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Full Length Research Article

Evaluation of the Repeatability and Accuracy of RTK GNSS under Tree Canopy

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ABSTRACT

Using the Real Time Kinematic (RTK) GNSS (Global Navigation Satellite Systems) Method, one may precisely estimate a location on Earth in "real-time" to within a few centimeters. However, significant limitations remain, such as accuracy loss due to poor satellite sight (e.g., high satellite obstructions from tree canopy and dense urban areas). It usually takes time to resolve the ambiguities or, on many occasions, results in failure. Several satellite systems have been deployed in recent years besides GPS and GLONASS, such as Galileo, BeiDou, and other satellite systems. GNSS is the replacement word for GPS, GLONASS, Galileo, and BeiDou. Theoretically, this GNSS system would be more beneficial than previous systems such as GPS; issues with decreased position accuracy and limited satellite visibility (for example, in the presence of a tree canopy) may be resolved. This study aims to reduce integer ambiguity resolution time using RTK GNSS and examine RTK GNSS's repeatability/accuracy in forested areas. The outcomes of GNSS positioning (compared with total station) in this study clearly showed improvement because of observing many satellites. The results suggest that the RTK GNSS system is preferred for surveying forested areas. This situation increases the accuracy of the RTK GNSS measurements and shortens the solution time for integer ambiguity. The horizontal component accuracy obtained in repeated RTK GNSS surveys in the forested areas remains 1–12 cm.

1. Introduction

The past decade has seen tremendous changes in the availability and diversity of satellite navigation systems on both a regional and a global scale. Next to the legacy GNSSs, GPS, and GLONASS, three regional systems (QZSS, BeiDou, and IRNSS/NavIC) provide operational services in the Asia-Pacific region. With BeiDou and Galileo, a total of four systems are now offering services on a global scale. Currently, most navigation satellites support dual-frequency open service signals for civil users, satisfying a growing interest in high-precision navigation in mass-market applications. This additional satellite system (GNSS) is theoretically adding value to others. GNSS System since more satellites can be observed. Satellite obstruction problems can be reduced by combining GPS, GLONASS, BEIDOU, GALILEO and others. Better results are also expected in the location. In this paper, we try to study the capability of RTK Multi GNSS in forest areas where we have difficulty in satellite signal observation. The advantage of having access to multiple satellites or GNSS is heightened accuracy, redundancy and availability. If the line of sight to a satellite is obstructed, having access to multiple satellites ensures uninterrupted service provision (Hofmann-Wellenhof et al. 2007; Wolf and Ghilani 2008).

RTK GNSS surveying is a relative positioning technique that measures the position of two GNSS antennas relative to each other in real time. One GNSS receiver/ antenna is set up on a static point with fixed coordinates and is commonly known as the reference (base) station. The RTK base station transmits its corrections to the rover(s) in real time, and the rover uses both the rover and base observations to compute its position relative to the base. This type of surveying requires a reliable communications link between the base and the rover, as the rover needs continuous observations from the base. Real-time Positioning is the communication between the base and the rover via a radio link. GNSS signal blockage is a common problem when performing RTK/RTN surveys under tree canopy or built-up areas. It can weaken the satellite geometry, lengthen the time required for a solution to initialize, and cause erroneous positioning. Since all points determined by RTK are single vectors propagating from the base (physical or virtual) towards the rover, it is necessary to include some quality control procedures to check the reliability of the results (measurements to be made with the Total station). The degree of control depends on the importance of the investigated point. RTK GNSS technology is widely used in tree mapping. The advantages of RTK systems are their high degree of flexibility and real-time measurement capabilities (Shi et al. 2019). The highest accuracy is obtained using the static technique, but it takes longer and needs post-processing (Seedahmed 2017; Bramanto et al. 2019). The system known as Real-Time Kinematic, or RTK, is based on carrier-based ranging and provides positions (and ranges) that are orders of magnitude more precise than code-based positioning. The calculated ranges continue to account for errors resulting from satellite clock and ephemerides, tropospheric and ionospheric delays, and other sources (Gao et al. 2023).

RTK performance requires measurements from the base station to the rover station. The number of complete cycles has to be ascertained using a complex process called "ambiguity resolution" (Shin et al. 2024). Though it is a challenging process, high-accuracy GNSS receivers can instantly resolve the ambiguities. To determine their position, rovers use techniques like ambiguity resolution and differential correction (Niu et al. 2019). Like DGNSS, the rover's position accuracy depends on many parameters, including how far it is from the base station, or "baseline," and how precisely the differential corrections are made. The accuracy of corrections is determined by the known position of the base station and the quality of its satellite observations (Fan et al. 2019; Jia et al. 2023). Base stations, rover receivers, and antenna quality are essential to reduce environmental effects such as multipath and interference (Liu et al. 2023; Yang et al. 2022). The phrase "Global Navigation Satellite Systems," or "GNSS," refers to all satellite-based positioning systems, such as Galileo, GPS, GLONASS, and Beidou (Abdi et al. 2022; Breßler and Obst 2017; Cho et al. 2022; Hoffman-Wellenhof et al. 2007; Wolf and Ghilani 2008). Applicability and accuracy in the trees have been studied for the whole range of GNSS receivers (Gumilar et al. 2019; Kim et al. 2023; McGaughey et al. 2017; Pirti and Yucel 2022; Zimbelman and Keefe 2018).

The GNSS is a radio positioning system that operates in space and comprises one or more satellite constellations. Global, regional, and enhanced satellite navigation systems are all included in its wide definition. For users worldwide or locally, GNSS transmits Positioning, Navigation, and Timing (PNT) information signals from space. GNSS receivers on Earth receive information from satellites in orbit. The position is then determined using this information. A solution that enables real-time, accurate position down to the centimeter level is the combination of GNSS-

RTK (Hou et al. 2023; Öğütcü et al. 2023; Wolf and Ghilani 2008). It is often used when a precise setup is necessary (Fan et al. 2019). Since GPS is a kind of GNSS, RTK GPS technology is often used interchangeably with RTK-GNSS technology. RTK technology is anticipated to be useful for any application needing centimeter-level accuracy, such as precision agriculture, robotics and automation, mining, automotive, marine, rail, and aerospace (UAS) sectors (Catania et al. 2020; Silva et al. 2019). A technique used to increase GNSS positioning accuracy is called RTK (Real-time Kinematic Positioning). The duration of a signal's journey from the satellite to the receiver is measured by GNSS receivers. The sent signal slows down and perturbs as it passes through the atmosphere and ionosphere (Brach et al. 2019; Su et al. 2019). As a result, the location can only be calculated and established with 2-4 meters of poor precision using the GNSS receiver (Na'aim and Manaf 2024; Zimbelman and Keefe 2108). It is resolved using RTK. For applications requiring more precision, it may provide users with a centimeter accuracy of up to 2 cm (Hofmann-Wellenhof et al. 2007; Wolf and Ghilani 2008).

RTK GNSS technology is a powerful tool that can be used to achieve highly accurate positioning and navigation data. With its ability to provide real-time data, long battery life, robustness, and low cost, it is an ideal solution for many industries. This article investigates using GNSS technology, particularly the RTK method (repeatability), in a tree environment. Ten points were marked in the trees and two in the open sky region. The study aims to reduce integer ambiguity resolution time using RTK GNSS, examine RTK GNSS's repeatability/accuracy in forested areas, and determine the accuracy-repeatability of using RTK GNSS (GPS, GLONASS, Galileo, and BeiDou) satellites. In addition, the total station was used to measure the coordinates of twelve points. These obtained coordinates were accepted as accurate using this study's total station.

2. Materials and Methods

2.1. Description of the Study Area

Five tests were conducted in the Davutpaşa region (Yıldız Technical University, Davutpasa Campus) on 19 October 2023 in Istanbul, Turkey. To achieve this aim, two reference stations (P5 and P6) were marked in the study area (clear line-of-sight; refer to **Fig. 1**). Static GNSS surveys computed the coordinates of the two reference points. At least 1.5 hours of observation were conducted during the static surveys of P5 and P6 stations on 15 October 2023. Data processing and network adjustments were performed using the Topcon Magnet Tools v.8.0.0 Software. During the adjustment process, the PALA station's (ISKI-CORS) ITRF20 coordinates were fixed (**Fig. 1**). The coordinates and standard deviations of the two reference stations (P5 and P6) are shown in **Table 1**.

Two experiments assessed the RTK GNSS method's performance in unobstructed and obstructed (tree) environments. Two reference stations (P5 and P6) in the project area (the Davutpasa region of Istanbul, Turkey; see **Fig. 1**) were selected for this study. Ten degrees was the minimum elevation cut-off angle, while ten seconds was the sampling rate.

2.2. Total Station Surveys

A total station is an electronic/optical tool for surveying and building construction. It is an electronic transit theodolite with an onboard computer for data collection and triangulation computations. EDM is incorporated to measure slope distance, vertical and horizontal angles, and the distance from the instrument to a specific point. The operator may access the remote control of an instrument from a distance using robotic or motorized total stations. As the operator holds the retroreflector and operates the total station from the observed position, theoretically, this removes the necessity for a staff helper. However, an assistant surveyor is often required while measuring in crowded places like a public roadway or building site. In automated configurations referred to as "automated motorized total stations," these motorized total stations may also be used (Wolf and Ghilani 2008).

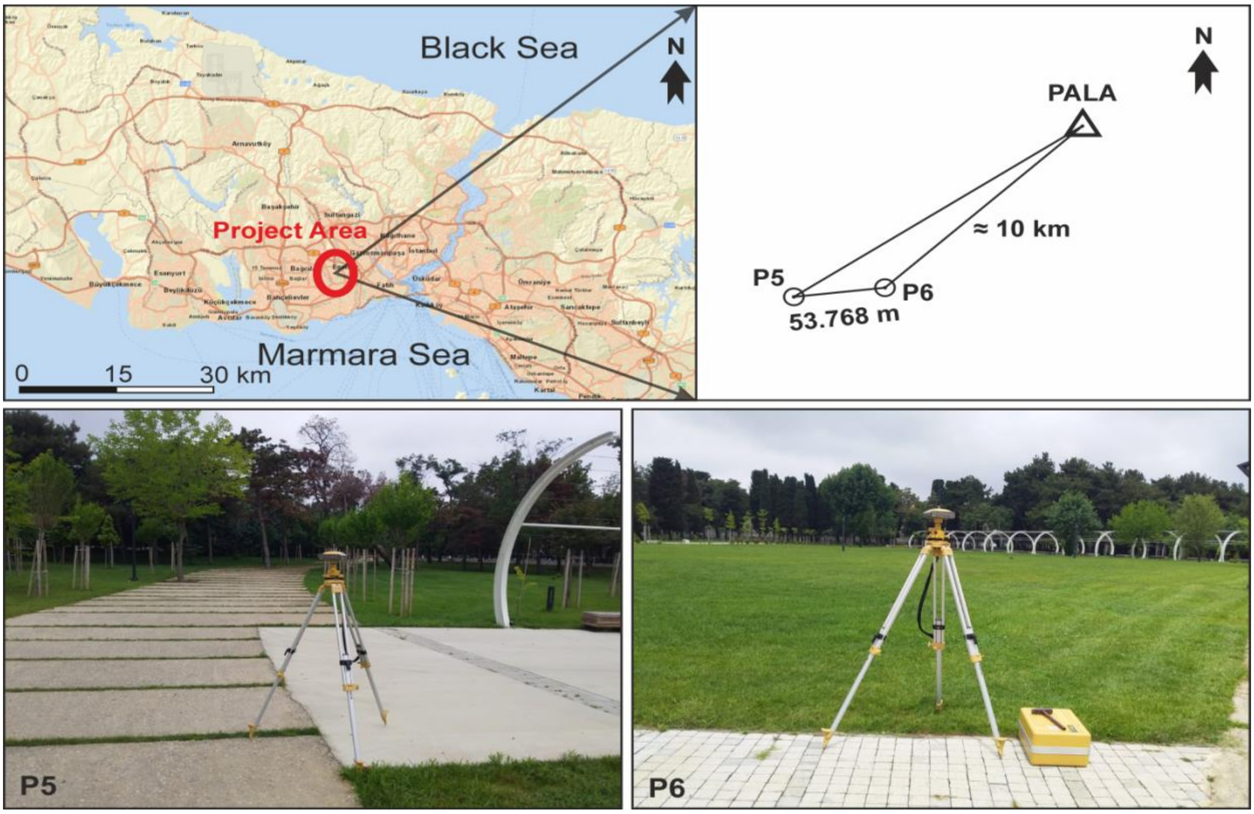


Fig. 1. Project region and GNSS network (upper) and reference points (P5 and P6) in the study area (lower).

Table 1. Standard deviation and coordinate values of the two reference points by using static surveys

Point	Grid Northing (m)	Grid Easting (m)	h (m)	Std N (mm)	Std E (mm)	Std h (mm)
PALA	4550678.133	412882.267	170.543	0	0	0
P5	4543860.778	406720.778	113.953	1	1	1
P6	4543807.128	406724.335	112.328	1	1	1

Total station surveying is known for its high precision and versatility, making it ideal for projects that require very accurate measurements. However, it has a limited range and is limited by visibility. On the other hand, GNSS surveying has a wide range and can be used in areas with limited visibility. However, it is known for its limited precision and depends on satellite signals. In conclusion, the choice between total station surveying and GNSS surveying will depend on the specific requirements of the project and the type of data needed. Both methods have advantages and disadvantages, and choosing the right method for your project is important. One advantage is that many total stations, such as the Geomax Zoom 30, are robotic. This means they can be operated at a distance, requiring only one surveyor in the field rather than the traditional two. For example, the robotic controller can stream the Total Station's view to a surveyor at a remote point, who can make measurements and change the target area without returning to the Total Station. Traditional ground surveys also determined the coordinates of points carried out with the total station equipment to serve as a reference (ground truth) against which to compare RTK GNSS positions.

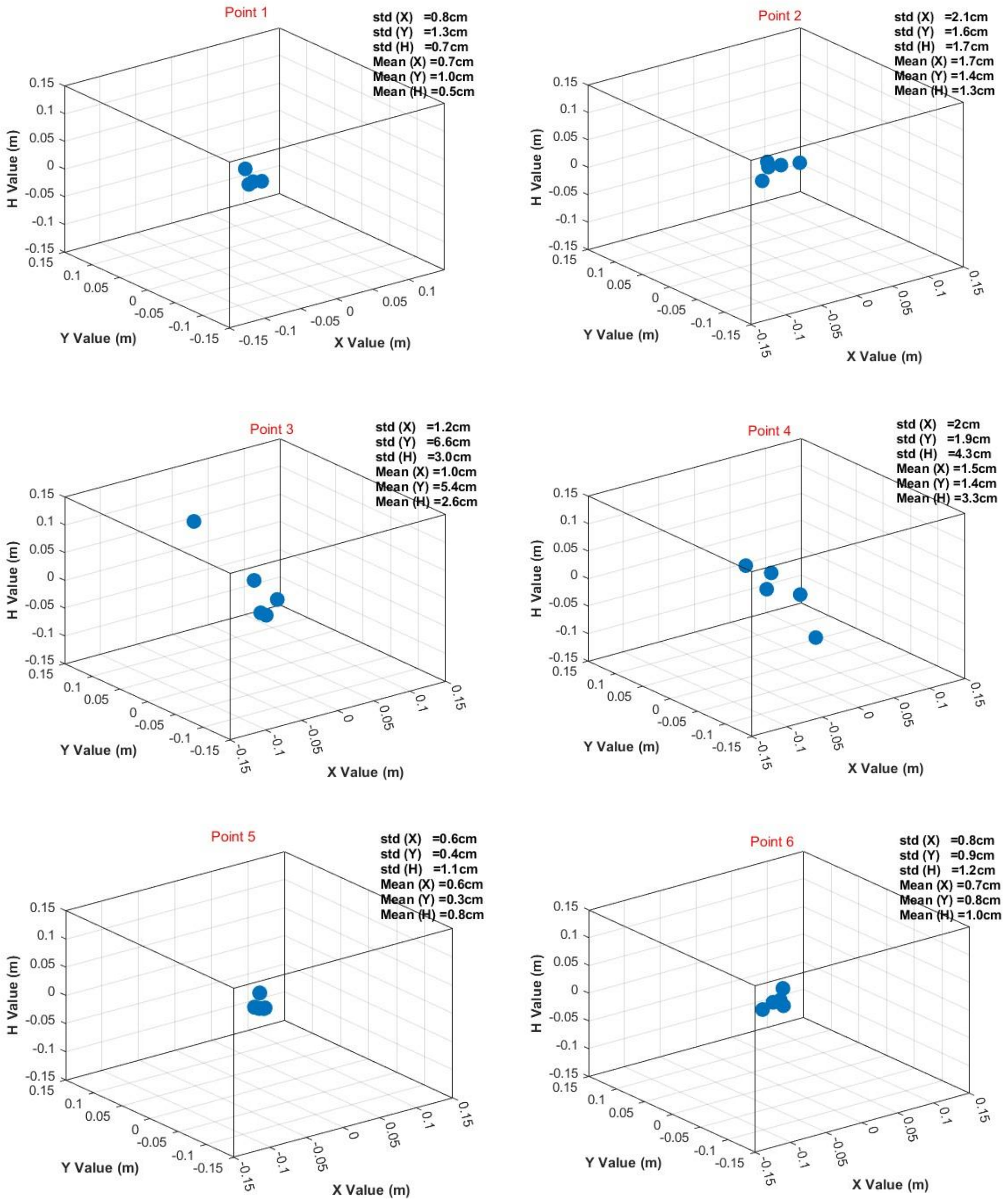
3. Results and Discussion

Using two reference stations (P5 and P6), the experiments try to determine the accuracy of RTK GNSS and verify the repeatability of the results under various satellite configurations. The coordinates of twelve points were compared to evaluate the RTK survey's accuracy and repeatability. The RTK GNSS survey was conducted in the following point order. As previously mentioned, a set of twelve points that were designated on the ground were coordinated by using two distinct survey techniques. The distribution of the tested sites is shown in **Fig. 2**.

Fig. 2. The plan of the 12 points in the project area.

3.1. RTK GNSS Survey Results and Comparisons

Five tests of RTK GNSS surveys were conducted, each occupying all test points and utilizing a reference point (P6) to assess the accuracy-repeatability of the RTK GNSS. To establish the independence of the results, the surveys were carried out by using various satellite configurations at different times of the day (P6) (19 October 2023, 9:00–10:00 h local time). The RTK GNSS reference station (P6) was about 55 m distant from the other reference station (P5), as shown in **Fig. 1** and **Fig. 2**. In open areas, there were 34 GNSS (GPS 8, GLONASS 6, Galileo 6, and Beidou 14) satellites visible, and the Position Dilution of Precision (PDOP) values were 1.068–1.433. However, on 19 October 2023, the Position Dilution of Precision values were between 1.092 and 2.516, with a satellite visibility of 9–17 GNSS satellites in the three regions. PDOP is the Position of DOP and can be considered 3D positioning or the mean of DOP, most often referred to in GNSS. For most purposes and GNSS receivers, PDOP values considered good for positioning are small, such as 3. Values greater than 7 are considered poor. The Position Dilution of Precision directly influences RTK GNSS positioning errors; 60 test point observations were collected for the 12 test points. Tree canopy density for points 1 and 12 is low, tree canopy density for points 2, 3, 4, 5, and 10 is moderate, and tree canopy density for points 6, 7, 8, 9, and 11 is high (**Fig. 3**).



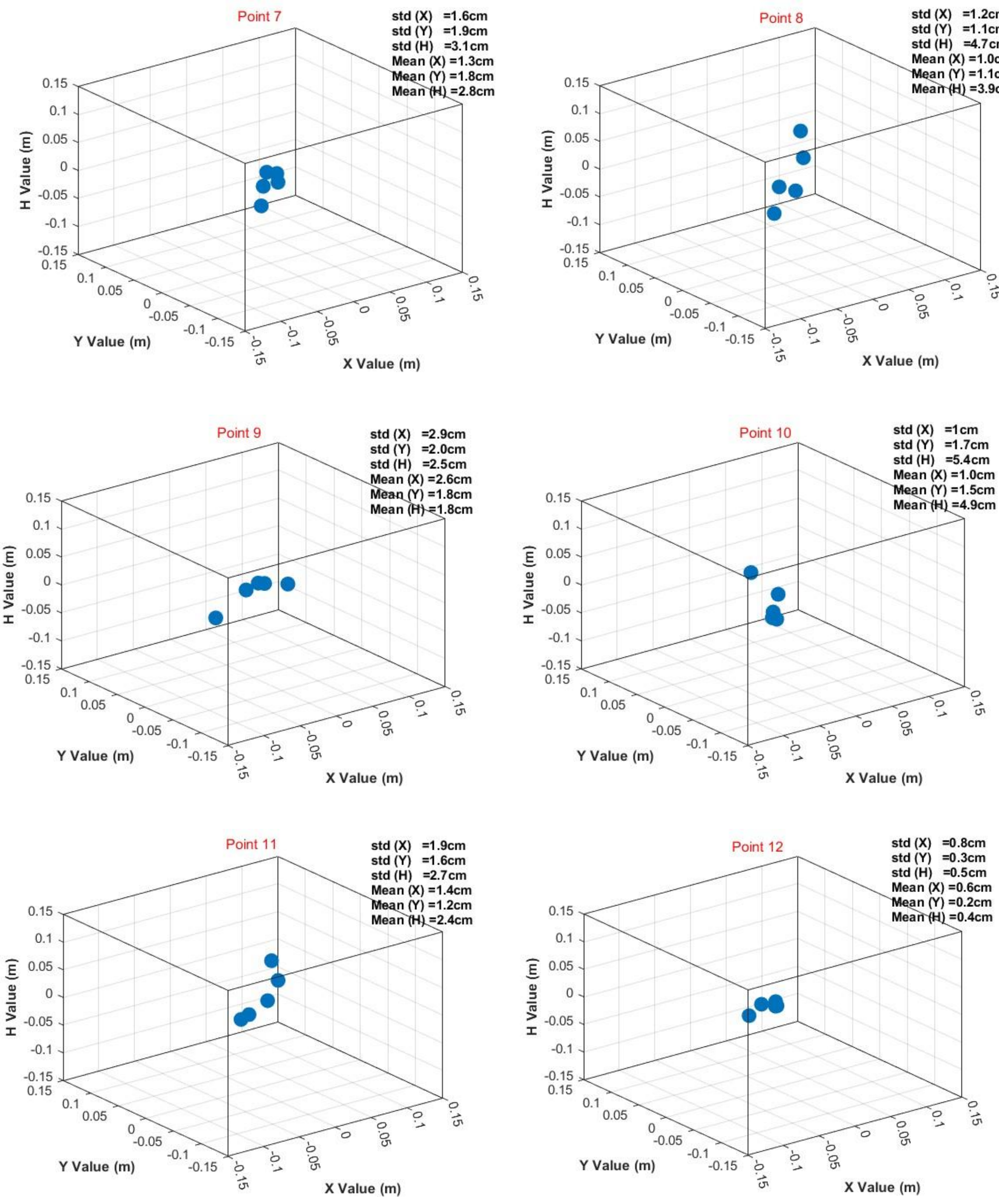


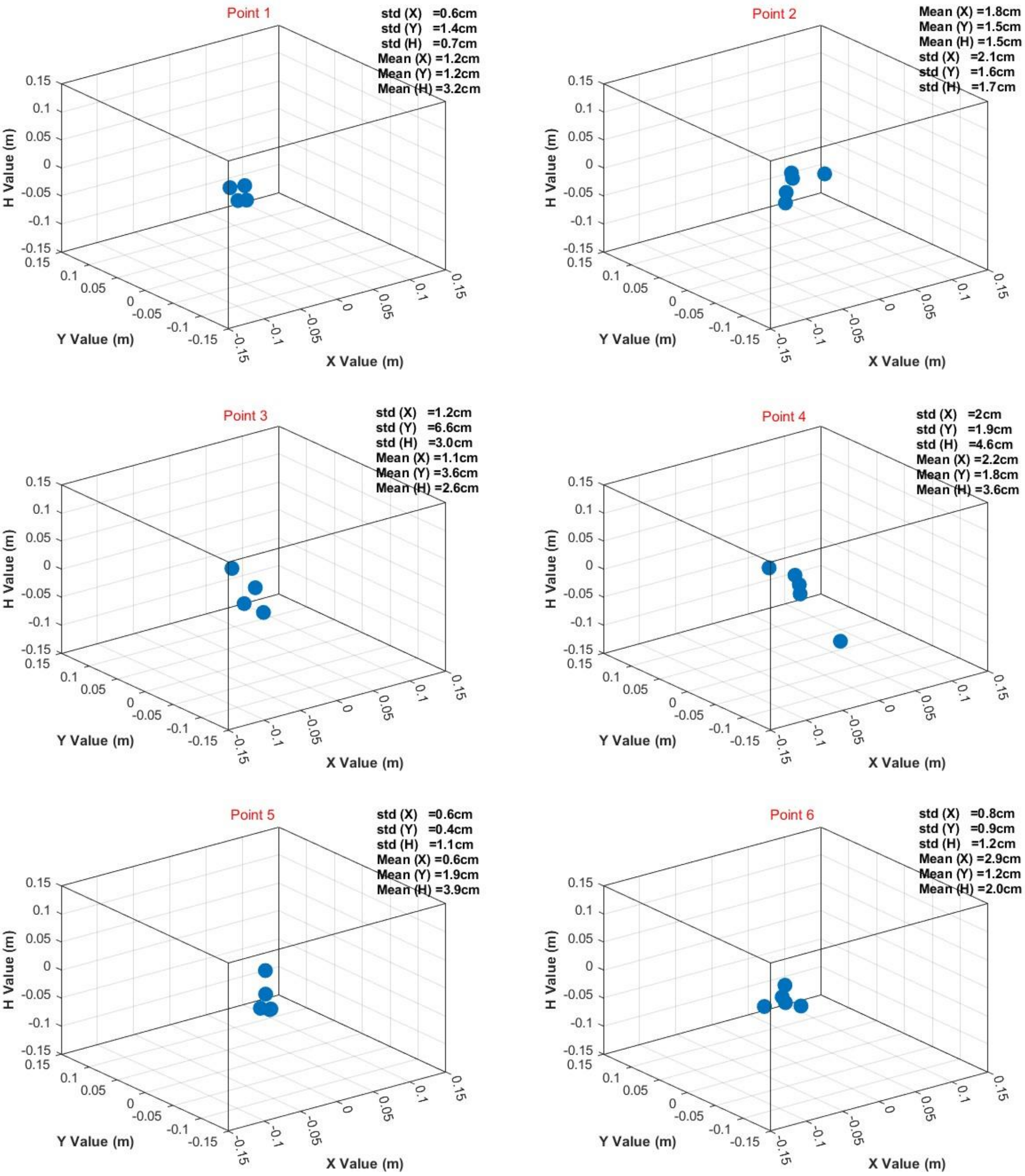
Fig. 3. Comparison of RTK GNSS coordinates of 12 points (five tests) using P6 as a reference station.

The mean of the coordinate values obtained from five RTK GNSS measurements was computed. To compute the internal accuracy of the RTK GNSS technique, the measurement values of each point were subtracted from the mean value calculated for five points in this study. The differences, together with their means and standard deviations, are shown for the twelve points in **Fig. 3**. The differences in horizontal coordinates ranged from a few millimeters to thirteen centimeters, according to the examination of the test for the RTK GNSS results. The height coordinate differences ranged from a few centimeters to almost 12.9 centimeters (**Fig. 3**). These obtained results are consistent with previous studies, showing that tree canopies can increase multipath errors by attenuating GNSS signals (Cho et al. 2024; Guo et al. 2021; Zimbelman and Keefe 2018). Due to the open area, the first and last points (Points 1 and 12) may be observed well by satellites (**Fig. 2**). Overall, RTK GNSS positioning performed well, according to the results of Points 1 and 12 in **Fig. 3**. The average discrepancies of the RTK system for these two points were, as seen in **Fig. 3**, less than 2.5 cm in the horizontal components and less than 1.3 cm in the vertical components. However, as shown in **Fig. 3**, the tree severely obstructed the sky at the ten points in the project area (especially for P3, P4, P8, P9, and P11, where the canopy is dense). The trees obscured some satellites, but the receiver could still follow them. As previously mentioned, at this time, 6–13 satellites were visible in the obstructed area (tree). Position Dilution of Precision value ranged from 1.103 to 2.516 for five experiments.

The results of ten stations further demonstrate that forested areas and tree canopies hampered RTK positioning because they regularly interfered with radio signals and obstructed satellite signals. Thus, the primary issue impeding the deployment of RTK GNSS in forested areas might be signal blockage/attenuation caused by tree canopies or forested environments, even in the presence of good satellite windows (Feng et al. 2021). RTK GNSS measurements of ten points were very lengthy on 19 October 2023 because of the aforementioned causes. For these ten points (five tests), the ambiguity resolution took around 50–60 minutes on 19 October 2023. The integer ambiguity was fixed within a few seconds at the points in the open area, while it took several minutes in the forested areas, depending on the obstacle condition. Between the RTK GNSS measurements, the horizontal coordinate differences of these ten stations were 0.1–12.9 cm (**Fig. 3**). There is no uncertainty in these ten points, with six to thirteen satellites. However, the forested region causes signal attenuation/blockage. The highest accuracy was obtained using the GNSS satellites as the primary observable and solving the integer phase ambiguity, i.e., a fixed solution (Cățeanu and Moroianu 2024). The largest variations have been found in the vertical coordinates of 10 stations. When comparing the five RTK sessions, the height component sometimes differed by up to 8.3 cm at the same points, although it was less constant than the horizontal components.

3.2. Comparison of RTK GPS Measurement Results with Total Station Measurement Results

A total station (Geomax Zoom 30) was used to compute the 12-point coordinates in the second part of the test. For the total station surveys, P5 and P6 reference stations were used as control points (**Fig. 1**). Using the Geomax Zoom 30 (angle accuracy: ±2", distance measurement accuracy: 3 mm+2 ppm), horizontal directions, zenith angles, and slope distances were measured to compute the coordinates of the 12 points. The sight distances should be fewer than 300 meters to reduce the errors caused by refraction and curvature. However, the maximum distance in this study was less than 200 meters. Since the manufacturer's accuracy criterion relates to the mean of measurements made on two sides, the total station measurements were conducted in FL and FR. There were three sets of reflectors/tripods available. Three tripods were used for the reflector setups on the points. A reflector set on a tripod and optically piped over each point was used to examine it. The reflector heights above the points were subtracted to get the point heights. Reference stations P5 or P6 were used as observation points, depending on the visibility of the test points (12). The twelve stations were surveyed in around 60–70 minutes using P5 and P6 stations. The RTK GNSS survey's performance was tested using a total station survey. Depending on the needs of the project, the station, and other variables, RTK GNSS may be employed. In open areas, the RTK technique seems to be the most appropriate. The coordinate discrepancies between the RTK and the total station survey are shown in **Fig. 4**.



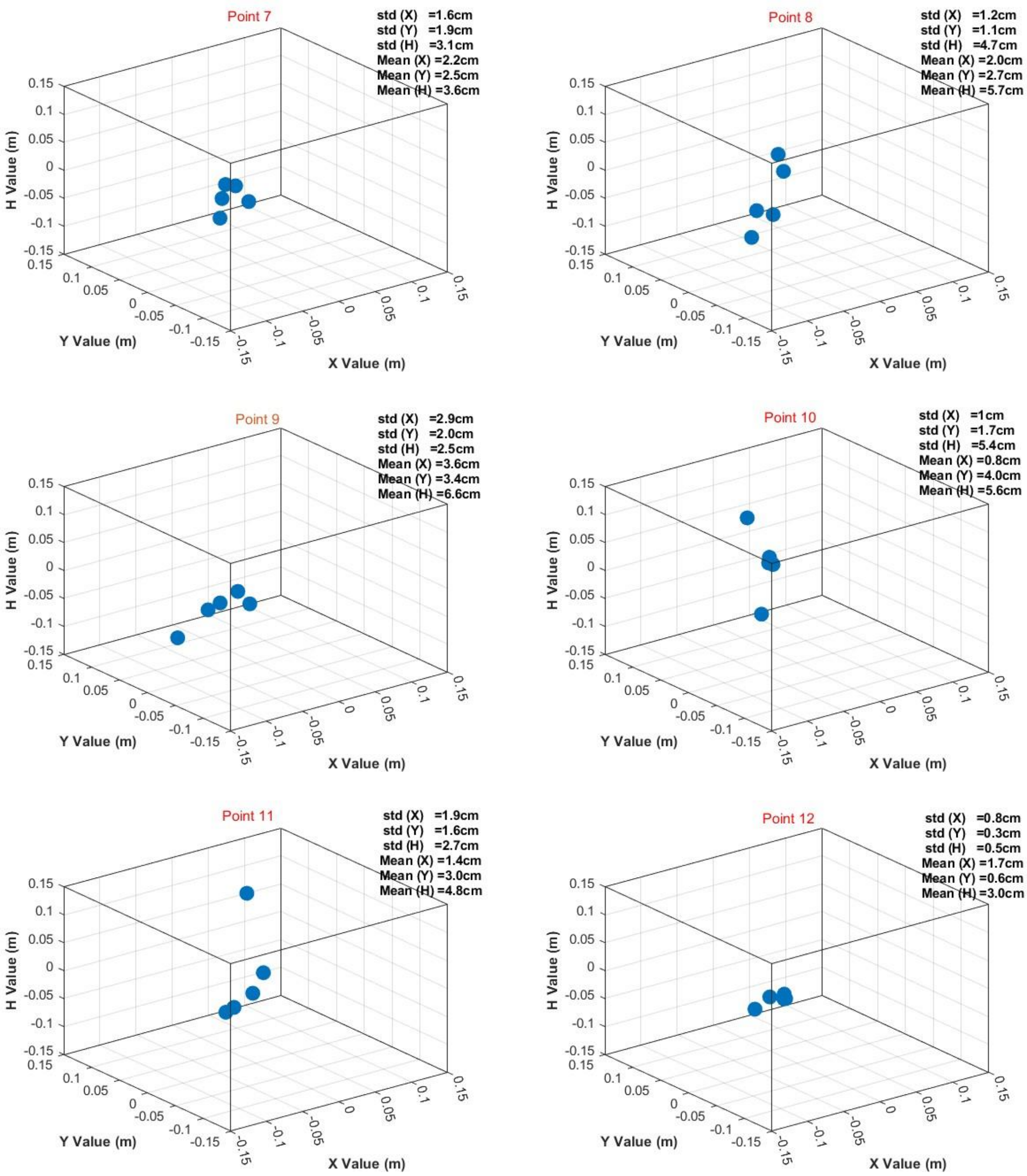


Fig. 4. Comparison of coordinates of 12 points in the project area between total station and RTK GNSS (19.10.2023) surveys.

In this test, the coordinates of a set of points (12 points) acquired by using P5 and P6 reference stations were compared with the coordinates established by the total station from P6/P5 to evaluate the accuracy and repeatability of the RTK GNSS survey (**Fig. 4**). When RTK GNSS survey results are compared with total station survey results (Coordinate values were calculated by averaging the three measurements), it becomes clear that there were more horizontal deviations and fewer height coordinates. The differences and their means and standard deviations are shown for 12 points in **Fig. 4**. On 19.10.2023, the horizontal coordinate differences had standard deviations of around 3–4 cm. On 19.10.2023, the height differences had a standard deviation of 4.3 cm. The means of the RTK GNSS (five tests) and total station surveys were less than 16 cm for the horizontal coordinates and less than 12 cm for the vertical coordinates, in **Fig. 4**. The findings of this study are consistent with the results of other research, which demonstrates that RTK GNSS can achieve centimeter-level accuracy in open areas. However, its performance is degraded in forested areas due to signal barriers (Abdi et al. 2022; Cho et al. 2024; Na'aim and Manaf 2024; Zimbelman and Keefe 2018). Once again, ten stations within the project area showed the greatest differences in horizontal and vertical coordinates (**Fig. 4)**. In the X–Y coordinates, the differences were around 0.2–15 cm, and in the H coordinates, they were roughly 0.7–12 cm. At challenging points, we will likely encounter notable variations in the horizontal and vertical coordinates. This paper's discussion of horizontal and vertical accuracy in open and blocked points is consistent with the results of the other authors (Gumilar et al. 2019; Kim et al. 2023; McGaughey et al. 2017; Zimbelman and Keefe 2018). Centimeter level of precision-accuracy is often achievable under a variety of operating situations. The results unambiguously demonstrate that the RTK GNSS methodology is a stable technology, except for the changing geometry of satellites inside the tree environment (ten points, see **Fig. 2**). The RTK GNSS technique is error-free, especially when horizontal precision at the centimeter level is needed. This study demonstrates that the RTK GNSS method may provide results comparable to those of terrestrial surveying.

4. Conclusions

This study aims to reduce integer ambiguity resolution time using RTK GNSS while achieving centimeter-level accuracy. The repeatability was tested for the RTK GNSS method, and results with centimeter accuracy were obtained. In this study, the discrepancies in horizontal and vertical coordinates between the RTK GNSS and total station measurements for the unobstructed environment were obtained as less than 1.7 cm and 3.9 cm, respectively. While the height values differed by approximately 12 cm, the horizontal coordinates varied up to 15 cm for ten points (tree environment). This study took approximately 40–50 minutes to measure 12 points using the RTK GNSS method with a single reference point (P6). The 12-point total station measurement took approximately 60–70 minutes to be completed in the field. In the experimental area, it took about 10 minutes for RTK GNSS to analyze and upload data. The transmission and processing of total station data took about 30 minutes to the office. A significant advantage of the RTK GNSS method over others is that the positions are determined directly in the field, which allows many independent ambiguity values and redundancies to be resolved in RTK GNSS positioning. As a result, the GNSS user community will benefit from stronger signals thanks to the developments in BeiDou, Galileo, the updated GLONASS, and the updated GPS. This can be greatly used for applications that need precise and quick positioning in the field. When GPS/GLONASS is combined with Galileo and/or BeiDou, all surveying operations are more reliable, accurate, robust, and economical. Since the RTK GNSS technique provides centimeter-accuracy results in a short time, it can be easily used in forest applications.

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Author Contributions

M.E.: Conceptualization, Methodology, Software, Validation; A.P.: Formal Analysis, Investigation, Resources, Data Curation, Writing – Original Draft Preparation, , Methodology Z.K.: Writing – Review and Editing, Visualization, Supervision, Project Administration, Funding Acquisition.

Conflict of Interest

The authors declare no conflict of interest.

Declaration of Generative AI and AI-Assisted Technologies in the Manuscript Preparation

Not applicable.

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