AVIATION AND SECURITY ISSUES NO. 3(1/2023)
ISSN 2720-197X / eISSN 2956-3380

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DOI: 10.55676/asi.v3i1.46

GALILEO HAS – FIRST PERFORMANCE TESTS DURING ITS INITIAL PHASE OF OPERATION

GALILEO HAS – PIERWSZE TESTY PARAMETRÓW OPERACYJNYCH SERWISU W JEGO POCZĄTKOWEJ FAZIE OPERACYJNEJ

Abstract

Galileo High Accuracy Service (HAS) became available in January 2023. As declared, in its final operational capability, it should be able to provide to users the Precise Point Positioning (PPP) at horizontal accuracy level better than 20 cm in real-time with 95% confidence globally. At the moment Galileo HAS works in its initial phase of operation with some limitations regarding its availability, convergence time and accuracy but gives the chance to observe the performance of positioning tool at the accuracy level which was available before by using differential measurement only. Galileo HAS PPP, free of charge and based only on satellite signals delivered by nominal Galileo constellation is unique in its kind between various GNSS positioning modes. This article presents the results of first, preliminary tests on Galileo HAS performance conducted in July 2023 in Gdynia, Poland. The field tests were conducted with Galileo HAS capable receiver in static conditions and focused on the verification the declared service performance in the real positioning scenarios. Additionally, the Galileo HAS PPP performance was compared with the simultaneous performance of other GNSS positioning methods such as EGNOS, DGPS, dual frequency GPS+Galileo or dual frequency GPS and dual frequency Galileo. This first experiences with Galileo HAS positioning should show all potential users what performance level can be achieved with this new, unique in its kind GNSS positioning method at the present state of its implementation.

Keywords: Galileo, Global Navigation Satellite System (GNSS), High Accuracy Service (HAS), Precise Point Positioning (PPP), Precise Navigation

Streszczenie

Galileo High Accuracy Service (HAS) stał się dostępny w styczniu roku 2023. Tak jak zadeklarowano, po osiągnięciu finalnej fazy operacyjnej serwisu powinien on zapewnić użytkownikom globalną możliwość realizacji trybu *Precise Point Positioning* (PPP) z dokładnością wyznaczania pozycji na płaszczyźnie na poziomie lepszym niż 20 cm w czasie rzeczywistym i na 95% poziomie ufności. Aktualnie serwis Galileo HAS pracuje w początkowej fazie operacyjnej z pewnymi ograniczeniami dotyczącymi dostępności, czasu inicjalizacji oraz dokładności, ale pozwala już na uzyskiwanie dokładności wyznaczeń pozycyjnych na poziomie dokładności, który wcześniej był osiągalny tylko z wykorzystaniem metod różnicowych GNSS. Ponadto, serwis Galileo HAS PPP jest serwisem ogólnodostępnym i wykorzystującym tylko nominalne satelity nawigacyjne systemu Galileo, co czyni go unikalnym wśród aktualnie dostępnych metod GNSS. W artykule zaprezentowano wyniki pierwszych, wstępnych eksperymentów oceniających parametry operacyjne serwisu Galileo HAS przeprowadzonych w Gdyni w lipcu 2023 r. Testy serwisu przeprowadzono w warunkach statycznych z wykorzystaniem odbiornika realizującego wyznaczenia pozycyjne z zastosowaniem sygnału Galileo HAS. Pomiary miały na celu weryfikację deklarowanych parametrów dokładnościowych i dostępnościowych serwisu w rzeczywistych warunkach pomiarowych. Dodatkowo, obserwowane parametry serwisu Galileo HAS PPP zostały porównane z rejestrowanymi równolegle wynikami wyznaczeń pozycyjnych uzyskiwanych innymi metodami GNSS, takimi jak: EGNOS, DGPS, dwuczęstotliwościowe pomiary GPS+Galileo oraz dwuczęstotliwościowy

Artykuł wpłynął do redakcji: 24.05.2023 / Zatwierdzono do publikacji: 24.06.2023

GPS i dwuczęstotliwościowy Galileo. Przedstawione w artykule wyniki pierwszych doświadczeń z wykorzystaniem serwisu Galileo HAS pokazują wszystkim potencjalnym użytkownikom, czego mogą się spodziewać, wykorzystując w procesie wyznaczania pozycji tę nową i unikalną w swoim rodzaju metodę pozycyjną GNSS na jej aktualnym etapie wdrażania.

Słowa kluczowe: Galileo, GNSS, HAS, PPP, nawigacja precyzyjna

1. INTRODUCTION

Since its very beginning, the design of Galileo satellite navigation system considered to deliver to users its service at several levels which vary in accuracy, availability, range and accessibility. Various Galileo services are designed to meet users expectations and to fulfil their specific needs regarding the positioning and navigation. Originally it was planned that among other capabilities, Galileo satellite navigation system will "offer a commercial service (CS) for the development of applications for professional or commercial use by means of improved performance and data with greater added value than those obtained through the open service"[1]. Further, the implementing decisions of European Commission started to define technical and operational specifications of the commercial service (CS) to fulfil the stated above function of the service. At first, the EU Commission Implementing Decision 2017/224 of 8 February 2017 provided that the general specifications of the 'CS high precision' service offered by the commercial service envisage a positioning error of less than a decimeter and that access to this 'CS high precision' service, monitored by one or more service providers, is subject to a fee depending on the pricing policy in force[2]. However, not much later on 02nd of March 2018 above decision was amended by EU Commission Implementing Decision 2018/321 where it was decided that the 'CS high precision' service will supply data in order to obtain a positioning error of less than 20 cm in nominal condition of use and moreover that the access to the Galileo high precision service will be free of charge[3]. This decision was motivated with several technical, commercial and political arguments. Among them the following statements are worth to be cited[4]:

– "fee-paying access to the commercial service's high precision service could slow the development of the applications required to use this service and hinder the promising growth of economic activities based on satellite navigation systems, particularly within the Union";

1 The European Parliament and The Council Of The EU. EU Regulation No 1285/2013 of 11 December 2013. Article 2(4)(c), Official Journal of the European Union L347/1, European Union, 2013.

2 European Commission, EU Commission Implementing Decision 2017/224 of 8 February 2017, Official Journal of the European Union L34/36, European Union, 2017.

3 European Commission, EU Commission Implementing Decision 2018/321 of 2 March 2018, Official Journal of the European Union L62/34, European Union, 2018.

4 Ibidem.

 DOI: 10.55676/asi.v3i1.46

- fee-paying access may "make it more difficult for the system established under the Galileo programme to penetrate global markets given that rival systems propose to offer high precision services free of charge";
- "changing the minimum precision requirement from one decimetre to two will thus reduce the time needed to achieve that precision";
- "enterprises in the expanding sectors most likely to use the high precision commercial service, such as those developing autonomous vehicles, robotics or drones, do not need such high precision positioning as initially envisaged for the commercial service. Positioning error of less than two decimetres is sufficient for those enterprises, and is more attractive if, in return, the time needed to achieve such precision can be reduced".

Finally, the new name of Galileo commercial service (CS) shaped out and in EU Regulation 2021/696 of 28 April 2021, which superseded previous documents defining implementation of Galileo satellite navigation system, this service was named as a high-accuracy service (HAS). This document states, that a Galileo high-accuracy service (Galileo HAS):

> "shall be free of charge for users and shall provide, through additional data disseminated in a supplementary frequency band, high-accuracy positioning and synchronisation information intended mainly for satellite navigation applications for professional or commercial use"[5].

In this way the legal directives created the fundamentals for the technical implementation and development of the Galileo based positioning method which brings satellite based, absolute and non-differential point positioning to the precise level of less than 20 cm. In the international context Galileo HAS is not the only among other planned PPP (Precise Point Positioning) solutions, which probably will be developed within other satellite navigation systems (GPS, Beidou, QZSS, Glonass) but it is unique in its class[6, 7]. The Japanese QZSS CLAS (Centimeter-Level Augmentation Service) and BeiDou PPP-B2b are already providing similar PPP services but on the regional scale only[8]. The Galileo HAS at its fundamentals is the first global high accuracy service free of charge.

The Galileo HAS was declared available for the public use on 24th January 2023. This date marked the start of Phase 1 called "HAS initial service". Galileo HAS Phase 1 was preceded by Phase 0 when the HAS data were available only during limited periods and to selected laboratories which were able to validate service dissemination capabilities and conduct various SIS (Signal-in-Space) tests. Results of these tests

5 The European Parliament and The Council Of The EU, EU Regulation 2021/696 of 28 April 2021.Article 45(1)(b), Official Journal of the European Union L170/69, European Union, 2021.

6 Blonski D., Choi S., *Standards and Interoperability of Precise Point Positioning Services*, Presentation at 14th Meeting of the International Committee on Global Navigation Satellite Systems, ICG-14, December 2019, Bengaluru, India.

7 Blonski D., de Blas J., Fernandez-Hernandez I., *Galileo High Accuracy Service*, Presentation from ICG Workshop GNSS Data Processing for HA Positioning, January 2021, Tokyo 2021.

8 Quasi-Zenith Satellite System Services Inc., *Quasi-Zenith Satellite System Performance Standard (PS--QZSS-003)*, The Cabinet Office, Government of Japan, March 2022.

delivered the preliminary estimation of the expected service performance before it went into its initial operational phase. Those tests referred to various aspects such as: the benefits of HAS in terms of coverage and accuracy[9], the quality of the transmitted correction[10], the ability of satellite anomaly detection based on HAS corrections[11]. All above announced very promising HAS service performance during its experimental and validation phase and creating a big expectations among users waiting for the Galileo HAS signal become available for the wide users community.

Making Galileo HAS available in January 2023, supported with publication of the service definition document[12], has opened the possibilities to explore service capabilities in the user domain[13, 14]. This article presents the results of tests on Galileo HAS performance conducted in July/August 2023 in Gdynia, Poland. The field tests were conducted with the first, generally available to users, the Galileo HAS capable receiver – "EOS Arrow Gold+", which is providing so called "out of box" positioning for various user needs. Implementing in tests the user "ready to go" GNSS equipment allows to check what users may "get" from the Galileo HAS service with the tools (receivers), which might be within their hand. The experiments described in the paper, as the first approach to the verification the declared Galileo HAS performance were set up in static conditions with antennas located at known, geodetically surveyed points. The main tests objectives were focused on:

- the verification of the relative and absolute accuracy of Galileo HAS positioning observed during various periods of the day (nighttime, daytime, sunset and sunrise) and for various service configurations (GPS+Galileo HAS, HAS GPS only and HAS Galileo only);
- the comparison of the Galileo HAS performance with positioning results observed simultaneously with other GNSS methods such as: EGNOS, dual frequency GPS+Galileo or dual frequency GPS and dual frequency Galileo;
- testing of the Galileo HAS convergence times before it reaches the expected performance level in the periods with nominal and limited satellites availability (various elevation masks applied for GPS and/or Galileo constellation).

The tests were conducted in the facilities of the Navigation Faculty of Gdynia Maritime University, located at the Polish Coast of The Baltic Sea as the author's main

9 Fernandez-Hernandez I., Chamorro-Moreno A., Cancela-Diaz S., Calle-Calle J.D., Zoccarato P., Blonski D., Mozo A., *Galileo High Accuracy Service: Initial definition and performance*, GPS Solutions 26 Article No.65 (2022), Springer, 2023.

10 Naciri N., Yi D., Bisnath S., de Blas J., Capua R., *Assessment of Galileo High Accuracy Service (HAS) test signals and preliminary positioning performance*, GPS Solutions 27 Article No. 73 (2023), Springer, 2023.

11 Martini I., Susi M., Paonni M., Sgammini M., Fernandez-Hernandez I., *Satellite Anomaly Detection with PPP Corrections: A case study with Galileo's high accuracy service*, Proceedings of the 2022 International Technical Meeting of The Institute of Navigation, 25–27 January 2022 Long Beach, CA, USA, 2022.

12 European Agency for the Space Programme (EUSPA), Galileo – High Accuracy Service - Service Definition Document (Galileo HAS SDD) Issue 1.0, EUSPA, January 2023.

13 Angrisano A., Ascione S., Cappello G., Gioia C., Gaglione S., *Application of Galileo High Accuracy Service on Single-Point Positioning*, Sensors 2023, vol. 23(9), 4223, MDPI, Basel, Switzerland 2023.

14 European Agency for the Space Programme (EUSPA), Galileo HAS Days (28 - 29 June 2023) Presentations, EUSPA, July 2023, https://www.euspa.europa.eu/european-space/galileo/ services/galileo-high-accuracy-service-has [access: 15.08.2023].

 DOI: 10.55676/asi.v3i1.46

interest is in the potential applicability of Galileo HAS in maritime applications. However, the scope of the conducted research, due to its cognitive nature during the initial operational phase of Galileo HAS may be valuable for all other potential service users. Additionally, all data collected during early stage of Galileo HAS operation are the good reference for future evaluations of the effects gained by the further service development towards its final phase (Galileo HAS Full Service - Phase 2).

2. GALILEO HAS DESCRIPTION

In general terms, the Galileo HAS definition executes goals set up EU regulations mentioned above and is an open access and free of charge service which allows the user to achieve improved positioning performance compared to the performance of the Galileo Open Service. The improved positioning performance is achieved by the provision of precise corrections (i.e. orbits and clocks) and biases transmitted in the Galileo E6 signal (E6-B, data component) from a subset of the Galileo satellites as well as via the internet[15].

In its concept, the Galileo HAS corrections are referring to following GNSS Signals and data:

- Galileo E1, E5a, E5b and E6 signals;
- GPS L1 C/A, L2C signals;
- Galileo satellite I/NAV navigation messages;
- GPS satellite LNAV navigation messages.

To obtain Precise Point Positioning (PPP), HAS corrections regarding orbit and clocks should be applied to correct data received via mentioned above navigational messages. Additionally, code and phase biases discriminated by the service can be used to correct ranging measurements obtained using above listed signals. It has to highlighted that currently, during Galileo initial phase of operation, only code biases are delivered to users to enhance accuracy of the ranging measurements.

Galileo HAS ground infrastructure in its majority is based on existing Galileo core system facilities. The service corrections are generated by High Accuracy Data Generator (HADG) which is hosted by European GNSS Service Center (GSC) located in Madrid, within National Institute of Aerospace Technology (INTA). HADG calculates Galileo HAS corrections based on data collected from worldwide network of Galileo Sensor Stations (GSS), which collect and forward Galileo SIS measurements and data to the Galileo Control Centers (GCC) and GSC in real time. The corrections generated by HADG are disseminated via GSC in two ways:

- forwarded to the Galileo Uplink Stations (ULS) and then uplinked to the Galileo satellites to be broadcasted via the Galileo E6-B signal component;
- formatted to be broadcast via internet in real-time using NTRIP Caster capabilities.

[15] European Agency for the Space Programme (EUSPA), Galileo – High Accuracy Service - Service Definition Document (Galileo HAS SDD) Issue 1.0, EUSPA, January 2023.

It is worth to highlight that, in the case of SIS broadcast, Galileo satellites will only broadcast high accuracy data when connected to an uplink station. Currently, it is planned that HAS data will be populated with up to 20 Galileo satellites of all available in the Space. The HADG has the capability to select the data to be broadcasted by each connected Galileo satellite to secure the proper scheduling the provision of high accuracy data to the potential Galileo HAS users located within the service area[16]. Currently, with Galileo HAS operating in its Initial Service phase, high accuracy data is calculated based on the network of 15 GSSs. The capability of Galileo to broadcast high accuracy corrections through the SIS will evolve over time along with the continuous infrastructure deployment. It will include the extension of GSS network and the number of uplink stations engaged by service. This will have direct and positive impact on service performance in the context of the accuracy, the availability and the enlarged service area. The Galileo HAS is executed within Galileo time and geodetic frames: Galileo System Time (GST) and Galileo Terrestrial Reference Frame (GTRF).

The SIS broadcast of the Galileo HAS is executed on E6B Galileo satellites' signals. The HAS corrections are encoded to C/NAV navigational data message. Galileo C/NAV E6B data are transmitted at the rate of 500 bits/second. HAS messages are formed as 448 bit pages of C/NAV format and all marked with Header containing Mask ID and IOD (Issue of Data) set ID. The Galileo HAS corrections are grouped into two types of HAS messages:

- "HAS slow messages" which contain the mask, satellite orbit corrections, code and phase biases;
- "HAS fast messages" which contain the satellite clock corrections.

HAS SIS broadcast scheme assumes that within 10 seconds period the following sequence is applied: 7 "HAS slow messages", 2 "HAS fast messages", 1 "HAS dummy message". HAS slow and fast messages are linked through the Mask ID and the IOD set ID parameters. The transmission of HAS encoded pages for each HAS message is not restricted to a single Galileo satellite. It enables the decoding of the HAS messages once a sufficient number of HAS pages has been retrieved by the user, independently of the Galileo satellite from which they were transmitted. So the user do not need to "wait" to collect full set of the HAS data from one satellite and may "compose" the required data package of the high accuracy data receiving it simultaneously from several Galileo satellites. In this way the HAS corrections latency can be reduced significantly.

The second channel of Galileo HAS data dissemination is executed via Internet Data Distribution (IDD). The IDD channel is governed by European GNSS Service Center (GSC) and available upon registration. The data are made available to users via NTRIP (Network Transport of RTCM via Internet Protocol) caster and are a subset of the messages defined in the RTCM 10403.3 standard.

[16] Ibidem.

 DOI: 10.55676/asi.v3i1.46

The Galileo HAS IDD provides the following set of data for Galileo and GPS satellites[17]:
– satellite orbit corrections to the broadcast Galileo I/NAV and GPS LNAV ephemeris;
– satellite clock corrections to the broadcast Galileo I/NAV and GPS LNAV clock parameters;
– code biases;
– Galileo I/NAV and GPS ephemeris (since July 2023).
– The above data are encoded into following types of RTCM messages:
– message type 1243 – SSR (Space State Representation) Galileo Combined Orbit and Clock Corrections;
– message type 1242 – SSR Galileo Code Bias;
– message type 1060 – SSR GPS Combined Orbit and Clock Corrections;
– message type 1059 – SSR GPS Code Bias;
– message type 1046 – Galileo I/NAV ephemeris (since July 2023);
– message type 1019 – GPS ephemeris (since July 2023).

The supported SSR correction messages are nominally provided with 10 seconds update rate. Additional information may be provided in the future as part of the HAS service evolutions towards the HAS full operational capability[18].

The design of Galileo HAS assumes that at its final shape the service will be delivered on two performance levels described as: Service Level 1 (SL1) and Service Level 2 (SL2). These two service levels will differ in the respect of the type of corrections served to users. Service Level 2 will be enhanced by giving users the ability of use atmospheric corrections. This will improve the final service performance in the user domain mainly by reducing the target convergence time. Additionally, while SL1 is assumed to be available globally, the enhanced SL 2 will be designed to cover only so called "The European Coverage Area – ECA". Table 1 summarizes the main features describing two service levels of Galileo HAS.

Table 1. Galileo HAS Full Service planned service levels

	Service Level 1 – SL1	Service Level 2 – SL2
Service area	Global coverage	The European Coverage Area – ECA
Correction type	orbits corrections, clocks corrections, code biases, phase biases	orbits corrections, clocks corrections, code biases, phase biases, atmospheric corrections
Delivery channels	HAS Signal-in-Space HAS Internet Data Distribution	HAS Signal-in-Space HAS Internet Distribution Data
Accuracy target (95%)	Horizontal – <20 cm Vertical – <40 cm	Horizontal – <20 cm Vertical – <40 cm
Availability target	99%	99%
Convergence time target	< 300 seconds	< 100 seconds

Source: European Agency for the Space Programme (EUSPA), Galileo – High Accuracy Service - Service Definition Document (Galileo HAS SDD) Issue 1.0, EUSPA, January 2023.

17 Ibidem.
18 Ibidem.

Currently, Galileo HAS operates in its Initial Service Phase (Galileo HAS Phase 1) which means that the users may experience the Service Level 1 operational quality but with following exceptions:

– the "global coverage" exclude the areas over Far East, Australia and Pacific Ocean between latitudes 60°N and 60°S and to the East from longitude 090°E and to the West from longitude 125°W;
– phase biases are not included in Galileo HAS message.

For the Galileo HAS Initial Service Phase the following Minimum Performance Levels (MPLs) are set[19]:

Table 2. Galileo HAS Initial Service Phase corrections accuracy and corrections availability MPLs

	Minimum Performance Level (MPL)	Conditions and Constrains
HAS orbit corrections accuracy	≤ 20 cm (95%) for Galileo ≤ 33 cm (95%) for GPS over the instantaneous constellation average (computed as RMS)	Calculated over a period of 30 days; All HAS-corrected and valid Galileo/GPS satellites in view from any point in the defined service area;
HAS clock corrections accuracy	≤ 12 cm (95%) for Galileo ≤ 15 cm (95%) for GPS over the instantaneous constellation average (computed as RMS)	
HAS code biases accuracy	≤ 50 cm (95%) for Galileo and GPS over the instantaneous constellation average (computed as RMS)	
HAS corrections availability	≥ 87% for Galileo only ≥ 95% for Galileo+GPS	5 degrees elevation mask; Calculated over a period of 30 days; At least 5 satellites in view for Galileo only mode or At least 8 satellites in view for Galileo+GPS mode (all HAS-corrected and valid) At the Worst User Location of the service area

Source: European Agency for the Space Programme (EUSPA), Galileo – High Accuracy Service - Service Definition Document (Galileo HAS SDD) Issue 1.0, EUSPA, January 2023.

Performance report covering first 3 months of Galileo HAS operation from January to March 2023 indicates that during this period the service fulfilled all target values of defined Minimum Performance Limits[20].

The main interest of this publication is the Galileo HAS performance in the user domain, It means what the main focus is set on the position horizontal and vertical accuracy, which may be achieved by service user. This type of minimum performance limits usually are not set precisely by service provider due to its dependence from the quality of users' equipment. However, the Galileo HAS Service Definition Document[21]

[19] Ibidem.
[20] Ibidem.
[21] Ibidem.

 DOI: 10.55676/asi.v3i1.46

describes the expected, typical positioning accuracy performance. Table 3 summarizes these parameters as expected by Galileo HAS provider.

Table 3. Typical, expected Galileo HAS Initial Service Phase positioning accuracy performance

	Signal Combination	Typical Performance	Conditions and Constrains
HAS horizontal positioning accuracy	GALILEO only: E1/E5a E1/E5b E1/E5a/E6-B	≤ 25 cm (68%)	- Over any 24 hours period; - All HAS-corrected and valid Galileo/GPS satellites in view from any point in the defined service area; - At least 5 satellites in view for Galileo only mode or at least 8 satellites in view for Galileo+GPS mode (all HAS-corrected and valid above 5 degrees elevation under open sky conditions); - Static User; - At Average User Location of the service area; *The impact of the following contributions is not considered in the computation of the and typical performance: - Signal distortions caused by propagation effects. - Receiver hardware/software faults. - Multipath and receiver multipath mitigation. - User antenna effects. - Receiver operator errors.
	GALILEO+GPS: E1/E5a + L1/L2C E1/E5b + L1/L2C E1/E5a/E6-B + L1/L2C	≤ 15 cm (68%)	
HAS vertical positioning accuracy	GALILEO only: E1/E5a E1/E5b E1/E5a/E6-B	≤ 30 cm (68%)	
	GALILEO+GPS: E1/E5a + L1/L2C E1/E5b + L1/L2C E1/E5a/E6-B + L1/L2C	≤ 20 cm (68%)	

Source: European Agency for the Space Programme (EUSPA), Galileo – High Accuracy Service - Service Definition Document (Galileo HAS SDD) Issue 1.0, EUSPA, January 2023.

Next sections of this publication describe tests and their results which allow to verify in the experimental way the expected, typical performance positioning parameters of Galileo HAS presented in Table 3.

3. GALILEO HAS PERFORMANCE TESTS SET UP

Testing of Galileo HAS performance described in the paper, as the first approach leading to the recognition of this service capabilities, was focused on checks of the service positioning accuracy observed in static conditions. The experiment was conducted in the facilities of The Navigational Faculty of Gdynia Maritime University on several days in July and August 2023. All positioning data was collected with two sets of GNSS receivers:

- EOS Arrow Gold+ – multisystem GNSS, Galileo HAS capable receiver – used to collect all Galileo High Accuracy positioning data;
- Trimble BX992 – multisystem GNSS, multi-frequency receiver – used to collect data observed simultaneously for other GNSS positioning methods.

The antennas of both receivers were located on the roof of the Faculty building were the open sky conditions can be secured with no risk of the multipath interferences. The antennas were placed in the points with known coordinates which were determined before experiment in post-processing calculations using precise GNSS observations (reported post-processing accuracy: latitude – 0.003 m; longitude – 0.003 m; height – 0.007 m). For the purpose of conducted tests the precise antennas coordinates were expressed in ITRF 2014 reference frame adjusted to the Epoch 2023.6 aligning them as close as possible to Galileo Terrestrial Reference Frame (GTRF) for the time of the experiment. During the analysis of the tests results, the known coordinates of the antennas positions were considered as a "true positions" and were used to evaluate the absolute accuracy of the recorded observations.

The experiment was organized in the several sessions, while the simultaneous observations of both receivers were recorded as the set of NMEA text messages outputted with 1Hz frequency into the logging computer. The observation sessions lasted for 24–48 hours to cover various times of the day (daylight, sunrise, night, sunset) and varying satellite constellation. In the subsequent measurements periods both receivers were set up in different modes of operations allowing the evaluation of Galileo HAS performance in various available service configurations and its comparison to the performance of other, simultaneously observed, GNSS positioning methods. Table 4 summarizes the receivers set up during all day sessions.

Table 4. The receivers set up during all day observations

	EOS ARROW Gold+			TRIMBLE BX 992		
	mode of operation	*GPS signals*	*Galileo signals*	*mode of operation*	*GPS signals*	*Galileo signals*
A	*Galileo HAS*	*L1/L2C*	*E1/E5a/E6-B*	*GPS+Galileo 2f*	*L1/L2C*	*E1/E5a*
B	*Galileo HAS (Galileo only)*	*not in use*	*E1/E5a/E6-B*	*Galileo 2f*	*not in use*	*E1/E5a*
C	*Galileo HAS (GPS only)*	*L1/L2C*	*E6-B (HAS data only)*	*GPS 2f*	*L1/L2C*	*not in use*
D	*Galileo HAS*	*L1/L2C*	*E1/E5a/E6-B*	*SBAS –EGNOS PRN 136*	*L1 (+PRN 136 GEO)*	*not in use*

Source: own study.

All above setups used for long term recording allowed to execute the accuracy parameters checks, which are presented in the next paragraphs of this paper.

Additional aspect of the conducted analysis refers to testing of the Galileo HAS convergence time before it reaches the desired performance parameters after enabling the reception of Galileo E6B signal. To execute this scope of testing the EOS Arrow Gold+ receiver was used in the several short term measurement sessions. The experiments were conducted in static conditions with the receiver antenna located at known point, same as for described above long term measurements. The Galileo HAS convergence time was estimated with receiver set up in various modes of operations and during periods, when the normal and reduced satellite constellation was observed. Before every test, the receiver was initialized in predefined configuration

DOI: 10.55676/asi.v3i1.46

from cold start and with disconnected antenna. The antenna was connected after data logging had been started. The recording was performed same as before by logging set of NMEA messages in 1 second intervals. The test usually lasted for 35–40 minutes which was in general enough to reach the desired Galileo HAS accuracy levels [horizontal < 20 cm (95%); vertical < 40 cm (95%)]. For the test purposes the Galileo HAS receiver was set up in the following modes:

- Galileo HAS (GPS+Galileo) – nominal Galileo constellation;
- Galileo HAS (GPS+Galileo) – bad Galileo constellation (5 Galileo satellites only);
- Galileo HAS (GPS+Galileo) – elevation mask – 30 deg;
- Galileo HAS (Galileo only).

The fact that the receiver antenna was located in fix, known location allowed to analyze the Galileo HAS accuracy convergence not only by observing reported by receiver estimated positioning accuracy (NMEA message type GST) but mainly by observed position error referred to antenna known position. The evaluation of observed data is presented in the subsequent paragraphs.

4. TESTING THE GALILEO HAS ACCURACY

Due to the cognitive nature of the experiment, while the new, unknown positioning service is tested in the field conditions, usually the first focus is on the accuracy, which can be achieved with this particular method. Table 5 and Figure 1 presents the results of data evaluation showing the accuracy of Galileo HAS observed during the conducted tests. The service accuracy is analyzed in two ways. First is a relative accuracy, which is described mainly as the standard deviation (sigma) of the position coordinates registered during experiment giving the idea of the positions spread around mean position during observations. Additionally, the mean position offsets from known, true position were calculated to show the potential systematic error of observed data set. The second factor which is taken into the analysis is an absolute accuracy. The absolute accuracy refers to known, true position and it is described as 68 percentile of the observed horizontal position errors and the observed vertical position errors. This accuracy parameter was selected to have the direct comparison with performance parameters stated in service definition documents (see Table 3). The value of 68 percentile can be interpreted as the horizontal and vertical range measured from true position, where 68 percent of observations are present.

To receive the comprehensive picture of the Galileo HAS performance, the accuracy parameters are calculated and presented for the various modes of operation and varied observation periods. The modes of operations under study vary in the context of the satellite constellation used to estimate position and include the following: joint GPS and Galileo constellation, Galileo only satellites and GPS only satellites. The varied observation periods show the service performance during various periods of the day (sunrise, daylight, sunset, night) to verify the consistency of accuracy parameters or its potential dependence from the changing propagation factors.

Table 5. The accuracy parameters of Galileo HAS for various modes of operation and varied observation periods

		RELATIVE ACCURACY							*ABSOLUTE ACCURACY*	
		mean position offset [m]				*sigma [m]*			*68 percentile of observed errors*	
		latitude	*longitude*	*2D offset*	*altitude*	*latitude*	*longitude*	*altitude*	*2D position [m]*	*altitude [m]*
GALILEO HAS *(GPS+GALILEO)*	*sunrise*	0,055	–0,040	0,067	0,021	0,032	0,037	0,040	0,102	0,038
	daylight	0,022	–0,035	0,041	0,003	0,032	0,025	0,092	0,062	0,100
	sunset	–0,008	–0,058	0,059	–0,113	0,044	0,025	0,047	0,087	0,142
	night	0,017	–0,053	0,056	–0,188	0,037	0,028	0,093	0,083	0,870
	all day – 24 h	**0,022**	**–0,043**	**0,048**	**–0,026**	**0,040**	**0,029**	**0,090**	**0,080**	**0,098**
GALILEO HAS *(GALILEO only)*	*sunrise*	–0,016	–0,051	0,054	0,099	0,019	0,022	0,051	0,076	0,074
	daylight	–0,028	–0,059	0,066	0,034	0,033	0,032	0,194	0,087	0,101
	sunset	–0,035	–0,016	0,039	–0,029	0,028	0,051	0,045	0,078	0,048
	night	–0,046	–0,058	0,074	–0,073	0,031	0,045	0,082	0,099	0,134
	all day – 24 h	**–0,030**	**–0,051**	**0,059**	**0,034**	**0,032**	**0,040**	**0,148**	**0,086**	**0,097**
GALILEO HAS *(GPS only; GAL E6 on)*	*sunrise*	–0,017	0,020	0,026	0,063	0,038	0,040	0,068	0,064	0,075
	daylight	0,028	–0,068	0,074	–0,041	0,069	0,070	0,151	0,125	0,143
	sunset	–0,026	–0,055	0,061	–0,058	0,066	0,052	0,146	0,115	0,142
	night	–0,035	0,027	0,044	0,047	0,062	0,048	0,047	0,086	0,124
	all day – 24 h	**0,001**	**–0,035**	**0,035**	**–0,035**	**0,069**	**0,073**	**0,139**	**0,107**	**0,126**

Source: own study.

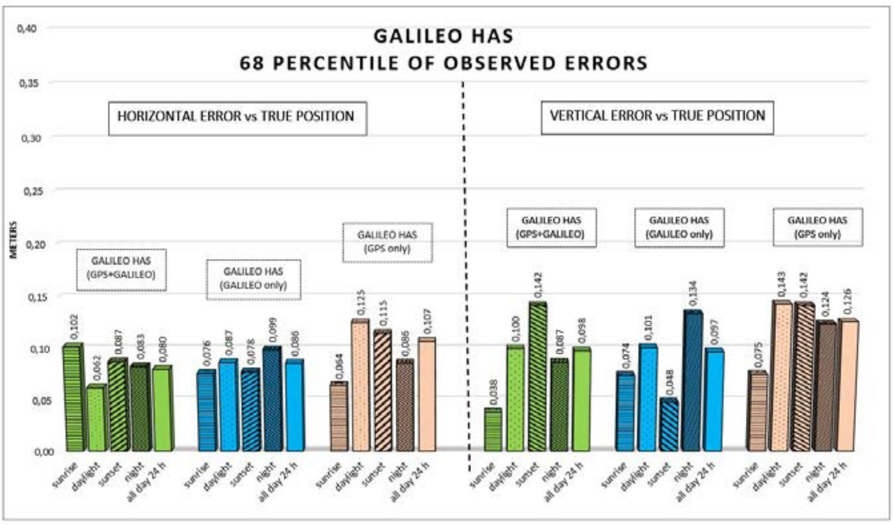

Figure 1. The accuracy parameters of Galileo HAS for various modes of operation and varied observation periods

Source: own study.

DOI: 10.55676/asi.v3i1.46

The results of tests presented in Table 5 and in Figure 1 show that the accuracy of Galileo HAS fulfills the expected service performance as declared in the service definition document[22]. For the nominal operational modes (GPS+Galileo and Galileo only), 68 percentile of horizontal position errors during 24 hours observations stays below 10 cm, while the expected accuracy is to be 15 cm for the GPS+Galileo constellation and 25 cm for the Galileo only mode. For the nominal operational modes (GPS+Galileo and Galileo only), 68 percentile of vertical errors during 24 hours observations is 1–2 cm worse than for 2D positions but still stays below 10 cm while the expected accuracy is to be 20 cm for the GPS+Galileo constellation and 30 cm for the Galileo only mode. The slightly worse service accuracy is observed when the GPS only constellation is used. The difference is minimal but noticeable. The adequate parameters are deteriorated by 2–3 cm for horizontal positioning and 3–4 cm for vertical axis. Though this mode of operation is not considered as the nominal mode of operation for Galileo HAS, its accuracy stays within the desired performance limits.

The short periods observations during various periods of the day are in general consistent with results obtained for 24 hour observations with differences +/–2 cm for 2D positions and +/–5 cm for vertical errors. Across all obtained results for 2D positioning the best 68 percentile value was 6.2 cm and was recorded for daylight observations (12 hour period) with the GPS+Galileo constellation in use. The worse value of the same accuracy parameter reached 12.5 cm and refers to 12 hour daylight observations while only GPS constellation was in use. While analyzing the vertical error accuracy the best accuracy go down to 3.8 cm and is observed for sunrise period (4 hours observation) during joint GPS+Galileo positioning but the highest values of 68 percentile are reaching 14.3 cm and are recorded for the GPS only mode during daylight (12 hours) and sunrise (4 hours) periods.

The observed data was evaluated as well to calculate 95 percentile accuracy parameters for 2D position and altitude. In this case the trends described above were followed with the minimal values of 95 percentile reaching 9.7 cm both for horizontal positions and vertical axis. Across all measurements sessions, the maximum value of 95 percentile was 35.0 cm for altitude and 21.6 cm for horizontal positions, but in both cases it was observed for the not nominal Galileo HAS mode of operation while the GPS only constellation was in use. While considering the nominal operational modes of Galileo HAS ie. using GPS+Galileo or Galileo only constellation, 95 percentile value always stays below 12.8 cm for the 2D positioning and below 20.3 cm for the altitude estimations.

The relative accuracy parameters of Galileo HAS describing the spread of estimated positions around mean value follow same trends as described above. They are consistent with the results expressed as 68 percentile of errors referred to the true position even though they are not biased by mean position offset. This is due to the

[22] Ibidem.

fact that observed mean position offsets are not significantly high and in general stay within 5–6 cm for horizontal positioning and 3–4 cm for vertical axis.

To have a full picture of the positioning quality delivered by Galileo HAS it has to be highlighted that during all measurements sessions the positions estimations were executed based on carrier-phase measurements with fixed integer ambiguity solution maintained almost all time. During all day (24 hours) observations the percentage of "fixed mode" solutions was as follows:

- HAS Galileo (GPS+Galileo constellation) "fixed integer mode" – 99.9% of observations;
- HAS Galileo (Galileo only constellation) "fixed integer mode" – 97.6% of observations;
- HAS Galileo (GPS only constellation) "fixed integer mode" – 97.9% of observations;
- Among all sessions, the highest percentage of float solutions was 4.8% and refers to the 12 hours daylight session conducted with HAS Galileo based on the GPS constellation only.

5. GALILEO HAS PERFORMANCE VS OTHER GNSS POSITIONING METHODS

During the conducted Galileo HAS performance tests, the next point of interest was focused on the comparison of the observed Galileo HAS accuracy with other available GNSS positioning methods. The Galileo HAS is classified as absolute positioning method, which is not augmented by any regional or local differential service.

Table 6. The accuracy parameters of Galileo HAS versus other positioning GNSS methods (24 hours of simultaneous observations)

	RELATIVE ACCURACY							***ABSOLUTE ACCURACY*** *68 percentile of observed errors*	
	mean position offset [m]				*sigma [m]*				
	latitude	*longitude*	*2D offset*	*altitude*	*latitude*	*longitude*	*altitude*	*position [m]*	*altitude[m]*
GALILEO HAS *(GPS+GALILEO)*	*0,022*	*–0,043*	***0,048***	*–0,026*	*0,040*	*0,293*	*0,090*	*0,080*	*0,098*
GPS+GALILEO 2f *(E1/E5a/E6-B + L1/L2C)*	*0,150*	*–0,219*	***0,265***	*–1,069*	*0,411*	*0,589*	*1,847*	*0,834*	*2,471*
GALILEO HAS *(GALILEO only)*	*–0,030*	*–0,051*	***0,059***	*0,034*	*0,032*	*0,040*	*0,148*	*0,086*	*0,097*
GALILEO 2f *(E1/E5a/E6-B)*	*0,014*	*–0,630*	***0,630***	*–1,896*	*0,695*	*0,542*	*2,164*	*1,165*	*3,758*
GALILEO HAS *(GPS only, GalE6 on)*	*0,001*	*–0,035*	***0,035***	*–0,035*	*0,069*	*0,073*	*0,139*	*0,107*	*0,126*
GPS 2f *(L1/L2C)*	*0,832*	*0,882*	***1,212***	*0,794*	*0,927*	*0,733*	*2,188*	*1,789*	*2,328*
GALILEO HAS *(GPS+GALILEO)*	*–0,029*	*–0,057*	***0,064***	*0,060*	*0,036*	*0,070*	*0,092*	*0,091*	*0,086*
EGNOS *(PRN 136)*	*0,001*	*0,006*	***0,006***	*0,406*	*0,279*	*0,195*	*0,626*	*0,342*	*0,745*

Source: own study.

DOI: 10.55676/asi.v3i1.46

So, as such, in the first approach, it was compared to GNSS positioning methods with similar status, ie. which are based on signals available to users solely from the navigational satellites creating the constellation of the particular system. In this way the following comparisons pairs were created and studied:

– HAS Galileo (based on GPS+Galileo constellation) versus GPS+Galileo dual frequency positioning;
– HAS Galileo (Galileo only constellation) versus Galileo dual frequency positioning;
– HAS Galileo (GPS only constellation) versus GPS dual frequency positioning.

For every comparison, the data was collected simultaneously in two different receivers as it is summarized in Table 4 (see the paragraph 3). Furthermore, having in mind almost worldwide coverage and the wide accessibility of Satellite-Based Augmentation Services (SBAS), the additional session was conducted to compare Galileo HAS (GPS+Galileo constellation) with EGNOS based positioning. The obtained results are presented in the Table 6, Figure 2 and Figure 3.

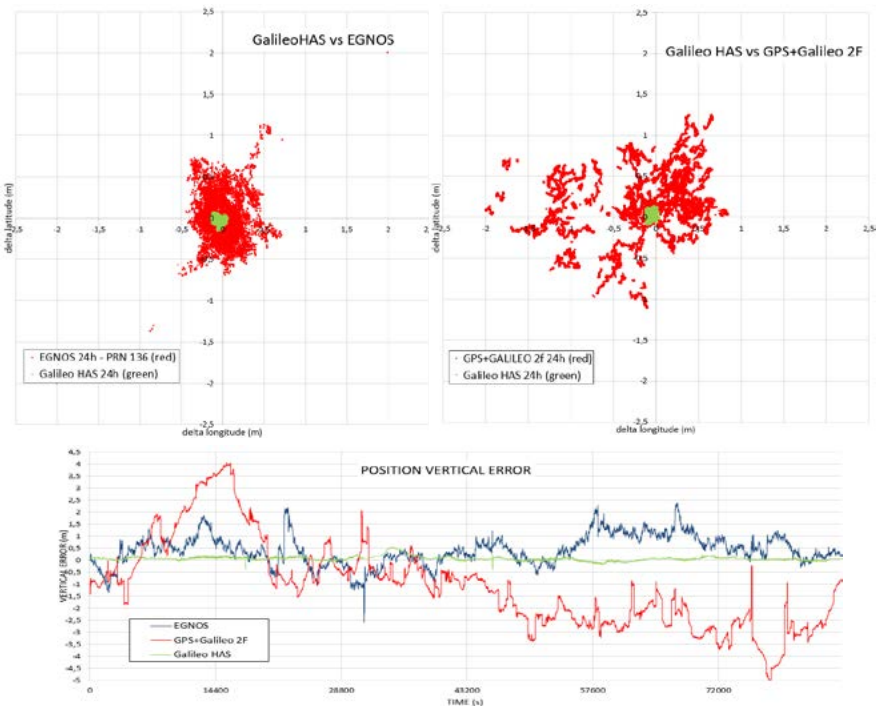

Figure 2. The accuracy parameters of Galileo HAS versus other positioning GNSS methods (24 hours of simultaneous observations)

Source: own study.

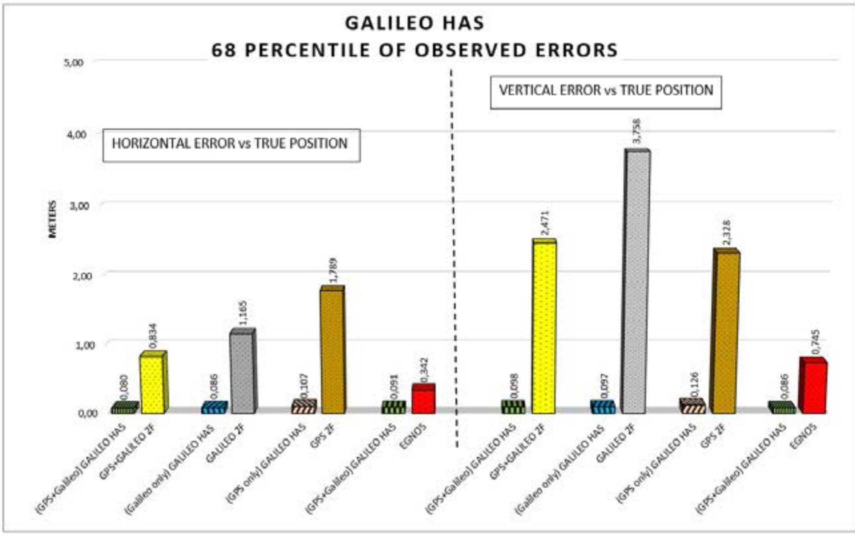

Figure 3. The accuracy parameters of Galileo HAS versus other positioning GNSS methods – 68 percentile of observed errors
Source: own study.

The performance of various GNSS positioning methods selected for the comparison is described with the same accuracy parameters as in the previous paragraph. Analysis of the observed relative and absolute accuracy shows clearly that the Galileo HAS is able to deliver the positioning accuracy which is an order of magnitude better than what can be achieved with the adequate dual frequency absolute GNSS positioning methods. It refers both to the horizontal positioning errors and the errors observed in vertical axis. Furthermore, the Galileo HAS, even being non differential system, by creating the ability to execute the standalone carrier--phase measurements, is significantly more accurate than the code-based, differentially augmented, positioning system represented during tests by EGNOS. While EGNOS maintains the submeter accuracies of the horizontal and vertical positioning (68 percentile/24 hours), the Galileo HAS is able to reach in the same conditions the subdecimeter precision (68 percentile/24 hours) for both the horizontal and vertical position estimations.

6. CHECKING GALILEO HAS CONVERGENCE TIME

The third aspect of testing the Galileo HAS performance refers to the checks of time required by the service to reach the converge to required accuracy level. As it was described in paragraph 3, The Galileo HAS convergence time was estimated with receiver set up in various modes of operations and during periods when the normal and reduced satellite constellation was observed. The results are presented in Table 7, Figure 4 and Figure 5.

 DOI: 10.55676/asi.v3i1.46

Table 7. The Galileo HAS positioning convergence times observed for various modes of operation and varied constellations

	CONVERGENCE TIME *to true position*		***CONVERGENCE TIME*** *to estimated 1-sigma**		*Integer fix* ***convergence time***	*REMARKS*
	2D distance < 20 cm	*delta height < 40 cm*	*2D sigma < 20 cm*	*1-sigma height < 40 cm*		
GALILEO HAS *(GPS+Galileo) good constellation*	*12 m 38 s (758 s)*	*01 m 37 s (97 s)*	***25 m 59 s (1559 s)***	*09 m 29 s (569 s)*	*24 m 04 s (1444 s)*	*7 x GAL; 9 x GPS; HDOP 0.7; PDOP 1.2*
GALILEO HAS *(GPS+Galileo) bad constellation*	***35 m 28 s (2128 s)***	*03 m 08 s (188 s)*	*16 m 58 s (1018 s)*	*11 m 48 s (708 s)*	*25 m 09 s (1509 s)*	*5 x GAL; 8 x GPS; HDOP 0.8; PDOP 1.4*
GALILEO HAS *(GPS+Galileo) elev. mask 30deg*	*22 m 43 s (1363 s)*	*23 m 54 s (1434 s)*	***28 m 03 s (1683 s)***	*21 m 44 s (1304 s)*	*no integer fix (35 min obs.)*	*5 x GAL; 5 x GPS; HDOP 1.2; PDOP 2.8*
GALILEO HAS *(GALILEO only)*	*22m 36 s (1356 s)*	*03 m 10 s (190 s)*	***32 m 38 s (1958 s)***	*31 m 05 s (1865 s)*	*no integer fix (35 min obs.)*	*6 x GAL; HDOP 1.2; PDOP 2.3*
GALILEO HAS *kinematic*			***16 m 20 s (980 s)***	*08 m 10 s (490 s)*	*27 m 4 0s (1660 s)*	*7 x GAL; 9 x GPS; HDOP 0.6; PDOP 1.3*

*as reported in NMEA GST message recorded in the Galileo HAS receiver

Source: own study.

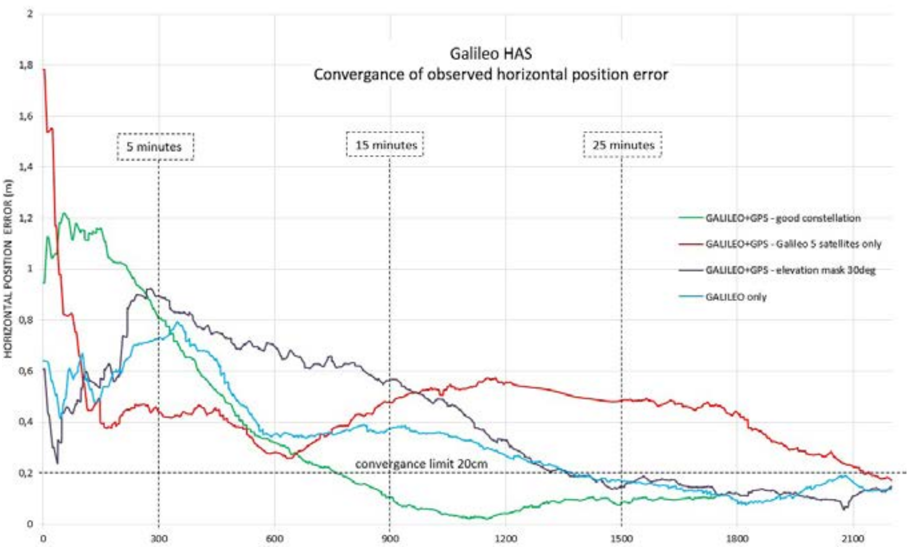

Figure 4.Galileo HAS – convergence of observed horizontal position error

Source: own study.

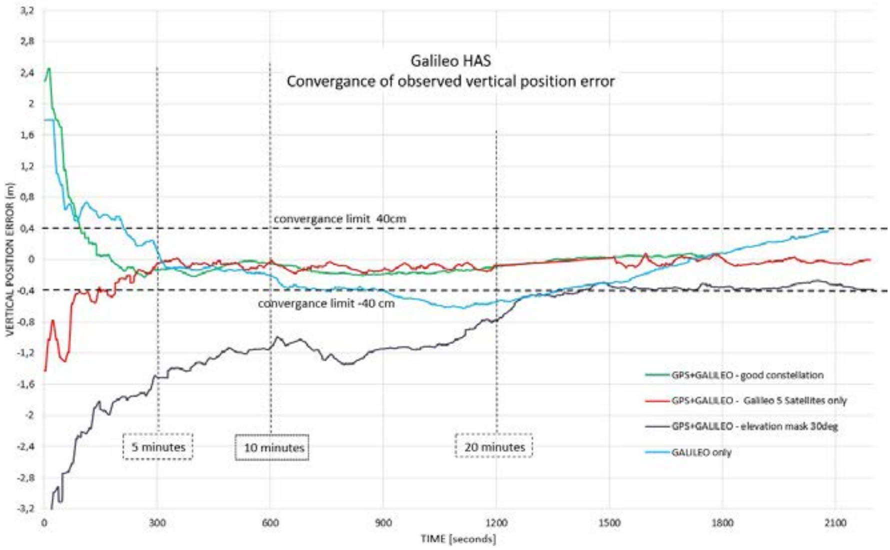

Figure 5. Galileo HAS – convergence of observed vertical position error
Source: own study.

The analysis of obtained data shows that the Galileo HAS needs the noticable period of time to converge to its nominal accuracy after initialization. The convergence time vary for various modes of operations and the constellation configurations. While observing the service error referred to true position the shortest convergence times are observed while Galileo HAS works with good joint GPS+Galileo constellation (7 x Galileo plus 9 x GPS satellites). In this conditions the observed convergence time to fulfil both the expected horizontal and vertical accuracy reaches almost 13 minutes.

During tests, while the constellation is not so favorable or the sky sectors are limited, the observed, full (vertical and horizontal) convergence times may reach almost 36 minutes which is significantly longer than desired 300 seconds (5 minutes). It is noticeable that usually the vertical accuracy of 40 cm is reached quicker than 20 cm of horizontal error limit. It is worth to mention that after initial convergence Galileo HAS maintains its desired horizontal and vertical accuracies without further position deteriorations. It seems that, at the actual stage of the Galileo HAS development, the long convergence time should be the first issue to be addressed in the context of the service applicability to the wide range of applications.

7. CONCLUSIONS

The Galileo High Accuracy Service (HAS) may give users, the unique in its kind, GNSS positioning tool potentially delivering free of charge, global, standalone, phase-based, precise point positioning with subfoot accuracy. The article presents the results

 DOI: 10.55676/asi.v3i1.46

of tests on the Galileo HAS performance in its initial operational phase. The experiment was conducted in July/August 2023 in Gdynia, Poland. As the first approach to the verification the declared Galileo HAS performance, the positioning sessions were set up in static conditions with antennas located at known, geodetically surveyed points. The Galileo HAS in field positioning were conducted with the first, generally available to users, the Galileo HAS capable receiver - "EOS Arrow Gold+" which is providing so called "out of box" positioning for various user needs. The main tests objectives were focused on:

- the verification of the relative and absolute accuracy of Galileo HAS positioning;
- the comparison of Galileo HAS performance with positioning results observed simultaneously with other GNSS methods such as: EGNOS, dual frequency GPS+Galileo or dual frequency GPS and dual frequency Galileo;
- testing of the Galileo HAS convergence time to reach the expected performance level.
- The detailed results of various measurement sessions were presented in the previous paragraphs and can be summarized as follows:
- in the nominal operational modes (GPS+Galileo and Galileo only), 68 percentile of horizontal position errors during 24 hours observations stays below 10 cm while the expected accuracy is to be 15 cm for the GPS+Galileo constellation and 25 cm for the Galileo only mode;
- in the nominal operational modes (GPS+Galileo and Galileo only), 68 percentile of vertical errors during 24 hours observations is 1-2 cm worse than for 2D positions but still stays below 10 cm while the expected accuracy is to be 20 cm for the GPS+Galileo constellation and 30 cm for the Galileo only mode;
- the short periods observations during various periods of the day are in general consistent with results obtained for 24 hour observations with differences +/– 2 cm for 2D positions and +/– 5 cm for vertical errors;
- across all measurements sessions the minimal values of 95 percentile reaching 9.7 cm both for horizontal positions and vertical axis;
- while considering the nominal operational modes of Galileo HAS ie. using GPS+Galileo or Galileo only constellation, 95 percentile value always stays below 12.8 cm for the 2D positioning and below 20.3 cm for the altitude estimations;
- mean position offsets from the true position stay within 5–6 cm for horizontal positioning and 3–4 cm for vertical axis;
- during all measurements sessions the positions estimations were executed based on carrier-phase measurements with fixed integer ambiguity solution present for: 97.6% of observations – the Galileo only mode, 99.9% of observations – the Galileo+GPS mode;
- Galileo HAS is able to deliver the positioning accuracy which is an order of magnitude better than what can be achieved with the adequate dual frequency absolute GNSS positioning methods;
- Galileo HAS (standalone, phase-based) is more accurate than the code-based, differentially augmented, positioning system represented by EGNOS.

- while EGNOS maintains the submeter accuracies of the horizontal and vertical positioning (68 percentile/24 hours), the Galileo HAS is able to reach in the same conditions the subdecimeter precision (68 percentile/24 hours) for both the horizontal and vertical position estimations;
- Galileo HAS needs the noticable period of time to converge to its nominal accuracy after initialization. This time vary for various modes of operations and constellation configurations;
- the observed Galileo HAS convergence times to reach its expected accuracies are from 13 minutes to 36 minutes, which is significantly longer than desired 300 seconds (5 minutes);
- after initial convergence Galileo HAS maintains its „subfoot" accuracy without position deterioration;
- at the actual stage of the Galileo HAS development the long convergence time should be the first issue to be addressed in the context of the service applicability to the wide range of applications.

The obtained results show that the Galileo HAS presents the potential to fulfil the existing niche where the accuracy of less than two decimetres ("subfoot accuracy") may be assumed to be sufficient for a wide range of applications. The Galileo HAS may find its applicability as positioning source for various solutions in any of the following domains:

- Aviation: positioning and navigation system for drones in the urban areas; geo-awarness systems;
- Airports: Integrated Surface Management Systems;
- Maritime: navigation and pilotage operations in ports; port bathymetry and coastal seabed survey; offshore support vessels with dynamic positioning (DP); port terminal cranes and carriers navigation; autonomous surface vessels;
- and many others in geomatics, agriculture, rail, road and space navigation.

However, to have a full picture of the Galileo HAS performance and its suitableness for the potential applications, the further service testing is desirable. It should consider the various user specific positioning requirements. Additionally, because the Galileo HAS is still under development and further service augmentations are planned, it is worth to monitor the service performance evolution in the context of its accuracy, availability, coverage, convergence time and other aspects, which may make it more or less suitable for particular user needs.

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