*Proceeding Paper*

# Galileo HAS accuracy and convergence performance results †

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† Presented at the European Navigation Conference 2024, Amsterdam, May 2024.

**Abstract** One year after Galileo High Accuracy Service (HAS) Initial Service declaration by the European Commission, this article present Galileo HAS accuracy and convergence comparative performance assessment between two different user algorithm configurations: static and dynamic. The assessment was conducted with two Galileo HAS User Terminal in parallel fed by the same antenna installation to obtain accuracy and convergence for the same period of time. The Galileo HAS User Terminal is a portable and autonomous device powered by a triple-frequency Galileo and GPS receiver and calculates a single (Galileo) or multi-constellation (Galileo + GPS) Galileo HAS using the Performance Characterization User Algorithm developed for the European Union Agency for the Space Programme (EUSPA). The performance assessment is completed with additional analysis in post-processing using a Precise Point Positioning (PPP) engine implementing the same algorithm than the User Terminal fed with International GNSS Service (IGS) stations observables and HAS Internet Data Distribution (IDD) corrections. The analysis is enhanced with an additional postprocessing analysis using the same IGS stations and CNES corrections. Results for static conditions, assuming zero velocity in the Kalman filter, deliver accuracy performance at decimeter level 68% both horizontal and vertical. Results with the dynamic configuration, with a Kalman filter adaptable to changes in user velocity and fit for dynamic applications, indicate slightly over one decimeter 68% both horizontal and vertical. This article also compares both static and dynamic results vs. the Galileo HAS Service Definition Document (SDD) Appendix E typical positioning accuracy performance and presents the convergence time, or time to first precise fix, against positioning horizontal and vertical thresholds.

**Keywords:** Galileo HAS; high accuracy; Precise Point Positioning; PPP; E6-B; RTCM; surveying;

**Citation:** Pintor, P.; González, E. Galileo HAS accuracy and convergence performance results.

Academic Editor: Terry Moore

## 1. Introduction

The Galileo High Accuracy Service (HAS), in its initial service, was declared in January 2023. Offered as one of the services by the European Global Navigation Satellite System, Galileo, the Galileo High Accuracy Service is an open access and free of charge service based on the provision of precise corrections transmitted in the Galileo E6-B signal from the Galileo space segment as well as via the Internet. The current HAS specification is described in references [1-3], which include the service definition document and signal and ground specifications.

In order to support the validation of the service and test its performance in different environments, European Union Agency for the Space Programme (EUSPA) launched a procurement for an algorithm and user terminal, which was awarded to an industrial team led by Spaceopal GmbH.

This article present Galileo HAS accuracy and convergence comparative performance assessment between two different user algorithm configurations: static and kinematics dynamics using the Galileo HAS User Terminal implementing Galileo HAS Performance Characterization User Algorithm. The performance assessment is completed with additional analysis in post-processing using a Precise Point Positioning (PPP) engine fed with International GNSS Service (IGS) stations observables and HAS

Internet Data Distribution (IDD) corrections. The analysis is enhanced with an additional postprocessing analysis using the same IGS station and CNES corrections.

## 2. Test equipment and tools

### *2.1. User Terminal*

The Galileo HAS User Terminal provides a precise positioning, velocity and time (PVT) solution based on the Galileo HAS User Algorithm for Service Level 1, guaranteeing access to the corrections from either the Signal-in-Space (SIS) or internet and offering a flexible approach to the configuration of the algorithm, communication means and logging capabilities.

The User Terminal (Figure 1) is a small (8cm, 18cm, 25cm), light (2.1kg), configurable, portable and autonomous device that includes a professional multi-constellation, multi-frequency receiver and calculates a single or multi-constellation (Galileo + GPS) Galileo HAS and Open Service (OS) PVT solution with an update rate ranging from 1Hz to 100Hz. The User Terminal can be configured to retrieve Galileo HAS corrections either from Galileo E6-B or RTCM 3 corrections over NTRIP and works in any of the User Algorithm dual and triple frequency modes.


**Figure 1.** Galileo HAS user terminal.

The Galileo HAS User Terminal has RF interference detection capabilities in the E1, E5 and E6 bands, its ingress protection is IP64 and its operating temperature range is -40$^0$–65 $^0$C. Its ruggedized aluminum housing was designed and tested against vibration, shock, temperature, humidity and corrosion to make the unit a resilient piece of equipment for future testing campaigns. It can be interfaced with a HMI application running on a PC for configuration and real-time monitoring purposes.

The Galileo HAS User Terminal has a wide logging capability: real time HAS/OS solution and monitoring streams, GNSS observations in RINEX and binary files (up to 100Hz) and HAS corrections in ASCII and binary format. It has 1TB internal memory and USB, WiFi and Bluetooth interfacing capabilities.

The Galileo HAS User Terminal can be powered through USB or Ethernet (PoE I/F). It has internal batteries allowing autonomy for more than 3 hours off the grid. Portability is also considered (transport box, external batteries).

Additional details on the development and verification of the User Terminal are provided in a previous paper [4]. Previous work on the HAS user performance can be found in [5].

### *4.2. PPP engine*

PPP Engine is a software solution that implements a PPP algorithm that seamlessly supports Galileo and GPS observations from various GNSS receivers and corrections from different providers, offering users with flexibility in data input.

Users can choose between real-time and post-processing modes based on their operational needs. In real-time mode, PPP Engine retrieves observables from a rover and corrections in RTCM format and delivers instantaneous position solutions, making it suitable for time-critical applications. Post-processing mode allows for offline analysis and refinement of positioning results, facilitating detailed data examination and quality assessment.

## 3. Method

### *3.1. Data campaign*

The data campaign took place in February 2024 utilizing two Galileo HAS User Terminal fed by a rooftop antenna in Spaceopal HQ (Munich, Germany). The receivers were configured to use Galileo HAS corrections over E6-B and Galileo E1-E5a + GPS L1-L2C as signal combination. The dual-receiver setup allowed for simultaneous accuracy and convergence performance data collection. The antenna used is a Novatel Vexxis 850.

To complement the analysis, the OBE4 (Oberpfaffenhofen, Germany) IGS station observables for February 2024 were retrieved from CDDIS [9]. OBE4 is equipped with Septentrio AsteRx4 and a PolaNt choke ring antenna. These observables were analyzed in post-processing with the PPP Engine and both Galileo HAS Internet Data Distribution (IDD) corrections and CNES corrections from PPP-Wizard project [10]. The PPP Engine was also configured to Galileo E1/E5a + GPS L1/L2C.

### *3.2. Performance parameters*

The PPP position calculated by the Galileo HAS User Terminal or the PPP Engine was compared to the reference position for each epoch. The differences in the horizontal and vertical position in the local tangent plane are the horizontal and vertical position error for each epoch, respectively. Table 1 identifies and defines the performance metrics [1] relevant to the campaign.

**Table 1.** Performance metrics.

| Performance metrics | Definition |
|---|---|
| Position error | defined as the instantaneous difference between the reference horizontal (respectively vertical) position and the horizontal (respectively vertical) position estimated by the user receiver at any time after convergence has been achieved. |
| Horizontal/vertical position accuracy | defined as statistical characterization of the position horizontal error (respectively vertical) over a reference period of time |

## 4. Campaign results

### *4.1. Positioning performance using the Galileo HAS User Terminal and Galileo Initial Service HAS corrections*

This section shows the Galileo HAS User Terminal performance in kinematic configuration using the Galileo HAS corrections over E6-B. The 68% and 95% positioning performance from 1 to 29 February 2024 in 24-hour periods from 0h to 24h UTC are presented in Table 2. The campaign was interrupted for a few hours to perform maintenance of the installation on 22 February 204. That day the Galileo HAS User Terminal was switched on again and the performance is impacted by this operation. The positioning performance was also impacted by two correction outages that happened during the campaign on 7 and 19 February 2024 both approximately lasting 50 seconds.

**Table 2.** Real time Galileo HAS User Terminal Horizontal and Vertical HAS positioning accuracy (68%/95%) in kinematic configuration over 24-hour periods using Galileo E1-E5a + GPS L1-L2C and Galileo Initial Service HAS corrections over E6-B. (*) Indicates Galileo HAS corrections outage. (**) Indicates maintenance on the equipment.

| Date | Vertical accuracy 68% / 95% (cm) | Horizontal accuracy 68% / 95% (cm) | Date | Vertical accuracy 68% / 95% (cm) | Horizontal accuracy 68% / 95% (cm) |
|---|---|---|---|---|---|
| 02.01 | 10 / 19 | 9 / 14 | 02.16 | 10 / 23 | 7 / 12 |
| 02.02 | 9 / 17 | 6 / 10 | 02.17 | 7 / 14 | 8 / 15 |
| 02.03 | 8 / 15 | 6 / 9 | 02.18 | 9 / 18 | 6 / 9 |
| 02.04 | 8 / 18 | 7 / 11 | 02.19* | 9 / 20 | 8 / 13 |
| 02.05 | 8 / 33 | 6 / 12 | 02.20 | 7 / 15 | 6 / 12 |
| 02.06 | 9 / 19 | 7 / 15 | 02.21 | 8 / 19 | 9 / 14 |
| 02.07* | 11 / 22 | 8 / 14 | 02.22** | 13 / 25 | 11 / 14 |
| 02.08 | 11 / 20 | 8 / 11 | 02.23 | 11 / 22 | 8 / 17 |
| 02.09 | 11 / 21 | 6 / 19 | 02.24 | 9 / 18 | 6 / 11 |
| 02.10 | 10 / 21 | 9 / 14 | 02.25 | 10 / 18 | 5 / 9 |
| 02.11 | 10 / 24 | 5 / 9 | 02.26 | 10 / 17 | 6 / 9 |
| 02.12 | 12 / 24 | 9 / 14 | 02.27 | 9 / 16 | 7 / 14 |
| 02.13 | 7 / 15 | 9 / 12 | 02.28 | 9 / 21 | 6 / 11 |
| 02.14 | 9 / 17 | 8 / 15 | 02.29 | 12 / 26 | 7 / 18 |
| 02.15 | 7 / 11 | 5 / 14 | | | |

The positioning accuracy results from Table 2 are representative of the performance in kinematic conditions which are the conditions assumed in the HAS SDD [1]. When comparing the positioning accuracy results, it can be observed all days are well within the HAS SDD of 15cm horizontal and 20cm vertical 68% typical positioning performance.

*4.2. Positioning performance using the PPP Engine and Galileo Initial Service HAS corrections*

This section shows the PPP Engine performance in static - assuming no velocity- and kinematic configuration using the OBE4 (Oberpfaffenhofen, Germany) IGS station and Galileo HAS corrections over the internet data channel. The 68% and 95% positioning performance from 1 to 29 February 2024 in 24-hour periods from 0h to 24h UTC are presented in Table 3 for kinematic and Table 4 for static dynamics algorithm configuration. The positioning performance was slightly impacted by the approach of running independently every 24h triggering a convergence process every day at start-up. It was also impacted by two correction outages that happened during the campaign on 7 and 19 February 2024 both approximately lasting 80 seconds.

**Table 3.** OBE4 (Oberpfaffenhofen, Germany) IGS station postprocessing Galileo HAS Horizontal and Vertical HAS positioning accuracy (68%/95%) in kinematic configuration over 24-hour periods using Galileo E1-E5a + GPS L1-L2C and Galileo HAS Initial Service corrections over the internet. (*) Indicates Galileo HAS corrections outage.

| Date | Vertical accuracy 68% / 95% (cm) | Horizontal accuracy 68% / 95% (cm) | Date | Vertical accuracy 68% / 95% (cm) | Horizontal accuracy 68% / 95% (cm) |
|---|---|---|---|---|---|
| 02.01 | 9 / 17 | 8 / 23 | 02.16 | 12 / 24 | 7 / 14 |
| 02.02 | 11 / 22 | 7 / 17 | 02.17 | 12 / 22 | 10 / 21 |
| 02.03 | 8 / 25 | 5 / 10 | 02.18 | 10 / 30 | 7 / 15 |
| 02.04 | 11 / 20 | 6 / 12 | 02.19* | 12 / 24 | 7 / 22 |
| 02.05 | 15 / 30 | 7 / 18 | 02.20 | 11 / 23 | 6 / 13 |
| 02.06 | 8 / 17 | 7 / 14 | 02.21 | 14 / 32 | 10 / 17 |
| 02.07* | 8 / 19 | 7 / 13 | 02.22 | 14 / 26 | 12 / 18 |
| 02.08 | 11 / 25 | 7 / 20 | 02.23 | 13 / 36 | 8 / 14 |

| | | | | | |
|---|---|---|---|---|---|
| 02.09 | 11 / 23 | 8 / 17 | 02.24 | 10 / 18 | 10 / 19 |
| 02.10 | 9 / 23 | 8 / 14 | 02.25 | 12 / 22 | 7 / 19 |
| 02.11 | 11 / 23 | 9 / 14 | 02.26 | 12 / 26 | 11 / 21 |
| 02.12 | 11 / 21 | 8 / 17 | 02.27 | 7 / 18 | 9 / 28 |
| 02.13 | 13 / 36 | 12 / 28 | 02.28 | 10 / 21 | 8 / 16 |
| 02.14 | 10 / 22 | 6 / 13 | 02.29 | 9 / 21 | 7 / 22 |
| 02.15 | 9 / 17 | 7 / 14 | | | |

The positioning accuracy results from kinematic configuration are representative of the performance in kinematic conditions which are the conditions presented in the HAS SDD [1]. When comparing the positioning accuracy results, it can be observed all days are well within the HAS SDD of 15cm horizontal and 20cm vertical 68% typical positioning performance.

**Table 4.** OBE4 (Oberpfaffenhofen, Germany) IGS station postprocessing Galileo HAS Horizontal and Vertical HAS positioning accuracy (68%/95%) in static configuration over 24-hour periods using Galileo E1-E5a + GPS L1-L2C and Galileo HAS Initial Service corrections over the internet. (*) Indicates Galileo HAS corrections outage.

| Date | Vertical accuracy 68% / 95% (cm) | Horizontal accuracy 68% / 95% (cm) | Date | Vertical accuracy 68% / 95% (cm) | Horizontal accuracy 68% / 95% (cm) |
|---|---|---|---|---|---|
| 02.01 | 4 / 10 | 3 / 9 | 02.16 | 1 / 5 | 5 / 15 |
| 02.02 | 3 / 5 | 3 / 9 | 02.17 | 4 / 5 | 5 / 7 |
| 02.03 | 1 / 8 | 2 / 3 | 02.18 | 6 / 8 | 2 / 12 |
| 02.04 | 1 / 7 | 4 / 9 | 02.19* | 3 / 7 | 3 / 20 |
| 02.05 | 3 / 8 | 4 / 17 | 02.20 | 3 / 5 | 5 / 6 |
| 02.06 | 2 / 3 | 1 / 14 | 02.21 | 4 / 5 | 2 / 9 |
| 02.07* | 2 / 11 | 4 / 7 | 02.22 | 2 / 6 | 5 / 8 |
| 02.08 | 3 / 6 | 1 / 5 | 02.23 | 4 / 7 | 3 / 8 |
| 02.09 | 4 / 5 | 1 / 7 | 02.24 | 3 / 3 | 4 / 14 |
| 02.10 | 2 / 7 | 4 / 7 | 02.25 | 5 / 11 | 6 / 11 |
| 02.11 | 2 / 7 | 5 / 10 | 02.26 | 1 / 10 | 2 / 14 |
| 02.12 | 2 / 6 | 3 / 14 | 02.27 | 2 / 6 | 3 / 15 |
| 02.13 | 2 / 4 | 3 / 6 | 02.28 | 8 / 9 | 3 / 9 |
| 02.14 | 1 / 4 | 2 / 9 | 02.29 | 4 / 6 | 2 / 17 |
| 02.15 | 6 / 7 | 2 / 6 | | | |

The results from static configuration are not representative of the performance conditions presented in the HAS SDD [1].

*4.3. Positioning performance using the PPP Engine and CNES corrections*

This section shows the PPP Engine performance in static - assuming no velocity- and kinematic configuration using the OBE4 (Oberpfaffenhofen, Germany) IGS station and CNES corrections [10]. The 68% and 95% positioning performance from 1 to 29 February 2024 in 24-hour periods from 0h to 24h UTC are presented in Table 5 for kinematic and Table 6 for static algorithm configuration. The analysis only uses a subset of CNES corrections (clock, orbit and code biases). The positioning performance was slightly impacted by the approach of running independently every 24h triggering a convergence process every day at start-up. It was also impacted by two correction outages that happened during the campaign on 7 and 19 February 2024.

**Table 5.** OBE4 (Oberpfaffenhofen, Germany) IGS station postprocessing Galileo CNES Horizontal and Vertical HAS positioning accuracy (68%/95%) in kinematic configuration over 24-hour periods using Galileo E1-E5a + GPS L1-L2C and CNES corrections. (*) Indicates corrections outage.

| Date | Vertical accuracy 68% / 95% (cm) | Horizontal accuracy 68% / 95% (cm) | Date | Vertical accuracy 68% / 95% (cm) | Horizontal accuracy 68% / 95% (cm) |
|---|---|---|---|---|---|
| 02.01 | 6 / 10 | 2 / 4 | 02.16 | 3 / 7 | 1 / 3 |
| 02.02 | 6 / 9 | 2 / 4 | 02.17 | 7 / 10 | 3 / 5 |
| 02.03 | 4 / 8 | 2 / 3 | 02.18 | 4 / 8 | 2 / 3 |
| 02.04 | 4 / 8 | 2 / 4 | 02.19 | 5 / 8 | 1 / 4 |
| 02.05 | 3 / 5 | 1 / 4 | 02.20 | 5 / 9 | 2 / 3 |
| 02.06 | 4 / 8 | 2 / 5 | 02.21 | 4 / 6 | 1 / 3 |
| 02.07* | - | - | 02.22 | 4 / 7 | 1 / 4 |
| 02.08 | 3 / 8 | 2 / 3 | 02.23 | 5 / 9 | 2 / 4 |
| 02.09 | 3 / 16 | 2 / 14 | 02.24 | 4 / 9 | 2 / 5 |
| 02.10 | 2 / 5 | 2 / 3 | 02.25 | 3 / 11 | 2 / 9 |
| 02.11 | 3 / 6 | 1 / 2 | 02.26 | 3 / 6 | 2 / 5 |
| 02.12 | 4 / 6 | 2 / 3 | 02.27 | 4 / 6 | 2 / 6 |
| 02.13 | 4 / 7 | 2 / 3 | 02.28 | 4 / 6 | 2 / 3 |
| 02.14 | 4 / 8 | 2 / 3 | 02.29 | 4 / 6 | 1 / 4 |
| 02.15 | 4 / 7 | 3 / 4 | | | |

**Table 6.** OBE4 (Oberpfaffenhofen, Germany) IGS station postprocessing Galileo CNES Horizontal and Vertical HAS positioning accuracy (68%/95%) in static configuration over 24-hour periods using Galileo E1-E5a + GPS L1-L2C and CNES corrections. (*) Indicates corrections outage.

| Date | Vertical accuracy 68% / 95% (cm) | Horizontal accuracy 68% / 95% (cm) | Date | Vertical accuracy 68% / 95% (cm) | Horizontal accuracy 68% / 95% (cm) |
|---|---|---|---|---|---|
| 02.01 | 4 / 4 | 1 / 2 | 02.16 | 2 / 3 | 1 / 1 |
| 02.02 | 3 / 5 | 1 / 1 | 02.17 | 5 / 5 | 1 / 3 |
| 02.03 | 3 / 3 | 1 / 1 | 02.18 | 4 / 4 | 1 / 2 |
| 02.04 | 3 / 3 | 1 / 1 | 02.19 | 5 / 7 | 1 / 4 |
| 02.05 | 2 / 5 | 1 / 1 | 02.20 | 5 / 6 | 1 / 2 |
| 02.06 | 2 / 2 | 1 / 1 | 02.21 | 3 / 4 | 1 / 2 |
| 02.07* | - | - | 02.22 | 3 / 3 | 1 / 2 |
| 02.08 | 4 / 8 | 1 / 2 | 02.23 | 4 / 5 | 1 / 4 |
| 02.09 | 3 / 3 | 1 / 1 | 02.24 | 4 / 4 | 1 / 4 |
| 02.10 | 2 / 2 | 1 / 2 | 02.25 | 4 / 4 | 1 / 4 |
| 02.11 | 2 / 3 | 1 / 2 | 02.26 | 2 / 2 | 1 / 1 |
| 02.12 | 3 / 3 | 1 / 1 | 02.27 | 3 / 3 | 1 / 4 |
| 02.13 | 3 /4 | 1 / 1 | 02.28 | 3 / 3 | 1 / 1 |
| 02.14 | 3 / 3 | 1 / 2 | 02.29 | 3 / 3 | 1 / 2 |
| 02.15 | 3 / 3 | 1 / 2 | | | |

### *4.4. Convergence assessment using Galileo HAS User Terminal using Galileo Initial Service HAS corrections*

A key matter for high accuracy applications is the convergence time. In this study, we have defined the convergence time as the time from warm start until the Galileo HAS

User Terminal provides the first solution with the required instantaneous positioning accuracy below the specified threshold.

The warm start assumes that the whole set of input broadcast data is already available at the receiver and in this way, the time to demodulate navigation data from SIS is excluded from the computation.

To consider the position converged, a horizontal and vertical threshold must be defined. In this study, we have chosen 30cm horizontal and 40cm vertical.

The set-up for the positioning accuracy was repeated but the second Galileo HAS User Terminal was operated to execute 1-hour warm restarts. The 1-hour restarts allow to evaluate 24 restarts every day. The overall statistics for convergence time are presented in Table 7.

**Table 7.** Real time Galileo HAS User Terminal convergence time 68th and 95th percentiles for February 2024 with 1-hour warm restarts using Galileo E1-E5a + GPS L1-L2C and Galileo HAS Initial Service corrections over E6-B for a kinematic filter configuration. The solution is considered convergence once the horizontal and vertical position error are simultaneously below their thresholds.

| | **Convergence time (seconds) 30cm H and 40cm V kinematic** |
|---|---|
| $68^{th}$ percentile | 322 |
| $95^{th}$ percentile | 1000 |

*4.5. Convergence assessment using PPP Engine and Galileo Initial Service HAS corrections*

The set-up for the positioning accuracy was repeated but the PPP engine was operated to execute 1-hour warm restarts. The analysis uses Galileo HAS corrections (clock, orbit and code biases). The overall statistics for convergence time are presented in Table 8.

**Table 8.** OBE4 (Oberpfaffenhofen, Germany) IGS station postprocessing convergence time 50th, 68th and 95th percentiles for February 2024 with 1-hour warm restarts using Galileo E1-E5a + GPS L1-L2C and Galileo HAS Initial Service corrections over E6-B for a static and kinematic filter configuration. The solution is considered convergence once the horizontal and vertical position error are simultaneously below their thresholds.

| | **Convergence time (seconds) 30cm H and 40cm V kinematic** | **Convergence time (seconds) 30cm H and 40cm V static** |
|---|---|---|
| $68^{th}$ percentile | 257 | 208 |
| $95^{th}$ percentile | 782 | 486 |

*4.6. Convergence assessment using PPP Engine and CNES corrections*

The set-up for the positioning accuracy was repeated but the PPP engine was operated to execute 1-hour warm restarts. The overall statistics for convergence time are presented in Table 9.

**Table 9.** OBE4 (Oberpfaffenhofen, Germany) IGS station postprocessing convergence time 50th, 68th and 95th percentiles for February 2024 with 1-hour warm restarts using Galileo E1-E5a + GPS L1-L2C and CNES corrections for a static and kinematic filter configuration. The solution is considered convergence once the horizontal and vertical position error are simultaneously below their thresholds.

| | **Convergence time (seconds) 30cm H and 40cm V** | **Convergence time (seconds) 30cm H and 40cm V** |
|---|---|---|

| | kinematic | static |
|---|---|---|
| 68th percentile | 160 | 119 |
| 95th percentile | 308 | 278 |

## 5. Conclusion

This article has presented results of the positioning and convergence performance for February 2024 delivered by the real-time Galileo HAS User Terminal and post-processing OBE4 IGS station observables using the Galileo Initial Service HAS and CNES corrections. The User Algorithm was configured to assume static and kinematic dynamics.

Results of the kinematic dynamics data campaign reached decimeter level for 68th percentile well within the performance in kinematic conditions which are the conditions assumed presented in the Galileo HAS SDD [1].

Galileo HAS positioning accuracy significantly improves with a static configuration as it is shown in Table 2 and Table 3. The improvement is due to a different process noise filter configuration. Such configuration might be and added value worth to be studied for static applications like surveying.

Positioning accuracy and convergence results are improved when using CNES corrections compared to Galileo Initial Service HAS corrections. Galileo Initial Service HAS reduced performance targets are expected according to Galileo HAS using a very limited network of worldwide stations -14 stations- [1] and, eventually will be improved in the future, the provision of a free of charge high accuracy service over an open SiS is in itself an enabler of multiple applications.

**Author Contributions:** Writing: E.G. (sec 1-5) and P.P. (sec 1-5); All authors have read and agreed to the published version of the manuscript.

**Funding:** The HAUT project was funded by EUSPA through the Fundamental Elements programme, contract GSA-OP-25-19.

**Data Availability Statement:** Galileo HAS corrections are publicly available.

**Acknowledgments:** It is deeply acknowledged the contribution of the industrial team to the development and validation of the HAS algorithm and user terminal, as well as the technical supervision of the work by the concerned EUSPA officers and partners.

**Conflicts of Interest:** The authors declare no conflict of interest.

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