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# Testing the Galileo High Accuracy Service User Terminal (HAUT) in Static Scenarios †

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**Abstract:** In just one year, Spaceopal and its partners developed the Galileo HAS Performance Characterization User Algorithm for the EU Agency for the Space Programme (EUSPA). The Galileo HAS User Terminal (HAUT) hosts the Galileo HAS Performance Characterization User Algorithm. The Galileo HAS User Terminal is a portable, configurable and autonomous device powered by a triple-frequency Galileo and GPS receiver and calculates a single- (Galileo) or multi-constellation (Galileo + GPS) Galileo HAS and Open Service (OS) positioning, velocity and time (PVT) solution. The User Terminal can be configured to retrieve Galileo HAS corrections either from Galileo Signal-in-Space (SIS) over E6-B or Internet Data Distribution (IDD) over NTRIP in an RTCM3 format and works in different frequency combinations that can be configured by the user. The User Terminal is a robust device (IP64) with multiple communication and logging capabilities. The Galileo HAS Initial Service was declared on 24 January by the European Commission, and provides free-of-charge, high-accuracy Precise Point Positioning (PPP) corrections (orbits, clocks) and code biases for Galileo and GPS to achieve real-time improved user positioning performance. The Galileo HAS Service Definition Document (SDD) and the HAS SIS Interface Control Document (HAS SIS ICD) are freely available to users on the web portal of the European GNSS Service Centre and HAS Internet Data Distribution Interface Control Documents (HAS IDD ICD) are available after registration. Using the Galileo HAS User Terminal, this article presents the results of Galileo HAS User Terminal's performance, configuring the User Algorithm to assume static dynamics. It is to be noted that this configuration provides a significant performance benefit with respect to a configuration compatible with kinematic operation. Preliminary results indicate the Galileo HAS User Terminal achieves excellent accuracy.

**Keywords:** Galileo HAS; high accuracy; PPP



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## 1. Introduction

The Galileo High Accuracy Service (HAS), in its initial stage, was declared in January 2023. In order to support the validation of the service and test its performance in different environments, EUSPA launched a procurement for an algorithm and user terminal, which was awarded to an industrial team led by Spaceopal GmbH (Munich, Germany).

This paper introduces the abovementioned algorithm and user terminal and provides performance results from the weeks following the launch of the service.

## 2. The Galileo High Accuracy Service

As one of the services offered 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 by the Galileo E6 signal from the Galileo space segment as well as via the Internet.

## 3. The HAUT Project

As indicated in the introduction, EUSPA procured the implementation of the Galileo HAS User Algorithm for the Initial Service within a User Terminal (UT) equipment that was later used in the service validation. This project (HAUT) was launched under the Fundamental Elements (FE) program.

The project was led by Spaceopal and conducted during one year (throughout the COVID-19 pandemic) together with its industrial partners: ANavS (responsible for algorithm definition and overall hardware design and assembly), DLR Institute of Communication and Navigation (in charge of the production of synthetic data and the provision of their GNSS testing infrastructure), IABG (responsible for housing and physical and environmental tests) and Iguassu Software Systems (in charge of the human–machine interface on the computer). Spaceopal conducted the project management and overall verification and validation tasks.

The requirements for this work targeted a wide range of applications, configurations, dynamics and environmental constraints. Five receivers were delivered to the customer for service validation and the algorithm was also provided as an offline tool, useful for experimentation and scenario replay. In the following sections, details about the UA and UT will be provided.

## 4. The Galileo HAS User Algorithm for HAS Initial Service

The Galileo HAS User Algorithm is a real-time precise positioning algorithm that processes the corrections provided by the Galileo HAS Initial Service (orbit and clock corrections and code biases) and calculates position and velocity referred to the GTRF (Galileo Terrestrial Reference Frame), time-stamped with respect to the GST (Galileo System Time) using Galileo L-Band observables and, in the case of a multi-constellation configuration, GPS L-Band observables as well. The User Algorithm was designed to work in all of the following dual- and triple-frequency modes:

- Dual-frequency modes:
    - Galileo only: E1-E5a/E1-E5b/E1-E5AltBOC/E1-E6B.
    - Galileo and GPS: E1-E5a/E1-E5b/E1-E5AltBOC/E1-E6B + L1-L2P/L1-L2C/L1-L5.
- Triple-frequency modes:
    - Galileo only: E1-E5a-E6B.
    - Galileo and GPS: E1-E5a-E6B + L1-L2C-L5.

The Galileo HAS User Algorithm used to characterize the typical positioning performance of the Galileo HAS described in the HAS SDD was configured for kinematic operation.

### *4.1. User Algorithm Description*

The selected position estimation technique for the User Algorithm was an extended Kalman filter (EKF) with state predictions and state updates to improve convergence and accuracy, as it achieves, in the opinion of the authors, an optimum trade-off between the measurement model and the state space model by minimizing the variance of the updated states. The User Algorithm processing follows an uncombined, satellite-to-satellite single-differenced (SD) processing.

Compared to an ionosphere-free approach, the proposed uncombined processing avoids the amplification of residual satellite orbit, clock, and phase bias errors, avoids noise amplification and brings no loss of information, which occurs when using measurement combinations. Conversely, ionosphere-free combinations do not require the integration of ionospheric corrections or models. Moreover, the significant bias amplification achieved by the wide-lane combination is considered more detrimental than the benefit of a larger wavelength.

When comparing the SD approach of the User Algorithm to an undifferenced setup, the elimination of receiver-specific errors and noise amplification by single differences are on a comparable performance level but only if the process noise of the clock and other receiver-specific unknowns can be modeled sufficiently well. Thus, the elimination of these unknowns by SD is the preferred option.

The algorithm has preprocessing steps, including outlier detection and elimination of single-satellite failure for each GNSS constellation with RAIM/DIA and detection and elimination of complete GNSS constellation outages. Preprocessing also addresses cycle slip detection and correction by using a time-differenced Melbourne–Wübbena combination and ionosphere-free phase combination. With this set of techniques, the proposed UA provides robustness to different fault behaviors on the site of satellites, the level of the correction service and the receiver and its environment.

### 4.2. Main Blocks of User Algorithm

The algorithm consists of two main blocks (Figure 1), including their input and output interfaces. The first main block is preprocessing of observation, navigation and correction data (PPO), which includes, e.g., the determination of the standard PVT solution and the forming of satellite–satellite single differences. The second main block includes the actual High Accuracy Service PVT solution (HAS) with an extended Kalman filter and partial integer ambiguity resolution.

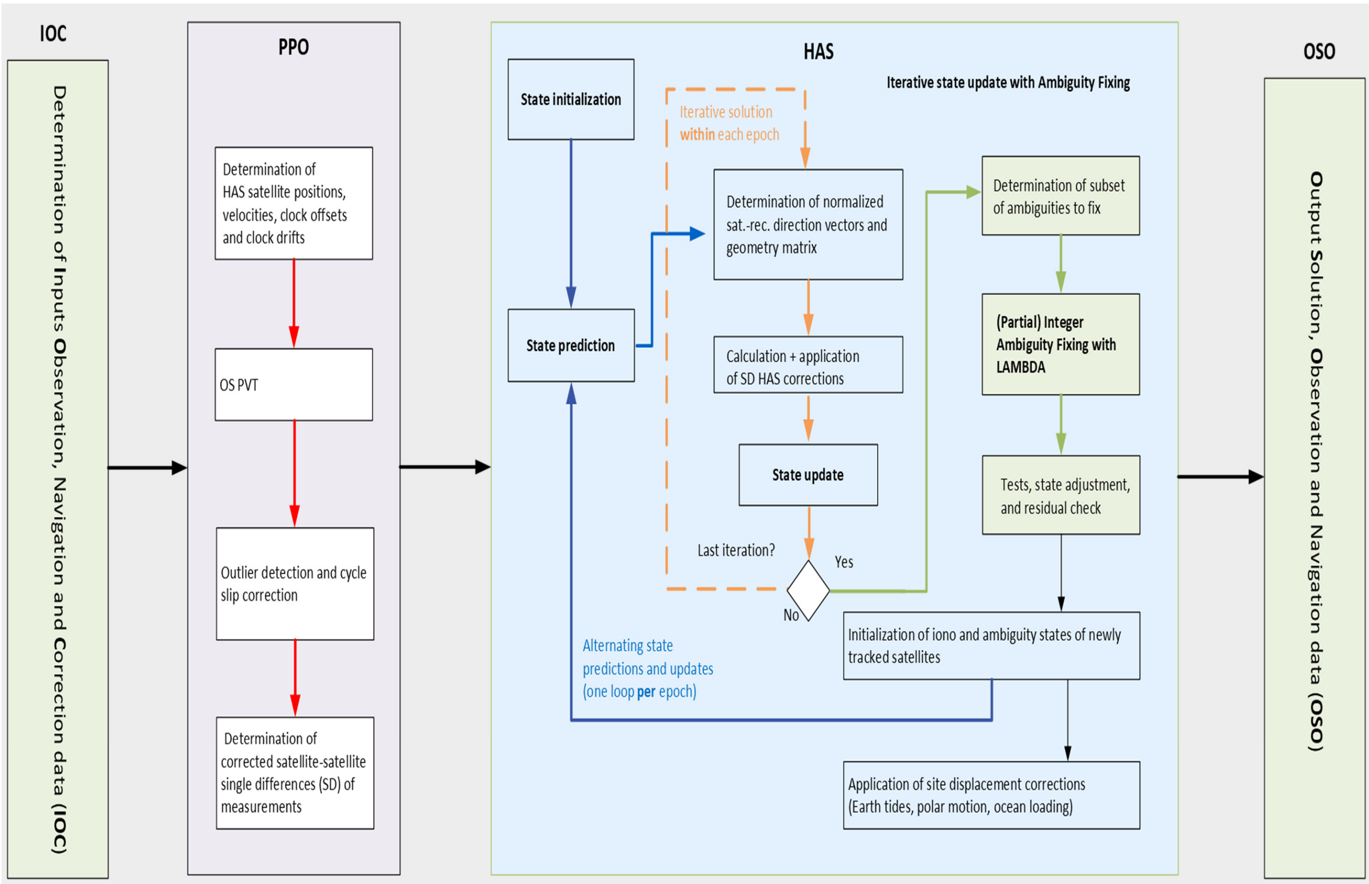


**Figure 1.** Main blocks of user algorithm.

Additional details on this algorithm are provided in a previous paper [1].

## 5. The Galileo HAS User Terminal

The Galileo HAS User Terminal provides a precise positioning, velocity and time (PVT) solution based on the Galileo HAS User Algorithm for SL1, guaranteeing access to corrections from either the SIS or the Internet and offering a flexible approach to the configuration of the algorithm, communication means and logging capabilities.

The User Terminal (Figure 2) is a small (8 cm, 18 cm, 25 cm), light (2.1 kg), 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 1 Hz to 100 Hz. 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 2.** HAUT user terminal.

The 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°–65 °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 an HMI application running on a PC for configuration and real-time monitoring purposes.

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

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

The current HAS specifications are described in references [2–4], which include the service definition document and signal and ground specifications. Additional details on the development and verification of the User Terminal are provided in a previous paper [1]. Previous work on HAS user performance from other developments and using different algorithms can be found in [5–7].

## 6. Positioning Performance by Galileo HAS User Terminal Using Galileo HAS Corrections

The positioning performance provided by the HAUT using Galileo HAS corrections and configuring the User Algorithm to assume no dynamics (as opposed to the configuration used for the Galileo HAS performance characterization presented in the HAS SDD, which considers kinematic conditions) was evaluated for a period of 31 days from 25 February to 27 March 2023. The Galileo HAS User Terminal, located in Munich (Germany), was switched on on 24 February to converge and left untouched until 8 March, when the campaign had to be interrupted for a few hours to perform maintenance of the antenna installation. The day on which the Galileo HAS User Terminal was switched on again is excluded from the analysis. The positioning accuracy provided by the HAUT for 30 days in 24 h periods from 0 h UTC is presented in Table 1.

**Table 1.** Real time Galileo HAS User Terminal horizontal and vertical HAS positioning accuracy (68%) over 24 h periods using Galileo E1-E5a, GPS L1-L2C and Galileo HAS Initial Service corrections over E6-B.

| Date | Vertical Accuracy 68% (cm) | Horizontal Accuracy 68% (cm) | Date | Vertical Accuracy 68% (cm) | Horizontal Accuracy 68% (cm) |
|---|---|---|---|---|---|
| 02.25 | 2 | 2 | 03.13 | 2 | 3 |
| 02.26 | 2 | 2 | 03.14 | 1 | 3 |
| 02.27 | 2 | 1 | 03.15 | 1 | 3 |
| 02.28 | 4 | 1 | 03.16 | 1 | 3 |
| 03.01 | 6 | 2 | 03.17 | 1 | 3 |
| 03.02 | 4 | 2 | 03.18 | 1 | 2 |
| 03.03 | 3 | 2 | 03.19 | 1 | 2 |
| 03.04 | 3 | 2 | 03.20 | 1 | 2 |
| 03.05 | 2 | 2 | 03.21 | 1 | 2 |
| 03.06 | 2 | 2 | 03.22 | 1 | 2 |
| 03.07 | 2 | 1 | 03.23 | 1 | 2 |
| 03.09 | 3 | 3 | 03.24 | 1 | 2 |
| 03.10 | 5 | 4 | 03.25 | 1 | 2 |
| 03.11 | 3 | 4 | 03.26 | 1 | 2 |
| 03.12 | 2 | 3 | 03.27 | 1 | 2 |

It is to be noted that the positioning accuracy results from Table 1 are only considered representative of static, open-sky conditions after full convergence time of the EKF. Therefore, they are not representative of the performance in kinematic conditions, which are the conditions assumed for the HAS performance characterization presented in the HAS SDD [2]. This explains the different level of performance between Table 1 results and the SDD performance levels.

## 7. Informative Convergence Assessment by Galileo HAS User Terminal Using Galileo HAS Corrections

A key matter for high-accuracy applications is 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.

A 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 converged position, a horizontal and vertical threshold must be defined. In this study, we have chosen two sets, the first being 15 cm and 20 cm, respectively. The second set is double these values, so 30 cm horizontal and 40 cm vertical.

The set-up for the first campaign was repeated, but the Galileo HAS User Terminal was configured to execute 1 h automatic warm restarts. One-hour restarts allowed us to evaluate 24 restarts every day. The User Terminal convergence time using HAS Initial Service corrections was evaluated for a period of 30 days from 29 March to 27 April 2023. The overall statistics for convergence time are presented in Table 2.

**Table 2.** Real-time Galileo HAS User Terminal convergence time 50th, 68th and 95th percentiles for 30 days with 1 h automatic warm restarts using Galileo E1-E5a, GPS L1-L2C and Galileo HAS Initial Service corrections over E6-B for two different thresholds.

| | Convergence Time 15 cm H and 20 cm V | Convergence Time 30 cm H and 40 cm V |
|---|---|---|
| 50th percentile | 345 s | 80 s |
| 68th percentile | 638 s | 170 s |
| 95th percentile | 1836 s | 586 s |

## 8. Conclusions

In a record one-year time, Spaceopal and its partners developed the Galileo High Accuracy Algorithm and the Galileo HAS User Terminal (HAUT), which hosts the algorithm for the EU Agency for the Space Programme (EUSPA).

The Galileo HAS User Terminal is a portable, configurable and autonomous device powered by a triple-frequency Galileo and GPS receiver and calculates a single- (Galileo) or multi-constellation (Galileo + GPS) Galileo HAS and Open Service (OS) positioning, velocity and time (PVT) solution. The User Terminal can be configured to retrieve Galileo HAS corrections either from Galileo E6-B or Internet link corrections over NTRIP in an RTCM3 format and works in all dual- and triple-frequency modes of the algorithm. The User Terminal is a robust device (IP64) with multiple communication and logging capabilities.

This article has presented the results of the positioning performance provided by the Galileo HAS User Terminal, using Galileo HAS corrections and configuring the User Algorithm to assume static dynamics (as opposed to the configuration used for the Galileo HAS performance characterization presented in the HAS SDD, which considers kinematic conditions) from February to April 2023. The results of the data campaign reach centimeter level at the 68th percentile.

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

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