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Seamless precise kinematic positioning in the high-latitude environments: case study in the Antarctic region

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Abstract

Scientific activities in the Antarctic regions have increased daily within the last decades to achieve many different projects. The ice sheet over 98% of the Antarctic continent, the coldest, driest, and windiest place in the world and has the largest desert, makes it very difficult to conduct any kind of study and research. Among them, precise hydrographic surveying should be conducted for many different applications that require reliable and accurate positioning. The output from these surveys plays a vital role in understanding sea level changes, global warming, sea ice movement, navigation and many others. The harsh atmospheric and topographic conditions of the region pose additional challenges to surveyors in the use of conventional terrestrial measurement techniques and satellite-based positioning methods (GNSS) to make positioning. Low quality and noisy GNSS observations with low satellite elevations made their positioning vulnerable to cycle slip, multipath, and discontinuity in Antarctica. This study analyses the performance of the post-processed kinematic Precise Point Positioning (PPP) based on the web-based online GNSS processing service for marine surveying in the high-latitude environment. Within this frame, two realistic experiments were carried out on a ship and zodiac boat during the 6th Turkish Antarctic Expedition (TAE). The results show that the PPP coordinates using an online GNSS processing service provide kinematic positioning with centimetre level of accuracy using a single GNSS receiver. The general results showed that the PPP technique allows for much faster and accurate positioning in remote and high-latitude areas at a lower cost.

Keywords:

Antarctica; GNSS; kinematic survey; Precise Point Positioning (PPP); online GNSS processing service

1. Introduction

The continent of Antarctica, the coldest, emptiest, and windiest place on Earth, has drawn intense attention from a wide variety of researchers and explorers over the past few decades. There are nearly a hundred science bases in Antarctica that host thousands of researchers from tens of countries to carry out many different areas of research, including glacier monitoring, climate change, global warming, marine, tectonics and seismology, geodesy, environment, mapping habitats, seafloor mapping, biology, medicine, space, creating digital twin, and so on in the difficult geographical and atmospheric conditions of Antarctica (**Oppenheimer, 1998; Bevis et al., 2009; Rückamp et al., 2011; Ji et al., 2014; Smith et al., 2015; Baranov et al., 2018; Jansen et al., 2018; Minowa et al., 2019; Still et al., 2023**). In all these studies, accurate, reliable, and robust 3D geodetic positioning turns into a very challenging job for both surveyors and equipment due to the nature of this challenging geography, i.e. the terrain is often covered with snow and ice, strong winds, harsh climate conditions, bright sunshine having extreme temperatures and other logistics requirements (**van Wegen, 2022**). No matter how challenging the conditions are, the data capturing and surveying process in this geography is carried out with many up-to-date methods.

Apart from the classical method, techniques such as the satellite-based positioning method (i.e. Global Navigation Satellite System-GNSS) and close-range remote sensing through unmanned aerial vehicles are used for different purposes in the region. Among them, GNSS has become today's standard positioning tool in many surveying applications. The GNSS method has gained immense popularity as an accurate positioning method. GNSS can be used at 7/24 and in all weather conditions. However, some issues that do not appear to be a problem when this method is applied under standard surveying circumstances can become important problems in Ant-

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arctica's extreme atmospheric and topographic conditions. For instance, the differential carrier-phase-based GNSS technique should be used to achieve accurate positioning. In this method, the double differences are established to effectively eliminate receiver and satellite clock errors. However, reference stations with known coordinates near the study area are necessary for the application of the differential method. Although there are geodetic network reference stations in Antarctica, the distance between these network stations can reach thousands of kilometres. If these points are used as references in the differential method, very long bases must be established. On the other hand, in the geographic region where the Antarctic continent is located, depending on the inclination angle of the GNSS satellites' orbits with respect to the Equator (satellite orbital inclination angle is 55° for GPS, 56° for Galileo, 64.8° for GLONASS and 55° for BDS constellations), it is often not possible to make satellite observations at high elevation angles and for long periods when compared to regions at mid- and low-latitudes. In high-latitude areas, the larger orbital inclination angle might offer better observing geometry (**Zheng et al., 2022**). In this case, satellites can be observed at low elevations and for shorter continuous periods, and thus it may be difficult to make simultaneous observations on the same satellites, and a reliable ambiguity-fixed solution cannot be guaranteed for long baselines (**Alkan et al., 2022**). The fact that it requires post-processing of the collected data to calculate the coordinates is another time-consuming factor of the method. This also requires proper GNSS software, which needs payment of a licence fee and a certain level of expertise and GNSS knowledge to use. Furthermore, establishing the new geodetic point requires a very difficult, time-consuming, and labour-intensive workload due to transportation, setup, and meteorological factors. This may degrade the GNSS solution accuracy. Furthermore, GNSS satellite observations are limited in zenith directions due to the satellite orbital inclination and this lack of data directly contributes to a noticeable reduction in the accuracy of the height component (**Alkan et al., 2022**). In real-time applications, outages and/or loss of internet connection/GSM cellular data may cause an extra restriction for differential real-time kinematic (RTK) applications. In addition, ionospheric scintillation is more common in the equatorial and polar regions due to geomagnetic activity and solar activity, and if not taken into account, positional accuracy is adversely affected (**Jensen and Sicard, 2010**). In summary, briefly mentioned above, the continent's unique geographical features and technical constraints prevent the effective application of the differential GNSS method.

The search for a new method that does not have these limitations while providing the same high accuracy has led to the development of the Precise Point Positioning (PPP) technique. Although this technique was originally proposed by Anderle in the 1970s (**Anderle, 1976**), it was first implemented by **Zumberge et al. (1997)** in its current form. In the PPP technique, the single or multi-frequency GNSS data collected with only one receiver is used to estimate the 3D coordinates together with precise satellite orbit and clock products and code/phase biases in post-process or real-time. It should be noted that, to obtain the most possible accuracy, the effects such as satellite antenna offset, sagnac effect, Earth rotation parameters, phase wind-up effect, solid Earth tides, tidal loadings, and others should be considered. The PPP technique can routinely achieve homogeneous cm- to dm-level accurate 3D point position effectively, economically, and quickly. However, the most significant drawback of the PPP technique is that it requires an average of 20-30 minutes, and more, convergence time to estimate the coordinates with cm accuracy. The convergence time increases if the measurement quality is low or there is a strong multipath or high noise (**Lipatnikov and Shevchuk, 2019**). This is an important constraint to the usability of the technique, especially in real-time applications.

The PPP coordinates can be calculated in different ways. One of them is online GNSS processing services that are offered by many organizations, academic, research, commercial institutes, and universities stand out. In the literature, many scholars have investigated the performance of commonly used different online GNSS PPP processing services in many applications (**Dawidowicz and Krzan, 2014; Abdallah and Schwieger, 2016; Jamieson and Gillins, 2018; Bezcioğlu et al., 2019; El Shouny and Miky, 2019; Masykur et al., 2021; Belcore et al., 2022; Diouf et al., 2023; Vázquez-Ontiveros et al., 2023**). Studies have shown that such services provide cm-dm level accuracy depending on the used data, occupation time, receiver type, and surveying environment. Among these studies, it is seen that there are very few studies on GNSS PPP technique in general and the performance of online processing services, in particular in the polar regions. Moreover, it was observed that these studies mostly used the IGS-like network reference stations' data (as a note, GNSS reference stations are usually established in ideal locations where the multipath, low signal quality, etc. that will adversely affect the measurements will be minimal, and they can observe from all possible satellites), so it cannot fully reflect the realistic PPP performance. There is a noticeable lack of studies in the literature on this subject, especially on the evaluation of PPP positioning performance from kinematic measurements made in water environments in the high-latitude polar regions.

The main motivation of this study is to investigate the performance of the PPP technique using an online processing service in the Southern Ocean's extreme environmental conditions. Within this scope, two realistic

 pp. 31-43, DOI: 10.17794/rgn.2024.2.3

kinematic experiments were conducted as part of the 6th Turkish Antarctic Expedition (TAE). In this way, the real accuracy performance of the PPP technique of the sailing vessel on the polar seas was truly assessed.

2. Canadian Spatial Reference System-Precise Point Positioning (CSRS-PPP) Online GNSS Processing Service

In this study, PPP coordinates were estimated with the Canadian Spatial Reference System-Precise Point Positioning (CSRS-PPP) online GNSS PPP processing service. The Geodetic Survey Division of Natural Resources Canada (NRCan) provided this worldwide free service. The service calculates the PPP coordinates using single and/or dual frequency data in static and kinematic mode options. It is sufficient for users to send the GNSS data via the user-friendly service's website. The CSRS-PPP uses GPS and GLONASS observations in PPP solution. The static processing mode produces the corrected averaged coordinates, while the kinematic processing mode produces a corrected track. The kinematic PPP coordinates are estimated with a forward-backward processing strategy. Within minutes, in general, the service sends PPP results with many outputs containing different information, graph, and detailed solution reports to the user via an e-mail address introduced by the user.

The NRCan upgraded the CSRS-PPP service from version 2 (v.2) to version 3 (v.3) on 20 October 2020 (**Banville et al., 2021**). This modernization process allowed the user to obtain a PPP solution with ambiguity resolution (PPP-AR) for the dual-frequency GPS data collected on or after January 1, 2018, using NRCan's new own products (satellite phase biases consistent with satellites' orbits and clocks). The service performs the partial ambiguity resolution approach for GPS satellites (this means not all ambiguities need to be resolved), but the ambiguities are resolved as a float for the GLONASS system. Resolving carrier-phase ambiguities accelerates the PPP-AR solution while providing cm-level accuracy faster. It should be noted that better improvement can be achieved in the longitude (east) component due to satellite geometry. The service provides up to mm-level positioning accuracy for processing long occupation time (24+ hours) in static mode, while a few cm accuracies typically are achieved in an hour (**Banville, 2020; Banville et al., 2021**). It should be noted that the CSRS-PPP employs the best available products from NRCan and/or IGS at the time of processing (**URL-1**).

The CSRS-PPP service uses uncombined code (C) and carrier phase (L) observables for the PPP-AR solution that are given below (**Banville et al., 2021**):

$$L^s_{G,f,r} = \rho^s_r + \mathrm{d}t_{G,r} + b_{G,f,r} - \mathrm{d}t^s_G + b^s_{G,f} + T^s_0 + m^s_\omega \delta T_z + m^s_R R_z - \mu_{G,f} I^s + \lambda_{G,f} N^s_{G,f} + \delta L^s_{G,f,r} \quad (1)$$

$$C^s_{G,f,r} = \rho^s_r + \mathrm{d}t_{G,r} + B_{G,f,r} - \mathrm{d}t^s_G + B^s_{G,f} + T^s_0 + m^s_\omega \delta T_z + m^s_R R_z + \mu_{G,f} I^s + \delta C^s_{G,f,r} \quad (2)$$

where, s is a satellite, r is a receiver, G is a GNSS, and f is the frequency; ρ^s_r is the geometric distance between satellite and receiver (m); $dt_{G,r}$, dt^s_G, $b_{G,f,r}$, $b^s_{G,f}$ and $B_{G,f,r}$, $B^s_{G,f}$ are the receiver and satellite clock corrections, receiver and satellite phase-biases, receiver and satellite code-biases for the satellite system G, respectively (m); T^s_0 is the a-priori slant total tropospheric delay mapped using the Vienna Mapping Function 1 (VMF1) grids (m); δT_z is the residual wet tropospheric zenith delay (m) and m^{sz}_ω is the wet VMF1 for it; $R_Z\left\{R_N \cos\left(satellite\ azimuth\right) + R_E \sin\left(satellite\ azimuth\right)\right\}$ is the gradient of the tropospheric zenith delay in north and east directions as a function of satellite azimuth (m) and m^s_R is the mapping function of the gradient part of the delay; I^S is the slant ionospheric delay (m) and $\mu_{G,f}$ is the frequency-dependent scaling factor for the delay; $N^s_{G,f}$ is the ambiguity for the carrier-phase of the satellite s at the frequency f; $\lambda_{G,f}$ is the carrier-phase wavelength (m) of the satellite system at the frequency f; and last terms of the equations contain the corrections and effects such as: antenna phase center variations, carrier-phase windup effect and tides (m).

More detailed information about CSRS-PPP service can be found in **Tétreault et al. (2005)**, **Mireault et al. (2008)**, **Donahue et al. (2018)**, **Banville et al. (2021)**, and the CSRS-PPP website accessible at https://webapp.geod.nrcan.gc.ca.

3. Kinematic experiment

To evaluate the performance of the PPP solutions using an online processing service, two realistic kinematic experiments were conducted. In the first one (Trial-1), the GNSS data collected on a vessel sailed from King George Island, about 120 km off the coast of Antarctica, to Horseshoe Island was within the 6th Turkish Antarctic Expedition in 2022 were used. The first kinematic test was carried out in the region of 64°57′S~65°29′S over the Southern Ocean on February 07, 2022 (Day of Year: 38) (see **Figure 1**).

The kinematic GNSS data was collected through about 9 hours at a 1-second sampling rate with a 10-degree elevation angle by tracking all available satellite constellations. The GNSS receiver was placed on the ship's deck. The vessel navigated through partially mountainous terrain while experiencing moderate windy conditions and a temperature of approximately -1°C. Research/Survey Vessel (BETANZOS IMO# 7310923) sailing under the flag of Chile has a length of 72.05 m and a width of 12.50 meters. During the measurements, the vessel sailed at an average speed of around 7–8 knots, and the total voyage distance was approximately 80.6 km.

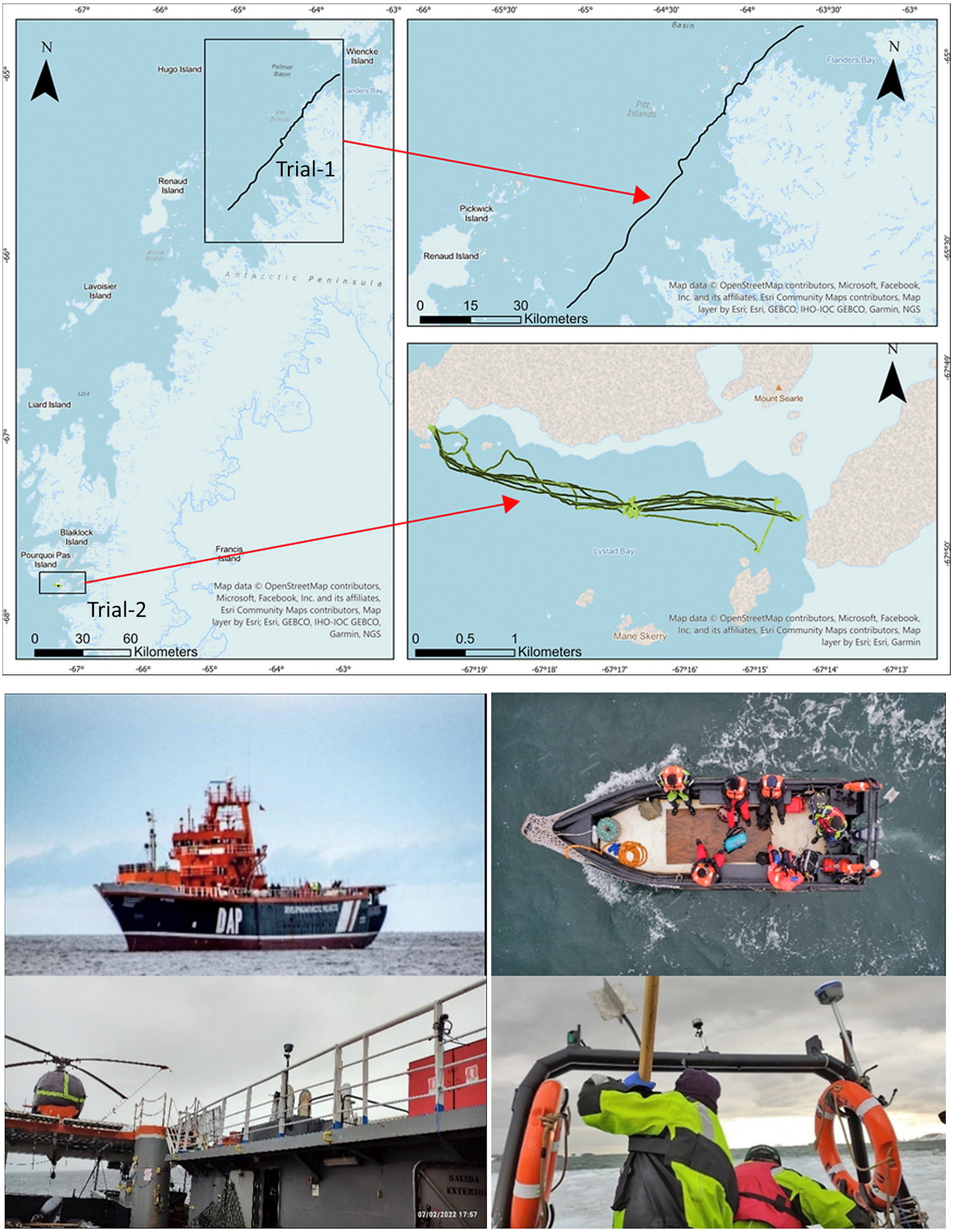

Figure 1: Study area (*top*) and kinematic tests (Trial-1 at *bottom left* and Trial-2 at *bottom right*)

In the second trial (Trial-2), a kinematic test was carried out in Lystad Bay with zodiac-type craft on February 22, 2022 (Day of Year: 53). Lystad Bay (approx. coordinates 67°50′S; 67°17′W) is a 5 km wide bay on the west side of Horseshoe Island. The study area was in the Antarctic Circle. The kinematic survey was carried out

Table 1: Kinematic test measurement specifications for Trial-1 and Trial-2

	Trial-1	Trial-2
Date	February 07, 2022 (Day of Year: 38)	February 22, 2022 (Day of Year: 53)
Data Collection Time Period (UTC Time)	12:55:55-21:59:59 (~9 h, 32639 epoch)	12:35:15-20:58:50 (~8.5 h, 5922 epoch)
Data Sampling Rate	1 second	5 second
Elevation cut-off Angle	10 degree	10 degree
GNSS Receiver	CHCNAV i90 Pro	CHCNAV i90 Pro
Survey Platform	Research/Survey Vessel	Zodiac-type Craft
Average Speed	7-8 knots	5-6 knots
Wind Speed / Sea State with Visual Clues	Moderate	Slight / moderate
Surveying Route/Area	Region of 64°57′S~65°29′S over Southern Ocean	Lystad Bay in Antarctic Circle (approx. coordinates: 67°50′S; 67°17′W)

Table 2: Main specifications of the receiver (CHCNAV i90 Pro) used in kinematic test measurements (**URL-2**)

Performance Specifications		
GNSS Performance	- 336 channels - GPS (L1C, L1C/A, L2E, L2C, L5) - GLONASS (L1C/A, L2 C/A, L3 CDMA) - Galileo (E1, E5a, E5b, E5AltBOC, E6) - BeiDou (B1, B2, B3) - QZSS (L1 C/A, L1 SAIF, L2C, L5, LEX) - IRNSS (L5) - SBAS (L1C/A, L5) - L-BAND (RTX)	
GNSS Accuracies		
PP Static	Horizontal	2.5 mm + 0.5 ppm RMS
	Vertical	5 mm + 0.5 ppm RMS
PP Kinematic	Horizontal	2.5 mm + 1 ppm RMS
	Vertical	5 mm + 1 ppm RMS
RT Kinematic	Horizontal	8 mm + 1 ppm RMS
	Vertical	15 mm + 1 ppm RMS
	Initialization time	<10 s

over 8.5 hours, and GNSS data were collected at a 5-second sampling rate from all available satellite constellations with 10-degree elevation angle (see **Figure 1**). The total boat route length was approximately 35.4 km. The GNSS data was collected under poor sky coverage conditions with obstacles surrounded by ice hills and rough topography on parts of the route. Some information about the measurements is given in **Table 1**.

In both measurements, the CHCNAV i90 Pro geodetic GNSS receiver was employed. It has an internal antenna. The receiver has 336-channel and can track GPS, GLONASS, Galileo, and BeiDou satellites. Some prominent specifications of the multi-constellation and multi-frequency receiver are given in **Table 2**. More information can be found at **URL-2**.

3.1. Visibility of tracked satellites: sky plots and PDOP values

The sky plots of the test measurements were plotted in **Figure 2**. The number of visible satellites with Position Dilution of Precision (PDOP) values were given in **Table 3**. In this study, GPS and GLONASS are represented by the letters G and R, respectively.

According to the values given in **Figure 2** and **Table 3**, it was seen that the number of GPS satellites ranged from 5 to 12 (mean 9) in the first trial carried out with the vessel, and this number ranged from 5 to 19 for the G+R (mean 14) that was observed. The number of satellites for the G+R solution was seen to be greater than that of the GPS-only solution. For the second trial carried out with a zodiac-boat in the Antarctic Circle (approx. coordinates of the survey area: 67°50′S; 67°17′W), the number of satellites ranged from 5 to 11 for the GPS-only solution (mean 8) and 5 to 16 for the combined GPS and GLONASS solution (mean 12). In both trials, it became evident that the additional GLONASS constellation improved the total number of satellites (on mean) compared with GPS-only. Depending on this, additional GNSS constellations improved the PPP accuracy by observing more satellites compared to GPS-only.

When the PDOP values indicating the effect of the satellite geometry on the calculated horizontal and vertical coordinates from **Figure 2** and **Table 3** were examined, for the first trial, it was observed that the minimum, maximum, and mean PDOP values for the GPS-only solution were 1.4, 4.4, and 2.1, respectively, and 1.1, 3.7, and 1.6 for the GPS+GLONASS solutions, respectively. These values were found as 1.5, 7.0, and 2.8 for GPS-only and 1.2, 6.9, and 2.0 for the GPS+GLONASS solutions, respectively, for the second trial. The results showed that the PDOP values of both G-only and G+R solutions in the Antarctic Circle were greater than in the Southern Ocean application (first trial). As can be seen from **Table 3**, when GLONASS observations were used in addition to GPS, PDOP values improved by a mean of 25% and 30% in the first and second trials, respectively. Besides, PDOP values for both trials were generally higher at measurement epochs where the number of satellites was low. From this point of view, it was concluded that PDOP values were inversely proportional to the number of satellites. The overall results show that the G+R compared to GPS-only, improves the PDOP value, which will make a positive contribution to the solution.

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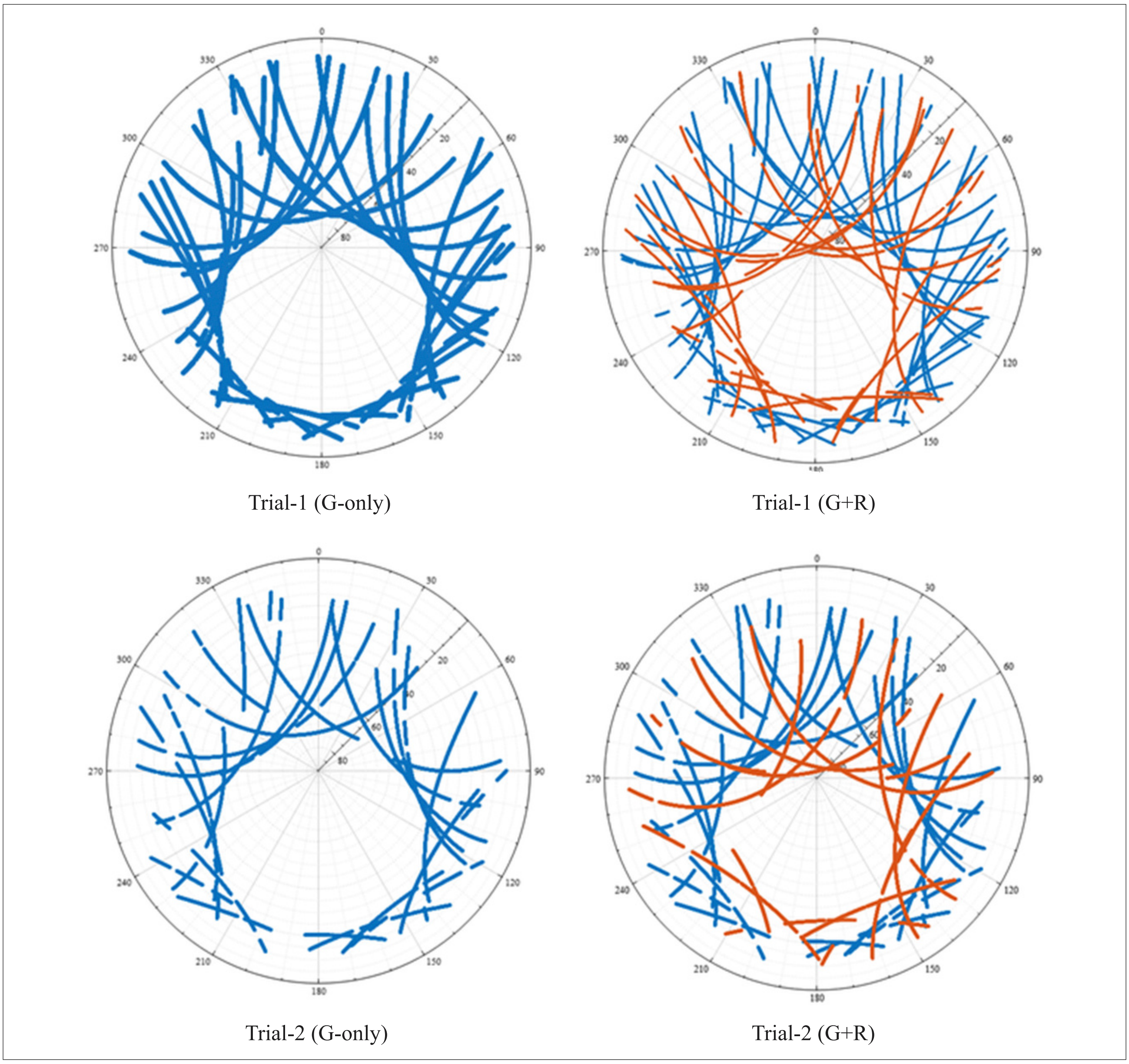

Figure 2: Sky plots of the kinematic measurements (*top*: for Trial-1; *bottom*: Trial-2)

According to the sky plots in **Figure 2**, it has been observed that continuous interruptions (discontinuities) were experienced. Furthermore, for the vessel test (Trial-1) over the Southern Ocean (64°57′S~65°29′S), the maximum satellite elevations reached to approximately 75° and 90° for GPS and GLONASS constellations, respectively. As can be seen, unlike GPS, some of the GLONASS satellites were observed in the zenith of the survey vessel. For the zodiac-boat test (Trial-2) (average latitude 67°50′S), the maximum satellite elevations reached to approximately 75° for the GPS constellation, while 85° for the GLONASS constellation. Due to the orbital inclination angle of the GLONASS constellation was greater than that of GPS, the GLONASS constellation offers superior GNSS tracking performance in these high-latitude regions than GPS. This increased the satellite availability for the GLONASS satellites in the first and second trials. In general, the GLONASS satellites have a much better elevation distribution than GPS in high latitude areas, and the additional GLONASS satellites to the GPS improved the satellite availability and geometry. While this is undoubtedly important in all surveying conditions, it becomes even more critical in the harsh environment of Antarctica. As will be remembered, the orbit inclination angle with respect to the equator is 55° for GPS constellation while 64.8° for GLONASS satellites' orbits. Since the latitude of the region where the measurements are made is greater than this orbital inclination angle, no observations can be made in the zenith direction. This resulted in a circular unobservable area (a hole) in the sky above the rover receiver for both trials (see **Figure 2**).

Table 3: Number of satellites and PDOP statistics for Trial-1 and Trial-2

Item	Stat.	Trial-1 (with research vessel)		Trial-2 (with zodiac-boat)	
		G-only Solution	G+R Solution	G-only Solution	G+R Solution
Number of Satellites	*min.*	5	5	5	5
	max.	12	19	11	16
	mean	9	14	8	12
PDOP	*min.*	1.4	1.1	1.5	1.2
	max.	4.4	3.7	7.0	6.9
	mean	2.1	1.6	2.8	2.0

3.2. Data processing

The collected GNSS data were converted to the standard RINEX observation files. As mentioned, the CSRS-PPP service uses GLONASS observations and GPS, if available. For this reason, although quad-constellations' satellites were observed and logged through the test measurements, RINEX files were produced as GPS-only and G+R to analyse the kinematic PPP performance under two different configurations, i.e. G-only and G+R combination with CSRS-PPP service. These RINEX observation files were uploaded to the service using the kinematic processing mode. After completing the processing of the uploaded data, the service sent an URL link that includes the results shortly after. In this way, the kinematic PPP coordinates of each measurement epoch were obtained. The used processing options for the service were given in **Table 4**.

Although the CSRS-PPP 3.50.2 uses the GPS and GLONASS observations for PPP solutions, it attempts to resolve the GPS ambiguities only with the PPP-AR algorithm. Within this frame, most of the ambiguities for GPS observations were resolved. The percentage of fixed ambiguities for GPS was given in **Table 5**. It should be noted that this value is defined as the ratio of the ambiguity-fixed carrier-phase observations in all phase measurements (**Banville et al., 2021**).

According to the fixed ambiguity percentage given in **Table 5**, it was observed that most of the GPS ambiguities were resolved with a ratio of 92% for the first trial. Conversely, in the second application, this rate was 74% for the G-only solution and 88% for the G+R solution. These results revealed that the success of ambiguity resolution was lower in this high latitude region (average latitude: 67°50′S), where satellite coverage was limited, and the number of visible satellites and their elevations were low. It should be noted that all GLONASS ambiguities were obtained float due to the CSRS-PPP ambiguity resolution algorithm that was performed only for GPS.

Table 4: GNSS observations processing parameters used by CSRS-PPP online service

Item	Trial-1 (with research vessel)		Trial-2 (with zodiac-boat)	
	for G-only Solution	for G+R Solution	for G-only Solution	for G+R Solution
Processing Mode	Kinematic			
GNSS System	GPS	GPS+GLONASS	GPS	GPS+GLONASS
Observations	Code & Phase			
Frequency	Double			
Precise Satellite Orbits	NRCan/IGS Final			
Precise Satellite Clocks	NRCan/IGS Final			
Biases	Code and Phase			
Phase-centre Corrections	IGS (ATX)			
Tropospheric Mapping Function	Vienna Mapping Function 1 (VMF1)			
Ionospheric Delay	Eliminated using the ionospheric-free linear combination			
Observation Interval	1 s		5 s	
Phase Wind-up	Modelled			
Solid Earth and Polar Tides	Modelled			
Product Interpolation	Yes			

Table 5: The fixed ambiguities percentage of GPS and GPS&GLONASS observations

Item	Trial-1 (with research vessel)		Trial-2 (with zodiac-boat)	
	for G-only Solution	for G+R Solution	for G-only Solution	for G+R Solution
Percentage of Fixed Ambiguities for GPS	92%	92%	74%	88%

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4. Results

To make a precise accuracy assessment of the kinematic PPP coordinates, the reference trajectory (known coordinates) should be established. Within this frame, the coordinates of each measurement epoch were calculated by the relative positioning technique, and these solutions were taken as reference trajectory for comparing the PPP coordinates. For the first trial, one of the nearest IGS continuous reference station, PALM (64°46′30.31856″S, 064°03′04.02397″W, and 31.144 m), was used as a reference station. The necessary GNSS data was retrieved from the related web page. The collected data was processed with CHCNAV Geomatics Office Software 2.0

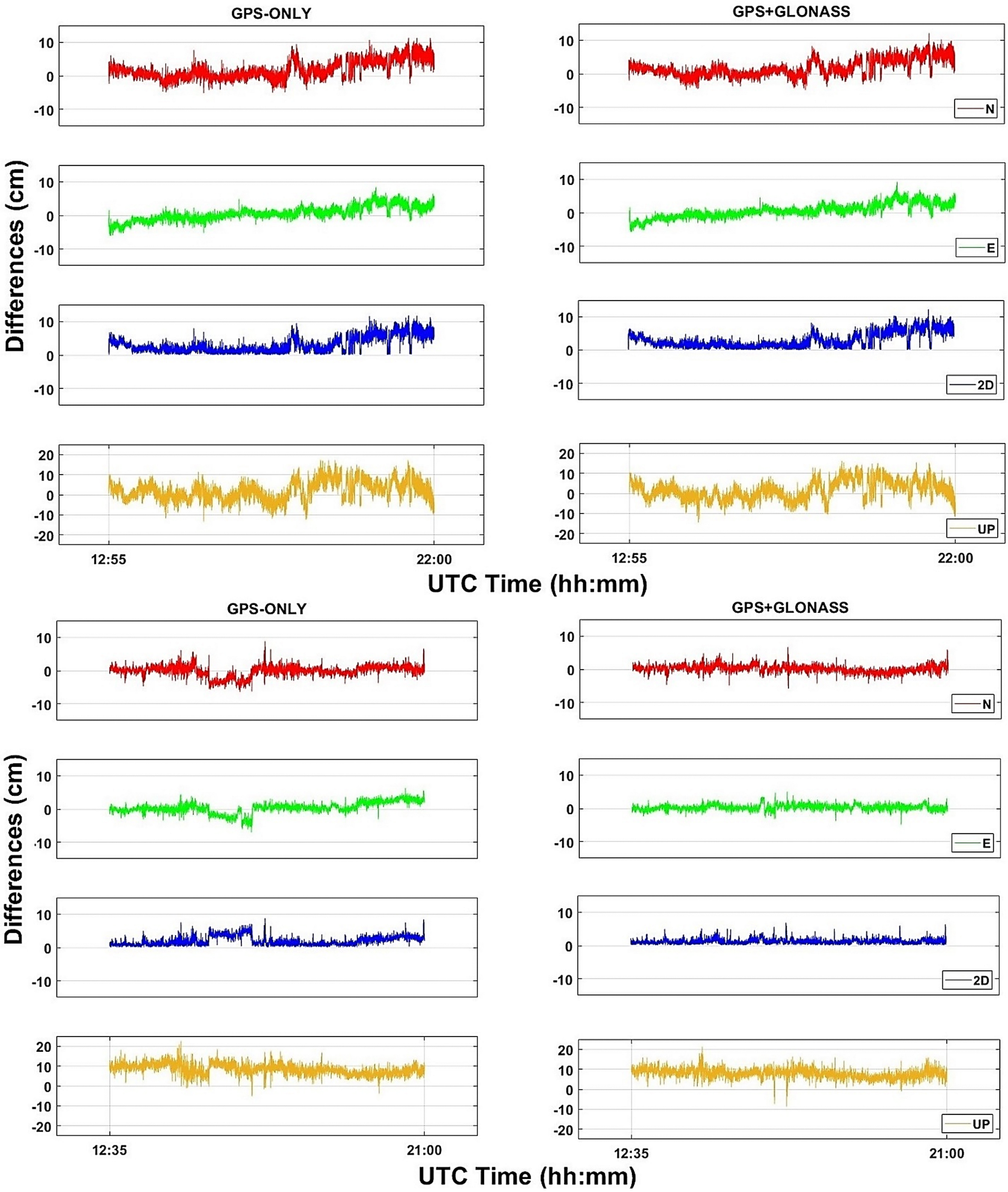

Figure 3: Time series of differences between kinematic PPP and relative GNSS solutions (*top*: for Trial-1, *bottom*: for Trial-2)

Table 6: Statistical results of Trial-1 and Trial-2 based on the differences between PPP and relative GNSS solutions for GPS and GPS&GLONASS observations

Trial-1 (carried out in the region of 64°57′S~65°29′S over Southern Ocean with research vessel)										
	GPS-only Solution (cm)					GPS+GLONASS Solution (cm)				
	min.	max.	mean	SD	RMSE	min.	max.	mean	SD	RMSE
Northing	-5	11	2	3	3	-5	12	2	3	3
Easting	-6	8	1	2	2	-6	9	1	2	2
2D	0	12	3	2	4	0	12	3	2	4
Up	-13	17	2	5	5	-15	16	2	5	5
Trial-2 (carried with zodiac-boat in Antarctic Circle, average latitude 67°50′S)										
	GPS-only Solution (cm)					GPS+GLONASS Solution (cm)				
	min.	max.	mean	SD	RMSE	min.	max.	mean	SD	RMSE
Northing	-6	9	0	2	2	-6	7	0	1	1
Easting	-7	6	0	2	2	-5	5	0	1	1
2D	0	9	2	1	2	0	7	1	1	1
Up	-5	23	8	3	9	-9	21	8	2	8

(CGO 2.0) GNSS data processing software, and the 3D coordinates of each measurement epoch were estimated by resolving the phase ambiguities within cm-level accuracy. The CGO 2.0 software can process the multi-GNSS static or dynamic GNSS raw data with relative methods or PPP algorithms. In addition to post-processing, CGO 2.0 provides a vast library of geodetic tools, such as coordinates and RINEX converters, an angle, distance, and volume calculator, a GNSS antenna manager, and a splitter and merge tool for GNSS observation files (**URL-3**). For the first trial, the baseline length varied from 26.5 km to 83.2 km between the vessel and the PALM reference station. The same procedure was applied for the second trial by using a reference station, TUR1 (67°49′54.37415″S, 067°14′17.03151″W, 11.902 m), installed in the vicinity of the Turkish Scientific Base located on Horseshoe Island. Each measurement epoch of the zodiac-boat was estimated by the relative method in cm-accuracy. For this trial, the boat moved within a radius of 4 km from the reference station.

The kinematic PPP coordinates were then compared to relative solutions (i.e. reference trajectory) for northing (N), easting (E), horizontal position (2D), and height (UP) components for each epoch. The differences were illustrated as the time-series in **Figure 3**. Furthermore, the obtained results were investigated statistically as minimum, maximum, and mean values of differences with Standard Deviation (SD) and Root Mean Square Error (RMSE) were given in **Table 6**.

The distribution of differences between the post-processed PPP and known coordinates were illustrated in a histogram in **Figure 4**.

5. Discussion

According to the analysis of the results from **Figure 3** and **Table 6**, the GPS-only solution provided coordinate differences between 0 cm and 12 cm with a mean of 3 cm for 2D horizontal component, while they were between -13 cm and 17 cm with a mean of 2 cm for the height component for the first trial. The GPS-only solutions achieved an accuracy (RMSE) at the cm level for all components. For the G+R solution, the differences varied between 0 and 12 with an mean of 3 cm for the 2D position and between -15 cm and 16 cm with an mean of 2 cm for the height component. The positioning accuracy (RMSE) of PPP solutions did not change after adding the GLONASS constellation to the GPS ones, they were 4 cm and 5 cm for 2D position and height components, respectively. This situation was the same for the standard deviation, and it was found that the standard deviations of both solutions were the same, and it was 2 cm for 2D position and 5 cm for height. In general, it was found that the GPS+GLONASS solution was very close to GPS-only with regard to performance and accuracy. It has been considered that this was because this kinematic measurement was performed under better conditions, while the CSRS-PPP Service resolves the phase ambiguities with a high ratio for GPS satellites (about 92%) by applying PPP-AR algorithms for this kinematic test.

In the zodiac-type craft-based kinematic test (Trial-2), for the GPS-only solution, the maximum differences were found better than 9 cm with a mean of 2 cm and 23 cm with a mean of 8 cm for 2D position and height components, respectively. The RMSE for the GPS-only solution was found as 2 cm in the 2D position and 9 cm in the height component. The differences for the GPS+GLONASS solution were similar to those of the GPS-only solution. For GPS and GLONASS combination, PPP-derived coordinates agree with the relative solution reaching to 7 cm and 21 cm maximum differences for 2D position and height, respectively. The GPS and GLONASS multi-constellation combination slightly im-

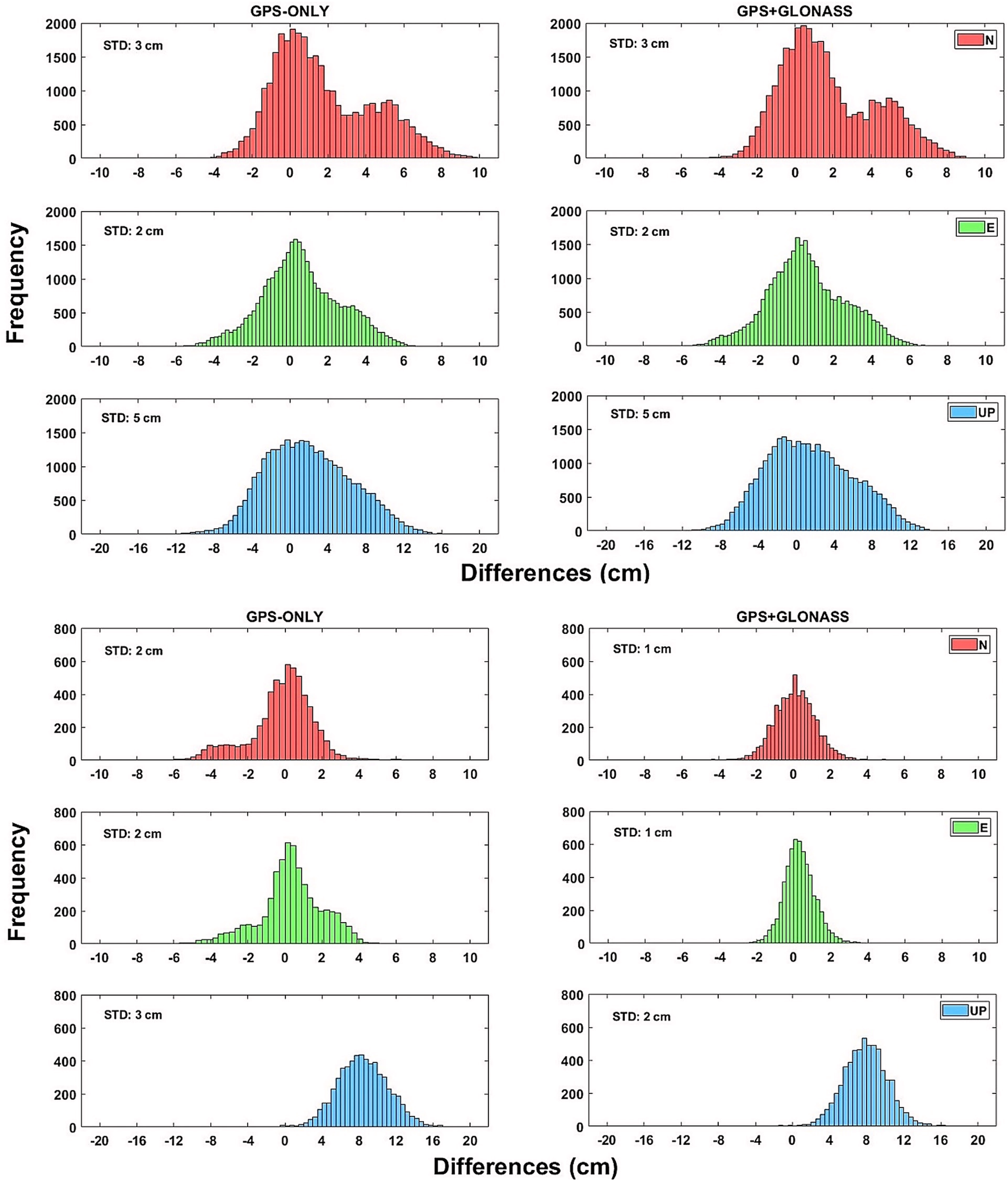

Figure 4: Histogram of the northing (N), easting (E), and height differences (UP) (*top*: for Trial-1, *bottom*: for Trial-2)

proved the positioning accuracy. As given in **Table 6**, the RMSE of the combined PPP solutions did not exceed 1 cm in the horizontal (2D) position component and 8 cm in the height component. In these measurements made in the Antarctic Circle, adding GLONASS observations to the GPS slightly improved the accuracy of the combined solution in terms of RMSE and SD compared to the GPS-only solution. However, in this application, there was a 6 cm bias for the height component between RMSE and SD values. This situation is also observed quite clearly in the histogram given in **Figure 4**. It has been evaluated that the most likely reason for this was this test measurement was carried out in the Antarctic Circle. In this test, fewer satellite observations at low

 pp. 31-43, DOI: 10.17794/rgn.2024.2.3

elevation angles and in short periods were made. In addition, due to the satellite orbital configuration, observations could not be made in the zenith direction (see **Figure 2**). All these negative aspects are likely to have played a significant role in reducing the accuracy of the height component.

When the differences obtained from the solutions of both kinematic tests were analysed, it was observed that the differences and accuracy for the east component were generally found to be slightly better than that of the north component. The most probable cause of this was that the CSRS-PPP service resolved the carrier-phase ambiguities with the PPP-AR algorithm, and as a result, this offers significant benefits for the east component.

When the differences given in **Figure 4** were examined, it was observed that the differences in the north component fell to between -5 cm and +12 cm, while those of the east component remained within a narrower interval with respect to all differences for both solutions (G-only and G+R combination) in the first test measurement. It can be seen that the east component gave better results than the north. The differences for GPS-only solution in the second test measurement were found within a few centimetres for the north and east components. It is also understood that the solutions obtained with the G+R combination are better than the G-only solution and fall into a narrower range. The height differences for the G-only and G+R solutions fell into the range of decimetre. In this test measurement conducted in the Antarctic Circle, it was easily understood that GLONASS significantly contributed to the PPP solution. Histograms are also a very useful tool for determining outlier values. When the histograms are examined in this respect, it was seen that there are no unusual values (in other words, outliers) in the data set.

6. Conclusions

This contribution investigated the potential use of the PPP technique in high-latitude regions. To assess the accuracy performance of the technique, two realistic experiments were conducted, and the PPP coordinates were calculated by processing the collected kinematic data with the online GNSS data processing service, CSRS-PPP. The solutions were realized in two different configurations as GPS-only and multi-GNSS (i.e. GPS+GLONASS). In this way, the effect of additional GLONASS satellite observations on the accuracy of kinematic PPP solution performance was also investigated. According to the results, GPS and GLONASS combined (G+R) solutions generally provided comparable or even better positioning performance than G-only. As stated above, the GLONASS constellation has an orbit inclination angle of about 10 degrees greater than other satellite systems. This would theoretically provide better satellite availability in the Polar Regions while providing better observation geometry. Thus, the addition of GLONASS observations is recommended for PPP solutions in high-latitude regions. The results showed that the realistic kinematic ship-borne test produced the centimetre-level horizontal and height accuracy in terms of RMSE using only one GNSS receiver data processing with CSRS-PPP ambiguity resolution (PPP-AR) solution strategy regardless of which constellation was used.

The applications carried out in high-latitude environments with sparse GNSS reference stations like Antarctica, the PPP technique stands out for its ease of application and its accuracy was comparable to that of the conventional differential method. According to the results obtained from the study, in general, the PPP technique can be a serious alternative to conventional GNSS positioning methods in terms of accuracy, speed, efficiency and fieldwork flexibility, especially for remote maritime and related applications.

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SAŽETAK

Besprijekorno precizno kinematičko pozicioniranje u okruženjima visoke zemljopisne širine: analiza slučaja na Antarktici

Znanstvene aktivnosti u antarktičkim regijama povećavaju se svakodnevno tijekom posljednjih desetljeća kako bi se ostvarili različiti projekti. Ledena ploča prekriva preko 98 % antarktičkoga kontinenta, najhladnije, najsušnije i najvjetrovitije mjesto na svijetu, te ima najveći pustinjski teren, što provođenje bilo kakvih studija i istraživanja čini vrlo teškim. Među njima precizna hidrografija trebala bi se provoditi za mnoge različite primjene koje zahtijevaju pouzdano i točno pozicioniranje. Rezultati ovih istraživanja igraju ključnu ulogu u razumijevanju promjena razine mora, globalnoga zatopljenja, kretanja morskih ledenih pokrova, navigacije i mnogih drugih područja. Teški atmosferski i topografski uvjeti regije dodatni su izazovi za mjernike u korištenju konvencionalnih zemaljskih mjernih tehnika i satelitskih metoda pozicioniranja (GNSS). Niska kvaliteta i šumovita opažanja GNSS-a s niskim elevacijama satelita čine njihovo pozicioniranje osjetljivim na ciklički preskok, višestruke odraze i prekide na Antarktiku. Ovo istraživanje analizira performanse postprocesiranoga kinematskog preciznog pozicioniranja točke (PPP) temeljenoga na internetskoj usluzi obrade GNSS-a za morsko istraživanje na visokoj zemljopisnoj širini. U okviru toga provedena su dva realistična eksperimenta na brodu i čamcu Zodiac tijekom 6. turske antarktičke ekspedicije (TAE). Rezultati pokazuju da koordinate PPP-a korištene uz internetsku uslugu obrade GNSS-a omogućuju kinematsko pozicioniranje s centimetarskom točnošću korištenjem jednoga GNSS prijamnika. Opći rezultati pokazuju da tehnika PPP omogućuje mnogo brže i točnije pozicioniranje na udaljenim i visokim zemljopisnim širinama uz niže troškove.

Ključne riječi:
Antarktika, GNSS, kinematsko istraživanje, precizno pozicioniranje točaka (PPP), internetska GNSS usluga obrade

Author's contribution

Reha Metin Alkan: proposed and defined the idea for the manuscript, guided the research, and wrote the article. **Mahmut Oğuz Selbesoğlu**: proposed and defined the idea for the manuscript, performed the field work, provided the analysis. **Hasan Hakan Yavaşoğlu:** performed the field work and provided technical suggestions. **Mehmet Arkalı**: processed the GNSS data and depicted the results.