www.czasopisma.pan.pl PAN www.journals.pan.pl

ADVANCES IN GEODESY AND GEOINFORMATION
(formerly GEODESY AND CARTOGRAPHY)
Vol. 71, no. 2, article no. e29, 2022
https://doi.org/10.24425/agg.2022.141916

Original paper

Part of Topical collection: "Advancements in Applied Geoinformatics"

The positioning performance of low-cost GNSS receivers in the Precise Point Positioning method

Mustafa Fahri Karabulut[1*], Nedim Onur Aykut[1], Burak Akpınar[1], Güldane Oku Topal[1], Zübeyir Bilal Çakmak[1], Bilge Doran[1], Ahmet Anıl Dindar[2], Cemal Özer Yiğit[2], Mert Bezcioğlu[2], Anıl Zafer[2]

[1]Yildiz Technical University, Istanbul, Turkey
e-mail: mfahri@yildiz.edu.tr; ORCID: http://orcid.org/0000-0001-8513-3475
e-mail: oaykut@yildiz.edu.tr; ORCID: http://orcid.org/0000-0002-5052-6217
e-mail: bakpinar@yildiz.edu.tr; ORCID: http://orcid.org/0000-0002-3076-1578
e-mail: guloku@yildiz.edu.tr; ORCID: http://orcid.org/0000-0001-7548-2276
e-mail: zubeyircakmak21@gmail.com; ORCID: http://orcid.org/0000-0001-7109-3249
e-mail: doran@yildiz.edu.tr; ORCID: http://orcid.org/0000-0001-6703-7279

[2]Gebze Technical University, Gebze, Turkey
e-mail: adindar@gtu.edu.tr; ORCID: http://orcid.org/0000-0003-3168-8322
e-mail: cyigit@gtu.edu.tr; ORCID: http://orcid.org/0000-0002-1942-7667
e-mail: mbezcioglu@gtu.edu.tr; ORCID: http://orcid.org/0000-0001-7179-8361
e-mail: a.zafer2020@gtu.edu.tr; ORCID: http://orcid.org/0000-0002-0393-5720

[*]Corresponding author: Mustafa Fahri Karabulut, e-mail: mfahri@yildiz.edu.tr

Received: 2022-02-28 / Accepted: 2022-07-11

Abstract: Satellite-based positioning, which started being developed in the mid-1960s for military purposes, is now used in almost every area. For the studies single and/or double frequency receivers are used. The cost of a receiver and antenna couple that have capable of high coordinate accuracies ranges from $3000 to $15000. With the production of Original Equipment Manufacturer (OEM) receivers, the cost of satellite-based location determination decreases to approximately one in 10 for the civilian user compared to the operations performed with geodetic receivers and antennas. However, although these receivers collect data in multi-Global Navigation Satellite System (GNSS) and frequencies, the accuracy of the coordinate values estimated is not as high as geodetic receivers and antennas. Therefore, it is necessary to carry out an accuracy study to obtain information about which studies can be used in. In this study, measurements were made at the UZEL point located on the roof of the Yıldız Technical University Geomatics Engineering Department by using the ZED-F9P-02B OEM multi GNSS receiver and ANN-MB L1/L2 multi-band GNSS patch antenna. The performance of the test results has been examined by comparing the results

The Author(s). 2022 Open Access. This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made.

from CSRS(Canadian Spatial Reference System)-PPP with the coordinates of the UZEL point. As a result of the comparison, the difference between the coordinate determined with collected 3.5 hr data and the coordinates of the UZEL point has been determined as – 1.4 cm, 2.8 cm, and 9.3 cm in the East, North, and Height directions, respectively.

Keywords: low-cost, GNSS, PPP, OEM receiver

1. Introduction

Satellite-based positioning systems, which started to be developed for military purposes in the mid-1960s, have been started to serve at full capacity in the early 1990s. In addition to its military use, it is used extensively in the field of agriculture, aviation, environment, marine, public safety and disaster relief, rail, recreation, roads and highways, space, surveying and mapping and timing (PNT, 2021). It has become indispensable for many users, from navigation to scientific studies. For these studies, single and/or double frequency receivers that have capable of from 1 to 100 Hz sampling rate have been used. The costs of receivers and antennas used to determine high-accuracy coordinates vary between $3000 and $15000. With the developing technology, the OEM (Original Equipment Manufacturer) receiver boards can collect multi-GNSS and multiband signals with prices starting from approximately $250.

There are many different studies in the literature to evaluate the performance of low-cost GNSS receivers In one of them the Odolinski and Teunissen (2016) carried out the RTK performance of low-cost GNSSs. As a result of the analyzes performed using geodetic and lowcost GNSS receivers at different locations, different satellite configurations (GPS – GPS and BeiDou), different signal types (L1 – L1 and L2) and various cutting angles. Based on the geodetic receivers, the experiment using low-cost receivers for the single frequency (L1-B1)-dual system (GPS+BeiDou) demonstrates that it has the ability to achieve equivalent ambiguity resolution performance to that of a dual frequency (L1+L2)-single system (GPS or BeiDou). Nie et al. (2020) carried out to test the performance of the data collected kinematically with a low cost GNSS receiver for 24 minutes with real-time PPP method, the position accuracy of the single frequency receiver was estimated 0.319 m, 0.185 m and 0.421 m in the east, north and up components, respectively and the dual frequency position accuracy that were analyzed different strategies has been obtained as 0.273 m, 0.160 m and 0.117 m, respectively. In another study, RTK (Real Time Kinematic) coordinate accuracies of 4 different receivers results (ZED-F9P module, Eclipse P326 OEM module, A325 smart antenna, and SPS855 modular receiver) have been examined in agriculture (Van Nguyen et al., 2021) and as a result of 24-hour RTK measurements, the horizontal position accuracy of low-cost positioning devices has been determined as 1 cm at short base length and 2 cm at long base length in open sky environment. The accuracies obtained as a result of the study performed by Hill et al. (2019) agree with these results. The standard deviations determined as a result of the study conducted by Janos and Kuras (2021) to test the performance of low-cost

GNSS receivers in different field conditions with the RTK method were determined as 1 cm in the X direction, 0.6 cm in the Y direction, and 1.7 cm in the height component for open-air conditions. For urban areas standard deviation has been calculated at 11.0 cm, 14.7 cm and 39.2 cm in X, Y and H directions, respectively. It is understood from the standard deviation values that the ANN-MB-00 antenna is adversely affected by the signals reflected from the trees and buildings around it. The performance of displacement determination of low-cost single frequency GNSS receivers was tested (Biagi et al., 2016). In this study two different tests were carried out with base and rover using u-blox receivers with 65 m and 130 m base lengths. As a result of the test, the standard deviation of the differences was calculated as 5 mm horizontally and vertically for the short base, and 5 mm horizontally and 13 mm vertically for the long base. The residuals of the low-cost receiver used in the study (Cina and Piras, 2015) conducted by testing the performance of the landslide observation was calculated as 3 mm, 6 mm and 17 mm in the east-north and height directions, respectively. To test the performance of coastal sea level change, a buoy has been designed using low cost GNSS by (Knight et al., 2020) and the sea level change measurement RMSE has been estimated as 1.4 cm based on tide gauge data. In another study, in which the use of low-cost GNSS receivers in structural health monitoring was investigated, it was mentioned that the position accuracy is 2 cm and concluded that these receivers provide complementary positioning information (Casciati et al., 2016). Cahyadi et al. (2021), as a result of their study using static, real-time kinematic and Precise Point Positioning (PPP) methods, it has been concluded that GNSS Tersus BX316 and Comnav K706 OEM receiver board can achieve the same accuracies as Stonex S800 GNSS geodetic receivers. In Wielgocka et al. (2021), 2.5 hours of data were recorded using the U-Blox ZED-F9P OEM receiver, and it was reported that a few centimeters accuracy was obtained by the PPP method, for 1 hour static data the horizontal and vertical accuracy has been obtained 20 mm and 15 mm respectively by trelative positioning method and for 1 hour static data the horizontal and vertical RMSE has been estimated 62 mm and 56 mm recpectively by absolute positioning.

The main purpose of this research is to determine the position accuracy of the low-cost GNSS receiver and antenna for precise point positioning applications. Our motivation is to evaluate the PPP performance by using the short term observations obtained by using low cost reveiver and antenna set. Here, U-Blox ZED F9P GNSS OEM low-cost receiver board has been used. GNSS data has been collected on UZEL reference point by 1-second interval for about 3.5 hours long with ANN-MB L1/L2 multi-band GNSS patch antenna. GNSS data were processed by CSRS-PPP online service and the differences in coordinates have been examined for in all directions.

2. Materials nd methods

The ZED-F9P-02B high precision low cost GNSS receivers have capable of collecting multiple navigation systems (GPS, GLONASS, Galileo and BeiDou). In addition, QZSS and SBAS satellites can be received simultaneously. Table 1 shows the signals supported by the ZED-F9P-02B receiver.

Table 1. Supported GNSS and signals on ZED-F9P-02B

GPS	GLONASS	Galileo	BeiDou
L1C/A (1575.420 MHz)	L1OF (1602 MHz $+k \times 562.5$ kHz, $k = -7, \ldots, 5, 6$)	E1-B/C (1575.420 MHz)	B1I (1561.098 MHz)
L2C (1227.600 MHz)	L2OF (1246 MHz $+k \times 437.5$ kHz, $k = -7, \ldots, 5, 6$)	E5b (1207.140 MHz)	B2I (1207.140 MHz)

U-blox ZED-F9P-02B high precision low cost GNSS receiver is suitable for real-time kinematic, network RTK, real-time PPP, and post-processing kinematic/static applications. It can be controlled by U-center or RTKLIB (Takasu and Yasuda, 2009) software using a computer or mobile phone/tablet. Real-time kinematic/PPP or network RTK data and raw GNSS data can be recorded in both software with UBX, NMEA and RTCM protocols. Raw GNSS data should be converted to RINEX format by RTKLIB 2.4.3_b34b software.

The test surveys have been conducted on a pillar named as UZEL reference station (Fig. 1), which is located on the roof of the Geomatics Engineering department at Yıldız Technical University in Istanbul. The known coordinates of this reference point that are given in Table 2 are in the ITRF96 datum and 2005.0 epoch. The coordinates have been estimated as a result of the evaluation of the data collected with a geodetic antenna and receivers with academic software. Raw GNSS data has been collected via U-center software. The U-blox ZED-F9P-02B OEM GNSS receiver and the ANN-MB-00 patch antenna were used in test surveys (Fig. 1). RTKCONV module of RTKLIB 2.4.3 software has been used to convert raw data to RINEX format.

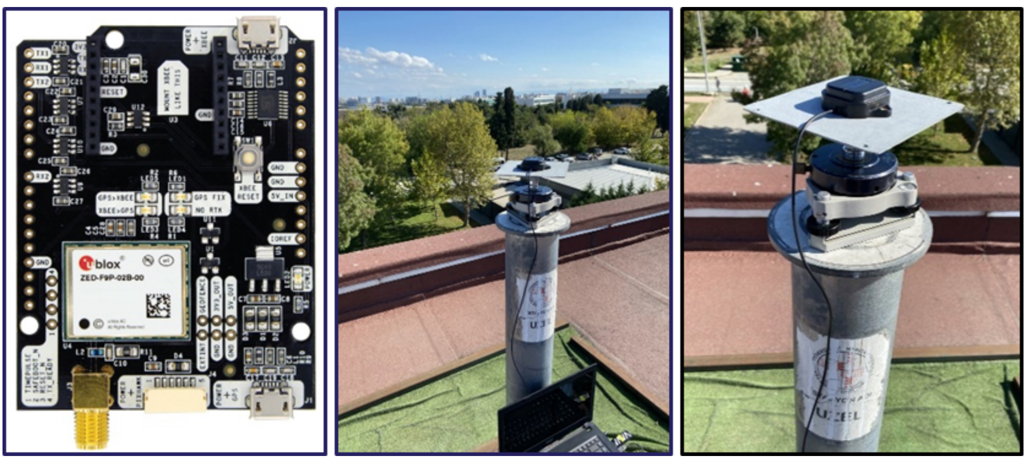


Fig. 1. YLDZ GNSS Station

Table 2. Cartesian coordinates and velocities of UZEL reference point (ITRF96, 2005.0)

	X (m)	Y (m)	Z (m)	Vx (m/yr)	Vy (m/yr)	Vz (m/yr)
UZEL	4219312.6915	2328109.7823	4164454.0083	–0.0179	0.0151	0.0083

The ratio of the signal strength to the GPS observations noise floor is called the Signal to Noise Ratio (SNR). It is used as a comparison of signal strengths between satellites and channels as a measure of receiver tracking power (Bilich et al., 2007). SNR values are computed in the dB scale for a specific receiver processing bandwidth. A more appropriate way is to store SNR values in units of dB-Hz. SNR value should be more than 42 dB-Hz in open-sky conditions. It is also known that the SNR value generally decreases at least 5–10 dB-Hz due to the loss of signal power caused by reflection, namely the multipath effect (Uaratnawong et al., 2020). The main source of error in GNSS positioning occurring at the cm level is the multipath effect caused by specular or diffuse reflections around their stations. Detection and reduction of carrier phase multipath errors could be affected by the actual power of the transmitted signal, atmospheric effects, field loss, antenna gain pattern, etc. may be based on the affected SNR values (Rost and Wanninger, 2009).

To get an idea about the quality of the collected RINEX data, values such as SNR were compared with the YLDZ station data that has a geodetic receiver and choke ring antenna located near the test point. RTKLIB software was used to get SNR and other values and to visualize them. After the quality assessment, the collected 3.5 hours of GNSS data were divided into 1 hour and 2 hours sessions.

The PPP method can achieve centimeter positioning precision using a geodetic receiver with static or kinematic data. The ionospheric error is eliminated using dual frequency data that is used to generate ionosphere-free (IF) linear combinations (Kouba and Héroux, 2001). The PPP uses un-differenced, dual-frequency, pseudorange and carrier-phase observations with precise satellite orbit and clock products (Teunissen and Montenbruck, 2017). The following equations are the IF combinations of dual-frequency GNSS pseudo-range (P) and carrier phase observations (ϕ) (Kouba and Héroux, 2001; Koub, 2009).

$$L_P = \rho + c(dt - dT) + T_r + \varepsilon_P \,, \tag{1}$$

$$L_\phi = \rho + c(dt - dT) + N\lambda + \varepsilon_\phi \,, \tag{2}$$

where L_P and L_ϕ are the IF combination of L1 and L2 pseudranges and carrier phases, respectively, dt and dT are the clock offset of the receiver and satellite from GPS time, c is the speed of light in the vacuum medium, T_r is the delay due to the atmosphere (primarily troposphere), λ is the carrier wavelength, N is the non-integer ambiguity of the carrier phase IF combination, ε_P and ε_ϕ are the noise components, including multipath, ρ is the geometrical range between satellites $(X_s,\ Y_s,\ Z_s)$ and stations $(x,\ y,\ z)$,

$$\rho = \sqrt{(X_s - x)^2 + (Y_s - y)^2 + (Z_s - z)^2} \,. \tag{3}$$

If the tropospheric path delay (T_r) expressed as a function of the zenith path delay (zpd) with mapping function (M), related the tropospheric delay to the elevation angle of the satellite, while removing the known satellite clocks (dT), the following mathematical model can be expressed as the following equations:

$$f_P = \rho + cdt + M \cdot zpd + \varepsilon_P - L_P = 0, \tag{4}$$

$$f_\phi = \rho + cdt + M \cdot zpd + N\lambda + \varepsilon_\phi - L_\phi = 0. \tag{5}$$

As a result, the unknown parameters are receiver position coordinates (x, y, z), receiver clock (dt), zenith path delay (zpd) and carrier-phase ambiguities (N). After that the adjustment procedure (Kouba and Héroux, 2001) was applied to the model. To increase the accuracy of point coordinates, some corrections such as satellite antenna offsets and variations, relativistic effects, carrier phase wind-up, ocean tide loading, and solid earth tide should be applied.

There are several software programs to calculate coordinates using the PPP method. Some of them are GIPSY (Zumberge et al., 1997) and BERNESE (Dach et al., 2015). which are academic software that requires installations and web-based PPP services. Among the web-based PPP services the CSRS-PPP provide good accuracy than the others (El-Mowafy, 2011; Bulbul et al., 2021). Therefore all data have been sent to CSRS-PPP online web service.

Since the coordinate systems must be the same for the results to be compared, the UZEL coordinates have been converted to the datum and epoch of the results from the CSRS. Therefore UZEL reference point coordinates have been converted to ITRF2014 and measurement epoch (2021.7). Then, the differences between the processed and known coordinates have been determined in East, North and Height directions.

3. Results and discussions

The quality of GNSS data collected by the U-blox ZED F9P OEM GNSS receiver and ANN-MB-00 antenna was given in Figure 2. Here, SNR and multipath values, satellite elevation, DOP values (Fig. 2c) and satellite visibility (Fig. 2d) were graphed with UTC. When viewed in Figure 2a and Figure 2b, it is seen that the multipath values are different from zero. It is also seen that SNR values sometimes decreased as low as 20 dB-Hz.

YLDZ reference station is located 5 meters away from the UZEL test point. Magellan Proflex800 GNSS receiver and AERAT_120 SPKE geodetic choke ring antenna are used for the YLDZ reference station. SNR and multipath values of the YLDZ station have been given in Figure 3. It is seen that the average of the multipath values is zero and the average of the SNR values is 42 dB-Hz. As a result of this comparison, it could be said that there was a multipath effect on GNSS data collected on the U-blox ZED F9P OEM GNSS receiver and ANN-MB-00 antenna as seen in Figure 2 and Figure 3 created by RTKLIB 2.3.4_b34b.

After the quality control assessment, the result values from the CSRS-PPP service have been obtained. In Table 3, the coordinates obtained as a result of each hourly

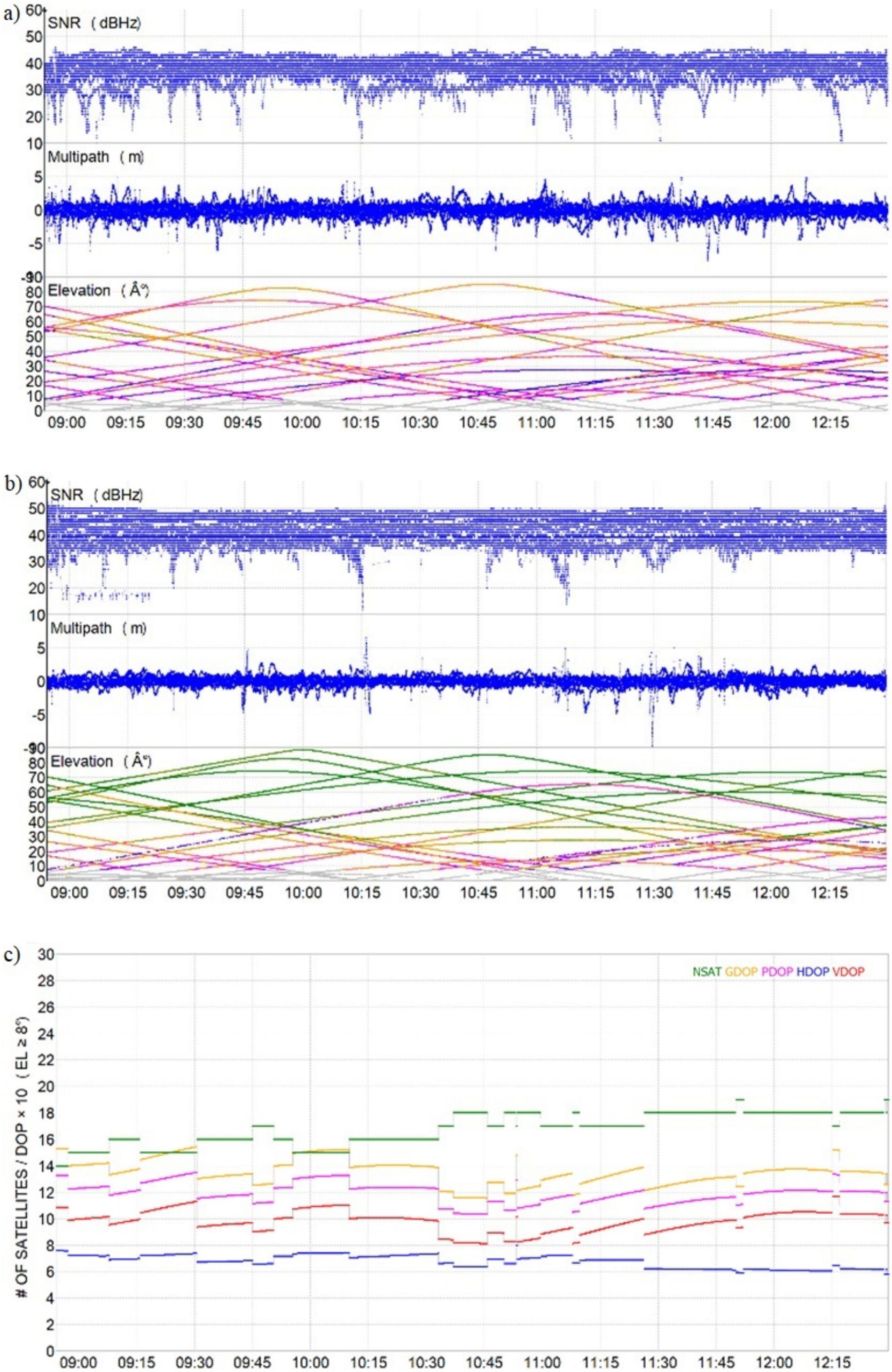

a)
SNR (dBHz)
Multipath (m)
Elevation (Â°)
09:00 09:15 09:30 09:45 10:00 10:15 10:30 10:45 11:00 11:15 11:30 11:45 12:00 12:15
b)
SNR (dBHz)
Multipath (m)
Elevation (Â°)
09:00 09:15 09:30 09:45 10:00 10:15 10:30 10:45 11:00 11:15 11:30 11:45 12:00 12:15
c)
NSAT GDOP PDOP HDOP VDOP
OF SATELLITES / DOP × 10 (EL ≥ 8°)
09:00 09:15 09:30 09:45 10:00 10:15 10:30 10:45 11:00 11:15 11:30 11:45 12:00 12:15

Fig. 2 (a), (b), (c)

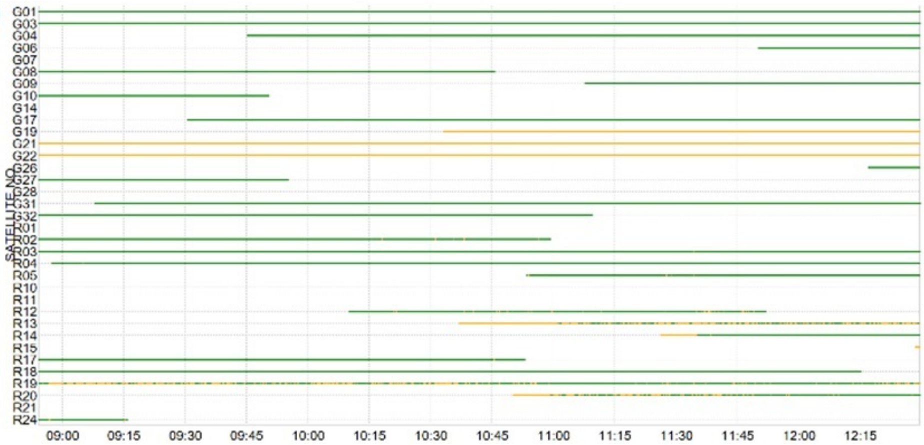
d)


Fig. 2. SNR, multipath and elevation angle of: a) L1 frequency, b) L2 frequency, c) DOP values, and d) satellite visibility of GNSS data by RTKPLOT application

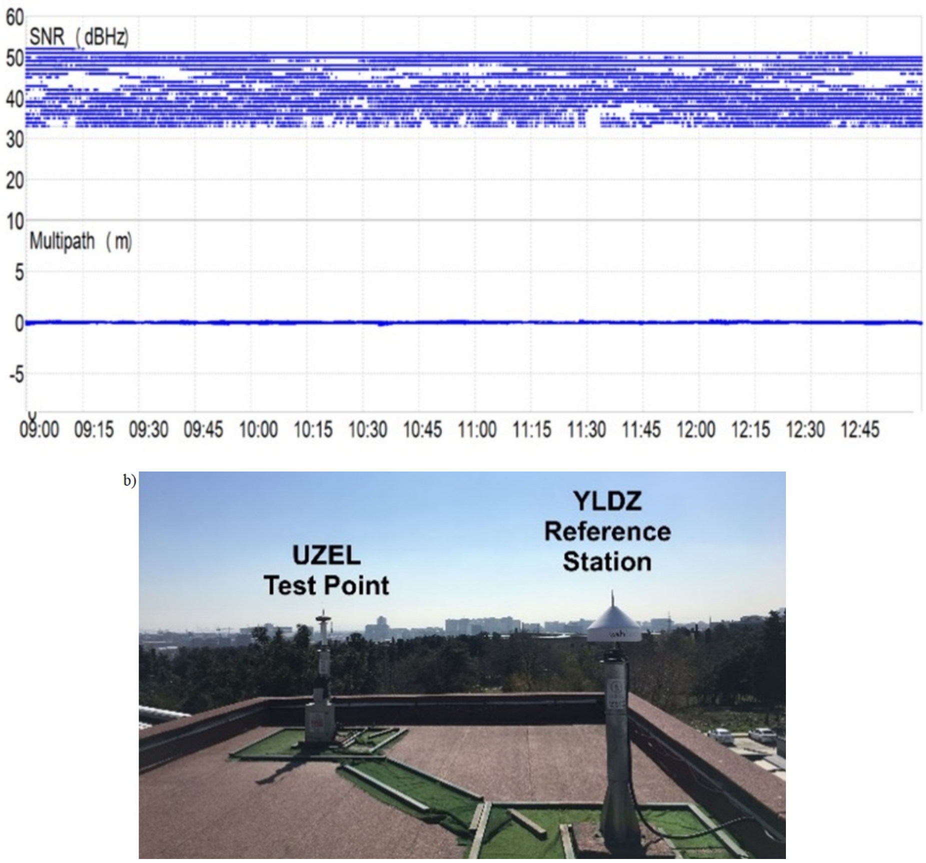
a)


Fig. 3. a) SNR, multipath values of L1 frequency for YLDZ station and b) view of UZEL and YLDZ stations

measurement session and the difference of these coordinate components from the known UZEL coordinates are given. In Table 4, the coordinates estimated from the first 2 hours and the all measurement session and their difference from the reference value are given.

Table 3. Processing results of 1 hour session data

Session	Duration	East (m)	North (m)	Height (m)	de (cm)	dn (cm)	dh (cm)
0–1 hr	1 hr	406541.5296	4543749.3336	126.8373	–11.9	4.7	8.9
1–2 hr	1 hr	406541.3662	4543749.3739	126.8523	4.5	0.6	7.4
2–3 hr	1 hr	406541.4363	4543749.3816	126.7743	–2.5	–0.1	15.2

Table 4. Processing results of 2 and 3.5 hour sessions data

Session	Duration	East (m)	North (m)	Height (m)	de (cm)	dn (cm)	dh (cm)
0–2 hr	2 hr	406541.5296	4543749.3458	126.8373	–11.9	4.7	8.9
0–3.5 hr	3.5 hr	406541.4246	4543749.3520	126.8523	4.5	0.6	7.4

The maximum coordinate differences determined in 0–1 hour session are 11.9 cm for the east direction, 4.7 cm for the north direction and 15.2 cm for the height direction. For the height component, the maximum difference value determined in in the 2–3 hours session as 15.2 mm. The average of the absolute value differences of the 1-hour session results are 6.3 cm, 1.8 cm and 10.5 cm for East, North and Height components, respectively and the horizontal position accuracy has been calculated as 6.6 cm. When the session time is doubled, the differences of the coordinates from the reference value decreased in the east and height components, but increased in the north direction. For the 2 hour data, the horizontal position accuracy is 4.0 cm. According to these values, approximately 40% improvement in the horizontal position accuracy and 35% improvement in the height have been observed. The horizontal position accuracy obtained as a result of the data with a measurement time of 3.5 hours has been calculated as 3.1 cm. This value is approximately 55% better than the horizontal position accuracy obtained as a result of 1-hour measurements, and approximately 20% better than two-hour measurement. In the height component, there is a 10% improvement compared to the 1-hour sessions but a decrease of approximately 30% compared to the 2-hour session result. As can be seen from the results, the horizontal position improved as the data duration increased. However, there is no significant improvement for the height component. The Figure 4 shows that the mean of the absolute differences from the known coordinates. As the session duration increases, the mean of the absolute difference values in the east direction decrease significantly, but there is no such decrease in the north and height components.

The standard deviations (σ) in all directions have been calculated using Eq. (6). The E_R, N_R and H_R are coordinates of the UZEL station; E_{PPP}, N_{PPP} and H_{PPP} are the PPP solution coordinates and n is the number of sessions. The standard deviation (SD) of

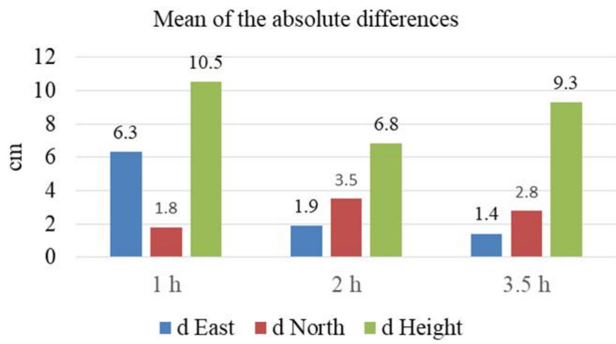


Fig. 4. Coordinate differences in all directions

1-hour data has been calculated 7.5 cm, 2.7 cm and 11.0 cm for East, North and Height respectively.

$$\sigma_{E(i)} = \sqrt{\frac{\sum \left(E_R - E_{\text{PPP}(i)}\right)^2}{n}}; \quad \sigma_{N(i)} = \sqrt{\frac{\sum \left(N_R - N_{\text{PPP}(i)}\right)^2}{n}}; \quad \sigma_{H(i)} = \sqrt{\frac{\sum \left(H_R - H_{\text{PPP}(i)}\right)^2}{n}}. \tag{6}$$

Wielgocka et al. (2021) compared the absolute positioning results of 1 hour static measurements with the actual coordinates and calculated the differences as ±5 cm, ±17 cm, and ±10 cm in the N, E, U directions, respectively. A few cm difference was observed between the coordinate values obtained as a result of 2.5 hours and more. These results are in agreement with the results of this study.

4. Conclusions

U-blox ZED F9P GNSS receiver and ANN-MB-00 antenna set have been used for determining the GNSS-PPP performance of low-cost GNSS receivers using short-term observation. To do this, the UZEL point located on the YTU campus and whose coordinates were determined by geodetic receivers and antennas has been used. To process the data collected for 3.5 hours, the ubx file must be converted to RINEX format. RTKLIB software has been used for this conversion process. For now, this software is the only option for converting multi-frequency .ubx files.

The collected GNSS data have been processed using CSRS-PPP online service and the differences between the processed and known coordinates have been determined. The maximum coordinate difference is the – 11.9 cm and 4.7 cm in the east and north directions respectively in the 0–1 hour session and 15.2 cm in the height direction in the 2–3 hours session. The mean coordinate difference of 1 hour sessions data has been calculated at – 3.3 cm, 1.7 cm and 10.5 cm and the standard deviation has been calculated at 7.5 cm, 2.7 cm and 11.0 cm in east, north and up directions respectively. The 0–2 hours session and 0–3.5 hours session coordinate differences have been calculated – 1.9 cm, 3.5 cm, 6.8 cm and – 1.4 cm, 2.8 cm, 9.3 cm respectively. The average height differences for all observations have been determined as approximately 8 cm. Horizontal position accuracy is 3.1 cm and height accuracy is 9.3 cm for the 3.5 hours session. If there is no base station with a known coordinate to be used as a fixed point in a study, then a station that has 3.1 cm in the horizontal and 9.3 cm in the vertical accuracy can be established by using low-cost GNSS. It can be used as a base station if it meets the desired accuracy.

It can be seen in Figure 4 that, east coordinate differences decrease when the observation period increase. However, this result is not observed for north and height direction differences. The low accuracy of the coordinate values obtained from geodetic GNSS receivers and antennas in the height direction is also observed in the results obtained in this study. In other words, the differences determined in the height direction have been turned out to be greater than the differences obtained in the horizontal position.

Author contributions

Conceptualization: N.O.A. and B.A.; research concept and design: M.F.K., N.O.A., B.A. and G.O.T. ; collection and assembly of data: M.F.K., N.O.A., Z.B.Ç. and İ.E.İ .; data analysis and interpretation: M.F.K., N.O.A. and G.O.T.; article writing: M.F.K., N.O.A, G.O.T., C.Ö.Y. and M.B.; critical revision and final approval of the article: B.A., B.D., C.Ö.Y. and A.A.D.

Data availability statement

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

Acknowledgements

This research was supported by Yildiz Technical University Scientific Research Project Coordinator Unit, project no: FCD-2021-4496 and presented at International Symposium on Applied Geoinformatics (ISAG2021). The authors thank CSRS-PPP online web service, NRCAN, TEQC and RTKLIB CONV, RTK PLOT softwares for processing and editing RINEX GNSS data.

References

Biagi, L., Grec, F.C., and Negretti, M. (2016). Low-cost GNSS receivers for local monitoring: Experimental simulation, and analysis of displacements. *Sensors*, 16(12), 2140. DOI: 10.3390/s16122140.

Bilich, A., Axelrad, P., and Larson, K.M. (2007). Scientific utility of the signal-to-noise ratio (SNR) reported by geodetic GPS receivers. In Proceedings of the 20th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS), 25–28 September 2007 (pp. 1999–2010), Fort Worth, TX, United States.

Bulbul, S., Bilgen, B., and Inal, C. (2021). The performance assessment of Precise Point Positioning (PPP) under various observation conditions. *Measurement*, 171, 108780. DOI: 10.1016/j.measurement.2020.108780.

Cahyadi, M., Handoko, E., Mardiyanto, R. et al. (2021). Comparative Analysis of Low-Cost GNSS OEM Board K706 AND BX316 (Case Study: Bulusidokare Village Sidoarjo Regency). In IOP Conference Series: Earth and Environmental Science, 26 August 2020 (vol. 731, 012024), Indonesia.

Casciati, F., Casciati, S., Fararelli, L. et al. (2016). Investigating the Performance of OEM Devices for Structural Monitoring. In 8th European Workshop on Structural Health Monitoring (EWSHM 2016), 5–8 July 2016 (pp. 1–8), Bilbao, Spain.

Cina, A., and Piras, M. (2015). Performance of low-cost GNSS receiver for landslides monitoring: test and results. *Geomat Nat Haz Risk*, 6(5-7), 497–514. DOI: 10.1080/19475705.2014.889046.

Dach, R., Lutz, S., Walser, P. et al. (2015). Bernese GNSS software version 5.2.

El-Mowafy, A. (2011). Analysis of web-based GNSS post-processing services for static and kinematic positioning using short data spans. *Surv. Rev.*, 43(323), 535–549. DOI: 10.1179/003962611X13117748892074.

Hill, A.C., Limp, F., Casana, J. et al. (2019). A new era in spatial data recording: low-cost GNSS. *Adv. Archaeol. Pract.*, 7(2), 169–177. DOI: 10.1017/aap.2018.50.

Janos, D., and Kuras, P. (2021). Evaluation of Low-Cost GNSS Receiver under Demanding Conditions in RTK Network Mode. *Sensors*, 21(16), 5552. DOI: 10.3390/s21165552.

Knight, P.J., Bird, C.O., Sinclair, A. et al. (2020). A low-cost GNSS buoy platform for measuring coastal sea levels. *Ocean Eng.*, 203, 107198. DOI: 10.1016/j.oceaneng.2020.107198.

Kouba, J. (2009). A guide to using International GNSS Service (IGS) products.

Kouba, J., and Héroux, P. (2001). Precise point positioning using IGS orbit and clock products. *GPS Solut.*, 5(2), 12–28. DOI: 10.1007/PL00012883.

Nie, Z., Liu, F., and Gao, Y. (2020). Real-time precise point positioning with a low-cost dual-frequency GNSS device. *GPS Solut.*, 24(1), 1–11. DOI: 10.1007/s10291-019-0922-3.

Odolinski, R., and Teunissen, P. J. (2016). Single-frequency, dual-GNSS versus dual-frequency, single-GNSS: a low-cost and high-grade receivers GPS-BDS RTK analysis. *J. Geod.*, 90(11), 1255–1278. DOI: 10.1007/s00190-016-0921-x.

PNT (2021). GPS Applications. Retrieved February, 2022, from https://www.gps.gov/applications/.

Rost, C., and Wanninger, L. (2009). Carrier phase multipath mitigation based on GNSS signal quality measurements. *J. Appl. Geod.*, 3(2), 81–87. DOI: 10.1515/JAG.2009.009.

Takasu, T., and Yasuda, A. (2009). Development of the low-cost RTK-GPS receiver with an open source program package RTKLIB. In International Symposium on GPS/GNSS, 4–6 November 2009, Jeju, Korea.

Teunissen, P.J., and Montenbruck, O. (2017). *Springer Handbook of Global Navigation Satellite Systems* (Vol. 11). Springer. DOI: 10.1007/978-3-319-42928-1.

Uaratanawong, V., Satirapod, C., and Tsujii, T. (2020). Optimization technique for pseudorange multipath mitigation using different signal selection methods. *Artif. Satell.*, 55(2), 77–86. DOI: 10.2478/arsa-2020-0006.

Van Nguyen, N., Cho, W., and Hayashi, K. (2021). *Performance evaluation of a typical low-cost multi-frequency multi-GNSS device for positioning and navigation in agriculture – Part 1: Static testing*. Smart Agricultural Technology, 1, 100004.

Wielgocka, N., Hadas, T., Kaczmarek, A. et al. (2021). Feasibility of using low-cost dual-frequency gnss receivers for land surveying. *Sensors*, 21(6), 1956. DOI: 10.3390/s21061956.

Zumberge, J., Heflin, M., Jefferson, D. et al. (1997). Precise point positioning for the efficient and robust analysis of GPS data from large networks. *J Geophys. Res. Solid Earth*, 102(B3), 5005–5017. DOI: 10.1029/96JB03860.