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Transmission of Ionospheric Parameters in Galileo HAS Phase 2 †

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Abstract

The Galileo High Accuracy Service (HAS) has been operational since January 2023, offering good and stable performance. The next phase of HAS is currently being implemented, offering enhanced performance and new functionalities. One of the improvements in HAS Phase 2 will be the provisioning of ionospheric parameters to users in the European Coverage Area (ECA). This paper focuses on the new Message Type 2 (MT2) which will contain the ionospheric parameters, i.e., ionospheric vertical delays (IVDs) and ionospheric vertical accuracies (IVAs). IVDs and IVAs will be provided for ionospheric grid points (IGPs) which receivers in the ECA can see down to a certain elevation. Data for two ionospheric layers is planned to be provided. Because transmitting the IVDs and IVAs for a vast number of IGPs requires a significant amount of bandwidth, an investigation was also launched into different approaches for compressing the IVD data. To assess the efficacy of the compression, the percentage decrease in size was assessed through post-processing of historical data. Compared to non-optimized encoding of the IVDs using a fixed number of bits, processing of historical data showed a median IVD block size reduction of about 27% and 41% under solar maximum and solar minimum conditions, respectively. The IVD block compression approach will be evaluated further during the HAS Phase 2 implementation.

Keywords: Galileo; HAS; PPP; ionosphere

1. Introduction

Historically, GNSSs have provided models to estimate ionospheric signal propagation effects, such as Klobuchar [1] for GPS or BDS and NeQuick-G for Galileo [2]. Usually, these models are global and the model parameters occupy only a few tens of bits of the navigation message and are often updated daily. Depending on the ionospheric activity, they correct only approximately 50% of the ionospheric error.

Regional systems such as SBAS provide ionospheric corrections over the region of interest, thanks to continuous monitoring, allowing to reach sub-meter accuracy. In the last decade, regional and global satellite navigation systems are targeting higher accuracies and started offering high accuracy services based on the Precise Point Positioning (PPP) concept [3,4]. The Galileo High Accuracy Service (HAS) provides the first-ever PPP service offered by a GNSS worldwide. Other examples are QZSS with MADOCA and CLAS [5], and BeiDou with BDS-PPP [6].

High accuracy services are traditionally based on the use of multiple-frequency measurement combinations eliminating most of the ionospheric error, which is frequency-

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dependent. However, such approaches still benefit from accurate ionospheric corrections for using uncombined measurements. In general, the availability of ionospheric corrections can increase the accuracy for single-frequency users and reduce the convergence times for both single-frequency and multi-frequency users.

PPP services offered by GNSSs expect to provide regional ionospheric corrections over a certain area. Specifically, the Galileo HAS service has committed to providing precise ionospheric corrections over Europe. This paper describes the transmission of ionospheric data which will be implemented in the Galileo HAS service.

2. Galileo High Accuracy Service—Current Status and Evolution

The Galileo HAS service provides correction parameters via the Galileo E6-B signal to the user—and alternatively via the internet—in a format similar to the Compact State Space Representation (CSSR) [7]. The service is free of charge and enables users to perform Precise Point Positioning (PPP) in real time [8,9]. It provides a decimeter-level satellite correction and user positioning performance worldwide, as per its Service Definition Document [10]. Readers can consult other references which provide further details on Galileo HAS corrections [11] or user performance for different user types [12].

The Galileo HAS service started offering an initial operational service (Phase 1) in January 2023, offering good and stable performance. In Phase 1, Galileo HAS provides orbit and clock corrections and satellite code biases for Galileo and GPS. This data is provided in what is called Message Type 1 (MT1) [7]. In the full HAS service (Phase 2), additional data blocks will be available for transmission through MT1 and a new Message Type 2 (MT2) will be transmitted. Phase 2 will be fully operational as of the HAS 'full service declaration' which is foreseen for Q1 2027.

In addition to the data blocks defined for Phase 1, the new data blocks for transmission through MT1 include:

- Satellite correction accuracies (SCA) block;
- Earth rotation parameters, solar and geomagnetic activity (ERP/SAGA) block;
- HAS message signature (HMS) block;
- Authentication key management (AKM) block.

The new data blocks for transmission through the new MT2 include:

- Ionospheric data blocks;
- HAS message signature (HMS) block;
- Authentication key management (AKM) block.

This paper only covers the MT2 ionospheric data blocks, as the other newly introduced data blocks extend beyond the scope of this paper. The details of all evolutions with respect to Phase 1 will be available in the Phase 2 HAS SIS ICD upon its public release.

3. Ionospheric Data Blocks in HAS Phase 2

The ionospheric data transmitted in MT2 covers the European Coverage Area (ECA). The boundaries of the ECA are shown in Figure 1. Two service levels are defined for HAS Phase 2:

- Service Level 1 (SL1) for users worldwide (including users in the ECA);
- Service Level 2 (SL2) for users in the ECA making use of the ionospheric corrections.

While Service Level 1 targets a convergence time of less than 300 s worldwide, Service Level 2 will target a convergence time of less than 100 s for users in the ECA thanks to the availability of the ionospheric corrections.

The ionospheric data is planned to be transmitted through the following MT2 data blocks:

- Iono Mask block;
- Iono Vertical Accuracies (IVA) block;
- Iono Vertical Delays (IVD) block.

These blocks are described in the next sections. Note that the definitions and values are under consolidation and may still change in the final HAS Phase 2 specification.

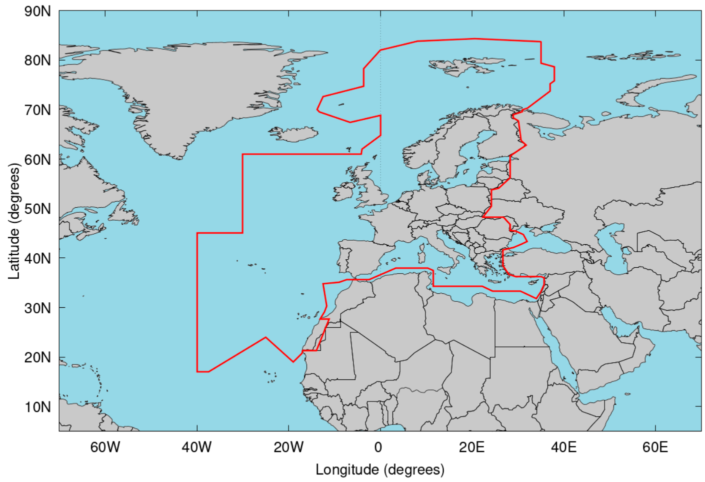


Figure 1. Boundaries of the European Coverage Area (ECA).

3.1. Iono Masks

The ionospheric data is based on a Global Ionosphere Model (GIM) including two layers of Ionospheric Grid Points (IGPs): the lower layer at 270 km (layer 1) and the upper layer at 1600 km (layer 2) [13,14]. The location of the IGPs in both layers in terms of Modified Dip (MODIP) latitude and geographical longitude is defined through a so-called 'Iono Mask'.

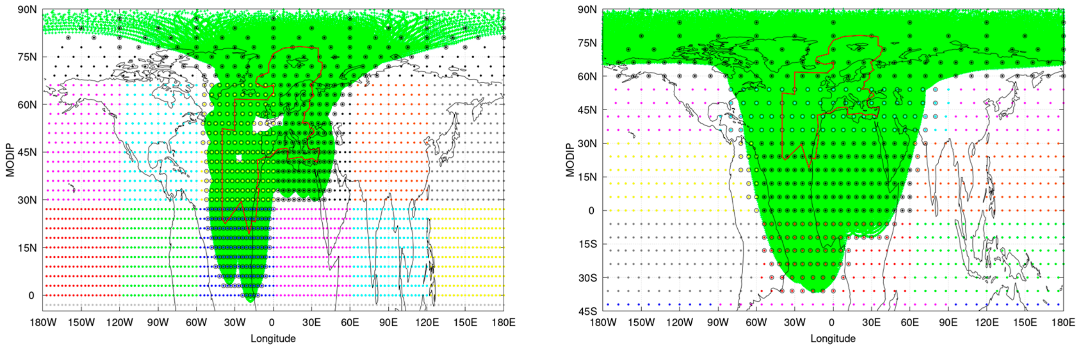
The MT2 header contains an 'Iono Mask ID' parameter which identifies the applicable Iono Mask:

- Iono Mask ID $\in [0, 49]$: Indicates an Iono Mask which is predefined in the HAS SIS ICD. Notably, Iono Mask ID = 0 indicates the Iono Mask for providing ionospheric data for the European Coverage Area.
- Iono Mask ID $\in [50, 99]$: Indicates that the Iono Mask is defined by an Iono Mask block that is transmitted in the MT2. This allows the flexibility to use ad hoc Iono Masks that are provided within the message itself.

In nominal cases, the predefined ECA Mask is used (Iono Mask ID = 0). The subsequent discussion will focus on this case. Because the Iono Mask block is not transmitted in case of a predefined Iono Mask, such as the ECA Mask, the Iono Mask block will not be detailed further.

There are 899 IGPs in the ECA Mask, i.e., 541 IGPs in the lower layer and 358 IGPs in the upper layer. These IGPs are a subset of a global grid of IGPs, grouped into bands, which are defined in terms of MODIP latitude and geographical longitude in the Phase 2 HAS SIS ICD.

The ECA Mask includes IGPs for providing ionospheric data in the region that receivers in the ECA would see down to a 10° elevation mask. These IGPs are illustrated in Figure 2, where the required grid points are embedded into black circles. The MODIP latitude grid has a spacing of 3° for layer 1 and 6° for layer 2. The longitude grid has a spacing between 3° and 60° for layer 1 and between 6° and 60° for layer 2, depending on the MODIP latitude [15]. The green area comprises the resulting ionospheric pierce points, when considering user locations at the border of the ECA and assuming the minimum elevation of 10°.



(**a**) (**b**)

Figure 2. Map with different IGP bands (colored dots). The green area comprises the ionospheric pierce points visible from a receiver at the border of the ECA (red line) considering a 10° elevation mask for: (**a**) Layer 1 at 270 km; (**b**) Layer 2 at 1600 km. The resulting IGPs for the ECA are circled in black.

3.2. Iono Vertical Accuracies

For each IGP in the applicable Iono Mask, the Iono Vertical Accuracies (IVA) block provides the 1-sigma uncertainty of the corresponding Iono Vertical Delay (IVD). Each σ_{IVA} value is encoded as a 3-bit 'IVA Index'. The mapping between the IVA Index and the σ_{IVA} value, expressed in Total Electron Content Units (TECUs), is shown in Table 1. Note that this mapping may still be revised.

Table 1. Mapping between IVA Index and IVA value.

IVA Index	σ_{IVA} (TECU)
0	0.5
1	0.9
2	1.5
3	2.4
4	3.5
5	5.3
6	8
7	'Not Monitored'

The IVA block provides an IVA Index for each IGP in the Iono Mask (e.g., 3 bits per ECA IGP results in a total of 2697 bits). Similarly, the Iono Vertical Delay block (see below) would provide an IVD value for each IGP in the Iono Mask. However, when an IVA Index is set to 7 ('Not Monitored'), the corresponding IGP is excluded from the IVD block. Using this additional method of masking, referred to as 'IVA Index masking', the scope of the IVD block can be restricted to a subset of the IGPs in the applicable Iono Mask.

3.3. Iono Vertical Delays

The values in the IVD block represent the Vertical Total Electron Content (VTEC) values expressed in TECU for each of the IGPs in the Iono Mask, except those excluded by IVA Index masking. In essence, the IVD and IVA blocks provide a two-layer map of VTEC values and their associated uncertainties. For each measurement, the user equipment should compute the slant ionosphere delay (expressed in a unit of length) and its variance from the available IVD and IVA data. The required computations for implementation in the navigation process are included in the Phase 2 HAS SIS ICD.

A crucial part of defining the MT2 is the encoding of the IVD block, since it makes up the bulk of the data volume. A first step in minimizing the data volume can be obtained by considering that the maximum VTEC for the upper layer is typically lower than that for the lower layer. This is due to the fact that the electron density in the ionosphere typically peaks at altitudes below 350 km.

As a first approach, it was considered to encode the IVDs as follows:

- IVDs for the lower layer IGPs encoded on 10 bits and supporting a range from −10.0 to 245.5 TECU;
- IVDs for the upper layer IGPs encoded on 9 bits and supporting a range from −10.0 to 117.5 TECU.

A limited range of negative values is permitted, since modelling inaccuracies and inter-layer correlations may give rise to negative values in one layer, which are offset by a corresponding excess in the other layer. The aggregated VTEC values, which are derived from the sum of both layers, must remain positive.

For the ECA Mask and in case IVDs are provided for all IGPs (i.e., no IVA Index masking), the total number of IVD bits would be 8632 (=541 × 10 + 358 × 9). Because a HAS page has a useful payload of 424 bits [7], transmitting the IVDs in the MT2 would require more than 20 HAS pages. Combined with the IVA block (see above), the MT2 size would amount to more than 26 HAS pages.

An investigation was launched into different approaches for reducing the MT2 size. Reducing its size would not only benefit Service Level 2 in Phase 2, because the time required to receive the ionospheric data is reduced, but it would also free up bandwidth for other MT1 and MT2 data. Because the primary chunk of data consists of the IVD block, the focus was on compression of the IVD block. A general discussion on ionospheric data transmission, including some compression methods in the state of the art and their performance, is provided in [16].

The most promising approach is currently being implemented in Version 2 of the High Accuracy Data Generator (HADG), which is the Galileo ground segment module that generates the HAS data. To the authors' regret, the details of this compression approach are not yet cleared for external dissemination. As the approach will be evaluated further as part of the HADG Version 2 activities, adaptations and corrections may still be required. Nevertheless, the next section presents results of the IVD block compression approach that are already available through post-processing of large datasets of historical data.

4. IVD Block Size Reduction

The IVD block size reduction percentages reported in the next sections are relative to the non-optimized encoding of the IVDs using the fixed number of bits as discussed above, i.e., 10 bits for the lower layer IGPs and 9 bits for the upper layer IGPs. Because the percentage decrease in size after compression depends on the variability of the original IVD values, historical data collected during periods with high and low solar activity levels was processed to assess the IVD block compression approach. The results are provided in the next sections.

4.1. IVD Block Size Reduction Under High Solar Activity

4.1.1. Input Data

The size reduction percentage of the IVD block was assessed by processing a set of Ionosphere Map Exchange Format (IONEX) files [17,18]. These IONEX files were provided by the research group of Astronomy and Geomatics (gAGE) of the Universitat Politècnica de Catalunya (UPC). These files contain TEC and RMS maps for the two layers as defined above. The resolution of the TEC values and the RMS values in the files is 0.1 TECU.

Each processed file covers 24 h with a 5-min interval. For each of the 288 epochs, four maps are provided: layer 1 TEC and RMS maps, and layer 2 TEC and RMS maps. Each map covers 5256 IGPs, covering all latitudes (with 2.5° spacing) and longitudes (with 5° spacing).

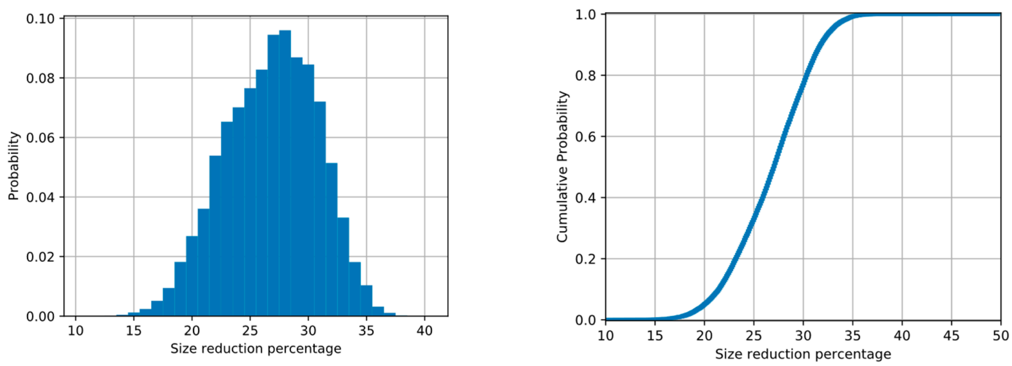
When a TEC value for a particular IGP with an associated RMS value above 8 TECU was read during the processing, the IGP was considered unmonitored and excluded from the IVD block. Such values are excluded from the processing as they would also be excluded operationally due to their high uncertainty. In total, 30,948 epochs spanning 108 days between 22 January 2024 and 6 June 2024 were processed. For each epoch, the size of the IVD block was calculated and the size reduction percentage was calculated.

4.1.2. Results

The overall statistics of the IVD block size reduction percentage under high solar activity are shown in the left-hand data column of Table 2. A normalized histogram and the cumulative distribution function are shown in panel (a) and (b) of Figure 3, respectively.

Table 2. IVD block size reduction results for the datasets of 2024 (high solar activity) and 2017 (low solar activity).

Size Reduction Statistics	High Solar Activity Dataset	Low Solar Activity Dataset
Standard deviation	4.0%	2.9%
Minimum	12.3%	26.7%
5th percentile	20.0%	35.1%
Mean	26.8%	40.3%
Median	27.1%	40.5%
95th percentile	32.9%	44.6%
Maximum	38.2%	47.9%



(**a**) (**b**)

Figure 3. Results for the dataset of 2024 (high solar activity): (**a**) Normalized histogram of IVD block size reduction; (**b**) Cumulative distribution function of IVD block size reduction.

4.2. IVD Block Size Reduction Under Low Solar Activity

4.2.1. Input Data

The evaluation was repeated using data from the solar minimum. For all days of 2017, IONEX files were provided by UPC. Compared to the previously processed files of 2024, there are some small differences in the files of 2017:

- The height of layer 1 used in the model was 268 km instead of 270 km.
- The interval is 15 min, resulting in 97 epochs per file.

- A spacing of 2.5° in longitude and latitude is used, resulting in 10,585 IGPs per layer.

These differences are inconsequential for the analysis of the size reduction percentage as was done using the files of 2024. The total number of epochs analyzed is comparable because, although the refresh rate is lower, the number of files is higher.

The same filtering was applied, i.e., TEC values with an associated RMS value above 8 TECU were excluded from the IVD block. Additionally, three days were excluded because the corresponding IONEX files were incomplete. In total, 34,752 epochs spanning 362 days of 2017 were processed.

4.2.2. Results

The overall statistics of the IVD block size reduction percentage under low solar activity are shown in the right-hand data column of Table 2. A normalized histogram and the cumulative distribution function are shown in panel (a) and (b) of Figure 4, respectively.

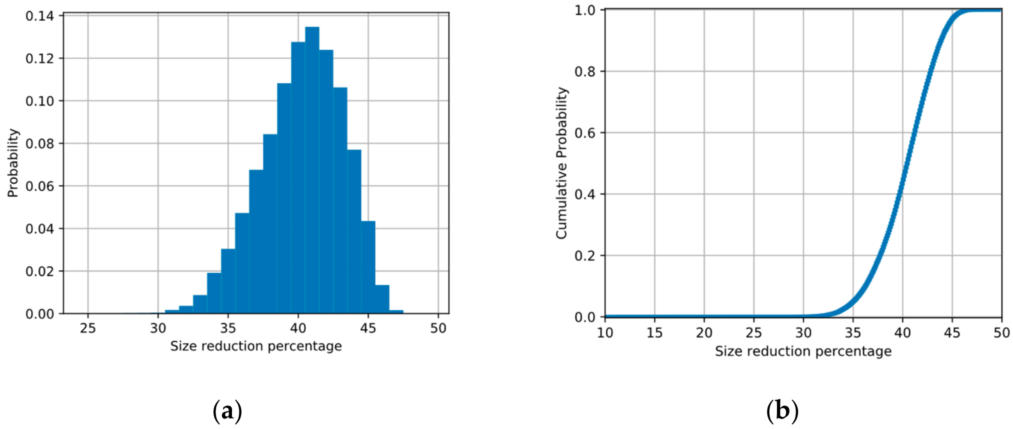


Figure 4. Results for the dataset of 2017 (low solar activity): (**a**) Normalized histogram of IVD block size reduction; (**b**) Cumulative distribution function of IVD block size reduction.

4.3. Results Discussion

Using 2024 data (around solar maximum), a median IVD block size reduction of 27.1% was achieved (corresponding to ca. 5.5 HAS pages). Using 2017 data (around solar minimum), a higher median IVD block size reduction of 40.5% was achieved (corresponding to ca. 8.5 HAS pages), which is due to the lower variability of this dataset. Although the IVD block compression approach may still need to evolve as it is being evaluated as part of the implementation of the HADG Version 2—during which it will be exercised using real-time data—these results show that a useful decrease in the IVD block size can be achieved. The details of the consolidated compression approach will be available in the Phase 2 HAS SIS ICD upon its public release.

5. Conclusions

The Galileo HAS service, which is already offering good and stable performance during its current 'initial operational service' phase, is committed to providing precise ionospheric data to users in the European Coverage Area as part of its 'full service' in Phase 2. The new MT2 data blocks that contain ionospheric data have been introduced, i.e., the Iono Mask, IVA and IVD blocks. Without optimization, the MT2 size would exceed 26 HAS pages under typical conditions. For reducing the MT2 size, compression of the IVD block is planned to be introduced. Although the IVD block compression approach is still being consolidated, the results which could be shared show a useful decrease in the IVD block size of about 27% and 41% for high and low solar activity, respectively. This would benefit users of the ionospheric data (i.e., Service Level 2 users) because the time required to receive the ionospheric data is reduced. Because additional bandwidth is available for other data, this would also reduce the time to receive data for all users (i.e., Service Level 1 and 2 users) in HAS Phase 2.

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Abbreviations

Abbreviations are defined where they first appear in the text, with the most pertinent abbreviations also listed below for ease of reference.

ECA	European Coverage Area
HAS	High Accuracy Service
ICD	Interface Control Document
IGP	Ionospheric Grid Point
IVA	Iono Vertical Accuracy
IVD	Iono Vertical Delay
MT	Message Type
SIS	Signal In Space
TEC	Total Electron Content
TECU	Total Electron Content Unit
VTEC	Vertical Total Electron Content

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