engineering proceedings

Proceeding Paper

The Galileo High-Accuracy Service: Evaluating the Quality of the Corrections and Initial PPP Performance †

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† Presented at the European Navigation Conference 2023, Noordwijk, The Netherlands, 31 May–2 June 2023.

Abstract: The Galileo High-Accuracy Service (HAS) is providing free Precise Point Positioning (PPP) corrections for Galileo and GPS satellites through the E6b signal and the internet. Currently, HAS should provide a horizontal and vertical 95% accuracy below 20 centimetres and 40 centimetres, respectively. To assess the accuracy of the current HAS corrections, software has been developed to receive, decode and use HAS corrections. HAS corrections were acquired in the Munich area (Germany) during two sessions in November 2022 and April 2023. The decoder was validated by comparing recorded corrections to data from the Galileo High Accuracy Reference Algorithm and User Terminal (HAUT). Then, the availability and quality of HAS corrections were analysed. The use of orbit and clock corrections significantly improves the broadcast product accuracy; for instance, the Galileo orbit RMS error decreases up to 43% and the GPS RMS up to 80%. The code bias accuracy is at sub-nanosecond level. Finally, to validate the use of HAS corrections, PPP positioning has been achieved. For the used station network, we reached a 95% horizontal and vertical accuracy of 19 cm and 34 cm, respectively, for the kinematic and bi-constellation positioning matching with targeted HAS performances.

Keywords: Galileo; high-accuracy service; precise point positioning

Citation: Parra, C.; Schütz, A.; Hugentobler, U.; Pany, T.; Baumann, S. The Galileo High-Accuracy Service: Evaluating the Quality of the Corrections and Initial PPP Performance. *Eng. Proc.* **2023**, *54*, 14. https://doi.org/10.3390/ENC2023-15450

Academic Editors: Tom Willems and Okko Bleeker

Published: 29 October 2023

1. Introduction

Since the 1990s, Precise Point Positioning (PPP) has become an increasingly popular alternative to the Real-Time Kinematic (RTK). While the RTK, or Network RTK (NRTK), is based on differential positioning, which uses one reference station or a local network to eliminate the measurement errors, the PPP technique relies on precise estimations of satellite orbit and clock products [1]. Moreover, nowadays, with the State Space Representation (SSR) of corrections, the PPP achieves similar performances to RTK with centimetre-level accuracy in real time [2] or post-processing and for multiple static [3] or kinematic applications [4].

However, with the evolution of our needs, centimetre accuracy is not essential for every application, so Quasi–Zenith Satellite System (QZSS), BeiDou and Galileo constellations have created free-of-charge services to meet decimetric needs. The Japanese Centimetre Level Augmentation Services (CLAS) [5] service is the first operational service of its kind, and perhaps the most comprehensive service available today, because it is the only satellite centimetre-level augmentation service to provide atmospheric corrections. The CLAS service has the same area coverage as QZSS and should achieve positioning with a 95% accuracy, better than 12 cm in horizontal and 24 cm in vertical. PPP-B2b is a Chinese regional PPP service that provides PPP corrections [6]. These BeiDou and GPS corrections are transmitted, through the B2b signal of the BeiDou's GEO satellites, for a user located in China or surrounding regions. The expected performances for 95% accuracy are 20 cm in the horizontal direction and 40 cm in the vertical direction. The targeted performances of each service are summarize in Table 1.

Like their Asian counterparts, in January 2023, Galileo initiated a similar service: the Galileo High-Accuracy Service (HAS). Indeed, since the beginning of the year, the Galileo HAS has officially provided corrections for PPP free of charge [7]. These corrections are openly available through the internet and the E6b signal. Nonetheless, thanks to their Medium Earth Orbit (MEO) satellites, this is the first globally available service and it utilizes a scheme called High-Parity Vertical Reed–Solomon (HPVRS). This scheme improves the reception performance of common corrections broadcast by different satellites [8]. The HAS is divided into two service levels: the first one (SL1), currently available worldwide, is broadcasting orbit and clock corrections and code biases. The second service level (SL2), which will be available in 2024 for the European Coverage Area (ECA), will send atmospheric corrections. For the two service levels, the Galileo HAS expected horizontal and vertical 95% accuracies were originally below 20 cm and 40 cm, respectively. However, with atmospheric corrections, the convergence time should be shorter than 100 s; in other words, three times faster than with SL1.

Table 1. PPP services provided by the constellations.

Service Name	Constellations with Corrections	95% Horizontal Accuracy [cm]	95% Vertical Accuracy [cm]	Coverage
Centimetre Level Augmentation Services (CLAS)	QZSS, GPS, Galileo	12	24	Regional
PPP-B2P	Beidou, GPS	20	40	Regional
Galileo High-Accuracy Service (HAS)	GPS, Galileo	20	40	Global (SL1), Regional (SL2)

Hauschild et al. [9] focused on the use of Galileo HAS for the orbit determination of satellites in Low Earth Orbit (LEO) and highlighted satisfactory results with Galileo HAS. Their results showed a Signal-In-Space Ranging Error (SISRE) Root Mean Square (RMS) of 7.4 cm for Galileo and 12.2 cm for GPS. A PPP solution for an International GNSS Service (IGS) permanent station has been computed too. They achieved a 95th percentile error of 11.7 cm, 14.5 cm and 29.7 cm for the North, East and Up component, respectively.

Despite these promising performances, with the publication of the Service Definition Document (SDD) in January 2023 [10], the European Union Agency for the Space Program (EUSPA) has relaxed the HAS performances and reduced the service area. Presently, the target horizontal and vertical accuracies are 15 cm and 20 cm respectively, but they are defined for the 68th percentile, for a static user and outside of the Pacific area. Users in this excluded area could still use the HAS corrections, but they may have downgraded results.

After a short description of the HAS data, the present study aims to confirm the targeted performances of HAS with respect to the expected performances published by the EUSPA. For this purpose, the HAS corrections availability and accuracy were analysed, and the HAS satellite code biases assessed with respect to IGS products. Then, once the quality of the corrections was proven, PPP was performed and compared to the expected accuracy. The article finishes with a discussion and conclusions for future work using the preliminary results of this study.

2. HAS Signal-in-Space

HAS provides free PPP corrections for high-accuracy global positioning applications [11]. These corrections are composed of orbit and clock corrections, as well as code and phase biases for four frequencies of Galileo (E1, E5a, E5b, E6) and the three frequencies of GPS (L1, L2C and L5). All these corrections are available in real time and are broadcast through the

E6b signal and the internet. Currently, because the network includes 5 uplink stations with 4 antennas each, a maximum of 20 satellites could transmit the corrections simultaneously.

The reference time of HAS is the Galileo System Time (GST) and the reference frame is Galileo Terrestrial Reference Frame (GTRF) [12]. The HAS corrections refer to the satellite Antenna Phase Center (APC). The APC is defined as the centre of the phase of the satellite antenna for the dual-frequency ionosphere-free signals combination for GPS and Galileo.

The orbit and clock corrections have to be applied to the navigation messages. The orbit corrections are provided in the Satellite Coordinate System NTW composed of the radial (N), tangential (T) and normal (W) components; thus, rotation must be performed to obtain the corrections in the Earth-Centred Earth-Fixed (ECEF) reference frame of the broadcast ephemeris. The clock corrections and the biases are added directly to the satellite clock error and to the measurements, respectively.

3. Data

For the first part of our work, we validated our Galileo HAS decoder, which was integrated in the software receiver Multi-Sensor Navigation Analysis Tool (MuSNAT) [13]. We compare our received corrections to the data decoded using the Galileo High-Accuracy Reference Algorithm and User Terminal (HAUT) belonging to EUSPA and developed by the SpaceOpal company [14]. Both receivers were connected to the same antenna (Trimble Zephyr 2) and received the same data feed. The data were recorded for two Days of Year (DOY)—days 307 and 308—in 2022.

To obtain more recent and longer-term data from after the service was notified as operational, a one-week dataset was recorded in April 2023, from DOY 091 to 098. As stated by EUSPA, no phase biases were broadcast at this time. It is important to note that the study was performed at the beginning of the service and the results presented in this paper may have evolved in the coming months.

The statistical results are similar for the two sessions, and except for the validation with the HAUT receiver, only the results from the second period will be shown.

As mentioned before, we compare our decoded corrections to the data from the HAUT receiver. We also conduct comparisons between the navigation messages that have been corrected by Galileo HAS and the precise products from an analysis center. To limit the potential causes of problems, and evaluate only Galileo HAS corrections, the broadcast messages used are the combined products from IGS. The precise products used are the final ephemeris and clocks products from the Groupe de Recherche de Géodésie Spatiale (GRG) and the Differential Code Bias (DCB) from the Chinese Academy of Sciences (CAS). These products could be used as a reference because they are among the most precise products available nowadays.

4. Assessment of HAS Data

4.1. Comparison between HAUT and MuSNAT

To verify the message readout, the correction parameters provided by MuSNAT were compared with an external reference, which was provided by the HAUT receiver, in a dedicated measurement campaign in November 2022. For this purpose, a zero-baseline test was performed by connecting both receivers to the same GNSS antenna using a splitter. This ensured that the same input signal was used for both receivers.

This measurement campaign successfully proved the correct functioning of the entire chain of our decoder. Figure 1 shows the difference between the orbit correction data received by MuSNAT and the reference. The disparity is plotted, in meters, for each component during the first 7 h of the DOY 307. Each color represents a different Galileo satellite.

The differences in the millimetre range that could occur during the day are due to differences in the time stamping with the reception time. The reception time is determined by means of code measurements in a Single Point Positioning (SPP) algorithm, which works independently on both receivers. That is the reason why these disparities can be observed at the same epoch for all three components. The results are similar for GPS and for the second day.

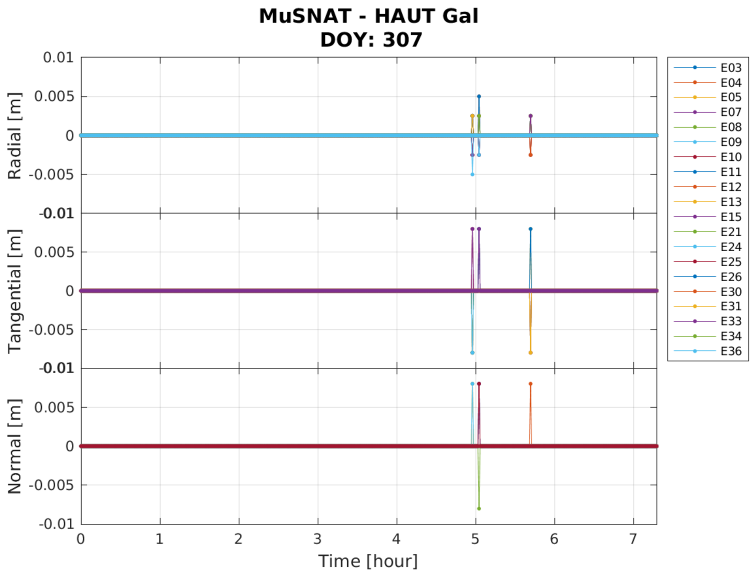

Figure 1. HAS orbit correction differences between Multi-Sensor Navigation Analysis Tool (MuSNAT) and High-Accuracy Reference Algorithm and User Terminal (HAUT) for DOY 307 of year 2022.

4.2. Availability Analysis

In this section, the availability of Galileo HAS corrections is analysed from DOY 091 to 098. During this period, the HAS messages contained orbit and clock corrections and code biases. As the code biases were always available during our assessment, the analysis only concerns orbits and clocks.

The availability of HAS corrections was checked every 30 s over the considered week. A filter was applied to flag every correction exceeding the interval of valid values defined in the ICD [12] and summarized in the Table 2. Indeed, if the corrections were not included in their interval, they were considered bad and not used. The code biases had a validity interval of 300 s, but they were relatively constant over the day.

Table 2. Range and validity interval of the HAS orbit and clock corrections and code biases.

Correction	Values Interval [m]	Validity Interval [s]
Orbit-radial	±10.2375	300
Orbit-along-track	±16.376	300
Orbit-cross-track	±16.376	300
Delta clock	±10.2375	60
Code bias	±20.46	300

Figure 2 shows the mean availability per satellite of usable HAS orbit corrections over the studied time interval. The HAS clock corrections availability is similar to the orbit corrections. Satellites E14, E18, E20 and E22 were not analysed because they were flagged as "not usable" by the Galileo operator. Satellites E24 and G02 were not usable, according to their constellation information, for DOY 091 and from DOY 096 to 098, respectively.

For the evaluated week, almost all the evaluated satellites had an availability above 90% (Figure 2), with an average value of 97% for Galileo and 95% for GPS. The lower availability of GPS was partly due to some unusable corrections. Indeed, only the GPS orbit corrections had some out-of-range values, which were the corrections exceeding the validity interval (Table 2), most of the time less than 1% for the time interval. However, spikes could be noticed for some satellites and for some days of up to 13%. Only the satellite

G02 had a mean availability below 90%, mainly because more than 5% of its corrections were set as unusable during its four days of availability. This could be because this satellite was set as unusable during 3 days and the corrections needed a period to converge.

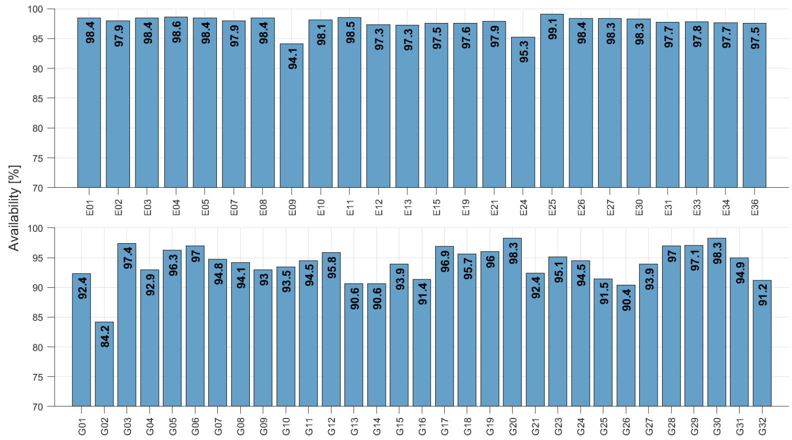

Figure 2. Mean availability of orbit corrections for Galileo (**top**) and GPS (**bottom**) from DOY 091 to 098.

To conclude the availability analysis for the evaluated week, the mean availability was 97% for Galileo and 95% for GPS. The expected availability of the Galileo HAS service was 99%, so this figure has yet to be achieved for both constellations, but these results are promising for further work. For the purpose of comparison, according to [15], the availability of GPS corrections with the RTS products of the IGS was similar to that obtained using Galileo HAS.

4.3. Products Comparison

To evaluate the HAS correction accuracy, corrected navigation messages were assessed over seven days with respect to precise products from the GRG for ephemeris and clocks, and from the CAS for code biases.

The orbit comparison was based on the difference between the broadcast and the GRG ephemeris coordinates, both in Earth-Centred Earth-Fixed frame (ECEF). As the GRG products refer to the centre of mass, while the HAS ephemeris refer to the ionosphere-free antenna phase centre, the satellite antenna corrections from IGS had to be applied using the latest ANTEX file [16]. Then, the conversion from ECEF to NTW was performed. In the clock comparison procedure, a mean value per constellation was estimated based on the difference between the broadcast clocks correcting with HAS and the GRG products, and subsequently eliminated. This value was due to the different reference clock used for the clock computation and could be removed because the receiver clock would absorb this offset during the user positioning and would thus not impact it. An alignment had to be performed, too, because the GRG clocks refer to the ionosphere-free combination of C1C/C5Q for Galileo and C1W/C2W for GPS [17], while HAS corrections refer to the ionosphere-free combination of the used navigation message, i.e., INAV (C1C/C7Q) for Galileo and LNAV (C1C/C2P) for GPS. All the signals were identified according to the RINEX convention [18]. This alignment was performed using the code biases from CAS.

Furthermore, to complete this comparison of the products, the Signal-In-Space Ranging Error (SISRE) was evaluated. The SISRE reflects the combined error of broadcast ephemeris and clock offset and thus shows the performance of the space and ground segment. In [19], Montenbruck et al. highlighted that SISRE could be a key indicator for the GNSS performance monitoring due to its dependence on the space segment (clock stability and predictability) and on the ground segment (orbit and clock determination performance). Table 3 summarizes the accuracy of the broadcast products with or without HAS corrections for the whole week. To detail the error distribution, Figure 3 represents the RMS errors for the radial, along-track and cross-track components, the clock error and the SISRE, for each satellite of Galileo and GPS, for the analysed time interval. Satellite G02 has been removed of the statistical analysis because its corrections were not broadcast for several days and it has a relatively high percentage of unusable corrections during the other days.

Table 3. RMS errors for radial, along-track and cross-track orbit components, clock error and SISRE RMS for broadcast ephemerides of GPS and Galileo corrected with HAS. The values to the left refer to the non-corrected broadcast.

Constellation	Radial [cm]	Along-Track [cm]	Cross-Track [cm]	Clock [cm]	Signal-In-Space Ranging Error (SISRE) [cm]
GPS	51/18	75/15	65/17	35/17	60/23
GAL	17/14	23/13	20/14	14/8	19/16

Without the HAS corrections, the Galileo ephemeris and clocks seem better than the GPS products. This is mainly because of the update rate. Indeed, Galileo navigation messages are updated every 10 min, while the GPS navigation messages are refreshed every two hours. So, with the higher update rate of HAS, the improvement was more significant for GPS. Thus, the GPS orbit errors decreased by 65%, 80% and 74% for the radial, tangential and normal components, respectively. For Galileo, the improvement was less significant, but remained above 17% for each component. Regarding the clock errors, the accuracy was improved with the use of HAS (51% and 43% for GPS and Galileo accuracies). For the SISRE, the analysis is similar. For GPS, the major error seems to be the imprecision of the clock, whereas for Galileo, the SISRE is dominated by the orbit errors.

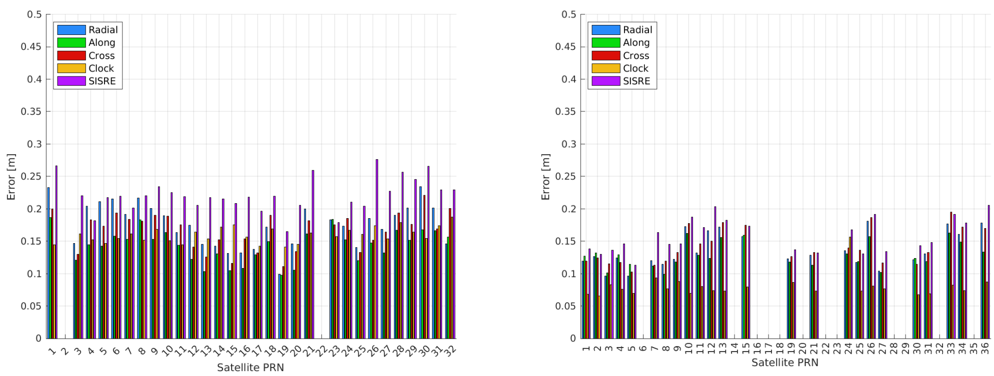

Figure 3. Orbit, clock and Signal-In-Space Ranging Error (SISRE) RMS errors for GPS (**left**) and Galileo (**right**) with respect to Groupe de Recherche de Géodésie Spatiale (GRG) final products, from DOY 091 to 098.

To conclude the HAS product evaluation, the biases were compared to the CAS DCB for the entire week. Contrary to the DCB, which is a difference between two code biases, the HAS code biases are given as observable-specific signal biases (OSB), thus non-differenced code bias. So, they have been differenced to obtain DCB. With the biases available, three Galileo combinations were possible: C1C-C5Q, C1C-C7Q, C1C-C6C; and one GPS combination: C1C-C2L. A constellation average value of –1.74 ns was removed from all the GPS bias differences. During the user positioning, this constellation-dependent mean is absorbed by the receiver clock estimation; thus, it has no impact on the positioning result. To conform to the CAS DCB convention, the results of this section are presented in nanoseconds and not in meters.

Figure 4 shows the median of absolute values and the standard deviation of the difference between HAS code biases and CAS DCB. For the week, the medians of the four couples are below 0.2 ns, with 0.12 ns for C1C-C5Q, 0.16 ns for C1C-C7Q, 0.11 ns for C1C-C6C and 0.14 ns for C1C-C2L. Furthermore, STDs are around 0.1 ns. This shows good consistency and stability of the DCB over the week. Similar results can be found in the literature [20,21].

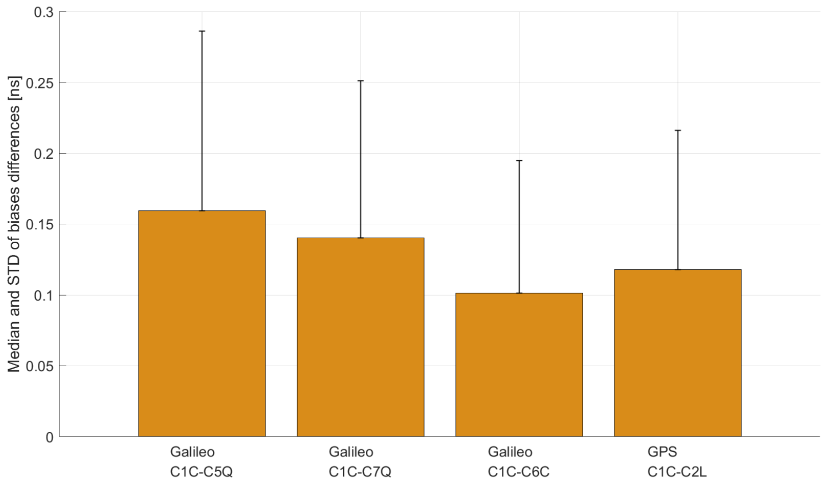

Figure 4. Median and STD of HAS code biases minus the Differential Code Bias (DCB) from the Chinese Academy of Sciences (CAS), from DOY 091 to 098 of year 2023 (except DOY 097).

5. PPP Application

5.1. PPP Configuration

To complete our analysis of HAS products, PPP is performed. The PPP engine is a custom-made software, which is currently under development as a part of the MuSNAT project [13]. The software is still quite new; nevertheless, it has already provided good results. The PPP is performed on a network of six European permanent stations (Figure 5) for the first 10 h of DOY 096 in the year 2023, with a sampling of 1 second. All the stations belong to the IGS network. The processing is performed in kinematic mode using an Extended Kalman Filter, with float ambiguities. The observations are processed in dual-frequency mode (L1C/L2W for GPS and E1C/E5Q for Galileo), with a between-satellite single-difference linear combination (BSSD) of un-combined measurements. BSSD combination should remove some receiver-related biases, like receiver clock error. Regarding the products comparison, the satellite and receiver antenna are corrected using the latest ANTEX file, and the combined broadcast file is used to compute the ephemeris. The accuracy is computed using the GNSS station position products file of the processed DOY. All three files are obtained from IGS. To remove the low elevation satellites, a cut-off of 10° is applied.

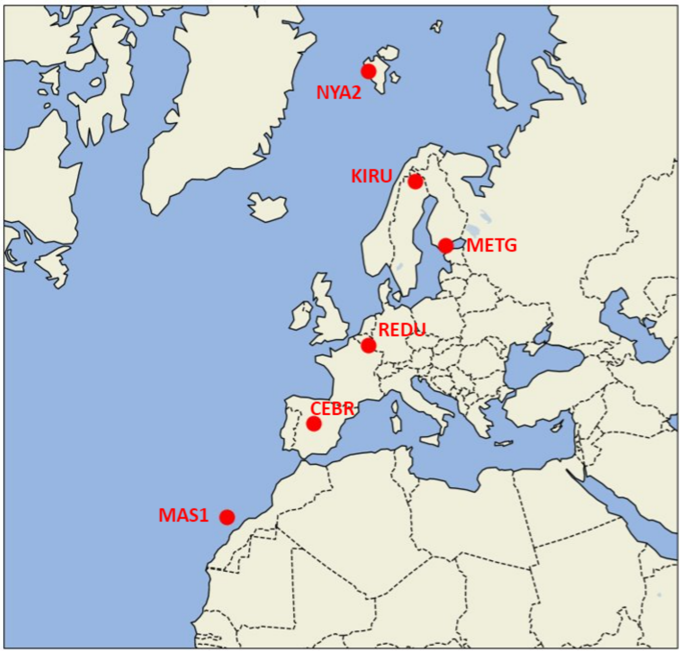

Figure 5. Permanent stations used for the PPP performance evaluation.

5.2. PPP Results

Figure 6 summarizes the accuracy obtained with the PPP processing. The accuracy is given as RMS of the 95% accuracies of the six stations during the 10 h of kinematic processing. It has been computed for joint Galileo GPS processing, but also separately.

All processes achieve a horizontal and vertical accuracy of a few decimetres. The GPS-Galileo and Galileo-only solutions have similar results, with horizontal and vertical accuracies of 18.9 cm and 34 cm for GPS-Galileo, and 15.8 cm and 37.9 cm for Galileo only. Both have accuracies better than the expected performance (20 cm and 40 cm according to [7]). The GPS-only solution has a slightly degraded result, with horizontal and vertical accuracies of 21.5 cm and 49.7 cm, respectively. This degradation is consistent with what we can expect. Indeed, the GPS-only position is degraded not only due to the lower number of satellites, resulting in reduced redundancy and poorer geometry, but also, as we observed during the HAS corrections evaluation, because the GPS SISRE is worse than that of Galileo.

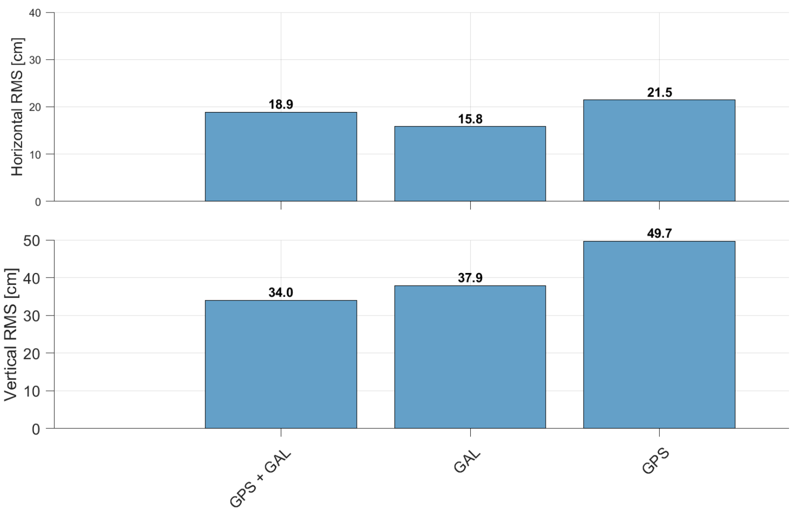

Figure 6. RMS of 95% accuracies for the Galileo + GPS, Galileo-only and GPS-only, in kinematic mode.

6. Discussion and Conclusions

With HAS, Galileo is providing a global PPP service for free and directly through the signal E6b. It is the first constellation to present such globally available service. The goal of this paper is to show an evaluation of the Galileo HAS corrections with a quality assessment of corrected products and with PPP positioning.

First, it is worth noticing that the HAS availability is quite good, with 97% and 95% availability for Galileo and GPS corrections over a one-week period. This is slightly below the expectations of 99% of availability, but this is promising for the future and similar to the availability of the RTS products of IGS. The GPS corrections are a little bit less available, mostly because some of them are flagged as "unusable". The accuracy of the corrected navigation messages with Galileo HAS obtained through comparison with IGS final products is high. The SISRE is 23 cm for GPS and 16 cm for Galileo, over the analysed week; this is dominated by the clock errors for GPS and by the ephemeris errors for Galileo. Furthermore, code biases have been evaluated with respect to the CAS DCB. They reveal a sub-nanosecond-level accuracy, with a median of 0.12 ns for C1C-C5Q, 0.16 ns for C1C-C7Q, 0.11 ns for C1C-C6C and 0.14 ns for C1C-C2L. These figures show good consistency over a week of the HAS code bias.

PPP positioning was achieved for a European network of six IGS stations. The results show consistency with the expected values (20 cm and 40 cm for the horizontal and vertical accuracy), because the Galileo and GPS solution achieves a horizontal and vertical accuracy of 18.9 cm and 34 cm, respectively.

In light of this paper, future work will involve the acquisition of new data as soon as phase biases are broadcasted, which should also allow ambiguity resolution. Moreover, a new Galileo Ground Sensor Station (GSS) is installed in Wallis, so an analysis of its contribution is planned. Finally, because Galileo HAS target markets are mainly moving users (as rail, road, maritime or space applications [11]), a test conducted in real kinematic conditions will be carried out on a train or a car.

Author Contributions: Methodology, C.P. and A.S.; software, C.P. and A.S.; visualization, C.P.; writing—original draft, C.P.; writing—review and editing, C.P., A.S., U.H., T.P. and S.B.; supervision, U.H., T.P. and S.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All data could be find in IGS archive center https://cddis.nasa.gov/archive, except the HAS data which are live stream recording.

Acknowledgments: The authors acknowledge the IGS for the provision of GNSS products used in this study. The authors would like to thank Munich Aerospace for the grant that made this study possible. The authors gratefully acknowledge SpaceOpal and EUSPA for the loan of the HAUT receiver.

Conflicts of Interest: The authors and IABG declare no conflict of interest.

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