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CENTIMETER-ACCURATE POSITIONING WITH HANDHELD GNSS RECEIVER

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SUMMARY

As a result of advances in technologies, the raw GNSS measurement (i.e., pseudorange, phase, and Doppler) can now be collected with smartphones, tablet computers, and handheld GNSS receivers/chipsets. The most important milestone in this field was undoubtedly Google's announcement in May 2016 that devices with Android Nougat v.7.x and higher operating systems can collect GNSS raw data. On the other hand, some manufacturers (like Garmin Ltd.) have allowed GNSS raw measurements to be recorded with handheld GNSS devices, which are mostly used for navigation, outdoor and sporting activities. This has paved the way for smartphones or handheld-type GNSS devices to be used as accurate 3D positioning systems in addition to their standard functions. In this study, the 3D positioning performance of the Garmin GPSMAP® 66sr handheld device using the raw measurements is presented. For this purpose, two static test measurements were made, one in a noisy environment without completely open sky visibility and having more multipath effects and the second one in relatively favorable environmental conditions. In these measurements, GPS (L1, L5), GLONASS (L1), and Galileo (E1, E5a) data were collected at 1-second intervals with a Garmin receiver, and the points were coordinated with the conventional relative method and PPP technique. In order to determine the effect of measurement time span on the accuracy performance, the data collected over a longer period were divided into sub-groups of 1-hour each and processed again using the same ways. The coordinates obtained from the Garmin receiver's solutions were compared with those measured by the geodetic receiver. The overall results show that the handheld GNSS receivers achieved centimeter-level accuracy with the relative technique, while meter-level accuracy could be obtained with the PPP technique.

KEYWORDS: **GNSS, LOW-COST POSITIONING, CENTIMETER-ACCURATE POSITIONING, PPP, GARMIN GPSMAP 66SR**

INTRODUCTION

Global Navigation Satellite System (GNSS) has become the most widely used method in many different areas as a fast, reliable, robust, and accurate positioning tool. This method can provide the 3D position of a static or moving object in meters, centimeters, and even millimeters level depending on the used method (i.e., absolute or relative) and the receiver type (number of frequencies, tracked GNSS constellations, geodetic- or -consumer- type, etc.). In general, it is possible to achieve meterslevel accuracy with code measurements in absolute mode while at the centimeter or even millimeterlevel with carrier-phase-based relative method. To make positioning with the first approach, essentially, a receiver of a few hundred USD is sufficient. On the other hand, for the second group surveying task, a multi-frequency and multi-constellation geodetic-grade receiver is required, with prices ranging from 5K USD to 20K USD or more (each). However, the absolute method cannot provide the accuracy required by many surveying applications. In order to achieve the cm-level accuracy, a relative solution technique using carrier-phase observations should be used. In the relative technique, the point(s) are coordinated from a reference station(s) with precisely known coordinates. Therefore, this method requires simultaneous observations of satellites with at least two or more GNSS receivers. This approach also requires GNSS processing software to evaluate the data.

Recent improvements have emerged in some new algorithms and methodologies that allow for high accuracy (cm-dm) positioning utilizing data obtained with a single GNSS receiver. Precise Point Positioning (PPP) is the most widely known and used technique in many different applications every day. With the PPP technique, the 3D position can be determined in static and kinematic modes with cm-dm accuracy level using the GNSS raw data collected with a single receiver together with the precise satellite orbits and satellite clock corrections, and code & phase biases and other products offered by many other analysis centers, especially by the International GNSS Service (IGS) (Zumberge et al., 1997; Cai et al., 2015; Choy et al., 2017; Duong et al., 2020; Erol et al., 2020; Akpınar, 2023; Hou and Zhou, 2023).

It should be noted that to obtain high accuracy performance from either the relative positioning method or the PPP technique (i.e., to determine the position with accuracy in the level of cm to dm), carrier-phase observations together with the code measurements should be done. However, this requires the use of at least one geodetic receiver for the PPP technique and at least two geodetic receivers for the relative method.

On the other hand, the use of low-cost Original Equipment Manufacturers (OEM) type GNSS receivers has started to use for high accurate positioning. They can be used as single or multifrequency receivers, allowing code and phase measurements to be logged, and it can also offer an RTK feature. However, such systems have only been used by certain researchers in certain projects due to the fact that there are many things users need to do in order to provide connections between components, data collection, and logging, not having a user-friendly interface and the requirement of developing several things by the users. More recently, the raw GNSS measurements (i.e., pseudorange, carrier-phase measurement, Doppler, S/N, and so on) have become possible with smartphones and tablet computers, and handheld GNSS receivers. Especially, Google announced that devices with Android v.7.0 or later operating systems could record code and phase measurements, in May 2016. This paved the way for the use of all devices with an Android operating system, especially smartphones and tablets, in low-cost high-accuracy positioning studies. Today, many devices, a significant number being smartphones, are equipped with a GNSS chipset. According to the 'EUSPA EO and GNSS Market Report 2022' prepared by the European Union Agency for the Space Programme (EUSPA), it is stated that there are around 6 billion GNSS devices used on different platforms (tablets, smartphones, digital cameras, portable computers, etc.), and that more than 10 billion GNSS devices will be in use worldwide by 2031 (URL-1). As a note, while the European Commission is supremely responsible for the Galileo program, EUSPA is responsible for service delivery and market development, as well as deploying the system and providing technical support for operational tasks. As a result of this development, billions of smartphones used for communication, navigation, and multi-media purposes, as well as all other devices with Android operating systems that have GNSS receivers, have paved the way for their use in geodetic positioning.

When the relevant literature is examined, it is revealed that the accurate-positioning performance of tablets and smartphones varies depending on the number of frequencies and measurements used (code/carrier phase), experimental setups, and environmental conditions. While the processing of the measurements made with the embedded antennas of the devices, especially those based only on code measurements, yielded accuracies in the order of meters, the use of carrier phase measurements along with the pseudoranges significantly increased the accuracy. The best results were obtained with an external geodetic antenna. This is because the measurements made on such devices are much more affected by multipath, and the measurements have high noise. According to the studies, the utilization of Android smart devices equipped with multi-frequency and multi-constellation GNSS chipset used with an external geodetic antenna achieved an accuracy at the order of cm-dm level in static mode. However, it is seen that lower accuracies are obtained in kinematic measurements (Håkansson 2019; Robustelli et al., 2019; Dabove et al., 2020; Heßelbarth and Wanninger, 2020; Wen et al., 2020; Alkan and Delice, 2021; Hu et al., 2023; Li et al., 2023). Unlike Android-based platforms, OEM-type GNSS receivers using geodetic antennas provided the resolving of the carrier phase ambiguities and thus offer cm-dm accuracy in static and kinematic modes (Constantin-Octavian, 2012; Alkan and Delice, 2021; Hamza et al., 2021; Romero-Andrade et al., 2021; Hohensinn et al., 2023).

The number of studies with handheld GNSS receivers has been limited compared to others. As far as is known, the first academic research based on handheld receivers was conducted by Hill et al. (1999). El-Mowafy (2005) demonstrated that the decimeter positioning accuracy could be achieved by processing the data with differential post-mission mode with Garmin handheld GNSS receivers. However, in these studies, raw GNSS data were not commercially available (were not provided by the manufacturer) but were obtained through proper software (GRINGO) coded by the researchers. As one of these studies, Lachapelle et al. (2018.a) conducted a series of measurements with the Garmin Rino 750 series. However, this device also did not provide the raw GNSS data commercially. The same year, in 2018, Garmin Ltd. made it possible to collect and record raw GNSS measurements (pseudorange, carrier phase, and Doppler data) with some models of handheld GNSS receivers. This made it possible to acquire code and phase measurements with a handheld GNSS receivers, paving the way for high-accurate positioning with such devices. One of the very limited number of publications with this device was conducted by Lachapelle et al. (2018.b). They collected the GPS and Galileo observations in static and kinematic modes with both handheld devices and Android smartphones. They used an external geodetic antenna throughout the measurement. According to their processing results, the Garmin device in kinematic mode provided better than 1 m RMSE in all components. They also concluded that using the external GNSS antenna achieved better results in the high multipath environment over a helix antenna by reducing the multipath and signal attenuation. Wanninger et al. (2022) investigated the performance of the Garmin GPSMAP® 66sr handheld-type GNSS device. They demonstrated that the device provided centimeter-accurate positioning.

The aim of this study is to demonstrate the static positioning performance of the Garmin GPSMAP 66sr handheld GNSS receiver by using pseudorange and carrier phase observations. The collected GNSS data were processed by both the relative positioning method and the PPP technique.

MATERIALS AND METHODS

Data Collection

To assess the accuracy performance of the Garmin handheld-type GNSS receiver, two realistic field test measurements were conducted in Istanbul Technical University (ITU) Ayazaga Campus in Istanbul, Türkiye. Within this scope, two control points were established, and static GNSS measurements were conducted. Within the scope of the study, in order to reveal the effect of measurement conditions on positioning performance, the points were installed in two different environmental conditions. In this context, the first of the points (CP-1) was established in a location having multipath conditions under partly limited sky conditions. The second one (CP-2), in contrast to the first one, was located on the roof of the Civil Engineering Faculty at ITU Ayazaga Campus, which provides a relatively clear sky observation without signal obstructions and low levels of noise and a multipath environment (Figure 1).

(a) **(b)**

Figure 1. The field test measurements; (a) first test, (b) second test

The Garmin GPSMAP 66sr (hereafter also called as 66sr) was introduced by Garmin Ltd. as the first dual-frequency multi-constellation handheld GNSS receiver with a quadrifilar antenna in 2020 (Wanninger et al. 2022). It observes the GPS (L1, L5), GLONASS (L1), Galileo (E1, E5a) and QZSS (L1, L5), and IRNSS (NavIC) (L5) satellite signals. The user can choose the satellite system as ′GPS only‵ for single-frequency positioning and ′Multi-GNSS‵ for multi-frequency positioning. It should be emphasized that the 66sr has a quad helix antenna. This provides to attenuate the multipath signals by generating a circularly polarized hemispherical radiation pattern (Wanninger et al., 2022). The main specification of the 66sr is given in Table 1 (URL-2).

Table 1. Main properties of the Garmin GPSMAP 66sr

GNSS Constellations	GPS (L1, L5); GLONASS (L1); Galileo (E1, E5a); QZSS (L1, L5); and IRNSS (NavIC) (L5)
Chipset	BCM47758
Antenna	Quad Helix
RINEX Logging	Internally in version 3.04 format
Dimensions and Weight	62 x 163 x 35 mm; 230 g
Operating Temperature	-20 to 60 °C
Battery	Built-in rechargeable lithium-ion and up to 36 hours in default mode

The static GNSS data were collected through the test measurements about 2 hours in the first trial on 09 July 2023 (GPS Day of Year 190) and about 5 hours in the second trial on 10 July 2023 (GPS Day of Year 191) by tracking all available GPS (L1, L5), GLONASS (L1) and Galileo (E1, E5a) satellites in view with a 4.5-degree minimum elevation mask angle. The data was collected at a 1-second sampling rate by default and cannot be changed. It should be noted that, in the first trial, a tripod or a prism pole was not used, instead the receiver was placed very near to the ground in order to make a more noisy measurement condition (Figure 1.a). This gives us more information about the performance of the Garmin receiver in challenging environmental conditions, having high levels of noise and multipath. At the end of the test measurements, the GNSS raw data was recorded in RINEX v.3.04 format and transferred from Garmin's internal memory to a PC using a micro-USB port.

The total number of tracked GNSS satellites and corresponding PDOP values were presented in Figure 2.

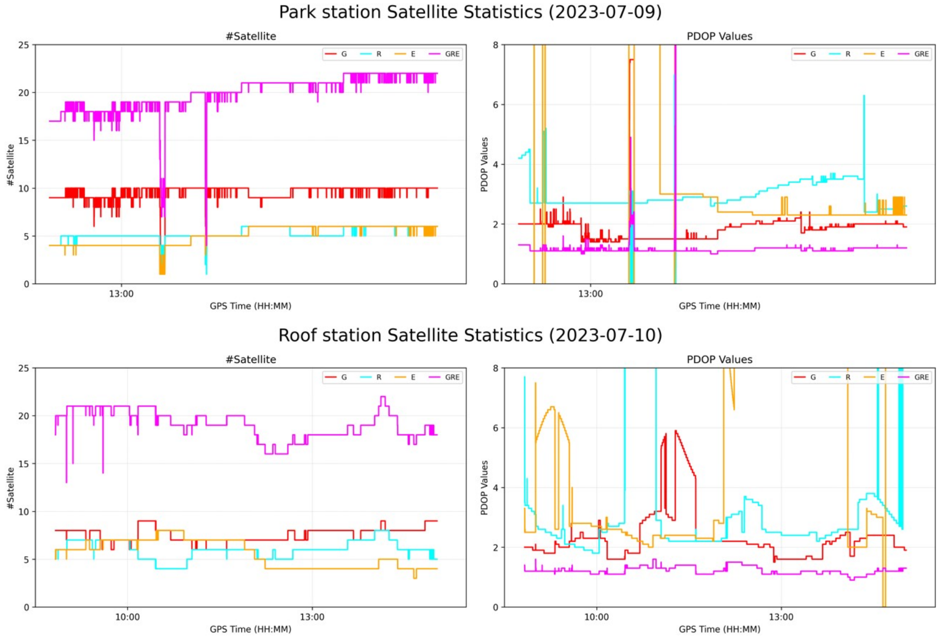


Figure 2. The tracked GNSS satellites and PDOP values for the field tests (*up*: first test, *down*: second test)

In both test measurements, the number of observed satellites was significantly increased compared to single-satellite systems. On the other hand, it can be seen from Figure 2 that the PDOP values change inversely with the number of satellites. However, the sudden and sharp changes in the number of satellites and PDOP values were considered to be due to the antenna that was used.

Data Processing and Numerical Results

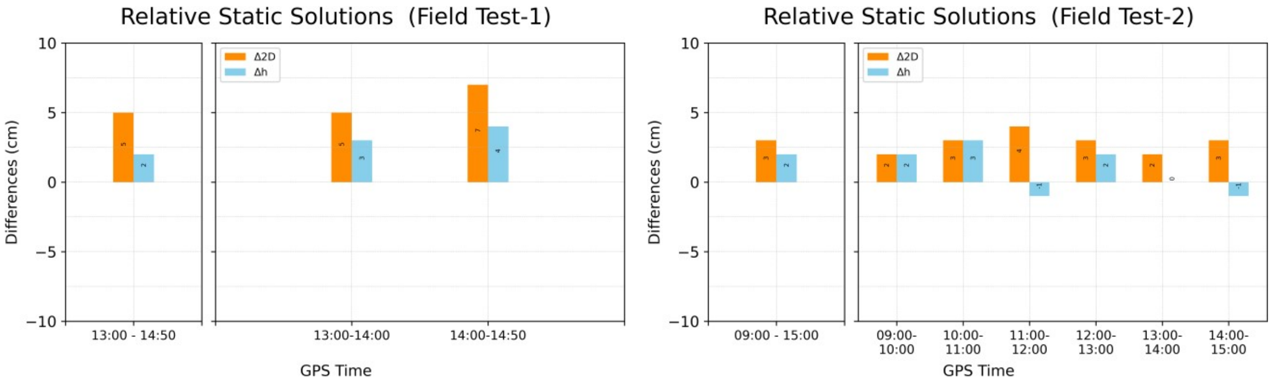
The accuracy performance of the Garmin GPSMAP 66sr receiver was evaluated with baseline solution (i.e., relative method) and PPP technique (i.e., absolute method). For the baseline solution, one of the nearest IGS continuous reference stations, ISTA (41□.104450 N, 29□. 019346 E, 147.245m), was used as a reference station. The collected data were processed in static mode using Trimble Business Center (TBC) commercial software. In the solutions, antenna phase-center corrections were applied according to the values determined by Wanninger et al. (2022). The CP’s coordinates were calculated within mm-level and cm-level horizontal and vertical precision, respectively, by partly fixing the integer ambiguities. On the other hand, whole measurement datasets were divided into 1-hour sub-measurement groups to determine the relationship between accuracy and occupation times. The data processing procedure was repeated again for the sub-data group.

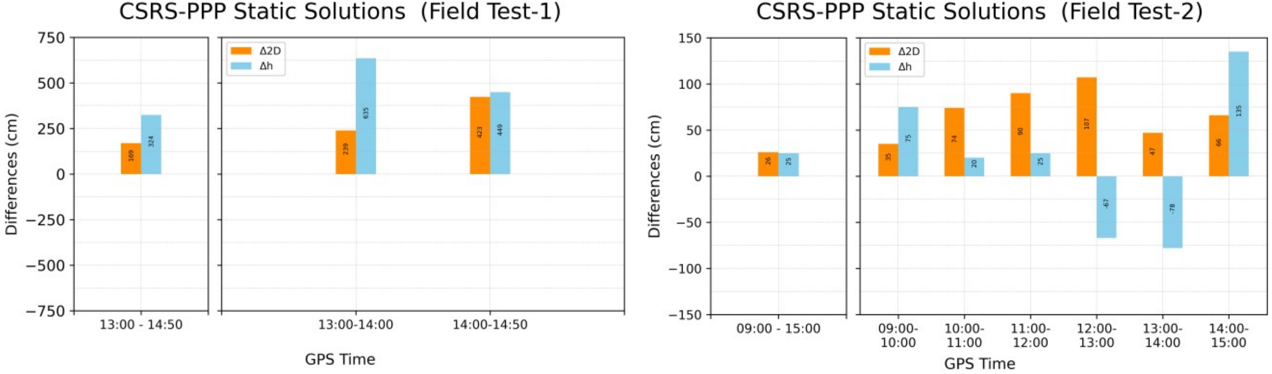
As a second processing step, the whole data set and sub-groups were processed using the Canadian Spatial Reference System-Precise Point Positioning (CSRS-PPP), an online GNSS PPP postprocessing service, to calculate the PPP-derived static coordinates. The service calculates the coordinates using precise satellite orbit, clock, and bias corrections in combination with the single or dual-frequency GPS and GLONASS data. It should be noted that the service only uses GPS and GLONASS data collected on L1 and L2 frequencies and does not accept other frequencies as well as Galileo observations. Shortly after the GNSS data in RINEX format collected in static/kinematic mode is sent via the service’s user-friendly web page, the service calculates the corrected averaged coordinate (for static mode), the corrected track (for kinematic mode), and other information, such as graphics, tables, etc. and sends this information to the user’s previously registered e-mail address. After the modernization of the CSRS-PPP service on 20 October 2020, the PPP solutions became possible with ambiguity fixed solutions for the GPS satellites (i.e., PPP-AR solution). More information about the service is available in Banville et al., 2021, and URL-3. As it may be recalled, GPS (L1 and L5) and GLONASS (L1) data can be collected with 66sr. Since the service is unable to process the GPS L5 frequency, the PPP coordinates were calculated by processing only GPS-L1 and GLONASS-L1 data as single-frequency solutions. As is known, single-frequency solutions provide much lower accuracy than dual/multi-frequency solutions. The processing parameters applied by the service are given in Table 2.

Table 2. The processing parameters applied by CSRS-PPP online processing service

PPP-client software & version	CSRS-PPP v3
Strategy	PP-PPP
Modes	Static
Observables	Raw code and phase observations
Satellite systems	G1+R1
Frequency	Single
Ambiguity solution	Float
Elevation cut-off angle	7.5 degree
Mapping function	Vienna Mapping Function (VMF1)
Reference frame	ITRF2020
Ephemeris products & Clock corrections	NRCan Rapid Products

To make a precise accuracy assessment, needed to establish the known coordinates of the control points (i.e., CP-1 and CP-2). For this purpose, the CP’s coordinates were calculated with the relative solution using the same reference stations (ISTA). For this purpose, the GNSS measurements were made with Trimble R8 geodetic-grade receivers. The static GNSS surveying accuracy of this receiver is given as 3 mm + 0.5 ppm RMS (for horizontal) and 5 mm + 0.5 ppm RMS (for vertical) for the fast-static mode (URL-4). Finally, all these coordinates obtained from baseline and PPP solutions in the static mode were compared with the known values in terms of 2D horizontal and height components. The results were given in Figure 3.





(a) (b)

Figure 3. The coordinate differences between calculated and known coordinates for the first test (a) and second test (b)

Discussion

It was seen from Figure 2 that the usability of the GLONASS and Galileo satellites, together with the GPS, significantly increased the number of satellites in both trials. This obviously strengthened the spatial geometry of the observed satellites and contributed significantly to the increase in accuracy.

The results shown in Figure 3 show that the measurements made at the noisier and multipath-exposed point (see Figure 1.a) were slightly worse than those made in clear-sky conditions, but the relative solutions of all measurement groups resulted in differences from the known coordinates for 2D position and height in cm-level. However, as a result of the processing of the 1-hour measurement groups, the differences were slightly worse than the long-period ones, but the maximum differences of 7 cm in position and height components were achieved. In general, it is considered that the collection of data with the device's quadrifilar helix antenna plays a major role in this high performance. As aforementioned, such antennas provide mitigation of multipath signals.

Looking at the results obtained using the CSRS-PPP service, the results agreed with the known coordinates within the 2 dm level both in 2D position and height components when the data was processed through a span of 5 hours. However, when the measurement time was reduced to 1 hour, the differences reached the order of meters. In the measurement made in a noisy environment, these differences were found to be in the order of several meters. As explained above, it has been evaluated that the main reason for this situation was that the CSRS-PPP online service uses GPS (L1, L2) and GLONASS (L1, L2) signals in the process and the receiver used in the study collected the GPS (L1, L5) and GLONASS (L1) observations, therefore depending on this, the service produced the singlefrequency solutions. In this case, especially the effect of unmodelled ionospheric delay may provide less accurate solutions.

CONCLUSIONS

In this study, the positioning performance of the Garmin GPSMAP 66sr handheld GNSS receiver by the processing of collected code and carrier-phase observations was investigated, and the usability of such devices in geodetic surveying projects was demonstrated. The overall results show that centimeter-level accuracy in the static mode can be achieved with a relative solution comparable to those obtained with a geodetic GNSS receiver, especially when long observation times were used. Unlike the relative solutions, it was concluded that the coordinates could be determined in PPP mode on the level of decimeters to meters level by the processing of the collected static observations at both favorable and challenging sites.

Today, in almost all countries of the world, especially surveying engineers and technical staff belonging to other professions working together with them are intensively using GNSS satellite-based positioning systems in order to get economical, fast, and accurate positioning. In this context, the low-cost handheld GNSS devices will be a strong alternative to expensive geodetic-grade receivers and will reduce the need for them. Considering the cost of these devices (typically a few hundred USD), it is considered that the cost of field studies will considerably reduce and that they will also impose a tolerable hardware cost on the project implementers in case of destruction/accident/loss, etc. The use of such systems in geodetic applications will reduce the need for expensive new geodetic sensors, thus will reduce the carbon footprint of surveying activities.

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