

Article

Vertical Accuracy Assessment of the MOASURE 2 for DTM Generation in Urban Environments

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Abstract

Digital terrain models (DTMs) are essential elevation datasets that represent the morphology of the Earth's surface and play a critical role in applications, such as urban planning, civil engineering, infrastructure design, and environmental assessment. However, the excessive cost remains the major challenge in obtaining accurate terrain models. Recent advancements in low-cost inertial navigation and motion-sensing technologies offer significant potential to enhance the cost-effectiveness of surveying projects. This study investigates the vertical accuracy and operational usability of a handheld inertial measurement unit (IMU) device (Moasure 2) for DTM generation in urban environments through the comparison with traditional total station and digital levels procedures. It also assesses the device compliance with The American Society for Photogrammetry and Remote Sensing (ASPRS) Positional Accuracy Standards. For this purpose, a comprehensive field survey was conducted in a small urban area characterized by varied terrain morphology. The vertical accuracy of the Moasure 2 was acceptable for many urban mapping applications based on a rigorous analysis of checkpoint data and error patterns, which were quantitatively assessed relative to reference surfaces. Profile-based validation showed that the elevation differences between similar terrain types were mainly within ± 25 cm, with minimal bias and symmetric error distributions. The findings indicate that Moasure 2 can be a viable alternative tool for fast DTM generation in low-cost urban projects. It offers significant advantages in terms of portability, ease of use, and reduced fieldwork time compared to conventional methodologies. Furthermore, this study addresses the critical gap in the validation of the new IMU-based surveying technology and provides evidence for choosing appropriate equipment for urban terrain modeling.

Keywords: Moasure 2; DTM; IMU; low-cost surveying; urban surveying



Academic Editor: Alessandro Vitale

Received: 10 May 2026

Revised: 2 July 2026

Accepted: 4 July 2026

Published: 6 July 2026

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1. Introduction

Digital terrain models (DTMs) are important elevation products that display the terrain morphology of the Earth's surface. These products have an important application in urban planning, civil engineering, infrastructure designing, and environmental assessment [1–3]. These geospatial products can be used for earthwork volume estimation, slopes, drainage planning, or flood risk assessment [4,5]. Accuracy and reliability are two main quality indicators of DTMs, which directly influence the quality of engineering decisions, costing, and feasibility studies. Hence, practitioners need to choose appropriate data acquisition methods for the desired models. The American Society for Photogrammetry and Remote Sensing

(ASPRS) has defined positional accuracy standards that are commonly accepted and that define acceptable error thresholds for various mapping applications [6]. These standards provide a framework for evaluating the suitability of different surveying technologies for specific use cases.

The development of terrain modeling technologies reflects an ongoing effort for the optimum accuracy requirement and operational efficiency and cost. Traditional surveying techniques using total stations and digital levels have always been the gold standard for high-precision applications. Under controlled conditions, these methods achieve a vertical accuracy of millimeter level [4,5]. These instruments serve as reliable reference frameworks for validating new technologies, such as unmanned aerial vehicles, global navigation satellite systems, and handheld mapping platforms.

Unmanned aerial vehicle-based structure-from-motion (UAV-SfM) photogrammetry has now made it possible to rapidly generate DTMs over large areas. UAV-SfM, in a semi-urban environment, can be a viable alternative to the standard topographic method, though they noted limitations with vertical precision [7–9]. Likewise, Kaamin et al. (2020) [10] and Usmani et al. (2020) [11] have reported some similar limitations in urban and construction zones, where tall buildings and narrow roads restrict UAV navigation and downgrade data quality. According to Fuad et al. (2018) [12], the accuracy of DTMs using a UAV-mounted LiDAR was evaluated at various flying heights and various terrains, whereby the researchers reported that despite the capability of impressive accuracy, these systems are costly and may run into issues, such as licensing, vegetation, weather, and power limitations. The cost and complexity of UAV-LiDAR systems inhibit their use in small, low-cost urban projects.

The availability of low-cost real-time kinematic global navigation satellite system (RTK-GNSS) devices has enhanced high-accuracy positioning accessibility. According to Wielgocka et al. (2021) [13] and Hamza et al. (2023) [14], low-cost RTK-GNSS devices can validate sub-decimeter vertical accuracy in open urban areas. The accuracy decreases beneath canopies or in overlapping parts of areas between buildings, where satellite visibility is limited. To overcome the abovementioned limitations, Ng et al. (2021) developed a 3D mapping database-aided GNSS RTK system that achieved an average positioning accuracy of 10 cm in an urban canyon by excluding non-line-of-sight satellites [15]. In spite of these developments, GNSS-based approaches continue to be vulnerable to signal blockage and multipath effects in dense urban areas.

Handheld mapping platforms are another emerging technology category that can be used in DTM generation. According to Jurjević et al. (2021), multiple technologies, notably close-range terrestrial laser scanners (TLSs), UAV-LS, and handheld mapping platforms, were evaluated with the demonstration that handhelds achieved RMSEs of (10–15) cm in comparison with total stations [16]. This type of performance is acceptable for reconnaissance-level mapping but may not be acceptable for engineering-grade applications. According to Taylor et al. (2017), while handheld systems sacrifice accuracy, as compared to surveyed methods, they provide convenience and portability and are easier to operate by one person [17].

On the other hand, in small-scale urban areas, the generation of DTMs is predominantly done through the use of high-end instruments, such as total stations, digital levels, and differential GNSS receivers. These conventional surveying tools provide excellent vertical accuracy, often achieving millimeter-level precision under controlled conditions [18]. However, they possess labor-intensiveness, need specialized training, and require significant fieldwork time, which makes them unsuitable for speedy projects or limited-resource settings [7]. The constraints of conventional processes have stimulated the quest for al-

ternative technologies that can ever more effectively balance accuracy requirements with operational efficiency and costs.

Novel low-cost inertial navigation and motion-sensing technologies emerged recently and promise to improve the productivity and cost-effectiveness of non-traditional surveying fieldwork [13,19]. Moasure ONE and Moasure 2 devices are portable inertial measurement unit (IMU)-based sensors that integrate accelerometers, gyroscopes, and magnetometers to track motion and estimate distances and changes in elevation [20]. Due to the ease of operation and portability, these devices are suitable for rapid data collection of terrain in urban areas. Numerous studies have investigated the performance of low-cost IMU devices across various applications, including road alignment surveying [21,22] and motion capture calibration through geodetic techniques [23]. Recent validation work by Kamel (2025) examined the Moasure ONE predecessor device, providing initial insights into IMU-based handheld surveying capabilities [24]. However, Moasure 2 represents an updated technology with potentially different performance characteristics that warrant independent validation.

Recent works have shown an increasing interest in low-cost IMU-based mapping systems, but many existing approaches are still limited by drift accumulation, environmental sensitivity, and inconsistent accuracy under urban conditions [25–28]. However, due to the use of low-cost micro-electromechanical system (MEMS) inertial measurement units (IMUs), the positioning accuracy typically degrades over time [29]. Despite the growing body of literature on low-cost surveying technologies [30–33], a critical gap remains regarding the validation of the Moasure 2 handheld IMU device for urban terrain modeling applications. This gap in the literature creates uncertainty for practitioners considering the adoption of this technology for urban DTM generation. This study addresses this gap by conducting a comprehensive evaluation of Moasure 2 performance for urban DTM generation. It employs multiple validation methodologies, including checkpoint analysis, grid-to-grid surface comparison, and elevation profile assessment, comparing Moasure 2 with traditional methodologies.

The contributions of this research can be summarized as the following:

- Conducting a comprehensive evaluation of the Moasure 2 device's vertical accuracy for terrain modeling in small urban areas.
- Comparing Moasure 2 results against conventional total station and digital leveling methods.
- Evaluating the results against ASPRS standards to assess the device's performance for a range of urban mapping applications.

Unlike previous studies that focused primarily on consumer-grade GNSS or handheld mapping systems, this research provides a comprehensive validation of a next-generation IMU-based handheld surveying device for DTM generation using multiple validation approaches and comparison against conventional geodetic surveying methods. This work provides empirical evidence that will assist practitioners in understanding and choosing technology for resource-constrained urban terrain modeling projects.

This paper begins by providing a brief introduction to the study followed by a description of the methodology in Section 2. Then, the obtained results are presented in Section 3, where Section 4 discusses the obtained results, limitations, and future work. Finally, Section 5 displays the conclusions of this study.

2. Materials and Methods

2.1. Study Area

This study was conducted within the campus of King Abdulaziz University (KAU) in Jeddah, Saudi Arabia. The KAU campus provides an urban landscape with moderate topographic variation and well-defined survey benchmarks.

As shown in Figure 1, two test sites were selected for testing the vertical accuracy of the elevation products generated using the handheld IMU, Moasure 2, under typical field conditions. The first site of approximately 3500 m² was situated in a safe and accessible zone near academic buildings and the second was a road segment of 1080 m long inside the campus of KAU. To ensure geospatial control, the first study area was overlaid with a 15 × 15 grid network, yielding 225 regularly spaced test nodes. These node locations were physically marked using painted survey nails to facilitate consistent identification across devices and sessions. For the second site the measurements were collected along the road centerline as well as along the inner and outer edges on both sides of the roadway.

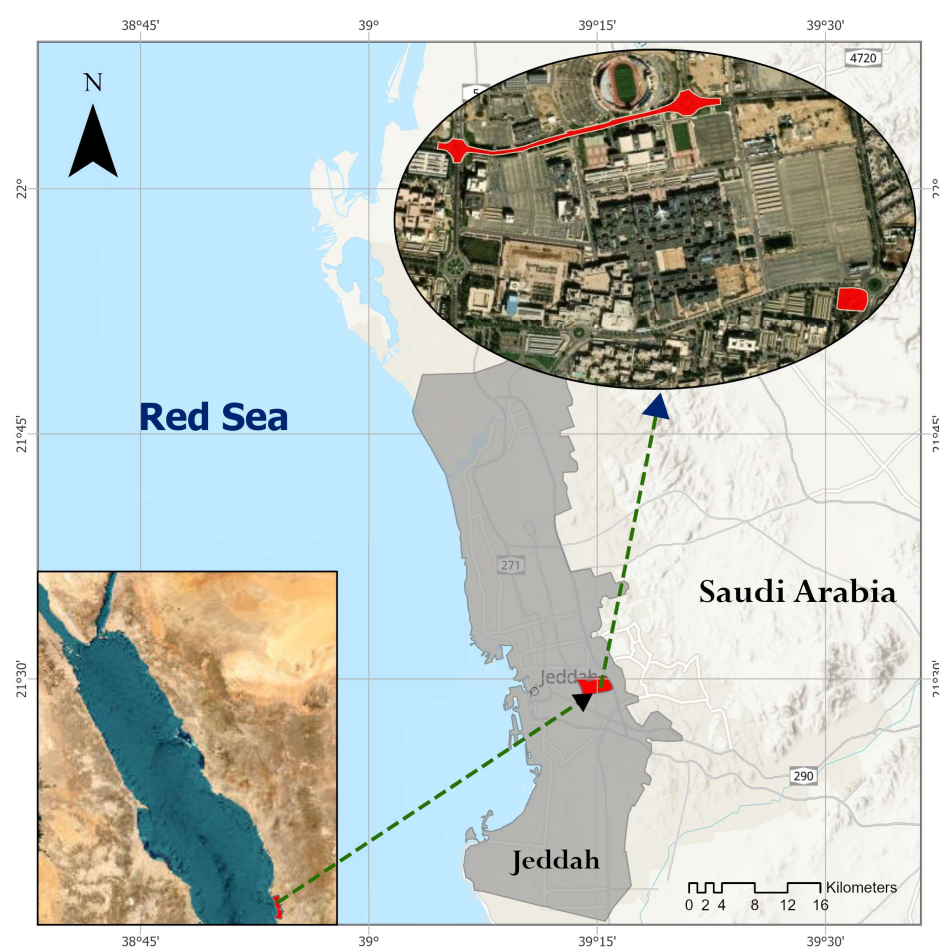


Figure 1. Overview of King Abdulaziz University Campus and the study site area.

For the optimized measurement strategy and surface modeling, the site was subdivided into three zones based on terrain variation and to address the Moasure 2's operational guidelines. According to the Moasure 2 technical documentation, continuous tracking paths should not exceed 20 m, and the recommended maximum area for individual measurement loops is ≤ 100 m² [20]. Segmenting the area helped enhance error control and reduce inertial drift across data collection tracks during terrain modeling, especially in areas with slight undulation or elevation transition.

2.2. Moasure 2 Instrument

The Moasure 2 device (Moasure, Warwick, UK), shown in Figure 2, is a handheld surveying instrument that employs an advanced IMU and proprietary motion-processing algorithms to determine three-dimensional positions without relying on satellite signals or external reference stations. The device allows for fast spatial measurements in environments where conventional GNSS-based surveying may not be feasible, by constantly following the movement of the sensor. Compact design and user-friendly mobile applications make it suitable for a wide range of applications, such as topographic surveying, construction layout, landscaping, and earthworks estimation. Moasure 2 is equipped with the X2 Inertial Sensor Engine, which improves measurement accuracy, accelerates data processing, and provides a more robust user experience compared to the Moasure ONE [20]. According to the manufacturer, the device can reach vertical accuracies of up to ± 5 cm under good operating conditions (smooth motion and relatively short survey trajectories). However, despite these reported capabilities, independent scientific validation of its vertical accuracy remains limited, particularly for engineering-grade DTM generation that requires compliance with established positional accuracy standards.



Figure 2. The Moasure 2 portable measurement device.

As shown in Figure 3, three distinct motion techniques were implemented to assess the consistency and suitability of the Moasure 2 device for terrain mapping. They are as follows:

- Zigzag: continuous lateral sweeps across the grid.
- Radial: concentric circular paths from a central origin.
- Ray-like: structured radial lines emulating conventional traverse-based acquisition.

Each method was deployed in a controlled sub-area under equivalent environmental and operator conditions. The IMU device recorded elevation and planimetric data, producing XYZ datasets for terrain modeling. These methods were configured and executed through the Moasure 2 mobile application, each representing a distinct approach to spatial coverage and sensor behavior.

After evaluating acquisition strategies, one method was selected for complete site implementation. Using the best tested strategy, Moasure 2 was applied sequentially across the study area. Data were exported in XYZ format and processed to construct DTMs.

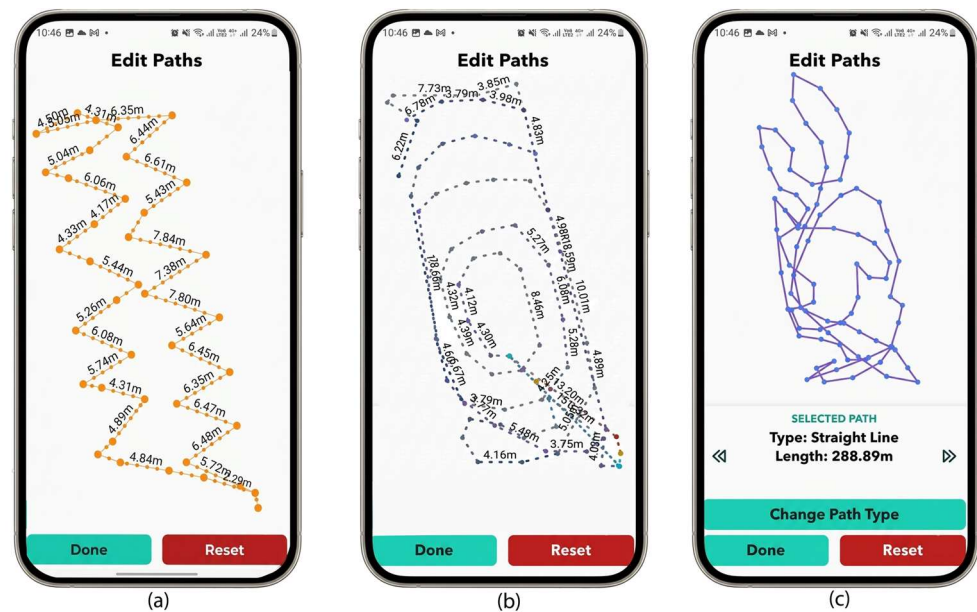


Figure 3. Motion paths applied using the Moasure 2 device: (a) zigzag, (b) radial, and (c) ray-like.

2.3. Ground Control and Reference Framework

To ensure geospatial fidelity and quantitative accuracy assessment, a geodetic control network was established within the study area. The vertical control network was referenced to a known benchmark BM36 (39.181 m) located on the KAU campus. A closed-loop leveling survey was conducted using the Leica Sprinter 150 digital level, offering a vertical accuracy of ± 1.5 mm per 1 km double-run, providing highly precise height transfer across the site.

Horizontal control was established using a Leica TCR1201 total station (Leica Geosystems AG, Heerbrugg, Switzerland), featuring angular precision of 3 s, and distance measurement precision of ± 1.5 mm + 2 ppm. The surveying polygon traverse was adjusted and validated according to ASPRS Class III tolerance limits appropriate for large-scale (1:500) mapping applications. For geospatial referencing and base station positioning, a Leica Viva GS15 GNSS receiver (Leica Geosystems AG, Heerbrugg, Switzerland), was used with manufacturer-reported accuracies of ± 10 mm + 1 ppm horizontally and ± 20 mm vertically under favorable satellite conditions.

Reference DTMs were produced using two conventional surveying techniques:

- Radiation survey using a total station device, which provides high-resolution distinguished elevation data.
- Leveling survey using a digital level device, which provides high precision of vertical data gathered in a regular grid.

All reference measurements were tied to the established vertical control network referenced to benchmark BM36. Independent checkpoints were used exclusively for validation purposes to minimize bias during surface comparison.

These reference digital terrain models were aligned to the same control network and used as baselines for elevation accuracy assessment.

2.4. Accuracy Assessment Procedures

Data collected by the Moasure 2 device were exported in XYZ coordinate format and processed using AutoCAD Civil3D 2026 software. For each Moasure-2-derived dataset, a DTM was generated and geospatially aligned to the ground control network established through total station and leveling instrumentation. Reference DTMs were independently

produced using dense topographic surveys from a total station and a digital level, serving as benchmarks for all comparative accuracy analyses. To evaluate the vertical accuracy of the Moasure-2-derived surface, multiple statistical and visual assessment techniques were applied: statistical accuracy indicators, conformity with accuracy standards, statistical significance testing, and visual and qualitative assessments.

2.4.1. Statistical Accuracy Indicators

Four core statistical metrics were calculated at two levels:

- Checkpoint-based comparison using 20 evenly distributed control points.
- Grid-to-grid comparison across the 117-sample DTM surface nodes.

The following indicators were used, consistent with standard DEM accuracy evaluation methods.

Mean error (ME) indicates the average deviation from the reference:

$$ME = \frac{1}{n} \sum_{i=1}^n (z_i - z'_i) . \quad (1)$$

Mean absolute error (MAE) measures the average absolute difference and reflects the average magnitude of vertical discrepancies:

$$MAE = \frac{1}{n} \sum_{i=1}^n |z_i - z'_i| . \quad (2)$$

Root mean square error of elevation (RMSE_z) quantifies the overall accuracy of the terrain dataset:

$$RMSE_z = \sqrt{\frac{1}{n} \sum_{i=1}^n (z_i - z'_i)^2} . \quad (3)$$

Standard deviation (SD) describes the spread of the errors around the mean value:

$$SD = \sqrt{\frac{1}{n} \sum_{i=1}^n [(z_i - z'_i) - ME]^2} , \quad (4)$$

where:

z_i : measured elevation at point i ,

z'_i : reference elevation at point i ,

n : number of checkpoints.

In both kinds of checkpoint and grid-to-grid analyses, the estimate of 95% confidence intervals (CIs) was computed for mean and standard deviation, providing bounds that estimate the range of likely population parameters.

2.4.2. Conformity with Accuracy Standards

The analysis follows ASPRS (2024) standards for positional accuracy of digital geospatial data [6], which recommend for projects under 500 km² that there must be at least 20 vertical checkpoints. These selected checkpoint locations were selected to ensure uniform distribution and surface representativeness, in accordance with FGDC Part 4 quality classification guidelines [34].

To determine whether observed accuracy differences between the three surfaces (Moasure 2, total station, and digital level) were statistically significant, a Friedman test was applied to the 20-point checkpoint error distributions. The Friedman test is a non-parametric statistical test used to determine if there are statistically significant differences between the distributions of three or more related groups.

Additionally, assuming the differences were normally distributed, a paired *t*-test was applied to 117-point grid-to-grid surface comparisons to determine whether the mean difference between two error surfaces is significantly different from zero.

Several visual tools were used to complement numerical metrics and offer insight into spatial reliability:

- Surface difference maps generated by subtracting Moasure 2 surfaces from the reference DTMs and visualized using color-coded thresholds (± 25 cm), highlighting the spatial error distribution.
- Elevation profile comparison of Moasure-2-derived profiles against ground profile lines surveyed by traditional methods across the study site.
- Violin plots used to illustrate the full distribution, density, and symmetry of vertical error values across methods, offering a compact view of central tendency and spread.

These multi-layered assessments enabled detection of potential systematic drift, terrain-specific biases, and outlier behavior not easily captured by aggregate metrics.

3. Results

3.1. Evaluation of Moasure 2 Data Collection Techniques

To determine the best reliable data collection strategy using the Moasure 2 device, three different motion-based acquisition methods were tested over a controlled sub-study area: zigzag, radial, and ray-like. A high-accuracy surface model obtained from a total station survey served as the reference dataset. Each Moasure-2-derived DTM was assessed against this reference using both visual inspection and quantitative error analysis. The comparison of the three Moasure 2 surfaces was done through the contour maps, as shown in Figure 4, and cross-sectional elevation profiles are presented in Figure 5. Figure 6 shows the elevation error surfaces of each method compared with the surface produced using the total station. The smoothest topography was produced by the ray-like method whose contours and terrain transitions closely matched the reference model. The zigzag method demonstrated erratic profiles, showing significant local elevation deviations and contour variations, pointing to error accumulation due to complex motion paths and IMU drift.

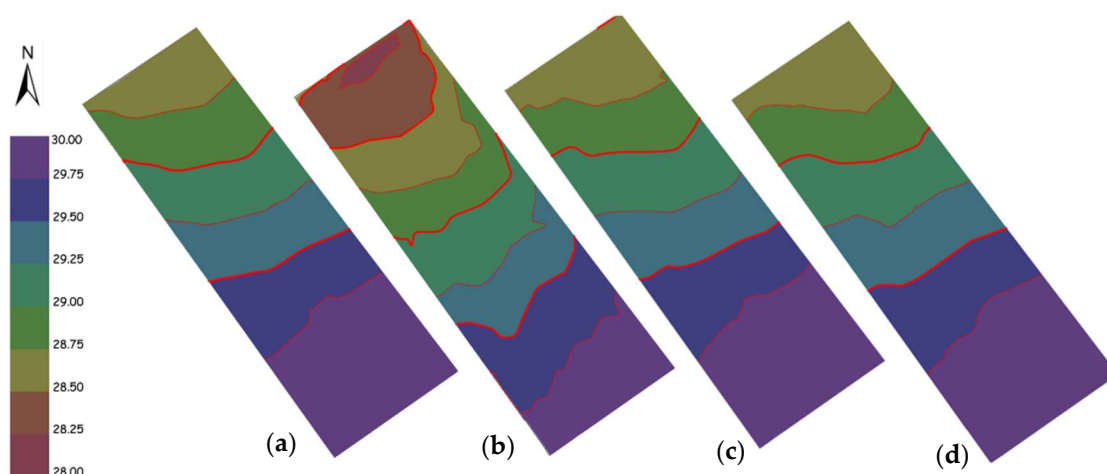


Figure 4. Contour lines comparison overlay of total station (a) and Moasure 2 methods: (b) zigzag, (c) radial, and (d) ray-like.

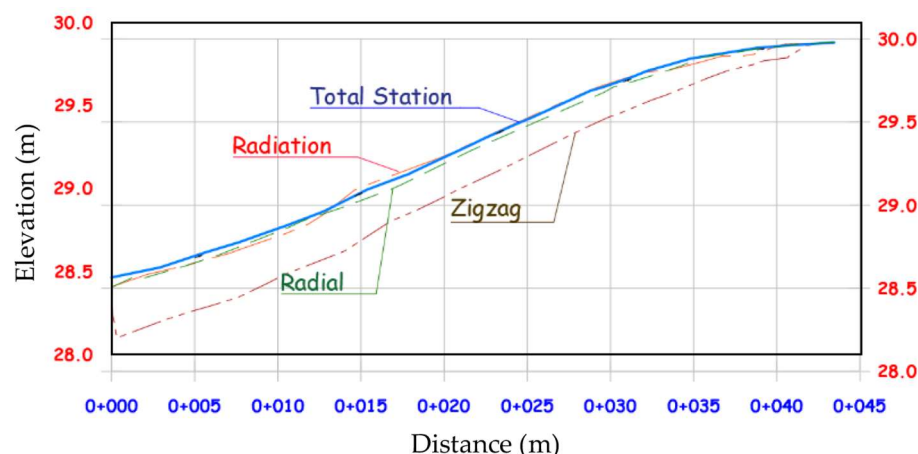


Figure 5. Elevation profiles across a reference path for zigzag, radial, ray-like, and total station surfaces.

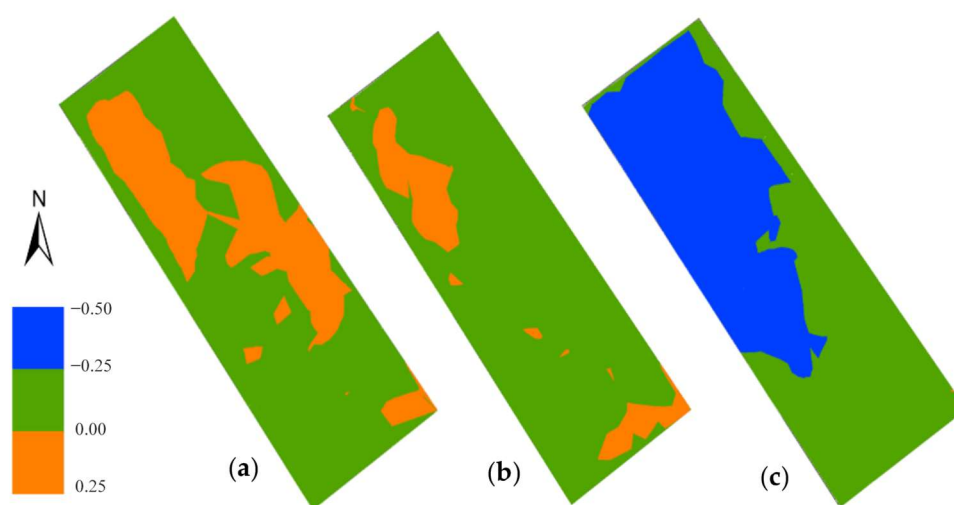


Figure 6. Elevation error maps between Moasure 2 surfaces: (a) zigzag, (b) radial, (c) ray-like, and total station, categorized in ± 25 cm intervals.

To quantify the accuracy of each method, elevation errors were calculated at matched grid points across the sub-study area. Table 1 lists the bias (mean error), RMSEz, and MAE, as well as the cut/fill volumetric differences compared to the total-station-derived terrain surface. The findings confirm that the ray-like method yields the most accurate surface, with the lowest RMSEz and MAE, minimal bias, and reduced volumetric discrepancy. The smoother interpolation and lower maximum errors confirm its spatial consistency.

Table 1. Elevation accuracy and volumetric differences of Moasure 2 acquisition methods.

Method	RMSE (cm)	MAE (cm)	Bias (cm)	SD (cm)	Min. Error (cm)	Max. Error (cm)	Cut (m ³)	Fill (m ³)	Net Volume (m ³)
Zigzag	30.26	28.60	−28.60	17.93	−61.40	+7.60	149.48	0.00	−149.48
Radial	3.52	2.92	−2.69	2.32	−6.00	+2.50	13.72	0.67	−13.05
Ray-like	2.41	2.21	−1.06	2.16	−4.70	+2.80	11.55	2.73	−8.82

3.2. Establishment of Ground Control Points

Ground control points (GCPs) were used to establish and reference the survey network. They were accurately measured using GNSS instruments to ensure horizontal accuracy. These GCP measurements were important for anchoring all subsequent spatial observations and for providing a uniform reference framework.

The leveling survey commenced from Benchmark BM36, which has a known orthometric elevation of 39.181 m. Eight GCPs were measured using a precise digital level. The allowable vertical misclosure was defined at 8 mm based on the total length of the leveling circuit, while the observed misclosure was 4 mm, which indicates that the measurements fell within acceptable Class III tolerance limits. This level of orthometric accuracy supports high-quality elevation referencing across the survey grid. The corrected elevation values served as the vertical control for subsequent terrain modeling.

However, independent checkpoints (CPs) were utilized exclusively for accuracy validation and error assessment to validate Moasure 2 and traditional surveying measurements. A total of 20 CPs were randomly selected, ensuring uniform spatial distribution and elevation variance across the site. These points were marked on the ground with painted nails for visibility during repeated measurements. A total station and digital level were used to acquire both horizontal and vertical coordinates of all CPs. The closed leveling showed a total misclosure of 3.5 mm, which is acceptable compared with the allowable misclosure of 4.75 mm. These CPs later formed the basis for digital terrain modeling and accuracy assessment.

3.3. Digital Terrain Model Production

Three digital terrain models were generated in this study. The reference DTMs were produced using high-accuracy elevation data acquired through two conventional surveying methods: digital level and total station measurements. A third DTM was derived from data collected using the handheld Moasure 2 device, specifically utilizing the ray-like motion technique, which was selected after preliminary evaluation of alternative motion strategies.

The reference DTMs served as benchmarks for all vertical accuracy assessments. Each surface was modeled using triangulated irregular network (TIN) interpolation within AutoCAD Civil3D 2026 software. For terrain surface generation, the software employed the Delaunay triangulation method to construct a TIN, using linear interpolation between adjacent elevation points. No smoothing or point densification algorithms were applied during the modeling process, ensuring that the original surveyed elevation points were preserved without modification. Terrain break lines were surveyed in the field using a total station and incorporated into the TIN model within the software environment. These break lines were used to accurately represent abrupt changes in elevation and terrain slopes, thereby improving the fidelity of the generated surface model. Furthermore, no extrapolation was performed beyond the boundaries of the surveyed area, and the terrain model was generated exclusively from the measured data within the limits of the study site. The resulting surfaces were inspected visually and analytically to assess slope smoothness and topographic fidelity. This setup enabled direct comparison between conventional surveying-derived surfaces and the inertial-based surface model obtained from the Moasure 2 device.

3.3.1. First Reference DTM from Digital Level

To obtain precise elevation values across the grid nodes of the study area, the Leica Sprinter 150 Digital level (Leica Geosystems AG, Heerbrugg, Switzerland), was used. The position of the instruments was to ensure that the entire 15×15 grid network was covered without obstruction. At each grid intersection where measurements were taken, the elevation difference was recorded—this produced a dense matrix of spot heights that were indicative of subtle changes in elevation. Adopting this leveling approach, the vertical measurement resolution achieved was ± 1.5 mm, ensuring high-confidence baseline data for surface modeling.

All recorded measurements were logged in structured tabular form, associating each elevation with a unique grid ID. This dataset was then processed into a TIN surface, producing a highly detailed and topographically consistent model of the site's terrain.

This method was selected due to its superior vertical accuracy and its suitability for relatively flat or smoothly varying surfaces. It also facilitated a systematic point-by-point elevation acquisition, in contrast to the vector-based trajectory of Moasure 2, thereby offering a fundamentally different sampling methodology. The surface produced served as one of the two primary ground-truth DTMs used for error analysis and comparison (Figure 7d).

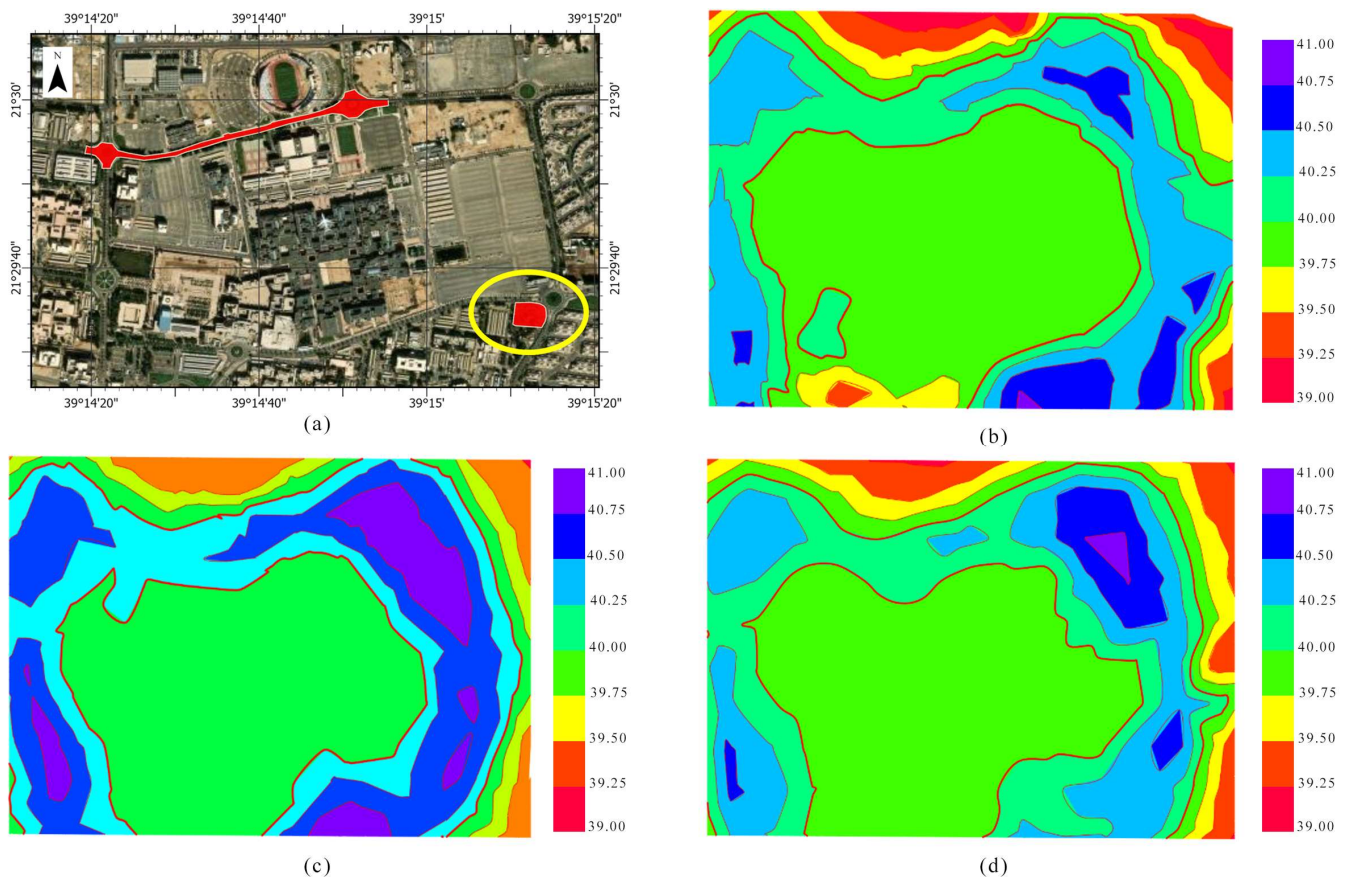


Figure 7. The resulting contour line of the DTM surface: (a) study area, (b) contour lines from ray-like Moasure 2, (c) reference DTM from total station, and (d) reference DTM from grid leveling.

3.3.2. Second Reference DTM from Total Station

The Leica TCR1201 total station was employed to capture precise three-dimensional coordinate data across the study area. This method provides flexible spatial data acquisition, especially for features not aligned to the regular grid network of the leveling survey. The radiation technique of total station surveying was chosen for its ability to accurately measure distances and angles in challenging site conditions while delivering dense spatial coverage. Topographic data collection focuses on recording elevation changes across visible terrain points. Special attention was given to nodes exhibiting slope inflection, micro-relief, or structural features.

To enhance the terrain model modeling and surface continuity, break lines representing terrain discontinuities (e.g., ridges and edges) were also surveyed. These linear features were integrated into the TIN model to prevent interpolation artifacts and to preserve the site's geomorphological structure.

The final dataset was processed into a TIN-based DTM using Civil3D software, producing a continuous and high-fidelity topographic surface of the site. This surface, illustrated in Figure 7c, served as the second reference benchmark against which the Moasure-2-derived DTM would be evaluated.

3.3.3. DTM from Moasure 2 Using the Ray-like Method

The final DTM was generated using elevation data collected with the Moasure 2 device, operated in the ray-like motion technique, which was previously selected as the most suitable method based on preliminary accuracy assessments.

During data acquisition, measurements commenced from known ground control points established during the ground control phase. The ray-like method does not follow a single rigid motion pattern; instead, it is adapted based on terrain morphology. In relatively flat zones, measurements were taken along paths resembling a grid-based layout, which ensures uniform spatial coverage. In moderately sloped or undulating areas, the operator traced paths that followed characteristic topographic features, such as slope and ridge lines, to better capture terrain variability and preserve morphological details. This strategy reflects practical adaptation of the device's motion capabilities to the terrain, enhancing the realization of the topographic surface continuity.

Moasure 2 data were exported in XYZ coordinate format via the mobile application and then imported into Civil3D software. A TIN surface was interpolated using the collected points, with additional attention to the alignment and smoothing of edges between zones. Manual editing was applied where necessary to remove outlier points or resolve surface discontinuities introduced during motion transitions. The resulting contour line of the DTM surface, shown in Figure 7b, presents a continuous representation of the terrain based solely on inertial-derived data.

To initiate the comparative analysis of the Moasure-2-derived surface, a visual overlay of contour lines was generated and compared against the two reference DTMs derived from total station and digital level data. The contours from all three models were generated using a consistent 0.25 m interval, enabling a uniform basis for visual evaluation. The Moasure-2-based contour surface, collected using the ray-like method, shows overall agreement in form and spacing with the reference DTMs across most of the study area. In relatively stable and flatter regions, contour alignment was particularly strong, indicating a close match in modeled elevation gradients.

In contrast, areas featuring greater elevation complexity, such as slopes or irregular terrain, exhibited localized mismatches in contour curvature, spacing, and continuity. These discrepancies may result from the following:

- Varying point density due to motion-based data acquisition,
- Minor deviations in measurement trajectories,
- Sensor drift and cumulative orientation error inherent to inertial systems,
- Obstacle avoidance or terrain accessibility constraints during data collection.

Although the Moasure-2-based surface employed the highest number of points (229 points), this did not uniformly translate to higher topographic fidelity. The maximum elevation value of the Moasure 2 surface ranges was recorded to be 40.872 m, which is more than the highest elevation of both total station (40.563 m) and digital level (40.613 m) surfaces. This might be due to its high sensitivity to varied levels. Despite this higher variance, the DTM produced with Moasure 2 retained topological consistency and terrain continuity while not having omitted features or anomalies that would affect model usability. The contour representation captures the major elevation transitions and forms a reliable basis for subsequent terrain analysis and validation. This visual comparison is supplemented

by additional evaluation methods in subsequent sections, including checkpoint-based metrics, profile views, and statistical distribution analysis.

3.4. Vertical Accuracy Assessment

This section presents a three-part analysis of the vertical accuracy of the Moasure-2-derived DTM compared to reference DTMs produced using total station and digital level measurements. The assessment includes:

- Checkpoint-based accuracy assessment,
- Grid-to-grid accuracy assessment,
- Profile-based accuracy assessment.

3.4.1. Checkpoint-Based Accuracy Assessment

To evaluate the vertical accuracy of the Moasure-2-derived DTM, a checkpoint-based comparison was conducted using 20 surveyed control points distributed across the study area. Elevation errors were calculated by subtracting the reference elevation from the corresponding surface elevation in each of the three DTMs: total station, digital level, and Moasure 2 (ray-like method).

Table 2 presents the results of the calculation of mean error (bias), mean absolute error (MAE), root mean square error (RMSE), and standard deviation (SD) for each surface, as well as the 95% CIs calculated for both mean error and standard deviation.

Table 2. Vertical accuracy metrics for checkpoint elevation errors (units in meters).

Metric	Total Station	Digital Level	Moasure 2 (Ray-Like)
ME	−0.0267	0.0016	0.0017
±95% CI (ME)	[−0.0584, +0.005]	[−0.0528, +0.056]	[−0.0779, +0.0813]
MAE	0.0555	0.0783	0.1214
RMSEz	0.0713	0.1102	0.1657
SD	0.0678	0.1130	0.1700
±95% CI (SD)	[0.0516, 0.0991]	[0.0859, 0.1651]	[0.1293, 0.2483]

The standard deviation of elevation errors in the Moasure 2 surface (0.1700 m) was significantly higher than that of the total station (0.0678 m) and digital level (0.1130 m), suggesting increased vertical variability.

The performance of the Friedman test on the error distributions conditional on the values ($\chi^2 = 4.80$, $p = 0.09$) was used to assess if the accuracy differences amongst the three methods were statistically meaningful. The differences between surfaces were not significant statistically, as p -values were greater than 0.05. This implies that although the performance of Moasure 2 exhibited slightly higher variability, its overall accuracy performance does not significantly differ from that of the reference surfaces in this regard.

The violin plot shown in Figure 8 was generated to visualize the distribution and spread of elevation errors across the three surfaces. The Moasure-2-derived error distribution displays a wider spread and longer tails, indicating greater variability in error magnitudes compared to the traditional methods, and reflecting its higher standard deviation, yet its central alignment remained close to both the total station and digital level distributions. This supports the interpretation that no systemic bias was introduced by the motion-based Moasure 2 measurements.

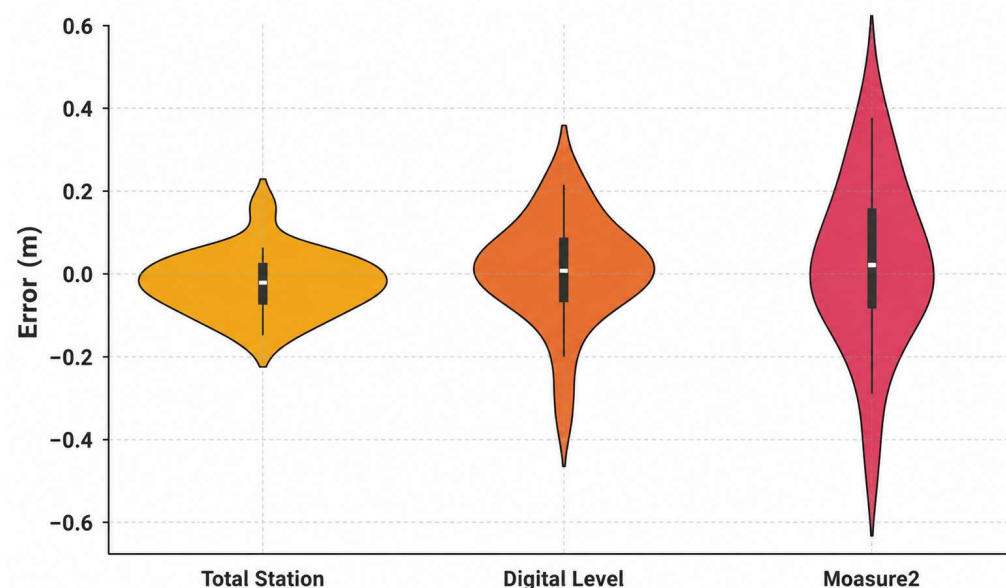


Figure 8. Violin plots of elevation errors for each surface method.

The results of this checkpoint-based evaluation confirm that the Moasure 2 ray-like method can achieve vertical accuracy comparable to traditional optical, direct, and indirect leveling instruments for small-scale topographic modeling. The accuracy is lower than those of the traditional instruments, but the differences are within acceptable statistical and practical limits. More importantly, it is easy to deploy and inexpensive operationally.

3.4.2. Grid-to-Grid Accuracy Assessment

To evaluate the spatial conformity of the Moasure-2-derived DTM against the reference surfaces, a point-by-point comparison was conducted across 117 regularly distributed grid locations. At each node, the elevation difference was calculated between the Moasure 2 surface and the corresponding value from both the total station and digital-level-generated DTMs.

Four accepted statistical accuracy metrics were computed for both comparisons: ME, MAE, RMSEz, and SD. In addition, CIs were derived at 95% for the SD and ME to assess the reliability of each estimate. The summary is presented in Table 3.

Table 3. Grid-to-grid surface accuracy metrics (units in meters).

Metric	Moasure 2 vs. Total Station	Moasure 2 vs. Digital Level
ME	−0.0265	−0.0019
±95% CI (ME)	[−0.0538, +0.0008]	[−0.0352, +0.0314]
MAE	0.1052	0.1232
RMSEz	0.1505	0.1803
SD	0.1486	0.1810
±95% CI (SD)	[0.1317, 0.1705]	[0.1644, 0.2077]

These results show that both comparisons yield reasonably low RMSEz values, with slightly better consistency in the Moasure 2 vs. total station comparison. The confidence interval for ME in both cases encompasses zero, indicating minimal vertical bias. The confidence intervals of the SD also support these results, confirming the expected range of variation of the elevation errors.

In addition to the numerical assessment, a violin plot was illustrated to visualize the distribution elevation errors in both comparisons, as depicted in Figure 9. Moasure

2 total station error distribution shows a more centered and compact distribution, while Moasure 2 digital level error distribution has a broader distribution and is slightly skewed. This indicates that the Moasure 2 output exhibits better surface smoothness and internal consistency when compared to total station data.

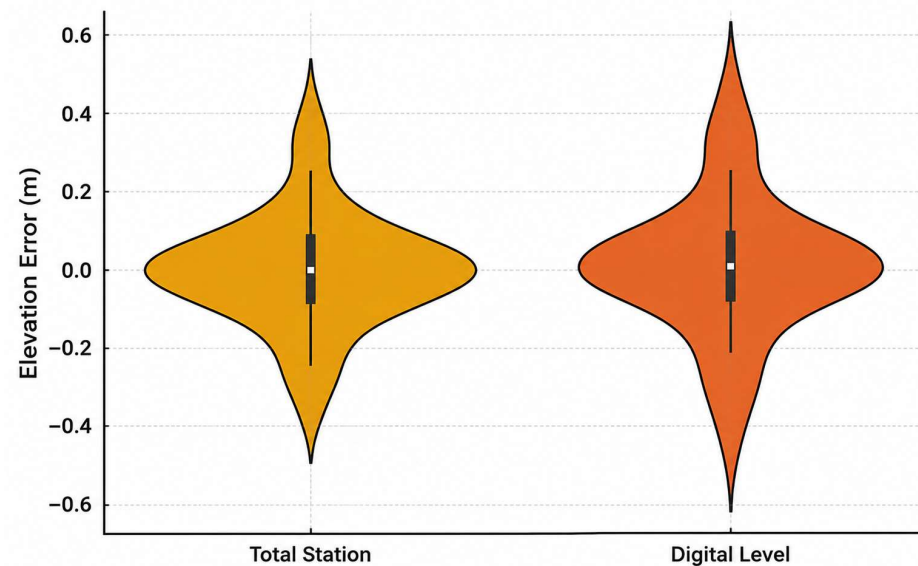


Figure 9. Violin plots of elevation errors in grid-to-grid comparison.

To determine if these differences were statistically significant, the paired t -test was applied comparing the two sets of Moasure 2 error differences, yielding a t -statistic of -2.81 and a p -value of 0.0058 . Since the p -value is below the 0.05 threshold, this indicates a statistically significant difference between the elevation errors of Moasure 2 relative to the two reference surfaces. This suggests that the way the Moasure 2 surface aligns with the total station surface differs significantly from how it aligns with the digital level surface, even if both are reference surfaces.

These results, taken together, confirm that while the Moasure 2 surface maintains a close vertical alignment with reference surfaces, certain spatial behaviors, especially in rugged or dynamic topography, may introduce error variability.

3.4.3. Profile-Based Accuracy Assessment

To further assess the vertical accuracy and spatial consistency of the Moasure-2-derived surface, four longitudinal and transverse profile lines were selected across the study area, each intersecting varied terrain types. These profiles were extracted from the Moasure 2 surface and compared against reference elevation profiles constructed using total station and digital level measurements. Each profile was visualized in overlay plots (Figure 10), showing how closely Moasure 2 data tracked the elevation patterns of the reference instruments.

Figure 11 presents violin plots of the elevation differences along the four profiles. The plots visualize the distribution and density of elevation errors between the Moasure 2 profiles and each reference surface, across all profile points.

The north and east side profiles show relatively tight and symmetric distributions, suggesting the Moasure 2 data are well-aligned with the reference instrument. The south profile has the greatest spread, especially when compared to total station, which could be due to complex terrain or movement. Digital level comparisons for all profiles are generally much closer to zero, with a narrower error range, likely due to less rough terrain or greater

line of sight during leveling. Most profiles show little bias, as the median error is centered around zero.

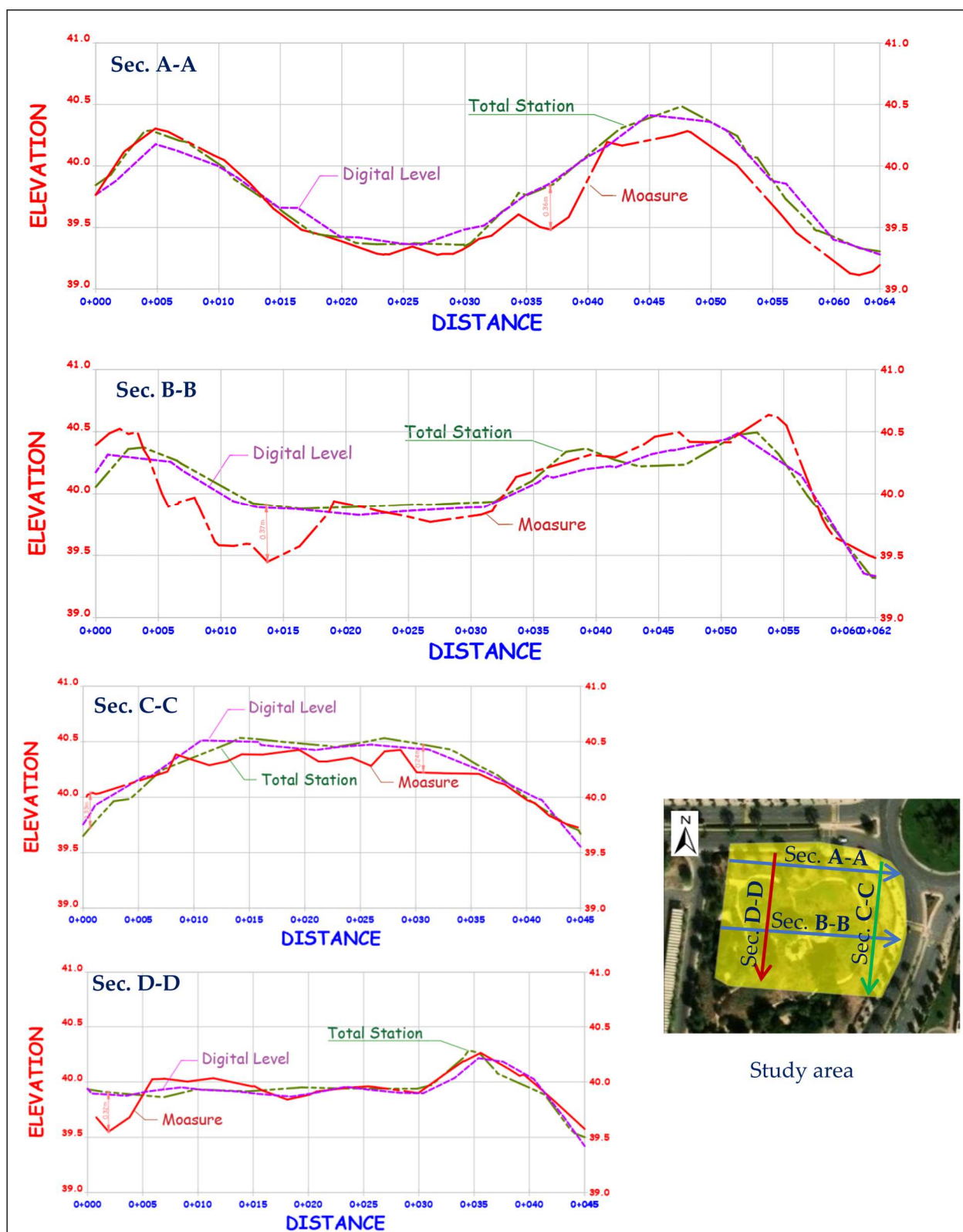


Figure 10. Elevation profile comparisons between Moasure 2 and reference profiles derived from total station and digital level surveys as sections shown in the subfigure, Study area.

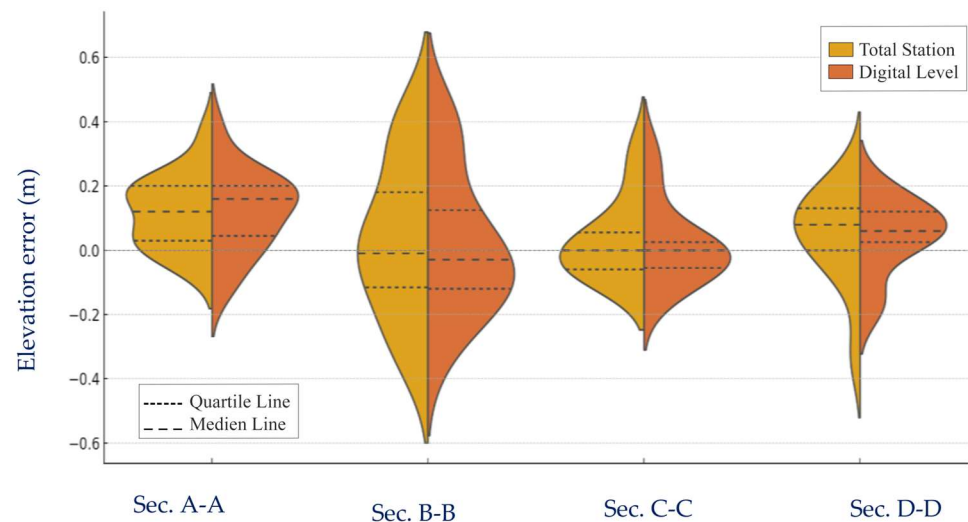


Figure 11. Violin plots show the elevation errors along four profile lines between the Moasure 2 surface and reference surfaces.

This profile-based analysis confirms that Moasure 2 achieves a high degree of local terrain conformity across varied terrain profiles, with systematic differences well within ± 25 cm in most cases. Profiles passing through steeper slopes or complex morphology yield broader error spreads, as expected for inertial-based acquisition methods. However, the absence of extreme outliers or skewed distributions supports the stability and reliability of the Moasure 2 device for limited-area DTM applications.

These findings complement the checkpoint and grid-to-grid assessments, offering an additional layer of qualitative and statistical validation. Visual overlays, violin plots, and confidence metrics collectively deliver a multi-dimensional impression of surface quality that is necessary to evaluate Moasure 2 for terrain modeling under real-world conditions.

3.5. Suitability for Road Surface Modeling

This part of the study was performed to assess the potential of the Moasure 2 device for modeling road surfaces and generating DTM from the elevation data acquired by the device. Field measurements were taken along three longitudinal survey lines, as described above—one along the road centerline and two along the outer edges of the roadway on either side. The data collected were processed and modeled in Autodesk Civil 3D to create a digital terrain surface. Figure 12 illustrates the modeled road section, where the ground elevations range from 29.88 m to 36.15 m.

One of the most important criteria used in determining the accuracy of digital elevation models is the average error, which is often referred to as altitude accuracy. It is the most important value that attracts the attention of digital model producers and investors. It is also known as the standard deviation, which is a numeric error indicator that reflects the matching of the digital model to the natural surface of the Earth. The sample size adopted for the study of the accuracy of the digital elevation model constructed for the road segment from Moasure 2 data was 24 points within an elevation range 29.88 m to 36.15 m, which represents the ground features (covers of the electricity, water, telecommunications, and drainage systems) that have been observed in the study area.

We can get the height of any point from the digital model with its coordinate's information, it falls within a triangle of the TIN network, and the surface equation defined by the three nodes formed the triangle in which it lies. Then, the errors can be calculated as the differences between known heights of the sample points and their corresponding heights derived from the digital surface model.

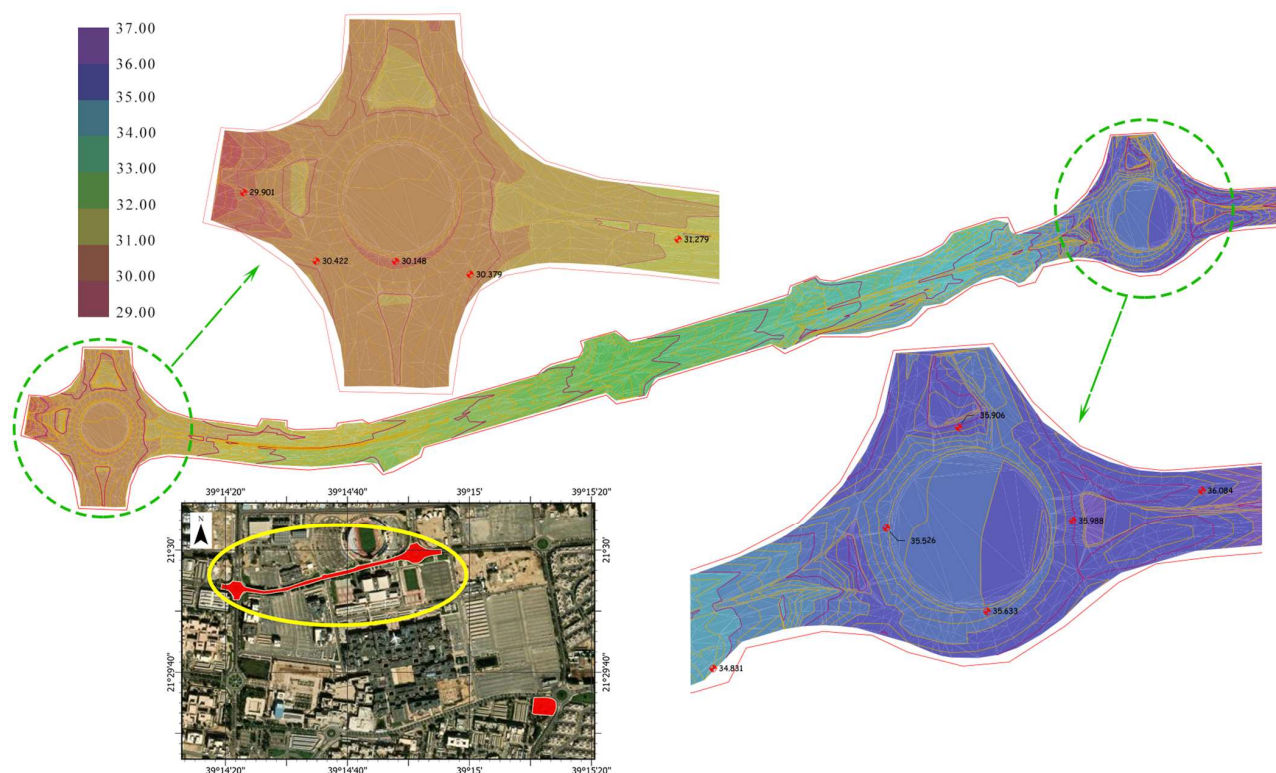


Figure 12. DTM of the road segment using Moasure 2 data.

The comparison between the elevations extracted from the Moasure-2-derived DTM and the independent total station measurements revealed elevation differences ranging from -0.27 m to $+0.21$ m, with a mean error of approximately 0.003 m and a standard deviation of 0.12 m. Table 4 shows the chosen ranges and relative frequency of error values, while Figure 13 presents the distribution of the error.

Table 4. Relative frequency of error values.

Range	$[-0.27, -0.19]$	$[-0.19, -0.11]$	$[-0.11, -0.03]$	$[-0.03, 0.05]$	$[0.05, 0.13]$	$[0.13, 0.21]$
Number of Errors	2	3	3	8	6	2
Frequency	8.30%	12.5%	12.5%	33.3%	25%	8.3%

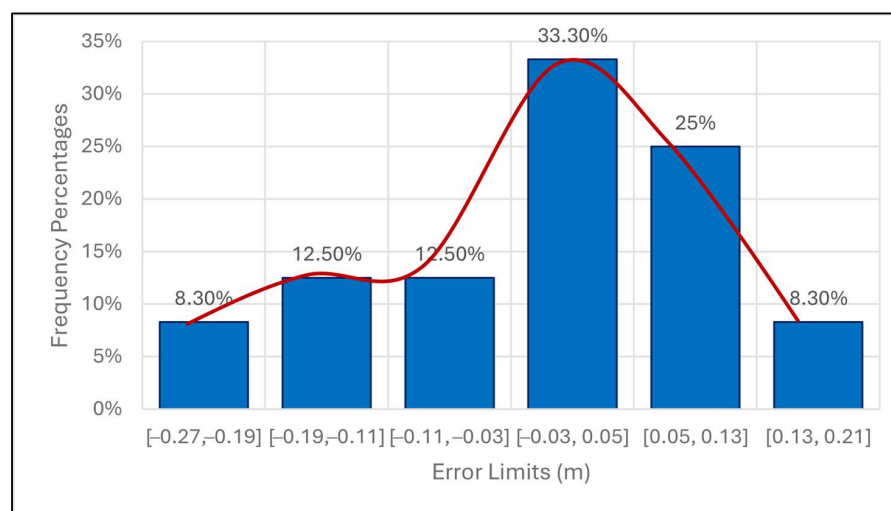


Figure 13. Error distribution of the selected sample.

The negligible mean error indicates the absence of significant systematic bias, while the observed variability reflects the random errors associated with inertial measurement drift, operator movement, and surface interpolation during DTM generation. These results demonstrate that the Moasure 2 device can reliably reproduce the overall geometry of the road surface and is suitable for rapid terrain mapping and preliminary engineering surveys.

4. Discussion

The primary objective of this study was to evaluate the vertical accuracy and operational suitability of the Moasure 2 handheld IMU device for DTM generation in small urban environments. The results obtained from a multi-phase validation scheme provided detailed insights into the functioning of the device. These findings are interpreted against existing geospatial accuracy standards [6,34], contrasted against literature on low-cost surveying technology, and the practical utility of urban terrain modeling is discussed.

The preliminary evaluation of motion-based acquisition methods was critical to the study's success. The ray-like method significantly outperformed the zigzag and radial techniques, achieving an RMSEz of 2.41 cm against the total station reference in the sub-area test, compared to 30.26 cm for the zigzag method (Table 1). This finding directly addresses the known susceptibility of IMU-based systems to error accumulation and sensor drift over complex motion paths [19,35]. The pattern of the ray-like method creates less deviation and more stable kinematic models for the sensor's fusion algorithms, which leads to better spatial consistency and topography fidelity. The implication is that for the best performance of such devices, how you operate them is as important as the device itself.

4.1. Vertical Accuracy and Conformance to Geospatial Standards

The core of this research lies in the quantified vertical accuracy of Moasure 2. The checkpoint analysis (Table 2) yielded an RMSEz of 0.1657 m for the Moasure 2 surface, with a 95% confidence interval for the standard deviation ranging from [0.1293 m to 0.2483 m]. To contextualize this performance against professional standards, we refer to both the FGDC and ASPRS frameworks.

Based on the RMSEz of 0.1657 m, Moasure 2 is in the (15 to 20) cm vertical accuracy class given in the ASPRS (2024). In the geospatial profession the vertical RMSE is about one-third of the contour interval, which a dataset can reliably support. This implies that the Moasure-2-derived DTM is suitable for generating contours with an interval of approximately 0.5 m.

Translating this accuracy into practical mapping applications, the FGDC Part 4 Standards provides direct guidance on appropriate map scales for various project types. Based on the RMSEz range observed in this study, Moasure 2 DTM is well-suited for grading and excavation plans, recreational site plans, and general construction site plans at scales of 1:500 to 1:1200. The lower end of the accuracy range (0.13 m) approaches the requirements for more detailed design work, while the higher end (0.25 m) is still perfectly acceptable for preliminary site grading and large-scale earthwork calculations. For master planning applications at scales of 1:5000 or smaller, the device's accuracy is more than sufficient.

Furthermore, the grid-to-grid comparisons provided robust spatial validation. The RMSEz of 0.1505 m when compared to the total station surface and 0.1803 m against the digital level surface are remarkably consistent with the checkpoint results. The 95% confidence intervals for the mean error in either comparison, $[-0.0538, +0.0008]$ m and $[-0.0352, +0.0314]$ m, are inclusive of zero, confirming the absence of any significant systematic vertical bias in the Moasure 2 data.

4.2. DTM Analysis and Spatial Consistency

The profile-based assessment (Figures 10 and 11) offers a qualitative yet powerful visualization of the device's performance across varied terrain. The close tracking of the Moasure 2 profiles with reference instruments, particularly on the north and east transects, demonstrates its ability to capture the general morphology and relative elevation changes accurately.

The fact that height differences were usually within ± 25 cm is a useful metric for practitioners, as it shows what the typical error envelope is likely to be. As the south profiles' error spread increases, they encounter a limitation concerning performance in areas with steeper slopes and more complex micro-topography. This is expected, as inertial sensors are sensitive to higher dynamic motions and rapid orientation changes. However, the lack of extreme outliers or asymmetrical distributions for all profiles would enhance the geometric stability and reliability of data for its intended purpose.

Moasure 2's RMSEz of approximately 0.17 m positions it as a distinct tool within the broader landscape of surveying technologies. It is orders of magnitude less accurate than the millimeter-level precision of the total station and digital level used as references in this study, confirming that it is not a substitute for these instruments when high-precision engineering tolerances are required. However, when compared to other low-cost or rapid-mapping techniques, its performance is noteworthy.

For example, its accuracy is comparable to some UAV-based photogrammetric surveys without dense GCPs. Kovaň et al. (2022) found that UAS RTK/PPK had a mean error of height of 0.112 m, which is similar to a Moasure 2's performance envelope [36]. UAV-based SfM approaches like the ones tested by Carrera-Hernández et al. (2020) [7] are effective for fast and extensive coverage. However, they may struggle in achieving vertical accuracy in complex urban settings and might be impacted by weather and airspace restrictions. According to Jurjević et al. (2021), handheld mobile mapping systems exhibited RMSEs of (10 to 15) cm, highly consistent with the Moasure 2 findings [16].

This study also builds directly upon the work of Kamel (2025), who assessed the predecessor Moasure ONE device for as-built plan production and reported horizontal RMSEs of 17.7 cm but did not examine vertical accuracy or DTM generation capability [24]. The current study extends that research by providing the first comprehensive vertical accuracy assessment of the updated Moasure 2 technology, confirming its enhanced capability for three-dimensional terrain modeling.

The key advantage of Moasure 2, therefore, is not its absolute accuracy but its combination of cost-effectiveness, portability, and ease of use. Unlike a UAV, it is unaffected by flight regulations, vegetation overhang in non-GNSS environments, and can operate in narrow pedestrian pathways. Its performance validates its use as a rapid-response tool for generating base maps at scales of 1:500 to 1:1200 for feasibility studies, preliminary earthwork estimates, or as-built verification for non-critical infrastructure, where the primary goal is speed and accessibility rather than centimeter-level precision.

Consequently, the main benefit of Moasure 2 is not how accurate it is. Instead, it is how reasonably priced, portable, and easy-to-use it is. Unlike a total station, it does not require a tripod, a second person as a rodman, or a clear line of sight. Different from a UAV, it is not subject to flight restrictions, obstruction of vegetation in non-GNSS terrains, and operates in narrow pedestrian paths. Based on the analysis of its performance, the Moasure 2 device can be considered an effective tool for the rapid production of topographic plans of a scale range between 1:500 and 1:1200. This makes it especially suitable for feasibility studies, preliminary engineering investigations, earthwork volume estimation, slope design, and for non-critical infrastructure projects where the main goal is fast data acquisition and operational simplicity rather than centimeter-level surveying accuracy. The instrument,

therefore, provides a practical and economic solution for preliminary topographic mapping, while traditional surveying methods are still preferable for applications requiring high-accuracy engineering measurements.

The generated DTM demonstrates that the Moasure 2 device can effectively capture the overall geometry of the road surface and reproduce its elevation variations with reasonable accuracy. The comparison with independent total station measurements showed altitude differences less than 27 cm, proving that the device gives a consistent representation of the terrain despite its relatively simple and portable measurement system. The differences depicted here are the result of the accumulated drift of the inertial measurement units (IMUs), the operator movement, and the interpolation used to generate the surface in Civil 3D. However, the resulting DTM could accurately represent the longitudinal and transverse surface morphology of the road. This shows that the device is suitable for rapid terrain mapping and preliminary road surveys. The device should be considered as an efficient and cost-effective alternative for reconnaissance surveys and preliminary DTM generation.

4.3. Limitations and Future Research Directions

Although the selected study area represents a realistic small urban terrain environment, it does not contain dense built-up features, such as buildings, paved roads, or urban canyons. Future studies should evaluate Moasure 2 performance across different land-cover types and artificial urban structures to further assess its applicability for detailed urban surveying and infrastructure mapping. Second, this research focused exclusively on vertical accuracy. A comprehensive evaluation of the Moasure 2's horizontal accuracy for planimetric mapping is a critical next step.

Third, the study occurred in a favorable setting. There still needs to be more trialing of the robustness of the device in more difficult conditions, such as when there is considerable magnetic interference that can affect the magnetometer. Finally, the ray-like technique was found to be the optimal method, but further acquisition protocol refinement and post-processing technique investigations could assist in reducing IMU drift. Also, future work should investigate operator-dependent variability and temporal repeatability to further evaluate the robustness and consistency of the device under practical field conditions.

5. Conclusions

This study provides the first independent, comprehensive validation of the Moasure 2 handheld IMU device for DTM generation in small urban environments. Through a rigorous, multi-faceted methodology comparing its output against high-precision total station and digital level surveys, the following key conclusions are drawn.

First, the choice of data acquisition techniques profoundly impacts the quality of the resulting DTM. The ray-like method was demonstrated to be significantly superior to zigzag or radial patterns, reducing RMSE_z by an order of magnitude and producing a topographically coherent surface.

Second, Moasure 2 was found to achieve a vertical RMSE_z of 0.1657 m by checkpoint validation, with a 95% confidence interval for standard deviation at [0.1293 m to 0.2483 m]. This performance matches the ASPRS (15 to 20) cm vertical accuracy class, thus supporting the derivation of 0.5 m interval contour lines. The 95% confidence intervals showed that there is no systematic vertical bias, implying errors are random and the data are geometrically correct.

Third, based on the FGDC standards [34], the Moasure-2-derived DTM is suitable for mapping at scales ranging from 1:500 to 1:1200, making it a practical tool for grading and excavation plans, recreational site plans, and general construction site plans. For master planning applications at smaller scales (1:5000 or less), its accuracy far exceeds requirements.

Fourth, the analysis, which is profile-based, shows that the Moasure 2 captures terrain morphologies with an elevation difference remaining in the envelope of ± 25 cm. It confirms its ability to create spatially consistent surfaces for its intended applications.

Fifth, the Moasure 2 effectively fills a gap between very accurate but labor-intensive conventional techniques and more complex and usually prohibitively expensive technologies, such as UAV-LiDAR. It can generate DTM in a low-cost and highly portable setup. It is useful for urban projects with time and budget constraints where sub-decimeter accuracy is not required. Because of its ease of use and ability to function in GNSS-challenged or obstructed environments, it offers unique operational advantages.

In conclusion, the Moasure 2 handheld IMU device is not a surveying instrument, but it is a portable handheld surveying device. Surveyors, engineers, and urban planners now have the evidence they need to make informed decisions. The study confirmed that for a significant range of mapping applications at scales of 1:500 to 1:1200, including preliminary site surveys, volumetric earthworks calculations, and as-built surveys of non-critical features, Moasure 2 is operationally efficient for selected terrain mapping applications.

Author Contributions: Conceptualization, A.K. and Y.M.; methodology, A.K., Y.M., and A.A.S.; validation, A.K. and A.A.S.; formal analysis, Y.M. and A.A.S.; writing—original draft preparation, A.K. and Y.M.; writing—review and editing, A.A.S.; visualization, A.K.; supervision, Y.M.; project administration, Y.M.; funding acquisition, A.K. All authors have read and agreed to the published version of the manuscript.

Funding: This project was funded by the Deanship of Scientific Research (DSR) at King Abdulaziz University, Jeddah, Saudi Arabia, under Grant No. IPP:356-137-2025. The authors, therefore, acknowledge with thanks the DSR for technical and financial support.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data that support the findings of this study are available upon request from the corresponding author.

Acknowledgments: The authors gratefully acknowledge the technical and financial support provided by the Ministry of Education and King Abdulaziz University, DSR, Jeddah, Saudi Arabia. Also, the authors are grateful to Abdulrhman Kateb, Faisal Al-Olayani, Mohammed Al-Shahrani, and Khalid Al-jarrah for their help in collecting data.

Conflicts of Interest: The authors declare no conflicts of interest.

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