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ORIGINAL ARTICLE

Initial performance assessment of Galileo High Accuracy Service with software-defined receiver

Peiyuan Zhou[1] · Guorui Xiao[1] · Lan Du[1]

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Abstract
The European Galileo High Accuracy Service (HAS) was officially declared as initial service status on January 24, 2023, which can provide freely and openly accessible real-time precise satellite orbit, clock and code bias products to global users through the Galileo E6B signals. We conducted initial performance assessment of the HAS GPS and Galileo satellite orbit and clock products collected with a commercial off-the-shelf software-defined receiver platform located in Zhengzhou, China, from March 11 to 20, 2023. The results show that the average availability of HAS GPS and Galileo satellite orbit and clock products is 86.9% and 91.7%, respectively. The average accuracies of HAS GPS satellite orbit products are 0.037, 0.106 and 0.057 m for the radial, along-track and cross-track directions, while those for HAS Galileo are 0.032, 0.094 and 0.065 m, respectively. Meanwhile, the average precision of HAS satellite clock products for GPS and Galileo are 0.24 and 0.18 ns, respectively. After that, Precise Point Positioning experiments are conducted with GPS and Galileo observations from all the International GNSS Service Multi-GNSS Experiment stations (over 380 stations). It indicates that the average static positioning accuracies with HAS GPS products are 2.80, 1.53 and 2.18 cm in the east, north and up directions, while those for HAS Galileo products are 1.40, 1.79 and 2.31 cm, respectively. On the other hand, the average kinematic positioning accuracies with HAS GPS products are 7.94, 5.55 and 13.39 cm in the east, north and up directions, while those for HAS Galileo products are 8.08, 5.28 and 12.43 cm, respectively. It is therefore concluded that the HAS products can support decimeter-level positioning accuracy in both static and kinematic modes, which will support various emerging real-time precise positioning applications on a global scale.

Keywords Global Navigation Satellite System (GNSS) · Galileo High Accuracy Service (HAS) · Precise Point Positioning (PPP) · Software-defined receiver (SDR)

Introduction

Thanks to the availability of real-time state-space representation (SSR) corrections, including real-time precise satellite orbits, clocks and code biases provided by various GNSS augmentation services such as the Internet-based Real-Time Service (RTS) of the International GNSS Service (IGS) (Caissy et al. 2011; Johnston et al. 2017), as well as those from commercial augmentation service operators such as Trimble (Chen et al. 2011), real-time Precise Point Positioning (PPP) is drawing increasing interests among the GNSS community as an innovative and useful technology to derive decimeter-level precise positioning solutions globally with a single GNSS receiver (Malys and Jensen 1990; Zumberge et al. 1997). In addition to those third-party GNSS augmentation services, some newly developed GNSS systems are also able to disseminate real-time augmentation services via navigation satellite signals, such as the Centimeter-Level Augmentation Service (CLAS) of the Quasi-Zenith Satellite System (QZSS) via the L6 signal (Cabinet Office 2020; Zhang et al. 2022) as well as the PPP-B2b augmentation service of the Beidou Navigation Satellite System (BDS) via Geostationary Orbit (GEO) satellites' B2b signals (CSNO 2020; Nie et al. 2021). The augmentation services provided by the GNSS system operators are independent of Internet connection and are freely and openly accessible to the users, which will further promote the development of cost-effective real-time PPP solutions for various emerging applications such as autonomous driving and precision farming.

✉ Guorui Xiao
xgr@whu.edu.cn

1 Information Engineering University, Zhengzhou 450001, China

On January 24, 2023, the Galileo High Accuracy Service (HAS) was declared operational as initial service, which disseminates real-time precise satellite orbit, clock and code bias products via the Galileo E6B signals (European Union 2022, 2023). As the latest GNSS system to provide real-time PPP augmentation service via navigation satellite signals, Galileo HAS is aimed to support decimeter-level real-time PPP solutions globally, although the rectangle area of latitudes − 60° to 60° and longitudes of − 125° to − 90° is currently excluded from the normal service area (European Union 2023). Before the official initial service declaration (ISD), initial performance assessments of the experimental Galileo HAS have been conducted with support from the Galileo control segment. Fernandez-Hernandez et al. (2022) analyzed the initial phase of Galileo HAS and showed that it could provide broad coverage with high correction accuracy and positioning accuracy. Hauschild et al. (2022) assessed the quality of the satellite orbit and clock corrections from the early HAS test signals from September 2021 and applied them to the real-time precise satellite orbit determination of Sentinel-6A. Naciri et al. (2023) assessed the HAS test signals broadcasted during the summer of 2022 and conducted a quality assessment of the experimental Galileo HAS using data, concluding that the signal-in-space ranging error (SISRE) of 11.8 and 10.6 cm for GPS and Galileo, respectively, which can support decimeter-level real-time PPP at the user. Fernandez-Hernandez et al. (2023) further introduced the infrastructure and initial performance of the Galileo HAS. Angrisano et al. (2023) also show that HAS could contribute to the performance improvement of single point positioning at the user. It is noted, however, most of the current work on HAS performance assessment is conducted with experimental services and customized receivers, while HAS performance after the ISD is still to be assessed with commercial off-the-shelf (COTS) devices which are available to the general public.

We aim to evaluate the initial performance of Galileo HAS after ISD from the user's perspective. Considering that no COTS GNSS receivers can receive and decode the HAS corrections disseminated by the Galileo E6B signals, we first developed a low-cost COTS software-defined receiver (SDR) to receive and decode Galileo HAS corrections in Zhengzhou, China. The received HAS corrections are then compared with IGS post-processed products for quality assessment. The following introduces the data collection and processing strategies via the developed low-cost COTS SDR. Then, the methodologies for quality assessment of the HAS products are introduced. Thereafter, 10-day-long Galileo HAS products, from March 11 to 20, 2023, are collected and assessed with respect to precise products from German Research Center for Geosciences (GFZ). After that, the PPP performance is extensively assessed with GPS and Galileo observations from all the IGS Multi-GNSS Experiment (MGEX) stations (over 380 stations) (Montenbruck et al. 2017). Finally, conclusions and future works are summarized.

Methodologies

In this section, we first present the collection of Galileo HAS corrections with a low-cost COTS software-defined receiver (SDR). After that, the method to recover Galileo HAS orbit and clock products is briefly presented. Finally, the method to assess the quality of Galileo HAS orbit and clock products is described.

Collection of Galileo HAS corrections

The Galileo E6B signal with a carrier frequency of 1278.75 MHz is used for the transmission of HAS corrections. The Galileo $\boldsymbol{e}_{\mathrm{E6B}}(t)$ baseband signal component can be written as (Fernandez-Prades et al. 2011; Gioia et al. 2022):

$$\boldsymbol{e}_{\mathrm{E6B}}(t) = \sum_{m=-\infty}^{+\infty} \boldsymbol{D}_{\mathrm{HAS}}\left[[m]_{5115}\right] \oplus \boldsymbol{C}_{\mathrm{E6B}}\left[[m]_{5115}\right] \cdot p\left(t - mT_{\mathrm{c,E6B}}\right) \tag{1}$$

where $\boldsymbol{D}_{\mathrm{HAS}}$ is the HAS correction data, which are modulated with the ranging code $\boldsymbol{C}_{\mathrm{E6B}}$ with chip period $T_{\mathrm{c,E6B}} = \frac{1}{5.115}$ μs.

In order to collect the HAS correction data transmitted by the Galileo E6B signals, we developed a flexible and low-cost software-defined receiver (SDR) platform, where the COTS Universal Software Radio Peripheral (USRP) B210 device is used as the frontend and the open-source GNSS-SDR (version 0.0.17, Fernandez-Prades et al. 2011) is used for Galileo E6B signal acquisition, tracking and telemetry decoding (Fig. 1). The GNSS-SDR is running in real time in a desktop computer with Intel 12900 k processor and 64 GB random access memory (RAM). The decoded HAS correction data, including the satellite orbit, clock and code bias corrections, are output to files for the recovery of HAS GPS and Galileo satellite orbit and clock products, which will be introduced in the next section.

Recovery of Galileo HAS orbit and clock products

The HAS satellite orbit corrections δR^{s} are given in the Satellite Coordinate System (SCS) composed of the radial, along-track and cross-track components and centered in the satellite's ionospheric-free antenna phase center (APC), which can be transformed to the earth-fixed–earth-centered (ECEF) frame by (European Union 2022, 2023):

$$\delta \boldsymbol{X}^{\mathrm{s}} = \boldsymbol{R}_{\mathrm{RAC}}^{\mathrm{ECEF}} \delta \boldsymbol{R}^{\mathrm{s}} \tag{2}$$

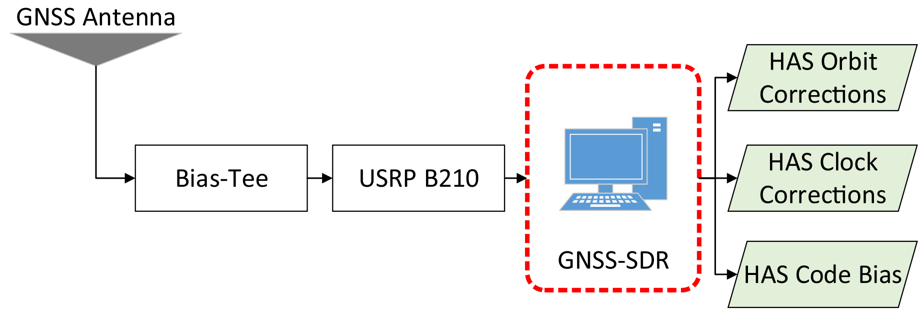

Fig. 1 HAS correction data collection with a software-defined receiver (SDR)

where $\boldsymbol{R}_{\mathrm{RAC}}^{\mathrm{ECEF}}$ is the transformation matrix and can be obtained as:

$$\boldsymbol{R}_{\mathrm{RAC}}^{\mathrm{ECEF}} = \left[\frac{\dot{\boldsymbol{x}}^{\mathrm{s}}}{|\dot{\boldsymbol{x}}^{\mathrm{s}}|} \times \frac{\boldsymbol{x}^{\mathrm{s}} \times \dot{\boldsymbol{x}}^{\mathrm{s}}}{|\boldsymbol{x}^{\mathrm{s}} \times \dot{\boldsymbol{x}}^{\mathrm{s}}|} \;\; \frac{\dot{\boldsymbol{x}}^{\mathrm{s}}}{|\dot{\boldsymbol{x}}^{\mathrm{s}}|} \;\; \frac{\boldsymbol{x}^{\mathrm{s}} \times \dot{\boldsymbol{x}}^{\mathrm{s}}}{|\boldsymbol{x}^{\mathrm{s}} \times \dot{\boldsymbol{x}}^{\mathrm{s}}|} \right] \tag{3}$$

where the satellite position $\boldsymbol{x}^{\mathrm{s}}$ and velocity $\dot{\boldsymbol{x}}^{\mathrm{s}}$ are computed using the broadcast navigation message as per its corresponding GNSS Interface Control Document (ICD).

The obtained satellite orbit corrections in the ECEF frame (δX^{s}) are then added to the broadcast satellite position $\boldsymbol{x}^{\mathrm{s}}$, and the recovered precise satellite orbit $\boldsymbol{x}^{\mathrm{s}}_{\mathrm{HAS}}$ in the Galileo Terrestrial Reference Frame (GTRF) frame can be derived as:

$$\boldsymbol{x}^{\mathrm{s}}_{\mathrm{HAS}} = \boldsymbol{x}^{\mathrm{s}} + \delta \boldsymbol{X}^{\mathrm{s}} \tag{4}$$

Similarly, the HAS clock corrections δC^{s} should be added to the ionospheric-free satellite clock $\mathrm{d}t^{\mathrm{s}}$ computed from the broadcast navigation message. The recovered HAS satellite clock $\mathrm{d}t^{\mathrm{s}}_{\mathrm{HAS}}$ can be derived as (European Union 2022, 2023):

$$\mathrm{d}t^{\mathrm{s}}_{\mathrm{HAS}} = \mathrm{d}t^{\mathrm{s}} + \Delta t^{\mathrm{s}}_{\mathrm{r}} + \frac{\delta C^{\mathrm{s}}}{c} \tag{5}$$

where c is the speed of light, and the relativistic correction $\Delta t^{\mathrm{s}}_{\mathrm{r}}$ can be computed as follows:

$$\Delta t^{\mathrm{s}}_{\mathrm{r}} = -\frac{2\boldsymbol{x}^{\mathrm{s}} \times \dot{\boldsymbol{x}}^{\mathrm{s}}}{c^2} \tag{6}$$

It is noted that the recovered precise satellite clock $\mathrm{d}t^{\mathrm{s}}_{\mathrm{HAS}}$ is referred to as Galileo System Time (GST) for Galileo satellites, while a possible common offset should be considered in the HAS GPS clock corrections.

Quality assessment of Galileo HAS satellite orbit and clock products.

The HAS satellite orbit and clock products are obtained with the decoded satellite orbit and clock corrections from the GNSS-SDR and the broadcast navigation messages. Currently, there are no operational multi-GNSS combined precise satellite orbit and clock products available (Chen et al. 2023), and we use the post-processed precise satellite orbit and clock products from German Research Center for Geosciences (GFZ) as the references for quality assessment (Männel et al. 2020). Since the recovered HAS and GFZ satellite orbit products refer to the antenna phase center (APC) and center of mass (CoM), respectively, the phase center offsets (PCO) should be applied to convert the HAS satellite orbit products from the APC to the CoM. Then, the HAS satellite orbit errors can be obtained as (Zhou et al. 2019; Nie et al. 2022):

$$\Delta \boldsymbol{x}^{\mathrm{s}} = \left(\boldsymbol{x}^{\mathrm{s}}_{\mathrm{HAS}} + \boldsymbol{A} \times \boldsymbol{d}_{\mathrm{PCO}}\right) - \boldsymbol{x}^{\mathrm{s}}_{\mathrm{GFZ}} \tag{7}$$

where $\boldsymbol{x}^{\mathrm{s}}_{\mathrm{GFZ}}$ are the satellite positions from the GFZ satellite orbit products. $\boldsymbol{A}$ is the satellite attitude matrix and $\boldsymbol{d}_{\mathrm{PCO}}$ are the PCO corrections obtained from IGS antenna file (Schmid 2017). The obtained satellite orbit errors can be further converted to the SCS frame by using the transpose of $\boldsymbol{R}_{\mathrm{RAC}}^{\mathrm{ECEF}}$.

Meanwhile, the recovered HAS clock products are compared with GFZ precise clocks for quality assessment. The HAS satellite clocks refer to the ionospheric-free combination of GPS C1C/C2P and Galileo C1C/C7Q, respectively, while the GFZ precise clocks refer to the ionospheric-free combination of C1W/C2W and C1C/C5Q (Männel et al. 2020). Currently, the observable-specific biases (OSB) for GPS C1C/C2P/C2L and Galileo C1C/C5Q/C7Q/C6C are disseminated in HAS (European Union 2022, 2023). Therefore, we use the P1C1.DCB products from the Center for Orbit Determination in Europe (CODE) to transform the HAS GPS satellite clock to C1P/C2P, while the code biases between different codes in the same frequency, i.e., C1P and C1W as well as C2P and C2W, are neglected (Villiger et al. 2019). On the other hand, the HAS OSBs are applied to transform the HAS Galileo satellite clocks to the ionospheric-free combination of C1C/C5Q. After that, the double-difference method is adopted to remove the biases between the HAS and GFZ clock products, which can be described as (Zhou et al. 2019; Nie et al. 2022):

$$\delta \mathrm{d}t^{\mathrm{s,i}}_{\mathrm{HAS,GFZ}} = \mathrm{d}t^{\mathrm{s,i}}_{\mathrm{HAS}} - \mathrm{d}t^{\mathrm{s,i}}_{\mathrm{GFZ}} - \frac{\sum_{i=1}^{N}\left(\mathrm{d}t^{\mathrm{s,i}}_{\mathrm{HAS}} - \mathrm{d}t^{\mathrm{s,i}}_{\mathrm{GFZ}}\right)}{N} \tag{8}$$

where N is the number of satellites, and $\delta \mathrm{d}t^{\mathrm{s,i}}_{\mathrm{HAS,GFZ}}$ is the obtained double difference for satellite i and can be used as the quality indicator for HAS satellite clock products.

Galileo HAS product quality assessment

To assess the performance of the Galileo HAS products, we collected HAS correction data of 10 days from March 11 to 20 (DOY 70–79), 2023, in Zhengzhou, China. The sampling frequency of the USRP B210 is set to 4 million samples per second (MSPS), and the HAS correction data are collected and processed by GNSS-SDR in real time. Although located outside of the current HAS service area, we can still obtain HAS data successfully in Zhengzhou, China, from 3 to 5 Galileo satellites thanks to the redundancies brought by the Reed–Solomon encoding (Fernandez-Hernandez et al. 2020; Hirokawa et al. 2021). In the following, the quality of the HAS products will be assessed from aspects of availability and accuracy.

Availability of Galileo HAS orbit and clock products

During the test period, the HAS orbit and clock corrections are updated every 50 s and 10 s, and the corresponding number of daily updates should be 1728 and 8640, respectively. The valid values of HAS orbit corrections range from – 10.2375 to 10.2375 m, – 16.376 to 16.376 m and – 16.376 to 16.376 m, for the radial, along-track and cross-track components, respectively, while the valid values of the HAS clock corrections range from – 10.2375 to 10.2350 m (European Union 2022). After excluding invalid HAS orbit and clock corrections, the daily availability of HAS orbit and clock corrections are calculated and plotted in Fig. 2. It is found that the daily availabilities of HAS orbit and clock corrections for most of the GPS satellites are greater than 70%. The HAS corrections of GPS G22 are not available during the whole test period, while those of GPS G28 are not available at the beginning of the period. On the other hand, the daily availability of HAS corrections for most of the Galileo satellites is greater than 80%, which is better than those of GPS satellites. The HAS corrections of Galileo E14 and E18 in highly eccentric orbits (not usable satellites) are not available during the whole test period, and the daily availabilities of HAS corrections for two Galileo satellites, i.e., E13 and E30, are below 50% during some days of the test period.

The availability is further assessed by recovering the satellite orbit and clock products at sampling intervals of 10 s from DOY 70–79, 2023, and the availability statistics are plotted in Fig. 3. It is shown that the mean value of the availability of the recovered HAS GPS satellite orbit and clock products during the whole test period is 86.9% (excluding

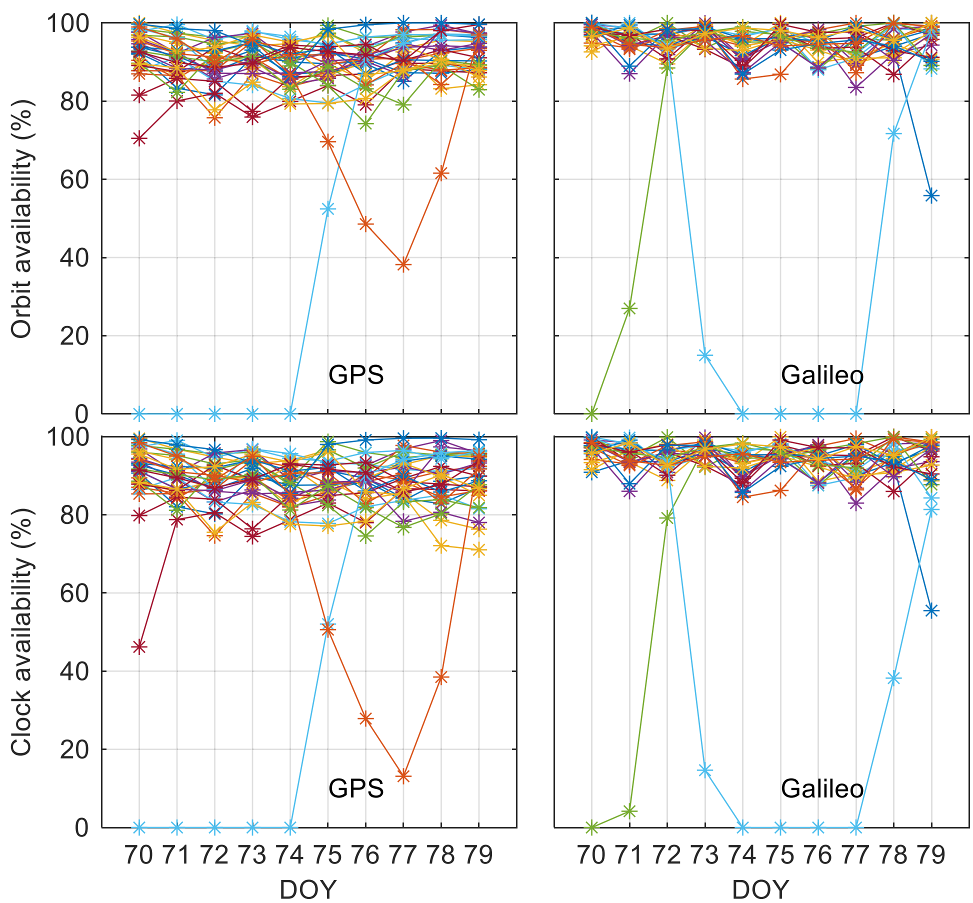

Fig. 2 Daily availability of HAS satellite orbit and clock corrections from DOY 70—79, 2023. The left column is for GPS satellites, and the right column is for Galileo satellites. Each color represents different GPS and Galileo satellites

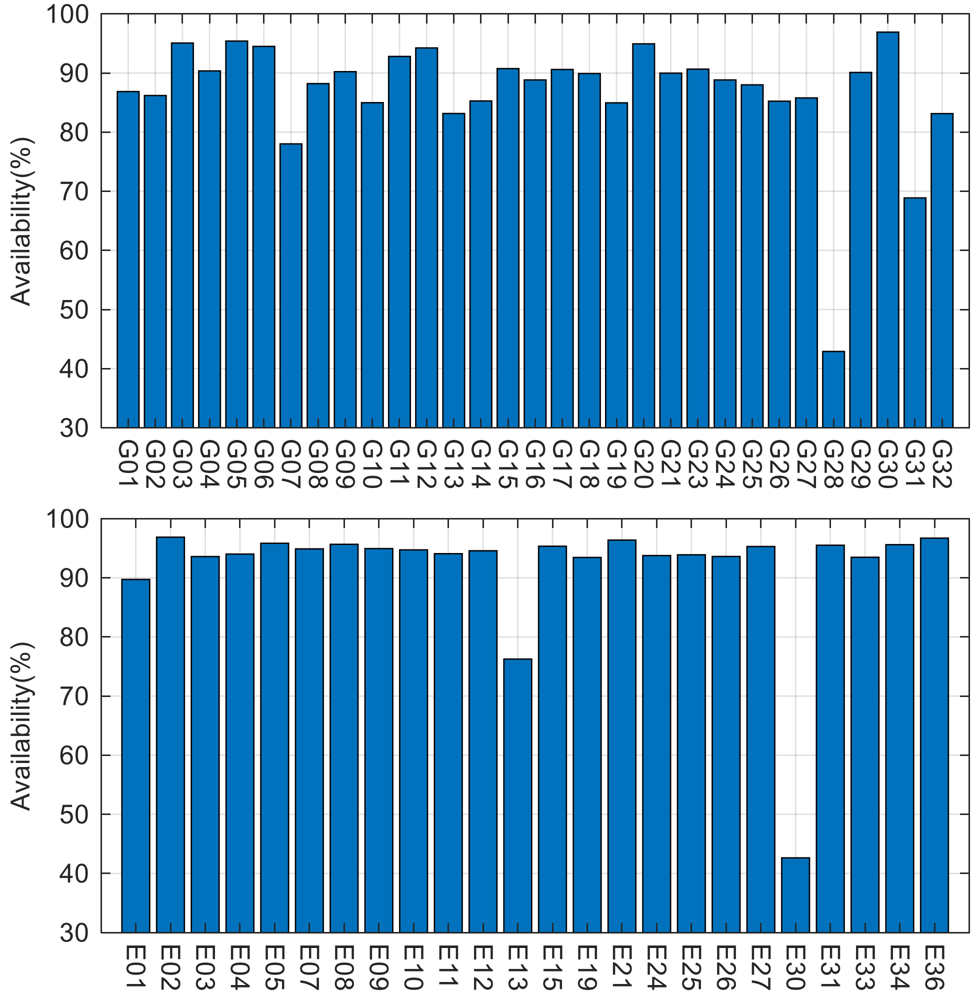

Fig. 3 Availability of the recovered HAS satellite orbit and clock products from DOY 70–79, 2023

GPS G22), while that of the recovered HAS Galileo satellite orbit and clock products is 91.7% (excluding Galileo E14 and E18 in highly eccentric orbits). The availability of HAS Galileo satellite orbit and clock products is higher than those of GPS satellites, which also reveals that the developed COTS SDR can receive and decode the HAS correction data.

Quality assessment of Galileo HAS orbit and clock products

In this section, the quality of the recovered HAS satellite orbit and clock products is assessed with respect to the GFZ precise satellite orbits with sampling intervals of 300 s and precise satellite clocks with sampling intervals of 30 s. The obtained HAS satellite orbit errors for DOY 70, 2023, are used as examples and are shown in Figs. 4 and 5 for GPS and Galileo, respectively. It is seen clearly that the HAS satellite orbit errors are centered toward zero. The HAS GPS orbit errors are within 0.5 m, and orbit errors in the radial directions are within 0.2 m. There are outliers in the GPS satellite orbit errors of the along-track direction, which should be further investigated in future work. Meanwhile, the HAS orbit errors for most of the Galileo satellites are within 0.5 m, except for the Galileo E01 in the along-track direction. Nevertheless, the HAS Galileo orbit errors in the radial directions are within 0.2 m.

The HAS satellite orbit root-mean-square errors (RMS) for each satellite in the radial, along-track and cross-track directions for DOY 70, 2023, are shown in Fig. 6. It is shown that the orbit accuracy in the radial direction is the best while the orbit accuracy in the along-track direction is the poorest among the three directions. The average RMSs of all the available GPS satellites for DOY 70, 2023, are 0.033, 0.091 and 0.050 m for the radial, along-track and cross-track directions, respectively, while those for all the available Galileo satellites are 0.032, 0.082 and 0.059 m, respectively.

The HAS satellite orbit accuracy statistics during the whole test period are listed in Table 1, and those of the broadcast satellite orbit products are also provided in Table 2 for comparison. It shows that the daily RMSs

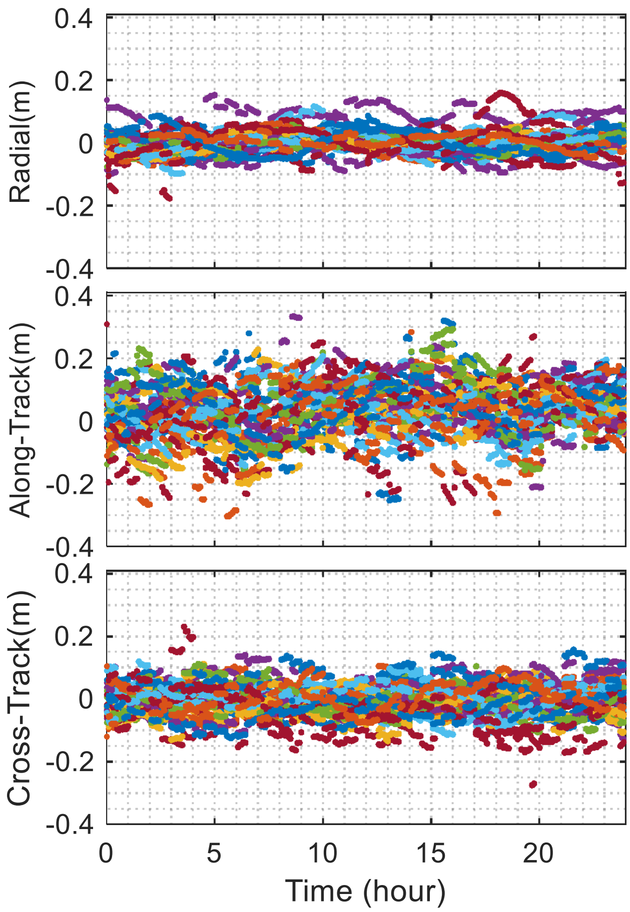

Fig. 4 HAS GPS satellite orbit errors at DOY 70, 2023. Each color represents different GPS satellites

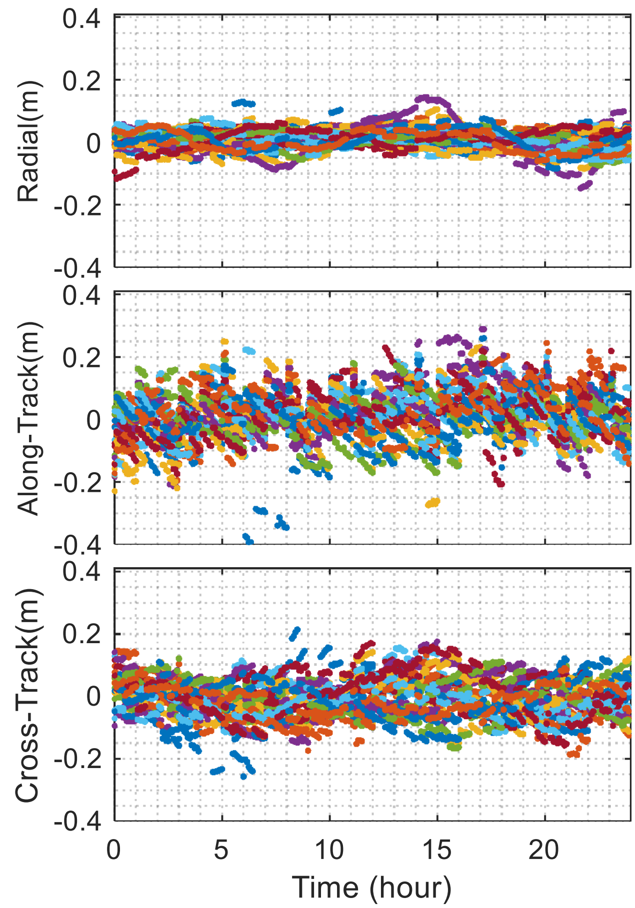

Fig. 5 HAS Galileo satellite orbit errors at DOY 70, 2023. Each color represents different Galileo satellites

of HAS satellite orbit products are stable during the test period, and the average RMSs for HAS GPS satellite orbit products during the whole test period are 0.037, 0.106 and 0.057 m, for the radial, along-track and cross-track directions, respectively, while average RMSs for HAS Galileo satellite orbit products are 0.032, 0.094 and 0.065 m, respectively. The accuracy of the radial direction is the best among the three directions, and the accuracy of the along-track direction is the poorest. Since the accuracy of the radial direction for both GPS and Galileo are well below 5 cm, it is therefore concluded that the HAS satellite orbit products can support decimeter-level PPP applications. On the other hand, the average RMSs for broadcast GPS satellite orbit products are 0.345, 0.968 and 0.426 m for the radial, along-track and cross-track directions, respectively. The quality of the Galileo broadcast satellite orbit products is better than those of GPS, with average RMSs of 0.115, 0.266 and 0.156 m, respectively, for the radial, along-track and cross-track directions. It is shown that applying HAS corrections to broadcast satellite orbit products significantly improves satellite orbit quality.

The quality of the HAS satellite clock products is also assessed using GFZ precise clock products as the reference. As examples, the double-difference HAS satellite clock errors for DOY 70, 2023, are computed according to (8) and shown in Fig. 7. As can be seen, the HAS GPS satellite clock differences vary from − 3 to 3 ns, while those for the HAS Galileo satellites vary from − 2 to 2 ns. Moreover, it is seen clearly that the HAS GPS satellite clock differences are more scattered than those of the HAS Galileo satellites. There are biases that exist in the HAS GPS satellite clock differences, which, however, will be absorbed by the receiver clock and phase ambiguities and, therefore, will not affect real-time PPP performance. The standard deviation (STD) of the HAS satellite clock differences with respect to the GFZ precise clock products is further computed as the indicator of clock precision and plotted in Fig. 8. The daily average of STDs for the HAS GPS and Galileo satellite are 0.22 and 0.15 ns, respectively, which implies that the precision of the HAS Galileo satellite clock products is generally better than those of the HAS GPS satellite clock products. It is further confirmed by the daily precision statistics during

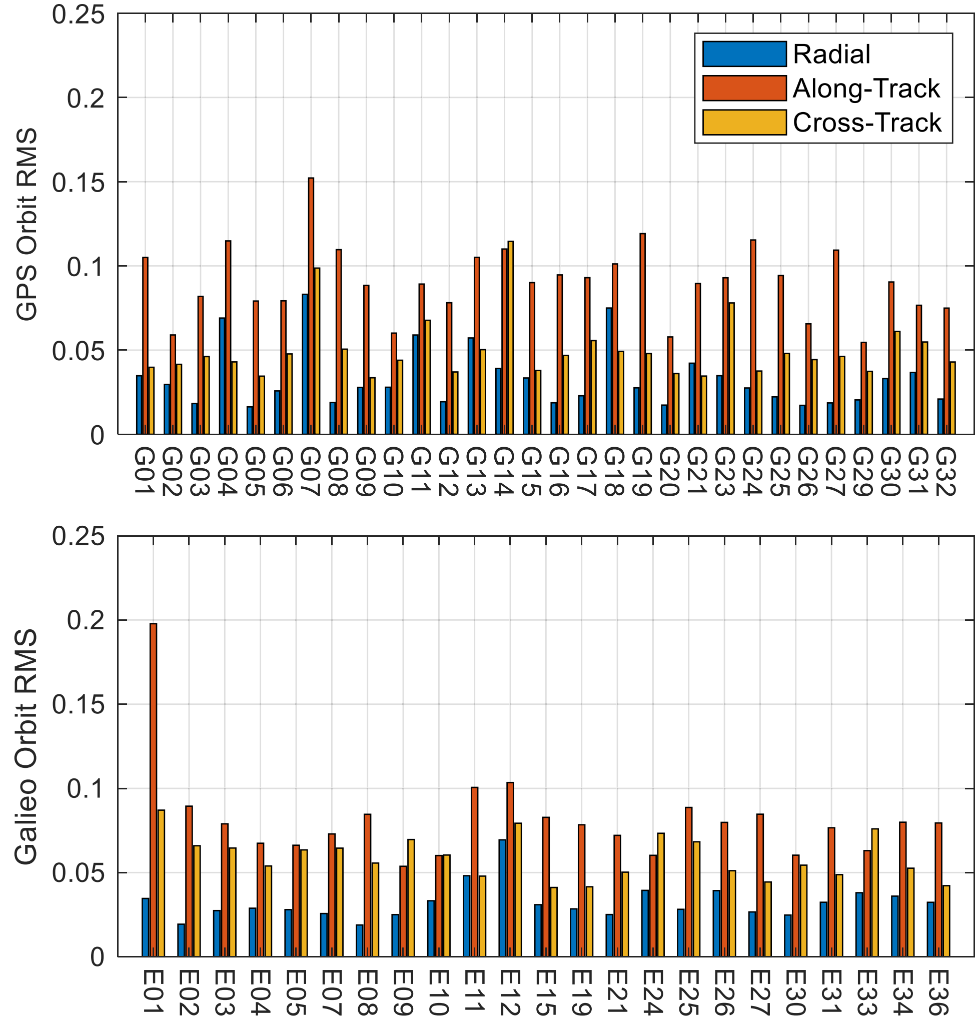

Fig. 6 RMS of HAS satellite orbit products at DOY 70, 2023

Table 1 Daily RMS of HAS satellite orbit products during DOY 70–79, 2023 (unit m)

DOY	GPS			Galileo		
	Radial	Along-track	Cross-track	Radial	Along-track	Cross-track
70	0.033	0.091	0.050	0.032	0.082	0.059
71	0.029	0.086	0.056	0.037	0.088	0.065
72	0.032	0.080	0.050	0.029	0.084	0.052
73	0.031	0.087	0.056	0.032	0.092	0.064
74	0.031	0.090	0.070	0.033	0.095	0.074
75	0.034	0.087	0.059	0.028	0.095	0.072
76	0.047	0.123	0.066	0.031	0.109	0.076
77	0.047	0.157	0.056	0.029	0.089	0.061
78	0.043	0.151	0.053	0.041	0.113	0.066
79	0.039	0.108	0.051	0.032	0.096	0.064
Average	0.037	0.106	0.057	0.032	0.094	0.065

Table 2 Daily RMS of broadcast satellite orbit products during DOY 70–79, 2023 (unit m)

DOY	GPS			Galileo		
	Radial	Along-track	Cross-track	Radial	Along-track	Cross-track
70	0.312	1.010	0.417	0.112	0.241	0.145
71	0.311	0.992	0.421	0.116	0.245	0.140
72	0.316	0.850	0.459	0.124	0.260	0.162
73	0.295	0.866	0.433	0.112	0.262	0.149
74	0.340	0.956	0.458	0.111	0.267	0.152
75	0.343	0.902	0.433	0.115	0.248	0.141
76	0.448	1.117	0.410	0.120	0.277	0.169
77	0.372	1.066	0.379	0.111	0.260	0.159
78	0.395	1.001	0.426	0.118	0.301	0.169
79	0.317	0.918	0.426	0.112	0.301	0.171
Average	0.345	0.968	0.426	0.115	0.266	0.156

the whole test period, as given in Table 3, which shows that the average HAS GPS and Galileo satellite clock precisions are 0.24 and 0.18 ns, respectively. Meanwhile, the average broadcast GPS and Galileo satellite clock precision are 0.69 and 0.45 ns, respectively. The results indicate that the HAS satellite clock corrections can correct errors in the broadcast satellite clocks and support high-precision real-time PPP.

PPP performance assessment

This section assesses the PPP performance of HAS products with all the GPS and Galileo observation data collected by the IGS Multi-GNSS Experiment (MGEX) network from March 11 to 20 (DOY 70–79), 2023. First, the data and processing strategies are presented. After that, the static and kinematic PPP performance are assessed from aspects of convergence performance and positioning accuracy.

Data and processing strategies

The IGS established the Multi-GNSS Experiment (MGEX) in order to prepare operational services for new and upcoming GNSS, such as the European Galileo, Chinese BeiDou, and regional systems, such as Japanese QZSS and Indian NAVIC system (Montenbruck et al. 2017). The MGEX stations, equipped with multiple brands of professional receivers, provide almost full and continuous tracking of GPS/Galileo signals. Therefore, all the data collected by the MGEX network from March 11 to 20 (DOY 70–79), 2023, are processed. Figure 9 shows the global distribution of the number of observable GPS and Galileo satellites with a cutoff elevation of 10 degrees. The cutoff angle is chosen to avoid the large noise of satellite observations with low elevation for PPP processing, a common processing strategy for GNSS positioning software. Note that it is different from the 5 degrees defined in the Galileo official service definition document (European Union 2023). It can be seen that the number of observable GPS satellites is significantly larger than that of Galileo. Although the number of observable Galileo satellites in most regions is larger than 4, it is found

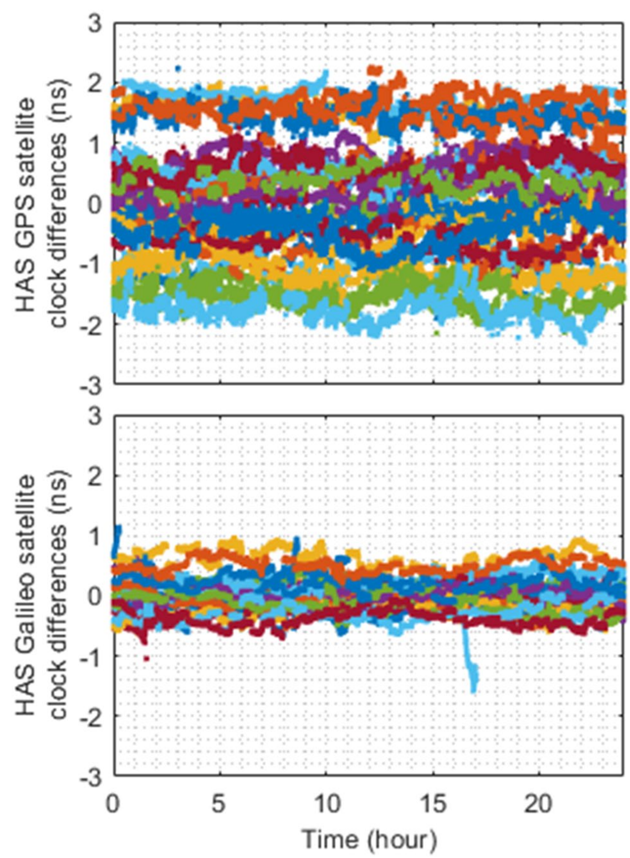

Fig. 7 HAS satellite clock differences with respect to the GFZ precise clock products for each satellite at DOY 70, 2023. Each color represents different GPS and Galileo satellites

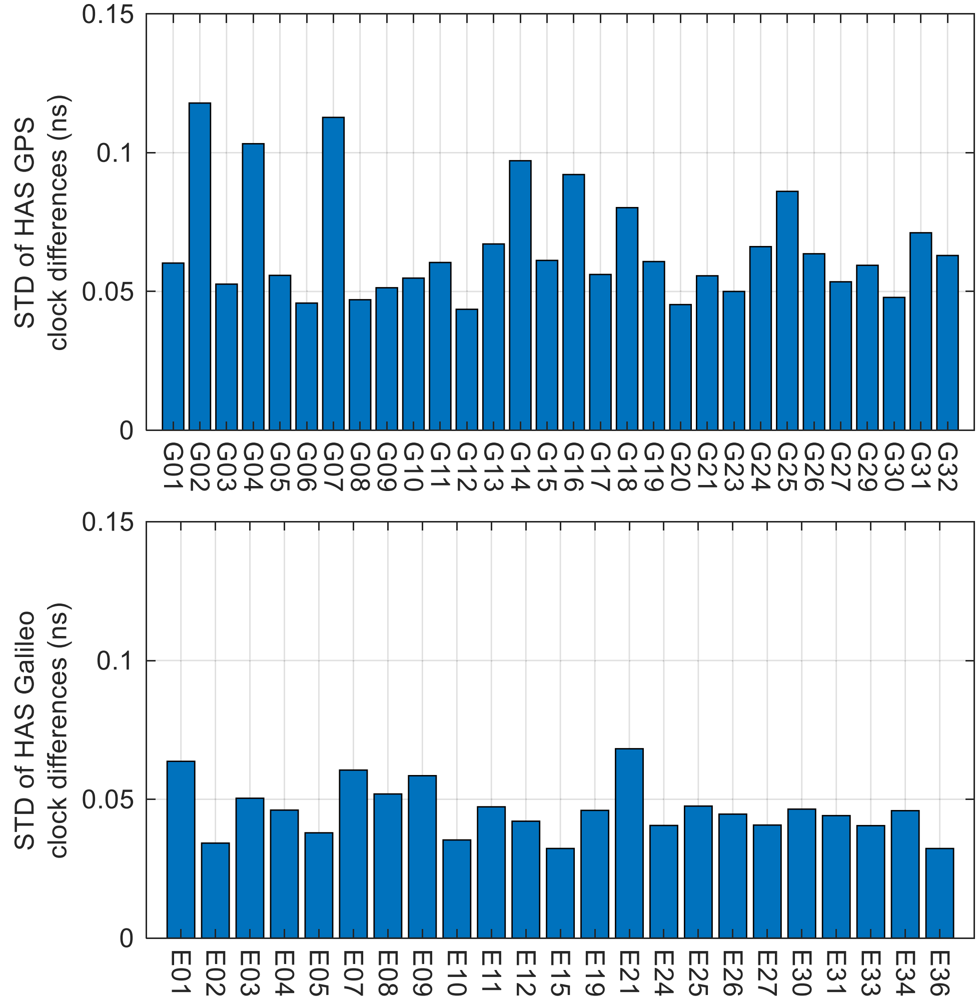

Fig. 8 STD of HAS satellite clock differences for each satellite at DOY 70, 2023

Table 3 Daily precision of HAS and broadcast satellite clock products during DOY 70–79, 2023 (unit ns)

DOY	HAS		Broadcast	
	GPS	Galileo	GPS	Galileo
70	0.22	0.15	0.64	0.42
71	0.23	0.16	0.69	0.42
72	0.24	0.19	0.66	0.49
73	0.23	0.17	0.81	0.46
74	0.24	0.20	0.81	0.43
75	0.25	0.19	0.83	0.44
76	0.27	0.18	0.73	0.48
77	0.28	0.16	0.60	0.48
78	0.25	0.19	0.55	0.48
79	0.23	0.16	0.57	0.44
Average	0.24	0.18	0.69	0.45

that a stand-alone Galileo PPP solution is still not feasible in a few regions due to data preprocessing and editing.

In the PPP processing, E1/E5a (C1C/C5Q) are used for Galileo, while L1/L2 (C1W/C2W) are used for GPS. These signals were chosen according to high availability and in accordance with the principle of orbit and clock generation (Uhlemann et al. 2020). Throughout the processing, MGEX precise products, including precise satellite orbit, clock and earth rotation parameters, provided by GFZ are used. The satellite phase center offsets and variations are corrected according to the IGS antenna file (Schmid 2017). As for the receiver antenna phase center offsets and variations, the correction values for GPS are employed for Galileo in accordance with the principle of orbit and clock generation (Prange et al. 2017). All the other errors, including the dry tropospheric component, phase windup effect and ocean tide loading, are corrected following the IGS conventions (Kouba 2009). The dual-frequency ionospheric-free linear combination model is employed, and the observations are weighted according to the satellite elevation with cutoff angle set to 10 degrees. The detail of our PPP strategy can be found in Xiao et al. (2018).

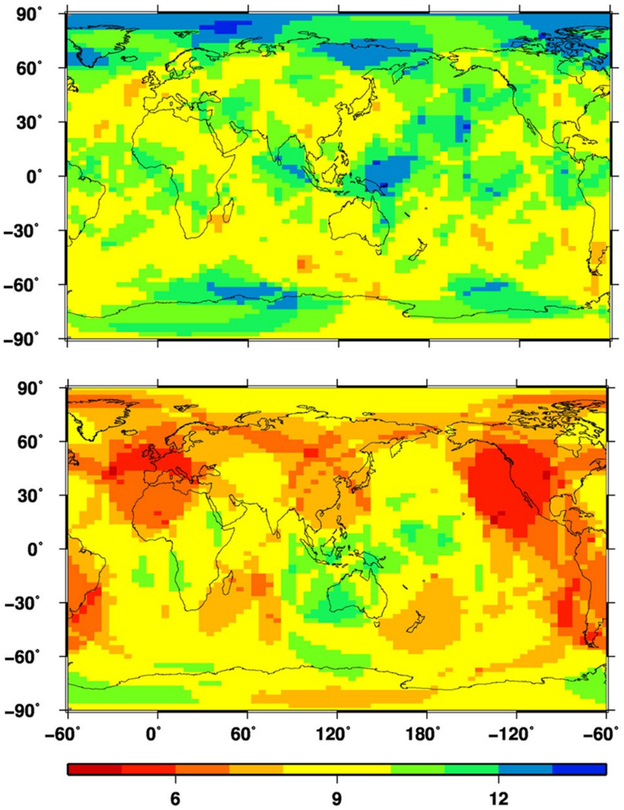

Fig. 9 Distribution of the number of observable GPS (up) and Galileo (bottom) satellites on DOY 70, 2023 with a cutoff elevation of 10 degrees. The pixel size is 0.5 degrees latitude by 0.5 degrees longitude

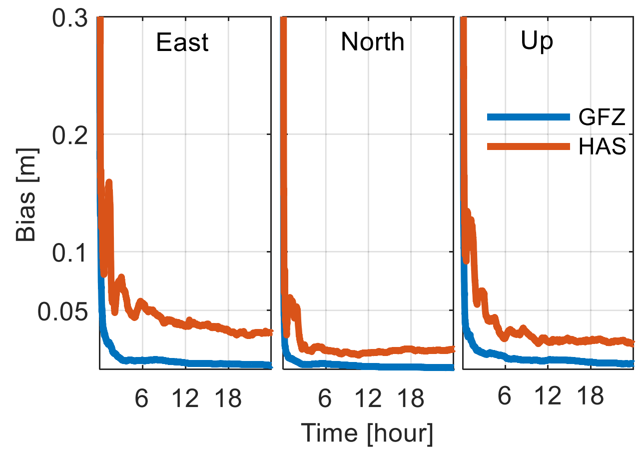

Fig. 10 Convergence performance of GPS PPP with GFZ and HAS products based on 360 stations under 50% confidence levels

Static PPP processing

In the static PPP processing, all the MGEX stations (over 380 stations) are processed in static mode with the products from GFZ and HAS. Considering that the HAS product provides corrections for two constellations, Galileo and GPS PPP are separately processed. After the processing, data edits are performed for comparison. First, the integrity of PPP solution should be guaranteed, which indicates that the epoch number of PPP solution should be larger than 2870 for 30 s sample of 24-h data (2880 in theory). Then, the two solutions using GFZ and HAS products are synchronized, which means PPP solutions should exist from both products. Finally, the PPP solutions for all the remaining stations are compared with truth values and east–north–up errors are calculated. Note that convergence time and positional accuracy performance is evaluated under different confidence levels for reliability (Lou et al. 2016).

Figure 10 shows the convergence performance of GPS PPP with GFZ and HAS products based on 360 stations under 50% confidence levels on DOY 070, 2023. Table 4 further presents the statistics for all 10 days. The average accuracy of GPS PPP with GFZ products is 0.32, 0.15 and 0.51 cm for the east, north and up components, respectively, while that for HAS products is 2.8, 1.53 and 2.18 cm, respectively. The results indicate that the quality of HAS products can support centimeter-level positioning, although it is slightly worse than GFZ products. As for the convergence, it takes 3, 6 and 15 min for GPS PPP with GFZ products to converge to three-dimensional 30, 20 and 10 cm accuracy, respectively, while that of HAS products is 15, 36 and 134 min, respectively.

Figure 11 shows the convergence performance of Galileo PPP with GFZ and HAS products based on 284 stations under 50% confidence levels on DOY 070, 2023. Due to the fewer observable satellites for Galileo, it is found that the number of successful solutions of Galileo PPP is significantly smaller than that of GPS. Table 5 further presents the statistics for all 10 days. The average accuracy of Galileo PPP with GFZ products is 0.48, 0.25 and 0.71 cm for the east, north and up components, respectively, while that for HAS products is 1.4, 1.79 and 2.31 cm, respectively. When compared with GPS PPP with GFZ products in Table 3, it is found that the accuracy of Galileo PPP with GFZ products is slightly worse, which is reasonable considering the fewer observable satellites of Galileo. However, the Galileo PPP with HAS products are significantly better than that of GPS PPP with HAS products. This further confirmed that the quality of HAS products for the Galileo constellation is better than that of GPS constellation. Although the accuracy of Galileo PPP with HAS products is already very accurate, it is found that the accuracy of the north component is obviously worse than that of the east component, which is unusual and may be improved by the PPP ambiguity resolution feature in the future. As for the convergence, it takes 4, 7 and 17 min for Galileo PPP with GFZ products to converge to three-dimensional 30, 20 and 10 cm accuracy, respectively,

Table 4 Daily accuracy of GPS PPP with GFZ and HAS products during DOY 70–79, 2023 (unit cm)

DOY	GFZ			HAS		
	East	North	Up	East	North	Up
70	0.33	0.12	0.48	3.12	1.70	2.15
71	0.34	0.17	0.63	3.79	1.06	2.71
72	0.40	0.14	0.65	3.02	2.09	2.85
73	0.26	0.12	0.54	2.40	1.46	2.17
74	0.33	0.23	0.56	4.28	1.52	1.97
75	0.42	0.13	0.55	3.19	1.45	1.86
76	0.27	0.13	0.45	2.99	1.79	1.92
77	0.17	0.14	0.41	1.41	1.37	2.49
78	0.45	0.15	0.56	2.13	1.10	1.41
79	0.21	0.14	0.29	1.64	1.75	2.24
Average	0.32	0.15	0.51	2.80	1.53	2.18

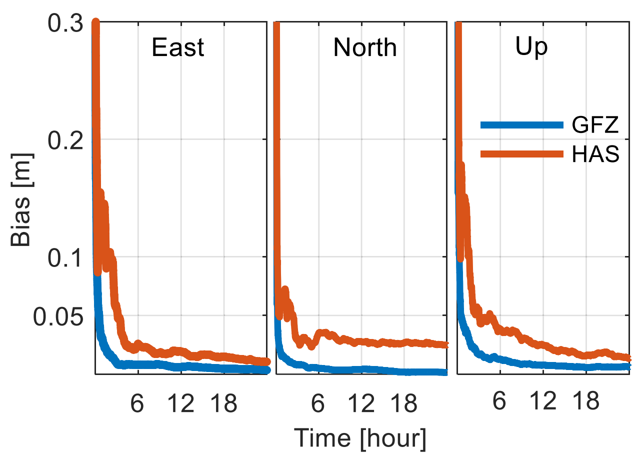

Fig. 11 Convergence performance of Galileo PPP with GFZ and HAS products based on 284 stations under 50% confidence levels

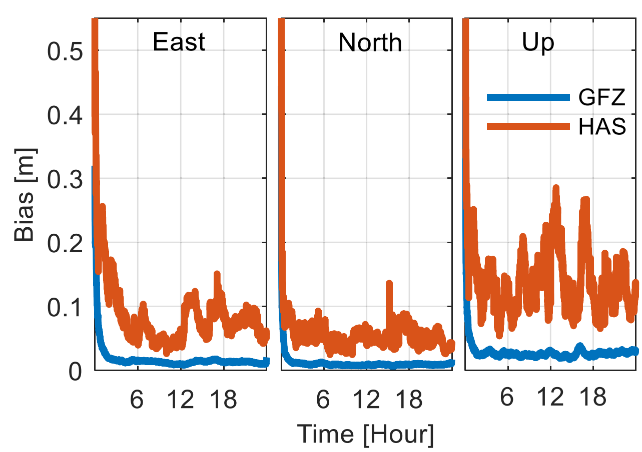

Fig. 12 Convergence performance of GPS kinematic PPP with GFZ and HAS products based on 368 stations under 50% confidence levels

Table 5 Daily accuracy of Galileo PPP with GFZ and HAS products during DOY 70–79, 2023 (unit cm)

DOY	GFZ			HAS		
	East	North	Up	East	North	Up
70	0.35	0.16	0.62	1.05	2.48	1.33
71	0.87	0.41	1.09	1.03	1.68	2.88
72	0.52	0.20	0.70	1.28	2.01	2.50
73	0.28	0.20	0.63	1.38	1.52	2.91
74	0.48	0.39	0.61	2.25	1.78	3.17
75	0.74	0.22	0.74	1.21	1.48	1.72
76	0.39	0.23	0.79	0.77	2.21	1.55
77	0.32	0.26	0.55	1.05	1.28	2.19
78	0.53	0.17	0.77	1.71	1.33	2.42
79	0.34	0.27	0.63	2.27	2.08	2.41
Average	0.48	0.25	0.71	1.40	1.79	2.31

while that of HAS products is 16, 25 and 148 min, respectively. The overall convergence time is slightly longer than that of GPS PPP due to the fewer observable satellites of Galileo.

Kinematic PPP processing

The data from the previous subsection are processed in kinematic PPP mode to further assess the kinematic PPP performance. The data edit strategy, conversion and statistics are the same as in the static PPP analysis. Figures 12 and 13 present the convergence performance of GPS and Galileo kinematic PPP with GFZ and HAS products, respectively. Tables 6 and 7 gives the statistics for all 10 days.

Figure 12 and Table 5 show that the average accuracy of GPS kinematic PPP with GFZ products is 1.27, 0.9 and 2.54 cm for the east, north and up components, respectively, while that for HAS products is 7.94, 5.55 and 13.39 cm, respectively. Although the worse quality of HAS products may result in low accuracy, we also found that the missing values in HAS products significantly influence kinematic PPP performance. Since the extend Kalman filtering is used to process the PPP, the missing values in HAS products will result in frequent re-initializations of ambiguity parameters and degradation of PPP performance. Nevertheless, decimeter-level positioning accuracy is achievable from HAS products.

Figure 13 and Table 7 show that the average accuracy of Galileo kinematic PPP with GFZ products is 2.17, 1.45 and 3.86 cm for the east, north and up components, respectively, while that for HAS products is 8.08, 5.28 and 12.43 cm, respectively. As for the large fluctuation, it is likely introduced by incomplete correction data. Based on the above results, it can be concluded that GPS and Galileo PPP with the current HAS products are able to achieve decimeter accuracy.

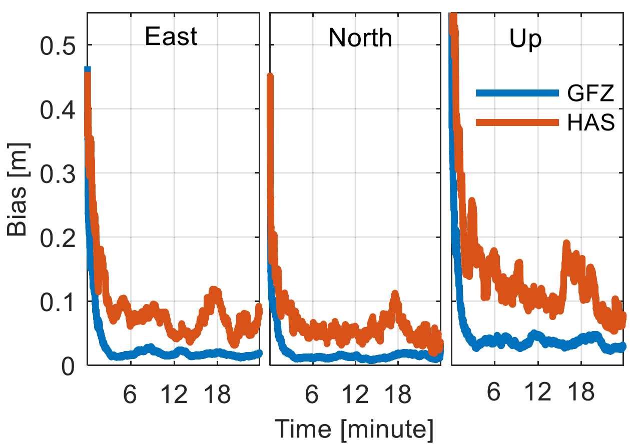

Fig. 13 Convergence performance of Galileo kinematic PPP with GFZ and HAS products based on 289 stations under 50% confidence levels

Conclusions

On January 24, 2023, the Galileo High Accuracy Service (HAS) was declared available for initial service, significantly expanding the current GNSS augmentation service portfolio in terms of accuracy, delivery methods and geographical coverage. A low-cost SDR platform with COTS devices is developed to receive and decode real-time precise satellite orbit, clock and code bias products disseminated via the Galileo E6B signals from March 11 to 20 (DOY 70–79), 2023, in Zhengzhou, China. The results show that the average value of the availability of the recovered HAS GPS satellite orbit and clock products during the whole test period

Table 6 Daily accuracy of GPS kinematic PPP with GFZ and HAS products during DOY 70–79, 2023 (unit cm)

DOY	GFZ			HAS		
	East	North	Up	East	North	Up
70	1.36	0.9	2.54	7.42	5.08	12.78
71	1.31	0.92	2.55	8.44	5.01	12.45
72	1.47	0.95	2.80	10.09	6.15	14.31
73	1.20	0.93	2.62	7.95	6.42	13.27
74	1.21	0.88	2.49	10.30	6.28	15.65
75	1.26	0.95	2.78	6.92	5.24	13.56
76	1.16	0.82	2.31	6.18	5.27	12.65
77	1.15	0.85	2.36	8.10	5.95	14.60
78	1.31	0.95	2.52	7.38	5.39	11.80
79	1.27	0.87	2.48	6.61	4.68	12.79
Average	1.27	0.90	2.54	7.94	5.55	13.39

Table 7 Daily accuracy of Galileo kinematic PPP with GFZ and HAS products during DOY 70–79, 2023 (unit cm)

DOY	GFZ			HAS		
	East	North	Up	East	North	Up
70	1.71	1.29	3.67	7.55	5.39	11.75
71	2.67	1.67	4.40	7.16	5.12	12.09
72	2.46	1.49	4.18	9.14	5.54	13.13
73	1.73	1.34	3.48	7.21	5.57	11.88
74	2.16	1.41	3.81	11.03	6.13	15.37
75	2.62	1.36	4.29	6.76	4.48	12.48
76	1.81	1.44	3.31	9.28	6.00	13.71
77	2.12	1.54	3.60	7.97	5.09	12.81
78	2.39	1.58	3.83	6.94	4.81	9.60
79	2.04	1.39	4.06	7.79	4.67	11.45
Average	2.17	1.45	3.86	8.08	5.28	12.43

is 86.9% (excluding GPS G22), while that of the recovered HAS Galileo satellite orbit and clock products is 91.7% (excluding Galileo E14 and E18 in highly eccentric orbits).

The recovered HAS products are then compared with GFZ precise products for quality assessment. It is found that the average RMSs for HAS GPS satellite orbit products during the whole test period are 0.037, 0.106 and 0.057 m, for the radial, along-track and cross-track directions, respectively, while average RMSs for HAS Galileo satellite orbit products are 0.032, 0.094 and 0.065 m, respectively. On the other hand, the average precision of HAS GPS and Galileo satellite clock products is 0.24 and 0.18 ns, respectively. The quality of the HAS products for GPS and Galileo is generally consistent and stable during the test period, which indicates that high-quality HAS products can be received, decoded and recovered at the user to support real-time PPP.

The PPP performance of the HAS products is extensively assessed with GPS and Galileo observations from all stations of the current IGS MEGX network (over 380 stations). The dual-frequency ionospheric-free linear combination model is employed, and the observations are weighted according to the satellite elevation with cutoff angle set to 10 degrees. The results indicate that PPP accuracies with HAS products are worse than those with GFZ final products. The GPS stand-alone PPP accuracies in static mode is 2.80, 1.53 and 2.18 cm in the east, north and up directions, while those for Galileo stand-alone PPP are 1.40, 1.79 and 2.31 cm, respectively. Moreover, the GPS stand-alone PPP accuracies in kinematic mode are 7.94, 5.55 and 13.39 cm in the east, north and up directions, while those for Galileo stand-alone PPP are 8.08, 5.28 and 12.43 cm, respectively. Overall, it can be concluded that decimeter-level PPP accuracy can be obtained utilizing the HAS products received from the developed COTS SDR platform. It highlights that Galileo HAS after ISD demonstrates great potential to support cost-effective real-time decimeter-level PPP on a global scale with a single GNSS receiver. It should be noted, however, the presented initial assessment is based on HAS products received by the developed COTS SDR platform located in Zhengzhou, China, which could be further validated with datasets from a reference source of HAS products.

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Author contributions PZ and GX conceived the presented idea, performed data collection and results analysis, and wrote the main manuscript. LD reviewed and edited the manuscript. All authors were involved in discussions throughout the development and contributed to the revision of the manuscript.

Data availability The Galileo HAS data are available from the corresponding author on reasonable requests, while the GNSS data and products can be downloaded from IGS.

Declarations

Competing interests The authors declare no competing interests.

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Peiyuan Zhou obtained his Ph.D. from the University of Calgary and is a lecturer at Information Engineering University, China. His current research focuses on GNSS precise positioning and remote sensing.

Guorui Xiao is currently an associate professor at Information Engineering University, China. He received his B.Sc. degree from the School of Geodesy and Geomatics at Wuhan University in 2011 and his Ph.D. degree from the Geodetic Institute of Karlsruhe Institute of Technology in Germany. His current research focuses on multi-GNSS and multi-sensor integrated precise positioning and applications.

Lan Du is a Professor at Information Engineering University, China, where she obtained a Ph.D. in geodesy in 2006. Her research interests include satellite navigation, space geodesy and astrodynamics.