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Evaluation of Post-Processing Kinematic (PPK) Accuracy in Urban Area in Turgutlu, Manisa, Türkiye

Abstract: In recent years, global navigation satellite systems (GNSSs) have emerged as a prominent technology for geolocation applications and services in urban settings. Urban environments should also be classified under difficult situations. Densely populated metropolitan areas such as urban centers obstruct the receipt of GNSS signals; these obstacles often result in the congestion of line-of-sight (LOS) signals and give rise to the receipt of diffracted or reflected echoes (often known as the multipath phenomenon). PPK (post-processing kinematic) is a GNSS data-processing method that achieves high-accuracy positioning by correcting errors in raw positioning data. Post-processing is widely used in applications that require precise geospatial information, such as surveying, mapping, and UAV operations. This research aims to evaluate the accuracy of the PPK application method in urban areas. For this aim, surveys were carried out in Turgutlu's province of Manisa on July 15, 2020, in Türkiye. The analysis compared the PPK surveys' results with those that were obtained from static surveys. PPK is very effective in difficult situations, but we were likely to encounter certain accuracy problems. Nevertheless, it is worth noting that achieving urban surveys with an accuracy from ±1 cm to ±2 cm may not always be feasible due to the challenging circumstances that might result in more-significant inaccuracies from ±10 cm to ±100 cm for both the horizontal and vertical components.

Keywords: static, post-processing kinematic (PPK), urban areas, accuracy, precision

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1. Introduction

Greater positioning accuracy and precision require direct satellite-signal reception [1–3]. Urban areas provide a challenge due to the presence of various natural and man-made structures that impede the transmissions of line-of-sight (LOS) signals from satellites to end users; therefore, the deteriorating signals impact measurements and lead to positioning errors. The precision is further diminished since the signals' accessibility to the users may be indirect signals (reflections, diffractions, or a combination of both). When analyzing the tracked signals, it becomes clear that more-complex propagation modes must be considered, as this is not always possible in urban environments where the signals occasionally reach the users after being reflected, diffracted, or blocked. Ideally, the transmission of a signal from a satellite to a GNSS receiver should occur inside the direct line of sight. Around a receiver, there are high concentrations of structures that obstruct signals; this impact is more pronounced when receivers are maintained close to the ground. In general, the urban environment is made up of huge surfaces like floors, roofs, windows, and walls. These smooth surfaces cause transmitted signals to be reflected; this allows them to travel in numerous directions to a receiver. Similar to how building edges bend satellite signals, diffraction is a kind of propagation that prevents LOS signals from reaching the receiver. The capacity to predict satellite availability is a valuable tool for route planning – particularly, regarding the security of crucial operations. Low GNSS signal reception and high satellite availability may be used as criteria for choosing one route over another. The only GNSS systems that were completely functional at the time of this study (July 15, 2020) were GPS and GLONASS. Galileo, a European GNSS, was anticipated to be fully operational by 2019. Determining how these advancements will affect positioning and navigation in urban settings is crucial. Developing an enhanced civilian signal known as L2C is intended to give GPS civilian users more tolerance for interference and reduce their sensitivities to multipath. L5, a third frequency, will be added for applications that require high levels of safety. Due to these advances, around 80 satellites will be available for GNSS-based location and navigation by 2015. The availability of satellites will rise as the number of satellites increases; the geometry will also improve, but positioning issues in deep metropolitan canyons will still exist. However, conventional commercial GNSS receivers have significant difficulties in an urban context [4–6]. This is primarily because GNSS-location performance may be greatly compromised by factors that include multipath effect, interference, restricted satellite vision, and other undesirable impairments such as vegetation attenuation [3, 7]. Extensive research has contributed to enhancements of the accuracy and dependability of GNSS positioning in urban settings. This progress can be attributed to developing various techniques that are meant to mitigate the adverse effects of multipath interference and non-line-of-sight (NLOS) signals. These techniques encompass antenna design, receiver-based approaches, and post-receiver methods [2, 4, 5]; however, these methods still need constant improvement – particularly, in terms of their adaptability and durability in a variety of demanding situations [1, 8–12].

While real-time kinematic (RTK) setups benefit from higher equipment and technical logistics, post-processed kinematic (PPK) surveys have locations that are just as exact and do not need a known base station. Instead, PPK needs a computer that is linked to the internet in order to download signals, evaluate them, and then calculate and apply corrections. The PPK method is widely used in various applications and fields of geosciences due to its high reliability and accuracy [4, 5]. In recent years, it has often been applied to photogrammetric surveys in environments where real-time correction through internet coverage is unavailable, thus making this methodology a valuable solution [5, 6, 13–16]. PPK may be advantageous when challenging terrain or logistical constraints hinder the transportation of additional equipment to the field. Similarly, post-processing might prove to be beneficial where the immediate availability of corrected data is not crucial or access to a monument or benchmark is unattainable. Except for engineering tasks that need on-site estimations of distances or other geometries, most topographic and geologic surveys do not require immediate processing. PPK equipment consists of a base station and a rover – both equipped with antennas and receivers. The rover is equipped with a controller that facilitates input management and data collection. PPK surveys gather brief 5- to 30-second occupancy signals with the rover and continuous static signals at the base station. Following the completion of fieldwork, the collected data is then downloaded, securely backed up, and meticulously cross-referenced with any data that was obtained from other continuously operating stations. To account for its geographical location and, afterwards, implement the necessary corrections to the rover's data, it is vital to analyze the base station data in the RINEX format and make modifications by comparing it with data from other permanent stationary stations within the vicinity. A sound survey design and subsequent effective data collection depend on an initial site investigation. We are preparing and making adjustments to ensure line of sight, multi-pathing, and adequate sky coverage. One approach for mitigating these obstacles involves the strategically placement of base stations in locations that minimize interference within the study area, thus optimizing the unobstructed view of the sky. The presence of elevated or tall objects such as trees, buildings, canyon walls, and similar obstructions may significantly impede the quality of surveys due to their abilities to limit the visibility of the sky, interfere with signal transmissions, and introduce mistakes in the receptions of signals via multiple paths. While it is true that PPK surveys may provide accurate and precise data over baseline lengths of up to 10 km, it is important to note that this range is not absolute and may vary depending on the specific circumstances [1, 7–10, 13, 17–19]. It is optimal to locate a base station within a few kilometers of a region to be surveyed.

Numerous studies have been conducted to tackle the multipath and NLOS problems; for instance, multipath effects can be mitigated through specific antenna designs or the use of signal processing techniques. GNSS multipath and NLOS signals can be detected by using a variety of features. These methods are simple, since the measurements can be checked satellite-by-satellite. For instance, the signal-to-noise ratio (SNR) (which tends to be lower for measurements that are contaminated by multipath and NLOS signals) has been extensively used as a detection indicator. In urban environments, multipath effects are predominantly attributed to the reflections and diffusions of signals. 3D building models have, thus, been used as a complementary data source to enhance the performance of GNSS in such areas. Improving GNSS positioning in urban canyons requires lateral thinking.

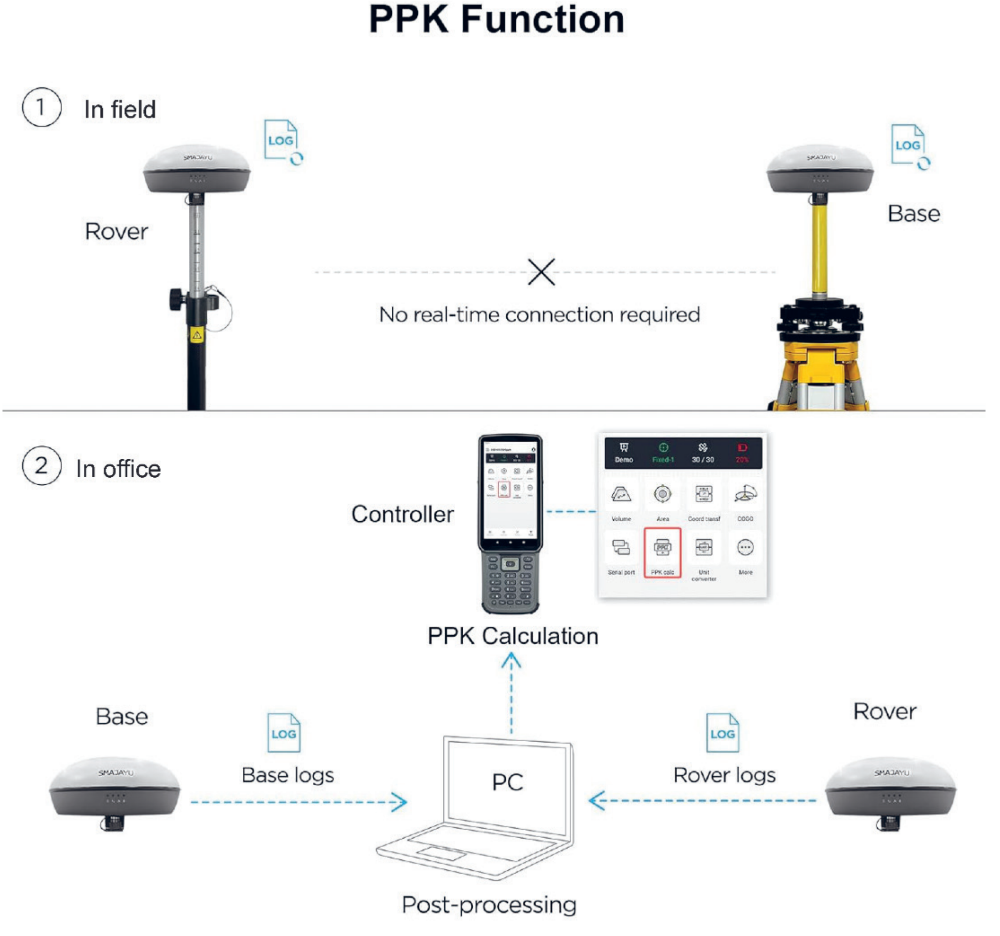

Fig. 1. Optimized PPK workflow solution for rapid, accurate, and cost-efficient aerial photogrammetry surveying, post-processing, geomodelling, and mapping operations: field time and costs were minimized due to streamlined workflow with less manpower and equipment while covering large areas quickly to deliver quality data with survey-grade "sub-centimeter"-level accuracy and resolution

If it is not possible to calculate a sufficiently accurate position solution that utilizes visible satellites, why not use nonvisible satellites as well? This is exactly what shadow matching does. If one knows where buildings are and how tall they are, one can deduce positional information from the knowledge that certain signals are being blocked; this requires a 3D model of a city's buildings. These are becoming more accurate and widely available, and they have already been used to predict GNSS signal availability and multipath interference. The principle of shadow matching is simple; due to obstructions by buildings in urban canyons, signals from many GNSS satellites will be receivable on some parts of a street but not on others. Where each direct signal is receivable can be predicted by using a 3D city model. By determining whether a direct signal is being received from a given satellite, the user can consequently localize their position to within one of two areas of the street [20–22].

PPK offers the major advantage of optimizing the data-processing activities during the post-processing, including forward and backward processing (Fig. 1). Other applications that need PPK are those where the data (image or LiDAR data, for example) is processed in a subsequent workflow (often on the cloud) and where the processing of the trajectory with GNSS post-processing software. In other words, it gives access to corrections, enhances a project's accuracy, and can even repair data losses or errors during a survey or installation after the mission. The use of GNSS applications in urban contexts (which are known for their challenging signal-reception circumstances) constitutes a significant aspect. This study aimed to evaluate PPK-survey accuracy in urban areas; for this aim, all of the surveys were carried out at the site of Turgutlu, Manisa, Türkiye, on July 15, 2020.

2. Materials and Methods

The study was conducted in Turgutlu, Manisa, Türkiye (as previously mentioned) (Fig. 2); a selected location was in the Selvilitepe District, which was characterized by medium-rise residential buildings that ranged from four to five stories along the street. In the Selvilitepe District, the three points (P1, P2, and P3) were marked near the structures. One of Station P3's defining characteristics is the area of interest in an urban setting with plenty of open sky.

Data distortion and signal losses from GNSS-receiver observations that are made in urban areas have an adverse effect on the precision and accuracy of these surveys. The three locations were chosen with the goal of creating the most diverse measurement circumstances possible; this indicated that the places were chosen for the survey in easy (clear LOS) and challenging (urban) regions. The three measurement locations were fastened with either asphalt nails or screws. Two places were chosen for this investigation in an urban area, while the third point was chosen in a location that was adjacent to an open region. The roadway where the two spots were selected was quite congested and had very little satellite visibility. In this research, no repeatability tests were employed in the preparation of the survey; the repeatability tests will be taken into consideration when designing surveys for further investigations. Three Satlab SL600 receivers were used for all of the static GNSS surveys; the coordinates of these three places were established by using a static GNSS survey. The surveys in this core network were conducted with a minimum of four hours of observation (5:30–9:30).

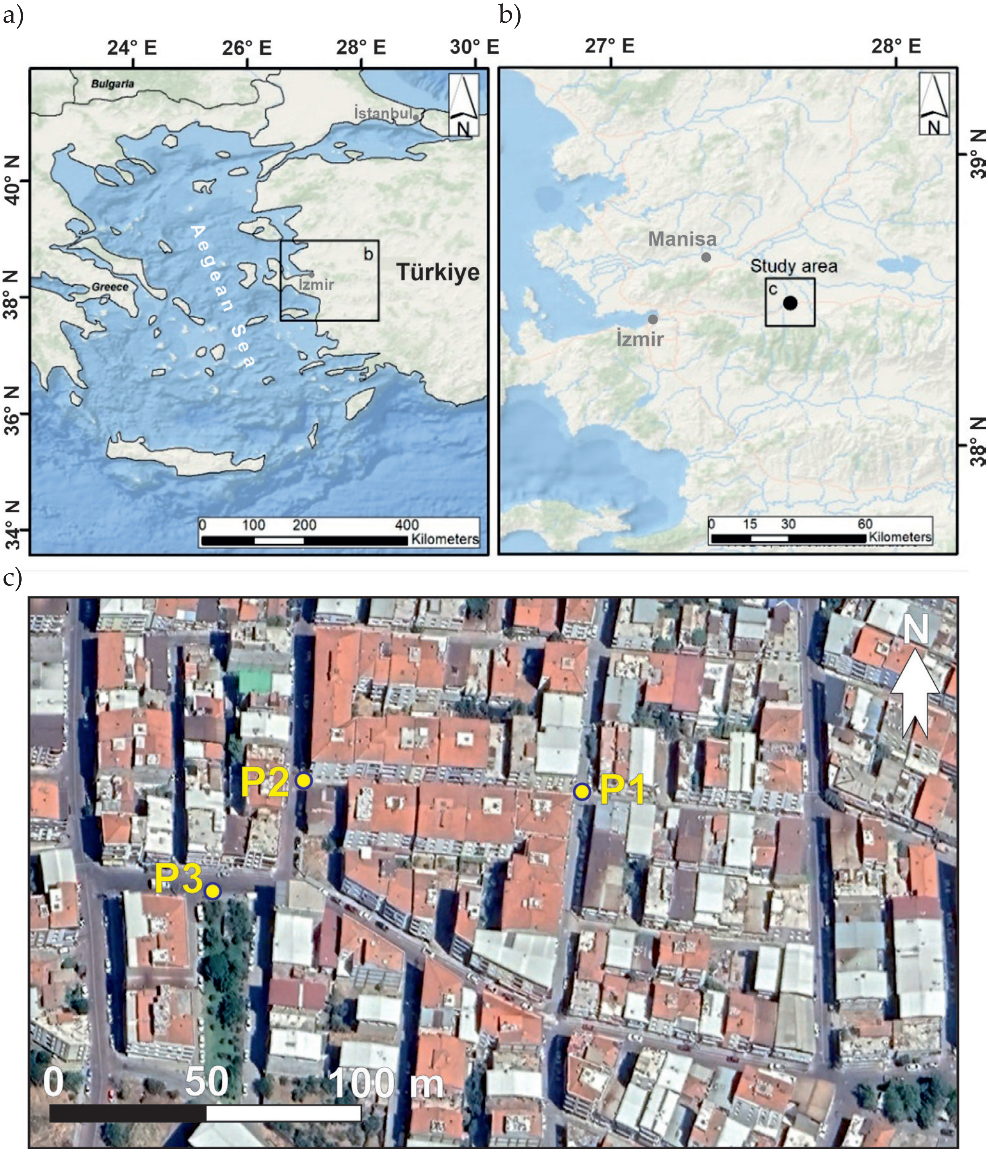

Fig. 2. Project area (a, b), and three points (P1, P2, and P3) at study site (c)

The data-collection frequency was set at a rate of 30 seconds, while the minimum angle for excluding low-elevation measurements was set at 10 degrees. The performance requirements of the Satlab SL600 receivers for horizontal positioning in kinematic mode were 8 mm (plus 1 ppm), while the requirements were 15 mm (plus 1 ppm) for the vertical positioning in kinematic mode. In static mode, the requirements for the horizontal positioning were 2.5 mm (plus 1 ppm), and for the vertical positioning, the requirements were 5 mm (plus 1 ppm). As previously stated, the three locations (P1, P2, and P3) were designated in the project area for this investigation. P3 was placed in an open location (as opposed to P1 and P2, which were both in urban settings) [7, 13, 17, 18].

MAGNET Tools Software streamlines the data-collection workflow for surveyors, contractors, engineers, and mapping professionals. The software allows one to post-process and adjusts field-survey data that is collected from the station and GNSS equipment. A key component of the MAGNET software workflow, MAGNET Tools provides customizable options such as the ability to visualize field work in Google Earth™ and to directly export data to 3D CAD software.

MAGNET Tools supports a large library of industry-file formats:

- process field measurements that are derived from both GNSS and optical total stations;
- visualize field work in Google Earth, 3D orbital view, CAD view, and more;
- automatically check errors for efficient processing of field measurements;
- generate and customize field-work reports;
- create and manage descriptive code libraries;
- export directly to Bentley iModel or Autodesk's AutoCAD Civil 3D software.

3. Results

3.1. Static Processing

The use of static data-collection methods yields outcomes that are characterized by high levels of accuracy and reliability; this is mostly attributable to the substantial volume of data that is acquired during each observation. One drawback that is associated with static data collection is its impact on productivity. Extensive observations that are conducted at each point result in a decrease in the quantity of points that can be gathered during a given day [1, 19]. The research used Topcon Magnet Tools software (7.2.0) for the data processing and network changes; the ITRF 2014 coordinates for the SALH point at the 2020.50 epoch were maintained as constant values during the adjustment process. This particular point (known as CORS-TR and used in the region of Manisa) was utilized for this purpose (as shown in Table 1). The CORS-TR station (SALH) was located about 37 km from the project site (as seen in Figure 2).

Table 1. Cartesian and geographic coordinates, heights, baselines and their standard deviations of three points in ITRF 2014 coordinates (2020.5 epoch)

Name	Northing *X* [m]	Easting *Y* [m]	***h*** [m]	Std(*X*) [m]	Std(*Y*) [m]	Std(*h*) [m]	Latitude [° ′ ″]	Longitude [° ′ ″]	Baseline	Distance [m]
SALH	4261179.749	598034.370	156.060	0.000	0.000	0.000	38° 28′ 59.1013081″	28° 7′ 24.7500581″	n/a	n/a
P1	4261496.676	561374.103	182.060	0.013	0.012	0.029	38° 29′ 3.6652885″	27° 42′ 12.7479274″	SALH-P1	36660.945681
P2	4261500.907	561283.764	178.208	0.017	0.019	0.042	38° 29′ 3.8175314″	27° 42′ 8.521857″	SALH-P2	36751.25757
P3	4261466.010	561253.769	173.114	0.007	0.007	0.017	38° 29′ 2.7223879″	27° 42′ 7.2734543″	SALH-P3	36781.476231

n/a – not applicable.

Poor GNSS positioning accuracy is common in urban canyons where tall buildings block the direct LOS signals from many (sometimes most) satellites. Without direct signals from four or more satellites, an accurate position solution cannot be determined. Sometimes, a degraded position solution can be obtained by using signals that can only be received by reflection off a building; these are known as NLOS signals. It has been widely acknowledged that the presence of buildings in the project area (particularly, at P1 and P2 points) significantly blocked the sky. This can be seen in Figures 2c, 3, and 4.

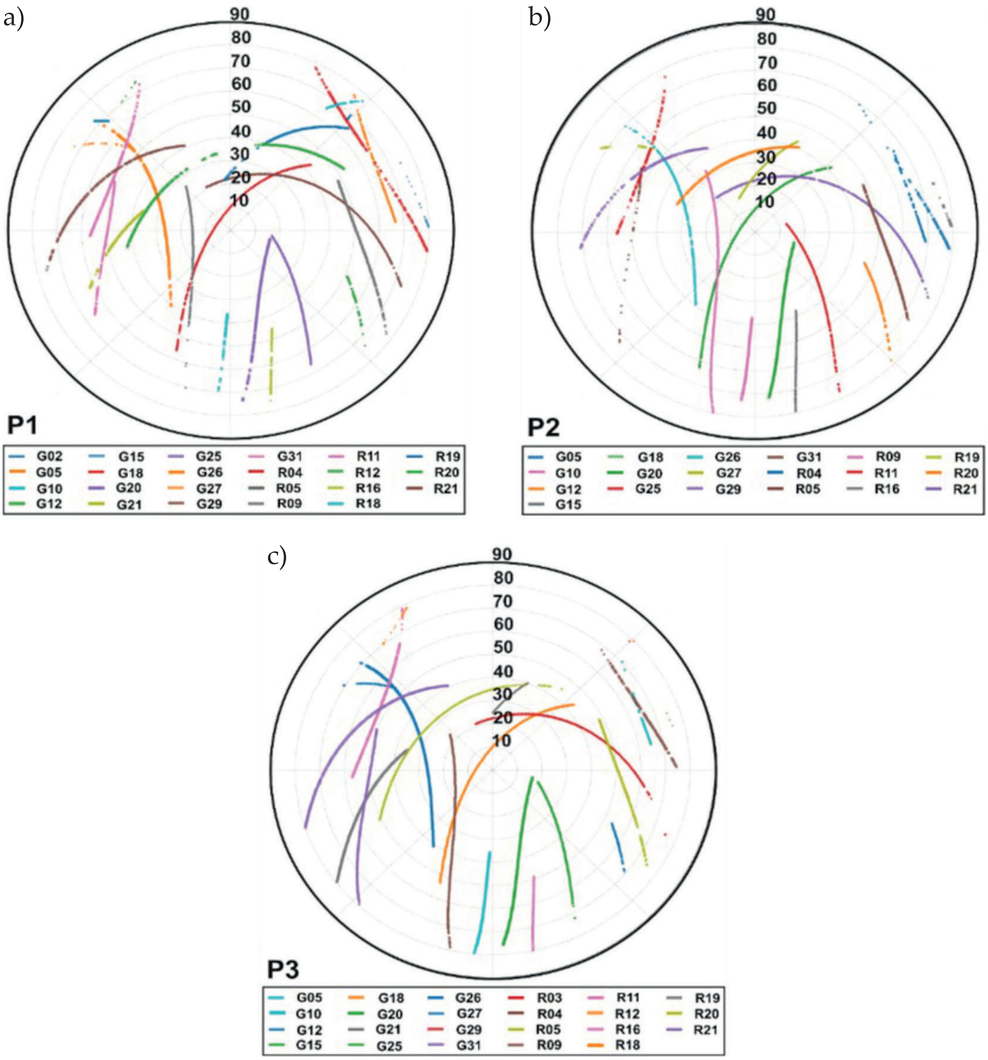

Fig. 3. Skyplots at P1 (a) and P2 (b) – strong obstructions by buildings; skyplot at P3 (c) in unobstructed area (between 5:30 and 9:30 on July 15, 2020)

Fig. 4. P1, P2, and P3 points in urban and unobstructed areas, respectively

The issue that is shown in the sky plot between the hours of 5:30 and 9:30 is representative of the whole day. During this period, several satellites were obstructed by structures; nonetheless, they were successfully monitored by the receivers (as seen in Figures 3a and 3b). However, it should be noted that the satellites that were seen at the P3 site did not exhibit shading like the other two places; this may have been attributed to the unobstructed line of sight (as shown in Figure 3c).

3.2. Post-Process Kinematic (PPK) Method

While kinematic data collection offers the benefit of increased productivity, it also presents several drawbacks. The accuracy that is achieved by static data collection is superior to other methods. The adverse effect of poor data quality on positioning outcomes is inherently more pronounced in kinematic positioning than in static processing. PPK is a GNSS data-processing method that achieves high-accuracy positioning by correcting errors in raw positioning data. Post-processing is widely used in applications that require precise geospatial information, such as surveying, mapping, and UAV operations [1, 7, 8, 13, 17–19].

Horizontal Accuracy

The investigation included a comparison between the static GNSS survey findings and the data that was obtained via the PPK-survey method. The coordinates of the three places (P1, P2, and P3) were compared by using the PPK (epoch-by-epoch) method; these results were then contrasted with the coordinates that were obtained from the static surveys. A static survey was conducted to monitor and assess the effectiveness of the PPK surveys. Figures 5–7 show the outcomes of the epoch-by-epoch kinematic processing (PPK) that was conducted on a session that lasted about four hours. The SALH-P1, SALH-P2, and SALH-P3 baselines were analyzed using the Topcon Magnet Tools software. Figures 5–7 depict the disparities that could be observed in the easting (*Y*) and northing (*X*) coordinate directions for the P1, P2, and P3 sites. The analysis of the outcomes that were obtained from both the PPK and the static surveys that were conducted at the P1 point revealed that the observed discrepancies in the horizontal coordinates were often ranging from ±10 cm to ±100 cm (except for the period between 6:30 and 7:30). This trend could be seen between 5:46:00 and 9:18:20. The resolution of uncertainty was not definitively determined within these time intervals. The presence of buildings induced signal dispersion, resulting in rather variable epoch findings. Specifically, the north and east components exhibited significant fluctuations, ranging from negative to positive values that ranged between 10 and 100 cm (as seen in Figure 5a). During the time interval between 6:30 and 7:30, the integer-ambiguity value sometimes became resolved. The disparities in the horizontal coordinate variations between the PPK surveys and the static surveys throughout this time period ranged to up to a maximum of about 10 cm (as seen in Figure 5b) [7, 13, 17, 18].

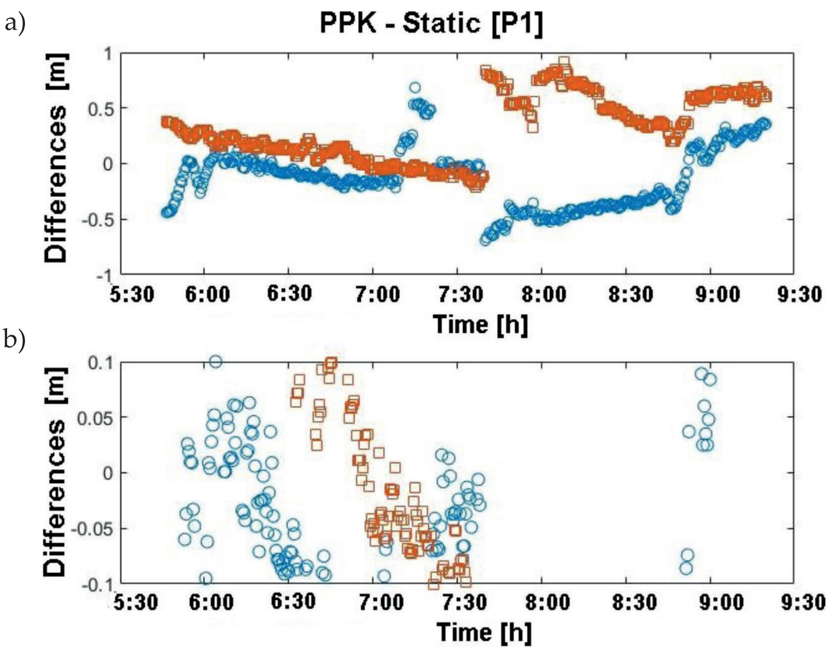

Fig. 5. Epoch-by-epoch horizontal coordinate differences of P1 point using PPK module (deviations from static results)

The analysis of the outcomes that were obtained from both the PPK and static surveys conducted on the P2 point revealed that there were consistent fluctuations that ranged at around 10–500 cm in the horizontal coordinates over the time period from 5:30 to 9:24. The resolution of uncertainty was not definitively determined within the time frame of 8:20–8:40. The presence of buildings led to significant signal dispersions, resulting in rather variable epoch findings. Specifically, the north and east components exhibited changing ranges from ±300 cm to ±500 cm (as seen in Figure 6a). The integer-ambiguity value was fixed for the time periods of 5:30–6:45, 7:45–8:00, and 9:00–9:05. The disparities in the horizontal coordinate variations between the PPK and static surveys over these time intervals ranged from ±2 to ±10 cm (as seen in Figure 6b) [7, 13, 17, 18].

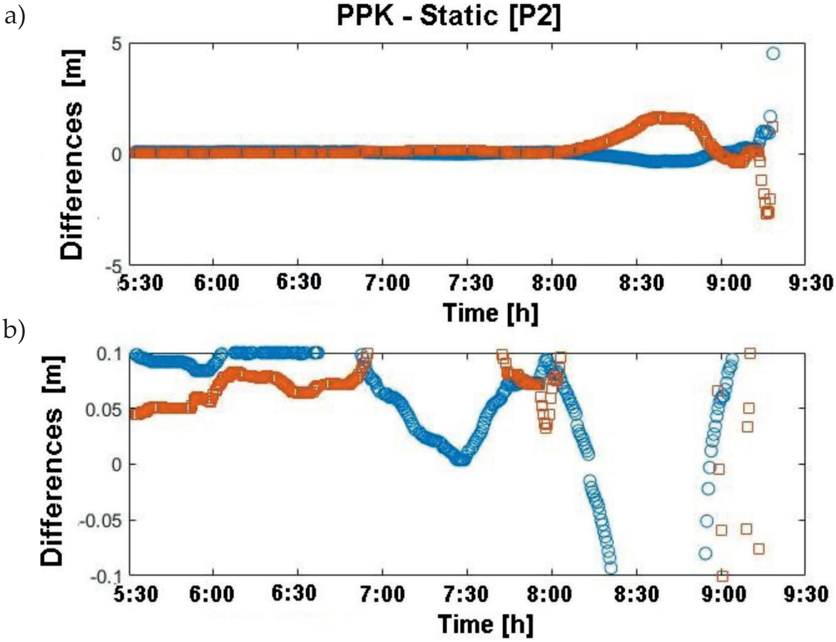

Fig. 6. Epoch-by-epoch horizontal coordinate differences of P2 point by using PPK module (deviations from static results)

The analysis of the collected data from both the PPK and static surveys that were conducted at the P3 point revealed that there were consistent fluctuations ranging from ±1 cm to ±50 cm in the horizontal coordinates over the time period of 5:46 to 9:28 (as seen in Figure 7a). During the time period of 5:46–9:28, the integer-ambiguity value remained constant for a significant portion of this duration for the P3 system. During this specific time period, there were variations in the horizontal coordinate disparities between the PPK and static surveys that ranged from ±1 to ±10 cm (as seen in Figure 7b).

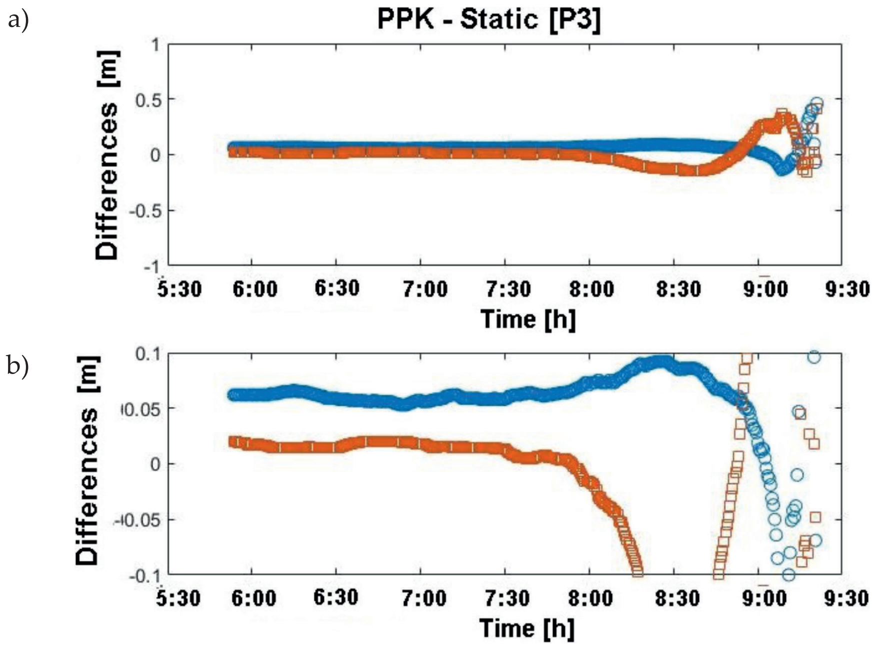

Fig. 7. Epoch-by-epoch horizontal coordinate differences of P3 point by using PPK module (deviations from static results)

Vertical Accuracy

The analysis of the data that was obtained from the PPK method as related to the static surveys that were conducted at the P1 point revealed that there were consistent fluctuations in the vertical coordinates that ranged from ±8 to ±272 cm over the time period between 5:46:00 and 9:18:20 (as seen in Figure 8a). It is worth noting that an exception to this trend occurred between 6:30 and 7:30. The resolution of the ambiguity has not been addressed yet. The integer-ambiguity value remained stable throughout the time interval between 6:30 and 7:30. The discrepancies in the vertical coordinate variations between the PPK and static surveys over this time period ranged from +20 cm to –20 cm (as seen in Figure 8b) [7, 13, 17, 18].

However, the urban region affected the geometries of the available GNSS signals as well as their numbers; those signals with lines of sight that traveled across the street were much more likely to be blocked by the buildings than those signals with lines of sight that traveled along the street. Since P2 point was surrounded by high-rise buildings (4–5 floors), the GNSS signals were exposed to more multipath effects than at the other two points (P1 and P3). The obtained coordinate differences of these points (shown in Figures 8–10) clearly proved this situation.

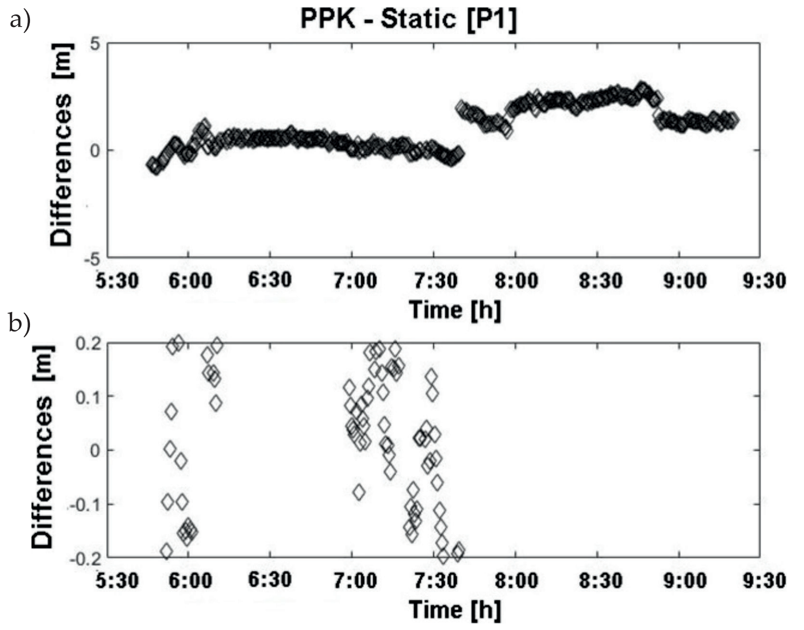

Fig. 8. Epoch-by-epoch vertical coordinate results of P1 point by using PPK module (deviations from static results)

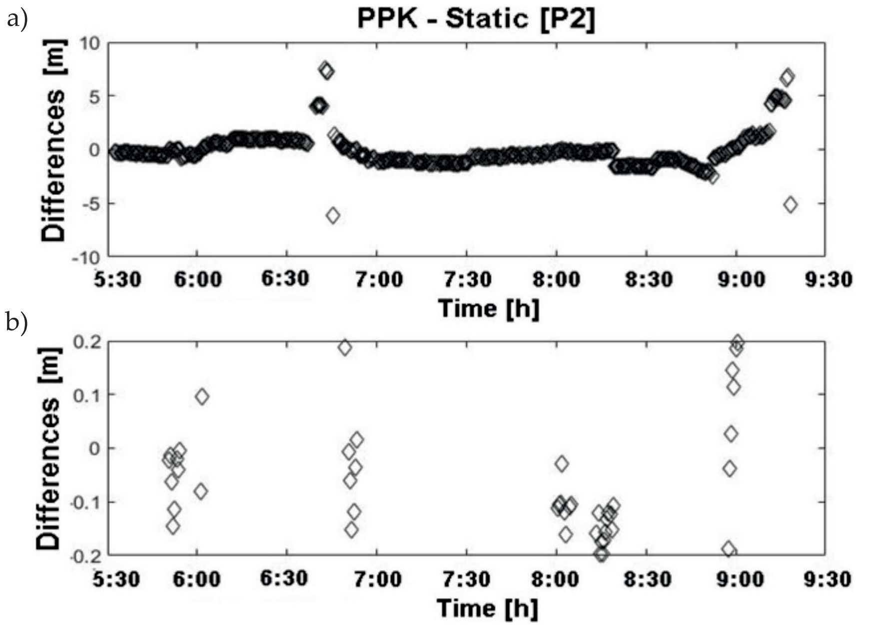

Fig. 9. Epoch-by-epoch vertical coordinate results of P2 point by using PPK module (deviations from static results)

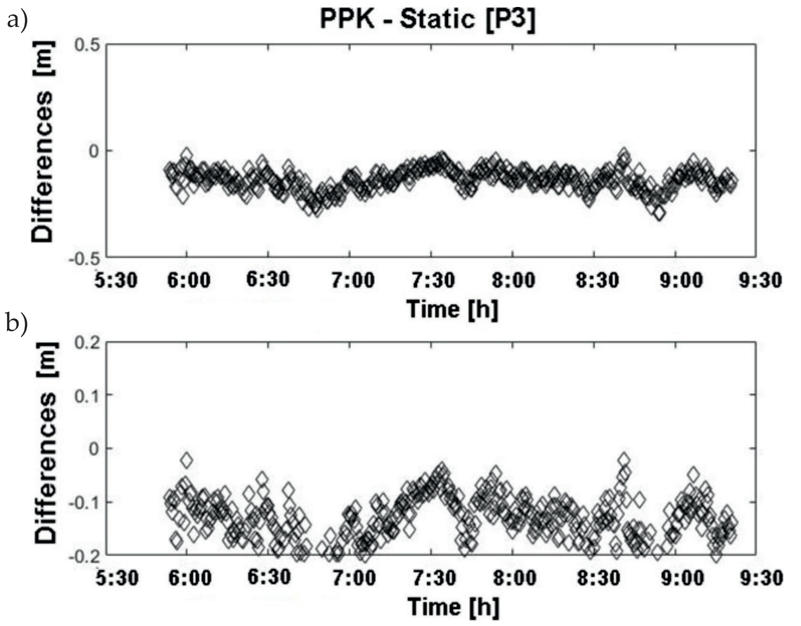

Fig. 10. Epoch-by-epoch vertical coordinate results of P3 point by using PPK module (deviations from static results)

3.3. Consistency of Static and PPK Results

If a survey's design allows for it, a surveyor must verify all measurements by ensuring that the eastings and northings of the lines are closed in all of the surrounding areas. Determining the misclose vector is achieved by calculating the magnitude of the vector (denoted as m_p) by using the following formula:

$$m_p = \sqrt{a^2 + b^2} \tag{1}$$

where a represents the misclose in the easting direction, and b represents the misclose in the northing direction.

In order to assess the compatibility between the PPK approach and the static technique, the three-dimensional (3D) misclosure vectors were calculated according to the references [7, 10, 11, 13, 17, 18]:

$$m_P^2 = (X_{PPK} - X_{Static})^2 + (Y_{PPK} - Y_{Static})^2 + (H_{PPK} - H_{Static})^2 \tag{2}$$

The misclosure vector (denoted as m_P) represents the discrepancy in the measurements (in meters) for all of the points. Y_{PPK} and X_{PPK} refer to the easting (Y) and northing (X) coordinates (in meters), respectively, of the three points that are obtained from the PPK survey coordinates. Similarly, Y_{Static} and X_{Static} represent the easting and northing coordinates of the three points (P1, P2, and P3), respectively, that are obtained from static surveys.

Figures 11 and 12 depict the horizontal misclose vectors that pertain to the aforementioned trio of sites. This research highlights the significance of two key factors in the PPK-measurement approach; namely, the survey duration, and the fixed value of the integer ambiguity. In addition to the proposed methods for addressing the partial and floating ambiguity issues at the P1, P2, and P3 sites (situated in urban and unimpeded areas – refer to Figure 12), the findings unequivocally demonstrated the reliability of the PPK methodology. Generally, an accuracy level from ±5 cm to ±20 cm can be achieved (as supported by several sources [1, 4, 5, 7, 10, 13, 17, 18]).

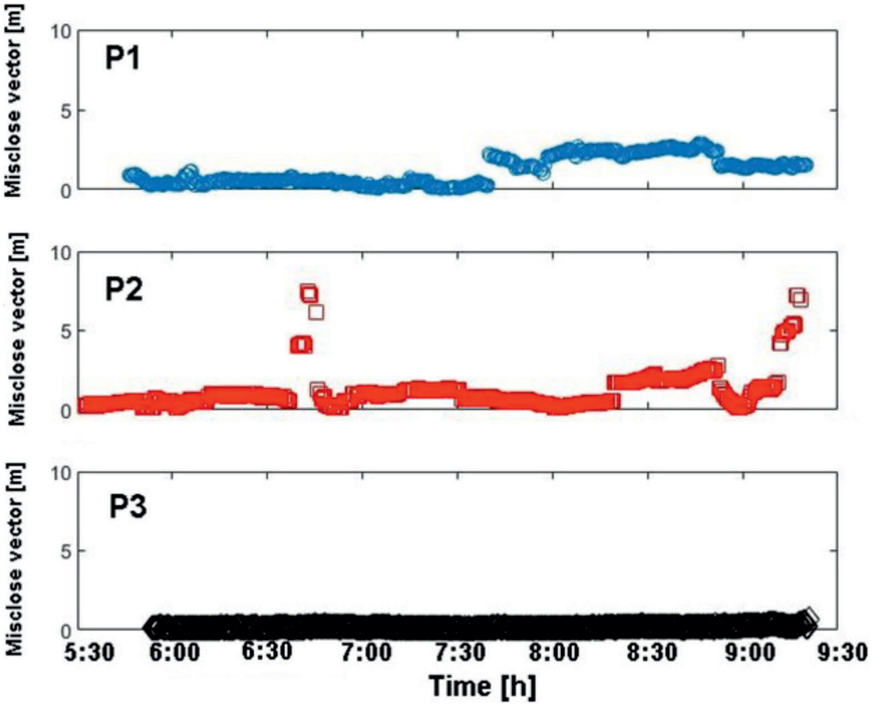

Fig. 11. 3D misclosure vectors for all three points in project area

This centimeter-level accuracy is adequate for specific applications, but it is not universally applicable. Knowledge of the pedestrian's side of the street is advantageous for visitor guidance and location-based advertising, while it is imperative for guiding the blind and visually impaired and for augmented-reality applications. Similarly, lane-level positioning is crucial for advanced intelligent-transportation systems that can direct individual vehicles in order to maximize traffic flow and prioritize emergency vehicles.

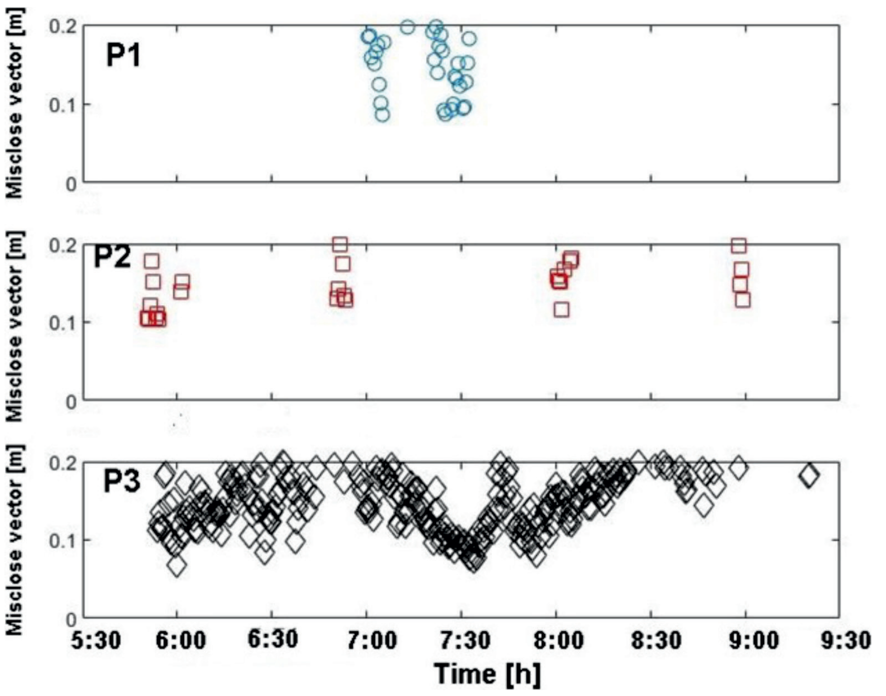

Fig. 12. 3D misclosure vectors for all three points in project area (below 0.2 m)

4. Discussion

For the highest-precision kinematic surveys, the RTK network, on-the-fly kinematic, and PPK methods can be used. PPK offers the major advantage of optimizing the data-processing activities during post-processing (including forward and backward processing). In contrast, real-time processing can suffer from interruptions or incompatibilities in the corrections and their transmission, thus leading to lower accuracy positioning. GNSS signals are weak, and there may be difficulties in receiving them indoors, under dense covers, or under conditions of high electronic noise in urban areas. GNSS signal blockage is a common problem when performing RTK/RTN surveys under tree canopies or built-up areas; this can weaken the satellite geometry, lengthen the time that is required for a solution to initialize, and cause erroneous positioning. Another challenge is multipath interference, where satellite signals bounce off surfaces like buildings or the ground; this causes the receiver to pick up multiple signals at slightly different times and results in inaccurate positioning. Stations P1 and P2 were surrounded by high-rise buildings (4–5 floors), so the GNSS signals were exposed to more multipath effects. Multipath effects and NLOS signals constitute two major obstacles to using GNSS in urban environments, with errors of up to hundreds of meters. Our results were consistent with those of many other researchers who made similar tests. The horizontal and vertical accuracy in the obstructed regions that was discussed in this study were in agreement with those of other authors [1, 4, 5, 6, 8, 21, 22].

5. Conclusions

Due to multipath and direct signal blockages, GNSS usage in urban environments is especially difficult for GNSS-signal reception; these factors substantially impact signal processing and further reduce location accuracy and availability. The study's findings indicated that, by using the CORS-VRS approach, the integer ambiguity cannot be resolved after around two hours of survey time in an urban region. Static and PPK methods were also used for this investigation. In this investigation, the collected outcomes were reported. It was determined that the findings that were produced in this investigation that used the PPK approach and the results that were acquired using the static method were consistent. Although the PPK approach is generally effective, we will sometimes run into accuracy issues in challenging scenarios. In this research, the two most crucial PPK-measuring-approach requirements were survey duration and fixed integer-ambiguity values. These findings from various ambiguity resolutions should have been applied to each location to increase the measurement reliability; this would have improved the validity and precision of the surveys. However, it seems that measurements in metropolitan areas with an accuracy of less than 1 cm cannot always be assured, since challenging circumstances may result in greater inaccuracies of between 10 and 100 cm for both horizontal and vertical components.

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