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Performance Evaluation of Single Frequency PPP using Smartphone's Raw GNSS Observations

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الملخص العربى :

توفر أرصاد نظام GNSS من الهواتف الذكية يسمح باستخدام مستشعرات منخفضة التكلفة لتحديد المواقع بدقة عالية. في هذا البحث، تم اختبار دقة تحديد المواقع باستخدام GNSS PPP للهاتف الذكى Xiaomi mi 8 حيث تم جمع ارصاد GNSS عبر تجربتين: ثابتة و متحركة لكل من الهاتف الذكي وجهاز الاستقبال الجيوديسيCS15 GNSS و تم معالجتها بنظام Differential معا وتم معالجة أرصاد GNSS للهواتف الذكية بنظام PPP باستخدام برنامج RTKLIB مع تصحيحات محطات IGS الدولية الدقيقة ومقارنتها بتحديد موقع المستقبل الجيوديسي. أظهرت النتائج أن GNSS PPP احادى التردد للهاتف في التجربة الثابتة قد حقق دقة تحديد الموقع فى الاتجاة الافقي و الرأسى بقيمة 0.374 م، 0.792 م، عند استخدام اقمار GPS, و حقق دقة 0.238م،0.66م عند استخدام اقمارGPS/GLONASS بالتتابع بعد ثلاث ساعات من الرصد، ولكن في الوضع المتحرك حقق GNSS PPP احادى التردد للهاتف دقة تحديد الموقع RMSE بقيمة 2.15 م، 2.30 م، 4.78 م فى اتجاهات الشرق، الشمال و الارتفاع بالتتابع و ذلك بالمقارنة مع حل جهاز الاستقبال الجيوديسي متعدد التردد بالحل اللحظى للارصاد RTK.

الكلمات المفتاحية: دقة تحديد الموقع PPP للهاتف الذكى، نظام الاقمار الصناعية GNSS, الحل اللحظى للارصاد RTK.

ABSTRACT :

The Availability of raw GNSS measurements from smartphones allows using low-cost sensors for high accurate positioning. In this research, the accuracy of the Xiaomi mi 8 smartphone's GNSS precise point positioning (PPP) is tested in both static and kinematic modes. Raw GNSS observations are collected over two experiments using both the smartphone, Leica GS15 GNSS geodetic-quality rover receivers and processed in a differential mode. The smart phone GNSS observation data is processed in PPP post processing mode using RTKLIB software with International GNSS Service (IGS) precise clock and orbital corrections and compared with the geodetic receiver positioning. The results showed that in static mode the smartphone's single frequency PPP achieved horizontal and vertical positioning accuracies 0.374 m, 0.792 m for GPS, and achieved 0.238 m, 0.660 m vertical for GPS /GLONASS respectively after three hours of data logging, however in kinematic mode the smartphone's single frequency PPP achieved positioning RMSE 2.15 m, 2.30 m and 4.78 m in easting, northing and height respectively in comparison with the geodetic receiver multi frequency GNSS RTK positioning.

KEY WORDS: Smartphone PPP, GNSS, RTK

1. INTRODUCTION

Precise Point Positioning (PPP) technique has been used extensively for Positioning of the Global Navigation Satellite System (GNSS). The benefits of PPP are its low cost, as well as no restriction of distance relative to the differential technique.

The single frequency receivers like smartphones have the benefit of the low cost compared to the high cost of the dual frequency receivers [1].

Google advertised the availability of raw GNSS measurements from Android 7 or later in May 2016. Therefore, developers can access carrier and code measurements and smartphone application navigation messages for the first time. Several benefits arise from the use of GNSS raw measurements on smartphones by enabling more advanced GNSS processing techniques that have so far been limited to more experienced GNSS receivers, their use can lead to increased GNSS performance [2].

Raw GNSS measurements are downloaded by several software applications that opened the way for developing precise positioning techniques using low-cost sensors. Single Frequency of GNSS smartphones were tested in static mode [3] and real-time kinematic network (NRTK) mode [4]. In May 2018 Xiaomi launched the world's first dual-frequency GNSS smartphone. It is equipped with a Broadcom BCM47755 chipset, it has a GNSS chip with the availability of recording code, carrier phase, Doppler and C/No measurements on GPS L1 & L5, GLONASS L1, Galileo E1 & E5a [5].

The Xiaomi mi 8 smartphone is designed with many sensors, such as accelerometers, gyroscopes, a compass, camera and barometer allowing it to generate a range of georeferenced data sets that are crucial for future smart cities [6], road surface monitoring [7], and low-cost mobile mapping systems [8]. Real time PPP can also be obtained by taking advantage of the precise real-time ephemeris service given, for example by the IGS stations [9]. The performance improvements due to this type of smartphone are important to assess, as it represents a major advance toward the evolution of smartphones in high-precision GNSS receivers. This progress will greatly reduce the number of devices needed to allow green communication solutions for sustainable smart cities [10].

Increased positioning accuracy can support many mass consumer applications, such as (i) mobile applications for increasing location-based ads, communication rates, and applications for augmented reality (AR). (ii) Mobile health security-related applications include medical and public health activities assisted by mobile devices, as well as enhancing the measurement of commitment, distance and speed of movement in sports such as soccer and athletics [2]. In this research, we will study and analyze static and kinematic experiments on GNSS raw observation obtained by the Xiaomi mi 8 smartphone and processed referenced to results of the dual frequency geodetic receivers. Positioning accuracy and root mean square error were used to evaluate the data quality and performance of smartphone's Raw GNSS data in single frequency PPP static and kinematic modes.

2. EXPERIMENTAL SETUP AND DATA COLLECTION

At the URL https://developer.android.com/guide, we can find all the devices provide raw measurements, information about the availability of constellations, the accessibility of phase measurements, and all devices need to run Nougat on Android or later. Battery consumption is the key problem to be addressed in order to obtain a reasonable efficiency from the smartphone's GNSS receiver [11].

There are Android applications capable of logging raw GNSS measurements such as GnssLogger [12], Geo++ RINEX Logger [13], and RINEX ON [14] were developed. The GnssLogger app was released by Google. This app allows the measurements listed in the GNSS Clock and GNSS Measurement classes to be documented in the online documentation of the Android location API [15]. Unfortunately, this app does not explicitly include observables of the pseudorange or carrier process and does not log data from ephemerides. Moreover, it could not allow raw data to be stored directly in the RINEX format, so it is not preferred to be used. The Geo++ RINEX Logger app was released in 2017 by the Geo++ company. Geo++ RINEX Logger records Android raw measurements in the RINEX file, allowing for further processing in different geodetic software. So far it is used in the data analysis of this research. It is available online at https://play.google.com/store/apps/details?id=de.geopp.rinexlogger at google store. It provides both navigation and observation files in format of RINEX 3.03 for GPS, Galileo and GLONASS satellite systems.

2.1 STATIC EXPERIMENTS:

The performance of Xiaomi mi 8 smartphone's single frequency precise point positioning (PPP) is tested in static mode, as we collected static raw observation data by this smartphone on January 30,2020 at the top of mining building at the Faculty of Engineering, Cairo University, as shown in Figure (1). First, a differential solution was made by the base and rover receivers of the Geomatics lab Leica Viva GS15 GNSS with a baseline around 4.5 m, as they were logged for two hours to provide the reference positioning solution for the smartphone as shown in Figure (2).

The base station is known as a control point at the Geomatics lab with known UTM coordinates. Second, the smartphone was centered at GNSS rover point as shown in Figure (3), Where the smartphone used Geo++ RINEX logger application to collect the code and phase raw data in two datasets: the first dataset collection observed for one-hour; and the second observed for three-hours. The results of the analysis of the collected data are shown in section 4.1.

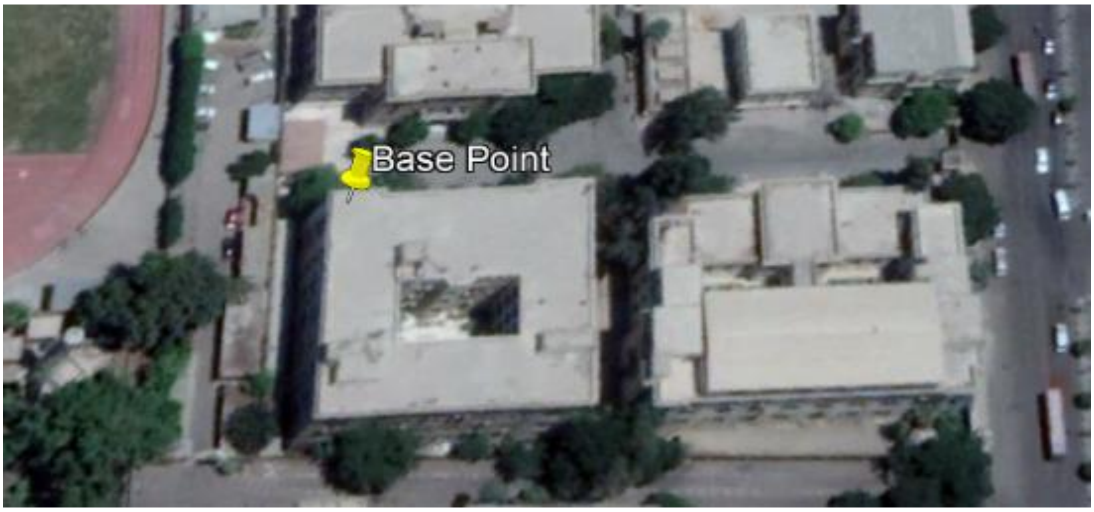


Figure 1. Location of Mining Building and Base Point

Figure 2. Setup of GS15 GNSS Geodetic Receivers

e tested in single frequency PPP post-processing

Figure 3. Setup of GS15 GNSS Geodetic Base and Smartphone

RTKLIB is an open source software package for precise positioning with GNSS raw data. RTKLIB consists of a program library and several application programs utilizing the library; it supports various positioning techniques such as: DGNSS, Single point positioning, Static PPP, Kinematic PPP for both real time and post processing modes, it gives the possibility for centimeter level precision of positioning as in reference [16].

RTKLIB supports many GNSS observation formats such as RINEX files, it is capable of processing code and phase observation; it processes single or dual frequency for static or kinematic data. Table (1) summarizes the RTKLIB processing parameters with respect to the software reference system, estimated coordinate system, datum, satellites ephemerides, model of ionosphere and model of troposphere.

Table 1. Processing parameters of RTKLIB:

Item	**processing parameters**
Reference	the International Terrestrial Reference Frame
Coordinate system	Universal Transverse Mercator (UTM)
Coordinate Datum	World Geodetic System (WGS84)
Satellites Ephemerides	Broadcast or Precise
Model of Ionosphere	Ionosphere free linear combination, SBAS, and IONEX TEC
Model of Troposphere	Saastamoinen model, estimate ZTD, and uses the Global Mapping Function

2.2 KINEMATIC EXPERIMENTS:

The performance of Xiaomi mi 8 smartphone's single frequency precise point positioning (PPP) technique based on GNSS raw observation is tested in kinematic mode. Kinematic trajectory was proved, where the two geodetic receivers of Leica GS15 GNSS were used to perform a Real Time Kinematic solution (RTK), and the base receiver occupied at the control point with known UTM coordinates and the smartphone was held on a truck 30 cm apart from the geodetic rover receiver as shown in Figure (4). The kinematic trajectory was done on Sunday 28 June,2020; and observed for about 30 minutes; and its length is approximately 9.2 km; and occurred in Madinaty city, in Cairo. The kinematic positioning mode was activated in the smartphone, where Geo++ RINEX logger application is used for logging code and phase GNSS raw data to be processed with geodetic receiver’s data. The reference positioning solution for the smartphone is the real-time kinematic (RTK) solution. The results of the Analysis of the collected data are shown in section 4.2.

Figure 4. Geodetic Base (the left) & Geodetic Rover and Smartphone (the right)

$$P_{Li}^{g} = \rho^{G} + c * (dt^{g} - dT^{g}) + d_{orb}^{g} + d_{trop}^{g} + d_{ion}^{g} + d_{multi/PLi}^{g} + \varepsilon_{PLi}^{g}$$
$$\emptyset_{Li}^{g} = \rho^{G} + c * (dt^{g} - dT^{g}) + d_{orb}^{g} + d_{trop}^{g} - d_{ion}^{g} + \lambda_{Li}^{g} + N_{Li}^{g} + d_{multi/\emptyset Li}^{g} + \varepsilon_{\emptyset Li}^{g}$$

$$P_{Gi}^{r} = \rho^{r} + c * (dt^{r} - dT^{r}) + d_{orb}^{r} + d_{trop}^{r} + d_{ion}^{r} + d_{multi/PLi}^{r} + d_{PLi}^{r}$$
$$\emptyset_{Gi}^{r} = \rho^{r} + c * (dt^{r} - dT^{r}) + d_{orb}^{r} + \mathrm{d}_{trop}^{r} - d_{ion}^{r} + \lambda_{Li}^{r} + N_{Li}^{r} + d_{multi/\emptyset Li}^{r} + d_{\emptyset Li}^{r}$$

rvation equations for GPS/GLONASS satellite systems in PPP static and kinematic modes can be expressed by the equations as follows in equations (1-4) [17]:

3-MATHEMATICAL MODEL

where: the superscripts g refers to GPS satellites, r refers to GLONASS satellites, and the subscripts L refers to the GPS frequency, G refers to the GLONASS frequency.

Pi is the pseudorange in meters; $\emptyset i$ is the carrier phase in meters; ρ is the geometric range in meters; c is the light speed in m/sec; dt is the receiver clock error in sec; dT is the satellite clock error in sec; d_{orb} is the satellite orbit error in sec; d_{trop} is the troposphere delay in meters; d_{ion} is the ionosphere delay in meters; λ is the wavelength in m/cycle; N is the ambiguity number in cycles; $d_{multi/Pi}$ is the multipath effect of pseudorange in meters; $d_{multi/}\emptyset_{i}$ is the multipath effect of carrier phase in meters; Ɛ is the measurement noise in meters

4.1 STATIC EXPERIMENTS

4.1.1 GNSS Differential Solution

For the differential solution of the geodetic base and rover receivers, raw data epochs were observed each one second and continued for about two hours to get the rover reference solution for the smartphone. Data are processed by Leica Geo Office (LGO) software, using GPS/GLONASS/Beidou satellites, and L1, L2 frequencies, table (2) shows UTM coordinates of the base and rover points.

Table 2. UTM coordinates of geodetic base and rover.

Point	Easting (m)	Northing (m)	Height (m)
Geodetic Base	327350.446	3322869.781	52.279
Geodetic Rover	327351.189	3322865.329	52.263

Table 3. UTM coordinates of geodetic base and smartphone.

Point	Easting (m)	Northing (m)	Height (m)
mi8 smartphone (m)	327350.811	3322865.819	51.043
Positioning Error (m)	0.379	0.490	1.220

For the differential solution of the geodetic base and Xiaomi mi8 Smartphone, table (3) summaries the result in UTM coordinates, the static positioning accuracy of Xiaomi mi 8 Smartphone in differential technique was calculated with reference to the rover coordinates in table (2). Data are processed by LGO software, using GPS satellites, and L1 frequency, and no ambiguity fixation.

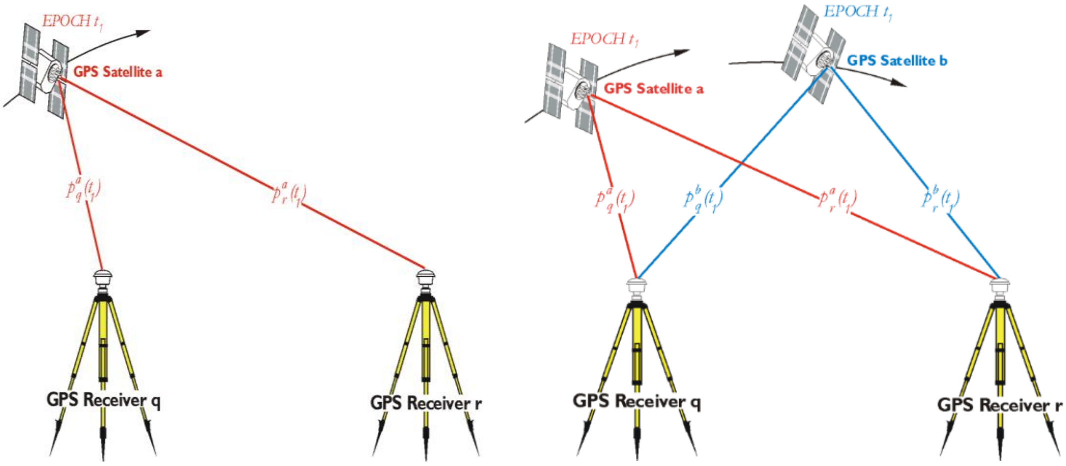


Figure 5. The between-receivers and the between-satellites differences

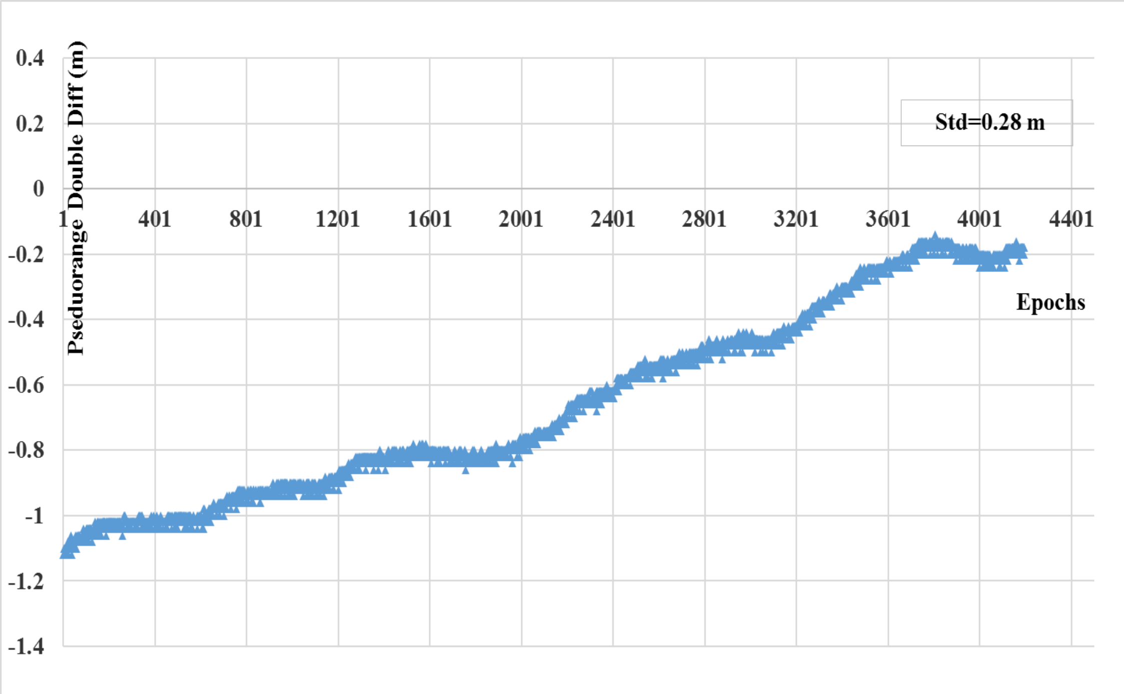


Figure 6. Pseudoranges Double Difference in case of Geodetic Base and Rover

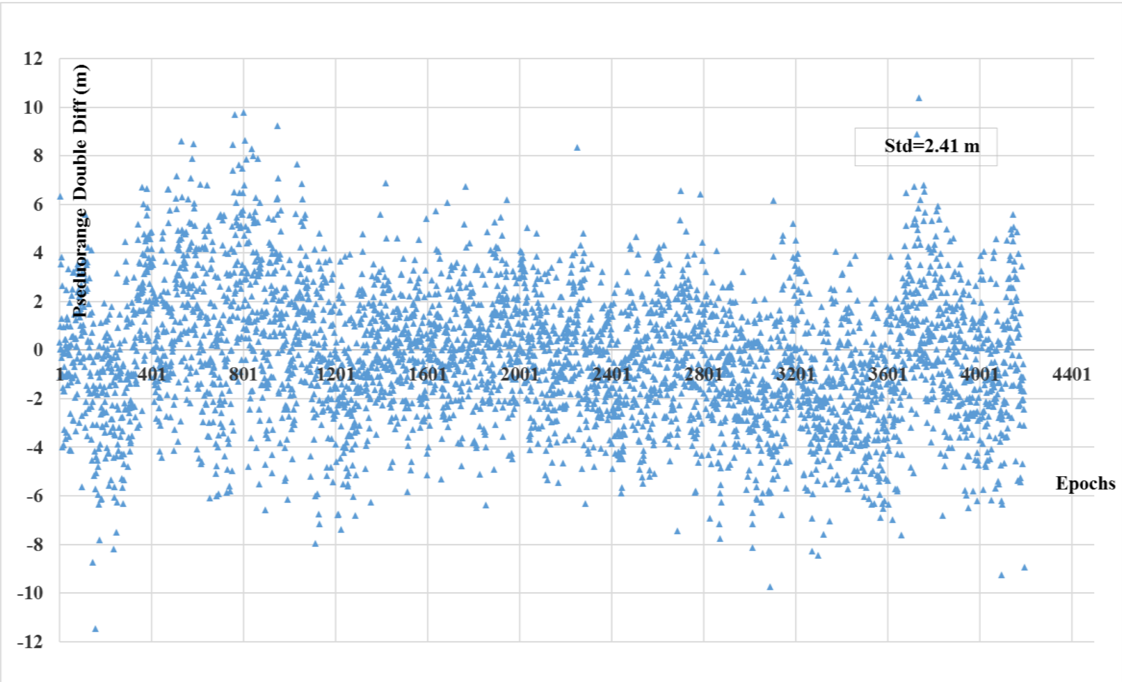


Figure 7. Pseudoranges Double Difference in case of Geodetic Base and Smartphone

The results show significantly much error in the differential solution, so an analysis for the measured Pseudoranges by geodetic base, rover and smartphone was done using the single difference and double difference for receiver and satellites, as shown in Figure (5). When performing the between-receivers difference and the between-satellites difference a double difference is created. This combination is virtually free of receiver clock errors, satellite clock errors and reduce the atmospheric effects in such a short base line but still there is a factor in the carrier beat phase observable that is not eliminated and the integer cycle ambiguity is still not removed.

MATLAB mathematical model is used to extract pseudorange observation for common two satellites from the geodetic base, rover and smartphone then the double difference is applied. The remaining errors are scattered with epochs in the case of geodetic base, rover and the case of geodetic base, smartphone as shown Figure (6), (7) respectively. Standard deviations are 0.28 m and 2.41 m for the two cases respectively, that indicate the low accuracy of the smartphone pseudorange observation due to the noise in the smartphone receiver compared to the geodetic receiver.

4.1.2 PPP Poisoning Performance

For the two collected smartphone datasets (1 hour & 3 hours), raw data RINEX files were processed using RTKLIB software with precise clock and orbital corrections downloaded from International GNSS Service (IGS), and solved in single frequency precise point positioning (PPP) technique using GPS and GPS/GLONASS satellite systems, the solution was in decimal latitude and longitude for each epoch (1-second), coordinates are transformed into UTM coordinates by Expert GPS Software. For the GPS satellites, Figures (8), and (9) are following to explain the positioning error in easting, northing and height sequentially in meters with reference to the geodetic rover coordinates, as in reference table (2). For more investigation and statistical analysis, another solution was proved for GPS/GLONASS satellites as shown in Figures (10), and (11).

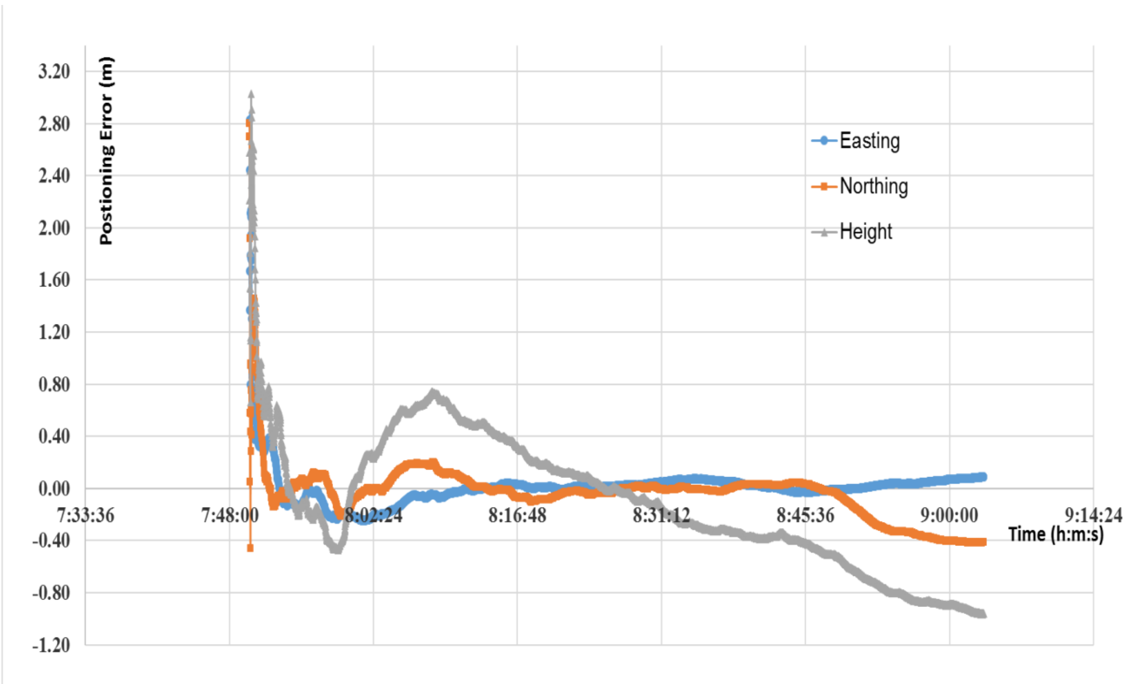


Figure 8. Positioning Errors for 1 hr. Dataset (GPS)

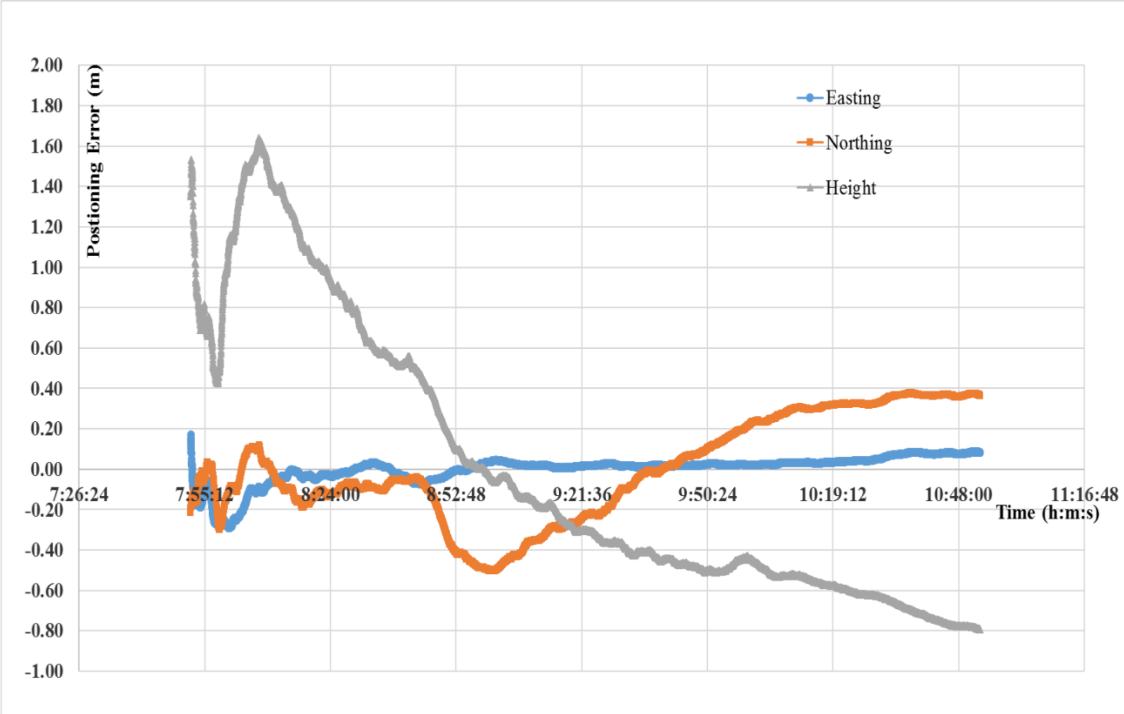


Figure 9. Positioning Errors for 3 hr. Dataset (GPS)

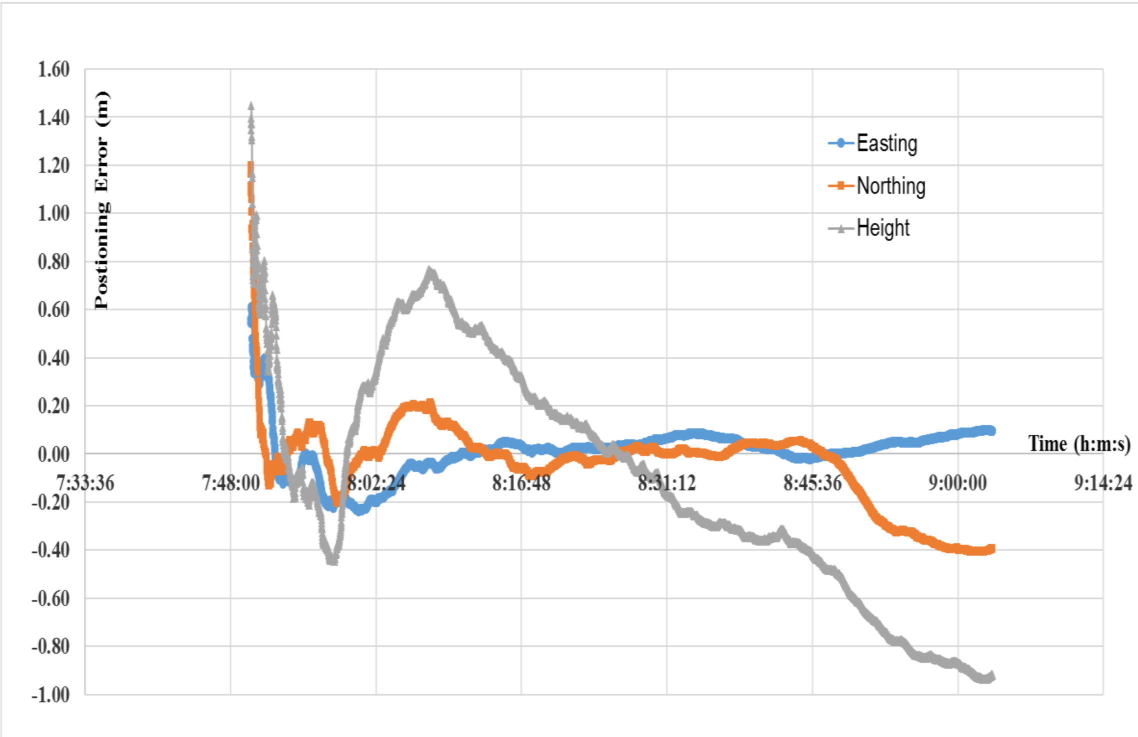


Figure 10. Positioning Errors for 1 hr. Dataset (GPS/GLONASS)

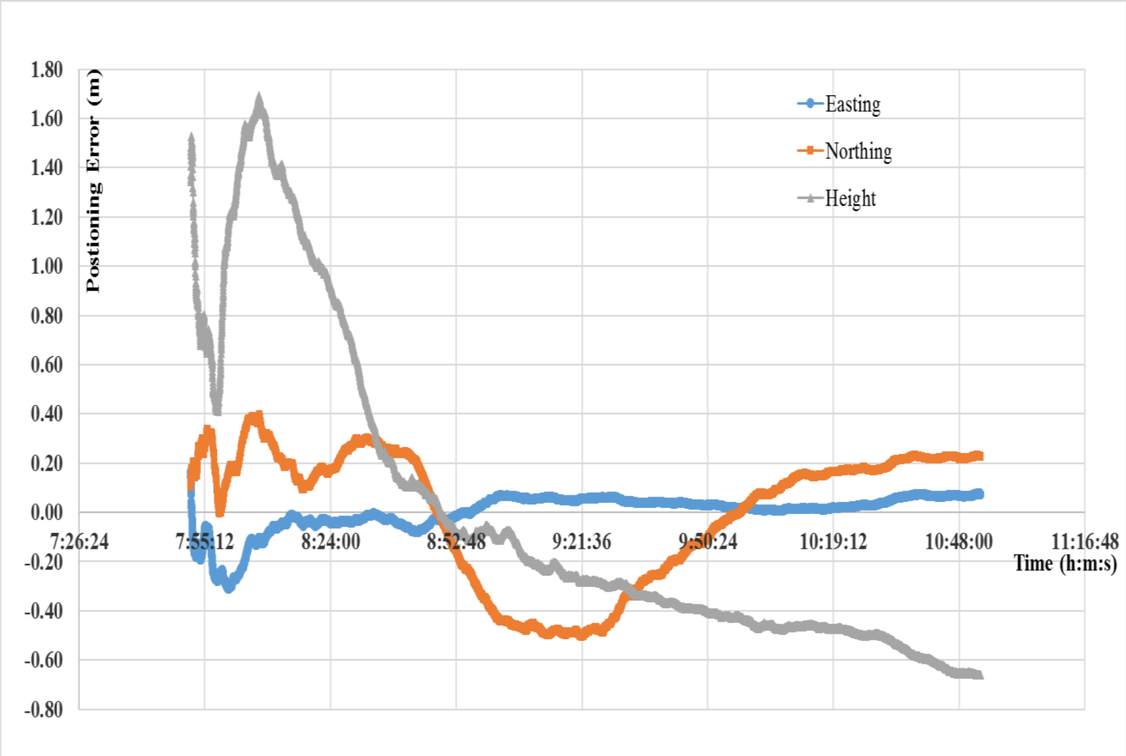


Figure 11. Positioning Errors for 3 hr. Dataset (GPS/GLONASS)

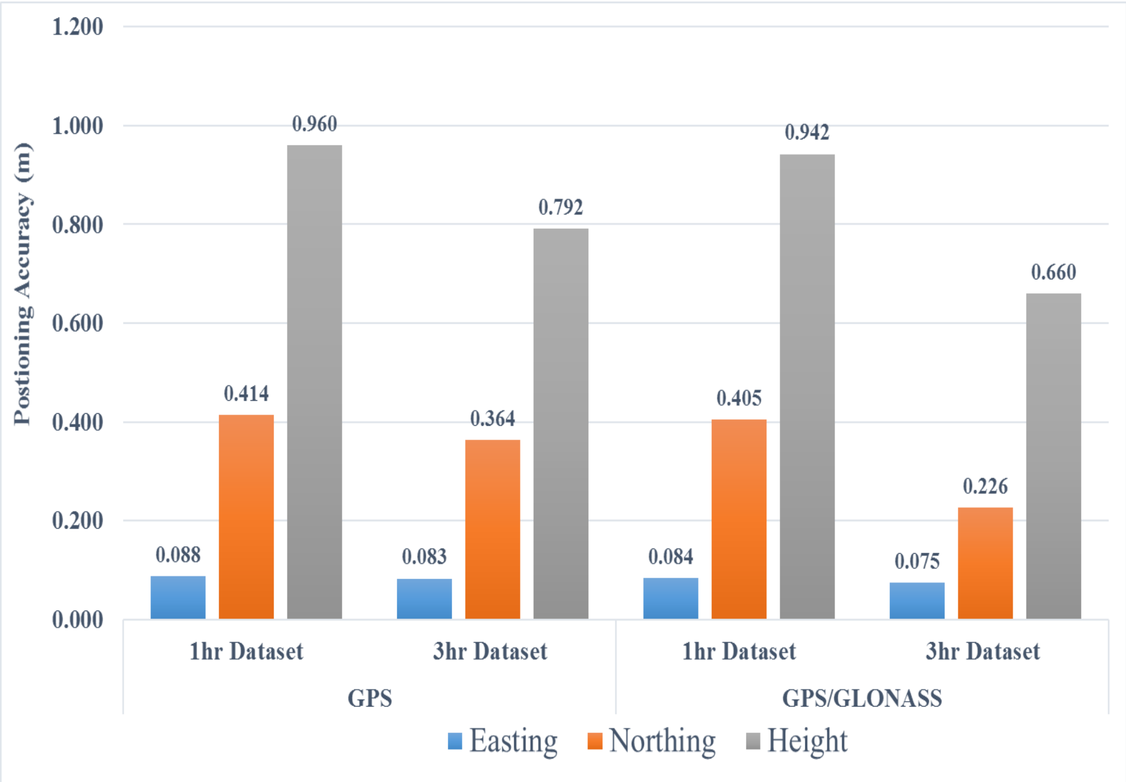


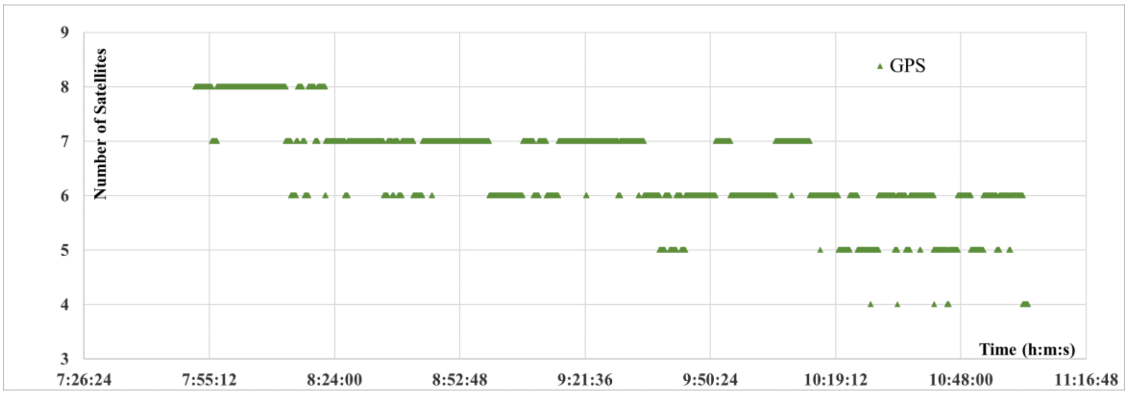
Figure 12. Positioning Accuracy for Two Datasets (GPS/GLONASS & GPS only)

Positioning accuracy of the resulting solution in case of GPS and GPS/GLONASS for the two time datasets is calculated and represented in figure (12). In case of GPS the positioning accuracy improved by approximately 6%, 12% and 23% in Easting, Northing and Height, respectively when increasing duration of smartphone data logging, and in case of GPS/GLONASS the positioning accuracy also significantly improved by approximately 11%, 47% and 30% in Easting, Northing and Height, respectively when increasing duration of smartphone data logging.

Table 4. Positioning accuracy in horizontal and vertical directions (GPS and GPS/GLONASS)

Positioning accuracy	GPS		GPS/GLONASS	
	1hr Dataset	3hr Dataset	1hr Dataset	3hr Dataset
horizontal (m)	0.424	0.374	0.413	0.238
vertical (m)	0.960	0.792	0.942	0.660

When using GLONASS satellites, the horizontal positioning accuracy significantly improved by about 3% and 36% in one-hour and three-hour datasets respectively; moreover, the vertical positioning accuracy improved by about 2% and 17% in one-hour and three-hour datasets respectively, as summarized in table (4). Visible number of satellites equivalent to each epoch time (1-second) for GPS and for GPS/GLONASS as shown in Figure (13).



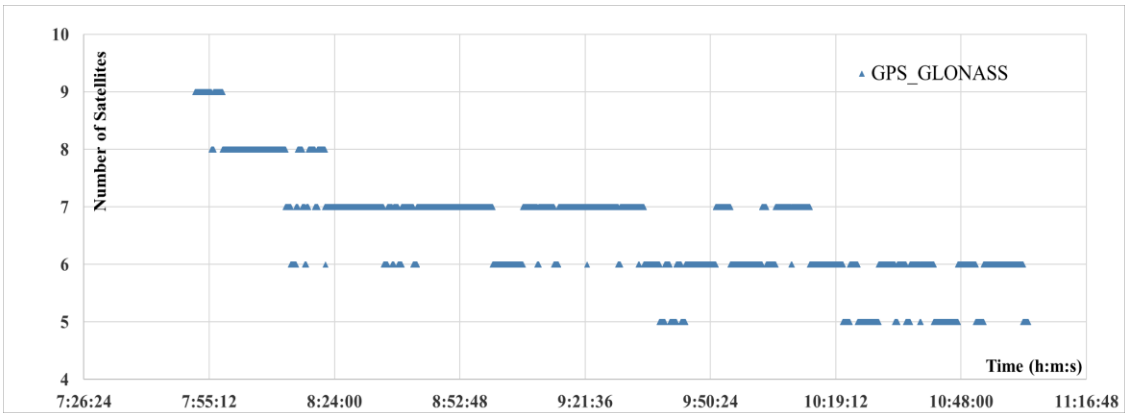


Figure 13. Static Experiment Visible Number of Satellites for GPS (the upper) and GPS/GLONASS (the lower)

4.2 KINEMATIC EXPERIMENTS:

For the kinematic trajectory, the used coordinate system is UTM for both smartphone and Geodetic Receiver. Solution of the geodetic receiver was the reference solution. The used Geo++ RINEX Logger application records Android raw measurements in the RINEX files. These raw measurements were processed using RTKLIB software with precise clock and orbital corrections downloaded from International GNSS Service (IGS), and processed in single frequency precise point positioning (PPP) technique using GPS satellite systems. The solution was in decimal latitude and longitude for each epoch (1-second), coordinates are transformed to UTM coordinates using LGO Software.

MATLAB mathematical manuscript is used to synchronize two results times, so that we can correlate two solutions and get the difference in positioning for each epoch in easting, northing and height. The results showed that Root mean square error values are 2.15m, 2.30 m and 4.78 m in easting, northing and height respectively. Figures (14), (15) and (16) explain points scatter of the positioning error versus time in easting, northing and height respectively with reference to geodetic rover Receiver coordinates.

In these Figures we can see some epochs slightly have much error than most of points scatter, when adding GLONASS satellites, it is noticed that no significant improvement of the positioning results, most probable reason for this is the low number of visible GLONASS satellites in the short experiment duration as shown in Figure (17).

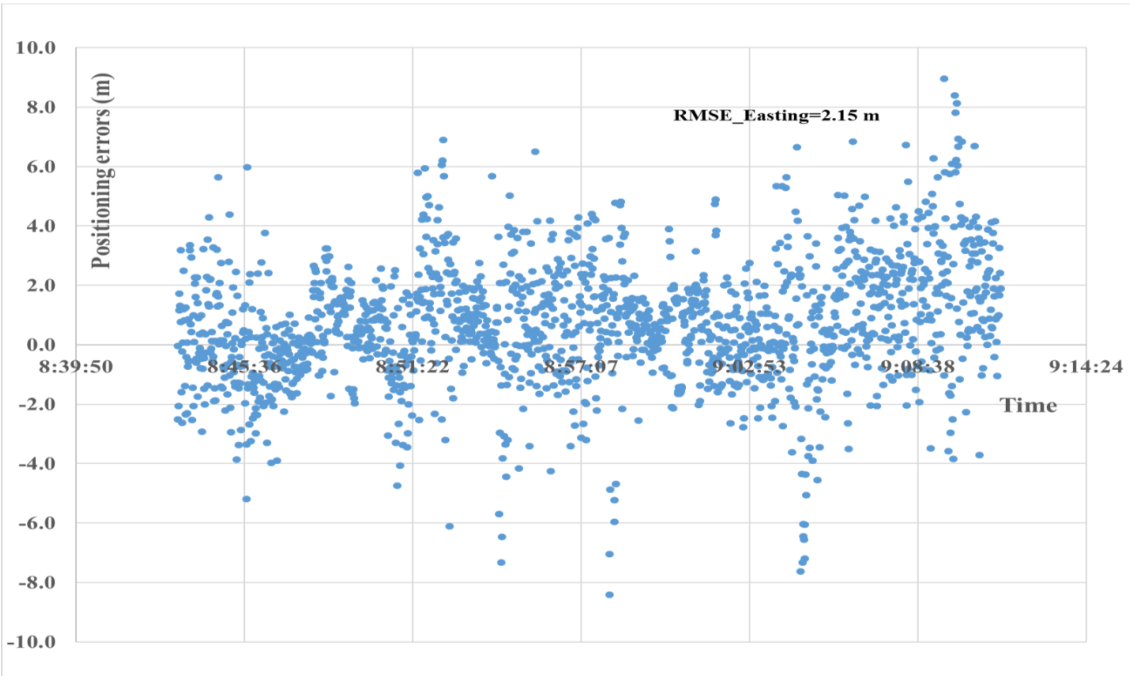


Figure 14. Positioning Errors in Easting Direction

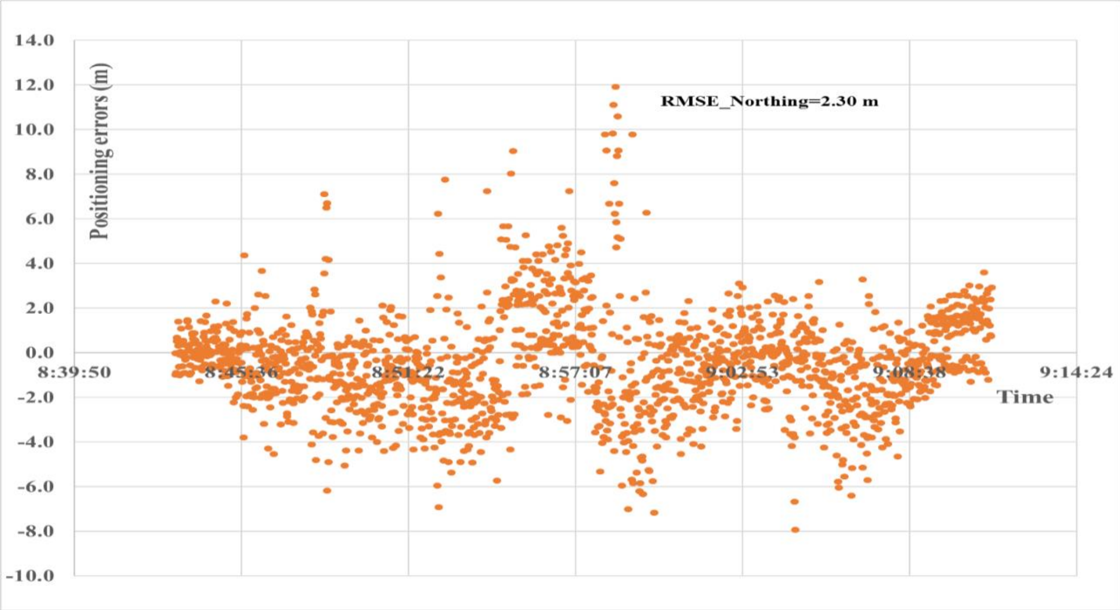


Figure 15. Positioning Errors in Northing Direction

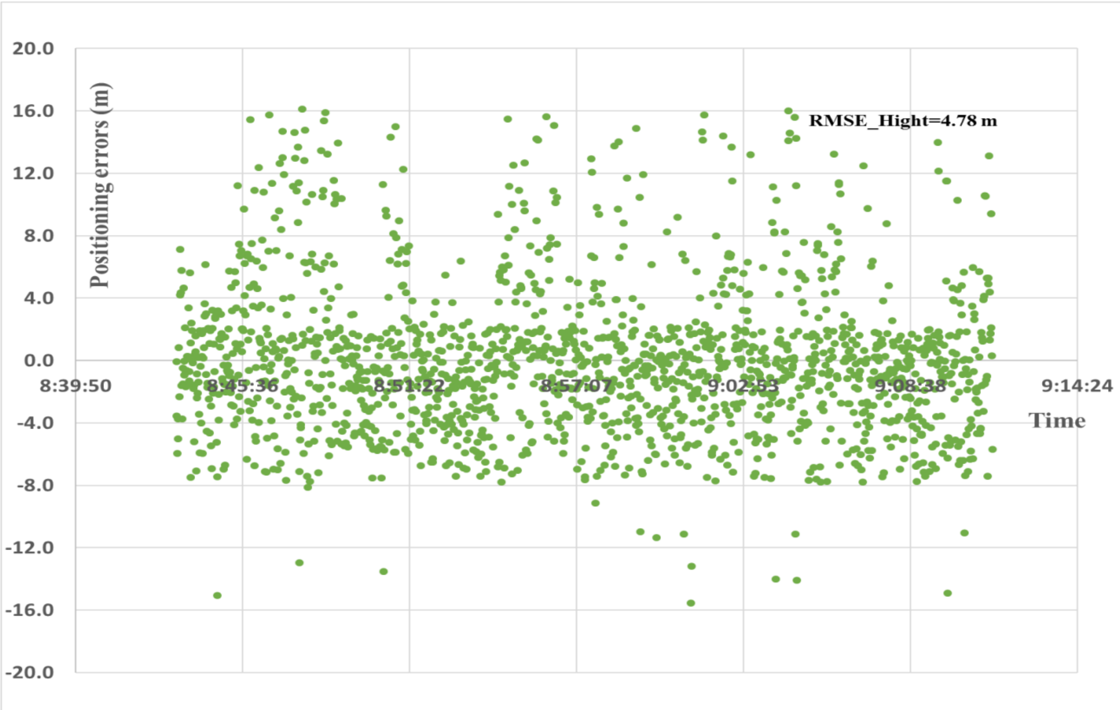


Figure 16. Positioning Errors in Height Direction

Google earth pro software is used to present layout plan of the two solutions of the trajectory and show the difference between the solutions. As shown in Layout Figure (18) red color is the smartphone solution and blue color is RTK GS15 GNSS solution.

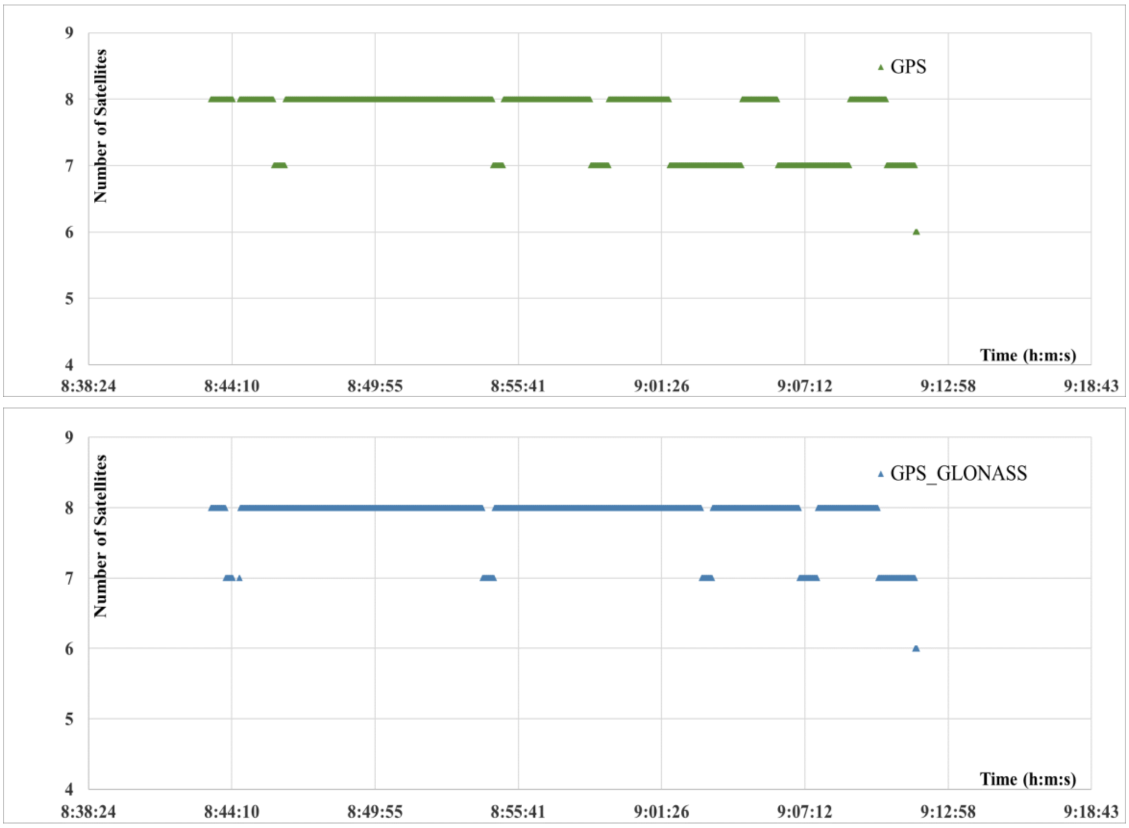


Figure 17. Kinematic Experiment Visible Number of Satellites for GPS (the upper) and GPS/GLONASS (the lower)

Figure 18. Kinematic Trajectory Layout

5 CONCLUSION

In this research the positioning accuracy of the single frequency precise point positioning (PPP) based on smartphone GNSS observation data was evaluated. The Xiaomi mi 8 smartphone was used to collect GNSS raw observation data in both static and kinematic modes. The geodetic receivers and smartphone datasets were processed in a differential mode by LGO software to assess the raw data performance and provide the reference solution for the smartphone. RTKLIB software with IGS precise clock and orbital corrections is used for PPP post processing.

In static mode the smartphone's single frequency PPP achieved horizontal and vertical positioning accuracies 0.424 m, 0.96 m for GPS satellites, and achieved 0.413 m, 0.942 m for GPS/GLONASS satellites after one hour of data logging respectively; however, after three hours the smart phone positioning achieved horizontal and vertical accuracies 0.374 m, 0.792 m for GPS, and achieved 0.238 m, 0.66 m for GPS/GLONASS respectively. In kinematic mode the smartphone's single frequency PPP achieved positioning RMSE 2.15 m, 2.30 m and 4.78 m in easting, northing and height respectively reference to the geodetic receiver dual frequency GNSS RTK positioning.

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