Early Demonstration of Galileo HAS User Performances

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ABSTRACT

The Galileo HAS Initial Service is currently in testing and will be officially declared in the next few months. The HAS SIS ICD is already public and users capable of receiving the E6 signal are starting it signal and decoding the HAS corrections. This paper presents the results of applying the HAS message in several stations worldwide, in order the have a preliminary characterization of the user availability and accuracy. A user PPP solution is calculated in 10 stations (Europe, Africa, America and Asia) for a 6-day period, based on a dual-constellation dual-frequency solution (Galileo E1-E5a, GPS L1C/A-L2C), without integer ambiguity resolution. This work constitutes, to the knowledge of the authors, the first global characterization of the HAS early user performance.

INTRODUCTION

High accuracy (HA) positioning services allow users to achieve sub-decimeter level positioning accuracy. Typically, high accuracy is provided through differential carrier phase positioning, or RTK (Real-Time Kinematics) [1] when performed in real time for kinematic users, or PPP (Precise Point Positioning), carrier phase-based absolute positioning using very accurate corrections for all error sources (satellite orbits, clocks, biases, etc.) [2]. Although RTK and PPP have been available for many years for professional use cases, the market is showing a massive interest on them for other applications, including all kinds of transport, agriculture, or energy [3], or even smartphone-based, consumer applications [4]. This growing interest is causing a change in the paradigm of the HA services, moving from niche sectors to applications targeting billions of users.

Considering this market trend and the potential economic impact, the European Commission (EC) adopted an Implementation Decision in 2018 to proceed with the procurement and provision of a new service as part of the Galileo portfolio, the Galileo High Accuracy Service (HAS) [5]. Galileo HAS is an open-access service based on the transmission of high accuracy corrections through the Galileo E6-B component [6], at a rate of 448 bps per Galileo satellite connected to an uplink station, and also through the internet.

This paper presents first a brief overview of Galileo HAS. Then, it presents the results of the performance analyses that have been executed, including availability and accuracy. We will finalize with the conclusions of the analysis.

GALILEO HAS OVERVIEW

The Galileo High Accuracy Service (HAS) is an open-access service aiming at a two-decimeter level accuracy (horizontal, 95%) worldwide. When declared, it will be provided by EUSPA (European Union for the Space Program Agency), based on the Galileo system core infrastructure developed by ESA (European Space Agency), and under the management of the EC (European Commission), which has been also responsible for the service initial definition, proof of concept, and HAS SIS ICD [7]. Further information is provided in EUSPA's HAS Info Note [8].

Galileo HAS is based on the dissemination of high accuracy corrections in real time. The transmitted corrections are clocks, orbits, code biases and phase biases, for the GPS and Galileo constellations. They are sent through two channels: one is the E6B signal of the satellites, and the other is the internet, through an NTRIP caster. The architecture of the service is supported by some of the pre-existent Galileo infrastructure. The Galileo sensor stations, or GSS, is the network of stations, currently up to 14, but to be extended in the future, that provide GNSS observations to the HADG (High Accuracy Data Generator). The HADG is the core component of the service. The GNSS corrections are computed in this component. Once generated, the corrections are sent to the core infrastructure for upload by the satellites, who transmit the data by the E6B signal, if connected to a ground mission uplink antenna. There are currently up to 20 mission uplink antennas.

Finally, the user will receive, decode and apply the corrections and calculate a PPP solution. In addition, the HADG publishes the corrections through an NTRIP caster that will be publicly open. Figure 1 presents an overview of the HAS architecture, and Table 1 presents the foreseen service levels (SL) in its final setup. SL1 will provide global corrections, and SL2 will provide in addition ionospheric corrections over a European coverage area (ECA in the table), speeding up convergence time.

HAS implementation is divided in three phases, as per [8]. Following the initial testing phase (Phase 0), aiming at validating Galileo's dissemination capabilities through the E6B channel and performing initial high-accuracy testing, the system is currently getting ready for Phase 1, or Initial Service, to be declared by early 2023 at the latest, and based on an operational high-accuracy data generation (HADG) element providing the PPP corrections. Phase 2 will include the full capability with, among others, a global coverage guaranteed and the ionospheric message over Europe.

Galileo HAS SIS has been transmitted over several stages in the last two years. Firstly, the HAS SIS tests were performed with the so-called Galileo CS Demonstrator, part of the AALECS (Authentic and Accurate Location Experimentation for the Commercial Service) project, which started transmitted the first global PPP corrections back in 2014 [13], yet with a delay of several minutes. It would take until 2021 to connect the CS Demonstrator in real time to the Galileo infrastructure and start transmitting HAS corrections in the final HAS SIS ICD format [9], as part of Phase 0. Since then, EUSPA has conducted a test phase involving other entities who have also had access to the service [14]. Finally, in summer 2022, the operational HADG was connected and ever since SIS tests with this element have been performed. As the HAS SIS ICD is published, anybody with an E6-B capable receiver is able to decode the SIS. An open-source decoder, called *HASlib*, has been developed for this purpose [15].

This paper focuses on the HAS global availability and user performance. An implementation of a HAS-enabled receiver was carried-out in the frame of the "Precise and Authentic User Location Analysis" (PAULA) project for this objective. The HA accuracy data transmitted during the Phase 0 campaign is retrieved in raw SBF (Septentrio Binary Format) by using a commercial high-end receiver (Septentrio Asterx4). This data is processed to derive the original HA corrections and, together with the observations and navigation of the receiver, perform a Precise Point Positioning solution based on GMV's magicPPP software [9]. Further information can be found in [9] on the HAS early definition and performance, [10] and [11] on the HAS SIS ICD encoding scheme, so-called HPVRS (High-Parity Vertical Reed Solomon), and dissemination capability, respectively, and [12] on the initial studies of the HAS future ionospheric message in Phase 2.

	Service Level 1 (SL1)	Service Level 2 (SL2)
Coverage	Global	ECA
Corrections	Orbit, clock, biases	Orbit, clock, biases + atmospheric corrections
Horizontal accuracy (95%)	< 20 cm	< 20 cm
Vertical accuracy (95%)	< 40 cm	< 40 cm

Table 1: Galileo HAS service levels

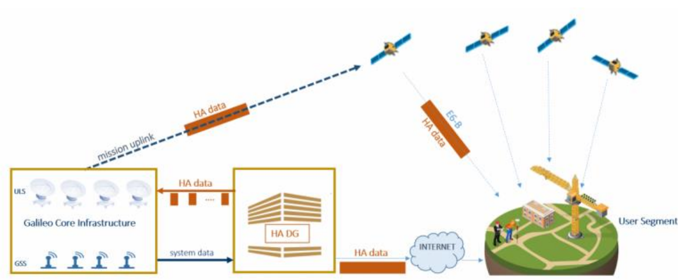

Figure 1: HAS architecture

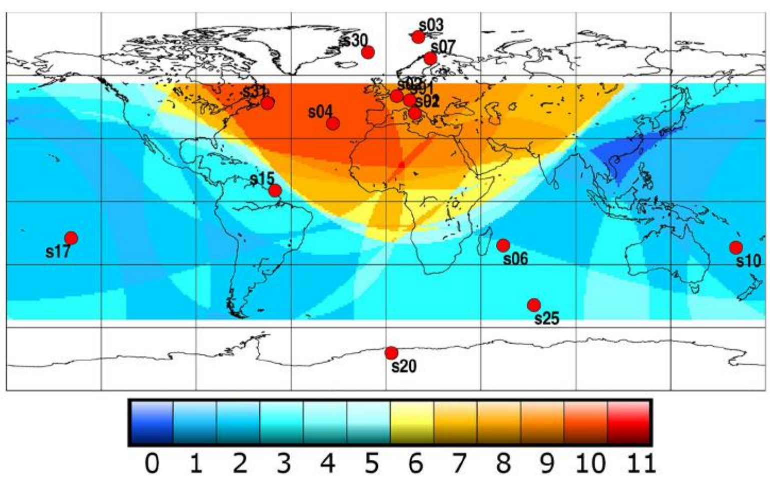

Figure 2: Current network of Galileo sensor stations (GSS) and Depth of coverage [9]

USER PERFORMANCE ANALYSIS

The HAS SIS data has been monitored over some weeks between August and September 2022 worldwide, and the results are presented for the first time in this section. Our results include a coverage-availability analysis, and HAS-based PPP performance in several locations worldwide.

Availability

First, a coverage/availability analysis was performed to the HAS corrections around the world. The testing setup consisted of 10 stations from GMV's global reference network (GGRN), which have been used to collect data. 10 HAS PPP instances have been run with real time data from those stations, computing a real time HAS solution for the 6 days. The HAS PPP solution is based on EC's PAULA project User Terminal. The PAULA Positioning Engine is compatible with Galileo HAS and is based on the GMV's GSharp Positioning Engine. The availability of HAS orbits and clocks have been calculated in a grid of coordinates with cells of a size of 10ºx10º (latitude x longitude) and a 30-second time step. The time window used for the analysis is one day (01/09/2022).

Then, we have used the real HAS Signal in Space data decoded from one of the stations, in order to determine what satellites are corrected in the HAS message. As the HAS message is one for the whole globe, and is transmitted globally, obtaining it from one station is sufficient. We also assume that the message is continuously received in *any* cell worldwide, which is realistic given that there should be about 20 Galileo HAS-transmitting satellites around the globe at any time, and only one of them is needed to retrieve the HAS message.

Then, for a certain satellite k and a cell i, we estimate its availability A_i^k as

$$A_i^k = \frac{T_{HAS,i,k}}{T_{i,k}} \tag{1}$$

Where $T_{i,k}$ is the amount of time that the ground projection of satellite k is in cell i, and $T_{HAS,i,k}$ is the amount of time that the satellite ground projection point of satellite k is in the cell i *and* there are HAS corrections for k.

The procedure for the availability analysis has been the following:

- First, the SIS data has been decoded for extracting all the HAS corrections transmitted during the complete day.
- Then, for every 30-second time step, satellite ground projections are computed from navigation data. They are then assigned to a cell and accumulated for all the time steps, to determine $T_{i,k}$.
- The same procedure is repeated but in this case the satellite is taken into account only if HAS valid corrections are available for that satellite, in order to determine $T_{HAS,i,k}$. The validity interval has been set to 60s for HAS clock corrections and 300s for HAS orbit corrections, as per the transmitted HAS message. They are analyzed separately.
- Finally, the ratio between occurrences of a satellite being in a grid tile with HAS corrections available and the occurrences of a satellite being in a grid tile without HAS corrections is computed for each grid tile, as per (1).

Note that we are aware of the fact that his metric is not the actual HAS availability (understood as the availability of a HAS-based position within specs at a certain location). Nevertheless, as the main bottleneck for HAS availability is the lack of sufficient monitoring stations in certain areas, this simplification is considered generally representative of the prospective availability. More refined user-based analyses such as those simulated in [9], but with real data, are expected to be performed as part of the future work.

The results obtained in the availability analysis are presented in Figure 3, where the clock correction availability is shown in the left, and the orbit correction availability is shown in the right. The availability for HAS orbits and clock corrections is higher in Europe and it presents some degradation for longitudes far from 0º, for example in the Pacific or in some parts of Asia. The reason for these results is that HAS corrections for a satellite cannot be computed when it is seen by a low number of GSS stations. The location of the stations in the GSS network provide a very good coverage for satellites located near the European region, but there are few stations in the Pacific, Asia or Australian regions. The results at the poles are not representative of the actual availability, as due to the Galileo satellite orbit 56º inclination, no satellites are observed at or close to the zenith at these latitudes (so therefore no satellites will be ground-projected in these cells). Previous results as those in [9] did not show such a polar degradation. The HAS clock corrections availability is the limiting factor for this analysis because clock corrections have a lower validity interval. A higher validity interval would provide a higher availability but the degradation over time of the corrections prevents the use long validity intervals. In any case, the results show high availability values almost worldwide, significantly beyond the expected minimum coverage in Europe for HAS Phase 1.

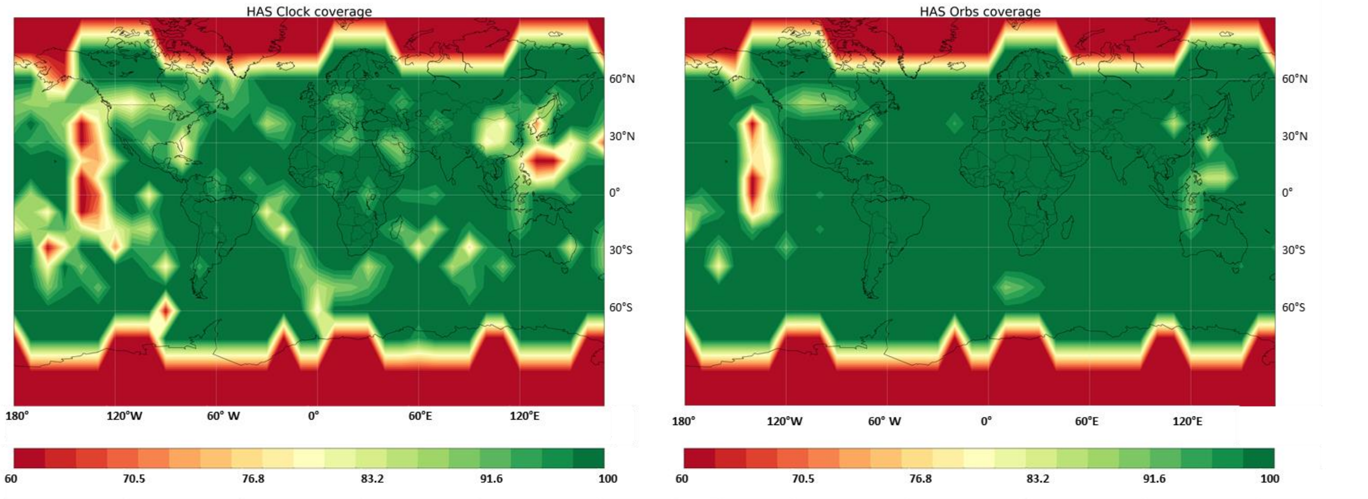

Figure 3: HAS estimated availability (the low availability in polar regions is due to the estimation method)

Accuracy

For the HAS accuracy analysis, we have selected 10 stations from the GMV Global GNSS reference Network. They are distributed globally as shown in Figure 4, right. The environment for the tests is open sky and static. They are geodetic stations based on state-of-the-art GNSS receivers. Figure 4, left shows a typical environment of a station. The HAS-PPP user configuration includes Galileo and GPS constellations with double frequency ionosphere-free and wide lane processing with float ambiguities. The signals used are E1-E5a for Galileo and L1C/A-L2CL for GPS. The HAS PPP implementation used is GMV's GSharp Positioning Engine, related to GMV's MagicPPP [16]. A high-level Kalman filter-based description of the HAS PPP user algorithm is provided in [9]. Further information about PPP user algorithms can be found in [17] or [18], Ch25. The state vector $\boldsymbol{\chi}$ estimated by the filter is defined as

$$\boldsymbol{\chi} = \left(x_u, y_u, z_u, \dot{x}_u, \dot{y}_u, \dot{z}_u, \overline{dt}_{u,IF}, H_{WL}, \delta\tau_u, \bar{M}_u^1, \dots, \bar{M}_u^m, I^1, \dots, I^m\right) \quad (2)$$

which includes the user receiver position (x_u, y_u, z_u), velocity $(\dot{x}_u, \dot{y}_u, \dot{z}_u)$, time bias for the iono-free combination $(\overline{dt}_{u,IF})$, code bias for the wide lane combination (H_{WL}), tropospheric residual $(\delta\tau_u)$, ionospheric delays $(I^1, \ldots)$ and carrier phase ambiguities $(\bar{M}_u^1, \ldots)$. Note that, as abovementioned, no integer ambiguity resolution (IAR) was performed, so no satellite or receiver phase biases are used. The transmission of satellite phase biases is part of the Galileo HAS but they are not yet used in this analysis.

We are grouping the results by regions because of the different conditions and performance obtained. The best performance is expected in Europe because of the distribution of the GSS network (Figure 2). As shown in Table 2 top, the performance for all the stations in Europe is similar and fulfills the Service Level 1 target accuracy. However, the station in Namibia, Africa (NAWI) shows comparable performance to that in Europe, in spite of the less monitoring stations.

Figure 4: Stations used for HAS-PPP user accuracy evaluation. Left: typical station environment, Right: location of stations.

Europe & Africa	Errors RMS (cm)		
	North	East	Height
SPTR	4.5	6.6	13.8
ROBU	5.7	6.6	14.0
SWOJ	6.5	6.1	14.6
NAWI	4.0	5.3	14.4

Europe & Africa	Errors p95 (cm)	
	Horizontal	Vertical
SPTR	19.5	26.5
ROBU	17.3	26.8
SWOJ	13.5	28.3
NAWI	18.1	25.3

America	Errors RMS (cm)		
	North	East	Height
USNA	6.0	8.3	17.5
CABU	6.1	9.0	21.9
CHSA	8.8	13.7	24.0
FRTA	9.1	9.7	24.2

America	Errors p95 (cm)	
	Horizontal	Vertical
USNA	19.8	32.9
CABU	21.4	38.1
CHSA	26.5	36.1
FRTA	27.0	40.7

Asia	Errors RMS (cm)		
	North	East	Height
INKO	5.8	8.7	21.8
TATA	8.6	15.9	27.0

Asia	Errors p95 (cm)	
	Horizontal	Vertical
INKO	19.1	35.7
TATA	33.1	52.2

Table 2: Galileo HAS user PPP accuracy results in Europe/Africa (top), America (middle) and Asia (bottom), RMS (left) and 95% (right)

For Europe/Africa, Table 2 (top) presents the RMS (root mean squared) error in each 3D component, showing a few (4.0 to 6.6) cm error in horizontal components and a higher (13.8 to 14.6 cm) error in the vertical one, in principle due to geometry. The 95% results are below the 20cm/40cm horizontal/vertical error 95% in all cases. A summary of the positioning performance for the stations located in America and the Pacific is shown also in Table 2, middle. The performance is better for the stations in the North American region (USNA, CABU), with a North/East RMS error between 6.0 and 9.0 cm, than in South America (CHSA) or the Pacific (FRTA). Finally, the results for the stations in Asia are shown at the bottom of the table. Some degradation seems to appear for the most eastern stations (TATA). Also, the differences between the RMS and the 95th percentile are higher than in other regions, especially for the station located in Taiwan (TATA). Lower availability of HAS corrections in this region can lead to some re-convergences and a worse geometry which impacts more on the higher percentiles. However, an accuracy similar to that in other regions is achieved when HAS corrections for sufficient satellites are available, as is reflected in RMS results, for example in the India station (INKO).

An example of the real time positioning results for one of the stations for the whole 6-day period is shown here, using the station from Sweden (SWOJ). The positioning error is represented for the North, East and Height components together with the number of satellites used by the HAS-PPP in each epoch. The RMS of the positioning error is also shown for each of the six days. We must note that the results in this and other stations, including position jumps and re-convergence, cannot only be attributed to HAS because, in spite of the static, good visibility environments, the network receivers may also be subject to processing glitches or local effects, especially for long duration tests such as this one, and which are also shown in the plots. Further results for some of the other stations are provided in the Annex.

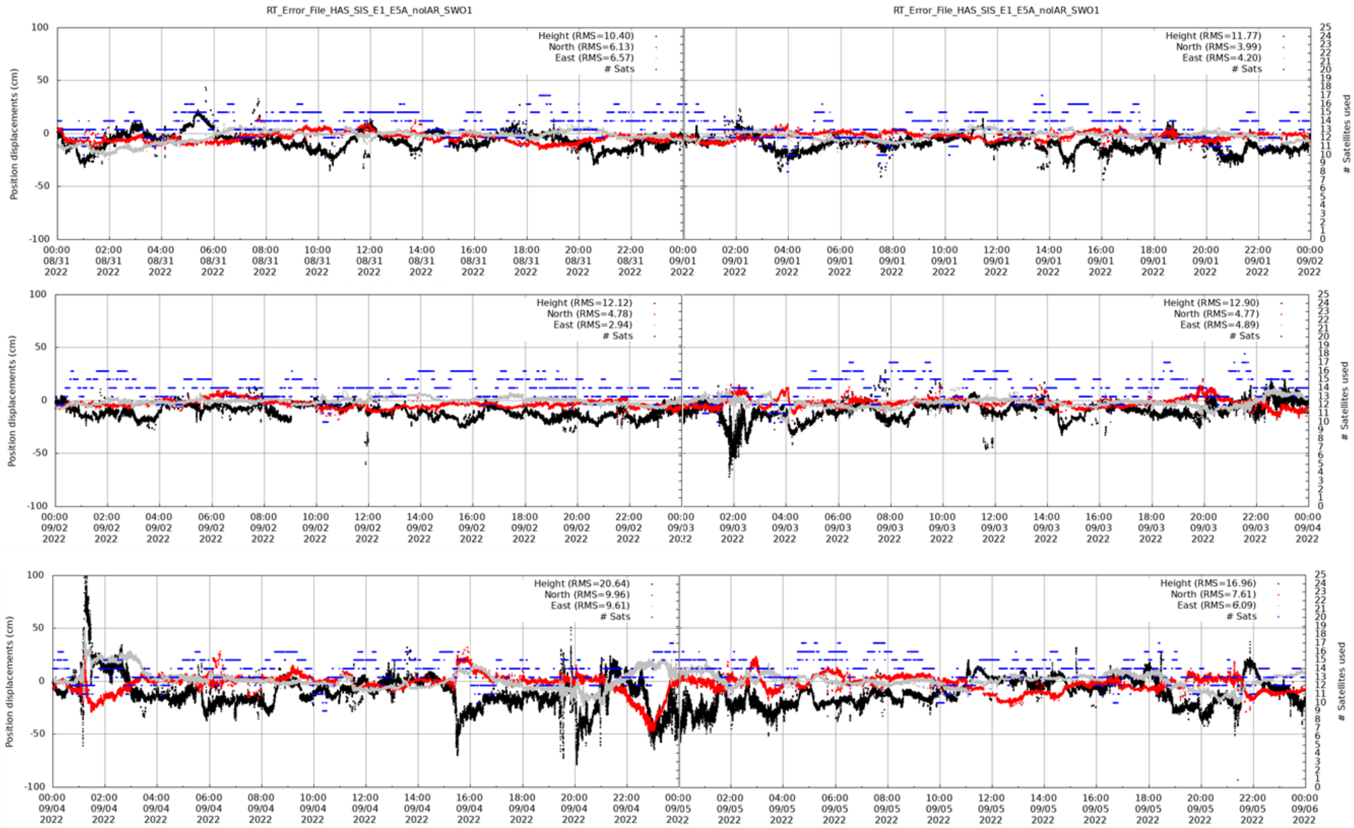

Figure 5: Instantaneous performance (after convergence) of SOWI (Sweden) station, 6 days.

CONCLUSIONS

The Galileo HAS is finalizing its testing phase, in view of an Initial Service Declaration in the next few months. As the HAS SIS ICD is already public, users are starting testing the HAS signal and benefit from it. We present the results of some recent data collection from September 2022, based on several stations worldwide from GMV's network. Our analysis shows first an estimation of the HAS availability worldwide based Galileo/GPS corrections availability from the real HAS message. Even if the results are just a proxy of the actual availability, they show a high availability worldwide, beyond the EU coverage initially expected for Phase 1.

HAS PPP user accuracy after convergence is also analyzed, for a continuous 6-day period in 10 receivers in the EU, Africa, America/Pacific and Asia. The results are compliant with the 20/40cm 95% horizontal/vertical accuracy given as a requirement from HAS in European longitudes, including also Africa. In America and particularly far Asia, the results are degraded, especially at 95%, due to some re-convergence events due to the lower monitoring capabilities of HAS ground segment, consisting at the moment of up to 14 stations. Anyway, most of the results are below one decimeter in the East/North components, even worldwide, which we consider beyond the expectations, and a remarkable result for such a reduced ground segment.

Further work will include characterizing the convergence time, not treated yet in this paper, and improving the availability metrics, among others. As the HAS SIS ICD is already public, the GNSS community is encouraged to use this HAS for experimentation and for reproducing these results even before the upcoming initial service declaration.

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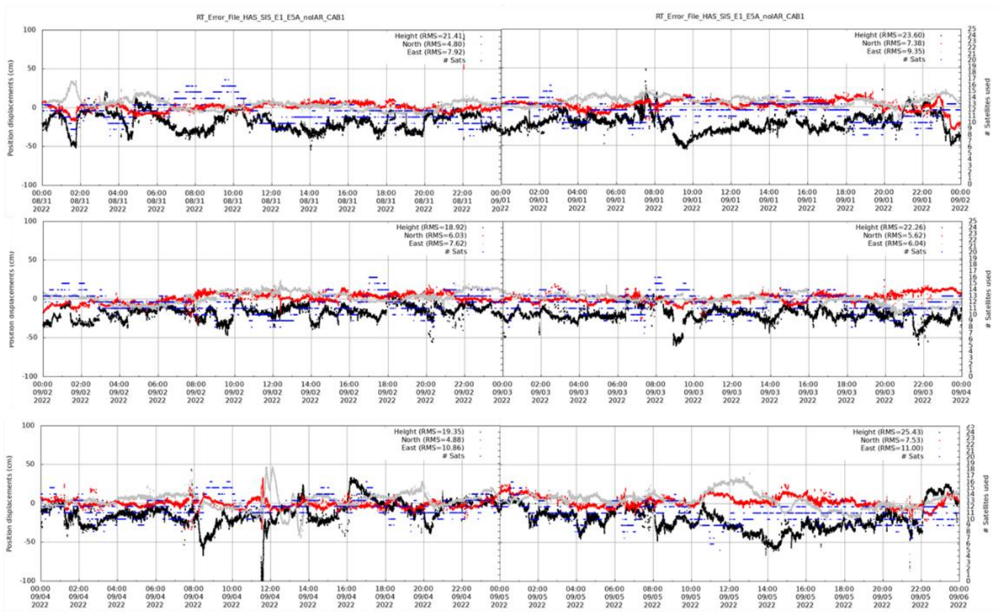
ANNEX

This annex presents the HAS PPP results in Canada (CABU) and India (INKO) stations.

CANADA



INDIA