comparative analysis of geoid model deviations relative to EGM2008 revealed distinct performance characteristics. EIGEN-6C4 achieved the smallest mean difference (0.08266 m) with an exceptionally narrow deviation range (0.08219 m to 0.08331 m) and low standard deviation (0.00030 m), reflecting strong agreement and internal consistency. GECO exhibited the largest mean difference (0.14584 m), indicative of a greater systematic offset, though its deviation spread remained small (0.00036 m), suggesting stable performance. SGGUGM-2 yielded the smallest minimum deviation (0.07735 m) but with slightly higher variability (standard deviation of 0.00050 m) compared to EIGEN-6C4 and GECO. XGM2019e presented a moderate mean difference (0.11035 m) but the widest deviation range (0.00265 m) and highest standard deviation (0.00078 m), pointing to reduced precision relative to the other models.

considered.

3.4 Comparative trends of orthometric heights across geoid models

Tata (2024) conducted a comprehensive evaluation of five global geoid models: EGM2008, EIGEN-6C4, GECO, SGG-UGM-2, and XGM2019e, within the context of GNSS-derived orthometric height determination in Nigeria. The findings provided valuable insights into model performance, which directly informed the methodological approach and comparative analysis undertaken in this study. Below is the implementation of same in the context of the study area; AATU.

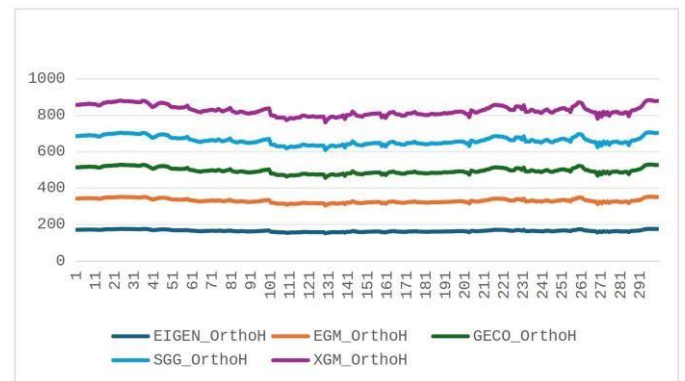


Figure 4: Orthometric Heights Trend Comparison

Figure 4 presents the spatial distribution of orthometric heights derived from five prominent global geoid models; EIGEN-6C4, EGM2008, GECO, SGG-UGM-2, and XGM2019e, plotted sequentially along the measurement profile. Although the height curves generated by each model exhibit broadly consistent fluctuation patterns, indicative of a shared representation of the underlying spatial variability in the gravity field, distinct vertical offsets are apparent between them. These systematic

separations arise primarily from inherent differences in the reference surfaces defined by each model, which in turn are governed by variations in the underlying gravity field solutions, the heterogeneity of input data sources, and the specific computational strategies employed during geoid determination (Förste et al., 2014).

The persistence of near-parallel trends across all five datasets underscores that, despite discrepancies in absolute height values, the models retain a high degree of concordance in representing relative spatial patterns. This observation implies that height transformation frameworks, such as datum unification, bias correction, or hybrid geoid model adjustments could feasibly be implemented to harmonize these models for operational geodetic, engineering, and infrastructure planning

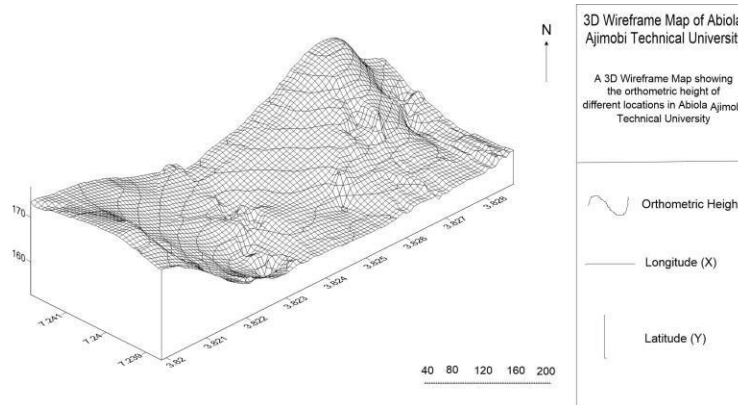


Figure 5: 3D Wireframe Map of Orthometric Heights for Abiola Ajimobi Technical University.

Across the five geoid models (EGM2008, EIGEN-6C4, GECO, SGG-UGM-2, and XGM2019e), orthometric heights within the AATU campus generally range between 152 m and 177 m. All models show a consistent spatial pattern:

- i. Northwest: Highest elevations, approaching the upper range ($\approx 175\text{--}177$ m).
- ii. Central and northeast: Intermediate elevations, forming gentle slopes from the northwest
- iii. high points.

applications.

3.5 Wireframe Representation of Orthometric Heights

The wireframe in Figure 5 reveals a moderately undulating topography, with elevations ranging from approximately 160 m to slightly above 170 m. The highest point, located toward the northeast quadrant of the map, corresponds to a natural rise in the local terrain, possibly influenced by built structures or small geomorphological features. Conversely, the southwestern edge exhibits relatively lower elevations, forming a gentle slope toward the periphery. The regular mesh structure aids in appreciating the continuity of the terrain, allowing for clear identification of gradient trends and potential drainage paths.

- iv. South and southeast: Lowest elevations ($\approx 152\text{--}155$ m).

While the absolute height values differ slightly among models; reflecting differences in their underlying gravity field data and resolution, the relative terrain pattern is stable across all. Contour lines are widely spaced in most areas, indicating gently undulating terrain with no abrupt relief. This agreement among models supports the reliability of the GNSS-derived dataset and confirms the campus's gradual slope from northwest to southeast.

3.6 Root Mean Square Error

Table 2: Root Mean Square Error (RMSE)			
Model	Bias (m)	Standard Deviation (m)	RMSE (m)
EIGEN-6C4	0.082655555	0.000298419	0.082656094
GECO	0.145838152	0.000357616	0.14583859
SGG-UGM-2	0.078111847	0.000503148	0.078113467
XGM2019e	0.110349642	0.000780369	0.110352401

Table 2 presents the bias, standard deviation, and root mean square error (RMSE) values obtained from the comparison of the four candidate global geopotential models (GGMs) against the reference dataset. Across all models, the RMSE values are numerically almost identical to the corresponding bias values. This relationship arises from the very low standard deviations (≤ 0.00078 m), which indicate negligible random error relative to the systematic offset. The results therefore imply that the discrepancies between each GGM and the reference are predominantly systematic in nature, manifesting as a constant vertical shift rather than random scatter. Among the tested models, SGG-UGM-2 exhibits the smallest bias and RMSE (0.0781 m), denoting the highest level of agreement with reference. EIGEN-6C4 follows closely (0.0827 m), while XGM2019e and GECO show larger offsets of 0.1103 m and 0.1458 m respectively.

4. CONCLUSION

This study evaluated the determination of orthometric heights at Abiola Ajimobi Technical University (AATU) using GNSS-derived ellipsoidal heights integrated with five contemporary global geoid models. The findings demonstrate that high-precision vertical positioning is attainable within a small-scale low-relief environment, with only minor variations observed among the geoid models. These differences remain within acceptable tolerance limits for typical geospatial, engineering, and infrastructural applications. The comparative assessment confirms that, in relatively homogeneous terrain, the choice of global geoid model exerts minimal influence on the resulting orthometric heights and their spatial distribution. Consequently, the workflow employed GNSS observations

supported by multiple global gravimetric geoid models is both operationally feasible and technically reliable for vertical referencing in similar contexts. Overall, the study underscores the potential of GNSS-based height determination as a practical alternative to conventional levelling, promoting efficiency, repeatability, and improved geodetic capacity for regions seeking cost-effective modernization of their height systems.

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