DOI: 10.36163/aon-2024-0007

POSITIONING USING THE PRECISION GALILEO HAS SERVICE

S.Savchuk
Institute of Navigation, Polish Air Force University
Deblin, Poland
s.savchuk@law.mil.pl

M.Grzegorzewski
Institute of Navigation, Polish Air Force University
Deblin, Poland
m.grzegorzewski@law.mil.pl

P.Gołda
Polish Air Force University
Deblin, Poland
p.golda@law.mil.pl

V.Kerker
Department of Geodesy and Astronomy, Lviv Polytechnic National University
Lviv, Ukraine
vladyslav.kerker.mhdkh.2022@lpnu.ua

ABSTRACT

Galileo High Accuracy Service (HAS) is an augmentation of GNSS that provides users around the world with precise satellite corrections directly via the E6 Galileo signal. Galileo HAS corrections, complemented by the deviations of the Galileo HAS signals, enable the calculation of a very accurate solution in real time. PPP positioning performance results show that the combined Galileo and GPS solution can already achieve the full-service HAS accuracy target. The purpose of this study is to evaluate the benefits of HAS corrections on SPP and PPP for Galileo E1, E5a, E5b and E6, for GPS L1 and L2, and for GPS/Galileo L1/E1. Comparison of emitted HAS patches with final CODE products shows good performance. The impact of HAS on SPP is assessed in terms of mean and root mean square (RMS) errors at horizontal, vertical, and 3D positions.

Keywords — GNSS, Galileo High Accuracy Service (HAS), Precise point positioning. Convergence time, open-source RTKLIB package.

1. INDRUCTION

To achieve the required levels of positioning performance and reliability, the best way is to combine information from several complementary sensors. Among them, global navigation satellite systems (GNSS) occupy a central position due to their ability to provide global location almost anywhere in the open area. Naturally, the requirements for accuracy and reliability of GNSS positioning constantly grow. Several technologies have been developed to achieve this goal, such as Precise Point Positioning (PPP), Real-Time Kinematics (RTK) and recently a hybridization of both, PPP-RTK [16]. Among the existing GNSS-based positioning methods, Real-Time Kinematics (RTK) is still the most accurate. However, due to their technological complexity and the associated cost, RTK is usually limited to specialized professionals, mainly in the field of geodesy. The "standard" PPP technology is currently used for a wide range of applications, but still has insufficient accuracy and a long convergence time.

Today, these methods and related variants (e.g., PPP-RTK) are gaining momentum and are beginning to be applied in other areas, one of which is the aviation sector. It is expected that the aviation industry will continue to implement high-precision navigation services to further improve the safety and efficiency of its air traffic control services. The same applies to a wide range of maritime applications, such as navigation, seabed mapping, underwater exploration, search and rescue, offshore drilling and pipeline laying.

For three decades (1990-2020), relative (or differential) positioning was the dominant method of precise positioning and data processing. In relative positioning, the coordinates of a point are determined relative to another reference point with known coordinates. This eliminates or reduces most GNSS observation errors that are spatially correlated in both unknown and reference points, thus providing a solution with high positioning accuracy. Initially, the implementation of this relative positioning technique involved a single reference station and one or more rover receivers operating in the local area in real time. Sub-meter to centimeter positioning accuracies can be obtained, with the accuracy mainly depending on whether pseudo-distance and/or carrier phase observations are used and, in the latter case, whether ambiguity resolution has been successful. Carrier phase processing provides the most accurate real-time positioning (RTK) results. For many years and up to now, RTK is the standard procedure for precise positioning and navigation [16]. A little later, to expand the coverage area, this technology moved to the network level "network-RTK" based on the formation of regional networks of reference stations. In this case, we are talking about the Observation State Representation (OSR), for which users are provided with a single correction option that corresponds to the sum of the corrections applied to the observations [16].

In "standard" PPP, as in other augmentation methods, such as differential GNSS subsystems (e.g., SBAS) based on code observations or differential phase measurements (e.g., RTK), a series of corrections from the reference station is required. However, instead of providing or calculating distance corrections, PPP takes a different approach. In PPP, reference stations function as monitoring stations, calculating very accurate ephemeris in near real time. It is these highly accurate ephemeris, rather than the predicted ephemeris received from satellites, that are then transmitted to and applied to the user's receiver. The advantages of this technique are obvious, only a few reference stations are needed around the world, and the corrections are universal. This makes a large-scale broadcast solution possible, especially when combined with transmitting satellites, which completely eliminates the need for cellular communications. PPP is particularly interesting for applications where centimeter accuracy is sufficient. However, PPP also has a significant drawback. Since only one receiver is used and ambiguity still needs to be resolved, a typical PPP convergence will take 20-40 minutes to achieve a horizontal error of less than 10 cm [16].

The ephemeris required for PPP are either downloaded from the global network (usually with post-processing) or broadcast from communication satellites. For global real-time applications, only commercial signals have been available so far (with the exception of the QZSS CLAS signal over Asia). A few servers provide free data, but these are used for post-processing or near real-time applications. The big drawback of commercial PPP so far has been vendor lock-in, as each add-on provider uses its own correction format, and receiver manufacturers usually only effectively support one or sometimes two formats [17].

In recent years, the absolute positioning market has been undergoing significant changes as positioning methods in the decimeter or even centimeter range become increasingly available. Commercial vendors for PPP have long provided accurate satellite orbits and clock correction. Trimble Inc. deployed CenterPoint RTX, Novatel developed Terrastar-X, and u-blox released Point Perfect. The first system to implement the PPP-RTK satellite augmentation was the Japanese Quasi-Zenith Satellite System (QZSS) through its Centimeter Level Augmentation Service (CLAS). After that, several countries, including South Korea, Australia, Germany, and Denmark, began experimenting with the deployment of PPP-RTK services.

In recent years, GNSS systems themselves have begun to broadcast PPP corrections in real time for free. For example, the BeiDou satellite system (in its BDS-3 version) began providing real-time PPP services in 2020 in the Asia-Pacific region. The trial Multi-GNSS Advanced Orbit and Clock Augmentation - Precise Point Positioning (MADOCA-PPP) service, available since September 2022, broadcasts precise corrections for

GPS, Galileo, BeiDou and GLONASS via the Signal In Space (SIS) of the Quasi Zenith Satellite System (QZSS) in East Asia and the Pacific and worldwide via the Internet.
To support this trend, the European Commission and the Galileo project announced the launch of the High Accuracy Service (HAS) on January 24, 2023 [4,5]. This service is intended to be the first globally available PPP correction service using Signal-In-Space (SIS) as a distribution method [5]. Galileo HAS works basically like any commercial PPP service, but with some significant differences. First, the signal is available for free via the Internet or directly through the Galileo E6-B signal [4]. Since the corrections are transmitted from the Galileo satellite and not from a geostationary communication satellite, it is much easier to receive corrections in semi-enclosed areas such as urban canyons, parkland, etc. A significant technical problem is the limited number of receivers that can implement Galileo HAS.
HAS is expected to become a basic positioning service for many areas, especially in aviation and maritime navigation, but the adaptation of such a new service often depends on its availability and usability. In addition, it should be remembered that there are already other similar services on the market, so increasing the availability of HAS and identifying its real positioning accuracy are urgent tasks. This paper is aimed at highlighting some of the problematic issues and showing our own variant of using the new service without significantly modifying the existing architecture.

2. GALILEO HAS AND OPEN-SOURCE PPP SOFTWARE PACKAGE

Since 2023, Galileo has introduced a new open access service called the High-Accuracy Service (HAS) with the goal of achieving decimeter-level accuracy. HAS provides corrections for GPS and Galileo systems and is intended for use in the Precise Point Positioning (PPP) algorithm [7]. Corrections consist of orbit and clock corrections, as well as code and phase offsets for four Galileo frequencies (E1, E5a, E5b, E6) and three GPS frequencies (L1, L2C and L5) [12]. All of these corrections (except for the phase offsets at this time) are available in real time and are broadcast via the E6b signal and the Internet [3]. They refer to the satellite antenna phase center (APC). The APC is defined as the center of phase of a satellite antenna for a dual-frequency combination of signals without ionosphere for GPS and Galileo, and the APC models used are based on IGS corrections published in Antenna Exchange Format (ANTEX) files. In metric terms, the expected positioning performance using HAS is about 20 and 40 cm for the horizontal and vertical components, respectively, with a 95% confidence level [5].
Galileo HAS corrections can be used in precision point positioning (PPP) algorithms in the form of state space representation (SSR) corrections [10]. A certain problem on the way to the widespread use of HAS correction data is the lack of a generally accepted standard for SSR corrections (standardization of the RTCM SSR format has been expected for several years). Galileo HAS corrections are provided in a proprietary format that resembles the compact SSR format [13]. In addition, they are encoded in the so-called High-Pair Vertical Reed Solomon Codes (HPVRS) to optimize the reception of HAS messages from multiple satellites [7]. There are various options for PPP processing, ranging from built-in receiver functions, commercial software, and open-source software [8,13,14]. One of the most popular open-source packages for accurate GNSS processing is RTKLIB [15]. While the current stable version of RTKLIB (version 2.4.3 b34) allows for high accuracy PPP processing, it only supports finalized RTCM SSR messages, which means no PPP support with Galileo HAS without internet access. To facilitate the use of Galileo HAS with existing software, several decoders have been developed - open-source programs that decode the navigation data blocks encoded by HAS HPVRS and convert the corrections to RTCM-SSR format. Among these programs, the most well-known are the HASlib [9] and GHASP [2] packages. They support several types of data from different receivers and convert E6B data messages written as binary streams into actual PPP corrections [17]. These corrections can be used for a variety of PPP software options, including RTKLIB.
It should be noted that the RTKLIB software package was developed for broader and more general applications and we have not implemented any improvements to the "standard" PPP algorithm in it. It follows that the inherent accuracy of RTKLIB may not fully reflect the accuracy of HAS corrections, as it was not

developed specifically for use with Galileo HAS. This can have an impact on the expected convergence time, as well as on the errors in the positional solution due to the lack of use of HAS code offsets in the RTKLIB PPP results. Since code offset corrections were not applied, the ambiguity was not resolved. It is known that part of the code offset can be absorbed by the filter as part of the phase ambiguity of the floating carrier and the receiver clock signal. RTKLIB uses an Extended Kalman Filter (EKF) with undifferentiated observations to compute solutions in PPP modes. The L1/L2 (for GPS) and E1/E5b (for Galileo) frequencies provide an ionosphere-free (IF) linear combination (LC). The zenith tropospheric delay (ZTD) is estimated during the PPP process using the Saastamoinen model and the Niell Mapping Function.

3. EXPERIMENTAL SETUP AND RESULTS

3.1 MEASUREMENT CAMPAIGN AND DATA PROCESSING STRATEGIES

The experimental work aimed to investigate the performance of HAS in the field of positioning using a low-cost compact multi-GNSS receiving module Septentrio Mosaic-X5 (HAS data source), software decoders HASlib and GHASP (RTCM-SSR stream source) and RTKLIB software package (results source). The Mosaic-X5 GNSS module, manufactured by Septentrio, was designed for mass market applications such as robotics and autonomous systems, which simultaneously uses satellite signals from multiple GNSS (GPS, GLONASS, BeiDou, Galileo, QZSS, SBAS, IRNSS) [6]. We evaluated the accuracy in the field of positioning by calculating the difference between the reference true position obtained from traditional RTK and the positions obtained using the HAS service. It should be noted that these differences were converted into topocentric coordinates N, E, U. Our main efforts were focused on the collected data and convergence time.

To comprehensively evaluate the performance of HAS PPP that can be achieved with mosaic-X5 and RTKLIB, we collected several datasets for five representative days between March 23 (083 GPS Day) and May 21 (142 GPS Day), 2024 in three different variants (configurations). The duration of one data set ranged from 30 minutes to 2 hours. In order to make them comparable, the same experimental conditions (hardware, software, and observation location) were guaranteed. The data were collected using a multi-GNSS module Septentrio Mosaic-X5 and a geodetic satellite antenna 3COAT903 (Fig. 1) in the western part of Ukraine.

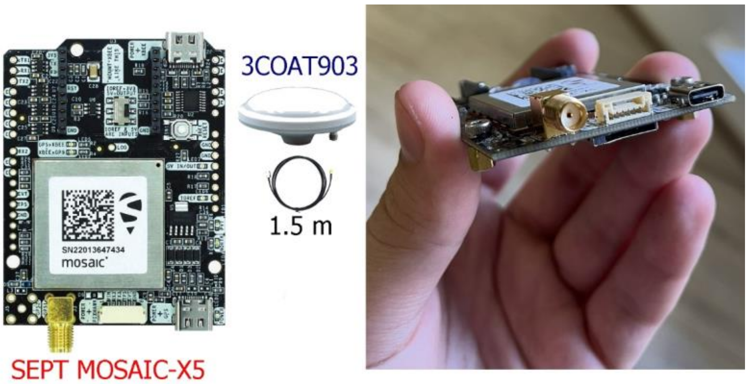

Fig. 1. The hardware used to collect HAS data

Table 1 summarizes all the configurations we used in RTKLIB.

Table 1. Positioning models

Positioning mode – PPP Kinematic	*Details*
PPP: Broadcast + SBAS	*SBAS corrections for GPS satellites are used*
PPP: Broadcast + SSR APC from SiS	*HAS corrections from Galileo satellites for the GPS + Galileo constellation are used using the HASlib decoder*
PPP: Broadcast + SSR APC from Internet	*HAS corrections from the Internet for the GPS+Galileo*

	constellation in RTCM3 format are used

Each of the datasets consisted of a session of observations using the multi-GNSS module Septentrio Mosaic-X5. The real-time data stream was sent to the decoder and then converted into RTCM3 messages. An alternative source of the RTCM3 stream was the SSRA00EUH0 mountpoint, to which we connected via the NTRIP protocol using the Ntrip client software. In our case, we used the open-source BNC client program, which was installed on a laptop. Table 2 shows the format of messages in the SSRA00EUH0 data stream and the update interval.

Table 2. SSRA00EUH0: Get data in RTCM 3.x format

Parameter	*RTCM message*	*Occurrence (sec)*
Galileo code biases	*1242*	*20*
Galileo orbits/clocks	*1243*	*20*
GPS Ephemerides	*1019*	*30*
Galileo I/NAV Satellite Ephemeris Data	*1046*	*30*
GPS code biases	*1059*	*30*
GPS orbits/clocks	*1060*	*30*

It should be noted that during the study period, the average update interval for RTCMSSR Clock&Orbit was 18.13±2.34 sec, and for RTCMSSR CodeBiases – 19.05±3.31 sec. These values refer to Galileo. For GPS (RTCMSSR Clock&Orbit), they are 27.92±3.64 sec.

Despite the use of a static station, we chose the kinematic mode to estimate the convergence time using the dynamic PPP solution. This approach allows us to estimate the time required to achieve a stable solution.

3.2 POSITIONING PERFORMANCE ANALYSIS

As already mentioned, the observation period covered a total of five sessions. In the first two sessions, we used the AH-4236-SSN Hi-Target navigation antenna, which is used in the drone and robotics industry. We were somewhat disappointed with the results of these sessions (see Fig. 2). As can be seen from this figure, convergence occurred quite quickly (less than 2 minutes), but then, within 13 minutes, unexplained "jumps" in the coordinates appeared twice, which negated all previous results. A similar situation repeated itself during the second observation session. We replaced this navigation antenna with a geodetic type 3COAT903 antenna (see Fig. 1). As the results of the next three observation sessions showed, no more such jumps in coordinates were observed after the convergence period. But at the same time, the problem of a significant extension of the convergence period was revealed.

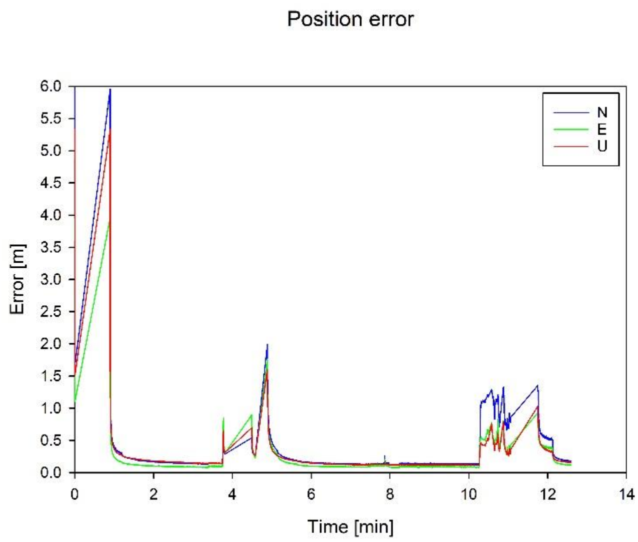

Fig.2. Positioning PPP HAS errors from the first measurement session

Fig. 3 shows the errors in determining the horizontal (2D) coordinates in real time from an hour and a half observation session (2801 values). Similar data are given for 3D coordinates (Fig. 4). As can be seen from Fig. 3, the accuracy of the horizontal (2D) coordinates of 20 cm occurs only after 18 minutes of convergence. Relatively small fluctuations in coordinate errors occur due to the quantitative change in GPS+Galileo satellites (from 18 to 11).

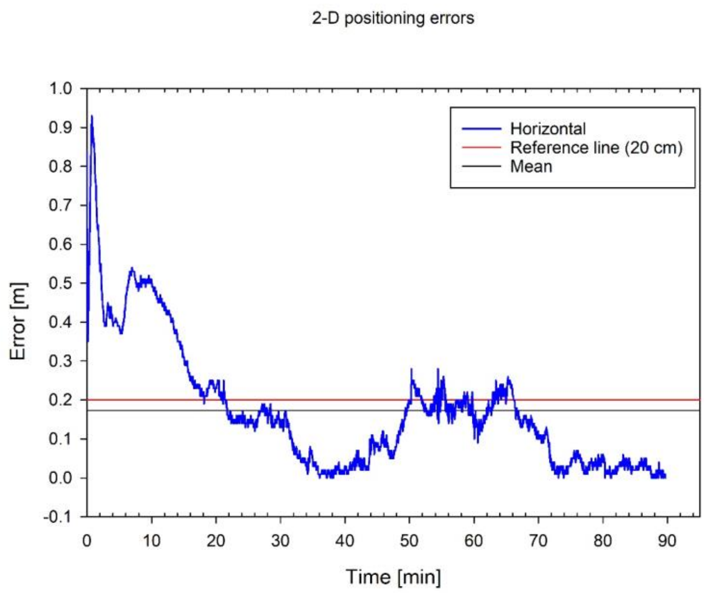

Fig.3. 2D positioning errors from PPP HAS solutions

The results, based on which Fig. 4 is constructed, indicate a significant deterioration in accuracy (even more than 60 cm) for 3D positioning with the same convergence period.

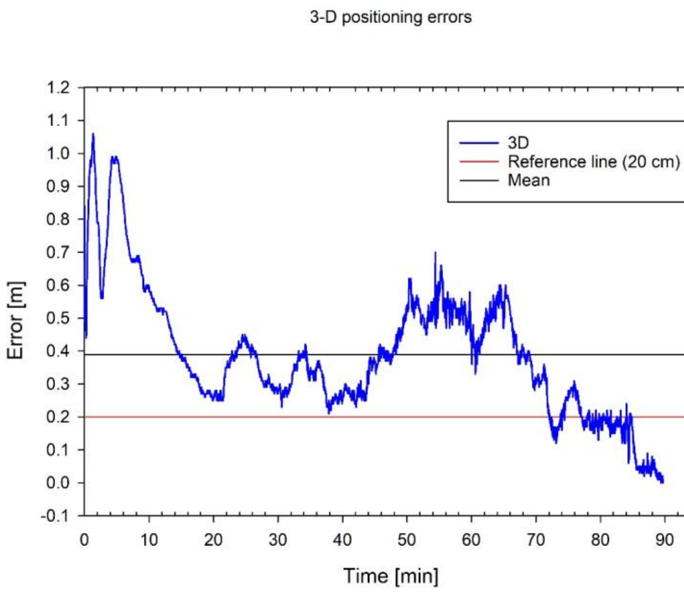

Fig.4. 3D positioning errors from PPP HAS solutions

Table 3 summarizes the PPP HAS real-time positioning statistics obtained for three observation sessions. Our results almost statistically confirm the declared accuracy of Galileo HAS in terms of coordinates, but the convergence time is still far from the declared one. It is possible that some factors related to the software implementation of the PPP HAS have manifested themselves here.

Table 3. Statistics of solutions obtained by PPP HAS

	RMS, cm	*Bias, cm*	*Std, cm*
Horizontal	*17.4*	*16.1*	*7.4*
3D	*39.0*	*35.3*	*12.1*

We should also note that we used different configurations of the working scheme setup described in Table 1 in different sessions. In one of the sessions, we used HAS corrections from Galileo satellites for the GPS+Galileo constellation using the HASlib decoder, and in the other, we used HAS corrections from the Internet for the GPS+Galileo constellation in the RTCM3 format. The resulting differences between these configurations are one order of magnitude smaller than the data shown in Table 3. Therefore, in this regard, we can state that the selected configurations are fully compatible. This also includes the absolute identity in the choice of decoder between HASlib and GHASP. Our research has shown absolute compatibility in the files decoded from the Septentrio mosaic-X5 receiver.

The initial research plan also included a comparison of the results of the Galileo High Accuracy Service and SBAS in the EGNOS implementation (see the corresponding configuration in Table 1). That is, during one of the observation sessions, we accepted SBAS corrections from PRN123 and PRN 136 in the *.sbs format. We do not present the results of this comparison here because of the low positioning accuracy of the SBAS PPPs. The fact is that our observation station was located almost at the edge of EGNOS coverage and therefore the accuracy obtained was not comparable.

CONCLUSIONS AND REMARKS

In this work, the capabilities of HAS in combination with open source real-time software were tested and the HAS corrections were analyzed in comparison with other service providers such as CODE.

While the compatibility of HAS products delivered directly via SiS and over the Internet is beyond doubt, as well as their compatibility with data from other centers, the performance of Galileo HAS is not yet so optimistic. In statistical terms, our results are close to the declared ones, i.e., they reach an accuracy of 20 cm and 40 cm in horizontal and vertical positions (95% confidence interval), respectively. Of concern is the variable behavior of the convergence process (from several to the first tens of minutes), which affects the real-time positioning accuracy.

One of the reasons for the variable behavior of the convergence process is the use of the Kalman filter, which could not maintain a stable convergence curve during the PPP filtering procedure. Perhaps the implementation of some other method, such as the SRIF (Square Root Information Filter) filter, could solve this problem to some extent. Perhaps the problem lies in the RTKLIB software package itself, because it was not designed for this task.

It is also difficult to assess the difference and compatibility between the HAS validity interval and the RTCM3 update interval. While the HAS validity interval is simple in its meaning (20 seconds), the update interval is more related to the expected speed of correction updates. These differences can be up to several seconds (approximate data are given after Table 2), which may have an impact on the minimum reliability of corrections.

Despite the above, it can be argued that Galileo High Accuracy Service is a viable option for real-time correction of classical GNSS data [1,11]. An alternative to HAS corrections is GNSS corrections provided by commercial services (with a subscription) via geostationary satellites. Another alternative is SBAS messages, but their positioning accuracy is at the level of one meter.

REFERENCES

1. Angrisano A, Ascione S, Cappello G, Gioia C, Gaglione S. Application of "Galileo High Accuracy Service" on single-point positioning. Sensors Vol.23:4223. https://doi.org/10.3390/s23094223
2. Borio D, Susi M, Gioia C. GHASP: a Galileo HAS parser. GPS Solutions, Vol.27:197, 2023. https://doi.org/10.1007/s10291-023-01529-y
3. European Union Agency for the Space Programme. Galileo Has Internet Data Distribution. Available online: https://www.gsc-europa.eu/galileo/services/galileo-high-accuracy-service-has/internet-data-distribution (accessed on 3 May 2024).
4. European Union. Galileo E6-B/C Codes Technical Note. 2019. Available online: https://www.gsc-europa.eu/sites/default/files/sites/all/files/ E6BC SIS _ Technical _ Note.pdf (accessed on 3 May 2024).
5. European Union Space Program Agency (EUSPA) (2019) Galileo open service—service definition document, issue 1.1. https://www.gsc-europa.eu/sites/default/files/sites/all/files/Galileo-OS-SDD_v1.1.pdf (accessed on 3 May 2024).
6. European Union Space Program Agency (EUSPA) (2023b) Galileo high accuracy service registration. https://www.gsc-europa.eu/galileo/services/galileo-high-accuracy-service-has/internet-data-distribution-registration-form (accessed on 3 May 2024).
7. Fernandez-Hernandez I, Chamorro-Moreno A, Cancela-Diaz S, Calle-Calle JD, Zoccarato P, Blonski D, Senni T, de Blas FJ, Hernández C, Simón J, Mozo A. Galileo high accuracy service: initial definition and performance. GPS Solutions, Vol.26:65, 2022. https://doi.org/10.1007/s10291-022-01247-x
8. Gunning K, et al (2018) Design and evaluation of integrity algorithms for PPP in kinematic applications. In: Proceedings of ION GNSS+2018, Institute of Navigation, Miami, Florida, September 2018, pp 1910–1939. https://doi.org/10.33012/2018.15972
9. Horst O, et al. HASlib: an open-source decoder for the Galileo high accuracy service. In: Proceedings of ION GNSS+2022, Institute of Navigation, Long Beach, California, January 2022, pp 2625–2633. https://doi.org/10.33012/2022.18261
10. IGS (2020) IGS state space representation (SSR) format. https://files.igs.org/pub/data/format/igs_ssr_v1.pdf. (Accessed on 3 May 2024)
11. Martini, I., Susi, M., Cucchi, L. *et al.* Galileo high accuracy service performance and anomaly mitigation capabilities. GPS Solutions, Vol.28:25, 2024. https://doi.org/10.1007/s10291-023-01555-w

12. Naciri N, Yi D, Bisnath S, de Blas FJ, Capua R. Assessment of Galileo High Accuracy Service (HAS) test signals and preliminary positioning performance. GPS Solutions, Vol.27:73, 2023. https://doi.org/10.1007/s10291-023-01410-y
13. Pintor P, et al Galileo high accuracy service (HAS) algorithm and receiver development and testing. In: Proceedings of the ION GNSS+ 2022, Institute of Navigation, Denver, Colorado, September 2022, pp 836–851. https://doi.org/10.33012/2022.18462
14. Prol, F.S., Kirkko-Jaakkola, M., Horst, O. *et al.* Enabling the Galileo high accuracy service with open-source software: integration of HASlib and RTKLIB. GPS Solutions, Vol.28:71, 2024. https://doi.org/10.1007/s10291-024-01617-7
15. Takasu T. RTKLIB: an open source program package for GNSS positioning. 2020. http://www.rtklib.com/. (Accessed on 3 May 2024).
16. Teunissen, P.; Montenbruck, O. Springer Handbook of Global Navigation Satellite Systems; Springer: Berlin/Heidelberg, Germany, 2017. 1327 p.
17. Zhou, P., Xiao, G. & Du, L. Initial performance assessment of Galileo High Accuracy Service with software-defined receiver. *GPS Solutions,* Vol.28: 2, 2024. https://doi.org/10.1007/s10291-023-01540-3