ARCTIC
VOL. 76, NO. 3 (SEPTEMBER 2023) P. 357–369
https://doi.org/10.14430/arctic78405

Assessment of Multi-GNSS RT-PPP Services for the Antarctic Region

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(*Received 27 October 2022; accepted in revised form16 May 2023*)

ABSTRACT. The international service that ensures access to data and products of global navigation satellite systems (GNSSs), known as the IGS, runs a real-time service (RTS) project to support users who need real-time access to precise products. Thanks to the RTS project, it is now possible to obtain real-time precise point positioning (RT-PPP) solutions. RT-PPP can be used in many real-time positioning applications that require a high level of accuracy, efficiency, and flexibility, including earth sciences, atmosphere sciences, marine sciences, natural hazards, and many more. In this study, we tested the impact of different worldwide RTS products and satellite configurations on the performance of RT-PPP accuracy, as well as convergence time, in the Antarctic's challenging environment and extreme atmospheric conditions. We applied RT-PPP solutions using real-time precise products (satellite orbit/clock corrections, and biases to conduct the real-time PPP) provided by the IGS and NAVCAST (a real-time PPP positioning service) based on different GNSS constellations: GPS-only, Galileo-only, and a combination of GPS and Galileo. In this way, the performance of two different real-time (RT) services was compared with each other. At the same time, the effectiveness of the Galileo global navigation satellite system for RT-PPP was also tested, and the Galileo system's contribution to the GPS-only RT-PPP solution was investigated. The PPP-WIZARD software was used to process the corrections and GNSS data from a reference station in the Antarctic region. Although GPS-only, Galileo-only, and multi-GNSS solutions obtained from both RT services were found to have very close accuracy to each other, the combination of the GPS and Galileo systems produced better accuracy than when using the GPS system alone. According to the numerical results of this study, it was concluded that the real-time PPP technique gave promising results in such a challenging environment of the Antarctic region. However, we also observe that the RT-PPP technique requires a stable and robust internet connection, which might limit its usefulness in remote regions. Overall, we found the RT-PPP technique to be a viable alternative to conventional relative GNSS positioning techniques, especially in areas where continuously operating reference networks or similar networks are lacking.

Keywords: Precise Point Positioning (PPP); RT-PPP; IGS-RTS; NAVCAST; Antarctica

RÉSUMÉ. Le service international qui assure l'accès aux données et aux produits de systèmes mondiaux de navigation par satellite (GNSS), connus sous le nom d'IGS, gère un projet de service en temps réel (RTS) pour venir en aide aux utilisateurs nécessitant un accès en temps réel à des produits de précision. Grâce au projet de RTS, il est désormais possible d'obtenir des solutions de positionnement de précision en temps réel (RT-PPP). Les techniques de RT-PPP peuvent être employées dans de nombreuses applications en temps réel nécessitant un grand degré d'exactitude, d'efficacité et de flexibilité, notamment pour les sciences de la terre, les sciences de l'atmosphère, les sciences de la mer, les risques naturels et bien d'autres. Dans le cadre de cette étude, nous avons testé les effets de différents produits de RTS et de configurations satellitaires d'envergure mondiale sur le plan de l'exactitude des RT-PPP, ainsi que le temps de convergence, dans l'environnement rigoureux et les conditions atmosphériques extrêmes de l'Antarctique. Nous avons appliqué des solutions de RT-PPP au moyen de produits de précision en temps réel (corrections d'orbites et d'horloges de satellites, et biais pour réaliser des PPP en temps réel) fournies par l'IGS et NAVCAST (un service de PPP en temps réel) en fonction de différentes constellations de GNSS : GPS seulement, Galileo seulement et une combinaison de GPS et Galileo. Cela a permis de comparer le rendement de deux services différents en temps réel (RT). Par la même occasion, l'efficacité du système mondial de navigation par satellite Galileo a été mise à l'épreuve en matière de RT-PPP, et l'apport du système Galileo à la solution de RT-PPP pour GPS seulement a été examiné. Le logiciel PPP-WIZARD a servi à traiter les corrections et les données de systèmes mondiaux de navigation par satellite d'une station de référence de la région de l'Antarctique. Même si les solutions GPS seulement, Galileo seulement et multi-GNSS des deux services de RT ont donné des résultats d'une exactitude très semblable, la combinaison des systèmes GPS et Galileo a donné une meilleure exactitude que le système GPS employé seul. Les résultats numériques de cette étude ont permis de conclure que la technique de PPP en temps réel a donné des résultats prometteurs dans l'environnement rigoureux de la région de l'Antarctique. Cependant, nous avons également observé que la technique de RT-PPP nécessite une connexion Internet stable et robuste, ce qui risque de restreindre son utilité dans les régions éloignées. Dans l'ensemble, nous avons

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constaté que la technique de RT-PPP constitue une option viable par rapport aux techniques de positionnement GNSS relatives conventionnelles, surtout dans les régions où il manque des réseaux de référence ou des réseaux similaires en continu.

Mots-clés : positionnement de précision (PPP); RT-PPP; IGS-RTS; NAVCAST; Antarctique

Traduit pour la revue *Arctic* par Nicole Giguère.

INTRODUCTION

Recent years have seen significant advances in GNSS satellite hardware, software, networks, and communication infrastructures. These advances have led to new, highly accurate precise point positioning (PPP) technique that uses single global navigation satellite system (GNSS) receiver data. The PPP technique processes single-, dual-, or multi-frequency GNSS data, along with precise satellite orbit and clock corrections, plus other products mainly produced by International GNSS Service (IGS). PPP provides a very accurate position in post-processing mode (Héroux and Kouba, 1995; Zumberge et al., 1997; Héroux and Kouba 2001; Bisnath and Gao, 2009; Rizos et al., 2012; Cai et al., 2015; Choy et al., 2017; Alkan et al., 2020). In order to achieve high positioning accuracy with the PPP technique, the phase wind-up, polar motion, polar tides, solid earth tides, ocean loading, atmospheric loading, relativistic effect, satellite/receiver antenna phase center offsets and variations, should be corrected or modelled (Teunissen, 2020). The major disadvantage of the PPP technique is the slow convergence time, which requires tens of minutes (typically 30 minutes or more) for high positioning accuracy (Li and Zhang, 2014; Duong et al., 2020a). However, with the advent of the IGS's multi-GNSS experiment (MGEX) project that was initiated in 2012, it became possible to use multi-constellation (GPS, GLONASS, Galileo, and BeiDou) solutions (Montenbruck et al., 2017). The use of observations not only from GPS satellites but also other global navigation satellite systems in PPP solutions (known as multi-GNSS PPP) improved convergence time. Multi-GNSS also improves the positioning performance while enhancing the geometrical strength of satellites (Chen et al., 2021). The generation of code and carrier phase biases in addition to precise products by the analysing centers provide the PPP solution with ambiguity resolution. The PPP ambiguity-fixed resolution (PPP-AR) algorithm significantly improves positioning accuracy and shortens convergence time with respect to traditional float PPP solutions (Ge et al., 2008; Abdi et al., 2017; Pan et al., 2017; Liu et al., 2019; Teunissen 2020; Vaclavovic and Nesvadba, 2020; Glaner and Weber, 2021). But although the PPP-AR solution significantly improves convergence time, it is still not sufficient for real-time kinematic applications in comparison to the classic real-time kinematic (RTK) technique (Abdi et al., 2017). The modernization of next-generation GNSS satellites provide additional new signal frequencies, and the usability of an additional three or more frequencies in PPP solutions also reduces convergence time (Duong et al., 2020a and b). The multi-frequency and multi-GNSS PPP has become a more and more popular, convenient, and accurate technique. The technique offers static and dynamic cm-dm level precise 3D positioning in a global coordinate system without the requirement of any network or reference-station data. Thus, PPP provides flexibility and efficiency for accurate positioning with low operation costs. PPP has become a strong alternative to conventional, differential GNSS positioning both in post-process and real-time modes.

Although the MGEX project has made significant progress with the multi-GNSS PPP concept, the latency (time delay) of its products has not been able to fulfil the needs of real-time GNSS applications. For this reason, in 2013, IGS established its real-time service (IGS-RTS). This initiative paved the way for the PPP technique to be used in a wide variety of real-time kinematic positioning applications in land, sea, and air environments (Alkan et al., 2022). Although the IGS-RTS were initially started to generate and disseminate the real-time corrections for GPS constellation, since then, many IGS analysis centers have begun to generate precise products for GLONASS, Galileo, and BeiDou satellite systems. Thanks to the real-time GNSS orbit and clock corrections introduced within the scope of IGS-RTS, multi-GNSS PPP has also been used successfully in real-time applications. Under the IGS-RTS project, there are many analysis centers, most of which provide the multi-GNSS real-time corrections for RT-PPP, including the Bundesamt für Kartographie und Geodäsie (BKG); the Chinese Academy of Sciences (CAS); the Centre National D'Etudes Spatiales, France (CNES); the German Space Operations Center of the Deutsches Zentrum für Luft- und Raumfahrt (DLR/GSOC); DeutschesGeoForschungsZentrum (GFZ); GMV Aerospace and Defence, S.A. (GMV); and Wuhan University (WHU) (IGS, 2023).

Scholars have been investigating the usability and performance of the RT-PPP technique for decades. Alkan et al. (2022) investigated the convergence and accuracy performance of the RT-PPP technique with different IGS state space representation (SSR) corrections in the Antarctic region. They found that after around 20 minutes of convergence time, the multi-GNSS RT-PPP approach produced an accuracy of a few cm-dm levels for horizontal and vertical components. Zhao et al. (2022), who assessed the accuracy performance and GNSS signal quality of multi-GNSS observations collected in polar regions, found that the multi-GNSS PPP slightly improved the positional accuracy while accelerating convergence time compared to a single constellation. Alcay and Turgut (2021) evaluated RT-PPP accuracy performance under different constellation combinations. According to their numerical results, the RT-PPP technique provided accuracy better than 5 cm for 2D position, and 10 cm for height components after the convergence period. Atiz et al. (2023a) assessed accuracy and convergence time performance of the RT-PPP technique with float and fixed solution using different GNSS constellations and software. The authors found that accuracy and convergence time were improved not only with ambiguity resolution solutions, but also using additional GNSS constellation. Luo et al. (2021) argued that integration of the Galileo constellation in challenging environments improved convergence time and position accuracy. Liu et al. (2020) processed the GNSS data set with different strategies as dual- and triple-frequency ambiguity-float (PPP-float) and ambiguity-fixed (PPP-AR) algorithms, both in kinematic and static modes, demonstrating that triple-frequency PPP-AR solutions achieved the fastest convergence time among the four solutions, both for static and kinematic cases; furthermore, triple-frequency PPP-AR solutions improved the convergence time and positioning accuracy compared to dual-frequency PPP-AR, especially when observing a small number of satellites. Meanwhile, Monico et al. (2019) assessed the accuracy of a RT-PPP solution based on a realistic kinematic test scenario using GNSS data collected with an airplane. They obtained RT-PPP coordinates within the average accuracy of 20 – 30 cm for all components. Wang et al. (2018) examined the accuracy performance of different SSR products from eight analysis centers. Based on the experiment results, they concluded that the SSR products used in the solution affected the accuracy of the RT-PPP coordinates. Abdi et al. (2017) analyzed RT-PPP performance in terms of convergence time and positioning accuracy under different GNSS constellation configurations; numerical results showed that the combination of GPS, GLONASS, and BeiDou constellations increased RT-PPP convergence time and accuracy. Additionally, both GPS&BeiDou and GPS&GLONASS combinations reduced convergence time while improving accuracy, as compared with the GPS-only PPP. Krzan and Przestrzelski (2016) investigated the impact of the different real-time streams on real-time positioning, showing that the accuracy of the obtained coordinates varies depending on the product used.

More recently, a new wave of free, RT-PPP services, such as NAVCAST and MADOCA (multi-GNSS advanced demonstration tool for orbit and clock analysis), that serve real-time precise orbit, clock, and bias products, have emerged all over the world. These services can efficiently and effectively provide the centimeter to decimeter level of 3D positioning accuracy in kinematic and static modes (Anantakarn and Witchayangkoon, 2019; Elemezayen and El-Rabbany, 2019, 2020; Lipatnikov and Shevchuk, 2019; Alkan et al., 2020; Atiz et al., 2023b; Yu et al., 2023).

Although, as the summary above shows, there have been many scientific studies on RT-PPP, to date, few studies have examined the use of RT-PPP with IGS-RTS products in the polar regions in general and Antarctica in particular. No studies that we know of have assessed the performance of NAVCAST RT-PPP service in the Antarctic region. This paper's unique contribution then, is to investigate the performance of the different RT-PPP services in Antarctica. We would like to underline that more research is needed in this unique geography, which attracts more and more attention with each passing day, and where human activity is ever-increasing. In this sense, we believe our study will make an important contribution to the real-time positioning needed in scientific and practical studies conducted in these regions, including geodesy, hydrology, oceanography, geophysics, seismology, climatology, biology, and natural hazard science.

In this paper, we tested the accuracy and convergence time performance of RT-PPP solutions using precise products from two different worldwide real-time services (Spaceopal NAVCAST-RTS and IGS-RTS) under different satellite configurations. To carry out these tests, we used PPP-WIZARD software (that is, PPP with Integer and Zero-difference Ambiguity Resolution Demonstrator). In this way, we investigated the new NAVCAST real-time service performance for the RT-PPP solution using different constellations in the Antarctic region and compared it with the IGS-RTS results. Thus, we demonstrated Galileo-only RT-PPP performance with two different service products, and the contribution of the Galileo constellation to the GPS-only RT-PPP solution. We used precise products of the CNES and DLR, which are among the many analysis centers for IGS-RTS. It should be noted here that the IGS DLR and Spaceopal NAVCAST (see below) products provide ambiguity-float RT-PPP solutions with PPP-WIZARD software, while IGS CNES products provide ambiguity-fixed RT-PPP solutions. Thus, we also examined the effect of ambiguity resolution type (the process by which determining the number of initial unknown cycles of carrier phase observations) on the accuracy and convergence time of the RT-PPP.

DESCRIPTION OF IGS AND NAVCAST RT-PPP SERVICES

IGS established the real-time working group in 2001 to study use of the PPP technique in real-time applications. Since April 2013, IGS has been serving precise products within its RTS. The PPP technique is now usable in real-time applications and an ideal option in areas lacking available or reliable local continuously operating reference networks and communication infrastructure (Harima et al., 2017). IGS analysing centers broadcast IGS-RTS precise products over the internet as RTCM SSR correction using networked transport of RTCM via internet protocol, NTRIP (Wang et al., 2018).

In October 2018, the primary contractor for Galileo operations, Spaceopal GmbH, launched a new global real-time correction service for high-accuracy PPP positioning service called NAVCAST. Based on real-time system for clock estimation (RETICLE) software developed by DLR, the service delivers real-time satellite orbit

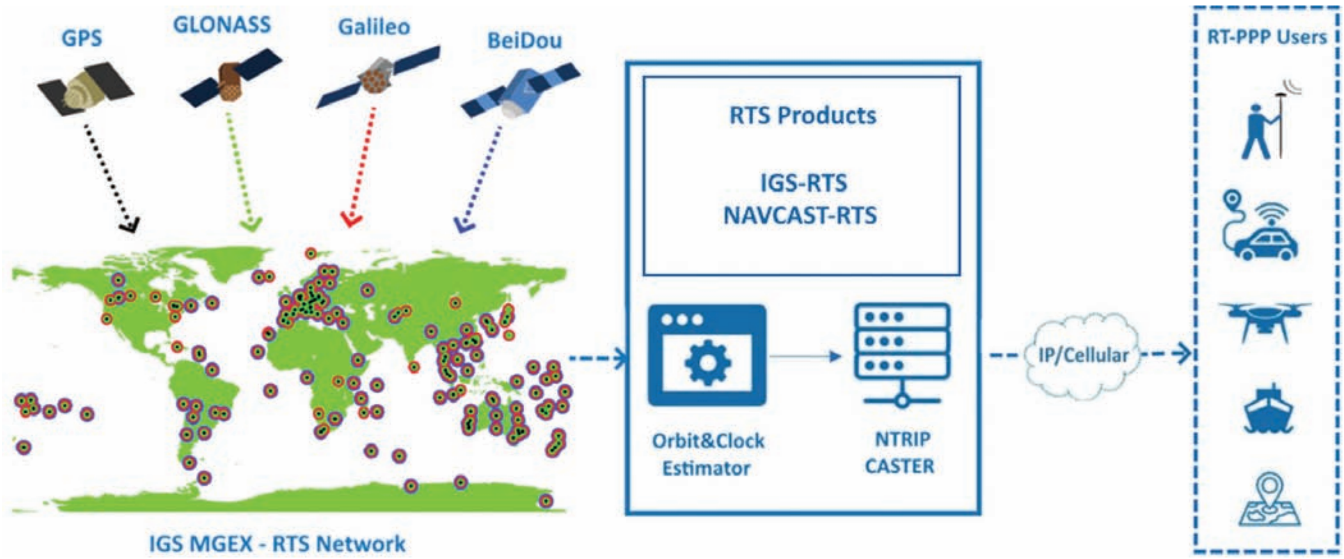

FIG. 1. Flowchart of the RT-PPP solution flowchart.

and clock corrections, code, and phase biases, together with the broadcast ephemeris for the GPS and Galileo constellations. Precise corrections produced using the observations collected at more than 100 IGS reference stations are supplied for free to registered users. NAVCAST supports GPS L1, L2, L5 and Galileo E1, E5a, E5b frequencies. Although NAVCAST corrections are broadcast to users through the internet using NTRIP, the service also plans to provide delivery to users through communication and navigation satellites. Ionospheric corrections in the NAVCAST stream are used to reduce convergence time, as well as solar and ionospheric effects (NAVCAST, 2023).

Precise orbit, clock, and bias products streamed in real-time by IGS and NAVCAST services are produced in real-time by transferring GNSS tracking station network observations to a server and processing them using product generator software. Users retrieve resulting products (produced in real time in SSR format) using NTRIP protocol with the help of PPP-client software connected to the internet. Users perform RT-PPP by processing these together with the GNSS observations collected by the receiver. Figure 1 provides the flowchart of this process. Each of the products produced by different IGS analysis centers use different global tracking networks and generators (i.e., software that generates orbit, clock, and bias). Therefore, the performance and accuracy of RT-PPP-based coordinates vary according to the products used.

Although there are many software packages that can be used as PPP-client software for RT-PPP applications, the most used and preferred ones are PPP-WIZARD developed by CNES; BKG NTRIP Client (BNC) developed by BKG; and Real-time Kinematic Library (RTKLIB) developed at Tokyo University of Marine Science and Technology. We used PPP-WIZARD software in this study. PPP-WIZARD is open source and also functions as a product generator; it can solve integer phase ambiguity (ambiguity-fixed) in real-time and stands out for its up-to-date algorithms (Laurichesse and Privat, 2015). In addition, users can integrate PPP-WIZARD into BNC and RTKLIB. The software is based on the undifferenced and uncombined functional model. It provides zero-difference ambiguity resolution by processing single-, dual-, and triple-frequency multi-GNSS code and phase measurements. This uncombined model, which was introduced by Laurichesse and Blot (2016), has some advantages over the classical uncombined formulation. First, the bias messages on RTCM are more difficult to standardize in the classical uncombined model. Second, while it is obligatory to use the same ambiguity solution method for the user side and the network side in the classical model, this is not required in the new model. Finally, the new uncombined method has made it possible to solve triple-frequency situations. Thanks to the PPP-WIZARD software's undifferenced and uncombined observation model, there are no linear or differencing operators' combinations in the observation equations, and the ambiguity parameters are combined (Liu et al., 2020). The latest version of the software (v. 1.4.3) supports GPS, GLONASS, and Galileo constellations. Because PPP-WIZARD is open source and can be used from the command line, users can customize the code. In addition to making solutions with the data published in RTCM format in real-time, the software also performs real-time position simulation if users input the relevant correction data and observation RINEX files after measurement. The software considers the sagnac effect, solid earth tide, relativistic effect, phase wind-up, troposphere, and receiver/satellites phase center offsets and variations (see PPP-WIZARD, 2023).

CASE STUDY AND RESULTS

For this study, we investigated the accuracy and convergence performance of RT-PPP using the precise

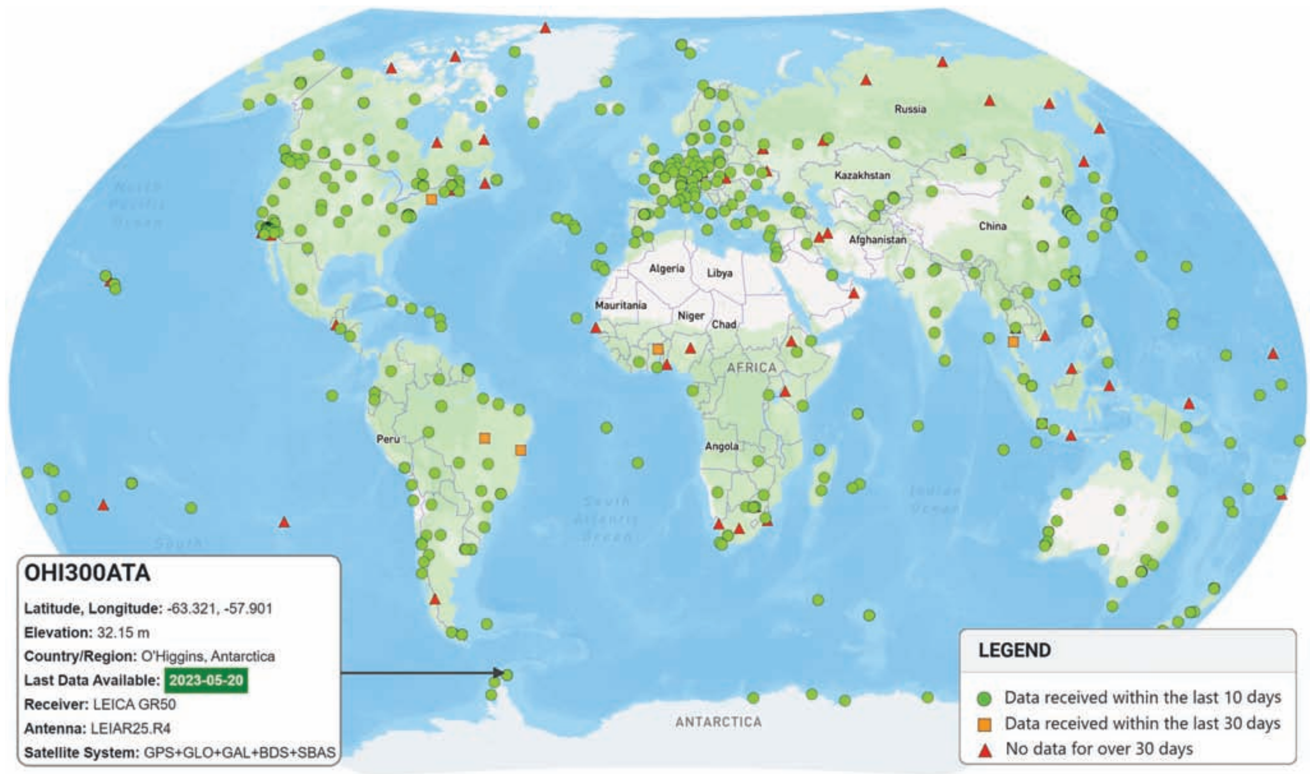

FIG. 2. Location of the OHI300ATA IGS multi-GNSS RTS station whose data was used in the study (https://network.igs.org).

products provided by IGS and NAVCAST real-time services under different GNSS constellations (GPS-only, Galileo-only, and a combination of GPS and Galileo) in the Antarctic region. Therefore, we compared performances of two different real-time services, tested the RT-PPP performance of Galileo as Europe's global navigation satellite system, and examined the contribution of the Galileo system to the GPS-only RT-PPP solution.

Study Test Area, Data, and Products

To evaluate the attainable accuracy and usability of IGS and NAVCAST real-time services in the harsh measurement environment of the Antarctica continent, we used OHI300ATA (OHI3) IGS-MGEX RTS station data. Figure 2 displays the location of the OHI3 reference station with explanatory information.

The station is equipped with the LEICA GR50 geodetic GNSS receiver and its corresponding geodetic antenna (LEIAR25.R4+LEIT). The receiver can receive signals from GPS (L1/L2/L5), GLONASS (G1/G2/G3), Galileo (E1/E5/E5a/E5b/E6), BDS (B1I/B1C/B2I/B2a/B3I), and SBAS satellites.

We processed the OHI3 data with the following solution strategies using three different SSR streams (from CNES, DLR, and NAVCAST):

Solution 1- GPS-only (G) solutions
Solution 2- Galileo-only (E) solutions
Solution 3- GPS+Galileo combination (G+E) solutions

Although the OHI3 station, from which we drew our data, collects GPS (G), GLONASS (R), Galileo (E), BeiDou (C), and SBAS (S) satellite observations, the solutions discussed in this study were made only according to these scenarios. Within the test study, we used 10-hour data from the station on 9 November 2021 (GPS week: 2183 and GPS day: 313).

We calculated the station's epoch-by-epoch RT-PPP coordinates using GNSS observations, broadcast ephemerides, and different SSR correction products provided by the IGS-RTS analysis center (CNES, DLR) and Spaceopal NAVCAST-RTS. We used the PPP-WIZARD software package to retrieve the GNSS data streams (observation and broadcast ephemerides) and SSR streams (satellite orbit and clock corrections, code, and phase biases) through NTRIP broadcasters. We calculated the RT-PPP coordinates using a multifrequency, uncombined observation model for G-only, E-only, and G+E using three different SSR real-time streams from two different real-time services. CNES SSR products are produced using multi-GNSS IGS-RTS and Regina (CNES, 2023) network observations with PPP-WIZARD generator software. Compatibility of PPP-WIZARD client software with CNES products enables the RT-PPP-AR (ambiguity-fixed) solution. Conversely, the DLR and NAVCAST products, generated using the same global tracking network and the same algorithm (RETICLE), provide ambiguity-float solutions with PPP-WIZARD. The RETICLE algorithm uses approximately 150 global multi-GNSS RT reference stations. The DLR Analysis Center produces SSR products

TABLE 1. The main features of IGS-RTS and NAVCAST-RTS streams used in this study.

Streams	GNSS	Messages content	Center/Generator
SSRA00CNE0	GREC	combined orbit and clock corrections code and phase biases	CNES (FRA)/ PPP-WIZARD
SSRA00DLR0	GREC	satellite orbit and clock corrections code and phase biases	DLR (DEU)/ RETICLE
CLKA0_DEU1	GE	satellite orbit and clock corrections code and phase biases	SPACEOPAL (EU)/ RETICLE

TABLE 2. Processing parameters of the software used in the study.

Items	Descriptions
PPP-client software and version	PPP-WIZARD v1.4.3
Strategy	RT-PPP
Observables	Undifferenced-uncombined raw code and phase observations
Satellite systems	G-only (L1/L2/L5); E-only (E1/E5a/E5b); G+E
Ambiguity solution	Float/Fixed
Elevation cut-off angle	7 degree
Sampling rate	1 second (1 Hz)
Weighting	$1/\sin^2$ (elevation angle)
Correction streams	SSRA00CNE0 and SSRA00DLR0 from IGS-RTS CLKA0_DEU1 from NAVCAST
Broadcast ephemeris	BCEP00 from IGS-RTS BCEP0_DEU1 from NAVCAST-RTS
Ionosphere	Estimated
Priori troposphere	Saastamoinen
Wet troposphere	Estimated
Mapping function	1/cos (zenith angle)
Phase wind-up, solid earth tide, relativistic effects	Applied
PCO and PCV	igs14.atx
Estimator	Kalman filter
Reference frame	ITRF2014

for four satellite systems, while NAVCAST produces only for GPS and Galileo satellites (at the time of the study). The RTS precise products/streams used in this study, together with the satellite constellations, message contents, analysis center, and generator (software) are given in Table 1. Table 2 presents the processing parameters we applied for RT-PPP using PPP-WIZARD.

Skyplots of Tracked Satellites

Figure 3 illustrates the number of satellites used in the solutions together with the position dilution of precision (PDOP) values (a measure of the effect of satellite geometry on horizontal and vertical coordinates) and skyplots at seven-degree elevation angle. Table 3 summarizes results. For GPS-only, the number of tracked GNSS satellites was between 6 and 12 (an average of 10), while, for Galileo-only, the number was between 6 and 9 (an average of 8). GPS and Galileo constellations combination provided significant improvement in the number of visible satellites, reaching an average of 18 (see Fig. 3, Table 3).

Concerning the PDOP measure, where lower values are optimal, the GPS-only solution provided slightly better values than the Galileo-only solution: the minimum, maximum, and mean values were 1.2, 2.6, and 1.8 for GPS-only, while 1.0, 1.5, and 1.2 for the GPS+Galileo combination, respectively. The mean PDOP value of the GPS+Galileo combination was about 33% and 40% improved compared with the GPS-only and Galileo-only single systems, respectively.

We deduced that multi-constellations (multi-GNSS) significantly increased the number of available satellites and satellite coverage in comparison to single systems. Multi-constellations enhanced satellite geometry and improved positioning availability, accuracy, reliability, and continuity. Combining constellations also provided high measurement redundancy for PPP solutions. Convergence time, which we discuss in detail below, accelerated with multi-GNSS usage.

Numerical Results

To accurately assess the positioning performance of the RT-PPP approach, we compared the estimated coordinates obtained for each measurement epoch for the three solution scenarios (using three different RTS products) with the ITRF coordinates of the OHI3 IGS-RTS station. Figure 4 presents the time series of the differences between the DLR, CNES, and NAVCAST RT-PPP solution coordinates of different constellations and the known coordinates of the station for the 2D horizontal and vertical (height) components.

Figure 5 shows the 2D scatter plot of differences of easting and northing components after we excluded the

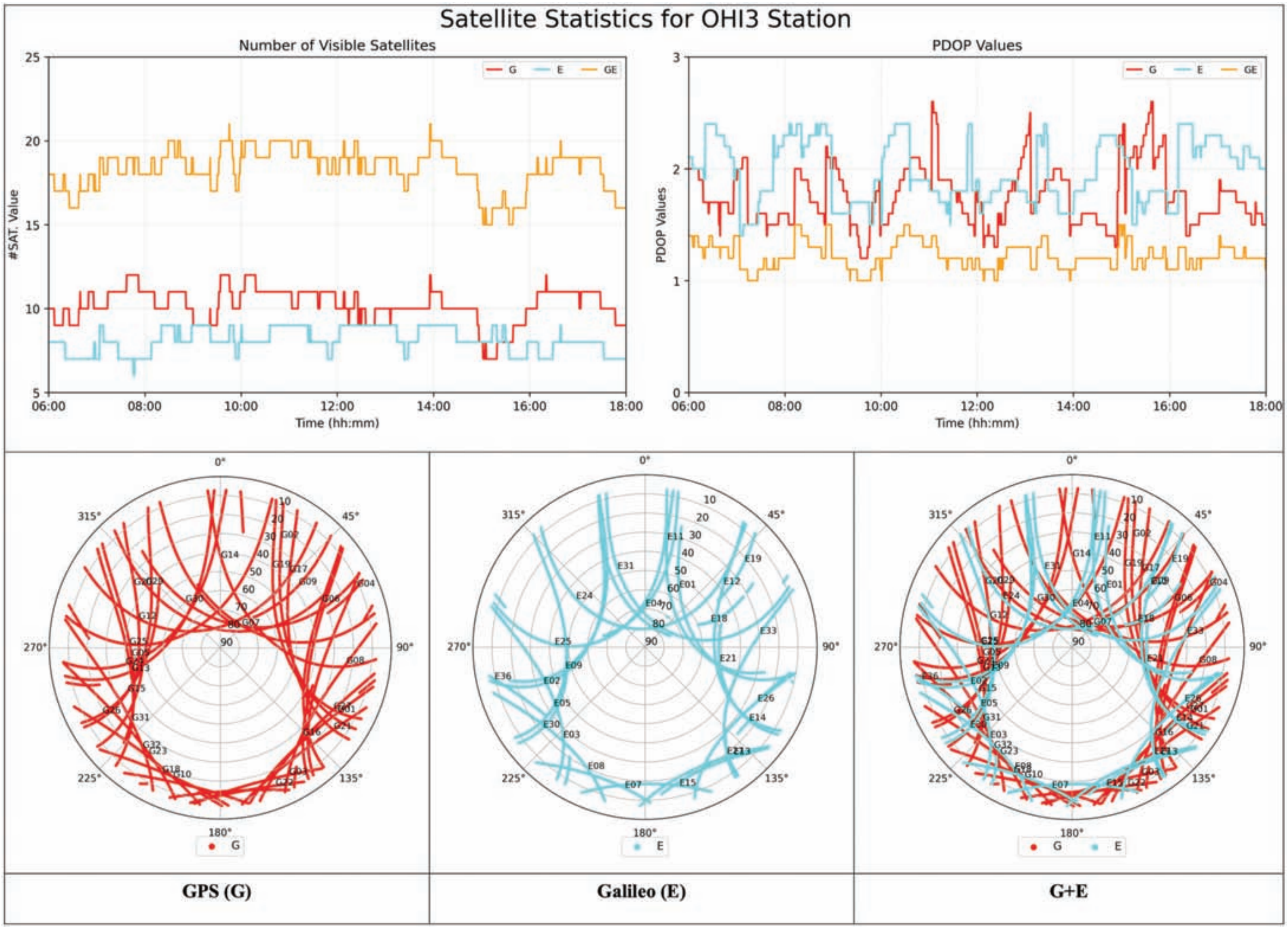

FIG. 3. Number of visible GNSS satellites, position dilution of precision (PDOP) values, and skyplots for OHI3 station.

convergence period of all solutions. We deemed convergence time to be the interval from the first valid measurement and the moment at which the 2D positioning error was 10 cm. It is worth mentioning that the positioning error is defined as the differences between the RT-PPP solution and the known coordinates of the station, not the accuracy value expressed as root mean square error (RMSE).

Convergence Time and Positioning Accuracy

Convergence time is considered a very important performance indicator for the PPP technique. Therefore, for comparative analysis, in Figure 6 we present the convergence times of all solutions using three different RTS products and three different satellite constellations. To evaluate the accuracy performance of the RT-PPP solutions, we calculated the RMSE values for horizontal (2D) position and height components for each tested RTS product and constellation. We also examined horizontal position and height differences statistically (Table 4). In order to better interpret our results, we provide the 2D and height RMSE and standard deviation (STD) values for the solutions separately (Figure 7).

TABLE 3. The satellites number and PDOP values

		GPS	Galileo	GPS + Galileo
#SAT	Minimum	6	6	14
	Maximum	12	9	21
	Mean	10	8	18
PDOP	Minimum	1.2	1.4	1.0
	Maximum	2.6	2.5	1.5
	Mean	1.8	2.0	1.2

DISCUSSION

As seen in Figure 3 and Table 3, using multi-GNSS observations improved satellite availability and geometry while increasing measurement redundancy. Incorporating an additional satellite system is crucial because the robustness of the single GNSS system cannot be guaranteed in extreme surveying conditions. Thus, multi-GNSS constellation can enhance PPP solution performance compared with a single system, especially in challenging areas like polar regions.

We found convergence times for the GPS-only RT-PPP solutions using DLR, CNES, and NAVCAST SSR products of 24, 22, and 34 minutes, respectively. For Galileo-only

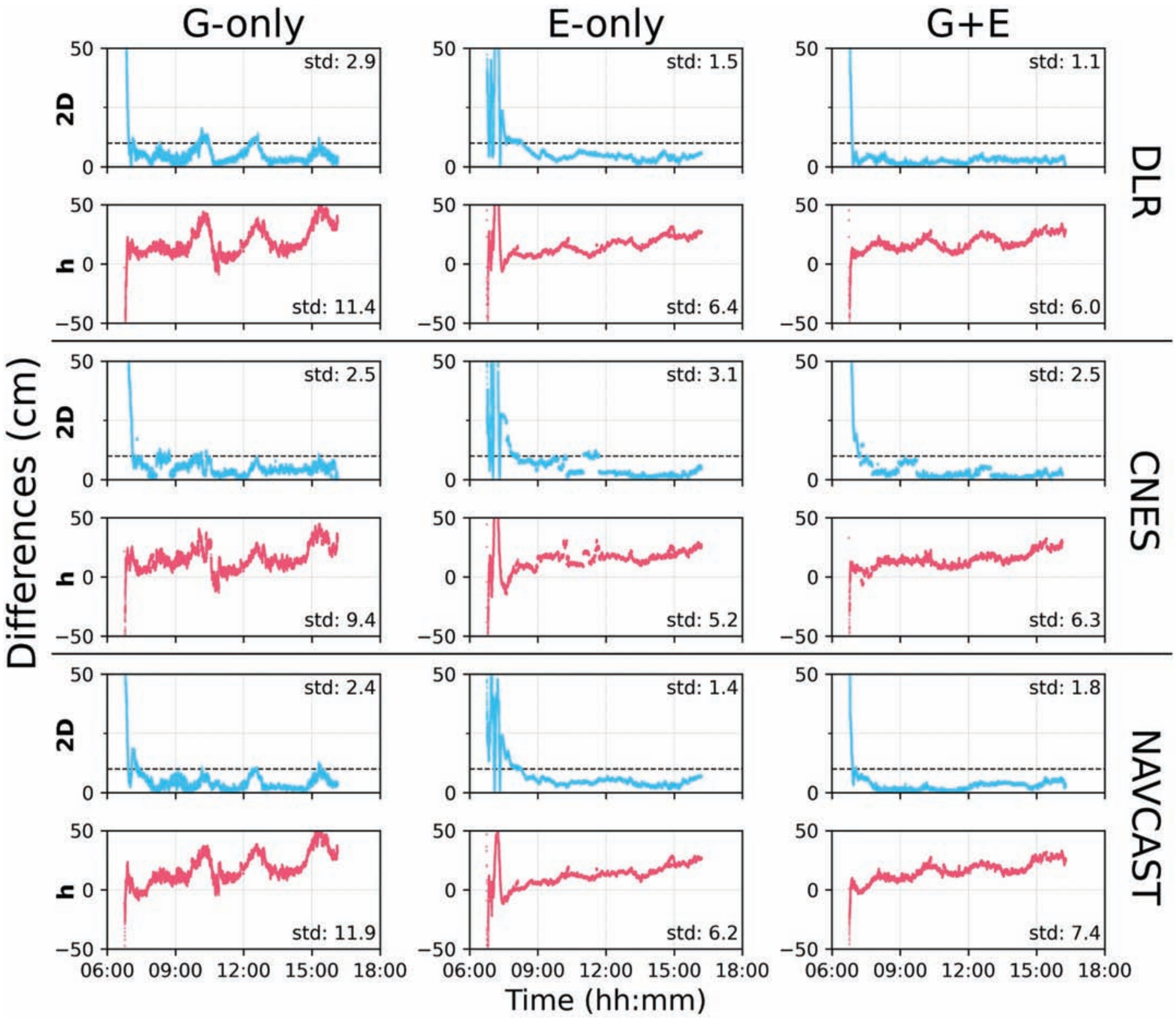

FIG. 4. Time series of differences between the RT-PPP solutions and known coordinates. The dashed line shows the 10 cm limit for convergence.

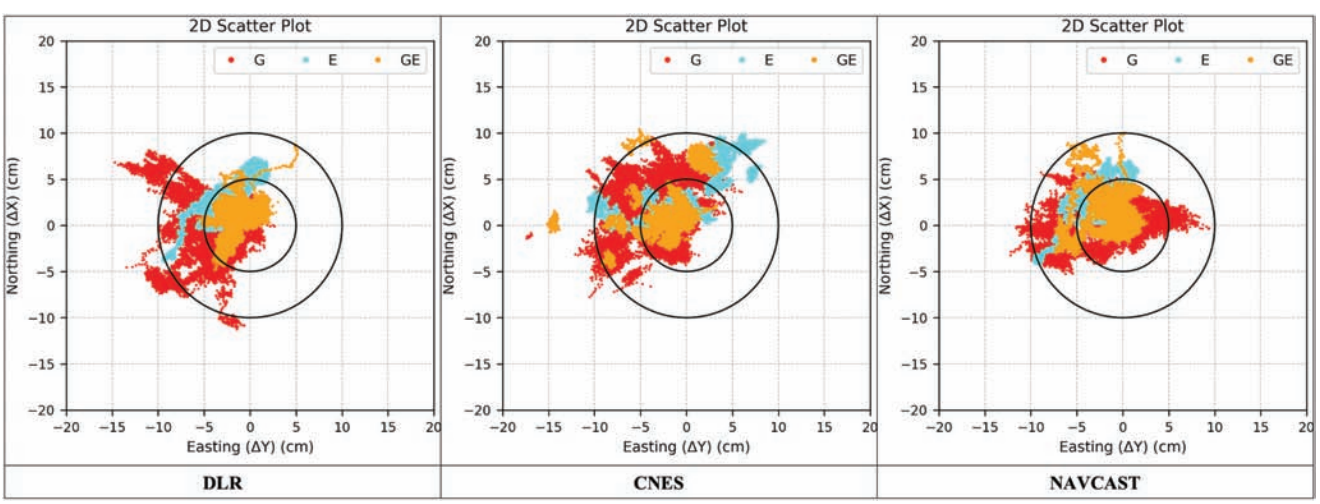

FIG. 5. 2D scatter plot of differences for DLR, CNES, and NAVCAST solutions.

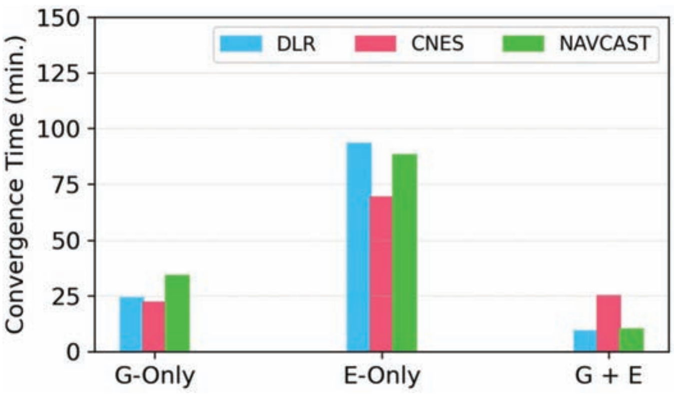

FIG. 6. Convergence times for the RT-PPP solutions.

solutions, the corresponding values were 93, 69, and 88 minutes. Thus, convergence time of GPS-only solutions for all RTS products used in the study was shorter than Galileo-only solutions. The RT-PPP-AR solutions using CNES products provided the shortest convergence time for GPS-only and Galileo-only solutions, but for the GPS+Galileo solution, the opposite situation occurred. The mean convergence time of the RT-PPP solutions from the GPS+Galileo combination for DLR and NAVCAST (10 minutes) was shortened by an average of 65% and 90% when compared to GPS-only and Galileo-only solutions. Thus, adding Galileo observations in addition to GPS observations significantly accelerated convergence time for DLR and NAVCAST RTS products. Based on our results, the shortest convergence time was an average of 10 minutes for GPS+Galileo constellations with DLR and NAVCAST SSR products.

When we examined the differences shown in Figures 4 and 5, and Table 4, those from GPS-only RT-PPP solutions, based on all SSR products, obtained better than 2 dm in the 2D position. However, the GPS-only solution using NAVCAST products produced better results than the DLR and CNES GPS-only solutions. When looking at the height component, it appeared that the differences were quite similar for all GPS-only solutions and produced results in the order of a few decimeters. Since we observed large height differences in all solutions obtained from all three services for GPS-only solutions, we deduced that there was no problem with the service products, and that the problem arose from the quality of GPS measurements of that day. Differences for Galileo-only solutions based on all products were better than about 1 dm and about 3 dm in 2D position and height components, respectively. Numerical results showed that the differences in the horizontal and height components obtained from Galileo-only solutions were better than GPS-only solutions, regardless of which SSR products were used. As can be seen in Figures 4 and

TABLE 4. Statistical analysis of the horizontal and height differences (after convergence)

Data Source	Used SSR Corrections Received	Ambiguity Sol. Type	2D Position (cm)				Height (cm)			
			Minimum	Maximum	Mean	RMSE	Minimum	Maximum	Mean	RMSE
IGS RTS										
	DLR (G)	Float	0	16	5	6	–9	52	19	22
	DLR (E)	Float	1	10	4	5	5	32	16	17
	DLR (G+E)	Float	0	10	3	3	5	34	18	19
	CNES (G)	Fixed	0	17	5	5	–13	45	16	18
	CNES (E)	Fixed	0	12	5	6	3	31	16	17
	CNES (G+E)	Fixed	0	15	3	4	–7	33	15	16
NAVCAST RTS										
	G-only	Float	0	13	4	5	–9	54	19	22
	E-only	Float	1	11	5	5	0	29	14	15
	G+E	Float	0	11	3	3	–3	33	16	18

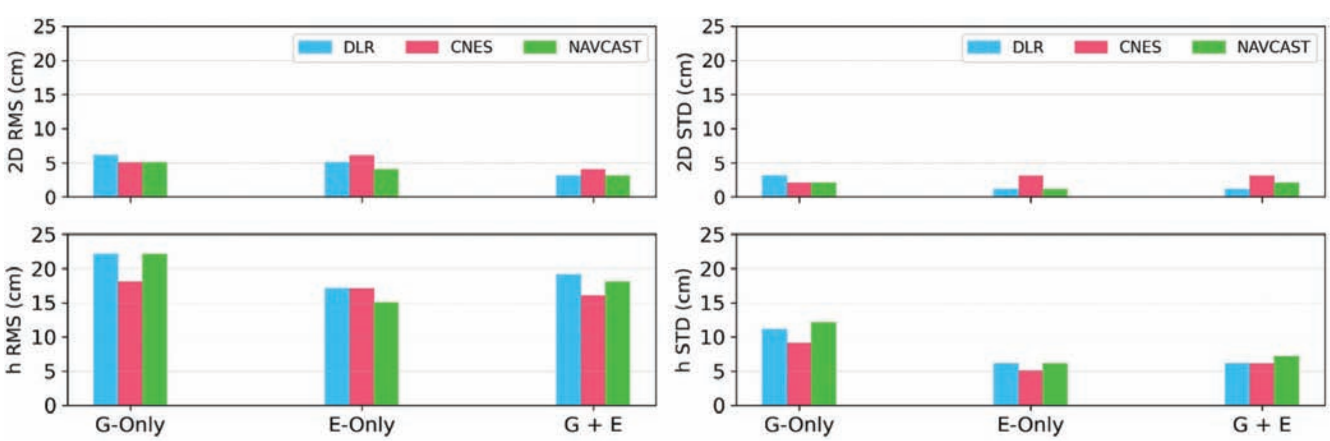

FIG. 7. RMSE and STD values for horizontal (2D) and height (h) components.

5, Galileo-only solutions remained more stable than GPS-only solutions in both the horizontal and height components after the convergence period for all service solutions. The differences in 2D position and height components of the GPS and Galileo combination solutions realized using all SSR products yielded very similar results to Galileo-only solutions. However, as can be seen from Figure 6, Galileo-only solutions required quite a long convergence time.

When examining the 2D accuracy obtained from the RT-PPP-AR (ambiguity-fixed) solution using CNES products and the RT-PPP-float solutions using DLR and NAVCAST products for all constellations, we noted that the 2D RMSE values were below 6 cm (Table 4 and Fig. 7). The GPS-only solutions produced almost the same level of 2D RMSE values as Galileo-only solutions for all RTS products. Adding Galileo to the GPS constellation (combination of G+E constellations) enhanced the 2D RMSE for all solutions regardless of which SSR precise products were used. We conclude that the Galileo system makes a significant contribution to the GPS system in terms of accuracy. The accuracies of the height component (RMSE) were found to be below 22 cm for all constellations and services. The solutions obtained using DLR and NAVCAST products for single and multi-constellations yielded very similar results because these two product groups were produced using the same global tracking network and the same algorithm, RETICLE. Our results show that the best RMSE value for the 2D position component was obtained using the G+E combination for all RTS corrections, whereas the NAVCAST solution using Galileo-only constellation produced the best height RMSE.

In general, the combination of GPS and Galileo GNSS observations provided the best RT-PPP performance in terms of both 2D horizontal accuracy and convergence time. We conclude that, compared to a single constellation solution realized as GPS-only or Galileo-only, a multi-constellation combination solution improved positioning accuracy and shortened convergence time.

CONCLUSION

In this study we considered the usability of the RT-PPP technique to obtain the three-dimensional (3D) coordinates needed by various professional disciplines in their projects in the Antarctic's challenging field conditions. We used two real-time services and three GNSS satellite constellation scenarios to investigate the applicability of the RT-PPP technique. We estimated the RT-PPP coordinates of the OHI3 station every second through about 10 hours of observations using different precise products (satellite orbit, clock, and biases) provided by IGS (DLR and CNES) and Spaceopal NAVCAST real-time services. Based on our assessment of results regarding the convergence time and attainable accuracy of the RT-PPP solutions, we concluded that centimeter-level accuracy for the 2D component, and decimeter-level for the height component were achieved after 10 to tens of minutes' convergence time. In general, compared to single-constellation (GPS-only or Galileo-only) PPP solutions, the multi-constellation combination enhanced 2D positioning accuracy while accelerating convergence time. Overall, findings reveal that the solution's accuracy and convergence time vary depending on the selected products and satellite constellation. As the number of real-time SSR products produced by IGS and other RTS increases, we can take advantage of the different levels of accuracy to conduct RT-PPP. Unlike the relative positioning method, the RT-PPP does not need reference station(s) data, and it has become a viable alternative to the conventional relative GNSS positioning technique, both in post-process and real time. The attainable accuracy shown in our study was sufficient for many geodetic and related applications, including engineering, geophysical hazard detection and warnings, mapping, marine surveying and seismic studies.

Despite the advantages of the RT-PPP technique, it also has some disadvantages. Convergence time still appears to be an important limiting factor in using this technique for real-time applications. On the other hand, in such IGS and NAVCAST real-time correction services, SSR corrections are transmitted to users via an internet connection. However, if there is no robust internet connection or a lack of cellular coverage during measurements, a stable RT-PPP solution is not possible. Therefore, one of the key factors for this method is the internet connection. Satellite-based internet services with global coverage, such as SpaceX's Starlink project, may solve this problem in the near future. However, if the SSR products used in RT-PPP are provided by communication satellites over the L-band instead of the internet, many of the aforementioned problems will be eliminated, and more robust, stable, seamless 3D positions will be achieved.

In summary, our study found very satisfactory results when using IGS, but also NAVCAST real-time service in Antarctica. Due to the many advantages of these services for users, we foresee more similar systems in the future.

ACKNOWLEDGEMENTS

The authors would like to thank the IGS and NAVCAST RTS for providing real-time SSR streams, and gratefully acknowledge the Centre national d'études spatiales for providing the PPP-WIZARD software package for the study. Lastly, the authors thank the editors and anonymous reviewers who made the article more powerful with their suggestions.

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