

Reliable Digital Terrain Modeling Using PPK GNSS Observations and Leveling-Constrained TIN Interpolation

Ahmed Al Shouny^{1, 2*}, Alshimaa A. Hussien², Ahmed Sedeek^{3, 4}

¹ Geomatics Department, Faculty of Architecture and Planning, King Abdulaziz University, Jeddah 21589, Saudi Arabia.

² Survey Research Institute, National Water Research Center, Giza 11211, Egypt.

³ Department of Mining Engineering, Faculty of Petroleum and Mining Engineering, Suez University, Suez 11252, Egypt.

⁴ Faculty of Petroleum and Mining Engineering, Suez National University, Suez 11252, Egypt.

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Abstract

Reliable Digital Terrain Models (DTMs) are crucial for most engineering and environmental applications, especially where accurate elevation is required. While conventional leveling offers high vertical accuracy, it needs long time periods, causing high work costs, particularly for wide regions. GNSS-based methods that provide fast data acquisition may serve as an effective alternative; however, achieving reliable vertical accuracy remains a challenge. Accordingly, this study proposed a practical approach that integrates the Post-Processed Kinematic GNSS technique with Constrained Triangulated Irregular Network (TIN) modeling to improve elevation accuracy. In this method, accurate leveling cross sections distributed along the study area are used as vertical constraints to improve interpolation reliability. The performance of the model is validated using independent cross-section data observed using precise leveling. Statistical analysis demonstrates a strong correlation between generated DTM elevations and leveling data, evidenced by a coefficient of determination (R^2) of 0.9915 and a vertical RMSE of 0.0608 m, with residuals mainly within ± 0.10 m for the majority of observations. The results validated that the Constrained TIN modeling method effectively maintains the accuracy of PPK-derived elevations and decreases vertical discrepancies. The proposed methodology, integrating PPK observations with constrained TIN modeling, achieves reliable decimeter-level vertical accuracy, making it appropriate for various engineering and environmental applications that needs high-precision terrain representation.

Keywords: PPK-GNSS; Digital Terrain Model; Constrained TIN; Height Accuracy; Engineering Applications.

1. Introduction

A digital terrain model is the digital representation of the bare-earth surface of the ground, describing terrain topographic data excluding natural and artificial objects such as trees and buildings, unlike digital surface models (DSMs), which include these objects with their height above the ground surface. Recently, DTM has been crucial for several engineering and environmental applications, including hydrology, transportation, earthwork computations, flood risk assessment, soil erosion, and costal protection works. DTMs have become one of the most popular models used as input in modern geospatial decision-making where elevation is directly linked to cost safety, and performance. DTMs are generally adopted in the style of a regular grid referred to as a Digital Elevation Model (DEM), offering easy data management, manipulation, and storage [1-3]. The concept of DTMs was first introduced in civil engineering, particularly in highway engineering. Roberts proposed using terrain models for highway design in 1957 [4]. Later Miller & Laflamme (1958) adopted terrain data to build cross-section (profile) models and formally introduced the concept of DTMs [5].

* Corresponding author: ametaowa@kau.edu.sa

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Several surveying and remote sensing methods can be used to collect data needed for producing DTMs. Precise leveling and total station methods represent the best traditional ground-based surveying that can offer high horizontal and vertical accuracy, but they are time-consuming, costly, and labor-intensive, particularly for extensive areas. Moreover, there are significant challenges in areas with poorly distributed benchmarks and control points. Remote sensing techniques, including light detection and ranging (LiDAR), terrestrial laser scanners, and photogrammetry, produce high coverage and point density, but they need strong ground point classification and may cause systematic errors, particularly within urban and vegetated areas. GNSS (Global Navigation Satellite System) modern techniques have become a practical alternative for collecting elevation points rapidly, especially along large areas and through projects where time and budget are limited. However, GNSS-derived heights are less accurate than the horizontal component, and they can be affected by several factors such as satellite geometry, multipath, atmospheric effects, antenna setup, and processing strategy. In addition, GNSS techniques produce ellipsoidal heights, which need to be converted into orthometric heights, relative to mean sea level, using a geoid model for most engineering project requirements, and any deficiencies in geoid modeling can cause additional vertical uncertainty. These factors mean that GNSS-based DTMs may be efficient to produce, but their vertical performance must be treated carefully before they can be trusted for high-precision work. Many GNSS methodology, including Real-Time Kinematic (RTK), Post-Processed Kinematic (PPK), and Precise Point Positioning (PPP), were adopted for collecting terrain datasets. The PPK technique can provide more accuracy than RTK technique due to the capability to remove data errors and apply more precise orbits, leading to better positioning accuracy [6-8], whereas PPP approach can provide a lower accuracy, particularly in vertical components [9].

It should be noted that DTM accuracy depends on not only the measurement techniques adopted for collecting points data but also the terrain surface modeling strategy, which plays an important role. The surface modeling, or DTM generation, is the process where measured elevation points are converted into a continuous terrain surface, and this selection of the modeling methods can noticeably change the final terrain shape. There are few popular approaches for DTM surface modeling, including Triangular Irregular Network (TIN) and grid-based data structures [1, 10, 11]. In TINs, points or vertices are selected and interconnected sequentially to form a network of triangles. The surface is modeled as a set of non-overlapping triangles connected together [12]. There are a number of methods for generating these triangles, but the most common one is the Delaunay triangulation, which is based on the idea that if a circle is drawn around three nodes, it will not contain any other nodes [3]. TINs are better than grid-based models as they can represent the surface at varying resolutions. Many times, high triangle resolution is necessary, especially for mountain peaks [13]. TINs are compatible with any data pattern and can include characteristics such as break lines [1, 11]. TIN is a commonly used vector data format for DTM and necessitates less computational capacity compared to gridded elevation models. Nevertheless, the irregularity of TIN complicates the organization, storage, and application of data compared to regular grid DEM [14]. TINs can be divided into constrained and non-constrained TINs [15]. A non-constrained TIN is used to model terrain by connecting elevation points using triangles, without enforcing terrain features, so important terrain features like channels and ridgelines may be smoothed or distorted [10]. In contrast, a constrained TIN includes features or control points that are predefined during the triangulation process, which will preserve discontinuities across the terrain and enhance vertical accuracy for engineering and environmental applications [1]. Figure 1 demonstrate the TIN modeling and a constrained TIN approach [16].

Another common method used is to model the surface using matrices of uniform squares or rectangles [1, 10]. These matrices are easier to manage, but require a high point density for the desired terrain accuracy [10]. When using grid-based modeling, a sequence of bilinear surfaces is obtained [1]. This technique works for grid or progressive sampling and there are several software programs that only accept gridded data [1]. Alternative interpolation techniques, including Kriging and Inverse Distance Weighting (IDW), and polynomial or spline-based techniques are also commonly employed in DTM generation. Kriging is a geostatistical approach that predicts elevations by learning how heights vary with distance (spatial autocorrelation), and it can also provide an uncertainty estimate for the predictions. In contrast, IDW method is a straightforward method that estimates each unknown elevation as a distance-weighted average of nearby measured points, so closer points influence the result more than distant ones. Polynomial (trend) surfaces fit a smooth mathematical surface to capture broad elevation patterns, while spline-based methods create a smooth, flexible surface that minimizes curvature; both can produce visually pleasing terrain but may smooth out sharp breaks (like embankments or channel edges) unless additional constraints are applied [11].

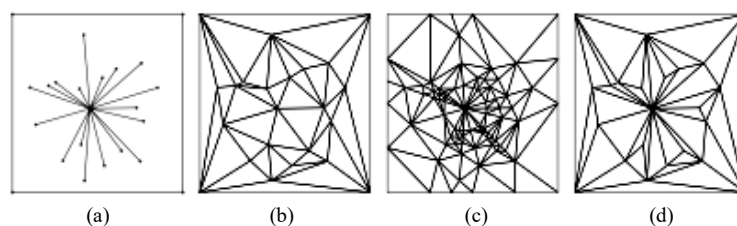


Figure 1. TIN modeling process (a) input elevation points, (b) Initial Triangulation, (c) unconstrained TIN triangulation, and (d) final TIN surface

Recent studies in DTM proved that both the collected data quality and surface modeling approach play a major role in achieving high vertical accuracy. Accordingly, many recent studies investigate various surface modeling methods and their performance in generating accurate DTMs with suitable vertical accuracy. He et al. [17], concluded that a constrained TIN approach using UAV point clouds can significantly improve surface modeling results and reduce errors compared to traditional methods such as IDW and Kriging. Wan et al. [18], presented a model that combines semantic constraints together within a constrained TIN model to enhance the representation of terrain and geometric consistency in complex coastal environments. Moreover, Syed Abdul Rahman et al. [19], concluded that the constrained TIN approach reduces artificial elevation inconsistencies and improves generating surfaces in urban and hydrodynamic modeling applications. A comparative study assessed several DEM generation methods and found that TIN modeling provides better accuracy and computational efficiency than other techniques in complex environments like dense forests [20]. Also, several TIN-focused studies conclude that TIN-based terrain modeling is an effective approach for representing irregularly distributed elevations and is widely used, but accuracy still depends on terrain complexity, sampling/point distribution, and enforcing constraints (e.g., breaklines) to avoid smoothing critical features [21, 22]. Research in recent years concerning terrain modeling indicates that constrained TIN approaches are better than traditional unconstrained methods in both terrain representation and accuracy. Constrained modeling proved its ability to preserve terrain characteristics and improve elevation accuracy [17, 23].

Several research discussed collecting data using various GNSS techniques and their effect on the quality of the generated terrain modeling. Many studies generally agree that GNSS techniques can produce DTM with suitable vertical accuracy, but the achievable performance depends strongly on the positioning technique, survey conditions, and modeling approach. In an RTK, PPK, and precise point positioning with ambiguity resolution (PPP-AR) comparison for unmanned aerial vehicle (UAV) mapping, Arkali & Atik [24] reported vertical RMSE values of 0.075 m (RTK) and 0.071 m (PPK), while PPP-AR showed much weaker vertical performance (0.659 m), leading to the conclusion that relative methods (RTK/PPK) are more suitable than PPP-type solutions for high-accuracy elevation modeling in that workflow. Similarly, Özdemir et al. [25], compared UAV-PPK, UAV Network-RTK, terrestrial RTK, and reference solutions against total station checks and found vertical RMSE ranging from 15 mm (RTK) to 64 mm (UAV Network-RTK) and up to 115 mm (UAV-PPK), concluding that UAV GNSS georeferencing can be efficient but height accuracy is variable and should be verified with independent ground control data for validation, especially when applications require reliable vertical performance.

Although both PPK-GNSS and constrained TIN techniques have been investigated separately in several studies, their combination for the purpose of generating high-accuracy DTMs received limited interest. So this study addresses that gap by developing an integrated workflow that combines PPK-GNSS measurements with a constrained TIN modeling approach to produce a high-accuracy DTM, with a specific focus on improving height accuracy. The research area is extended along the Mediterranean shore in the Rosetta region of the central Nile Delta, extending roughly 65 km in length and averaging approximately 600 m in width, with a total area of nearly 39 km². Due to the ongoing coastal erosion, this area has a major need for accurate and updated topographic surveys to support planning and appropriate site selection for continuous protection works along the area [7]. The flat characteristics of this area with minor elevation variations require high vertical DTM accuracy to preserve small surface details, and the interpolation approach must avoid smoothing effects, particularly to ensure that features such as small depressions and ridges are accurately represented in the topographic map. An accurate PPK and precise leveling measurements were performed in this area by Shouny et al. [7] for generating an accurate topographic map. The PPK GNSS observations and their derived elevation were used in this study to first generate a baseline terrain surface model for the area. Then this surface model was improved by integrating 14 cross-section data sets distributed along the area and observed using precise leveling as vertical constraints within a constrained TIN modeling framework. Finally, six independent check cross sections were used to validate the final DTM, assess its achieved vertical accuracy, and quantify the extent of vertical accuracy through independent validation. This study is organized as follows: we will initially describe the study area and the collected measurements are introduced. Next, we will introduce the methodology applied in this research for generation DTM. Subsequently, we will describe and analyze the results of the generated DTM. Finally, we will conclude this work with recommendations for future work.

2. Material and Methods

2.1. Study Area and Data

The research area is extended along Egypt's Mediterranean coastal zone in the northern region of the Nile Delta as shown in Figure 2. It extends from Rosetta City in the east (approximately E 30° 23' 18") to Al-Burullus City in the west (approximately E 30° 57' 51"), covering about 60 km of coastline. The area width ranges from 400 to 600 m perpendicular to the coast, resulting in an approximate area of 39 km². This coastal strip was selected because it is continuously exposed to shoreline erosion, which increased the need for construction of coastal protection works. Therefore, updated and accurate topographic mapping is repeatedly required to support the ongoing surveying activities conducted by the Egyptian Coastal Protection Authority (ECPA). The surveying measurements collected along this area were performed by the Survey Research Institute [26] for the purpose of producing an accurate topographic map that

achieves accuracy within 15 cm in height. The details of collected GNSS measurements, static and kinematic datasets, and precise leveling observations were discussed by Shouny et al. [7]. The following section presents a brief presentation for the data sets adopted for the current research.

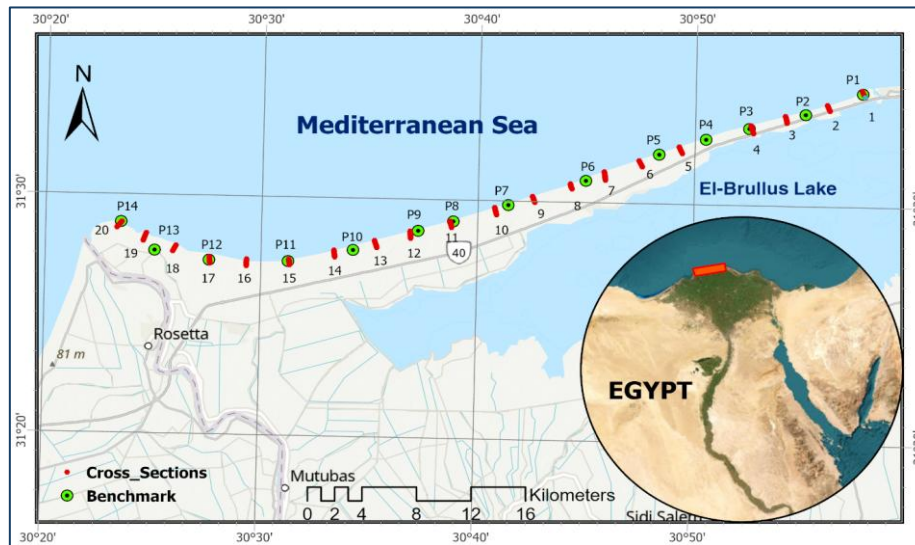


Figure 2. Location of study area and the distribution of both Benchmarks and cross sections

2.2. Static Observations

Since permanent reference stations are scarce along most of the coastline zones, as our study area, a reliable control network points covering the area should be established and observed before starting of the field survey. Fourteen control stations were installed across the study area, as included in Figure 2, spaced at roughly 5 km intervals, differing according to the topography and nature of the installed location. These points were designed not only to support these measurements, but also to remain available for future surveying activities along the same zone, so each point was constructed as a solid concrete prism with an overall height of approximately 1 m, of which about 50 cm was embedded below ground level to ensure stability. The prism's upper and bottom cross-sectional measurements were 40 x 40 cm and 60 x 60 cm, respectively. A steel cylinder was installed at the top of the prism, anchored by a 10 cm steel bar fixed into the concrete. Representative photographs of two installed points are shown in Figure 3.



Figure 3. Representative photographs of two established control stations

Static GPS observations were performed at the 14 stations to compute their three dimensional coordinates (latitude, longitude, and ellipsoid height). These stations were connected to 2 Egyptian Surveying Authority (ESA) first-order triangulation stations and configured as an over-constrained network [27]. Observations were collected using 4 Trimble 5700 dual-frequency instruments with of session duration of roughly 2–3 hours according to baselines lengths, then processed in Trimble Business Center Software (TBC), with 95% confidence accuracy level, using precise ephemeris and applying standard correction models, such as ionosphere, tropospheric delay and antenna phase center [28]. The final coordinates satisfied the required precision, achieving approximately $\pm (2 \text{ cm} + 1 \text{ ppm})$ (part per million) horizontally and $\pm (5 \text{ cm} + 1 \text{ ppm})$ vertically.

2.3. Precise Leveling Measurements

In this study, precise spirit leveling was carried out for two main purposes. First, it was used to determine accurate orthometric heights for the fourteen control points established throughout the study area. Second, it was applied to obtain

accurate orthometric heights for the cross-sections distributed across the study area. These cross-sections were used as high-accuracy vertical constraints to improve the reliability of the generated DTM and to provide independent validation for accuracy assessment. Twenty cross-sections were established throughout the study area, regularly spaced at approximately 3 km intervals, as shown in Figure 2. All precise leveling measurements were performed to satisfy first-order class standards [29], with allowable misclosure limits of $\pm 5\sqrt{L}$ mm, where L is the one-way leveling distance in kilometers. To achieve these standards, a Wild N3 sensitive optical level [30], with 0.1 mm micrometer accuracy, and an invar staff were used for the measurements. The sight length was limited to 50 m, and the backward–forward sight differences were maintained within 2 m [29]. The leveling process adopted a closed leveling loop that started and ended at two known first-order Egyptian Survey Authority (ESA) benchmarks, using forward and backward measurement procedures. The final orthometric heights of each control point and cross-section point were obtained after adjustment calculations.

2.4. Kinematic Observations

As mentioned before, the main objective of this research is to develop and evaluate an integrated workflow that combines PPK-GNSS measurements with a constrained TIN modeling approach to produce a high-accuracy DTM, with a specific focus on improving height accuracy. So to produce a DTM for the study area, kinematic measurements using the PPK technique and stop and go observations mode were adopted for collecting data. Three GNSS receivers were used during the field surveys, divided as follows: one receiver was installed over one of 14 established control points as a base station, while two others were deployed as rovers for collecting data. The study area was divided during the observation process into a series of cross-sections oriented perpendicular to the coastline with spacing of approximately 100 m. Each of these cross sections extended between 400 and 600 m, depending on local site conditions. Measurements along each section were collected in Stop-and-Go mode at approximately 10 m intervals, providing a dense dataset suitable for terrain modeling. Over 50,000 kinematic observations were collected during the approximately three-week field study. The observations' point density, with an average of approximately 380 points/km² and an average point spacing of about 7 m, provides strong spatial coverage and supports reliable DTM generation. The distribution of the collected kinematic data across the study area, along with a sample data layout, is illustrated in Figure 4.

All collected observations were subsequently processed with TBC software to derive accurate three-dimensional coordinates (latitude, longitude, and ellipsoid height). Transformation of ellipsoidal heights into orthometric heights was a challenging step due to unreliable geoid undulation models, which affect the accuracy of the derived orthometric heights. Ellipsoid heights derived from GNSS observations are generally more affected by various GNSS error sources, including ionospheric and atmospheric effects, and multipath, compared to orthometric heights. Therefore, Shouny et al. [7] suggests a methodology to obtain orthometric heights directly from processing GNSS data results without the need to use any geoid modeling approach. He equally divided the area between each consecutive control point into two segments, and each was surveyed using the closest control station as a base. The base-rover distances were limited to approximately 3 km, which was calculated depending on the geoid undulation variation throughout the study area, to fulfill ECPA requirements of height accuracy (not more than 15 cm) [7]. Accordingly, the calculated geoid undulation values were fixed at each control station, and they were applied to all segments surveyed from that station. During the data processing stage, the finalized geodetic coordinates and orthometric heights, derived using precise leveling measurements, of these stations were used for calculating the accurate coordinates and elevations for kinematic observations.

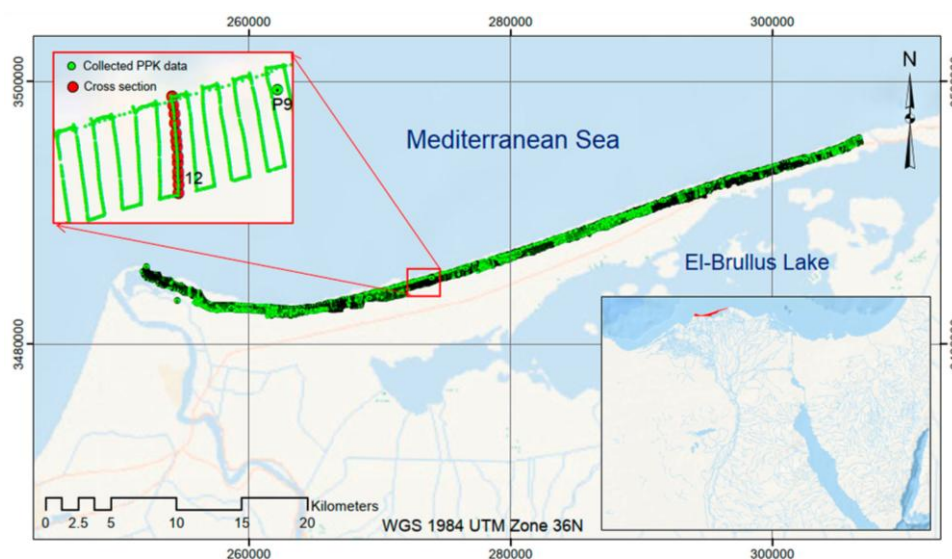


Figure 4. The collected post-processed kinematic (PPK) measurements

2.5. Methodology

After completing all field measurements, including kinematic observations and precise leveling works, and applying their processing and adjustment strategies to determine accurate three-dimensional coordinates, latitude, longitude, and orthometric heights, as discussed previously. Next, the proposed DTM was generated using the dense PPK point cloud which includes about 50,000 observations with an average of 380 points/km². Modeling DTM using a traditional TIN model does not represent sharp changes in terrain, including ridges, breaklines, drainage channels, or engineered edges, which can reduce the generated surface accuracy. In order to reflect these changes and breaklines during triangulation and produce a more precise and realistic terrain representation, a constrained TIN modeling approach was used in this study. Delaunay triangulation was used to carry out the interpolation procedure. This TIN model considered accurate elevations of the cross-sections, obtained using precise leveling measurements, as a hard vertical constraint during the interpolation process to enhance the height accuracy of the produced terrain model. Fourteen out of the 20 measured cross-sections were used during DTM construction, while the remaining six cross-sections were completely excluded from the modeling process and used as independent values for only validations. These cross sections were distributed approximately uniformly across the study area to support accurate modeling and provide a fair basis for validation. The flowchart of the research methodology is shown in Figure 5.

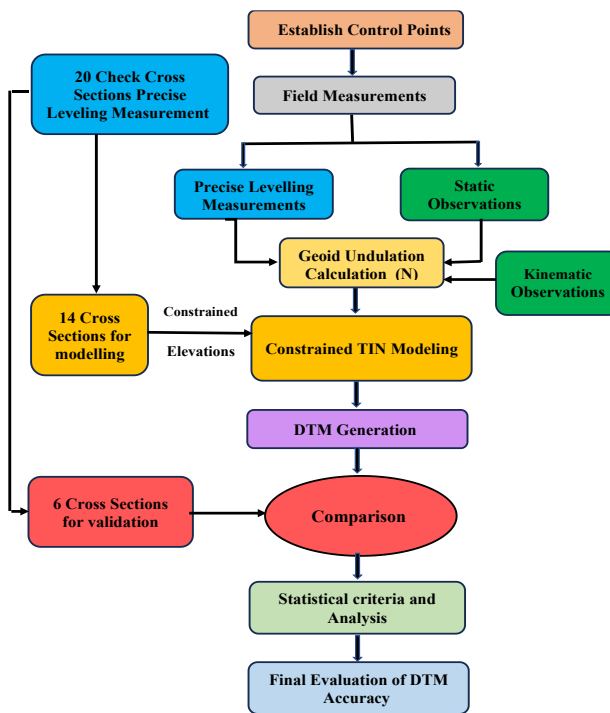


Figure 5. Flowchart of the research methodology

3. Results and Validations

Independent cross-section data with accurate elevations estimated using precise leveling measurements were used to evaluate the final vertical accuracy of the proposed DTM generated from PPK observations using a constrained TIN surface modeling approach. Validation was conducted on a total of 82 points distributed along six cross-sections across the study area. Vertical residuals of these points are calculated and analyzed to assess the vertical accuracy, error behavior, and statistical robustness of the proposed methodology for generating DTM. The summary of these residuals' statistical values, such as minimum, maximum, mean, standard deviations, and root mean square error (RMSE) is presented in Table 1. The Results indicates an insignificant systematic vertical bias with a mean error value of -0.0066 m. The RMSE of 0.0608 m, verifying the decimeter-level vertical accuracy for the proposed DTM. The residuals range from -0.134 m to $+0.164$ m, with a standard deviation of 0.0609 m, indicating that the errors are mainly concentrated around the mean and the model performance is stable. The residuals' concentration around zero confirms that the interpolation method does not consistently overestimate or underestimate and that the vertical differences are primarily due to random factors. The normality of residuals was tested using a Shapiro–Wilk test, and the p-value was 0.134 , which is greater than the significance level of 0.05 m, thus confirming that the errors are approximately normally distributed and mainly random and not systematic. This suggests that the errors are probably caused by measurement noise and local surface irregularities and not by deficiencies in the modeling process itself.

Table 1. Statistics of DTM vertical residuals for validation cross-sections points

	Min	Max	Mean	RMSE	SD	Shapiro-Wilk (p)
Value (m)	-0.134	0.164	-0.0066	0.0608	0.0609	0.134

The overall distribution of the vertical residuals histogram, as shown in figure 6, indicates that values are centered near zero, with a similar amount of positive and negative errors, and appears near symmetric, with most residuals falling within ± 0.10 m, with a limited number of points exceeding this value. This pattern further confirms that the model maintains a balanced error distribution and avoids localized distortions or extreme deviations. Figure 7 shows the vertical error distribution for each cross-section using boxplots. The median across each section is close to zero and the interquartile ranges are quite comparable, showing that the vertical surface accuracy of the DTM is spatially consistent across the study area. The spreads are slightly wider in sections 6 and 9, but there is no irregular variation or outliers were noticed. This small spread is due to variations in terrain properties and/or point distribution, not the instability of the model. The whiskers show that most residuals remain within about ± 0.10 m, which is consistent with the overall RMSE (0.0608 m) and confirms that accuracy is broadly uniform along the corridor.

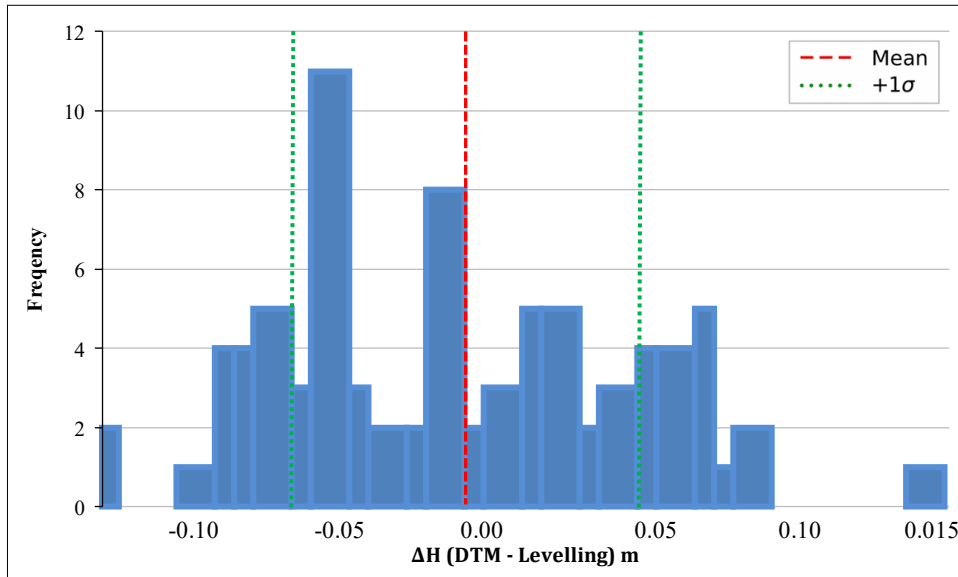


Figure 6. Histogram of vertical residuals (DTM-precise leveling)

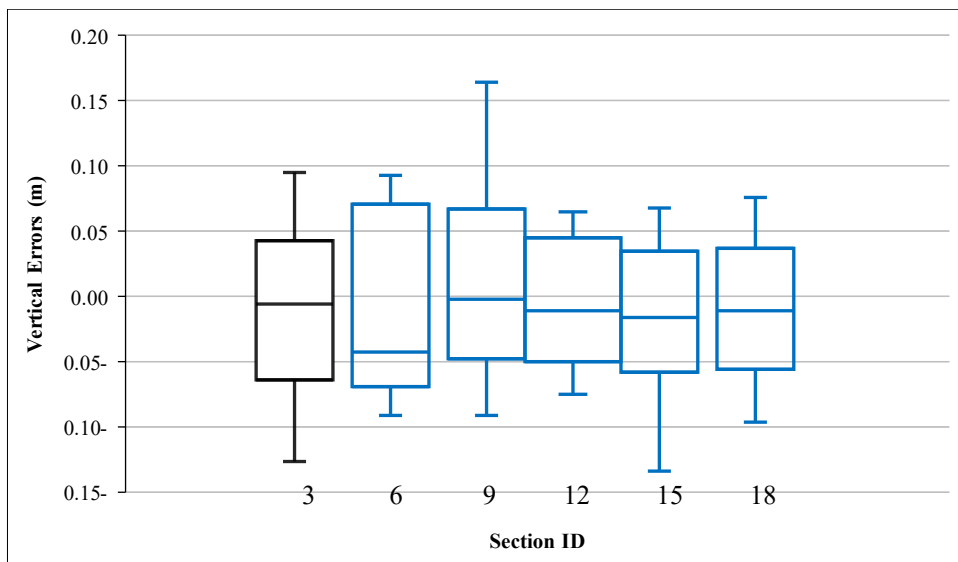


Figure 7. Box plot of elevation residuals (DTM-precise leveling) for each cross-section

Agreement between DTM elevations generated using a constrained TIN approach and that estimated via precise leveling measurements is summarized in a scatter plot in Figure 8. The scatter distribution aligns closely with the reference line, reflecting very strong agreement across all elevation data. The high value of the coefficient of determination (R^2) of 0.9915 confirms that more than 99% of the variation in DTM elevations closely follows the leveling data, with no obvious curvature or fan-shaped pattern visible. The detailed residuals between DTM and precise leveling elevations for all cross-section points are presented in Figure 9. Residuals stay close to zero, with a mix of positive and negative values, without any cumulative shift in error along any section. Even though Sections 9 and 15 show slightly larger variations, they are still within normal engineering limits, indicating that PPK height data were accurately integrated within the TIN model.

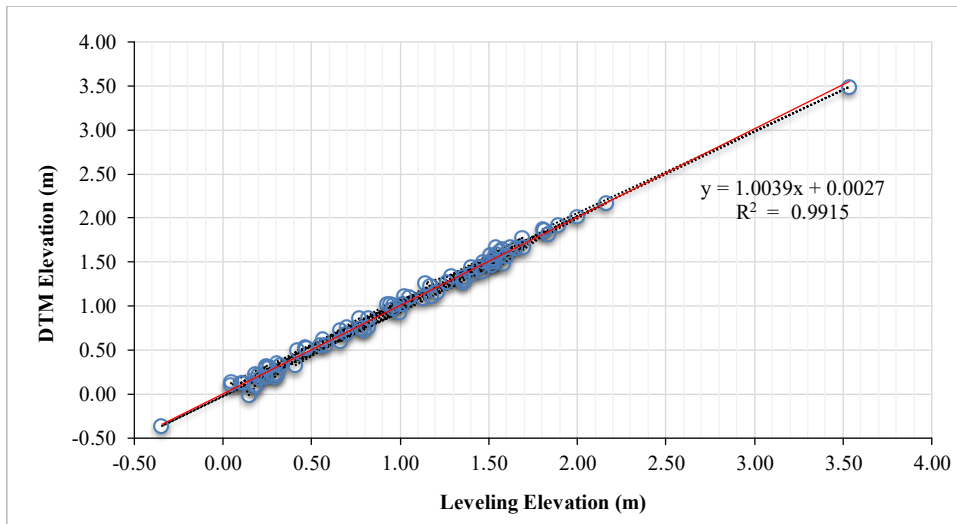


Figure 8. Scatter plot of DTM and precise leveling elevations

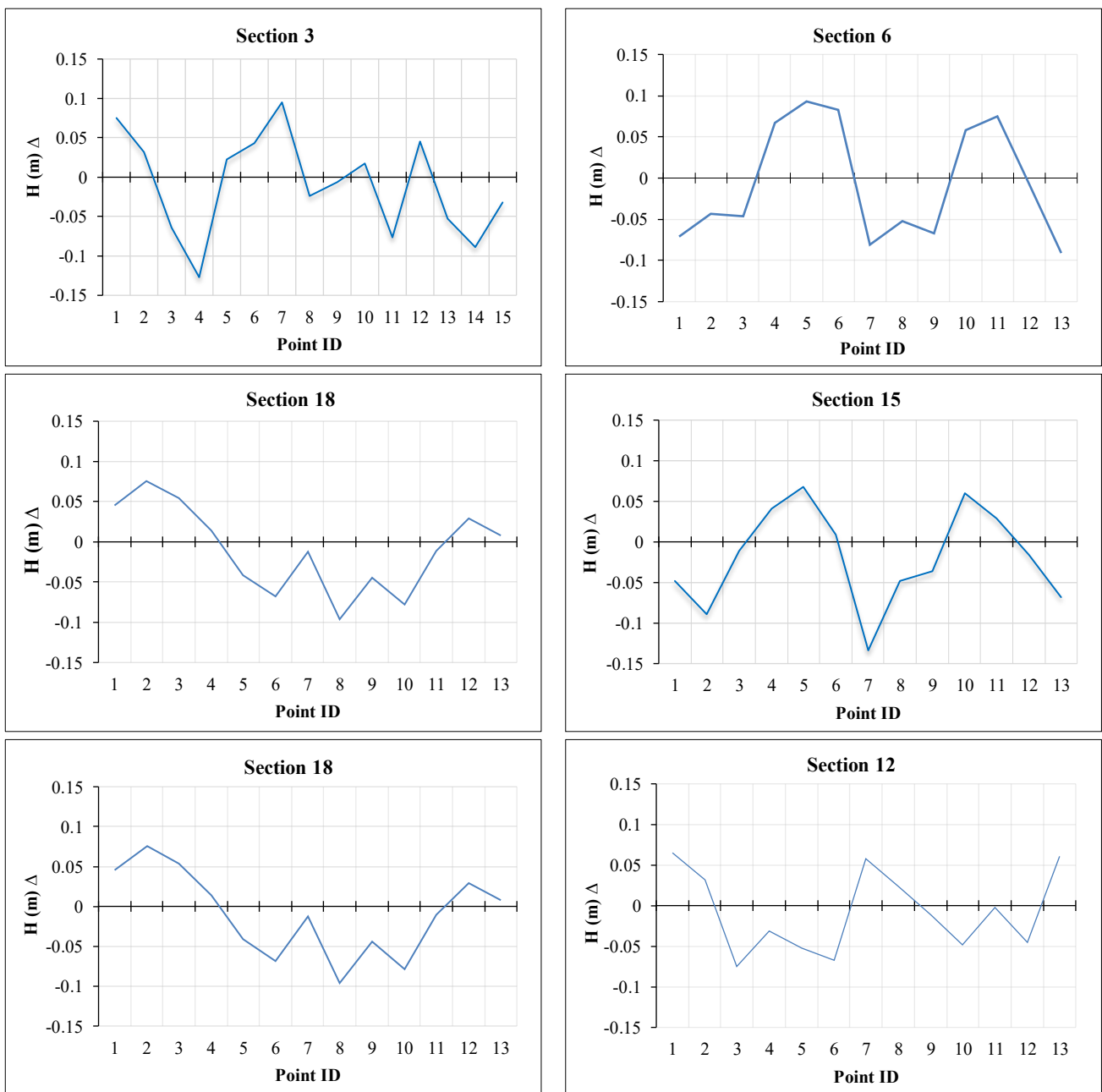


Figure 9. details residuals between DTM and precise leveling elevations for cross-section points

4. Discussion

The validation results confirm that the proposed DTM generated from PPK observations using a constrained TIN surface modeling approach provides reliable vertical accuracy for engineering and environmental applications. The near-zero mean error of -0.0066 m and RMSE of 0.0608 m together indicate negligible systematic vertical bias, while the limited spread of residuals (mostly within ± 0.10 m) with a standard deviation of 0.0609 m clearly shows consistent decimeter-level performance across the study area. Which is more than sufficient for most engineering and environmental tasks. These findings show that the interpolation process effectively maintained the original accuracy of the PPK-derived elevations when generating the continuous terrain surface.

The error-distribution analysis supports this interpretation. The residual histogram centered around zero, and the Shapiro–Wilk test ($p = 0.134$) confirms that the errors follow an approximately normal distribution. This implies that the remaining discrepancies are mainly random in nature rather than systematic modeling errors; the discrepancies are primarily random and systematic. Moreover, the cross-section boxplots show medians close to zero and similar spreads from one section to another, demonstrating that vertical accuracy remains spatially stable across the study area. Although Sections 6 and 9 exhibit slightly wider spreads, they do not contain abnormal outliers and remain within the overall accuracy level. Furthermore, the strong linear agreement between DTM elevations and precise leveling measurements, as reflected by the coefficient of determination $R^2 = 0.9915$, combined with low bias and moderate spread, confirms the robustness of the interpolation process. The uniform scatter pattern, without curvature or fan-shaped spreading, indicates that the constrained TIN approach effectively regulated interpolation behavior across different heights without introducing distortion.

Consistent with previous research, the use of a constrained TIN modeling approach improves terrain representation and reduces errors caused by the interpolation process compared with other methods for generating reliable and efficient DTMs. In addition, the estimated vertical accuracy is comparable to the recent GNSS-RTK and PPK studies, which commonly achieved RMSE values generally approximately of 0.10 m. The improved accuracy obtained in this study is mainly related to the effective integration of precise PPK measurements with the constrained TIN interpolation approach. Overall, the findings confirm that the combination of dense PPK-GNSS observations with a constrained TIN interpolation approach can produce an accurate DTM suitable for engineering and environmental applications that require decimeter-level vertical precision. Higher accuracy requirements and complex terrain may require targeted densification or extra leveling checkpoints.

5. Conclusion

Accurate Digital Terrain Models (DTMs) are essential for a wide range of engineering and environmental applications, where reliable elevation data is required. The generation of accurate DTMs depends not only on the quality of collected data but also on the performance of the surface modeling approach. This study investigated the generation of accurate DTMs by integrating PPK-GNSS observations with a constrained TIN modeling approach. To fairly evaluate the generated DTM results, validation was conducted using precise leveling across multiple cross section data. The results demonstrate that this integration can yield reliable vertical accuracy at the decimeter-level, which is applicable for many practical engineering and environmental applications. The results prove the ability of the proposed methodology to preserve the quality of the original accuracy of the PPK-derived heights. Statistical evaluation confirms a strong correlation between the generated DTM and reference leveling data, with residuals centered close to zero and the absence of systematic error trends. The distribution of errors is approximately normal and spatially stable along the study area, confirming that the interpolation process effectively provides high-precision terrain representation that's suitable for many engineering and environmental applications.

A major strength of the proposed method is applying a constrained TIN approach alongside precise leveling data and dense PPK observations, which maintain terrain details, improve vertical accuracy, and ensure stable reconstruction, achieving a consistent vertical accuracy and reliable surface modeling. However, some limitations should be considered and need more investigation in the future. Alternative constraint strategies and geoid models should be more investigated, as well as the influence of decreasing or increasing the density of points and control sections on accuracy. Furthermore, comparative research with alternative interpolation approaches utilizing various terrain conditions would provide valuable benchmarks to evaluate the findings reported here. It is important to note that the proposed simplified approach of fixing geoid undulation values at control stations is practical, reduces the geoid modeling bias, and simplifies the processing workflow, particularly in areas where geoid variations are large. Future studies could further investigate applying this approach in more complex terrains with larger geoid undulation variations and evaluate its impact on improving vertical accuracy in terrain modeling.

6. Declarations

6.1. Author Contributions

Conceptualization, A.A. and A.H.; methodology, A.A. and A.S.; software, A.A., A.H., and A.S.; validation, A.A. and A.H.; formal analysis, A.A. and A.S.; investigation, A.A., A.H., and A.S.; resources, A.A. and A.H.; data curation, A.A. and A.S.; writing—original draft preparation, A.A., A.H., and A.S.; writing—review and editing, A.A., A.H., and A.S.; visualization, A.A., A.H., and A.S.; supervision, A.A.; project administration, AA.; funding acquisition, AA. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data used in this study are available from corresponding author upon reasonable request.

6.3. Funding and Acknowledgments

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6.4. Conflicts of Interest

The authors declare no conflict of interest.

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