Advanced Engineering Science
http://publish.mersin.edu.tr/index.php/ades
e-ISSN 2791-8580

Performance analysis and kinematic test of the BeiDou Navigation Satellite System (BDS) over coastal waters of Türkiye

Volkan Akgül *1, Kurtuluş Sedar Görmüş 1, Şenol Hakan Kutoğlu 1, Shuanggen Jin 2,3

[1] *Zonguldak Bulent Ecevit University, Department of Geomatics Engineering, Türkiye, volkan_akgul@beun.edu.tr; ksgormus@beun.edu.tr; shakan.kutoglu@beun.edu.tr*
[2] *Chinese Academy of Sciences, Shanghai Astronomical Observatory, China, sgjin@shao.ac.cn*
[3] *Henan Polytechnic University, School of Surveying and Land Information Engineering, China*

Cite this study: Akgül, V., Görmüş, K. S., Kutoğlu, Ş. H., & Jin, S. (2024). Performance analysis and kinematic test of the BeiDou Navigation Satellite System (BDS) over coastal waters of Türkiye. Advanced Engineering Science, 4, 1-14

Keywords
GNSS
Performance analysis
Kinematic test
SPP
PPP

Research Article
Received: 12.12.2023
Revised: 29.12.2023
Accepted: 01.02.2024
Published: 09.02.2024

Abstract
Global Navigation Satellite System (GNSS) is essential for current civilization because it is used in many areas such as transportation, construction, agriculture, meteorology, disaster monitoring, risk management, etc. Therefore, developed countries strive to establish their positioning service to use the benefits they provide. BeiDou Navigation Satellite System (BDS) is a positioning service developed by China that recently achieved global coverage. Like other GNSS, BDS is subjected to various tests before commissioning. The system's control is the same as other positioning services, and it is tracked by ground control stations. In this context, position dilution of precision (PDOP), pseudorange multipath, and carrier phase signal-to-noise ratio (SNR) performance analysis were carried out with 30 seconds interval BDS data of ZBEU (Zonguldak Bulent Ecevit University) GNSS monitor station. BDS's multipath and SNR results were compared with other global positioning services. Single and multi-system precise point positioning (PPP) solutions were examined comparatively using the 2019 and 2023 data of the ZBEU station. In addition, BDS kinematic test results were examined with 1-second interval data of transects along the coast of the Black Sea and the Mediterranean Sea. Satellite visibility, PDOP, and positioning performance were analyzed along the offshore survey route. In terms of SNR and multipath, the results showed that the performance of BDS signals was similar to other GNSS. Depending on the satellite visibility change, SPP results in the Mediterranean were better than the Black Sea. It has been observed that BDS PPP results were improved from 2019 to 2023, and achieved almost the same results as other GNSS.

1. Introduction

The Global Positioning System (GPS) comes first to mind as a well-known positioning service. Although GPS is a top-rated positioning service worldwide, nowadays, the Global Navigation Satellite System (GLONASS) of Russia, the BeiDou Navigation System Satellite (BDS) of China, and Galileo of the European Union are the available alternative positioning services. While the GLONASS has been wholly under service since 2011, the BDS has become fully operational with the satellite launched on June 23, 2020 [1]. The Galileo constellation started to serve at full capacity in 2022. Satellite-Based Augmentation Systems (SBAS) are also used to increase the accuracy and precision of these positioning services. The GPS, GLONASS, BDS, Galileo, and SBAS are collectively called Global Navigation Satellite Systems (GNSS) [2].

BDS has three stages of being commissioned as a global positioning service. Initially, BeiDou Satellite Navigation Experimental System covering China and nearby regions was commissioned in 2000. The system, also called BeiDou-1 (BDS-1), consisted of 3 satellites, offered navigation services in the narrow coverage area, and was left out of service in 2012. BeiDou-2 which was fully operational at the end of 2012, covers the Asia Pacific countries. This second-generation system, COMPASS (BDS-2), consisted of 14 satellites. The space segment of BDS-2 includes five geostationary earth orbit (GEO), five inclined geostationary earth orbit (IGSO), and four medium earth orbit (MEO) satellites. This system offers users positioning, navigation, timing (PNT), and short message service. BeiDou Navigation Satellite System (BDS), the third and last generation positioning system, is also known as BeiDou-3. The nominal constellation of BDS-3 consists of 30 satellites: 3 GEO, 3 IGSO, and 24 MEO [3].

Performance tests of GNSS systems are evaluated with pseudorange multipath, position dilution of precision (PDOP), signal-to-noise ratio (SNR), single point positioning (SPP), and precise point positioning (PPP). There is a highly inverse correlation between the multipath effect and the satellite elevation angle, and the multipath effect decreases as the elevation angle increases [4]. It is also valid for BDS satellites except for GEO satellites. When the characteristics of BDS multipath effects are examined by spectral, and correlation analyses for B1/B2 and B1/B3 signals combinations, periodic patterns are found in the multipath time series of most satellites, and daily repeated components always play a dominant role [5]. In addition, the measurement quality of BDS-3 outperforms BDS-2 in terms of SNR and multipath values for the same type of satellites [6].

SNR, multipath and pseudorange SPP accuracy of GPS, BDS, GLONASS, and Galileo are investigated over the Asia-Pacific region. BDS gives similar results to GPS for SNR and multipath error, while GLONASS gives more significant errors. In addition, the positioning accuracy of the BDS is approximately the same as GPS, while BDS shows better results than GLONASS for the GNSS receiver used in a central location of the areas covered by the BDS satellites [7].

PPP is another method used in performance analysis. Ground object positions can be obtained precisely using the final precise ephemeris products and satellite clock offsets. Precise positioning, Zenith Tropospheric Delay (ZTD), Inter-Frequency Bias (IFB), and Differential Code Bias (DCB) can be analyzed by BDS PPP models, and multi-frequency BDS observations will significantly improve the PPP performances [8]. In this study, single and multi-system PPP solutions for the ZBEU observation station were examined. Additionally, the PPP results were also used to determine the accuracy of offshore kinematic observations.

The GNSS is briefly defined as a set of satellites used to obtain 3D positioning at any point in the world with signals sent from satellites at any time and weather conditions. The reliability of the positioning services is directly proportional to the signal quality transmitted from the satellites to GNSS receivers. Therefore, GNSS are subjected to tests in this context until they become fully operational.

Studies on BDS kinematic tests are limited in this study area. The offshore kinematic observations conducted in the south and north of Türkiye were carried out similarly to the land BDS kinematic tests conducted by [9] to test their results. BDS performance tests in terms of SNR, multipath, satellite visibility, and PDOP were generally conducted in China and its nearby areas [9,10]. In addition to the BDS kinematic tests over Türkiye, 30 seconds of observation of the ZBEU station for the BDS B1 and B2 signals were used. The obtained SNR and multipath values were compared with the results of other positioning systems. The experiment aims to investigate the performance of BDS over some sections of the coastal waters of Türkiye.

The following objectives or tasks were performed towards achieving the aim of the study:

- Satellite visibility and PDOP of BDS at the ZBEU permanent GNSS station on DOY 152, 2019.
- Mean multipath and SNR of BDS during 30 days on June 2019 at the ZBEU, and comparison with GNSS.
- Single and multi-system GNSS PPP solutions using with different year data of the ZBEU station.
- Kinematic performance of BDS over the Black Sea with accuracy assessment.
- Kinematic performance of BDS over the Mediterranean Sea with accuracy assessment.

2. Data and Method

2.1. Data

The ZBEU is a permanent monitoring station working with a ComNav GNSS receiver and choke ring antenna. In this study, 30-second sampled data collected over 30 days during June 2019 at the ZBEU station located in Zonguldak, Türkiye, was processed and analyzed further. Mean SNR and multipath comparisons of different global systems were performed with a 30-day data set. In order to observe the PPP performance change of GNSS between 2019 and 2023, 1 day data of ZBEU from June 1st, 2019 and June 1st, 2023 were also evaluated.

As the satellite elevation angle decreases, the path of the GNSS signals becomes longer due to atmospheric refraction [11]. Therefore, data with low satellite elevation angles are not used. This study used observations with a satellite elevation angle of > 7° for the static and kinematic observations. The kinematic tests are carried out at a distance of approximately 10 km from the Mediterranean and Black Sea coastlines to prevent a decrease in visible satellites due to the earth's surface objects. Since the duration of the kinematic observations at sea was short, observations with a sample interval of 1 second were carried out and evaluated.

The BDS kinematic test was carried out along the approximately 30 km long survey route, located some 10 km offshore of the Black Sea. One-second interval observations were carried out on 23 July 2019, between 7:28 and 9:44 UTC, using UR4B0 GNSS receiver in the Black Sea. Another survey was planned in the Mediterranean Sea.

Unfortunately, unforeseen circumstances (military exercise) did not allow us to execute that plan. However, an approximately 35 km randomly route was still followed, and the measurements were successfully collected.

Consequently, 1-second BDS data were available on 5 September 2019 between 6:29 and 9:32 UTC using the UR4B0 GNSS receiver for kinematic tests in the Mediterranean Sea. Figure 1 shows the locations of the Black and Mediterranean Sea survey route.

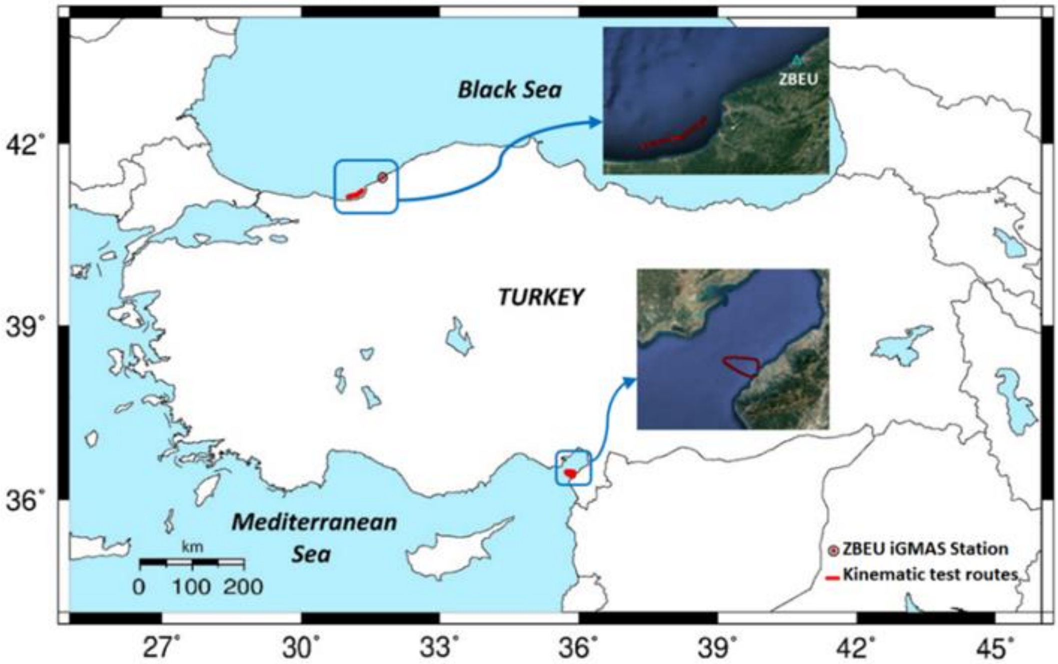

Figure 1. Location of transects along the Black and Mediterranean Sea coastlines.

2.2. Method

2.2.1. Signal quality assessment

In this study, 30-second sampling interval BDS data of the ZBEU station was subjected to performance analysis with satellite visibility, PDOP, pseudorange multipath, and carrier phase SNR.

The geometric distribution of the satellites according to the receiver is an essential factor in determining the three-dimensional position with global positioning services. However, the mutual positions of the satellites and the receiver cause errors in determining the receiver coordinates. This is known as the Dilution of Precision (DOP) factor. Position dilution of precision (PDOP) is one of the DOP parameters commonly used to characterize the accuracy of the position determination.

The high PDOP value indicates that the satellite geometry is unsuitable for accurate positioning (satellites are too close to each other). In contrast, the lower PDOP value shows better satellite distribution [12]. There is an inverse correlation between visible satellites and the PDOP. The higher number of visible satellites, the higher chance of a suitable satellite geometry. The correlation between the number of visible satellites and PDOP for the ZBEU BDS observations is discussed in Figure 2.

The pseudorange multipath (M_{ρ_1} and M_{ρ_2}) is obtained with the carrier phase and pseudorange observables for the frequency 1 and 2, expressed as Equation 1 and 2 [13]:

$$M_{\rho_1} = \rho_1 - \frac{f_1^2 + f_2^2}{f_1^2 - f_2^2} \lambda_1 \varphi_1 + \frac{2f_2^2}{f_1^2 - f_2^2} \lambda_2 \varphi_2 + \varepsilon_{\rho_1} \quad (1)$$

$$M_{\rho_2} = \rho_2 - \frac{2f_1^2}{f_1^2 - f_2^2} \lambda_1 \varphi_1 + \frac{f_1^2 + f_2^2}{f_1^2 - f_2^2} \lambda_2 \varphi_2 + \varepsilon_{\rho_2} \quad (2)$$

where ρ_1 and ρ_2 refer pseudorange observables, φ_1 and φ_2 are the carrier phase observations. While f_1 and f_2 represent the frequencies of carrier phase observations, λ_1 and λ_2 are the wavelengths of these signals. ε_{ρ_1} and ε_{ρ_2} correspond to the sums of the constant part of the multipath effect, the hardware delay, and the carrier phase ambiguity. The equations given with code and phase observations result from subtracting satellite clock error, first-order ionospheric delay, tropospheric delay, receiver clock error, and distance between satellite and receiver from the observation equation between satellite and receiver. The multipath error in the carrier phase observation is less than a quarter of the carrier wavelength, considerably less than the multipath error in pseudorange measurements [13, 14].

In addition to the observation environments, multipath effects are also correlated with SNR, satellite elevation angle and tracking algorithms of the receivers. The SNR, a kind of GNSS observable value, represents the strength of the signal received by the receiver antenna [15]. The antenna gain model is a parameter that affects the SNR. According to this model, the higher the satellite elevation angle of the signal coming to the receiver, the greater the gain and the smaller the receiver noise power. Therefore, when the quality of observation data is to be analyzed, the higher the SNR value, the better the data quality [16].

2.2.2. Positioning assessment

The equation of the BDS pseudorange observation of one satellite-user pair is as Equation 3 [9]:

$$P = \rho + c(\delta t_r - \delta t^s) + \delta_{tgd} + \delta_{ion} + \delta_{trop} + \delta_{rel} + M_p + \varepsilon_p \tag{3}$$

The where P is pseudorange, ρ is the geometric distance between satellite and receiver; δt_r, δt^s and δ_{tgd} represents the receiver clock offset, satellite clock offset, and time group delay, respectively; δ_{ion}, δ_{trop}, and δ_{rel} refers to ionospheric delay, tropospheric delay and relativistic effects, respectively; $M_p$and ε_p are multipath effect, and pseudorange observation noise, respectively.

According to [17], the parameters required in the positioning solution and the errors in Equation 3 are corrected by using the algorithm, and specific constants to calculate the satellite orbit and satellite clock offset with broadcast ephemeris. During the SPP solutions, BDS broadcasted ephemeris files from Test and Assessment Research Center, CSNO. While the ionosphere free solution was used to calculate the ionospheric delay, the Saastamoinen model corrected the tropospheric delay. In addition, the time group delay was fixed using the broadcast ephemeris's time group delay parameters.

The critical task in kinematic positioning performance analysis is the realization of precise positioning to be referenced to test positioning accuracy. While [18] used the GPS-only PPP results in phase ambiguity fixed epochs as a reference, [19] used the RTK (real time kinematic) survey results in their kinematic tests. According to [9, 20], both of these studies are implemented in asmall-scale region but unsuitable for large-scale kinematic testing. Therefore, RT-PPP technology, which has globally uniform positioning accuracy, and can achieve a positioning accuracy of decimeters to a centimeter in real-time, has been considered, and used as a reference for large-scale kinematic tests. Furthermore, using precise orbit and clock products, the PPP provides the opportunity to obtain results close to relative positioning accuracy [21].

PPP post-process results were chosen as a reference for kinematic surveys. While PPPLib software was used for PPP, adjusted coordinates were obtained using with the online GPS processing service AUSPOS [22, 23]. The adjusted coordinate used as a reference for PPP positioning accuracy assessment. While applying the PPP solutions, Earth Rotation Parameters, precise ephemeris and clock products were used from the GNSS data center of Wuhan University. A dual-frequency, ionosphere free solution was applied to remove the first-order ionospheric delay. The Saastamonian model was applied for the tropospheric correction.

3. Results

3.1 Signal quality results

The increased satellite visibility improves the probability of accessing appropriate PDOP values and position accuracy. Satellite visibility and PDOP of the ZBEU station DOY 152, 2019 data are as in Figure 2.

When BDS-2 and BDS-3 are used together to improve the geometric distribution of satellites, the visibility of BDS satellites at the ZBEU station ranges from 9 to 18. There is an inverse correlation between satellite visibility and PDOP values as seen in Figure 2, and the decrease in PDOP values is remarkable as the number of satellites increases. Generally, the PDOP values ranging from 1 to 2 are excellent, and provide sufficient accuracy for most precise positioning applications.

Multipath is the phenomenon of fluctuations in signal strength caused by the reflection or scattering of signals coming directly to the receiver from different directions. The structure of these reflected or scattered signals differ in amplitude and phase compared to the nature of the directly received signals. This is because, along with the lengthening of the path travelled by the multipath signals, a sudden phase change of the wave occurs during the reflection or scattering of this signal. Consequently, the amplitude of the signal decreases.

The multipath effect of the ZBEU station on the BDS B1I and B2I signals of DOY152, 2019, is as in Figure 3.

As shown in Figure 4, the satellite visibility for the B2 signal is less than B1. The main reason for this is that while the B1 signal is valid for the BDS-2 and BDS-3 systems, the B2 signal no longer exists with the BDS-3 system.

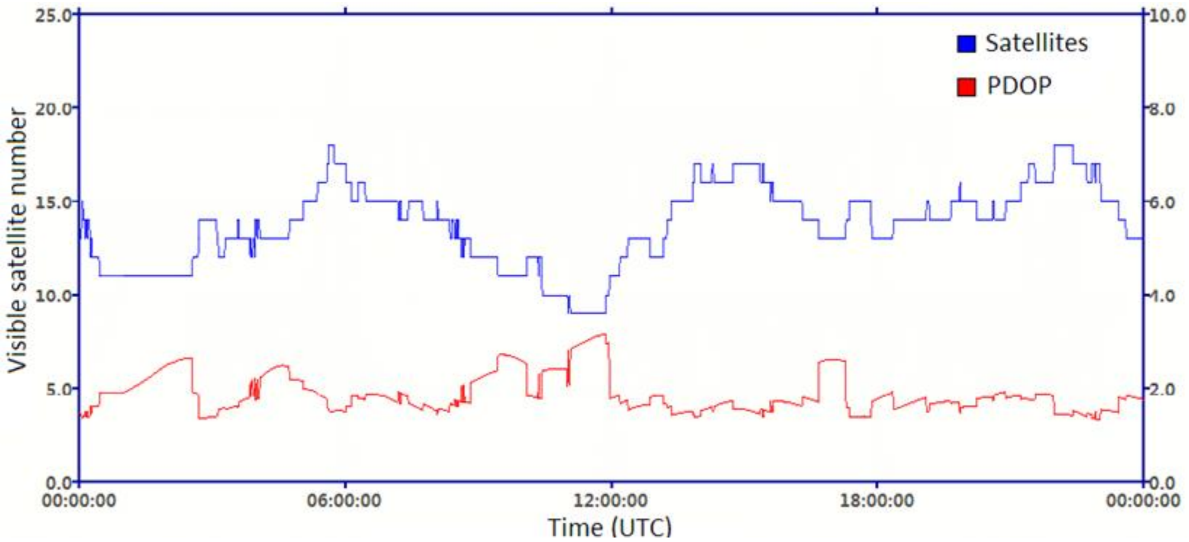

Figure 2. Satellite visibility and PDOP of BDS on 1 June 2019 at ZBEU station.

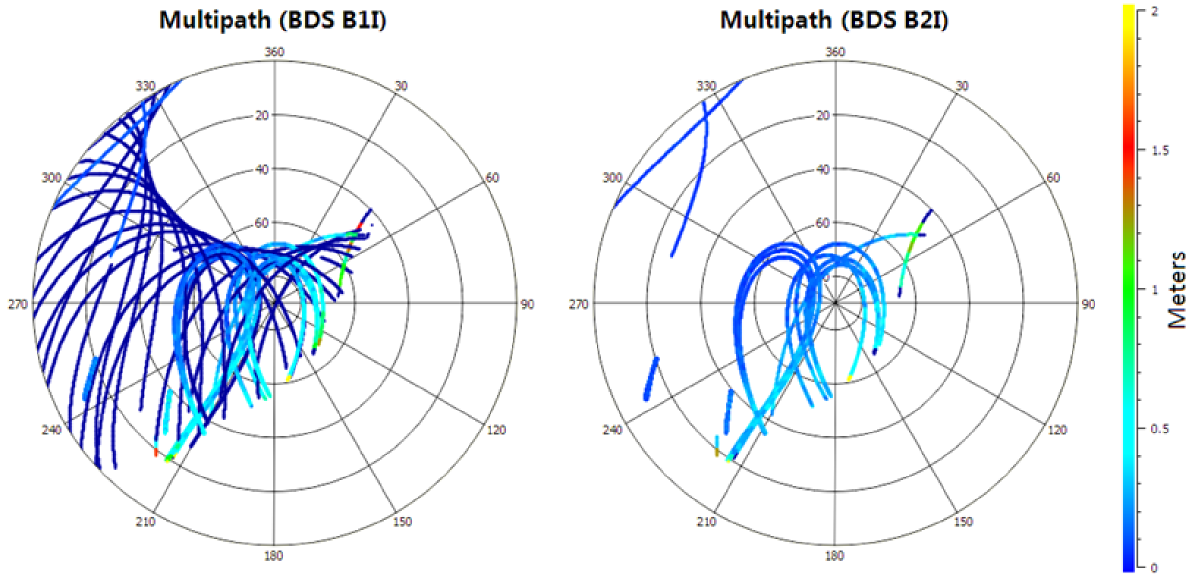

Figure 3. Pseudorange multipath with elevations on 1 June 2019 at ZBEU station.

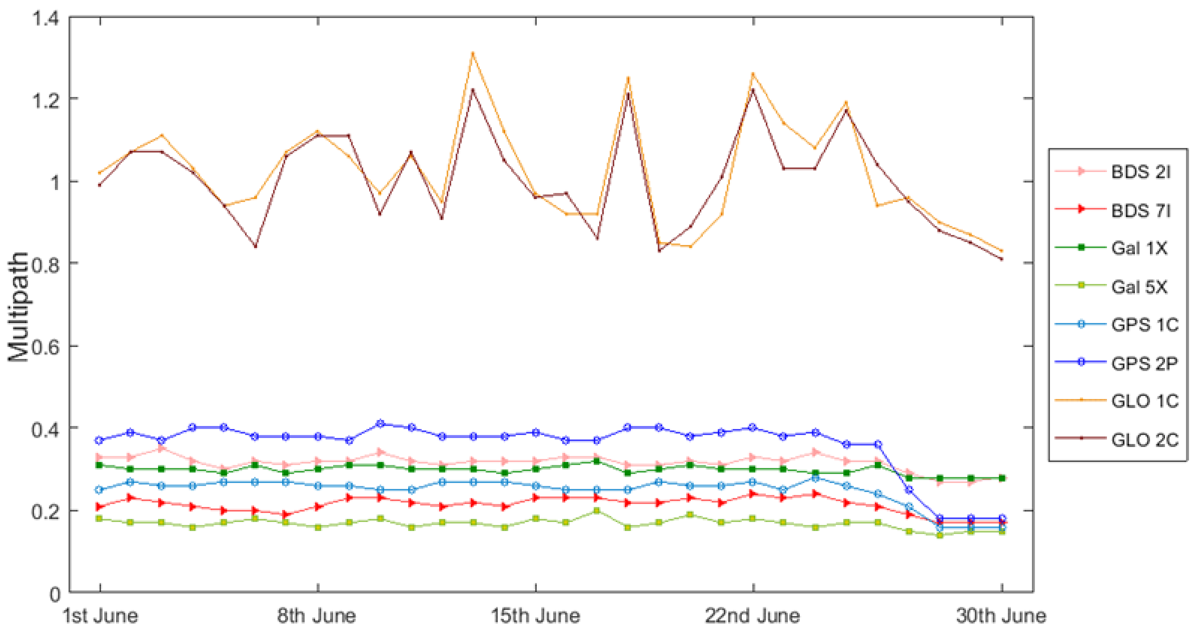

Figure 4. Daily mean pseudorange multipath comparison of GNSS at ZBEU station (June 2019).

The increase in the multipath causes an effect that reduces the positioning accuracy. Therefore, a multipath comparison was made with the 30-day data of June 2019 to compare the BDS with the other positioning services. A comparative graph using the average daily multipath is as in Figure 4.

BDS 2I, BDS 7I, Gal 1X, Gal 5X, GPS 1C, GPS 2P, GLO 1C, and GLO 2C are the observation codes respectively belong to BDS B1, BDS B2, Galileo E1, Galileo E5a, GPS L1, GPS L2, GLONASS G1, and GLONASS G2 frequency bands. Looking at the daily average multipath has been identified in Figure 4, the multipath effect on BDS 2I, 7I, Galileo 1X, 5X, GPS 1C, 2P, GLONASS 1C, and 2C signals are 0.32, 0.21, 0.30, 0.17, 0.25, 0.36, 1.02, and 1.00m, respectively.

Nowadays, GNSS is not only used for positioning. It can also retrieve the environmental parameters around the receiver antenna using SNR, creating a new field of study. In this topic, some scientists have proposed GPS-MR technology based on signal-to-noise observations. Snow surface, sea level, vegetation, and other surface environment were analyzed using the SNR's multipath reflection component, and several results were obtained [24-26].

The SNR for each visible satellite depends on the elevation angle at the ZBEU station on the BDS B1 and B2 signals of DOY152, 2019, as shown in Figure 5.

The increase in the SNR value is a factor that increases the position accuracy. Daily mean SNR values for 30 days of June 2019 compared for BDS and other systems. A comparative graph using the average of daily SNR values is as in Figure 6.

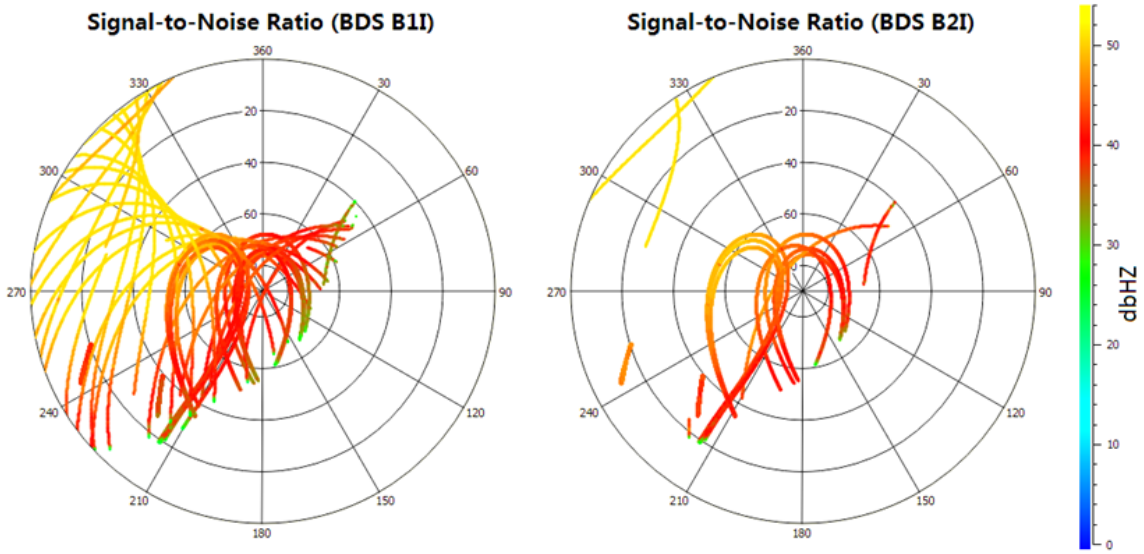

Figure 5. SNRs with elevations on 1 June 2019 at ZBEU station.

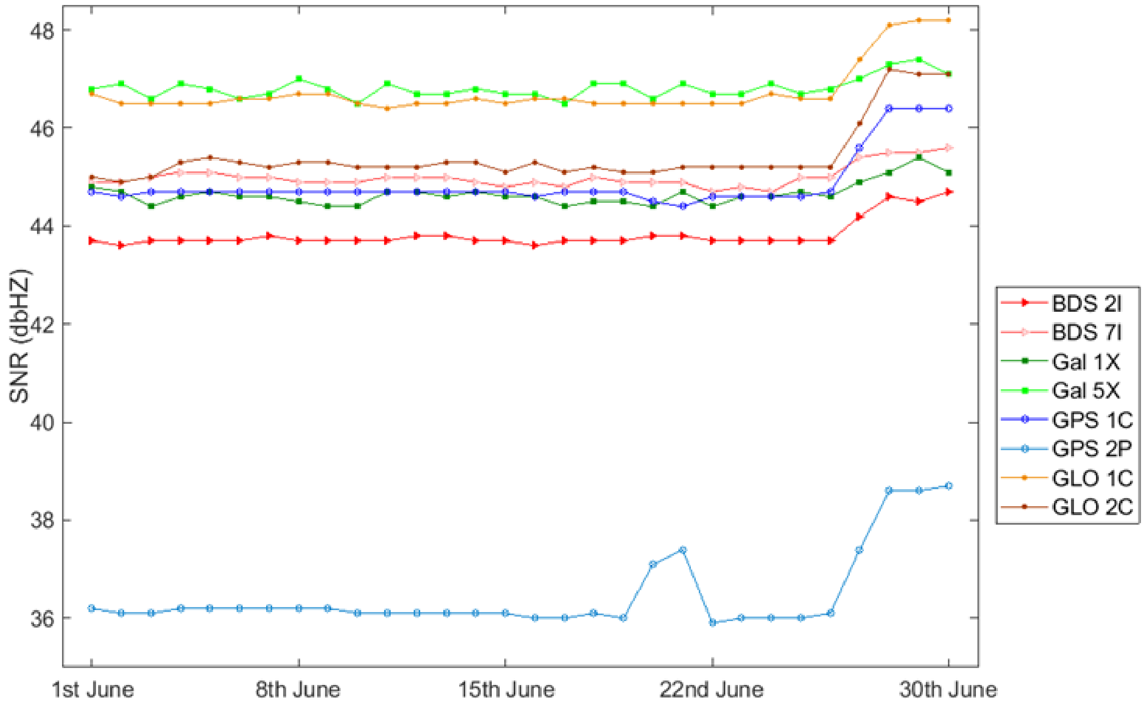

Figure 6. Daily mean SNR comparison of GNSS at ZBEU station (June 2019).

Considering the daily average SNR has been identified in Figure 6, the SNR values of BDS 2I, 7I, Galileo 1X, 5X, GPS 1C, 2P, GLONASS 1C, and 2C signals are 43.82, 45.00, 44.65, 46.82, 44.86, 36.47, 46.74 and 45.42 dB Hz, respectively.

3.2 Positioning results

3.2.1 Precise point positioning results

Especially with the improvement of precise satellite orbit and clock information, the PPP positioning accuracy is improved. Since the performance of BDS is discussed within the scope of this study, firstly the performance of BDS PPP in different years was examined with convergence time and RMS (root mean square) error. If an accuracy of 10 cm or less was achieved in the north, east and up components and an accuracy below 10 cm continued to be achieved for a minimum of four epochs, the initial epoch was accepted as the convergence time. And, the adjusted coordinates of the ZBEU station were used as a reference to determine the PPP positioning accuracy. DOY 152, 2019 and DOY 152, 2023 data of the ZBEU station were used with BDS PPP solutions (Figure 7).

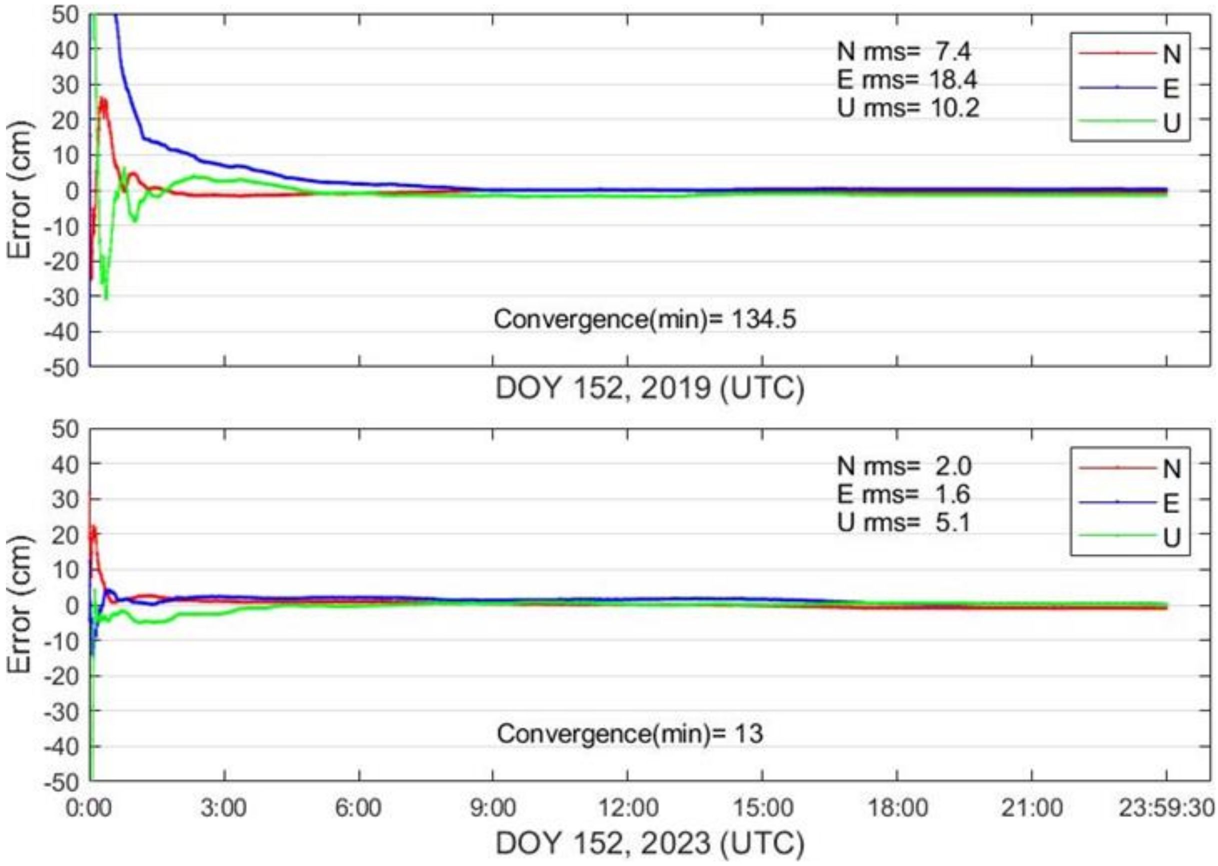

Figure 7. The ZBEU station BDS PPP results comparison of DOY152 2019 and 2023.

Figure 7 shows that while the convergence time has been 134.5 minutes for 2019, it will be 13 minutes for 2023. The main reason for it is that BDS does not provide full capacity service in 2019. There has been an increase in the number of visible satellites with the new satellites launched until 2023. Thus, BDS satellite geometry has been improved. The positive developments in BDS in the 4-year interval have brought about a decrease in the mean square error values in position determination.

Individual performances of global systems in terms of convergence time and RMS errors are also handled in Figure 8 and Figure 9. Convergence times were determined as 9.5, 7.5, 13.0, and 12.5 minutes for the GPS, Galileo, BDS, and GLONASS, respectively. The Galileo showed the best performance in terms of convergence time and horizontal positioning accuracy, and the GPS showed the best performance in vertical component accuracy.

Changes between 2019 and 2023 in PPP convergence times, mean satellite visibility and RMSE (root mean square error) for Multi-GNSS, and their combinations are given in Table 1.

While BDS and Galileo were not operating at full capacity in 2019, all global systems became full capacity operational in 2023. The average number of visible satellites in 2019 and 2023 stands out as an increase of approximately two satellites for Galileo and BDS. It is observed that in systems with increased satellite visibility, convergence times and RMSE improve from 2019 to 2023. Convergence time and RMSE values of multiple system evaluations were better than single system evaluation.

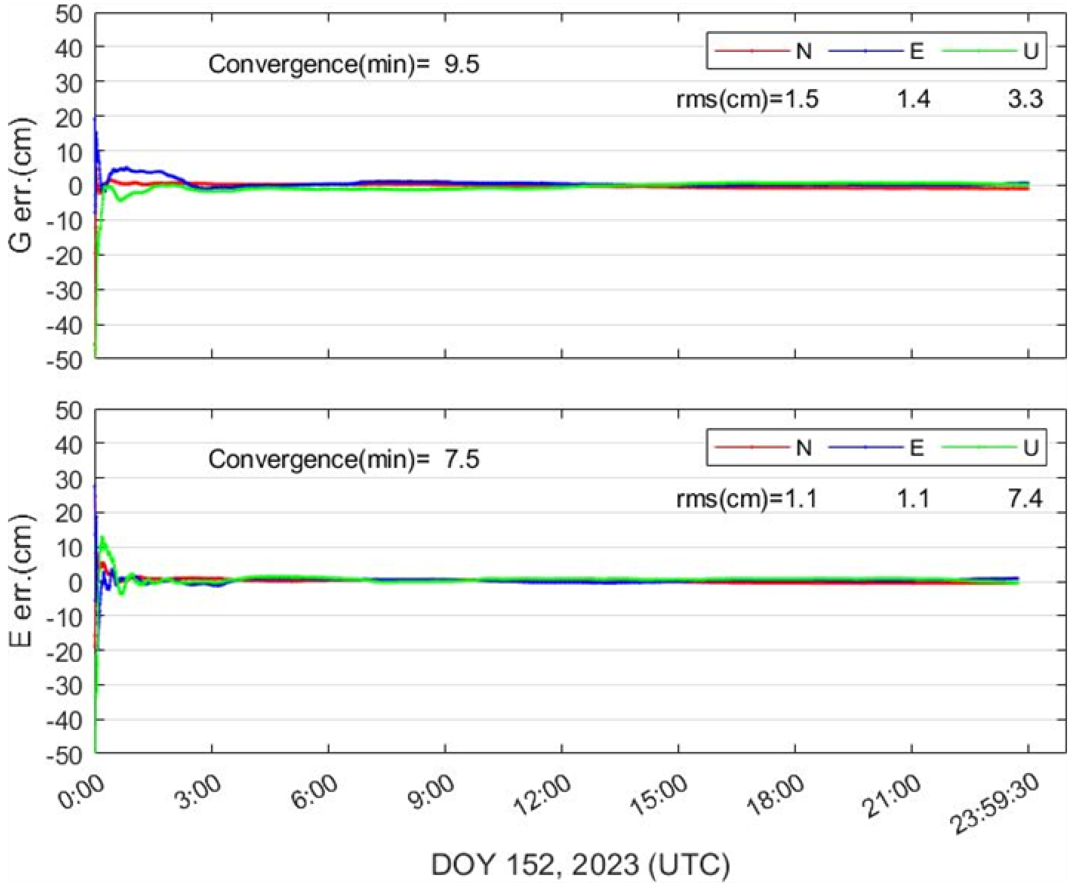

Figure 8. The ZBEU station GPS(G) and Galileo(E) PPP results comparison on DOY152, 2023.

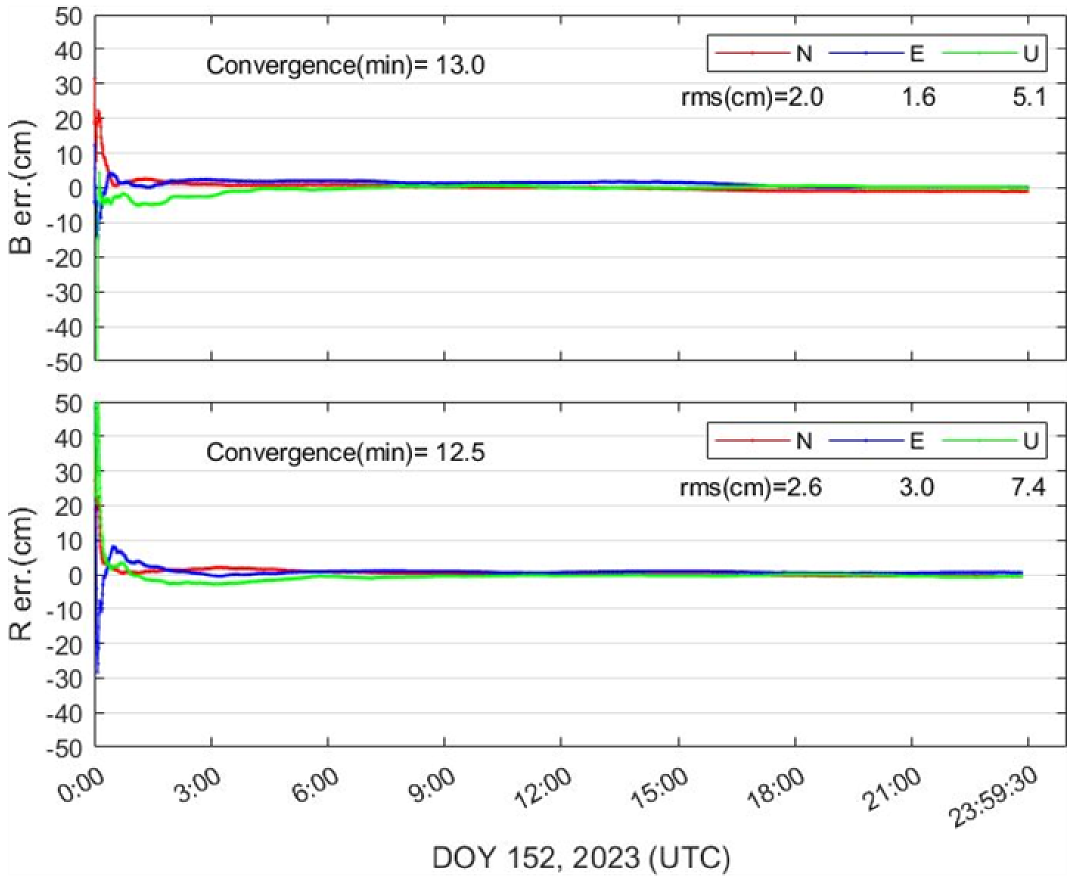

Figure 9. The ZBEU station BDS(B) and GLONASS(R) PPP results comparison on DOY152, 2023.

Table 1. Multi-GNSS PPP results comparison on ZBEU with data from 2019 and 2023.

System	Convergence Time (min)		Mean vis. satellites		RMSE (± cm) N		E		U	
	DOY 152 Year 2019	152 2023	152 2019	152 2023	152 2019	152 2023	152 2019	152 2023	152 2019	152 2023
GPS (G)	8.5	9.5	9.3	8.8	1.8	1.4	0.9	1.5	7.7	3.3
BDS (B)	134.5	13.0	10.8	12.6	18.4	1.6	7.4	2.0	10.2	5.1
Galileo (E)	10.5	7.5	5.3	7.2	1.5	1.1	2.0	1.1	5.6	7.4
GLONASS (R)	18.5	12.5	6.1	6.0	3.8	3.0	1.4	2.6	10.8	7.4
G+B	5.0	6.5	20.1	21.3	1.1	1.2	1.4	0.9	6.5	4.3
G+B+E	7.5	6.0	25.4	28.5	0.6	1.0	0.7	0.9	3.1	4.7
G+B+R	5.5	6.0	26.3	27.4	0.9	1.3	1.0	1.0	4.9	2.5
G+B+E+R	1.5	5.0	31.5	34.5	0.7	1.2	0.6	1.0	2.6	3.1

3.2.2 Black Sea kinematic test results

In order to test the kinematic performance of BDS, approximately 30 km of measurement was carried out parallel to the Black Sea coastline. In addition, 1-second interval observations are handled during the kinematic testing route over the Black Sea (Figure 10).

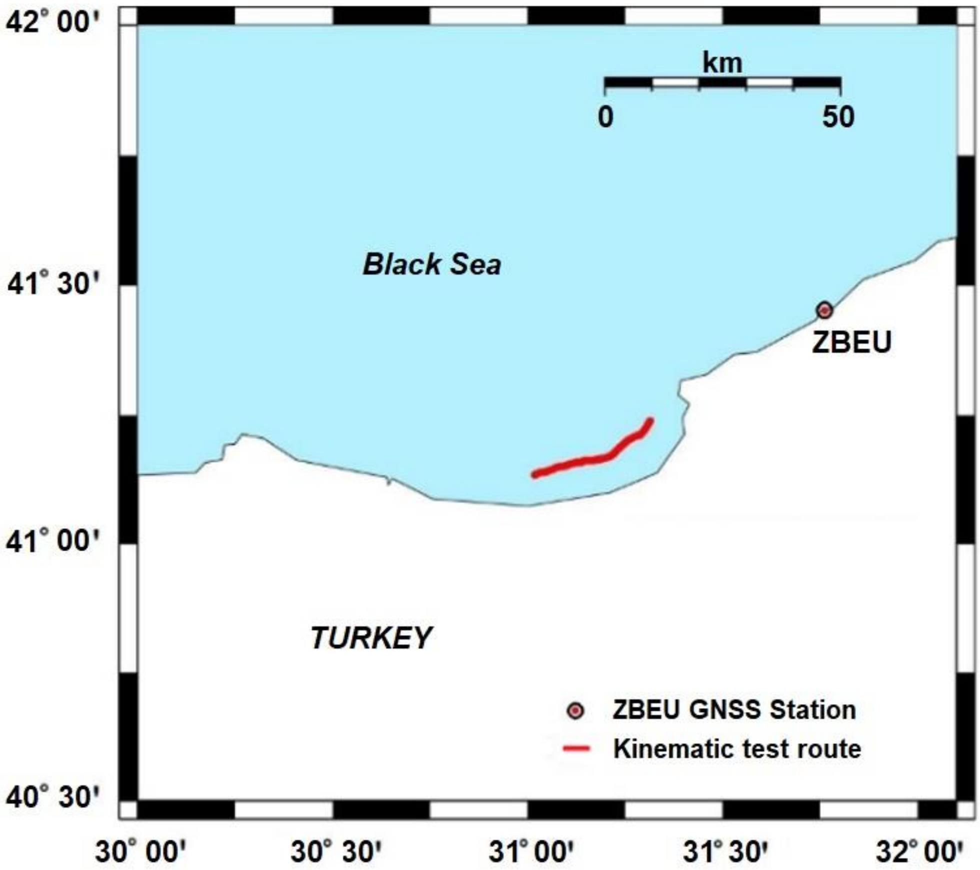

Figure 10. Kinematic test route over the Black Sea.

The B1I, B3I signals for regional Beidou-2 (BDS-2) and global Beidou-3 (BDS-3) were examined separately. When the BDS-2 and BDS-3 data are used together, changes in the number of satellites and PDOP are examined. When the BDS-2 and BDS-3 data are evaluated separately alone, the decrease in the number of visible satellites and the increase in PDOP values affect the positioning accuracy negatively. The lower the PDOP, the more reliable the positioning. In this context, those with a PDOP value above six have not been evaluated. Horizontal and vertical positioning accuracy in the 95% confidence interval of kinematic measurements performed in the Black Sea is as in Table 2. PPP (precise point positioning) results were used to determine the accuracy of SPP (single point positioning) results.

Compared with BDS-3, BDS-2 have more visible satellites, but due to bad geometric configuration, the PDOP value and the positioning results were not good. However, with better satellite geometric configuration, the PDOP value and the positioning results of BDS-3 were better than BDS-2. Therefore, when using BDS-2 and BDS-3 jointly, users can have more visible satellites, good PDOP, and positioning accuracy results.

Table 2. Black Sea BDS SPP Accuracy on 23 July 2019 (PDOP≤6).

Frequency		H (m)	V (m)	SatNum(mean)	PDOP (mean)
BDS-2	B1I	4.12	5.46	6.4	5.5
	B3I	3.70	5.28		
	B1IB3I	6.45	6.51		
BDS-3	B1I	1.05	1.69	6.2	3.4
	B3I	1.47	2.19		
	B1IB3I	0.59	1.93		
BDS (BDS-2 + BDS-3)	B1I	1.57	1.55	12.6	1.84
	B3I	2.11	2.23		
	B1IB3I	1.81	3.55		

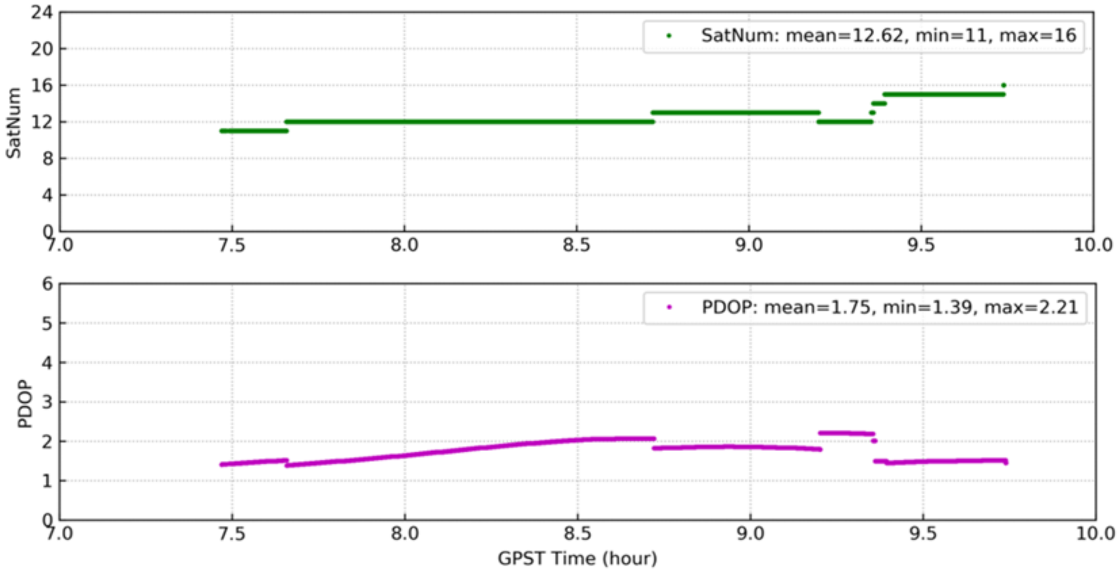

Figure 11. The Number of Visible Satellites and PDOP of BDS over the Black Sea.

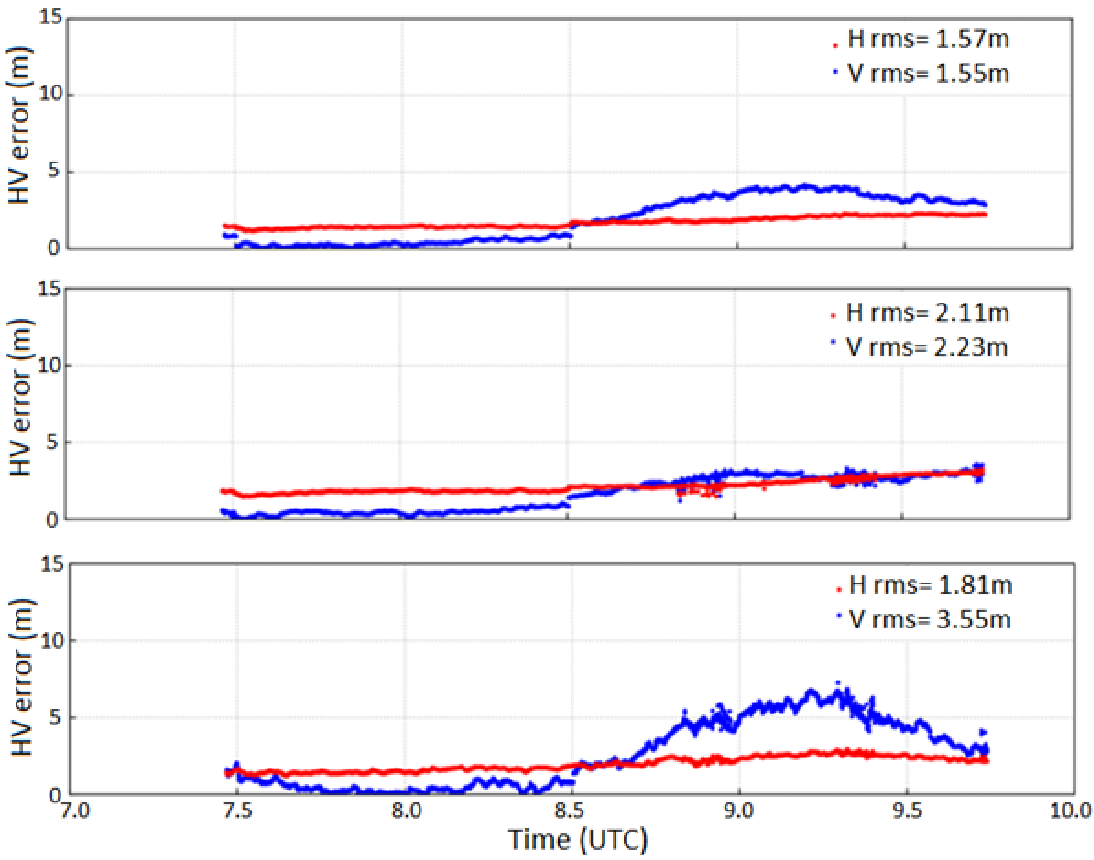

Figure 12. BDS B1I, B3I, B1IB3I SPP Accuracy over Black Sea.

Theoretically, dual frequency positioning is effective for ionosphere-free, improving positioning accuracy. However, compared to single-frequency positioning, some pseudorange error effects (e.g. ionosphere delay) could be minimized, and some (e.g. multipath, hardware delay and measurement error) could be enlarged. The number of visible satellites and PDOP of BDS over the Black Sea is shown in Figure 11.

Under the condition of PODP≤6, the BDS kinematic positioning accuracy (95%) at the Black Sea in Türkiye is; BDS (BDS-2 + BDS-3) B1I horizontal direction is 2.23m, the vertical direction is 3.94m; B3I horizontal direction is 2.97m, the vertical direction is 3.02m; B1IB3I horizontal direction is 2.64m, the vertical direction is 6.07m; The number of visible satellites for BDS is 12.6 in average, PDOP is 1.8. BDS B1I/B3I/B1IB3I positioning results over the Black Sea can be shown in Figure 12.

3.2.3 Mediterranean Sea kinematic test results

In order to test the kinematic performance of BDS over the Mediterranean Sea, randomly chosen approximately 35 km of measurement was carried out. In addition, 1-second interval observations are handled during the kinematic testing route over the Mediterranean Sea (Figure 13).

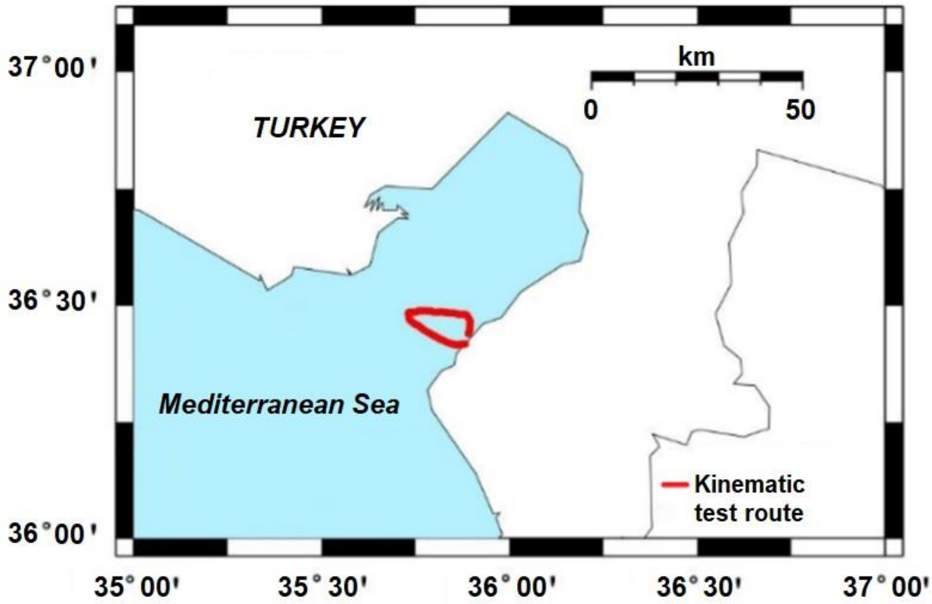

Figure 13. Kinematic test route over the Mediterranean Sea.

Table 3. Mediterranean Sea BDS SPP Accuracy on 5 September 2019 (PDOP≤6).

Frequency		H (m)	V (m)	SatNum (mean)	PDOP (mean)
BDS-2	B1I	1.00	6.08	8.5	3.0
	B3I	1.15	6.85		
	B1IB3I	1.03	4.63		
BDS-3	B1I	0.54	1.18	6.0	2.6
	B3I	0.89	1.71		
	B1IB3I	0.57	1.00		
BDS (BDS-2 + BDS-3)	B1I	0.48	1.73	14.5	1.5
	B3I	0.71	2.75		
	B1IB3I	0.77	2.74		

The B1I and B3I signals for regional BDS-2, global BDS-3, and all together BDS were examined. The change in the number of visible satellites and PDOP for BDS-2, BDS-3, and BDS data were examined. When the BD2 and BDS3 data are evaluated alone, the decrease in the number of visible satellites and the increase in PDOP values affect the positioning accuracy negatively. In order to use more reliable positioning data, the PDOP values above six have not been evaluated. Horizontal and vertical positioning accuracy in the 95% confidence interval of kinematic measurements performed in the Mediterranean Sea is as in Table 3.

When comparing the BDS-3 data with the BDS-2 data, the BDS-2 have more visible satellites. However, because the geometric distribution of satellites is not good enough, the positioning results in the vertical direction were not good. With better satellite geometric configuration, the PDOP value and the positioning results of BDS-3 were better than BDS-2. Therefore, when using the BDS-2 and BDS-3 jointly, we can have more visible satellites, good PDOP, and positioning accuracy results. The number of visible satellites and the PDOP of BDS over the Mediterranean Sea is shown in Figure 14.

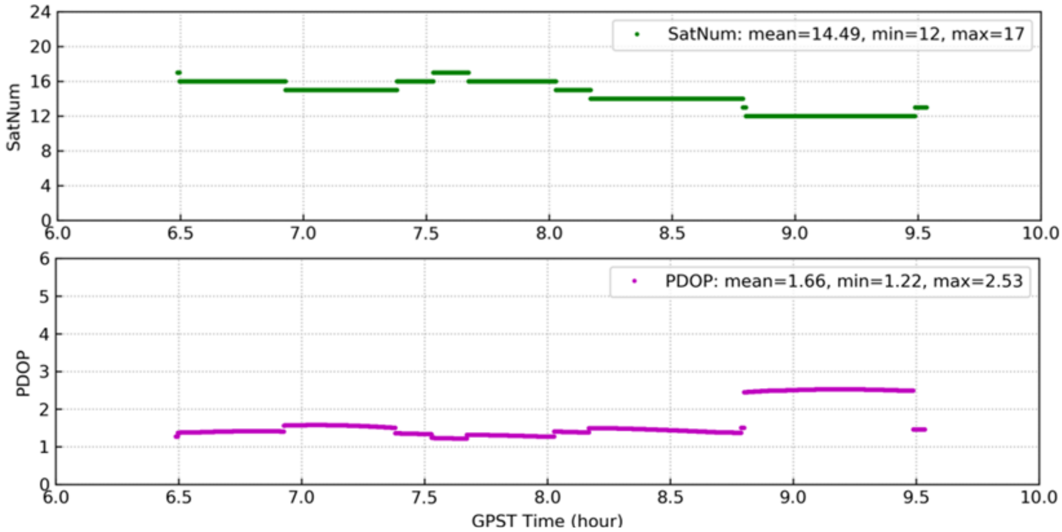

Figure 14. The Number of Visible Satellites and PDOP of BDS over the Mediterranean.

Under the condition of PODP≤6, the BDS kinematic positioning accuracy (95%) at the Mediterranean Sea in Türkiye is: BDS (BDS-2 + BDS-3) B1I horizontal direction is 0.82m, the vertical direction is 2.16m; B3I horizontal direction is 1.27m, the vertical direction is 4.34m; B1IB3I horizontal direction is 2.48m, the vertical direction is 5.71m; The number of visible satellites for B1I/B3I/B1IB3I is 14 in average, PDOP is 1.2. BDS B1I/B3I/B1IB3I positioning results over the Mediterranean Sea can be shown in Figure 15.

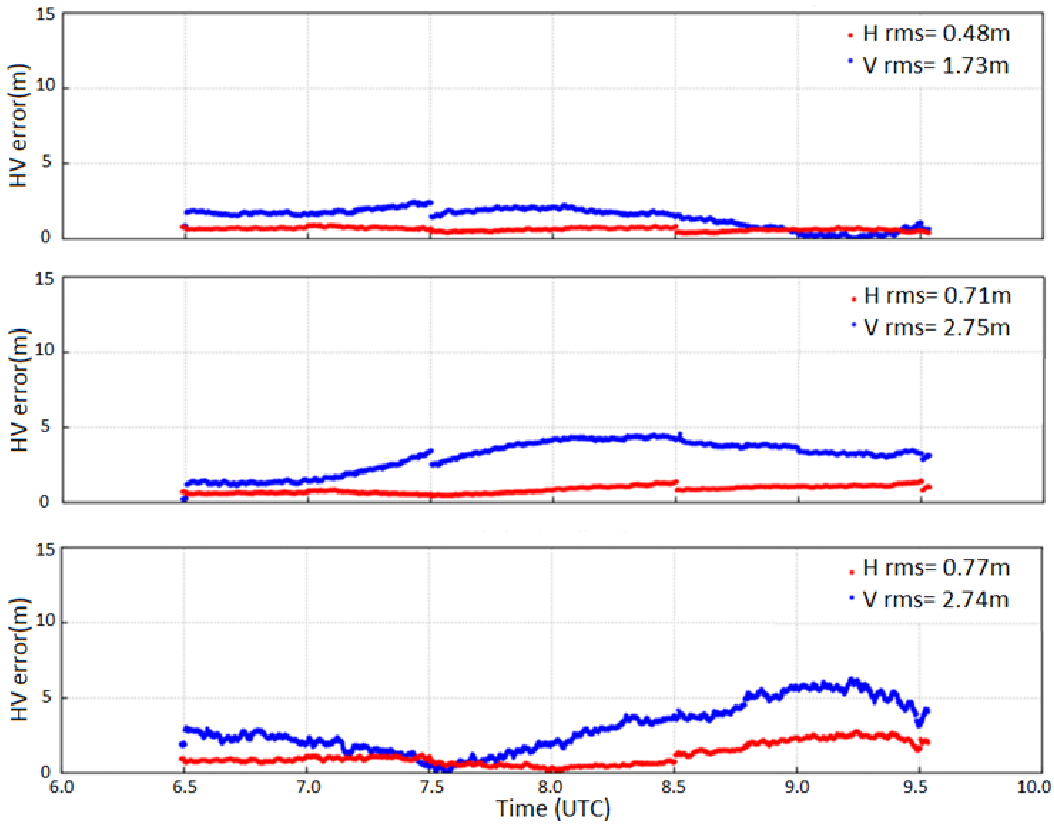

Figure 15. BDS B1I, B3I, B1IB3I SPP Accuracy over the Mediterranean Sea.

4. Discussion and Conclusion

Global positioning services are used for navigation, transportation, construction, agriculture, meteorology, disaster monitoring, risk management, etc. Although the installation of global positioning services requires great costs, they are preferred due to their gains. In this context, developed countries are in a race for technology, and the development of a global positioning service under their control. BDS is a product of Chinese investments in this regard, and it has been operational at full capacity with the satellite launch on June 2020. This new global positioning service is preferred for users depending on the system's accuracy, continuity, and satellite visibility. In this study, the BDS was tested with ZBEU station data and offshore kinematic measurements in this context.

Satellite visibility of BDS at the ZBEU station is about 12 satellites, and PDOP values are generally less than 2, and it is accepted as excellent for many precise positioning applications. When the multipath effect on BDS signals is compared with other services, the BDS signals have similar multipath results with GPS and Galileo but are better than GLONASS. Average SNR values ranged between 43 and 47 for all positioning services but only 36-39 on the GPS 2P signal.

In 2019, BDS-3 satellites were not at full capacity. It has been operating at full capacity since June 2020. With the newly installed satellites, the average number of visible satellites of BDS at ZBEU station increased from 10.8 to 12.6. While the convergence time with DOY 152, 2019 BDS data was 134.5 minutes, with DOY 152, 2023 data, the convergence time decreased to 13 minutes. The RMS error of the North, East, and Up components were found ± 7.4cm, 18.4cm, and 10.2cm, respectively, for 2019, and ± 2.0cm, 1.6cm, and 5.1cm, respectively, for 2023. Looking at the PPP results for 2023, the BDS shows as good results as other systems. For the ZBEU station observations, Galileo performed best in terms of convergence time and horizontal positioning accuracy, while GPS performed best in terms of vertical component accuracy.

According to the kinematic measurement results performed in the Black Sea, satellite visibility was observed as 6.4, 6.2, and 12.6 for BDS-2, BDS-3, and BDS (BDS-2 + BDS-3), respectively. When the PDOP values are analyzed, it is determined as 5.5, 3.4, and 1.8 for the BDS-2, BDS-3, and BDS, respectively. An increasing number of satellites with BDS improves the geometric distribution of satellites, which leads to a decrease in PDOP values. When the positioning accuracy of BDS is analyzed, horizontal and vertical positioning accuracies of 95% confidence interval in the Black Sea were found as 1.81 and 3.55m, respectively (Table 2).

In kinematic observations during the Mediterranean Sea survey, mean satellite visibility was found to be 8.5, 6.0, and 14.5 for the BDS-2, BDS-3, and BDS, respectively. PDOP values for BDS-2, BDS-3 and BDS were obtained at 3.0, 2.6 and 1.5, respectively. As seen, the increase in satellite visibility brings along a decrease in PDOP values. Regarding positioning accuracy, the BDS horizontal and vertical positioning accuracies of 95% confidence interval in the Mediterranean Sea were obtained as 0.77 and 2.74m. The BDS positioning results were found to be stable and reliable. As seen in Table 3, single-frequency positioning accuracy has improved using more than one signal. When the BDS-2 and BDS-3 are used together, satellite visibility increases, and suitable satellite geometry occurs. Thus, more accurate results can be obtained.

Acknowledgement

We want to thank CSNO (China Satellite Navigation Office) for providing the ZBEU iGMAS (International GNSS Monitoring & Assessment Service (iGMAS)) station to Türkiye, a member of APSCO (Asia-Pacific Space Cooperation Organization). Special thanks to CSNO for sending another GNSS receiver for offshore testing.

Funding

This research received no external funding.

Author contributions

Volkan Akgül: Data curation, Software, Visualization, and Writing. **Kurtuluş Sedar Görmüş:** Writing-Reviewing and Editing. **Şenol Hakan Kutoğlu:** Methodology, Writing-Reviewing, and Editing. **Shuanggen Jin:** Writing-Reviewing, Editing, and Supervision.

Conflicts of interest

The authors declare no conflicts of interest.

References

1. Karimi, H. (2021). An analysis of satellite visibility and single point positioning with GPS, GLONASS, Galileo, and BeiDou-2/3. Applied Geomatics, 13(4), 781-791. https://doi.org/10.1007/s12518-021-00391-2
2. Revnivykh, S., Bolkunov, A., Serdyukov, A., & Montenbruck, O. (2017). Glonass. Springer Handbook of Global Navigation Satellite Systems, 219-245. https://doi.org/10.1007/978-3-319-42928-1_8
3. China Satellite Navigation Office (2021). BeiDou Navigation Satellite System Open Service Performance Standard (Version3.0)
4. Malik, J. S. (2020). Performance analysis of static precise point positioning using open-source GAMP. Artificial Satellites, 55(2), 41-60. https://doi.org/10.2478/arsa-2020-0004

5. Wang, G., de Jong, K., Zhao, Q., Hu, Z., & Guo, J. (2015). Multipath analysis of code measurements for BeiDou geostationary satellites. GPS Solutions, 19, 129-139. https://doi.org/10.1007/s10291-014-0374-8
6. Xie, X., Geng, T., Zhao, Q., Liu, J., & Wang, B. (2017). Performance of BDS-3: measurement quality analysis, precise orbit and clock determination. Sensors, 17(6), 1233. https://doi.org/10.3390/s17061233
7. Dou, S., Kuang, C., Zhou, Y., & Yi, Z. (2017). Analysis of signal quality and navigation performance for beidou system. In China Satellite Navigation Conference (CSNC) 2017 Proceedings: I, 671-681. https://doi.org/10.1007/978-981-10-4588-2_57
8. Jin, S., & Su, K. (2020). PPP models and performances from single-to quad-frequency BDS observations. Satellite Navigation, 1(1), 1-13. https://doi.org/10.1186/s43020-020-00014-y
9. Fang, C., Chen, L., Geng, C., Ma, Z., & Mao, Q. (2018, May). The Study on BDS Dynamic Positioning Performance Assessment. In China Satellite Navigation Conference, 159-169). https://doi.org/10.1007/978-981-13-0029-5_15
10. Zhao, Q., Wang, G., Liu, Z., Hu, Z., Dai, Z., & Liu, J. (2016). Analysis of BeiDou satellite measurements with code multipath and geometry-free ionosphere-free combinations. Sensors, 16(1), 123. https://doi.org/10.3390/s16010123
11. Akgul, V., Gurbuz, G., Kutoglu, S. H., & Jin, S. (2020). Effects of the high-order ionospheric delay on GPS-based tropospheric parameter estimations in Turkey. Remote Sensing, 12(21), 3569. https://doi.org/10.3390/rs12213569
12. Kaplan, E. D., & Hegarty, C. J. (2006). Understanding GPS: Principles and Applications, Norwood, MA: Artech House.
13. Wang, S., Jia, X., Ji, G., Ai, Q., Guan, M., & Peng, T. (2017). Multipath Effect Analysis of Beidou Satellite Pseudorange and Its Correction. In China Satellite Navigation Conference (CSNC) 2017 Proceedings: I, 547-559. https://doi.org/10.1007/978-981-10-4588-2_47
14. Wanninger, L., & May, M. (2001). Carrier-Phase Multipath Calibration of GPS Reference Stations. Navigation, 48(2), 112-124. https://doi.org/10.1002/j.2161-4296.2001.tb00233.x
15. Zhang, C., Zhang, S., Che, T., Wang, Y., Zhang, N., Qi, W., Wan, T. (2018). GPS-MR for Altai Snow Depth Monitoring. In: Sun, J., Yang, C., Guo, S. (eds) China Satellite Navigation Conference (CSNC) 2018 Proceedings. CSNC 2018. Lecture Notes in Electrical Engineering, 497. https://doi.org/10.1007/978-981-13-0005-9_18
16. Mao, M., Wang, L., Zhang, S., Wang, X., & Hu, P. (2017). Correlation Analysis Among GPS-SNR, Precipitation and GPS-PWV. In China Satellite Navigation Conference (CSNC) 2017 Proceedings: Volume I, 97-106. https://doi.org/10.1007/978-981-10-4588-2_9
17. China Satellite Navigation Office, (2019). Beidou Navigation Satellite System signal in space interface control document, open service signal B1I (Version 3.0).
18. Jing, Y., Zeng, A., Zhao, A., Xu, Y., & Ma, Y. (2019). Analysis on Performance of BDS/GPS Fusion Pseudorange Positioning with ISB and Its Influence on DOP. In China Satellite Navigation Conference (CSNC) 2019 Proceedings: I, 380-388. https://doi.org/10.1007/978-981-13-7751-8_38
19. Maldaner, L. F., Canata, T. F., Dias, C. T. D. S., & Molin, J. P. (2020). A statistical approach to static and dynamic tests for Global Navigation Satellite Systems receivers used in agricultural operations. Scientia Agricola, 78. https://doi.org/10.1590/1678-992X-2019-0252
20. Dixon, K. (2006). StarFire: A global SBAS for sub-decimeter precise point positioning. In Proceedings of the 19th international technical meeting of the satellite division of the institute of navigation, 2286-2296.
21. Angrisano, A., Dardanelli, G., Innac, A., Pisciotta, A., Pipitone, C., & Gaglione, S. (2020). Performance assessment of ppp surveys with open source software using the gnss gps–glonass–galileo constellations. Applied Sciences, 10(16), 5420. https://doi.org/10.3390/app10165420
22. Chen, C., & Chang, G. (2021). PPPLib: An open-source software for precise point positioning using GPS, BeiDou, Galileo, GLONASS, and QZSS with multi-frequency observations. GPS Solutions, 25(1), 18. https://doi.org/10.1007/s10291-020-01052-4
23. AUSPOS - Online GPS Processing Service (2023). https://www.ga.gov.au/scientific-topics/positioning-navigation/geodesy/auspos
24. Larson, K. M., Small, E. E., Gutmann, E., Bilich, A., Axelrad, P., & Braun, J. (2008). Using GPS multipath to measure soil moisture fluctuations: Initial results. GPS Solutions, 12, 173-177. https://doi.org/10.1007/s10291-007-0076-6
25. Larson, K. M., Gutmann, E. D., Zavorotny, V. U., Braun, J. J., Williams, M. W., & Nievinski, F. G. (2009). Can we measure snow depth with GPS receivers?. Geophysical Research Letters, 36(17), L17502. https://doi.org/10.1029/2009GL039430
26. Small, E. E., Larson, K. M., & Braun, J. J. (2010). Sensing vegetation growth with reflected GPS signals. Geophysical Research Letters, 37(12), L12401. https://doi.org/10.1029/2010GL042951