Combining Galileo's HAS and the E5 AltBOC signal for terrestrial mobile mapping

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Abstract

We discuss the precision and multipath robustness properties of the Galileo E5 AltBOC signal, the Galileo High Accuracy Service (HAS) for Galileo and GPS, and the potential advantages of combining HAS with the E5 AltBOC ranging signals in view of the current HAS corrections being limited to the E1, E5a and E5b signals. For this purpose we analyse the behaviour of HAS for static positioning in ideal conditions and by just using pseudorange measurements. We do this for the conventional E1/E5a HAS combination and for the E1/E5 AltBOC one using a simple rough approximation of the future E5 AltBOC HAS corrections (HAS pseudo-corrections for E5 AltBOC). This provides initial insight and shows how the E5 AltBOC measurements benefit from the pseudo-corrections. We then proceed analogously with kinematic measurements in a urban environment. We conclude by recommending that HAS be extended to provide corrections for the E5 AltBOC signals.

1. Introduction

While the main reason for the Global Positioning System (GPS) to be created was military positioning, navigation and timing (PNT), its use by civilians was already envisioned by its parents. While this shall be acknowledged, it is also true that human ingenuity has turned GPS and its offspring —the family of global navigation satellite systems (GNSSs)— into a fundamental infrastructure of our society far beyond the expectations and imagination of the GPS parents. Over time, the more applications of GNSS were envisioned and tried, the more weaknesses of the technology were identified. Far from being a problem, or more to the point, in addition of being a problem, these weaknesses and challenges have sparked a positive feedback reinforcing loop of GNSS refinements, new methods and new applications. Examples thereof are differential GNSS, geodetic carrier phase processing, satellite- and ground-based augmentation systems, sophisticated signal modulations, navigation integrity and fusion with many other motion sensing devices. Among the challenges, the need of trusted navigation stands out. It started with the use of GNSS for aviation that resulted in complex augmentation systems and integrity algorithms. And it its continuing with even more challenging requirements put by applications like autonomous vehicles (AVs), urban air mobility (UAM), terrestrial robots or maps for AVs —the so-called high definition maps (HD maps). In the just given examples, requirements like accuracy, integrity, continuity and availability of positioning and navigation shall be met in —as opposed to aviation— difficult GNSS reception environments where the [in the GNSS argot] "local effects" introduce measurement errors whose detection and removal may not be easy.

Apart from unintentional GNSS signal interference or jamming (intentional interference) the dominant error sources in terrestrial GNSS PNT are signal multipath and non-line-of-sight (NLOS) reflexions. There are many ways to mitigate multipath (Groves et al., 2013). While there are methods, since long, that detect multipath using the code and carrier-phase measurements like the multipath combination (MPC) (Hilla and Cline, 2004), it is generally admitted that the best performant methods happen at the signal processing level and even before, at the very signal modulation level. This is the case of the Galileo E5 AltBOC signal which features exceptionally low signal-in-space (SIS) noise and, even possibly more interesting, low sensitivity against multipath. The practical benefits of the E5 AltBOC were identified and anticipated (Silva et al., 2012, Schüler and Abel Oladipo, 2013b, Schüler and Abel Oladipo, 2013a) soon after the signal modulation details where published in 2010. Today, the available live signals have confirmed the predictions for ionospheric delay estimation (Chen et al., 2024) while despite the quality of the E5 AltBOC signal (Silva et al., 2018) has yet to be fully exploited.

GNSS signal NLOS reflexions are a related but different problem of multipath despite sometimes multipath is used for both. To begin with, both multipath and NLOS reflexions can be dealt with at the GNSS receiver signal processing level —polarisation analysis, narrow correlator spacing, multipath estimating delay lock loops and other— or even before that at the original signal design phase —e.g., the Galileo and Beidou AltBOC signal modulations. If not being detected at the receiver's signal processing level, the multipath and NLOS reflexions are treated differently. In the case of NLOS reflexions, the goal is to detect the problem, identify the faulty measurement and remove it as if it were a measurement outlier. For this purpose, measurement redundancy and sensor diversity is paramount as an effective outlier detection and removal (ODR) is based on sufficient redundancy. As for multipath, adaptive weighting of the measurements can be used.

2. The Galileo E5 AltBOC signal

The Galileo E5 AltBOC signal is a highly advanced satellite navigation signal used in the European Galileo GNSS. It is a high bandwidth, complex signal whose precision and multipath mitigation makes it a key feature distinguishing Galileo from other GNSS systems. It uses Alternative Binary Offset Carrier (AltBOC) modulation, specifically AltBOC(15,10). This is a sophisticated form of BOC modulation that enables the simultaneous transmission of multiple signal components within a single wideband channel. The signal is centred at 1191.795

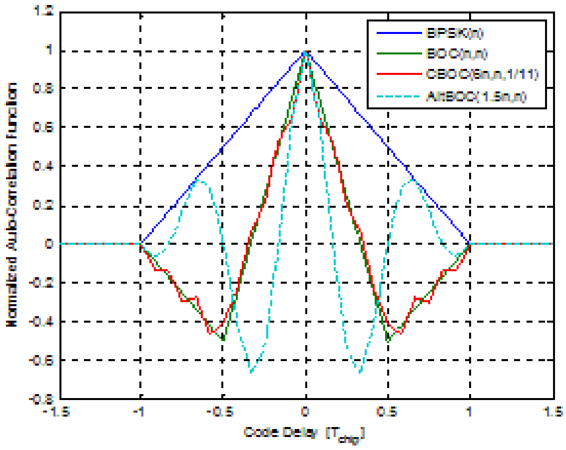

Figure 1. Autocorrelation function of the BPSK, QPSK and AltBOC signals (Silva et al., 2012).

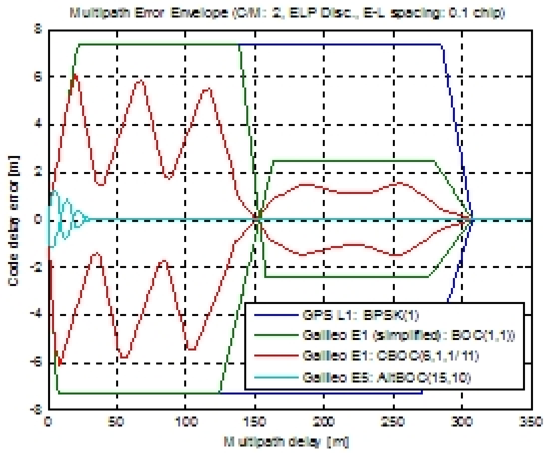

Figure 2. Multipath envelop of BPSK (GPS L1), Galileo E1 and Galileo AltBOC signals (Silva et al., 2012).

MHz and spans a wide bandwidth of about 51 MHz, making it the GNSS signal with the largest spectrum bandwidth currently in use. As mentioned, E5 AltBOC, features high precision and robustness against multipath. Indeed, the wide bandwidth and steep correlation peak of the AltBOC signal (figure 1) provide extremely precise code measurements, with ranging precision on the order of a few cm in open-sky scenarios. The signal structure and bandwidth make the E5 AltBOC signal highly robust (figure 2) against multipath effects, which are common sources of error in GNSS positioning and navigation, in artificial and natural canyons. A particular case however of the utmost relevance is positioning and navigatio in urban canyons. (The E5 AltBOC design was later adopted by the Chinese Beidou GNSS thus resulting in the B2 AltBOC(15,10), that is functionally and structurally similar to Galileo's E5 AltBOC.) The great interest of the Galileo E5 AltBOC signal for surveying and mapping was recognised (Colomina et al., 2012) early.

In fact, E5 AltBOC combines the four signal components (E5a-I, E5a-Q, E5b-I, E5b-Q) into a single, wideband signal covering both E5a (centred at 1176.45 MHz) and E5b (centred at 1207.14 MHz) frequencies, so E5 AltBOC "lays" exactly in between E5a and E5b.

3. Galileo's High Accuracy Service (HAS)

Galileo's High Accuracy Service (HAS) is a free, open-access positioning, navigation and timing (PNT) service whose main purpose is to deliver real-time, high-accuracy positioning corrections, enabling users to achieve significantly improved accuracy compared to standard services (GSA, 2020, Fernández-Hernández et al., 2022). HAS is a service for both Galileo and GPS users. It can be seen as an augmentation of the Galileo Open Service (OS) and of the GPS Standard Positioning Service (SPS). Its concept and method is that of real-time Precise Point Positioning (PPP), i.e., of a real-time global differential method.

HAS is being deployed according to two service levels. Service level 1 offers a global coverage, broadcasting orbit, clock and code corrections through both signal in space via Galileo E6-B signal (1278.75 MHz) and internet distribution (HAS IDD). It has an availability target of 99% and a convergence time of 300 s. This service is expected to include phase bias corrections that are still not provided. As of today, the corrections can be applied to Galileo ranging signals E1, E5a and E5b, and to GPS L1 and L2. With a suitable PPP algorithm (Zumberge et al., 1997), the current service level aims for horizontal positioning errors of less than 20 cm and vertical errors of less than 40 cm (95% confidence level) in nominal conditions.

(The minimum performance levels of the Galileo HAS are specified in (EUSPA, 2023b). Quarterly HAS performance reports have been published by the European GNSS Service Centre (EGSC) for 2023 and 2024, e.g. (EGSC, 2025). Independent reports on HAS performance abound, e.g. (Yi et al., 2023, Gao et al., 2025, Smyrnaios et al., 2025).)

Service level 2 will have a regional coverage and broadcast the level 1 service plus atmospheric corrections. It is expected to have the same distribution channels, accuracy and availability as the current service, but reduce the convergence time to 100 s.

3.1 Other high-accuracy services

Global real-time PPP services were available long before Galileo's HAS was. However, in contrast, they were and are commercial services and what makes Galileo's HAS unique is its free-of-charge nature. To our best knowledge, the first global commercial real-time PPP service was John Deere's StarFire, introduced in 1999. Its initial accuracy was at the 10 cm level. Later on it was upgraded to reach the 5 cm level by leveraging dual-frequency GPS and GLONASS PPP with ambiguity fixing. StarFire marked the transition of PPP from a scientific and post-processing method into a real-time, commercial, and global solution. Other commercial PPP services, such as Trimble's CenterPoint RTX and NovAtel's TerraStar, emerged later in the 2010s.

The International GNSS Service (IGS) must be creditetd for launching in 2013 the IGS Real-Time Service (IGS RTS) after several years of pilot operation. It provides real-time accurate GNSS orbit and clock corrections as well as code and phase biases for global high-accuracy applications.

Last, we mention the research and global rehearsal on a real-time PPP comparable to Galileo's HAS recently conducted by the US Jet Propulsion Laboratory (JPL) (Naciri et al., 2024).

3.2 Currrent Galileo's HAS and the E5 AltBOC measurements

Although future HAS evolutions may include phase biases and corrections for additional signals such as Galileo E5 AltBOC and GPS L5, as of today, in principle, one cannot simultaneously benefit from the features of the E5 AltBOC signal and of the HAS service. This is unfortunate and somewhat contradictory considering the HAS target markets (GSA, 2020). A potential beneficiary of such HAS and E5 AltBOC combination is terrestrial mobile mapping where dm- to cm-level accuracy is sought and where fast integer ambiguity solution and multipath resistance are required. Other growing applications that would benefit of HAS for E5 AltBOC are navigation of autonomous vehicles, drones for delivery and all sorts of terrestrial robots.

3.3 Combining E5a and E5b HAS data for E5 AltBOC

The Galileo HAS orbit corrections for signals E1, E5a and E5b are identical because they target the satellite position errors that are independent of the signal frequency. Thus, it make sense to also use them for the E5 AltBOC signals. A similar rationale can be applied to the satellite clock corrections as clock errors are also independent of the signal frequency. Both types of corrections are provided in the HAS message (EUSPA, 2022) on a per satellite basis.

Bias corrections are something else. In principle, since the AltBOC signal is essentially a coherent combination of E5a and E5b sub-signals, it is theoretically possible to combine the signal individual HAS biases for E5a and E5b to form a composite correction applicable to AltBOC measurements. In principle, this would require careful alignment and weighting of the corrections considering the signal structure and relative power of the E5a and E5b components within the AltBOC modulation. The combination is not straightforward because the AltBOC signal processing exploits the wide bandwidth and specific correlation properties of the combined signal, which differ from processing E5a and E5b separately. Simply averaging or linearly combining the HAS corrections for E5a and E5b may not fully capture the error characteristics or biases present in the AltBOC composite signal. In the sequel, we will refer to the empirically combined E5a and E5b HAS corrections as E5 AltBOC pseudo-HAS corrections or, simply, as pseudo-corrections.

4. Positioning and navigation method and the NEXA system

The point and trajectory determination results reported in this article have been obtained with GEONUMERICS' NEXA software system. NEXA stands for New Extensible State-Space Approach. It implements a generic/extensible sensor-agnostic approach based on plug-and-play sensor mathematical models (figure 3). At the core of the system there is the NEXA estimator, a sequential non-linear robust least-squares estimator together with a 4th order multi-step variable step size predictor-corrector numerical integration method (Rosales and Colomina, 2005). The mathematical models can be either stochastic equations (SE) —the classical observation equations— and stochastic differential equations (SDE) used respectively in the update and prediction steps of the sequential estimation process.

As the NEXA estimator can be seen as a sensor fusion engine, we divert here from the main thread of the paper to put NEXA in the context of the sensor fusion methods and strategies. In our context, sensor fusion is parameter estimation from measurements and models, where the measurements originate from more than one sensing device. Thus, sensor fusion involves sensing devices, mathematical models that relate measurements to parameters, estimation methods, numerical algorithms and software.

Sensor fusion, over time referred to with different names, is a classical research and application topic, already considered a classical problem in the early 1960s (Kálmán, 1960). In photogrammetry and remote sensing it acquired relevance when GPS started being used at the end of the 1980s for aerial surveys and became a standard procedure with the use of inertial measurement units for both mobile aerial and terrestrial surveys. It was referred then as integrated sensor orientation.

Sensor fusion methods can be classified from different perspectives: centralised or decentralised; loose or tight; sequential or simultaneous; real-time or post-mission; total-state- or error-state-based; and other.

In a centralised approach all sensor measurements are sent to a central processing unit. In a totally decentralised or distributed approach, whenever possible, each sensor estimates a solution and forwards the result to a central "fusion" engine that estimates a weighted average solution. Many times, a mixed centralised and decentralised approach is used. A particular case of mixed centralised and decentralised fusion is INS/GNSS integration where GNSS raw measurements can be pre-processed independently (loose coupling) and the GNSS "measurements" are time-position-velocity GNSS-derived measurements or processed in the update steps (various levels of coupling).

Sequential estimation approaches allow for both real-time (forward estimation) and post-mission "simultaneous" estimation (smoothing of forward and backward solution).

In our context of sequential parameter or state estimation, total- or full-state estimation refers to the direct estimation (prediction and update) of the states of interest, e.g., the position velocity and attitude unknowns. In contrast, error-state estimation refers to the estimation of the errors of an independently predicted —accumulated— total-state vector. In error-state estimation two state vectors must be carried, the accumulated state —does not directly participate in the update step— and the error state that contains the difference between the accumulated estimate and the full state. The common approach is that of the error state because of numerical stability properties. However, the total-state approach is conceptually simpler and more amenable to multi-sensor systems and measurement outlier detection in both SE and SDE models.

NEXA can support both centralised and decentralised, and real-time and post-mission approaches. It is based on a total-state approach. Its high-level architecture is depicted in figure 3. Each motion sensing devices (ms) provides measurements to its corresponding driver (sensor driver) where trivial to very complex preprocessing and formatting, can take place. Sensor drivers provide NEXA-formatted (Navarro et al., 2017) time-tagged measurements to the toNEXA module that transforms a number of parallel sensor measurement streams into a single stream of time-sorted measurements to the NEXA estimator. In the real-time mode, upon receiving the measurements, the estimator seeks and loads the attendant mathematical models and performs an iterative non-linear least-squares adjustment. The solution is provided to the NEXAto module that transfer it to

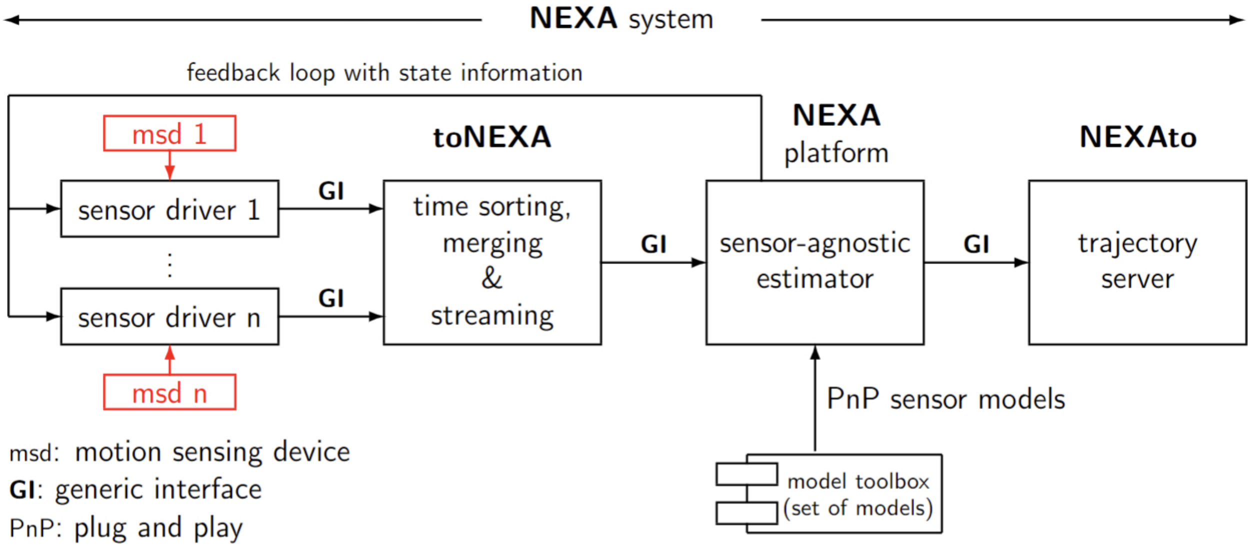

Figure 3. High-level NEXA architecture.

NEXA clients accounting for coordinate reference frame transformations, output frequency requirements and format transformations.

5. HAS and E5 AltBOC mathematical models

HAS corrections can be applied to any PPP algorithm, since the core computation framework remains unchanged. The integration of HAS involves adjusting the broadcast ephemeris and receiver observations accordingly, allowing for high accuracy in real time (EUSPA, 2022).

Related to measurements, phase biases are currently unavailable. For the pseudorange observations, the code bias d_j^S is the offset to apply to the specific signal targeted by the bias, this is, for frequency j of satellite S. The updated pseudorange to use in the positioning equations is

$$\tilde{P}_j^S = P_j^S + d_j^S, \tag{1}$$

where the broadcast group delays and timing group delays are already taken into account and therefore no further correction is to be applied to the measurement.

Since the clock correction, described below, is defined consistently with the code biases which also include group delay effects, if we plan to apply corrections to E5 AltBOC signal we should define a compatible code bias. Although a more thorough investigation is needed, we adopt a simple approximation that could reasonably approach the bias for AltBOC signal:

$$d_{\text{AltBOC}}^S = \frac{d_{E5a}^S + d_{E5b}^S}{2}. \tag{2}$$

For satellite parameters, HAS SiS offers first order corrections for orbits and clocks, while HAS IDD includes second order corrections for the orbit and up to third order corrections for the clock. Here we specify how to apply the full corrections and HAS SiS users would consider the higher order terms to be zero.

The clock correction δC^S is satellite S specific and it is added to the clock error dt^S computed from the navigation message

$$\tilde{dt}^S = dt^S + \delta C^S/c, \tag{3}$$

being c the light speed in vacuum. The correction is computed from the coefficients emitted in the HAS message,

$$\delta C^S = C_0 + C_1(t - t_0) + C_2(t - t_0)^2. \tag{4}$$

The factor $(t - t_0)$ is the elapsed time between the correction message and the current time.

The orbit corrections are provided in NTW satellite coordinate system and frame (n) and must be rotated to the broadcast ECEF (e) frame. The rotation matrix depends on the position x^S and velocity $\dot{x}^S$ of the satellite and is commonly reported in literature:

$$\mathbf{R}_n^e = [\mathbf{e}_n \quad \mathbf{e}_t \quad \mathbf{e}_w], \tag{5}$$

with

$$\mathbf{e}_t = \frac{\dot{x}^S}{|\dot{x}^S|} \tag{6}$$

$$\mathbf{e}_w = \frac{x^S \times \dot{x}^S}{|x^S \times \dot{x}^S|} \tag{7}$$

$$\mathbf{e}_n = \mathbf{e}_t \times \mathbf{e}_w. \tag{8}$$

The updated satellite position is computed as

$$\tilde{x}^S = x^S - \delta x^S. \tag{9}$$

(We note that the sign of the correction differs between the HAS ICD (EUSPA, 2022) and the HAS IDD (EUSPA, 2023a). The latter transmit corrections in SSR format, which uses an opposite sign convention for clock corrections to the specified in the HAS message.)

The correction is computed rotating the broadcast offset:

$$\delta x^S = \mathbf{R}_n^e \cdot (\delta R^S + \delta \dot{R}^S (t - t_0)) \tag{10}$$

(EUSPA, 2023a)

For the tests performed below, several positioning strategies are evaluated to compare the impact of HAS corrections and modelling sophistication.

We denote as Standard Positioning Service (SPS) the baseline solution using pseudorange observation equations and broadcast orbit and clock parameters. This configuration is extended in SPS HAS, which uses the same pseudorange-only formulation but applies the HAS corrections to satellite orbits, clocks and code biases.

To assess the benefit of including carrier-phase data, we define PPP HAS as the model that incorporates both pseudorange and carrier-phase observation equations, still relying on broadcast ephemerides augmented with HAS corrections. Since phase biases are not available this model is not expected to fulfill its accuracy capabilities.

Finally, we define PPP as the high-accuracy model combining pseudorange and carrier-phase measurements, but replacing the broadcast information with precise satellite orbits and clocks from offline products.

6. Preliminary tests

6.1 Study logic

We empirically show that, despite the a priori theoretical considerations (section 3.3), the combination of the E5a and E5b signals HAS corrections and its subsequent use for the E5 AltBOC signal, leads to acceptable results under nominal ideal conditions, e.g., for open-sky signal reception with geodetic-grade receivers. This is the case for the measurements of permanent GNSS stations.

In a second step we analyse the performance of the E1/E5a HAS-corrected measurements and of the E1/E5 AltBOC HAS-pseudo corrected measurements in a less GNSS-friendly environment.

In this research, we concentrate on code measurements for two reasons. First, the combination of the HAS service with code measurements is of interest by itself in the case of the E5 AltBOC signal as such a combination would inherit three important properties: (i) high-precision ranging (below the 1 dm level); (ii) high-accuracy real-time satellite orbit and clock corrections, pseudorange corrections and carrier-phase biases (HAS service level 1); and atmospheric corrections (HAS service level 2); and (iii) multipath low sensitivity (below 1 m). Secondly, before investigating the use of the E5 AltBOC carrier-phase measurements in a future extension of HAS to E5 AltBOC, the behaviour in urban environments of the E5 AltBOC where NLOS reflexions may dominate —i.e., NLOS reflexions masking the benefits of E5 AltBOC mitigated multipath,— must be understood.

6.2 Data and methods

To evaluate the performance of Galileo HAS under nominal conditions, we employed 1 Hz data from permanent GNSS stations within the International GNSS Service (IGS) network. Two stations were selected for this preliminary study, and both yielded coherent results. The first is station ZIM, located in Zimmerwald, Switzerland —a well-known European IGS site situated at a latitude favorable for ionospheric correction estimation, and equipped with an atomic clock. As a control, we selected a second arbitrary station: DJI, located at the Observatoire Géophysique d'Arta in Djibouti. The inclusion of geographically distinct stations allows for a cross-check of the results and provides confidence in the generalizability of the findings. GNSS observations were collected for the 3rd of April 2025, encompassing a 24-h period. After analysing the data we realised there were some anomalies in the carrier phase measurements from 3 to 5 am, and therefore to asses the quality of measurements, the final analysis is conducted on a 18-h period, from 5 am to 23 pm.

The HAS corrections are obtained via the Galileo HAS IDD interface, the SSRA00EUH0 stream available at the ntrip.gsc-europa.eu caster. The RTCM messages transmitted were decoded by the BKGNTRIP Client (BCN) v2.13.2 software.

To analyse the performance of a kinematic receiver moving in an urban scenario we use data collected at Graz, Austria, as part of the GAMMS project on the 7th of May, 2025. We use a GrAnt-3L antenna connected to both a JAVAD DELTA-3S and a Mosaic-x5 receiver with a TW-164 splitter. In this particular test, we use the rinex data generated from the Mosaic receiver. To obtain a reference trajectory, we process the GNSS data in differential mode using as a base the measurements from the GRAZ permanent station, part of IGS network. This reference trajectory is processed using commercial software Grafnav v8.90. We select as a reliable reference the part of the trajectory with low uncertainty and use it to calculate the error of our computed trajectories.

6.3 Preliminary results

6.3.1 Static positioning We process the data of both stations, ZIM and DJI, in static mode, allowing for 5 min of convergence time before imposing a zero velocity constraint. The models used are SPS and SPS HAS in order to evaluate the improvement of performance given by HAS corrections in pseudorange-only models. Two configurations are analysed, one using Galileo E1+E5a and the other with Galileo E1+E5 AltBOC.

Figure 4 shows the positioning errors at ZIM using Galileo E1+E5 AltBOC signals for both the SPS and SPS HAS models. The corresponding results for E5a are qualitatively similar and are therefore omitted for brevity. The SPS solution exhibits errors of up to 1 m in each coordinate component and displays oscillatory behavior, failing to fully converge during the static observation period. In contrast, the SPS HAS solution —incorporating HAS corrections derived via IDD and employing the naive code bias approximation for E5 AltBOC— showcasing a substantial reduction in error magnitude. Both horizontal and vertical errors remain within HAS performance specifications, and the solution converges to a stable, low-error state with improved temporal stability.

Table 1 reports the root mean square (RMS) error of SPS and SPS HAS models in local coordinates for ZIM station, calculated after the 5 min convergence period. The results indicate that, under nominal conditions, the pseudo-HAS corrections applied to E5 AltBOC achieve comparable performance to those officially provided for E5a.

Similarly, table 2 reports the RMS errors for the DJI station, calculated following the same convergence time period. Once

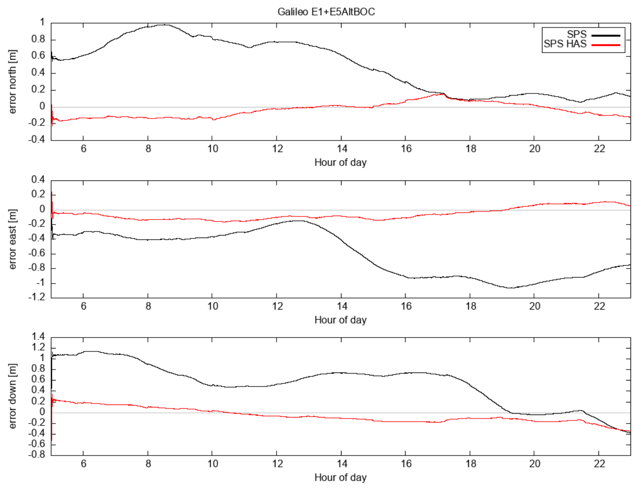

Figure 4. Trajectory computed for static station ZIM along 18 hours using Galileo E1+E5 AltBOC.

second freq.	mode	rms of errors (units: m) n	e	d
E5a	SPS	0.536	0.668	0.513
AltBOC	SPS	0.582	0.671	0.665
E5a	SPS HAS	0.135	0.112	0.249
AltBOC	SPS HAS	0.091	0.098	0.144

Table 1. Results of the 18 h static test for the ZIM permanent station in local coordinates n-e-d.

again, the application of HAS corrections yields a clear improvement in positioning accuracy, both for the official E5a correction and the pseudo-corrections adaptation for E5 AltBOC.

6.3.2 Kinematic positioning The kinematic test consists of a car route through an urban area with low-rise buildings, introducing typical GNSS signal propagation issues such as satellite occlusion and multipath. The dataset spans 40 min, with approximately the first half recorded in static conditions for sensor calibration and the second half during vehicle motion.

To ensure sufficient satellite availability, we process data from both GPS and Galileo constellations. Additionally, we apply ODR on the run to remove measurement blunders. As a reference of expected performance, we calculate a PPP solution with commercial software Grafnav v8.90 using GPS and Galileo constellations in forward mode. The RMS with respect to the reference in local coordinates is 0.625, 0.609 and 1.627 m in the n, e, d local geodetic components respectively.

second freq.	mode	rms of errors (units: m) n	e	d
E5a	SPS	2.243	2.287	5.584
AltBOC	SPS	2.211	2.257	5.520
E5a	SPS HAS	0.131	0.165	0.203
AltBOC	SPS HAS	0.105	0.135	0.283

Table 2. Results of the 15 h static test for the DJI permanent station in local coordinates n-e-d.

mode	rms of errors (units: m) n	e	d
SPS	2.45	1.69	1.45
SPS HAS	1.27	0.98	1.97
PPP HAS	1.06	0.93	2.21
PPP	0.91	1.12	0.99

Table 3. Results of kinematic test in local coordinates n-e-d (GPS L1+L2, GAL E1+E5a).

mode	rms of errors (units: m) n	e	d
SPS	2.21	2.19	0.96
SPS HAS	0.97	1.66	2.18
PPP HAS	1.03	1.07	2.20
PPP	0.88	1.28	1.08

Table 4. Results of kinematic test in local coordinates n-e-d (GPS L1+L2, GAL E1+E5 AltBOC).

Tables 3 and 4 summarise the RMS error of our computed trajectories against the reference solution. We can see that, overall, the accuracy of the solution improves with the complexity of the model. The application of HAS correction does lead to an improvement of the solution although not as significant as the one reported in nominal conditions. This reduced gain is likely due to the challenging GNSS environment, which limits the effectiveness of the HAS augmentation service. The use of the carrier phase along HAS corrections does not make a significant impact, pointing to the need of phase corrections for a full high-accuracy performance. The PPP model overall performs similar to commercial software, thus validating our results.

Figures 5 and 6 display the difference of the four models with respect to the reference trajectory. SPS presents the larger error, starting off at the static part and remaining with the larger error for the rest of the test. The models with HAS reduce the error significantly, being PPP HAS a bit more stable. This could be expected given the addition of the carrier phase information. Comparing both figures we can see that the behaviour is similar when using E5a or E5 AltBOC, showcasing that the AltBOC signal can indeed benefit from the augmentation service.

7. Conclusions

This work indicates that Galileo E5 AltBOC signals can effectively benefit from HAS corrections, even in the absence of officially provided code biases. Through a simple empirical approximation —averaging the existing biases for E5a and E5b— we have shown that it is possible to leverage the HAS corrections (orbits and clocks) to significantly improve the accuracy of positioning using E5 AltBOC. Under nominal conditions, the results obtained with E5 AltBOC are comparable to those achieved with E5a, confirming the soundness of the approach and suggesting its practical viability.

The use of pseudorange-only models has proven to be a valuable tool for assessing the isolated contribution of HAS corrections. The SPS model, when augmented with HAS corrections, showed a clear improvement in accuracy. This is a significant outcome for scenarios where phase measurements are undesirable or impractical, for example, due to long convergence times and recalibration after cycle slips. In such cases,

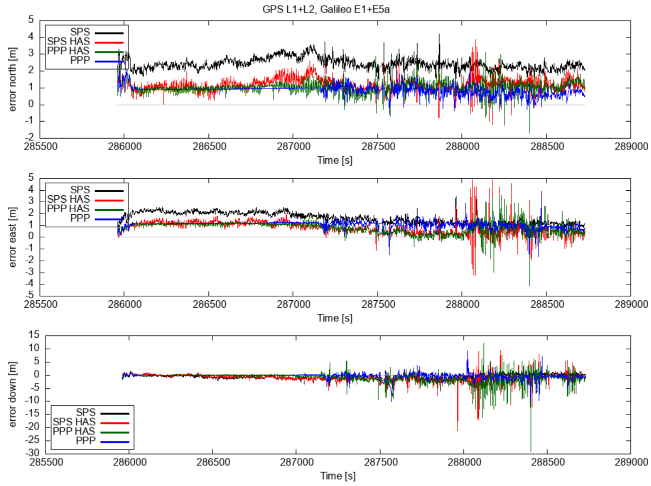

Figure 5. Kinematic test trajectory differences with reference. Processed signals are GPS L1+L2, GAL E1+E5a.

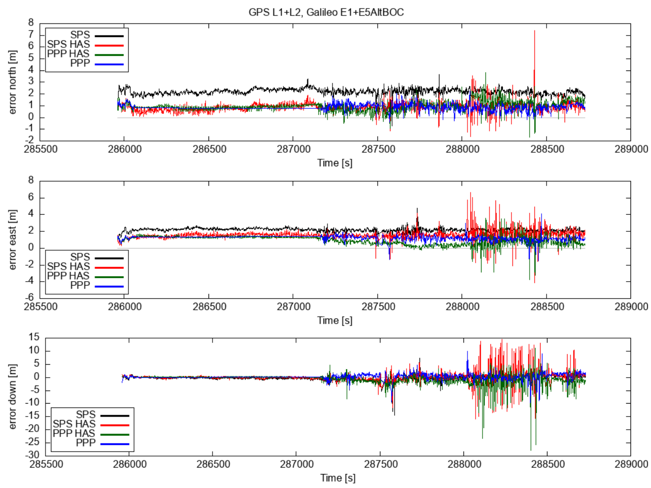

Figure 6. Kinematic test trajectory differences with reference. Processed signals are GPS L1+L2, GAL E1+E5 AltBOC.

applying HAS corrections to pseudorange-only solutions could yield a good and stable performance. In kinematic scenarios, such as urban driving with satellite occlusion and multipath, the benefit of HAS corrections is still visible, though limited. Urban and suburban environments introduce measurement outliers not addressed by satellite-side corrections alone —the so-called local effects. Indeed, while the E5 AltBOC signal modulation is robust against multipath, it cannot deal with the outliers caused by NLOS reflexions. As we know, efficient ODR methods and multi-sensor redundancy are instrumental in removing those outliers. This also highlights the importance of including carrier phase measurements to further enhance positioning performance. The results also indicate that the HAS phase corrections —which are not yet available— could be a critical component for fully realizing the benefits of HAS in complex real-world applications. Overall, this study indicates that HAS corrections can be effectively applied to E5 AltBOC signals, combining the robustness of the signal with the precision of HAS. Even with a preliminary and straightforward implementation, the approach delivers results comparable to those using officially supported frequencies. While challenges remain in kinematic environments, these initial findings support the potential of the combination of HAS and Galileo E5 AltBOC to enhance GNSS positioning performance across diverse scenarios. Hence the convenience that HAS be provided for E5 AltBOC.

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