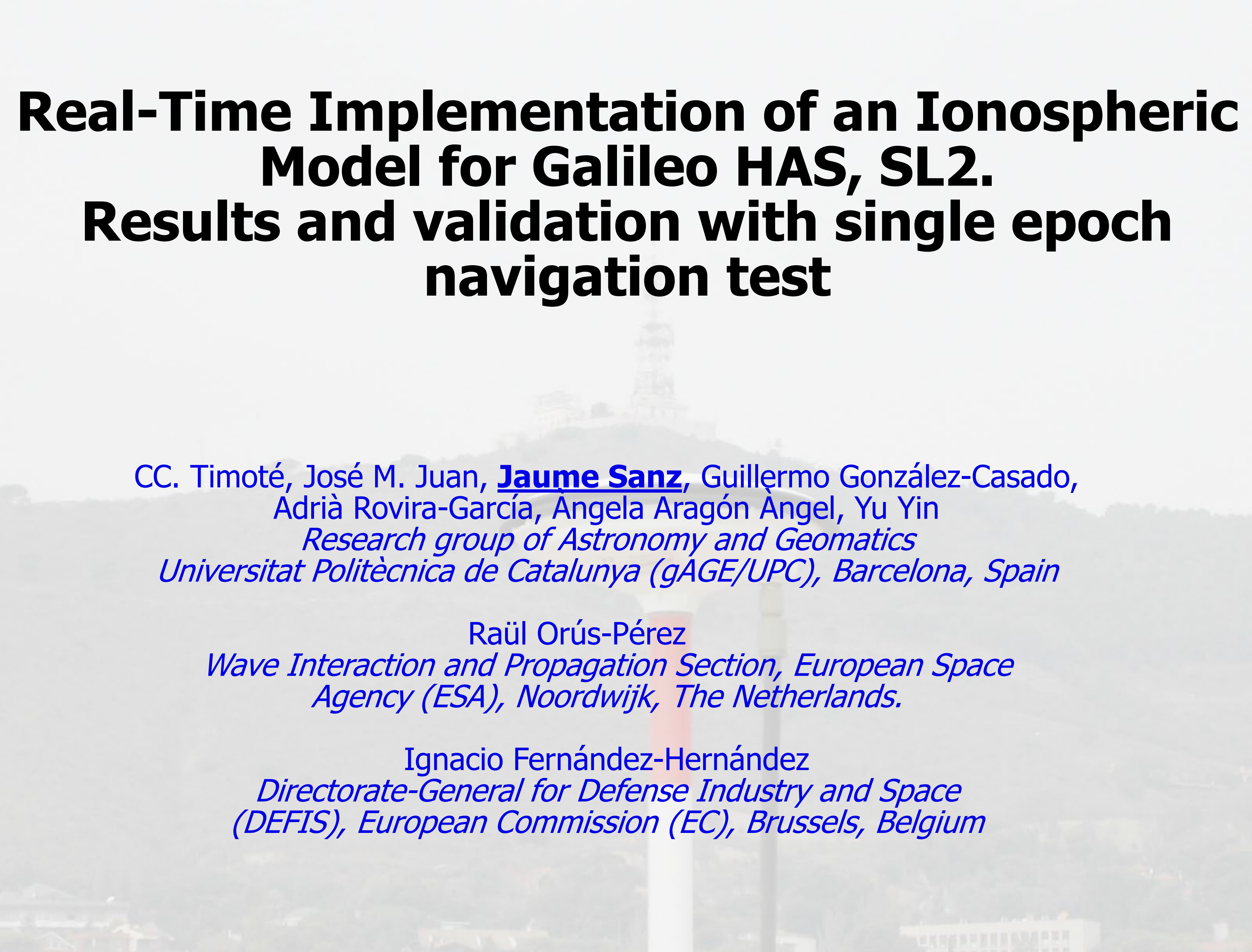

# Real-Time Implementation of an Ionospheric Model for Galileo HAS, SL2. Results and validation with single epoch navigation test

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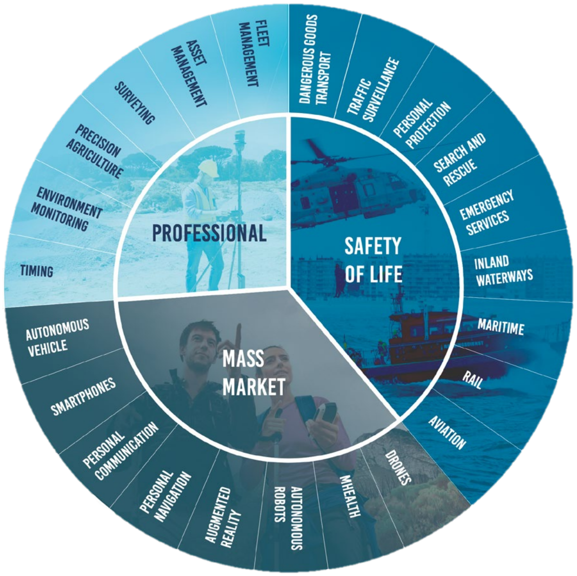
# Contents

# **1. Introduction:** Galileo HAS

## **Galileo High Accuracy Service (HAS)**

Enabling Precise Point Positioning (PPP) on a global scale



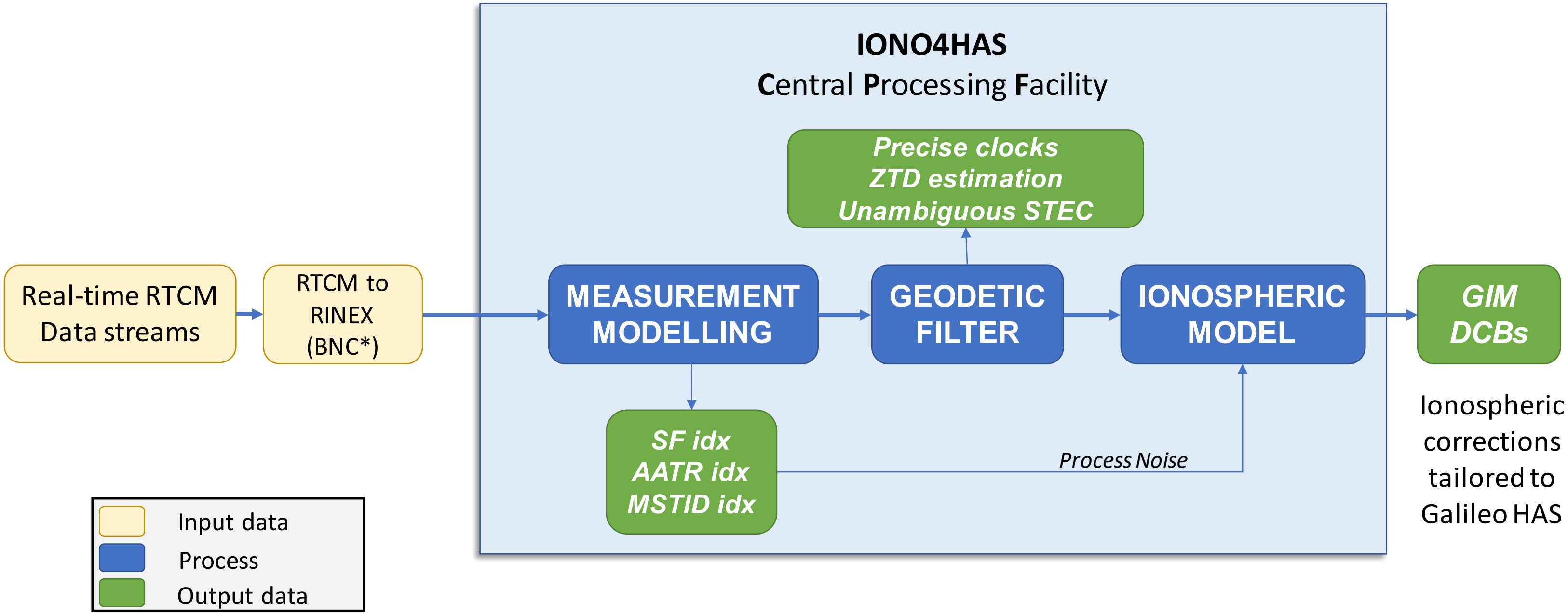
| **GALILEO HAS** | **Service Level 1** | **Service Level 2** |
|---|---|---|
| **Coverage** | Global | European Coverage Area |
| **Corrections** | Orbit, clock, biases (code and phase) | Orbit, clock, biases (code and phase), **ionospheric corrections** |
| **Constellations** | GPS, Galileo | GPS, Galileo |
| **Hor. Accuracy (95%)** | < 20 cm | < 20 cm |
| **Ver. Accuracy (95%)** | < 40 cm | < 40 cm |
| **Convergence Time** | < 300 s | < **100 s** |

Service Level 1 (SL1) comprises satellite orbit and clock corrections (i.e. non-dispersive effects), and dispersive effects such as code and phase biases. **Service Level 2 (SL2) incorporates ionospheric corrections for Fast-PPP navigation (at least over Europe).**

# 2. The IONO4HAS CPF:

In the context of the ESA project ESA Real-Time Ionospheric Continental Caster (eRTICC) project, gAGE/UPC has developed and deployed the IONO4HAS CPF.

*A Real-Time Implementation of an Ionospheric Model for Galileo High Accuracy Service, SL2.*



IONO4HAS CPF is not only generating the ionospheric corrections, but also precise satellite and receiver clocks, code and carrier phase biases, among other parameters, which would correspond to the HAS SL1 corrections data, allowing to navigate the user receiver in PPP, and in Fast-PPP (i.e. SL2) mode with the ionosphere corrections data.

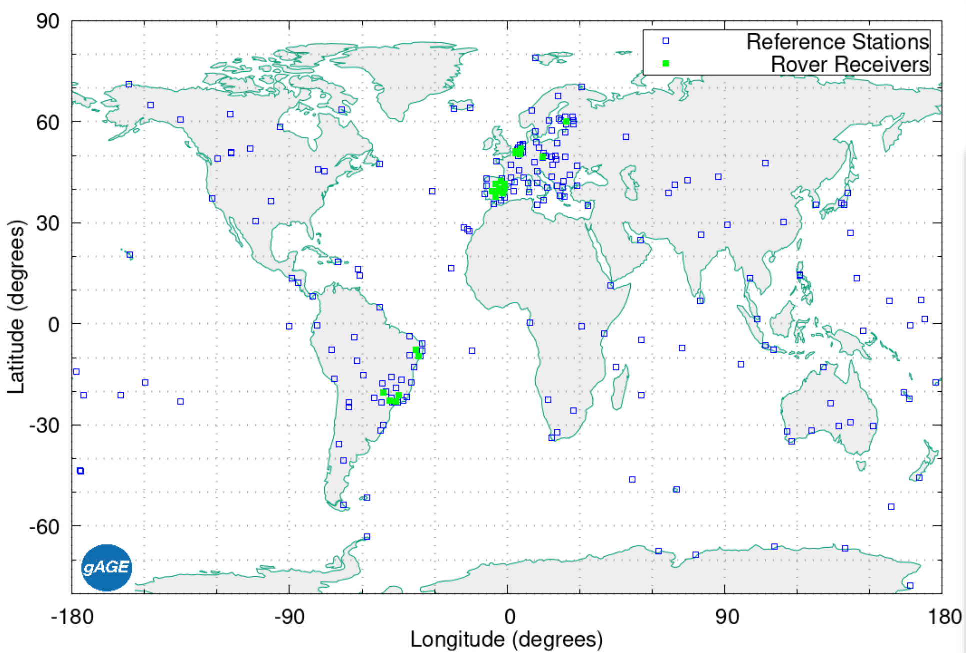
# **2. The IONO4HAS CPF:** Measurements Modelling

**Measurements Modelling**

✓Outliers removal
✓Cycle slip detection
✓Modelling (cm level)

**Geodetic Filter**

**Ionospheric Filter**



GNSS data streams providers

*IGS*
***EUREF***
*AUSCORS*

*IBGE*
*RAMSAC*
*IGM*
*UNAVCO*

IONO4HAS NETWORK FEATURES

- ✓ up to 200 GNSS streams on a daily basis
- ✓ 5 seconds rate
- ✓ Multi-constellation: GPS,GAL,GLO,BDS
- ✓ 21 permanent stations profiled as rover receivers (users):
  - European sub-networks latitudes:
    *Mid* (35° and 45°)
    *Mid-high* (45° and 55°)
    *High* (59° and 62°)

# 2. The IONO4HAS CPF: Geodetic Filter

**Measurements Modelling**

- ✓Outliers removal
- ✓Cycle slip detection
- ✓Modelling (cm level)

**Geodetic Filter**

- ✓Satellite clocks
- ✓Station clocks
- ✓Tropospheric Residuals
- ✓Phase Biases for Ambiguity Fixing

**Ionospheric Filter**

1

$B_{IF}$ ambiguity in the Ionospheric-free combination

$B_{WL}$ ambiguity in the Wide lane combination

2

$B_{GF}$ ambiguity in the Geometry-free combination

$B_{IF}$

$B_{WL}$

$B_{GF} = \alpha[B_{WL} - B_{IF}]$

$$L_{GF}{}^{sat}_{rec} - B_{GF}{}^{sat}_{rec} = STEC^{sat}_{rec} + DCB_{rec} + DCB^{sat}$$

These **unambiguous** Geometry-free combinations of **carrier phases** are the main input for the ionospheric filter

# **2. The IONO4HAS CPF:** Ionospheric Filter

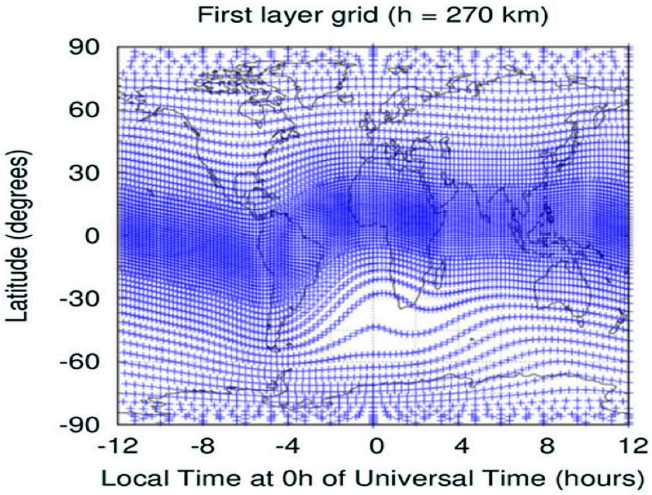
**Measurements Modelling**
- ✓Outliers removal
- ✓Cycle slip detection
- ✓Modelling (cm level)

**Geodetic Filter**
- ✓Satellite clocks
- ✓Station clocks
- ✓Tropospheric Residuals
- ✓Phase Biases for Ambiguity Fixing

**Ionospheric Filter**
- ✓**VTEC**
- ✓**DCBs**

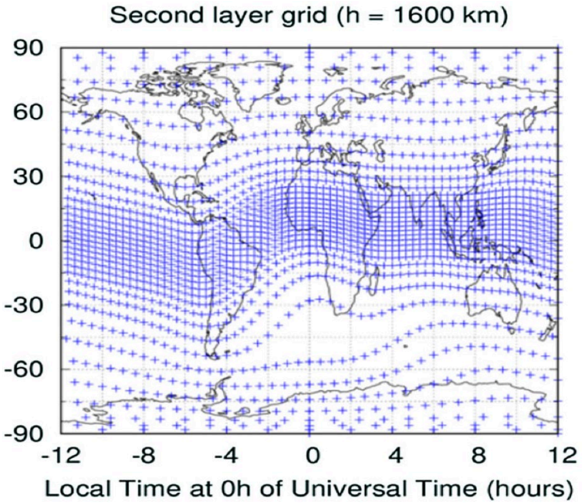
A two-layer model of the ionosphere mainly feed with unambiguous carrier phases

First layer
*main ionospheric content*



Constant **MODIP** lines

Second layer
*plasmaspheric content*



**MOdied DIP** latitude (MODIP)
(related to geomagnetic field)

# 2. The IONO4HAS CPF: Ionospheric Modelling

**Measurements Modelling**
- ✓Outliers removal
- ✓Cycle slip detection
- ✓Modelling (cm level)

**Geodetic Filter**
- ✓Satellite clocks
- ✓Station clocks
- ✓Tropospheric Residuals
- ✓Phase Biases for Ambiguity Fixing

**Ionospheric Filter**
- ✓**VTEC**
- ✓**DCBs**

The unambiguous carrier-phase measurements ( $L_{GF}{}^{sat}_{rec} - B_{GF}{}^{sat}_{rec}$ ) are separated in the ionospheric delay term (STEC) and hardware biases (DCBs).

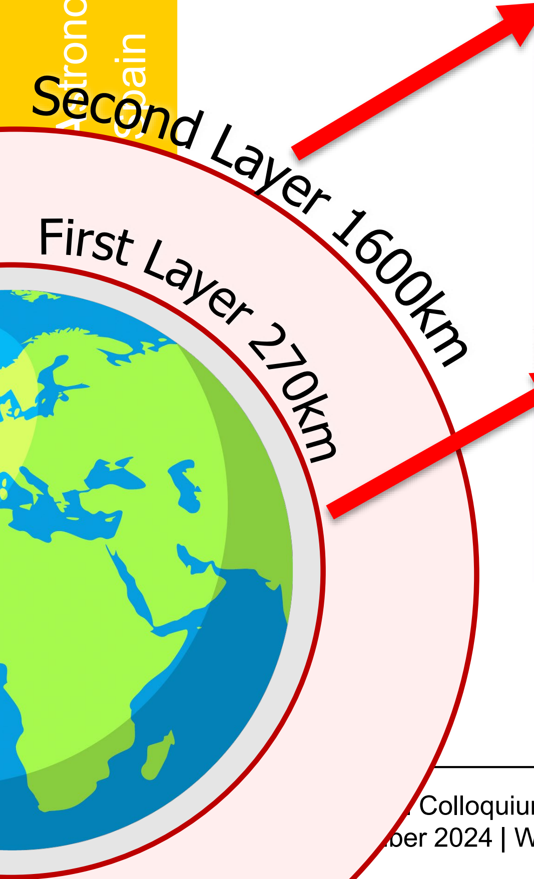
$$L_{GF}{}^{sat}_{rec} - B_{GF}{}^{sat}_{rec} = STEC^{sat}_{rec} + DCB_{rec} + DCB^{sat}$$

The STEC is decorrelated for DCBs with a two layers ionospheric grid model

were:

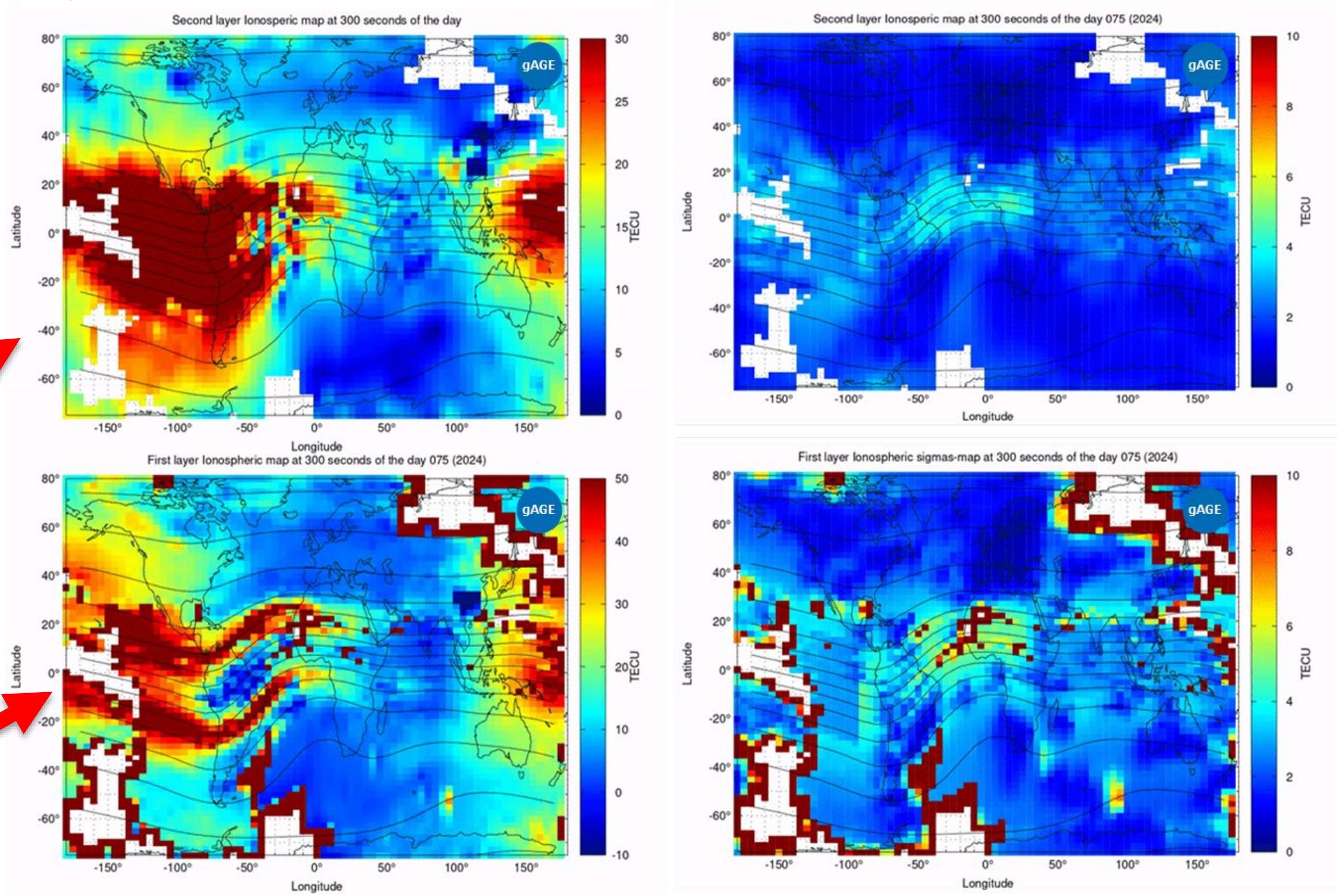
$$STEC^{sat}_{rec} = M_1(\epsilon)\sum_{i=1}^{4}\alpha_i \cdot V_i + M_2(\epsilon)\sum_{j=1}^{4}\beta_j \cdot V_j$$

# 2. The IONO4HAS CPF: Ionospheric Modelling



$V_i$ (Vertical Electron Content)

SIGMA_$V_i$


Second layer Ionosperic map at 300 seconds of the day

Second layer Ionosperic map at 300 seconds of the day 075 (2024)

First layer Ionospheric map at 300 seconds of the day 075 (2024)

First layer Ionospheric sigmas-map at 300 seconds of the day 075 (2024)

$$STEC_{rec}^{sat} = M_1(\epsilon)\sum_{i=1}^{4}\alpha_i \cdot V_i + M_2(\epsilon)\sum_{j=1}^{4}\beta_j \cdot V_j$$

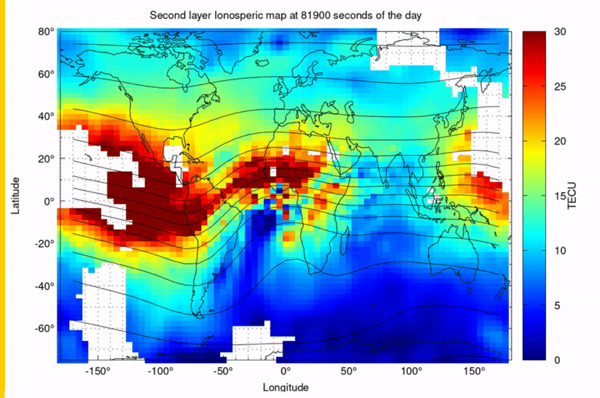
# Monitoring the ionosphere during the geomagnetic storm on May 10, 2024

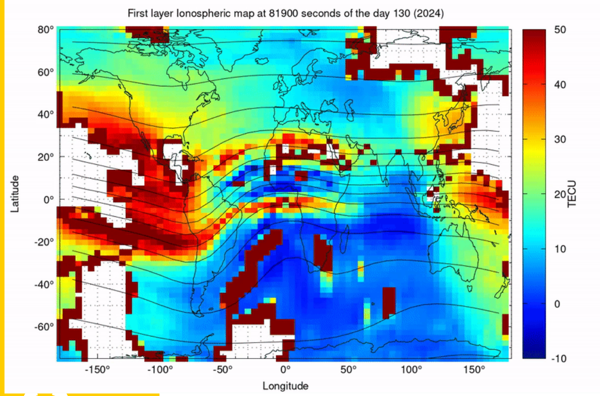
NASA's Solar Dynamics Observatory (SDO) captured this image of an X5.8 solar flare peaking at 9:23 p.m. EDT on May 10, 2024. The image shows a subset of extreme ultraviolet light that highlights the extremely hot material in flares.
NASA SDO

The IONO4HAS CPF has been operating continuously since January 1st 2022 and the processing results are stored in a database. This historical data includes the last geomagnetic storm on May 10, 2024.

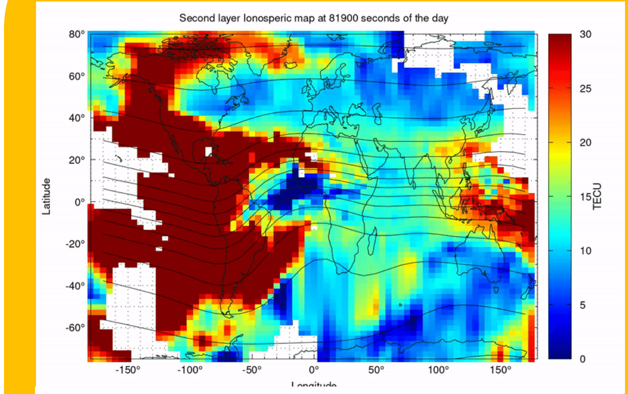
# Monitoring the ionosphere during the geomagnetic storm on May 10, 2024

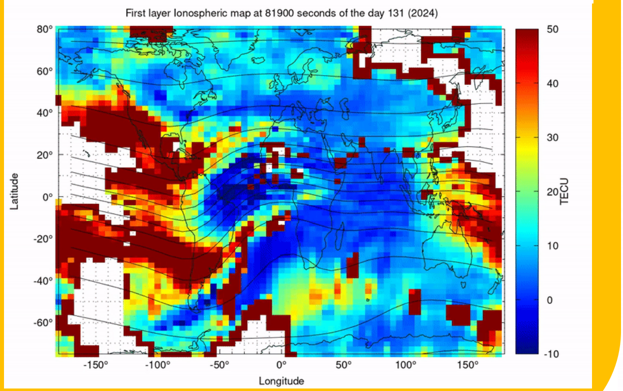
## Thursday (May 9)


Second layer Ionosperic map at 81900 seconds of the day

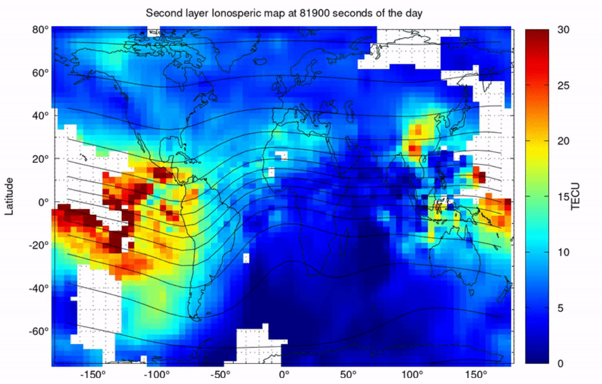

First layer Ionospheric map at 81900 seconds of the day 130 (2024)

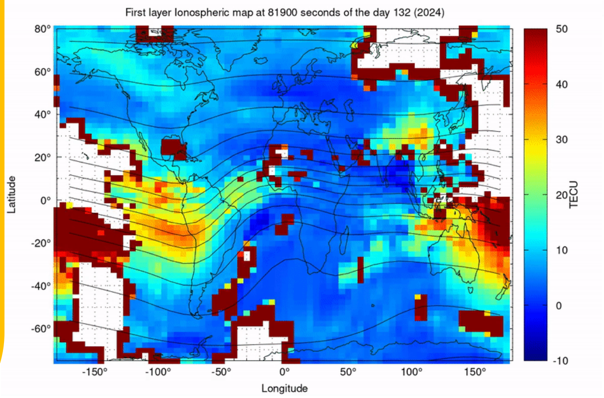
## Friday (May 10)


Second layer Ionosperic map at 81900 seconds of the day


First layer Ionospheric map at 81900 seconds of the day 131 (2024)

## Saturday (May 11)


Second layer Ionosperic map at 81900 seconds of the day


First layer Ionospheric map at 81900 seconds of the day 132 (2024)

At the end of Friday 10th, there is an strong enhancement of electron content in the upper layer, with a plumb around north pole.
On Saturday 11th, the upper layer and also the lower layer appear more emptied.

# 3. Ionospheric corrections assessment tests

Different tests to assess the performance of the computed corrections in both Signal-In-Space (SIS) and User Domain (UD).

- **Signal-in-Space (SIS) Test:**
  This test is based in using unambiguous geometry-free combinations of carriers $L_{GF}$.
  These unambiguous carrier combinations ($L_{GF}$) should be equal to the ionospheric model prediction (STEC) except for two hardware biases, one for the satellite and other for the receiver.

$$\boxed{L_{GF}{}_{\boldsymbol{rec}}^{\boldsymbol{sat}} - \alpha\, STEC_{\boldsymbol{rec}}^{\boldsymbol{sat}} = k_{\boldsymbol{rec}} + k^{\boldsymbol{sat}}}$$

  The test consists on estimating these code biases ($k_{\boldsymbol{rec}}, k^{\boldsymbol{sat}}$) and **analyzing the residuals of the fitting** (see Rovira et al. 2021)**. The smaller the better!**

- **User Domain (UD) tests:**
  - **Wide-lane Instantaneous positioning test**:
    This single epoch test is based on navigating with unambiguous wide-lane combinations of carrier phases. Thus, the positioning error is linked to the STEC accuracy (see Timote et al. 2024).
  - **Fast-PPP navigation** (Kalman filter navigation test).
    This test consist in applying the Fast-PPP positioning technique, and asses the convergence time. **The Fast-PPP solution is compared with the PPP one.**

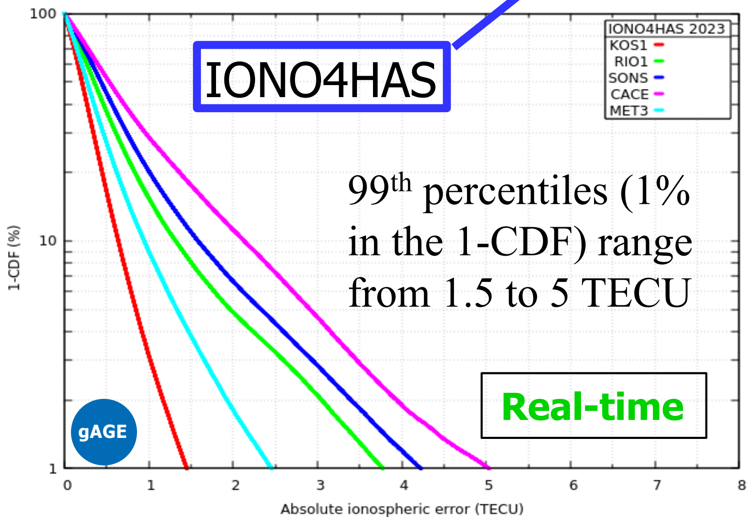
# Signal-in-Space (SIS) Test:

The method uses LS to fit the differences between $L_{GF\,rec}^{\;sat} - \alpha\, STEC_{rec}^{sat}$ for all receivers and satellites during 24 h, to a daily constant per receiver ($k_{rec}$) and a daily constant per satellite ($k^{sat}$):

$$L_{GF\,rec}^{\;sat} - \alpha\, \boxed{STEC_{rec}^{sat}} = k_{rec} + k^{sat}$$

**The metric of the test is the post-fit residuals of the estimated $k$ values obtained with LS.**

$$Res_{rec} = L_{GF\,rec}^{\;sat} - \alpha\, STEC_{rec}^{sat} - \left(\hat{k}_{rec} + \hat{k}^{sat}\right)$$

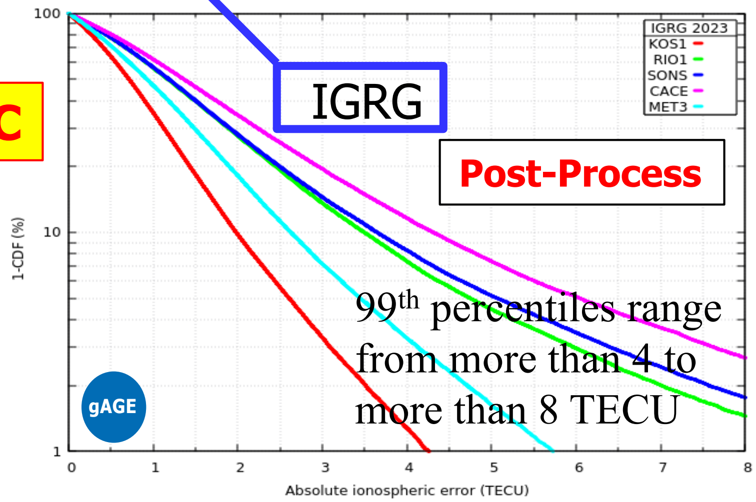


**IONO4HAS**

99th percentiles (1% in the 1-CDF) range from 1.5 to 5 TECU

**Real-time**

**STEC**



**IGRG**

**Post-Process**

99th percentiles range from more than 4 to more than 8 TECU

Data set of 100 days in 2023, from day of the year 200 up to 300

KOS1 in central Europe at around 100 km from the nearest reference receiver.
RIO1 in Spain, at more than 100 km from the nearest reference receiver.
SONS in Spain, at more than 300 km from the nearest reference receiver.
CACE in Spain at more than 400 km from the nearest reference receiver (at East).
MET3 in the Finland Gulf at less than 100 km from the nearest reference receiver.

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Rovira-Garcia A, Juan JM, Sanz J, González-Casado G, Ibáñez-Segura D (2016) "Accuracy of ionospheric models used in GNSS and SBAS: methodology and analysis" Journal of Geodesy 90(3):229-240. DOI 10.1007/s00190-015-0868-3

# User Domain test: Wide-lane Instantaneous positioning test

Once wide-lane ambiguities are fixed:

$$\Delta L_{w}{}_{rcv}^{sat} - \boldsymbol{\alpha}\left(\boldsymbol{STEC}_{rcv}^{sat} + \boldsymbol{DCB}^{sat}\right) = \boldsymbol{G}\,\boldsymbol{\Delta r} + cT_{rcv} + \epsilon_{L_w}$$

Direct link between ionospheric corrections and rover positioning error.

$\Delta L_w$: Residuals of unambiguous wide-lane combination after modelling all non-dispersive effects

$\boldsymbol{G}$: Geometry matrix

$\boldsymbol{\Delta r}$: positioning error

$T_{rcv}$: receiver clock

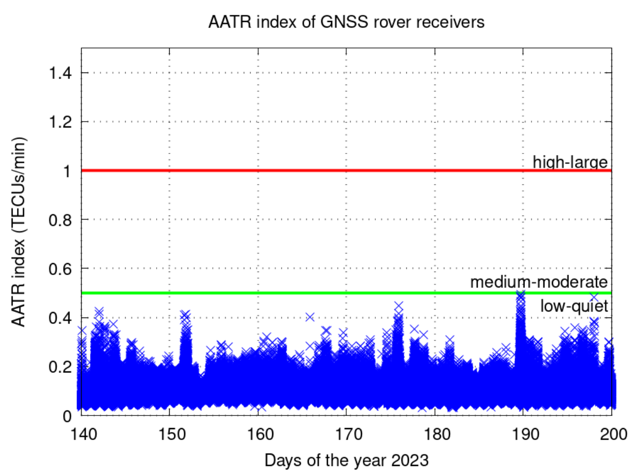
$\epsilon_{L_w}$: noise term

Timoté CC, Juan JM, Sanz J, Rovira-Garcia A, González-Casado G, Orús-Pérez R, Fernández-Hernández I, Blonski D (2024) "Ionospheric corrections tailored to Galileo HAS: validation with single-epoch navigation", GPS Solutions 28(2):A93:1-12

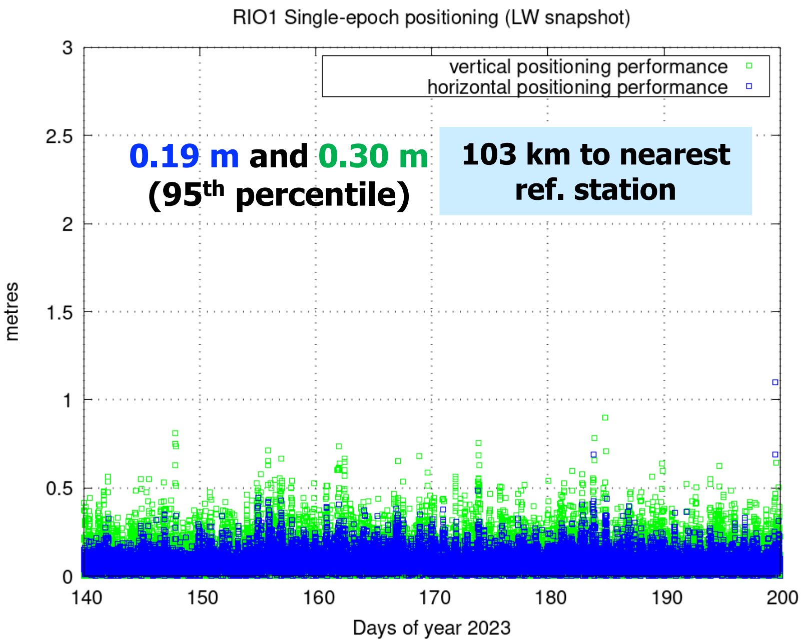
# User Domain test: Wide-lane Instantaneous positioning test

A period with nominal ionosphere was selected to test the prototype: Data window: from DoY 140 up to 200 (2023)

$$\Delta L_{W}{}_{rcv}^{sat} - \boldsymbol{\alpha}(\boldsymbol{STEC_{rcv}^{sat}} + \boldsymbol{DCB^{sat}}) = \boldsymbol{G}\,\boldsymbol{\Delta r} + cT_{rcv} + \epsilon_{L_W}$$



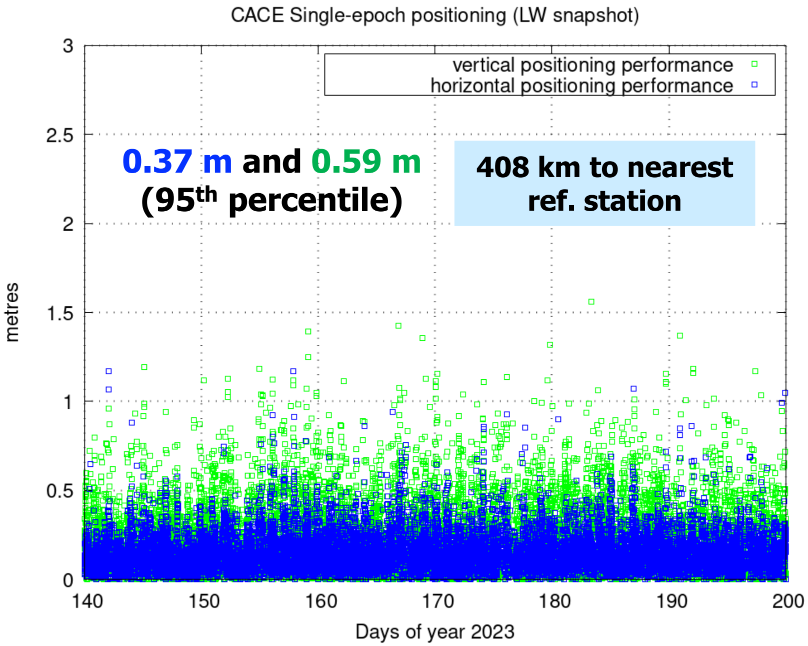
## Real-time Position error due strictly to ionospheric mismodelling



**0.19 m and 0.30 m (95th percentile)**

**103 km to nearest ref. station**

of



**0.37 m and 0.59 m (95th percentile)**

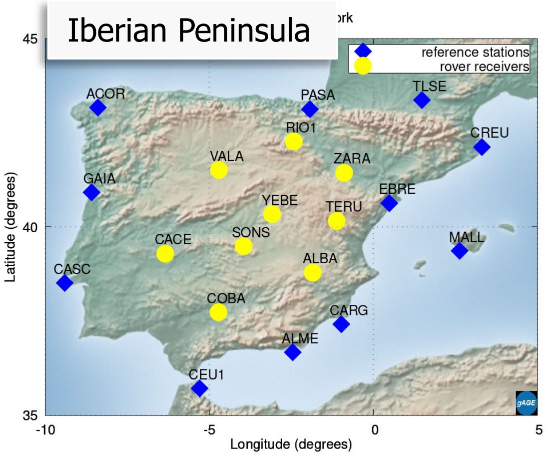
**408 km to nearest ref. station**

**gAGE**

**gAGE/UPC** research group of **Astronomy and Geomatics**
Barcelona**TECH**, Spain

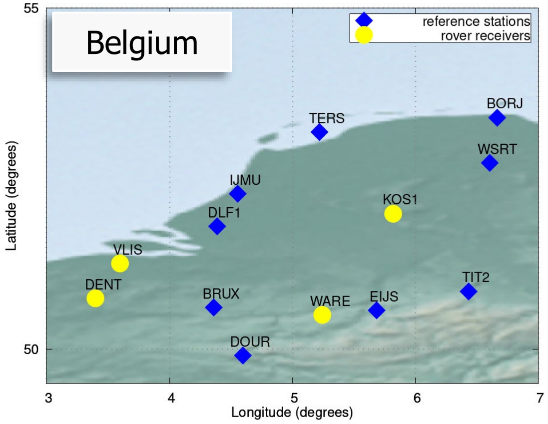
# Performance comparison with other products:

Requirement Galileo HAS (in 100s)
hor. 20 cm
ver. 40 cm



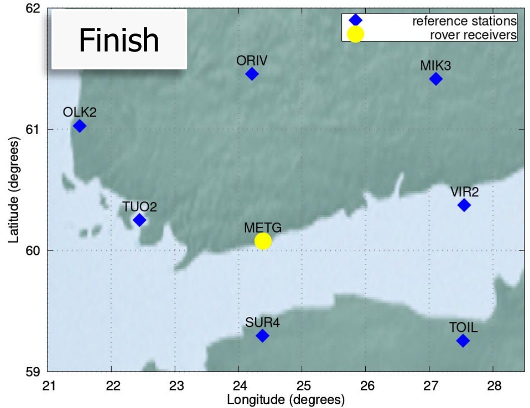
| 95th percentile horizontal error (m) | | |
|---|---|---|
| | IGRG | IONO4HAS |
| RIO1 | 0.58 | 0.19 |
| TERU | 0.61 | 0.21 |
| ZARA | 0.60 | 0.19 |
| ALBA | 0.56 | 0.23 |
| COBA | 0.61 | 0.25 |
| VALA | 0.57 | 0.22 |
| YEBE | 0.65 | 0.22 |
| SONS | 0.62 | 0.25 |
| CACE | 0.71 | 0.32 |

| 95th percentile vertical error (m) | | |
|---|---|---|
| | IGRG | IONO4HAS |
| RIO1 | 0.91 | 0.32 |
| TERU | 1.07 | 0.41 |
| ZARA | 1.00 | 0.32 |
| ALBA | 0.95 | 0.37 |
| COBA | 1.06 | 0.41 |
| VALA | 0.90 | 0.37 |
| YEBE | 1.15 | 0.46 |
| SONS | 1.10 | 0.45 |
| CACE | 1.22 | 0.52 |



| 95th percentile horizontal error (m) | | |
|---|---|---|
| | IGRG | IONO4HAS |
| WARE | 0.56 | 0.12 |
| VLIS | 0.54 | 0.13 |
| DENT | 0.57 | 0.14 |
| KOS1 | 0.59 | 0.12 |

| 95th percentile vertical error (m) | | |
|---|---|---|
| | IGRG | IONO4HAS |
| WARE | 0.92 | 0.18 |
| VLIS | 0.85 | 0.20 |
| DENT | 0.94 | 0.21 |
| KOS1 | 1.00 | 0.19 |



| 95th percentile horizontal error (m) | | |
|---|---|---|
| | IGRG | IONO4HAS |
| METG | 0.37 | 0.18 |
| MET3 | 0.61 | 0.19 |

| 95th percentile vertical error (m) | | |
|---|---|---|
| | IGRG | IONO4HAS |
| METG | 0.59 | 0.26 |
| MET3 | 1.08 | 0.29 |

(snapshot) Instantaneous positioning error
(single-epoch navigation with unambiguous WL)

**IGRG: Post-Process ; IONO4HAS: Real-Time**

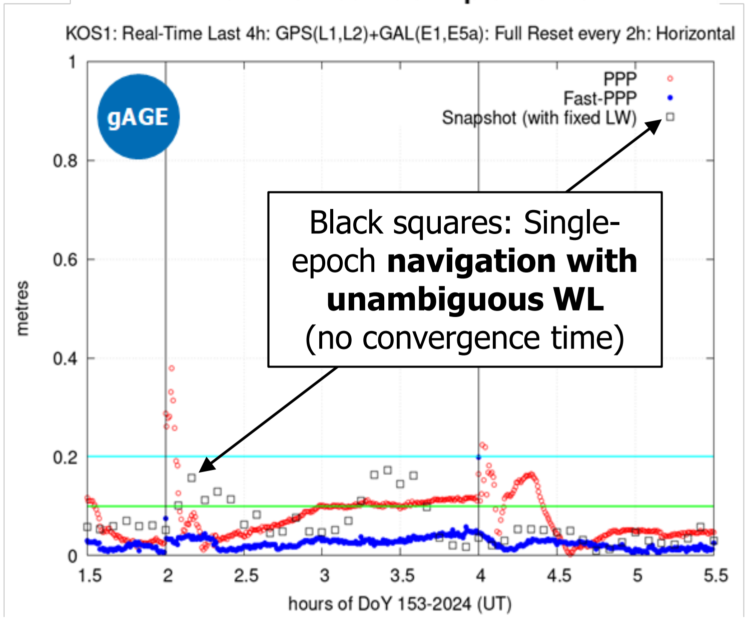
$$\Delta L_{W_{rcv}}^{\ sat} - \boldsymbol{\alpha}(\boxed{STEC_{rcv}^{sat} + DCB^{sat}}) = \mathbf{G}\,\boldsymbol{\Delta r} + cT_{rcv} + \epsilon_{L_W}$$

# User Domain test: Fast-PPP v.s. PPP navigation
(SL2) (SL1)

Requirement Galileo
HAS (in 100s)
hor. 20 cm
ver. 40 cm

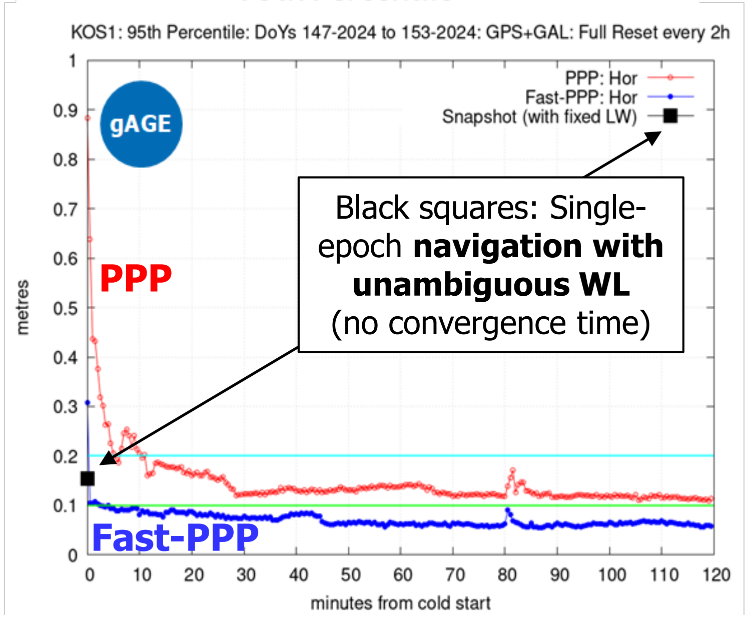
Depicted data corresponds to last 4 hours
Full reset every 2 hours → Statistics during the last 7 days

Horizontal component



Black squares: Single-epoch **navigation with unambiguous WL** (no convergence time)

95th Percentile



Black squares: Single-epoch **navigation with unambiguous WL** (no convergence time)

Example of performance at the user level of kinematic positioning for DENT station with Classical PPP (red), Fast-PPP (blue) and Single-Epoch positioning (Snapshot) with Wide-Lane fixed (black squares). Left hand plot shows the Horizontal component error as a function of time, resetting navigation filter every two hours. Right hand plot shows 95th percentile of horizontal error, as a function of elapsed time from the cold start filter reset, computed over one-week solutions (25 May to 1 June 2024).

**Only IONO4HAS CPF products are used** for the data processing

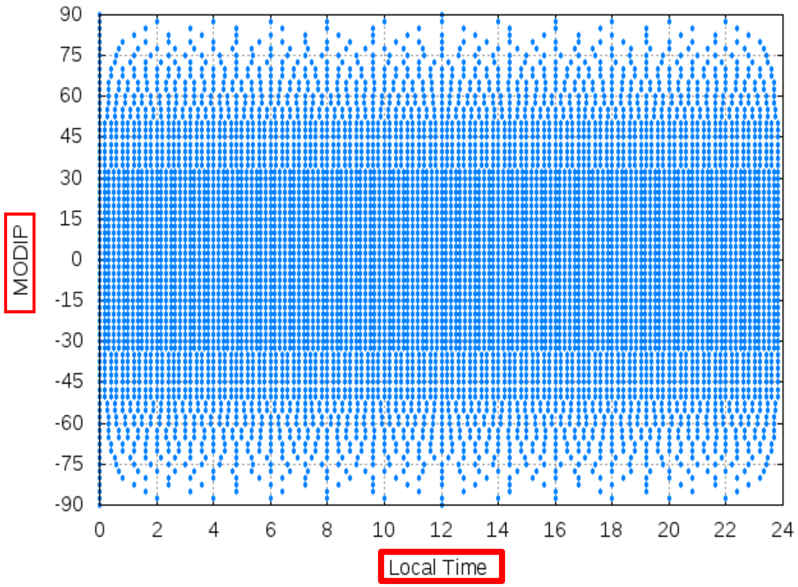
# 4.- The selected ionospheric model for Galileo HAS SL2

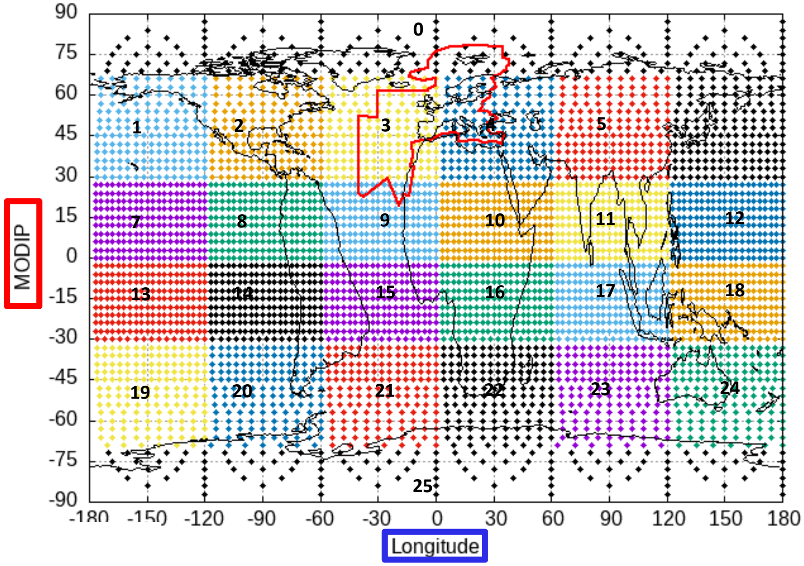
Thanks to the successful results of IONO4HAS project, the IONO4HAS ionospheric model has been selected for the Galileo HAS SL2 (see *Galileo High Accuracy Service E6-B Signal-In-Space Message Specification for Phase 2, Issue/ver. 1.0, 25/04/2024, EC/EUSPA/ESA*).

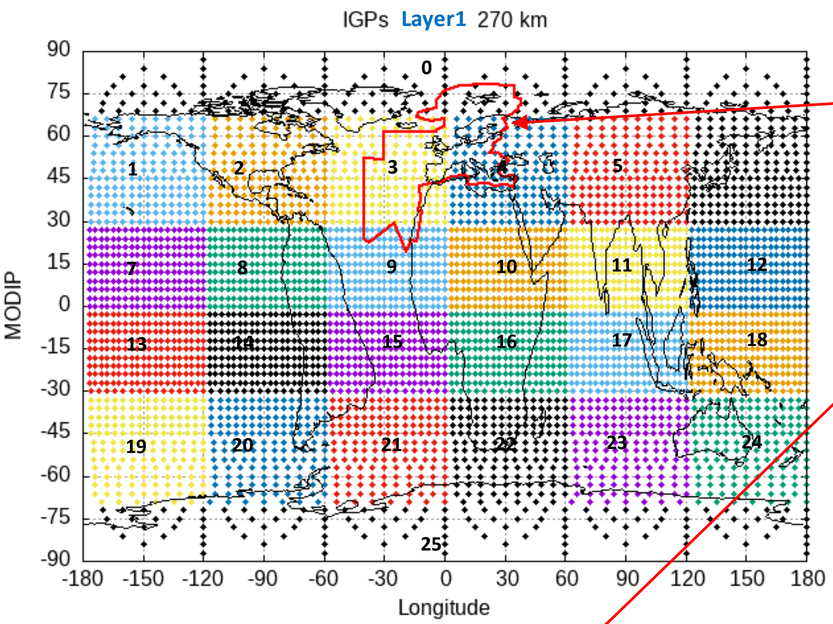
Minor upgrades were introduced, due to limitations in infrastructure and bandwidth:

- **The distribution of the reference stations** for computing the HAS corrections (close to 200 from public servers in IONO4HAS worldwide distributed).
- **The grid step for MODIP**:
  - IONO4HAS baseline : 2.5º (1st layer) and 5.0º (2nd layer)
  - Galileo HAS SL2: 3.0º (1st layer) and 6.0º (2nd layer)

IGPs of layer 2 are a subset of layer 1 IGPs



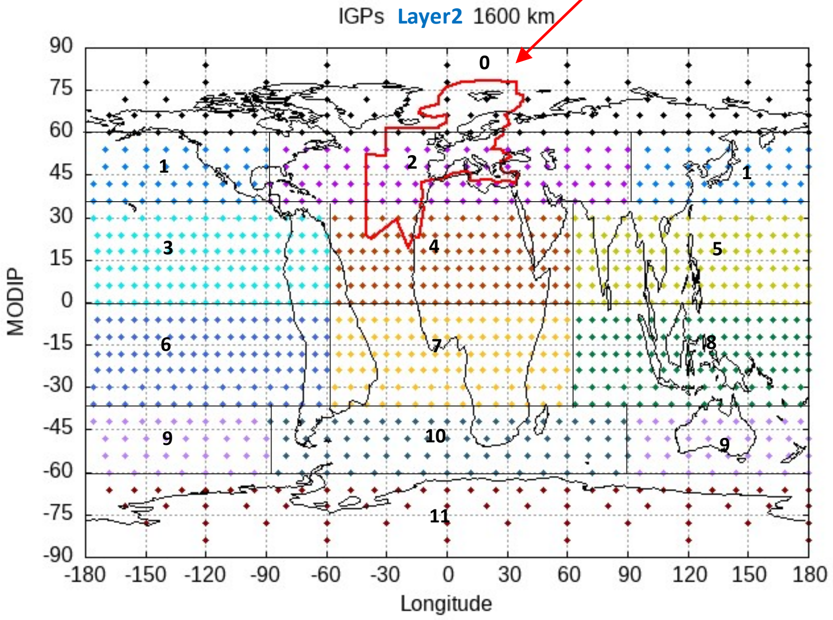




166 IGP0_BN00 [64%]
166 IGP0_BN01
166 IGP0_BN02
**166 IGP0_BN03 [96%]**
**166 IGP0_BN04 [81%]**
166 IGP0_BN05
166 IGP0_BN06
200 IGP0_BN07
200 IGP0_BN08
**200 IGP0_BN09 [70%]**
200 IGP0_BN10
200 IGP0_BN11
200 IGP0_BN12
195 IGP0_BN13
195 IGP0_BN14
195 IGP0_BN15
195 IGP0_BN16
195 IGP0_BN17
195 IGP0_BN18
157 IGP0_BN19
158 IGP0_BN20
158 IGP0_BN21
157 IGP0_BN22
158 IGP0_BN23
158 IGP0_BN24.
126 IGP0_BN25.
**4604 total IGPs Layer 1**

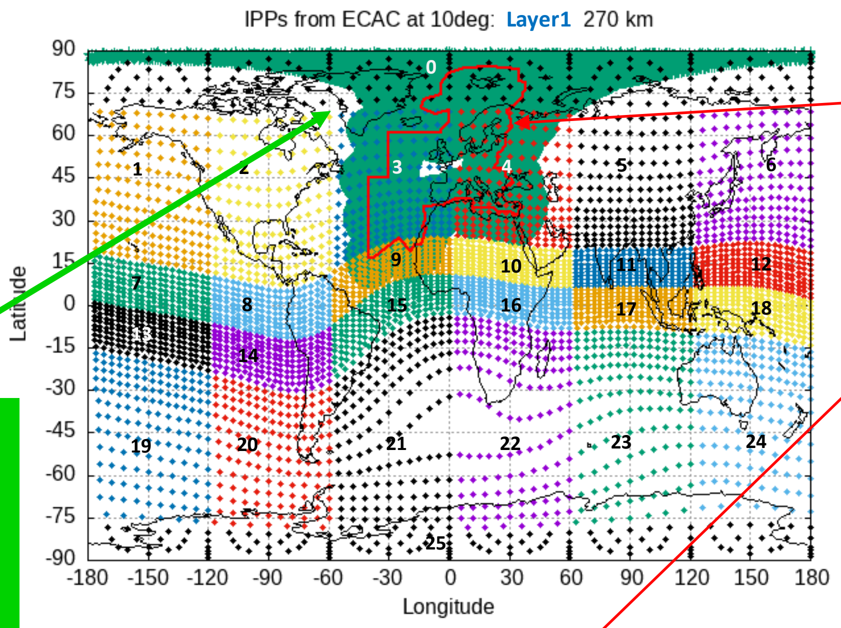
**ECA area**

**IGPs are split in different Block-Masks**



**96 IGP1_BN00:** (0 NM) **100%**
80 IGP1_BN01:
**82 IGP1_BN02:** (7 NM) **90%**
115 IGP1_BN03: ( 13 to Monitor)
**115 IGP1_BN04:** ( 0 NM) **100%**
115 IGP1_BN05: ( 4 to monitor)
110 IGP1_BN06:
**110 IGP1_BN07:** (38 NM) **65%**
110 IGP1_BN08
73 IGP1_BN09
74 IGP1_BN10
66 IGP1_BN11

**1146 total IGPs Layer 2**

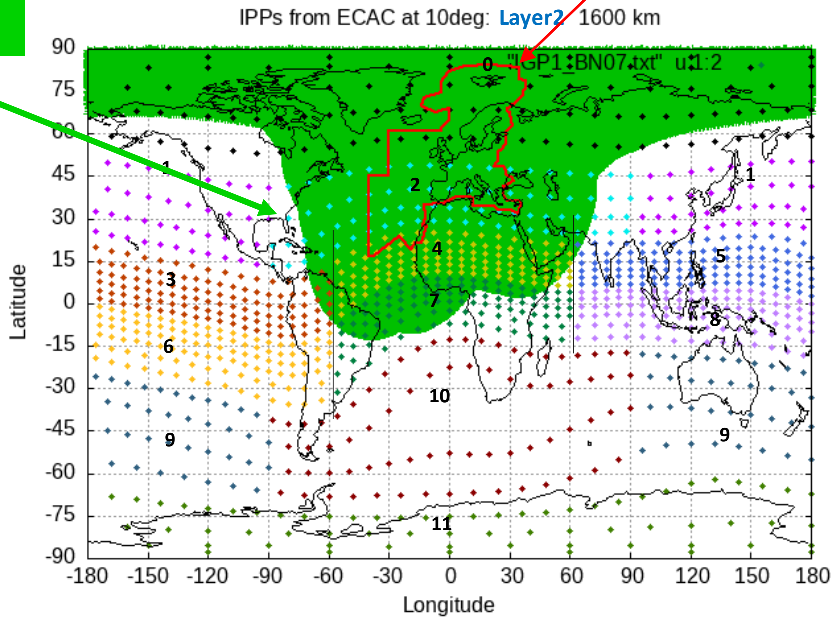


**166 IGP0_BN00 [64%]**
166 IGP0_BN01
166 IGP0_BN02
**166 IGP0_BN03 [96%]**
**166 IGP0_BN04 [81%]**
166 IGP0_BN05
166 IGP0_BN06
200 IGP0_BN07
200 IGP0_BN08
**200 IGP0_BN09 [70%]**
200 IGP0_BN10
200 IGP0_BN11
200 IGP0_BN12
195 IGP0_BN13
195 IGP0_BN14
195 IGP0_BN15
195 IGP0_BN16
195 IGP0_BN17
195 IGP0_BN18
157 IGP0_BN19
158 IGP0_BN20
158 IGP0_BN21
157 IGP0_BN22
158 IGP0_BN23
158 IGP0_BN24.
126 IGP0_BN25.
**4604 total IGPs Layer 1**

**BN00+BN03+BN04+BN09:**
**698** (157 NM)**: 78%]**

**ECA area**

IPPs for rays down to 10° of elevation for receivers in ECA area.



**96 IGP1_BN00:** (0 NM) **100%**
80 IGP1_BN01:
**82 IGP1_BN02:** (7 NM) **90%**
115 IGP1_BN03: ( 13 to Monitor)
**115 IGP1_BN04:** ( 0 NM) **100%**
115 IGP1_BN05: ( 4 to monitor)
110 IGP1_BN06:
**110 IGP1_BN07:** (38 NM) **65%**
110 IGP1_BN08
73 IGP1_BN09
74 IGP1_BN10
66 IGP1_BN11

**1146 total IGPs Layer 2**

**BN00+BN02+BN04+B07:**
**403** (45 NM)**: 89%]**

**ECA predefined Ion Mask:**
Required grid points in Layer 1 and Layer 2 to provide Ionospheric parameters down to 10° of elevation for receivers in ECA area.

# 5.- Conclusions:

- The Galileo High Accuracy Positioning Service (HAS) is an existing capability of Galileo, the European Global Navigation Satellite System (GNSS), to offer user positioning with decimeter-level accuracy, employing multiple constellations.

  Available since January 2023, Galileo HAS is a global precise point positioning (PPP) service, to be deployed in two service levels:
  - Service Level 1 (SL1) comprises satellite orbit and clock corrections (i.e. non-dispersive effects), and dispersive effects such as code and phase biases.
  - Service Level 2 (SL2) incorporates ionospheric corrections for Fast-PPP navigation (at least over Europe).

- In the context of the ESA project ESA Real-Time Ionospheric Continental Caster (eRTICC) project, gAGE/UPC has developed and deployed the IONO4HAS CPF: *A Real-Time Implementation of an Ionospheric Model for Galileo High Accuracy Service, SL2.*

- Thanks to the successful results of IONO4HAS project, the IONO4HAS ionospheric model has been selected for the Galileo HAS SL2.

  IONO4HAS CPF is not only generating the ionospheric corrections, but also precise satellite and receiver clocks, code and carrier phase biases, among other parameters, which would correspond to the HAS SL1 corrections data, allowing to navigate the user receiver in PPP, and in Fast-PPP (i.e. SL2) mode with the ionospheric corrections.

# More details in:

- Timoté CC, Juan JM, Sanz J, Rovira-Garcia A, González-Casado G, Orús-Pérez R, Fernández-Hernández I, Blonski D (2024) "Ionospheric corrections tailored to Galileo HAS: validation with single-epoch navigation", GPS Solutions 28(2):A93:1-12, DOI 10.1007/s10291-024-01630-w
- Rovira-Garcia A, Timoté CC, Juan JM, Sanz J, Gonzalez-Casado G, Fernández-Hernández I, Orus R, Blonski D (2021) "Ionospheric corrections tailored to the Galileo High Accuracy Service" Journal of Geodesy 95(12):A130:1-14. DOI 10.1007/s00190-021-01581-x
- Rovira-Garcia A, Ibánez D, Orus R, Juan JM, Sanz J, González-Casado G (2020) "Assessing the quality of ionospheric models through GNSS positioning error: Methodology and Results" GPS Solutions 24(1):A4:1-12. DOI 10.1007/ s10291-019-0918-z
- Rovira-Garcia A, Juan JM, Sanz J, González-Casado G, Ibáñez-Segura D (2016) "Accuracy of ionospheric models used in GNSS and SBAS: methodology and analysis" Journal of Geodesy 90(3):229-240. DOI 10.1007/s00190-015-0868-3
- Rovira-Garcia A, Juan JM, Sanz J, Gonzalez-Casado G (2015) "A Worldwide Ionospheric Model for Fast Precise Point Positioning" IEEE Transactions on Geoscience and Remote Sensing 53(8):4596-4604. DOI 10.1109/ TGRS.2015.2402598

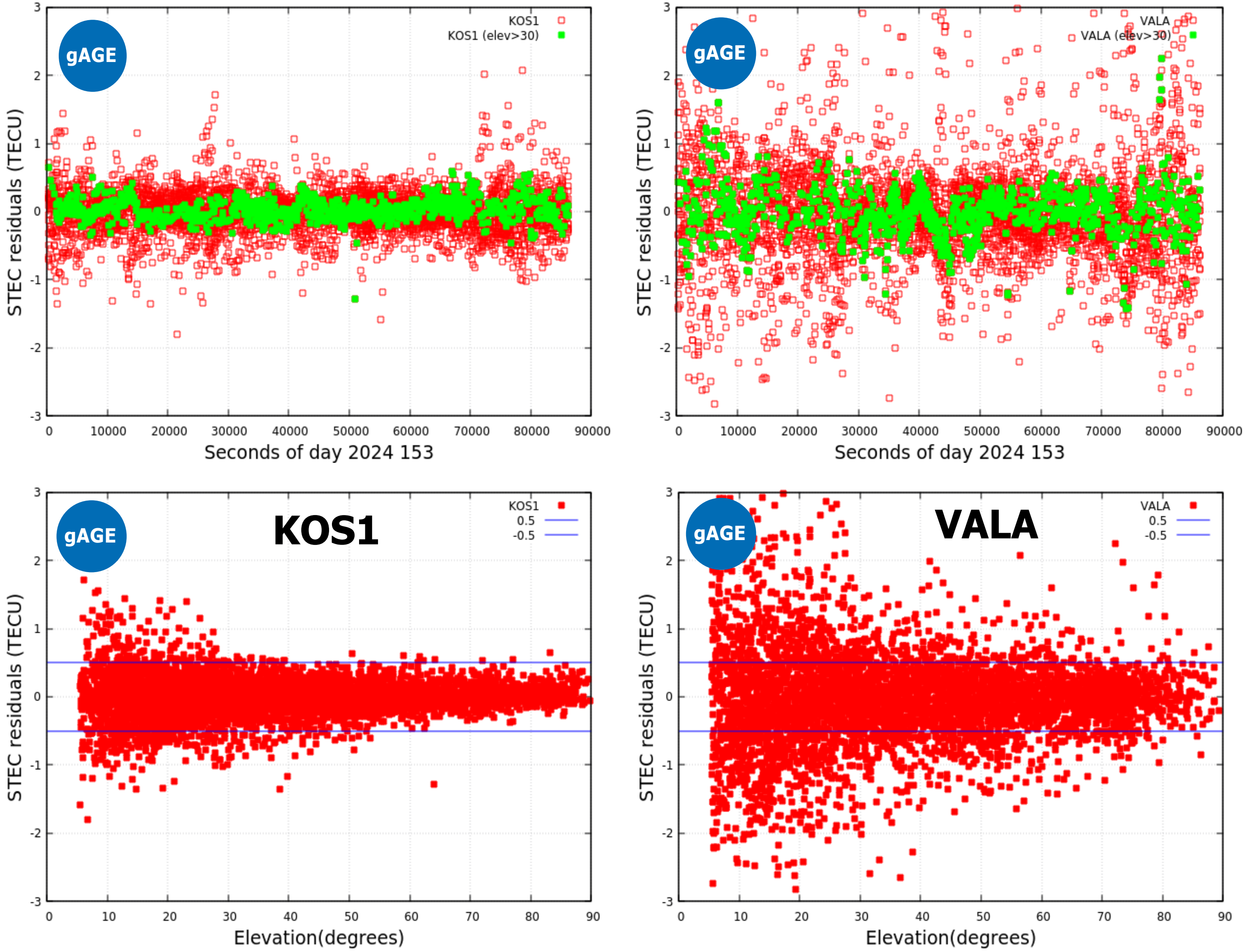
# Thank you !!

gAGE/UPC

*Research group of Astronomy & Geomatics*
**Technical University of Catalonia, Spain**
**http://www.gage.upc.edu**

**Contact: jaume.sanz@upc.edu**
**Campus Nord UPC Jordi Girona 1-3, 08034 Barcelona (Spain).**

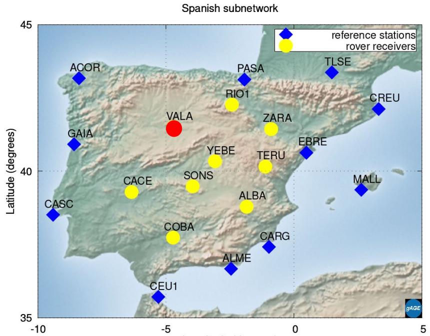
# Back up slides



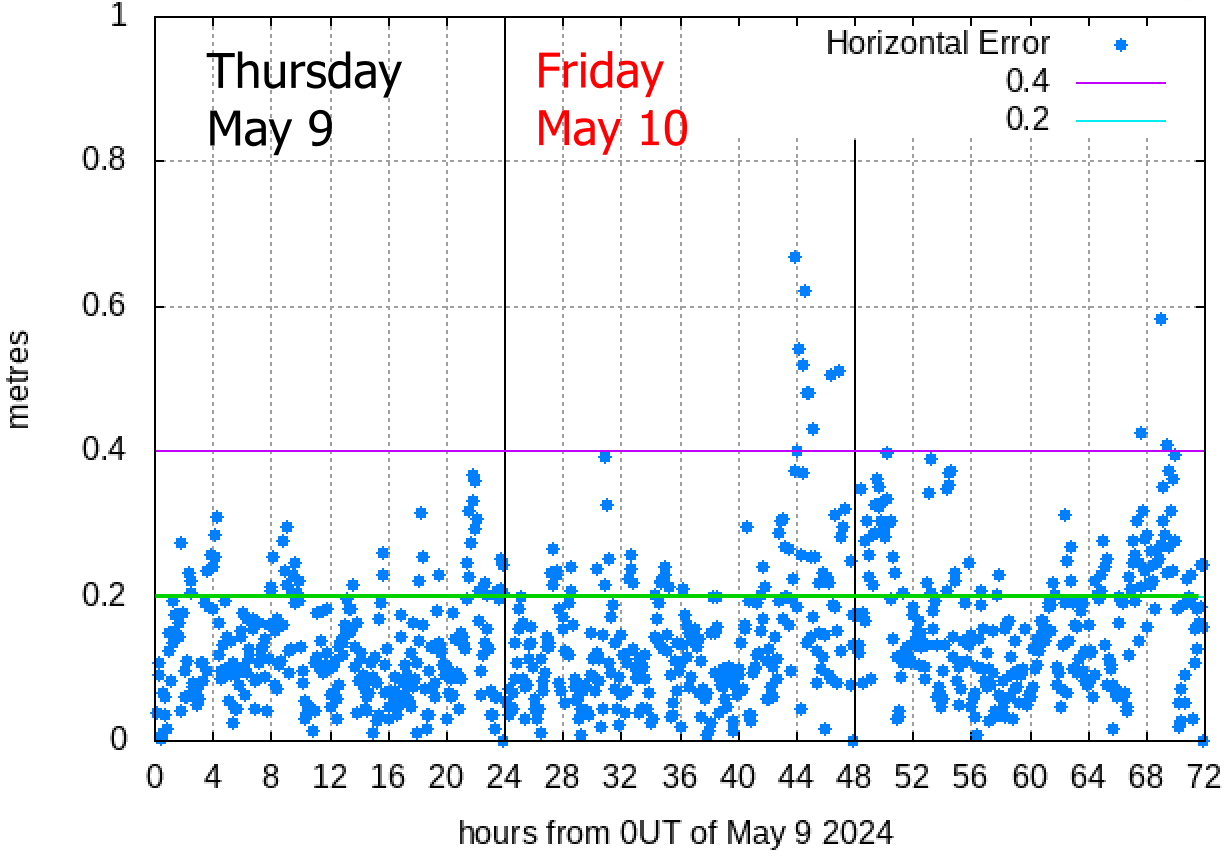
IONO4HAS Central Processing Facility SIS Ionosphere Test: Slant Total Electron Content (STEC) error for the rover receiver KOS1 (100 km from the nearest sta. ) and VALA (around 300 km), in TECUs for 24 hours in 1st June 2024. In green are depicted the STEC residuals for elevation high than 30 deg. Top row plots show the residuals as a function of time. Bottom row plots are as a function of elevation.

# 2024 May storm

## IONO4HAS



VALA: Single epoch positioning (LW snapshot)



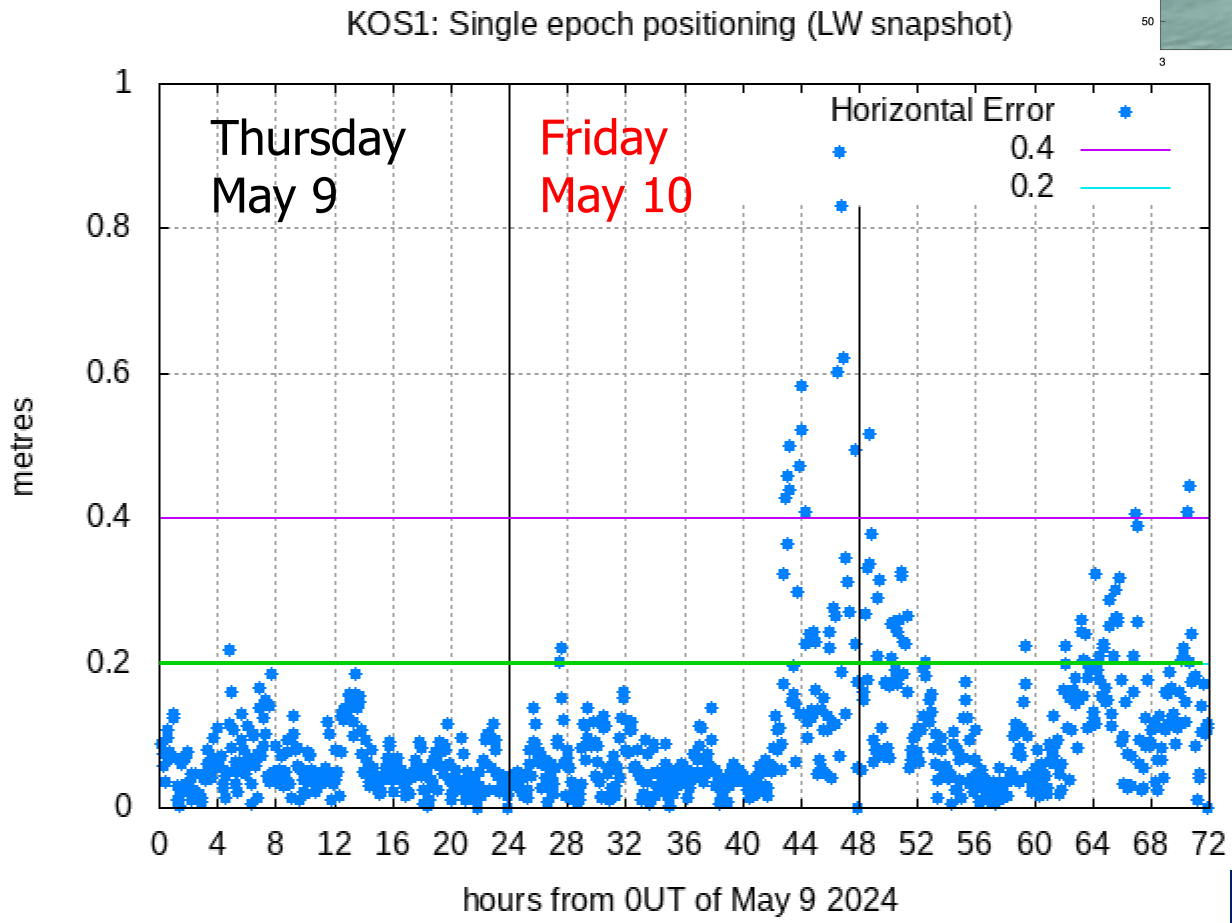
Iberian Peninsula

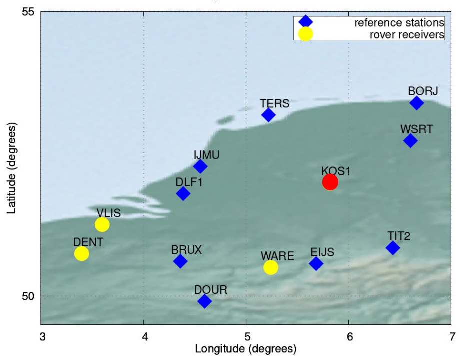
**300km**

Requirement Galileo HAS (in 100s)
hor. 20 cm
ver. 40 cm

# 2024 May storm

## IONO4HAS





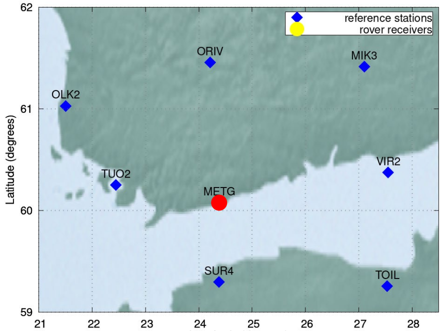
Belgium

**100km**

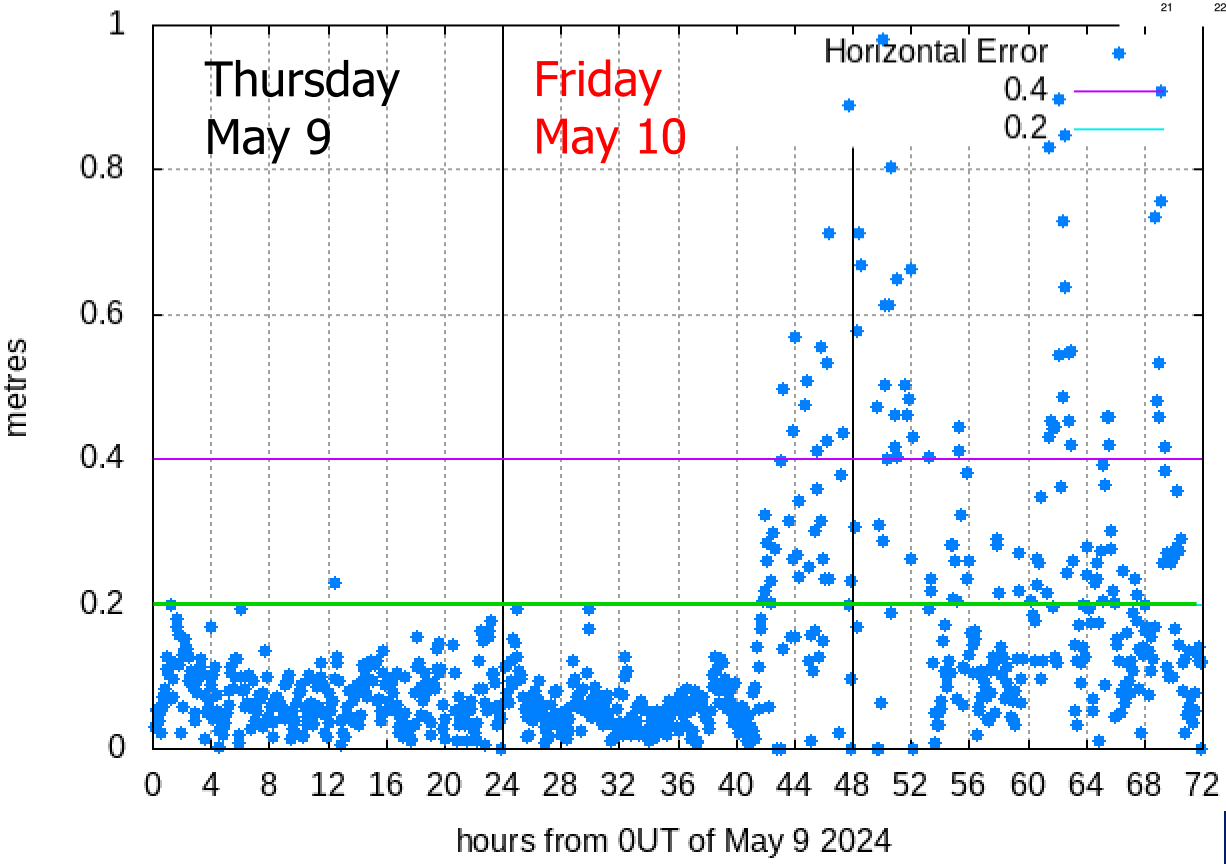
Requirement Galileo HAS (in 100s)
hor. 20 cm
ver. 40 cm

# 2024 May storm

## IONO4HAS



METG: Single epoch positioning (LW snapshot)



Finish

**90km**

Requirement Galileo HAS (in 100s)
hor. 20 cm
ver. 40 cm

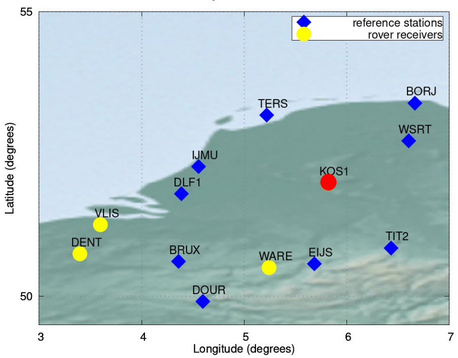
# 2024 May storm navigation results

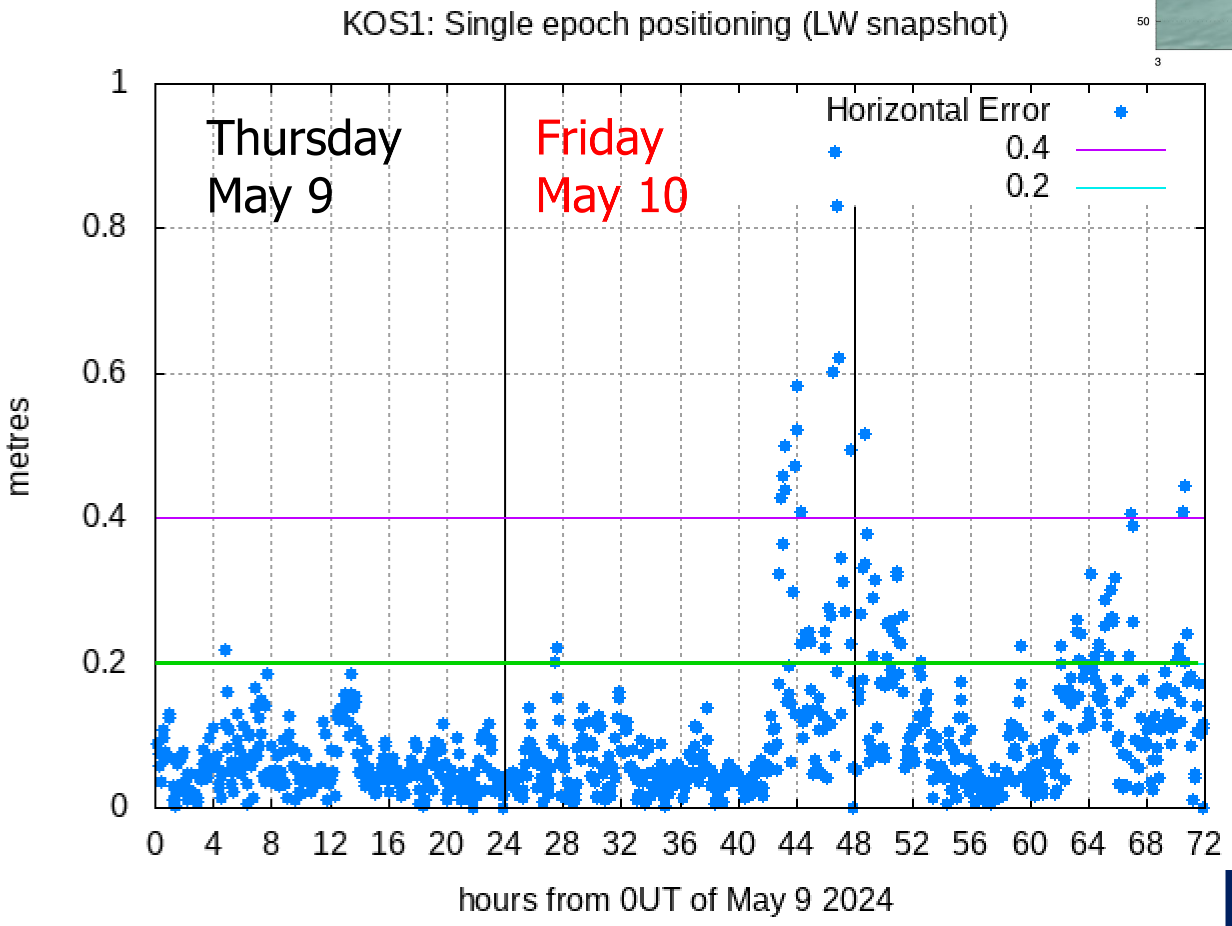
gAGE

gAGE/UPC research group of Astronomy and Geomatics
BarcelonaTECH, Spain

# 2024 May storm

## IONO4HAS





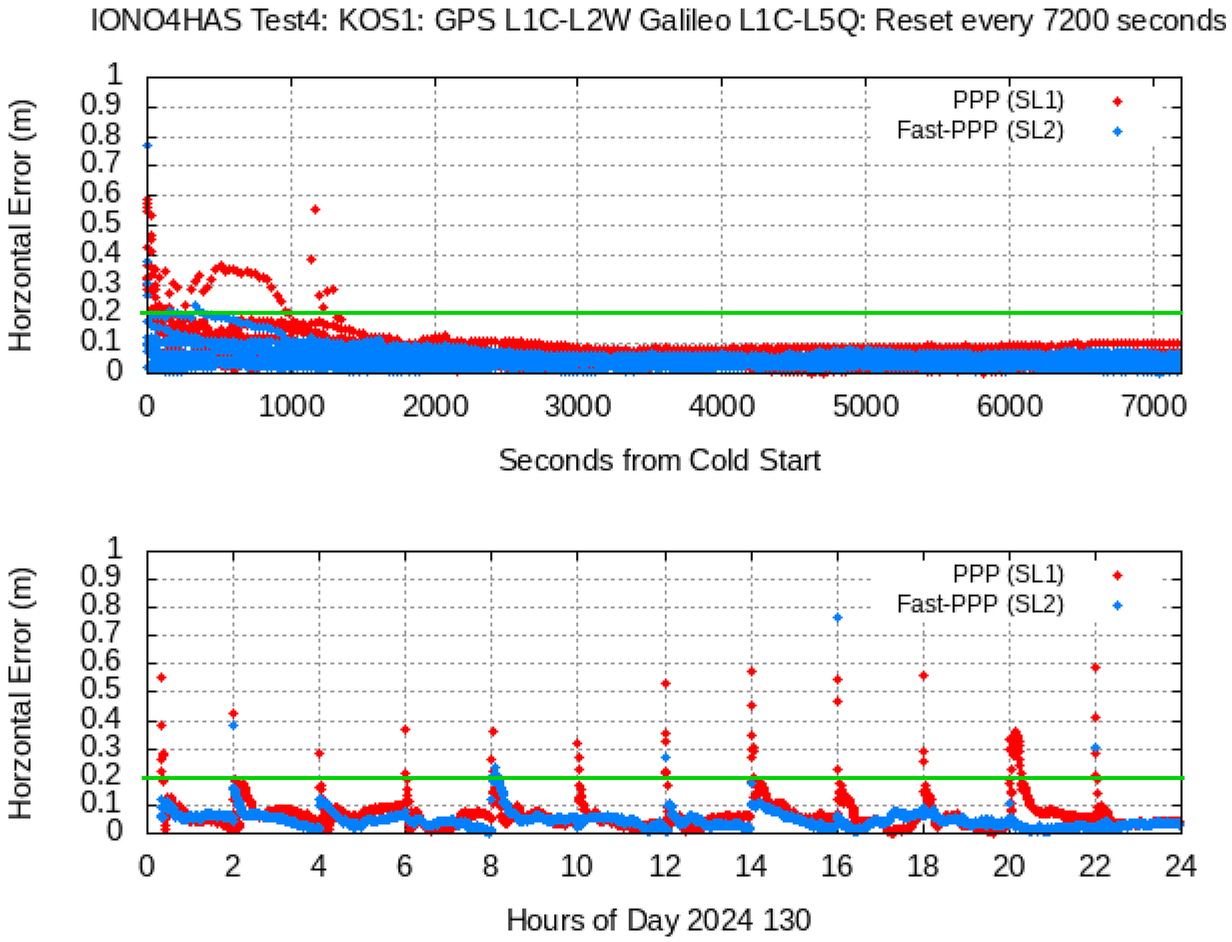
Belgium

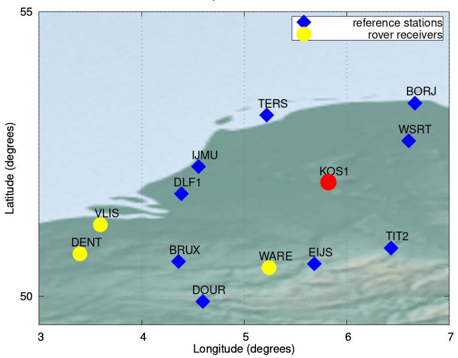
**100km**

Requirement Galileo HAS (in 100s)
hor. 20 cm
ver. 40 cm

# 2024 May storm

## Day before Storm (Thursday, May 9)





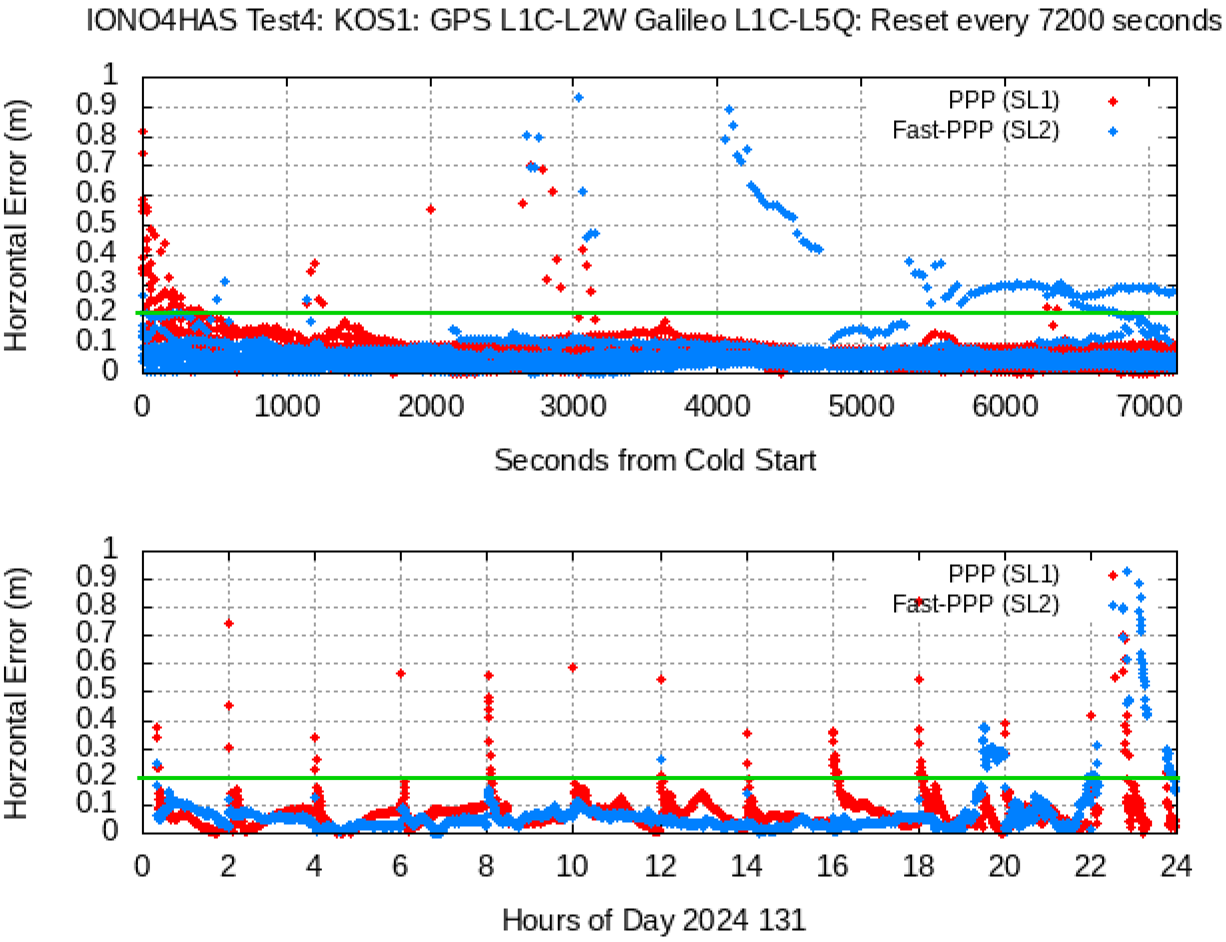
Belgium

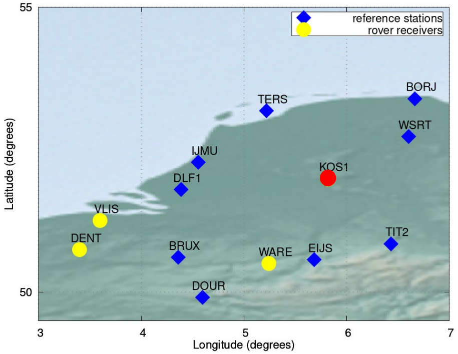
100km

Requirement Galileo HAS (in 100s)
hor. 20 cm
ver. 40 cm

# 2024 May storm

## Storm day (Friday, May 10)





Belgium

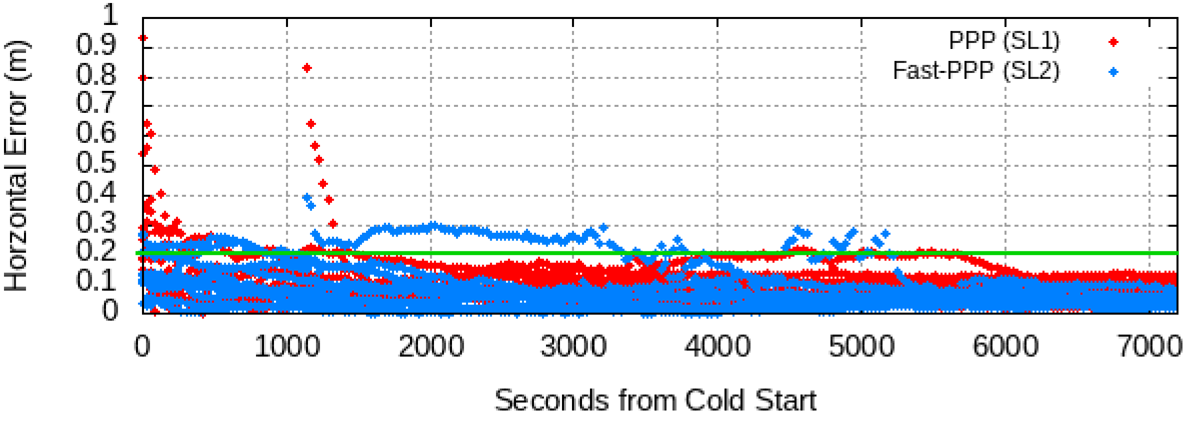
**100km**

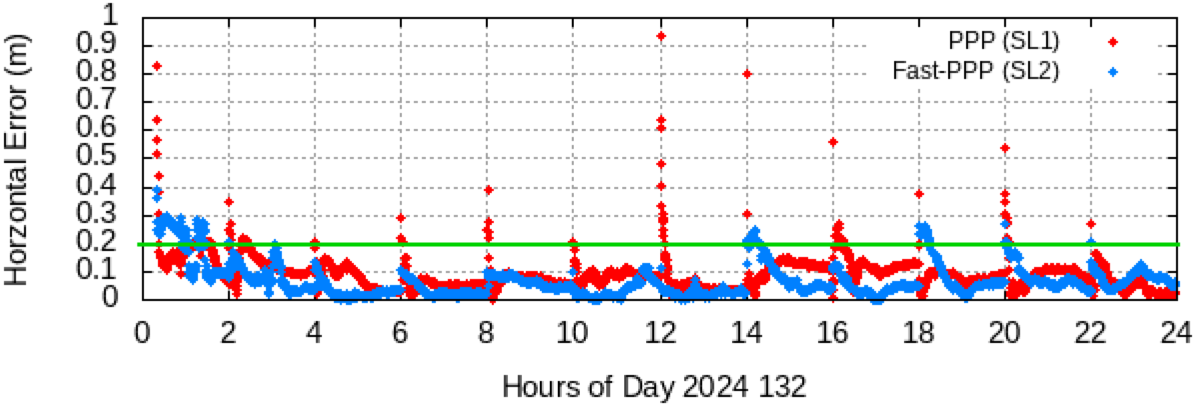
Requirement Galileo HAS (in 100s)
hor. 20 cm
ver. 40 cm

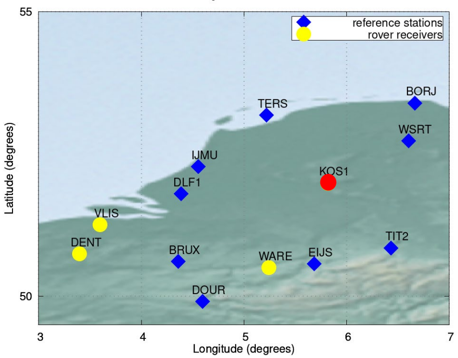
# 2024 May storm

## Day after (Thursday, May 11)

IONO4HAS Test4: KOS1: GPS L1C-L2W Galileo L1C-L5Q: Reset every 7200 seconds







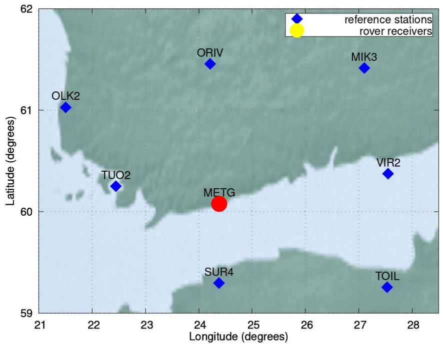
Belgium

**100km**

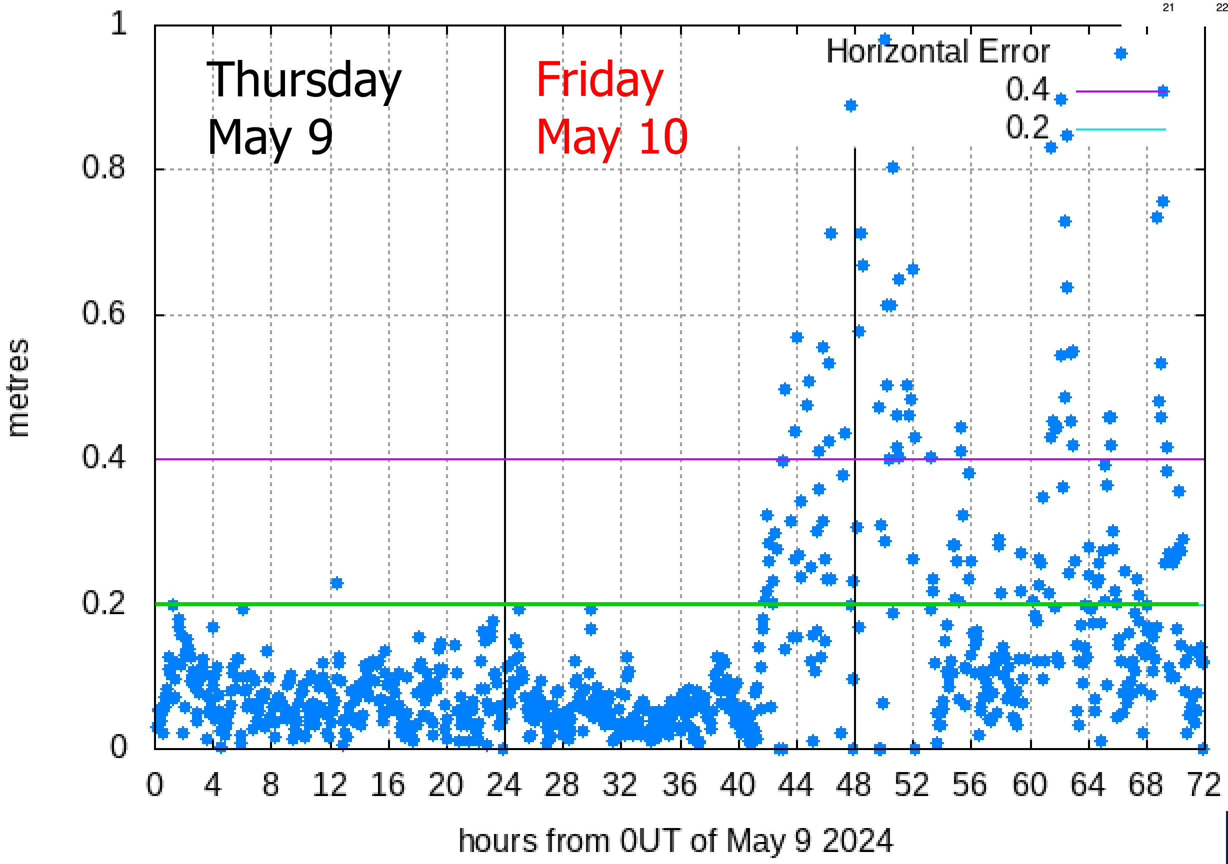
Requirement Galileo HAS (in 100s)
hor. 20 cm
ver. 40 cm

# 2024 May storm

## IONO4HAS



METG: Single epoch positioning (LW snapshot)



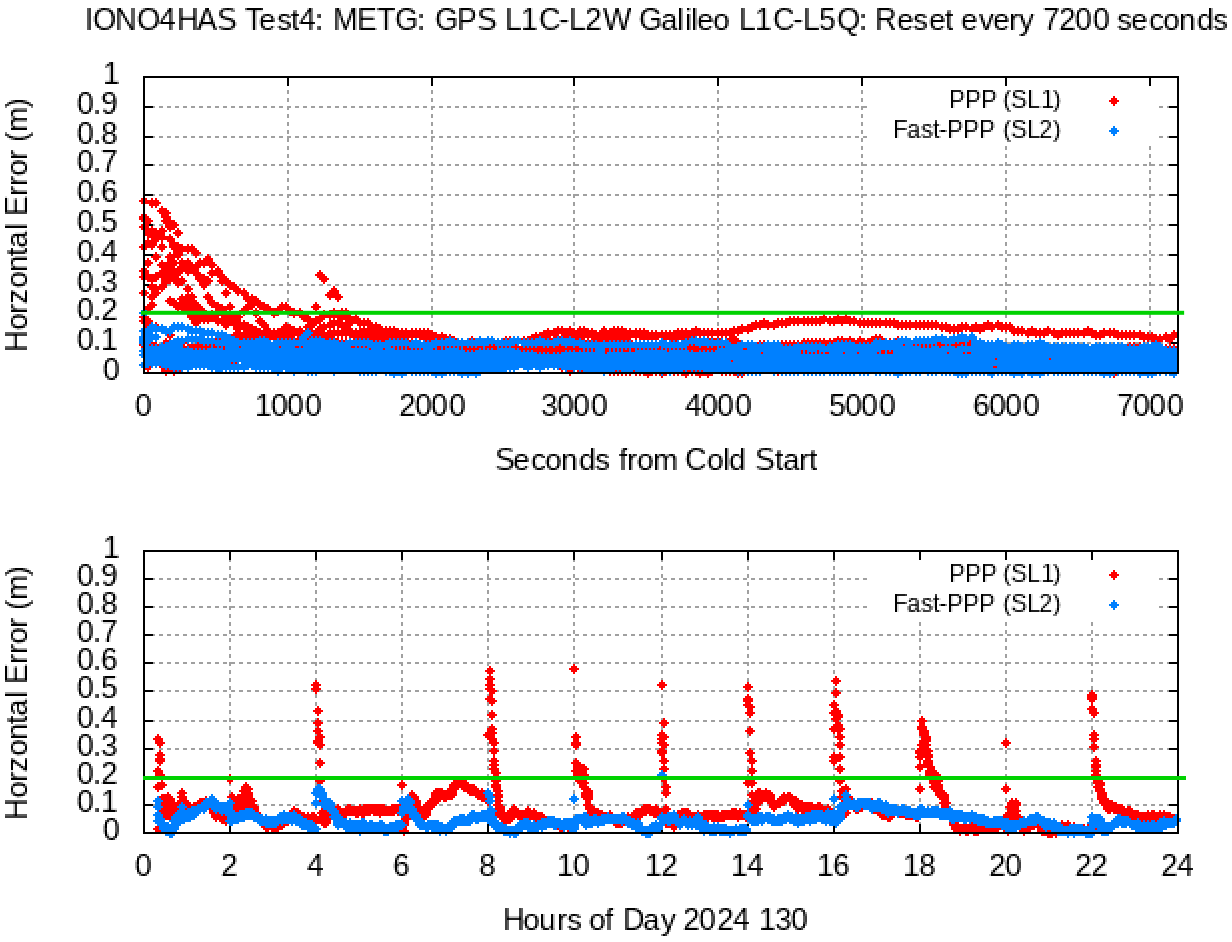
Finish

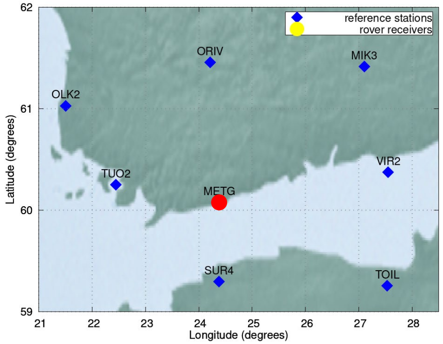
**90km**

Requirement Galileo HAS (in 100s)
hor. 20 cm
ver. 40 cm

# 2024 May storm

## Day before Storm (Thursday, May 9)





Finish

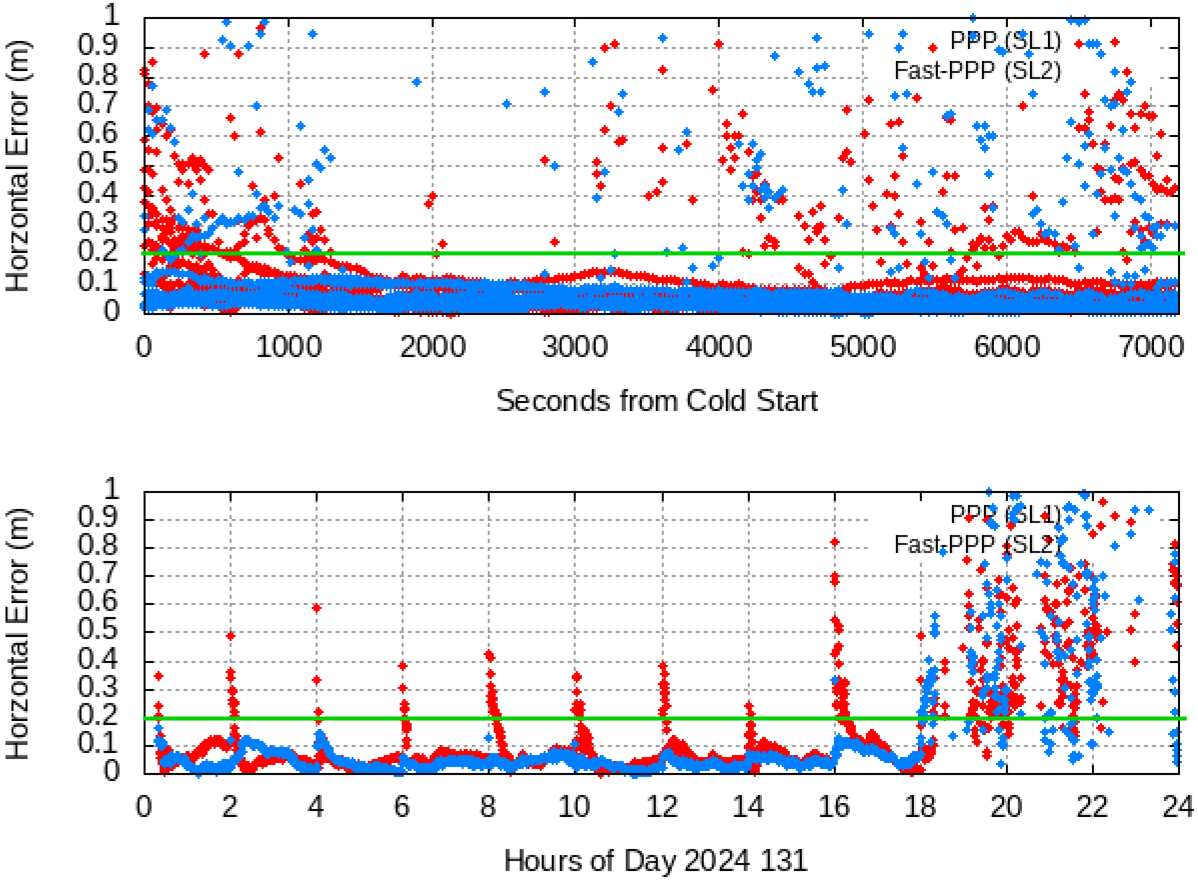
**90km**

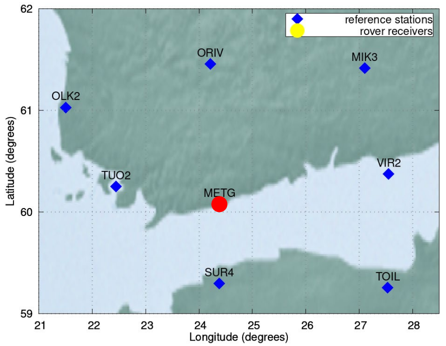
Requirement Galileo HAS (in 100s)
hor. 20 cm
ver. 40 cm

# 2024 May storm

## Storm day (Friday, May 10)

IONO4HAS Test4: METG: GPS L1C-L2W Galileo L1C-L5Q: Reset every 7200 seconds





Finish

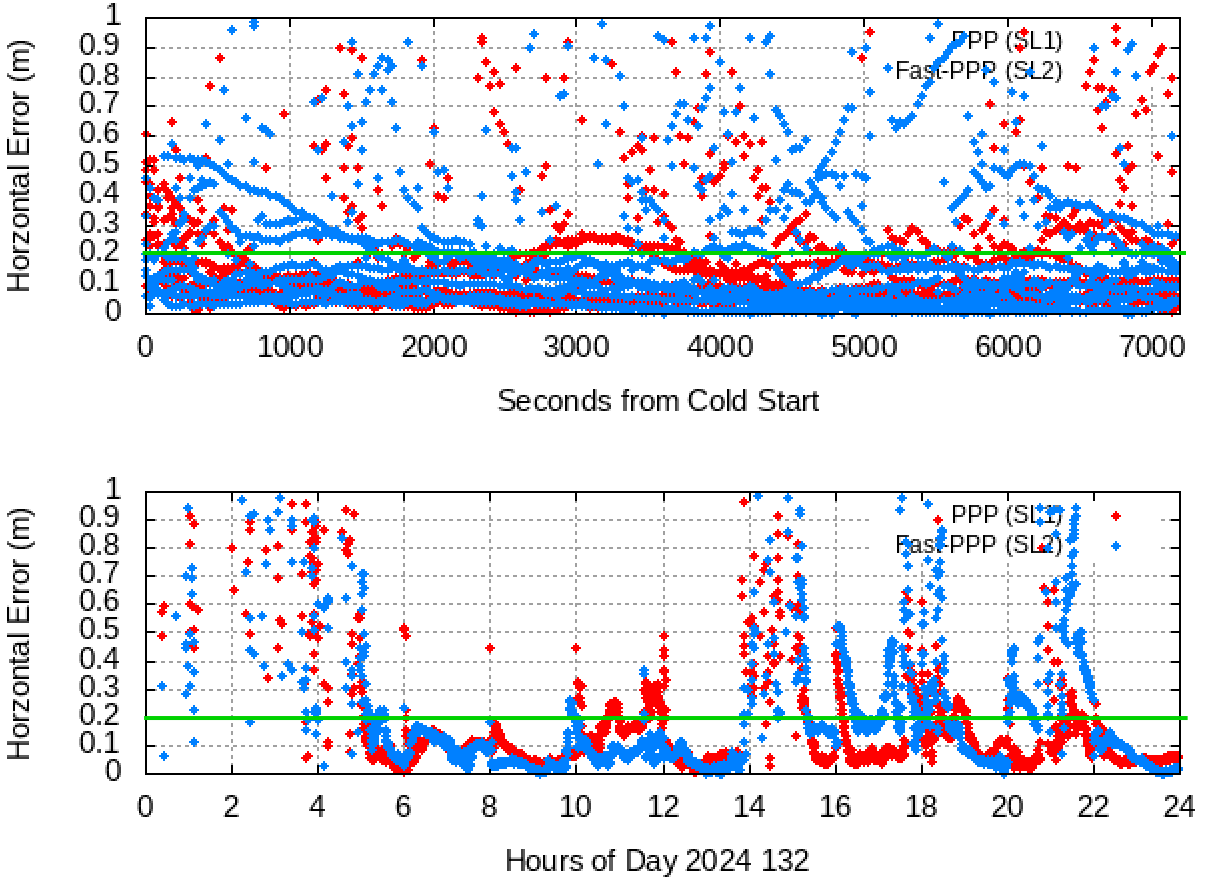
**90km**

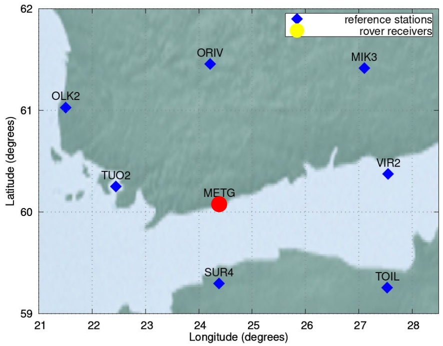
Requirement Galileo HAS (in 100s)
hor. 20 cm
ver. 40 cm

# 2024 May storm

## Day after (Thursday, May 11)

IONO4HAS Test4: METG: GPS L1C-L2W Galileo L1C-L5Q: Reset every 7200 seconds

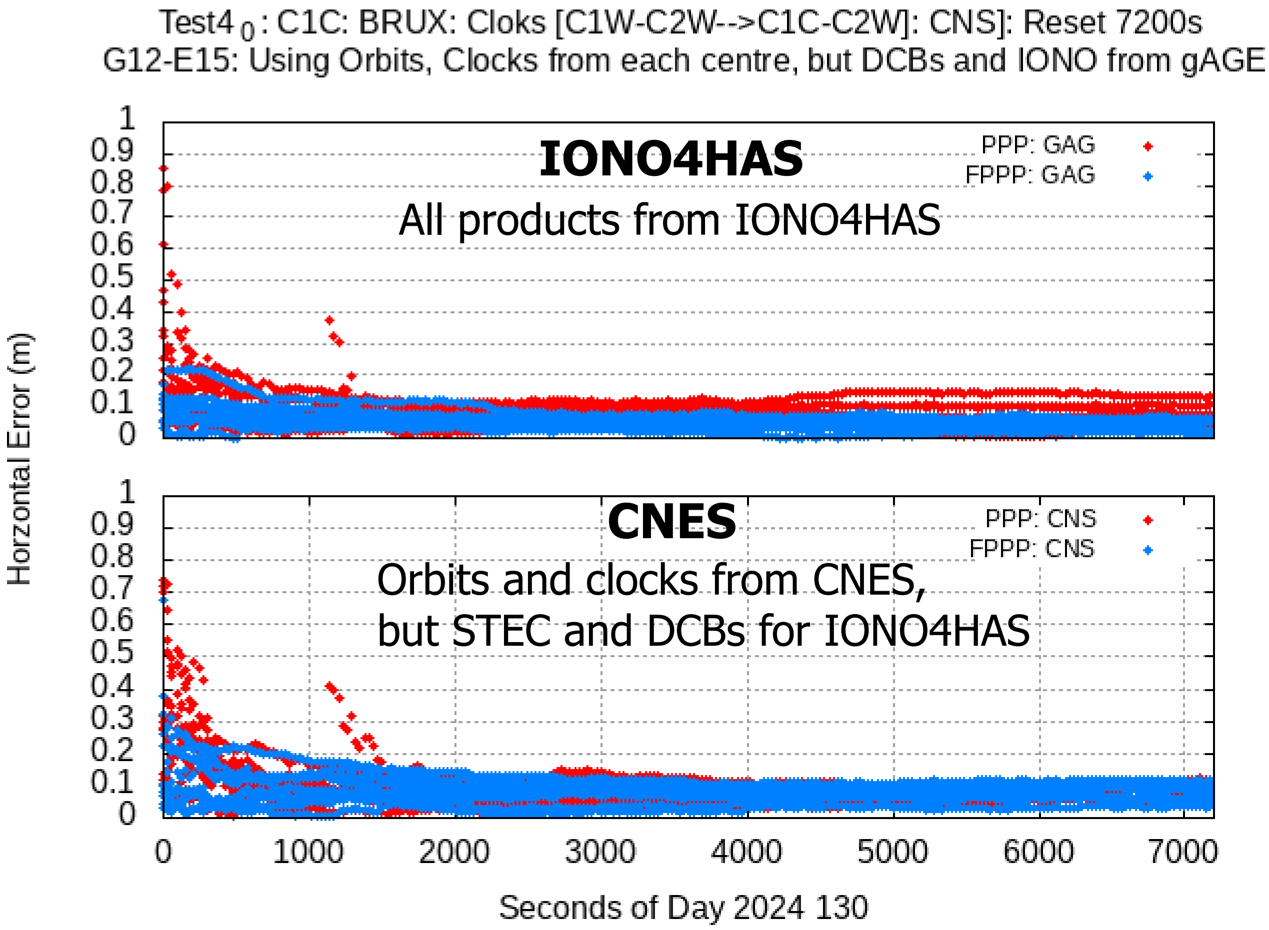




Finish

**90km**

Requirement Galileo HAS (in 100s)
hor. 20 cm
ver. 40 cm



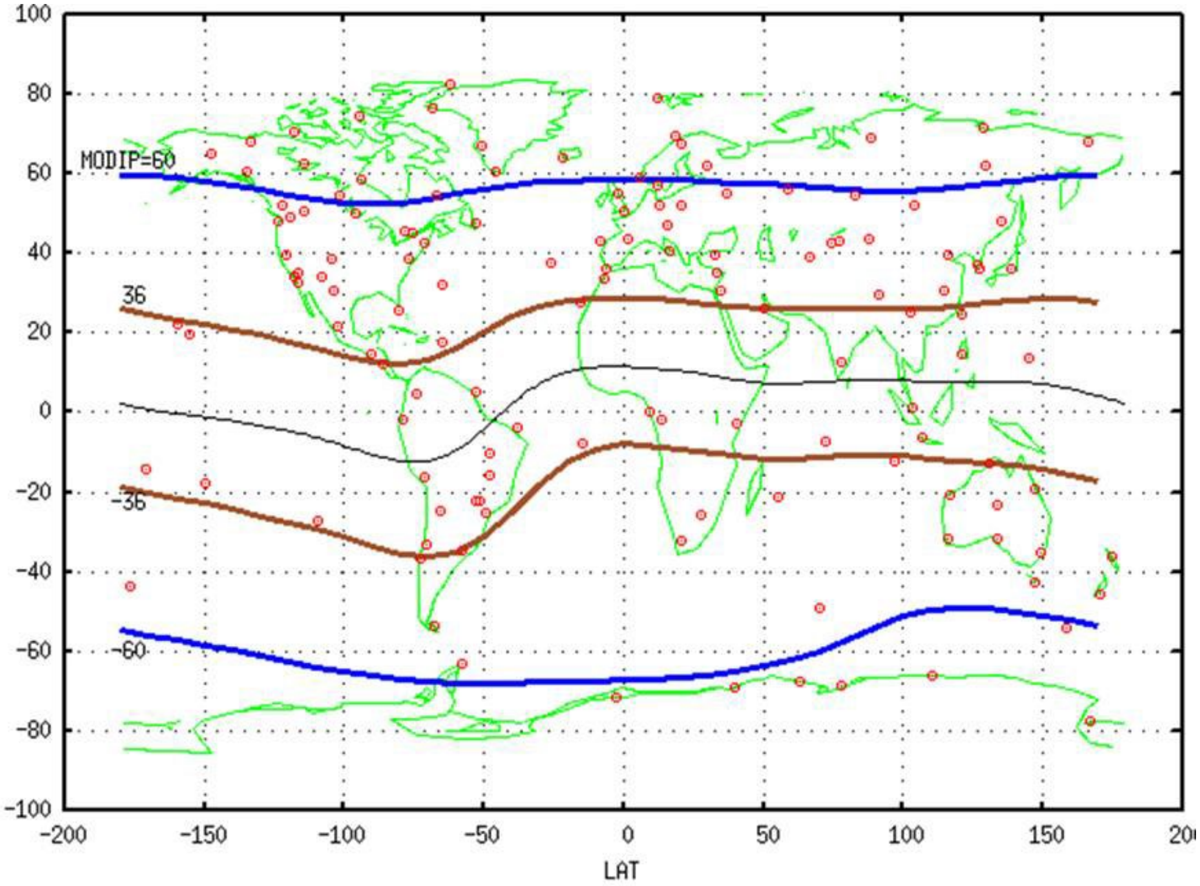
**IONO4HAS**

All products from IONO4HAS

**CNES**

Orbits and clocks from CNES,
but STEC and DCBs for IONO4HAS

# MODIP bounds

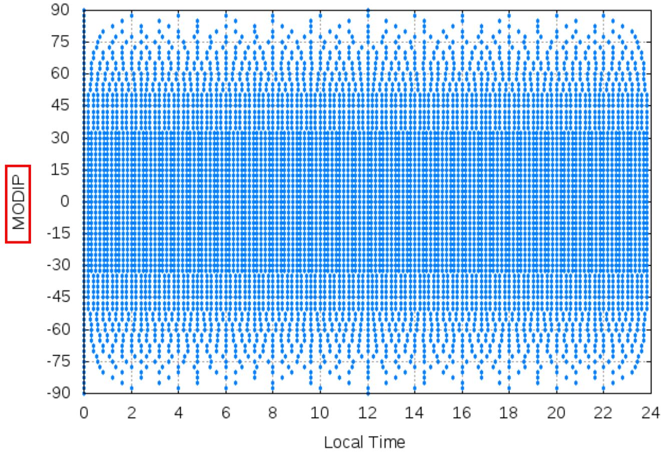


**MOdied DIP** latitude (MODIP) $\mu$,

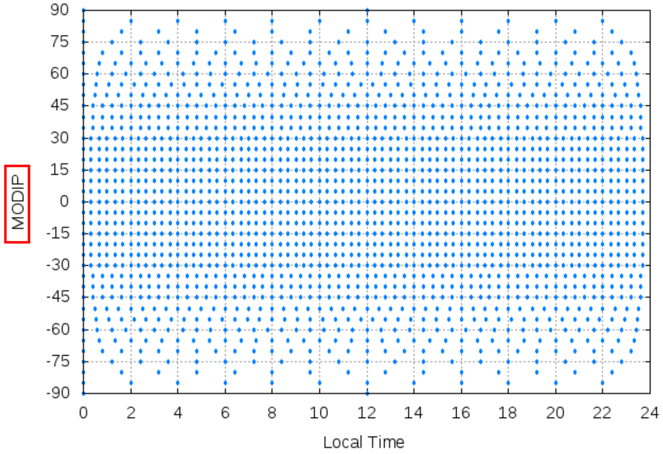
$$\boxed{\tan \mu = \frac{I}{\sqrt{\cos \varphi}}}$$

with $I$ the true magnetic inclination, or ***dip*** in the ionosphere (usually at 300 km), and $\varphi$ the geographic latitude of the receiver.

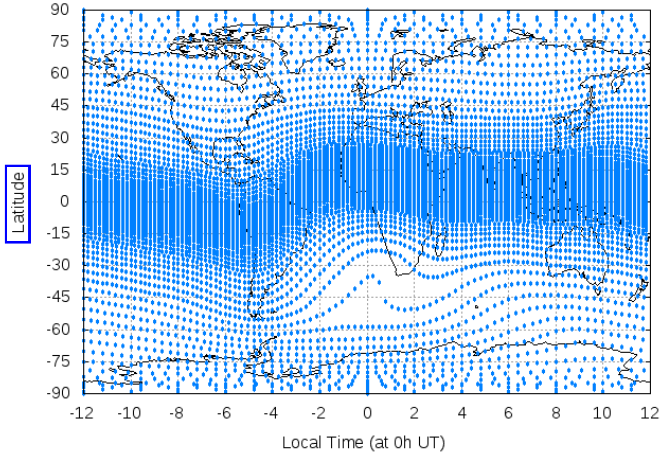
First layer grid (270 km in height)



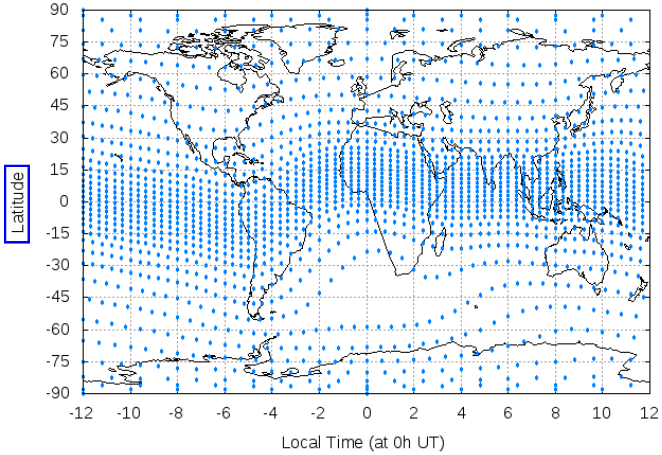
Second layer grid (1600 km in height)

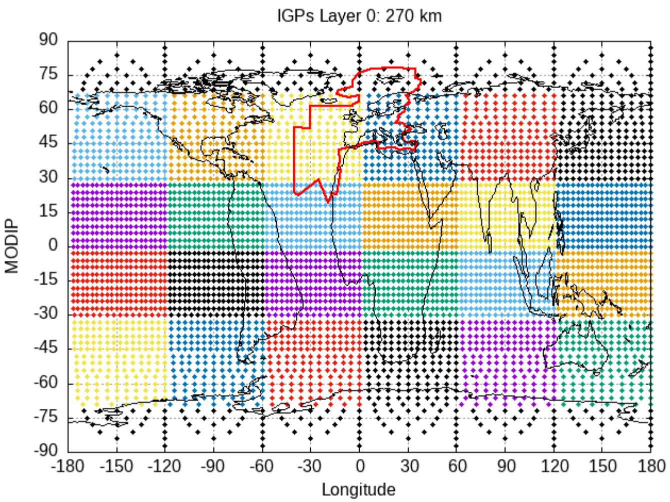


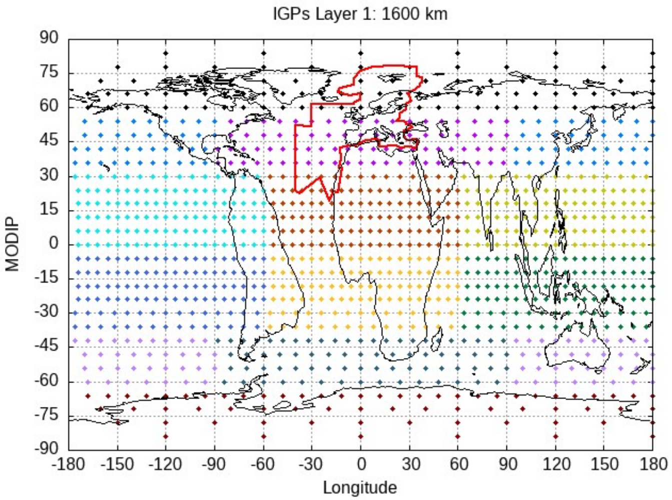
First layer grid (270 km in height)

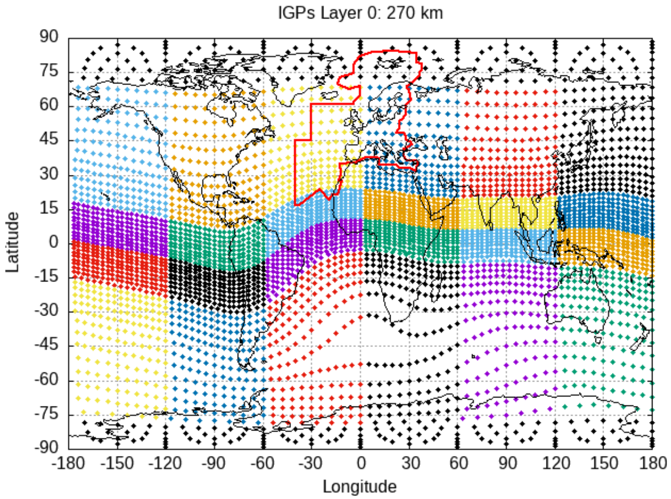


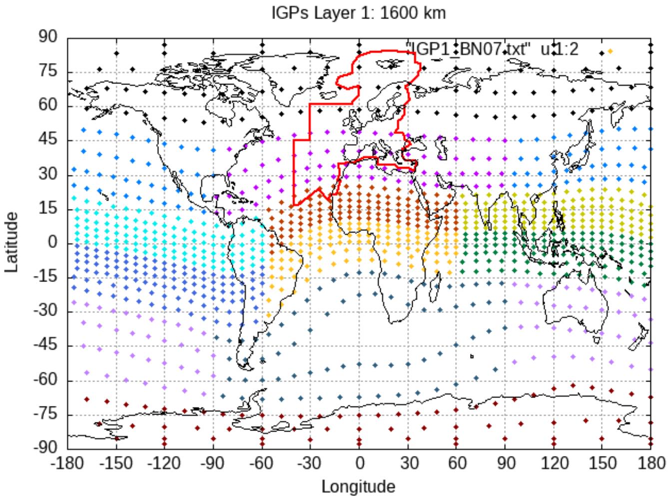
Second layer grid (1600 km in height)



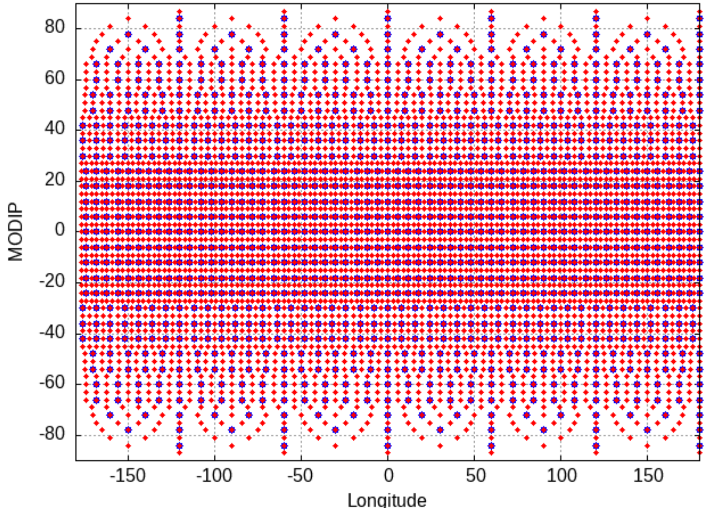

IGPs Layer 0: 270 km

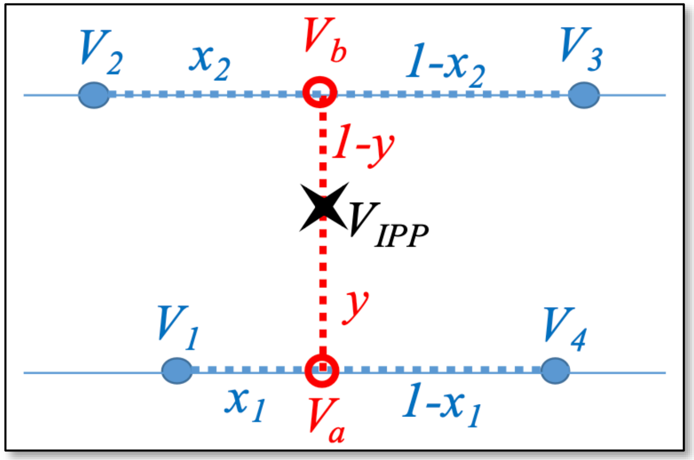

IGPs Layer 1: 1600 km


IGPs Layer 0: 270 km


IGPs Layer 1: 1600 km

# Interpolation scheme





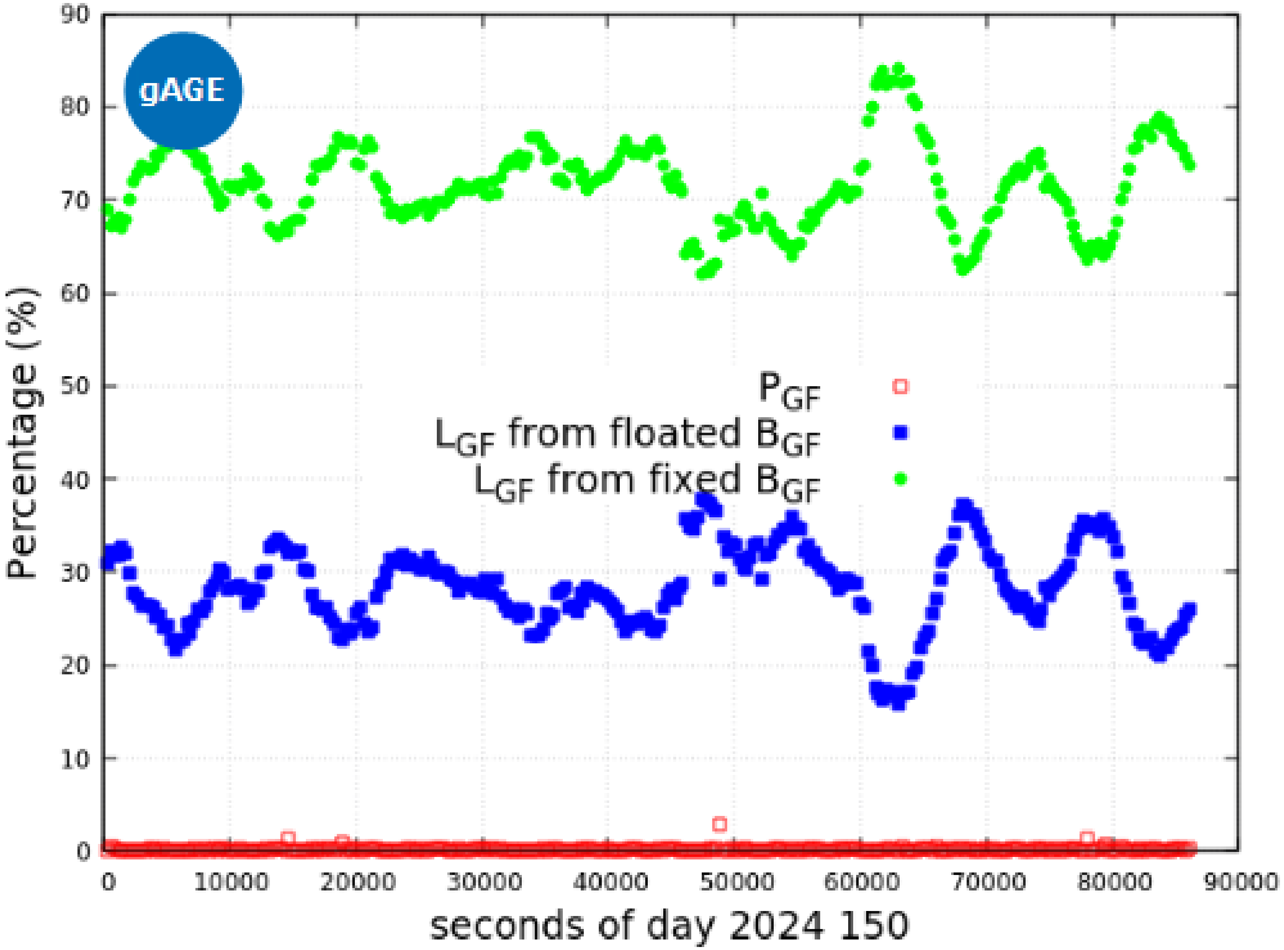
$$\boldsymbol{V_{IPP} = (1-y)V_a + yV_b}$$

where

$$V_a = (1-x_1)V_1 + x_1V_4$$

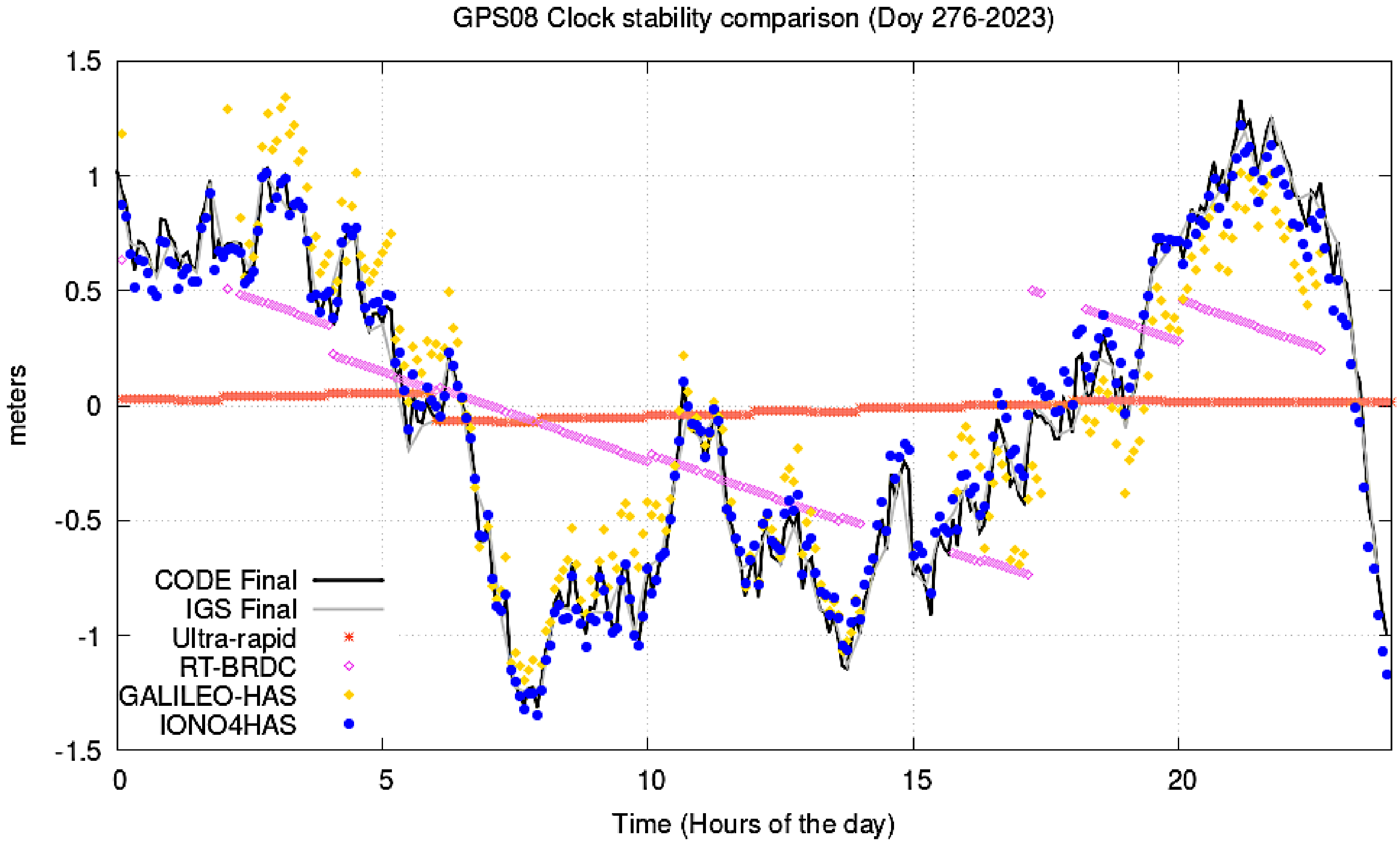
$$V_b = (1-x_2)V_2 + x_2V_3$$

$$V_{IPP} = (1-y)(1-x_1)\cdot V_1 + y\cdot(1-x_2)\cdot V_2 + (1-y)x_1\cdot V_4 + y\cdot x_2\cdot V_3$$



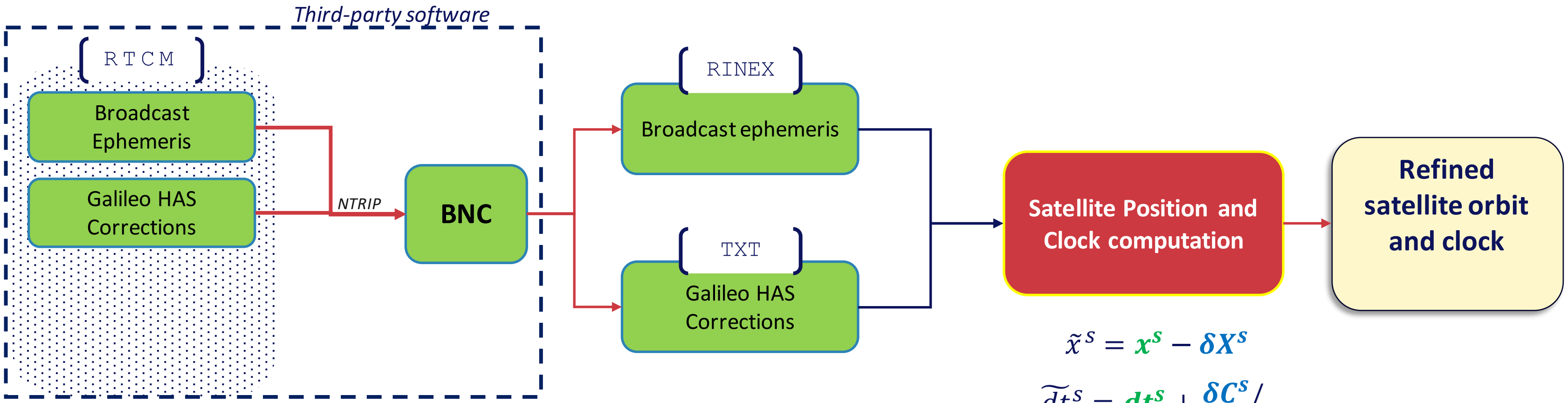
Example of the percentage of geometry-free combinations of carriers ($L_{GF}$) used in the Ionospheric filter **with ambiguities fixed (green colour)**, **with floated ambiguities (blue colour)**. In red the percentage of measurements corresponding to non-consolidated carrier arcs. In this case the code ($P_{GF}$) is used (red colour). The data set is for 29 of May2024.

# Real-time estimates of satellite clocks.
# Detrended clocks



# Galileo HAS testing: Orbits and clocks.

Using the correction message transmitted over NTRIP



*Third-party software*

RTCM

Broadcast Ephemeris

Galileo HAS Corrections

*NTRIP*

**BNC**

RINEX

Broadcast ephemeris

TXT

Galileo HAS Corrections

**Satellite Position and Clock computation**

**Refined satellite orbit and clock**

$$\tilde{x}^s = \boldsymbol{x^s} - \boldsymbol{\delta X^s}$$

$$\widetilde{dt}^s = \boldsymbol{dt^s} + \boldsymbol{\delta C^s}/c$$

***BRDC***

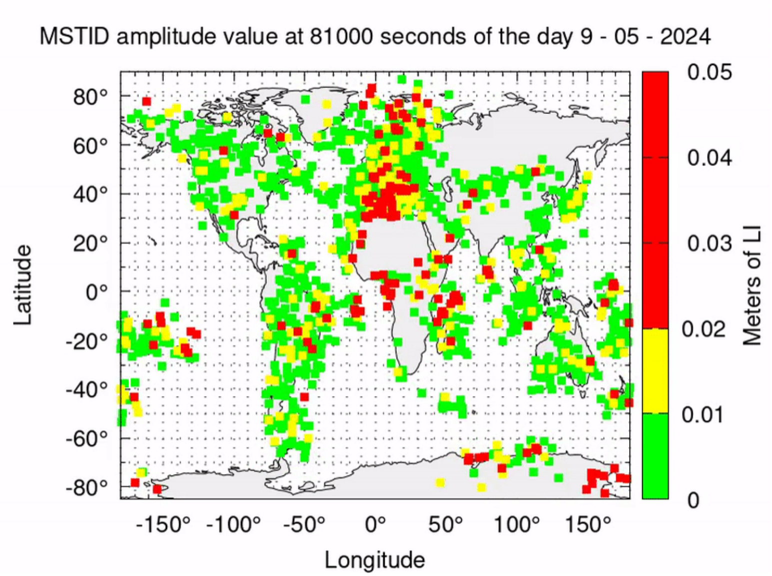
***GAL HAS Corrections***

# 2. IONO4HAS tool

Ionospheric monitoring indexes: **MSTID index**

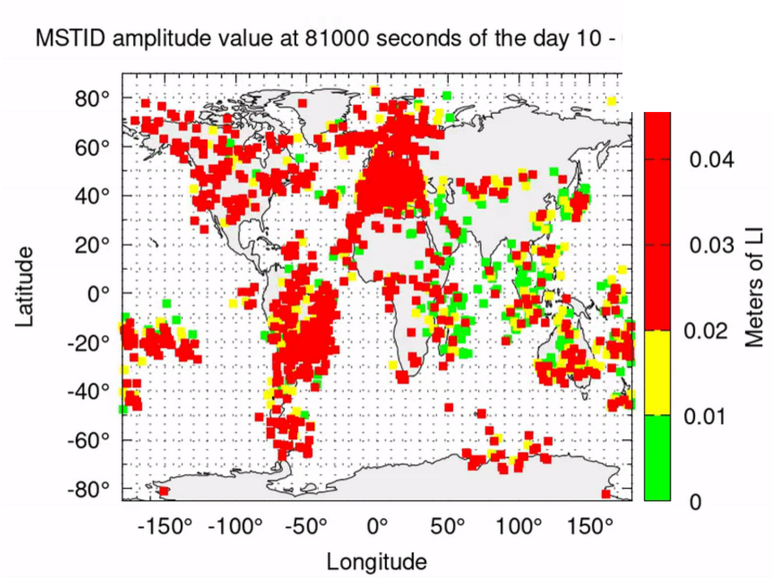
**Thursday (May 9th)**

From 12:00 to 23:59 (UTC)



**Friday (May 10th)**

From 12:00 to 23:59 (UTC)



$$MSTID^2_{IDX}(t) = \frac{1}{20}\sum_{i=t-2\tau}^{n}\left(\Delta^2 STEC(i)\ /M(\epsilon)\right)^2$$

$\Delta^2 STEC(t)$ :  $0.5 \bullet \left(STEC(t+\tau) + STEC(t-\tau) - 2 \cdot STEC(t)\right)$

$\tau$ : tuning parameter (MSTID periods of 10 min)

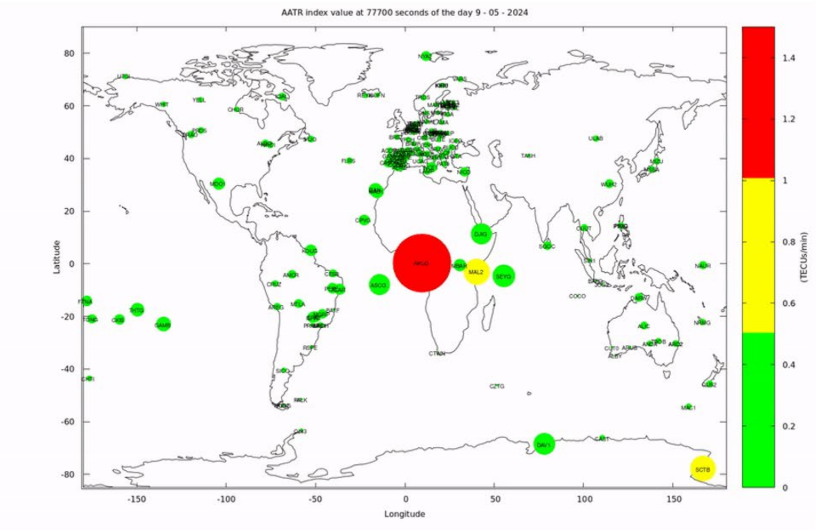
$\mathrm{M}(\epsilon)$ is an obliquity factor for mitigating larger values of $\Delta^2\mathrm{STEC}$

# 2. IONO4HAS tool

Ionospheric monitoring indexes: **AATR index**

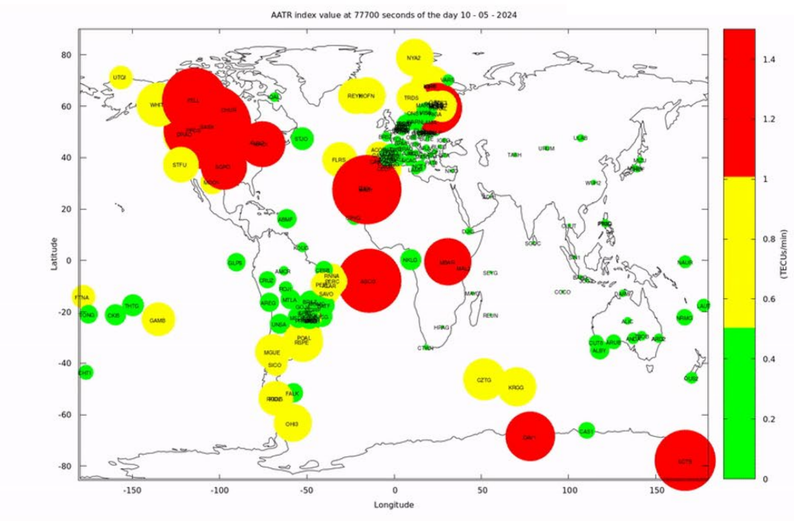
### Thursday (May 9th)

From 12:00 to 23:59 (UTC)



### Friday (May 10th)

From 12:00 to 23:59 (UTC)

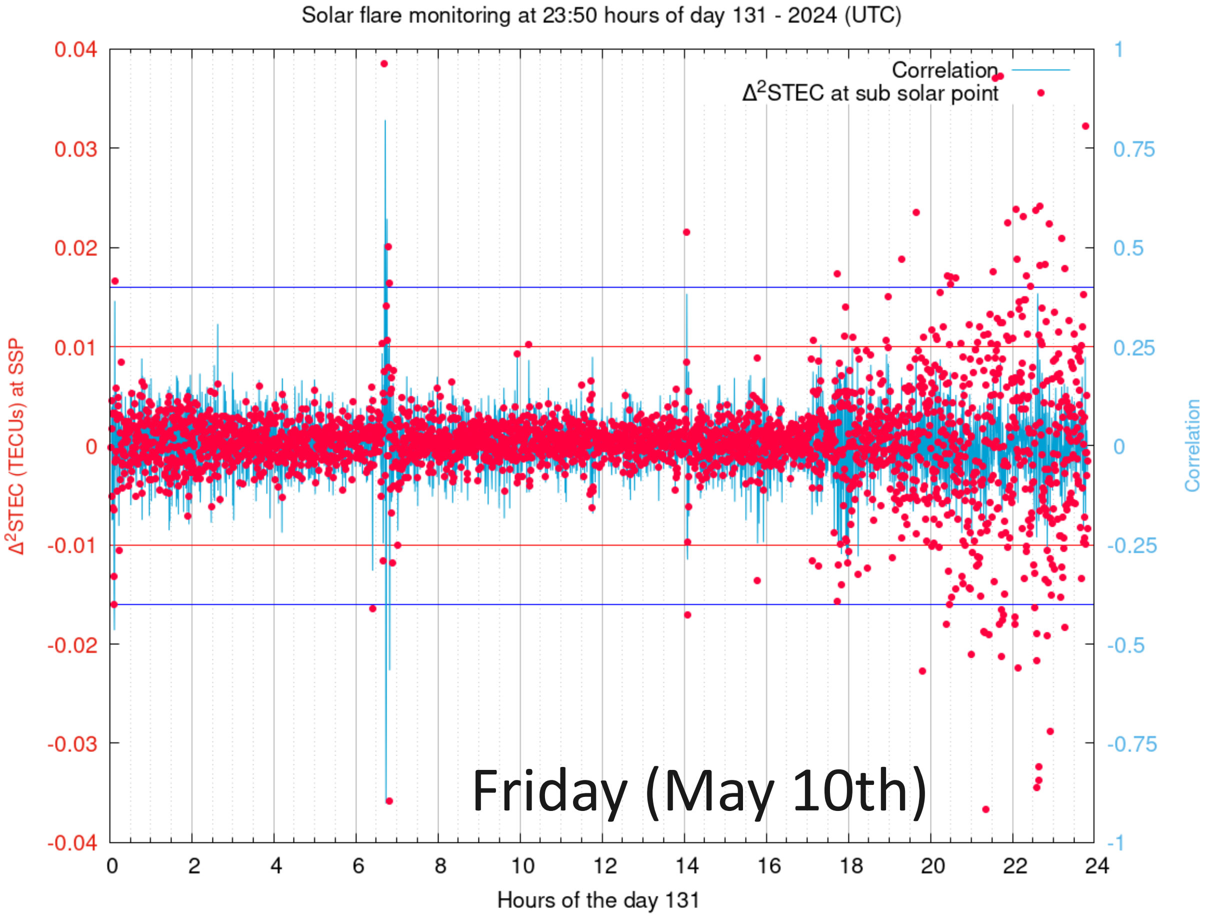


Along-Arc TEC Ratio is defined as:

$$AATR_i^j(t) = \frac{1}{\left(M(\epsilon)\right)^2} \frac{\Delta STEC_i^j(t)}{\Delta t}$$

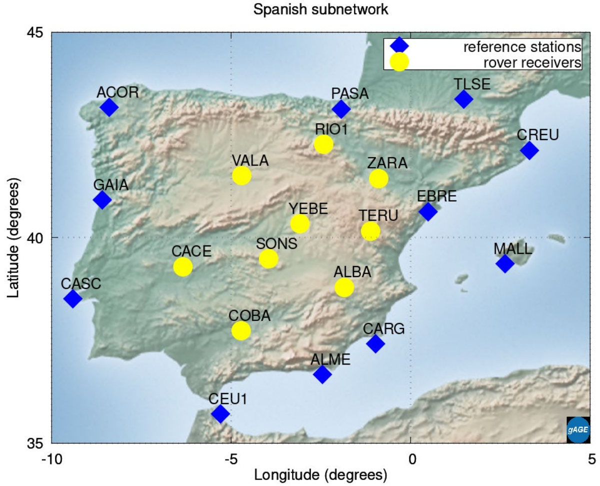
$$\Delta STEC_i^j(t) = \left(LGF_i^j(t) - LGF_i^j(t-\Delta t)\right)$$

# IONO4HAS Ionospheric monitoring Tool: GNSS solar flares detector



# OTHER Stuff

# User Domain test: Wide-lane Instantaneous positioning test

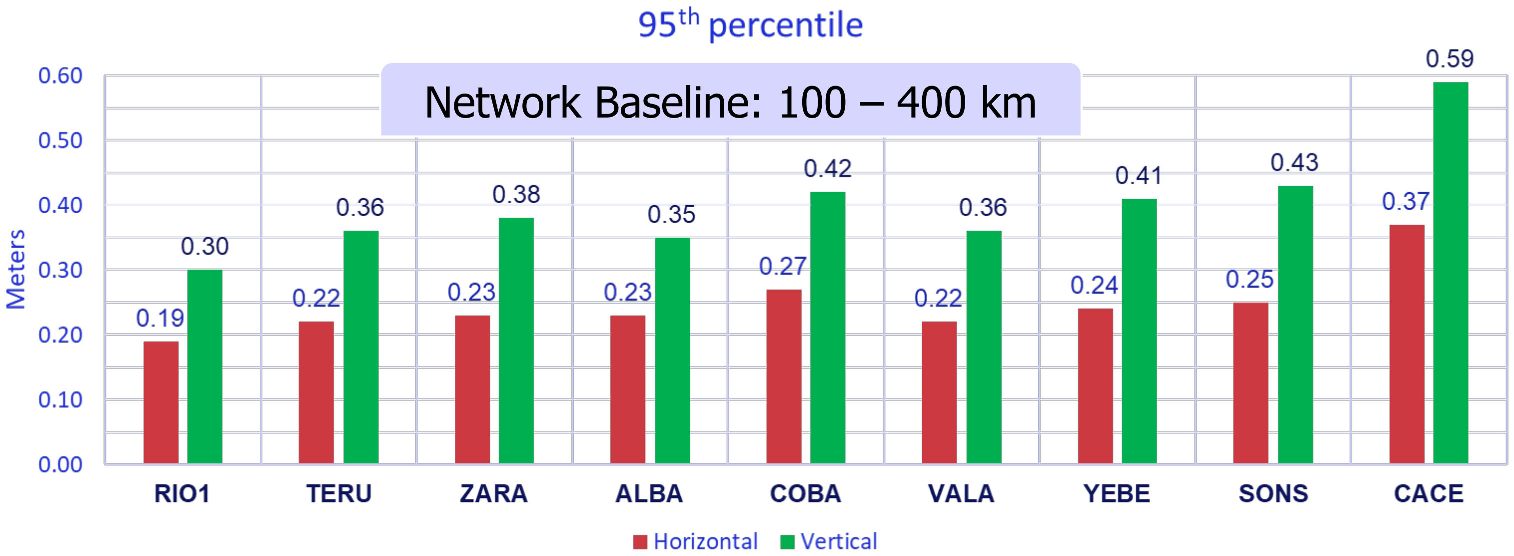


$$\Delta L_{w\,rcv}^{\,sat} - \boldsymbol{\alpha}(\boldsymbol{STEC_{rcv}^{sat}} + \boldsymbol{DCB^{sat}}) = \boldsymbol{G}\,\boldsymbol{\Delta r} + cT_{rcv} + \epsilon_{L_w}$$

<u>Instantaneous positioning error</u>
(no convergence time):

- 19 to 37 cm (hor)
- 22 to 59 cm (ver)

<u>Requirement Galileo</u>
<u>HAS (in 100s)</u>
<u>hor. 20 cm</u>
<u>ver. 40 cm</u>



Positioning error related with distance of the user receiver to nearest ref. receiver

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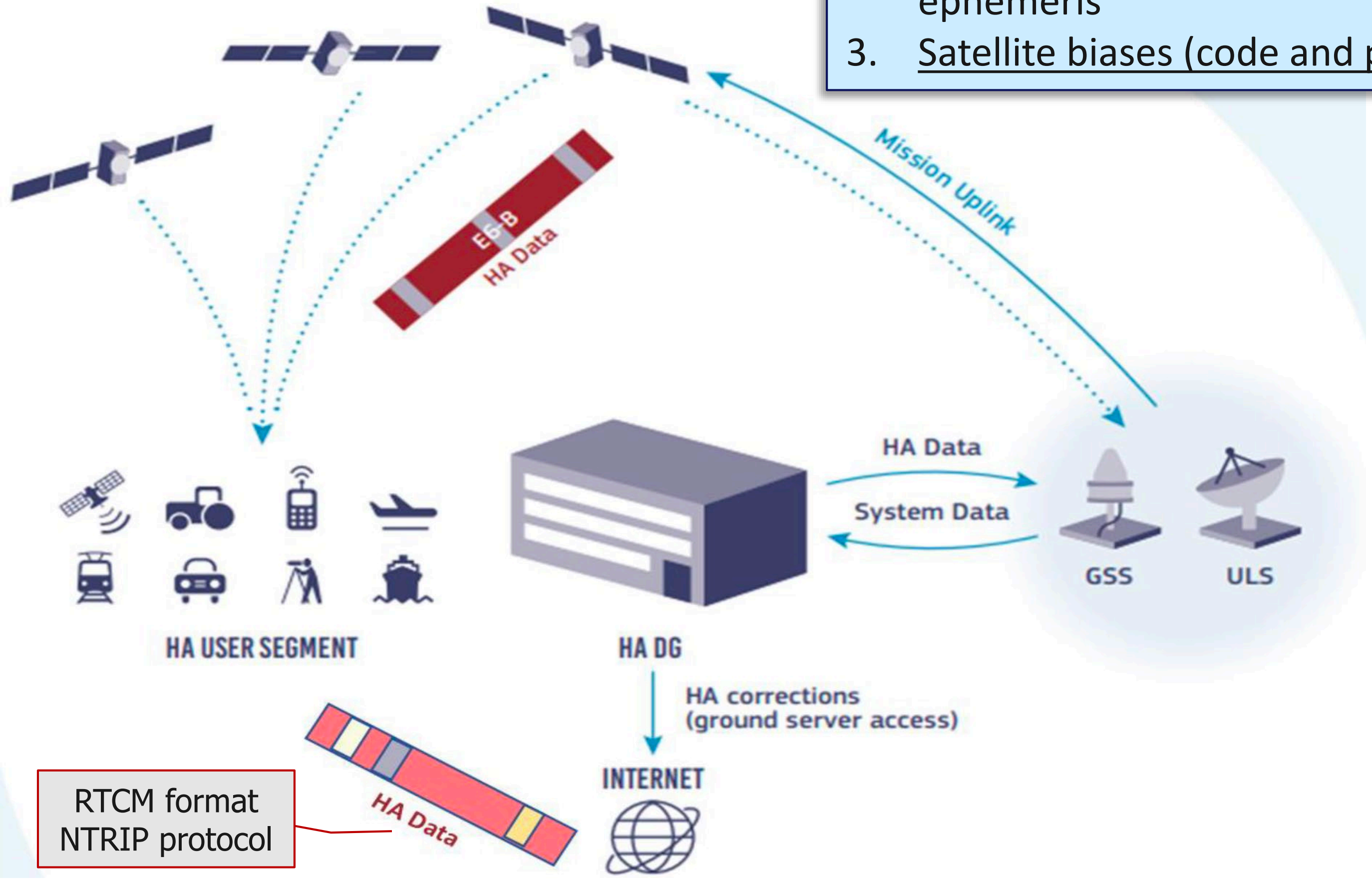
Timoté CC, Juan JM, Sanz J, Rovira-Garcia A, González-Casado G, Orús-Pérez R, Fernández-Hernández I, Blonski D (2024) "Ionospheric corrections tailored to Galileo HAS: validation with single-epoch navigation", GPS Solutions 28(2):A93:1-12

# 1. Introduction: Galileo HAS Architecture

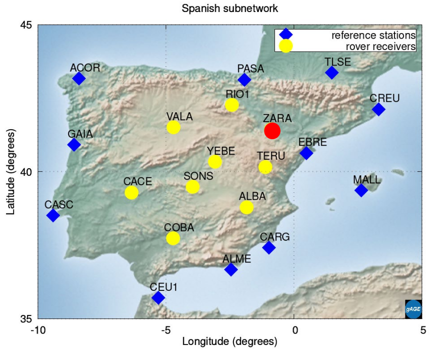
The Galileo High Accuracy Service (**HAS SL1**) provides (*every 10 s*):

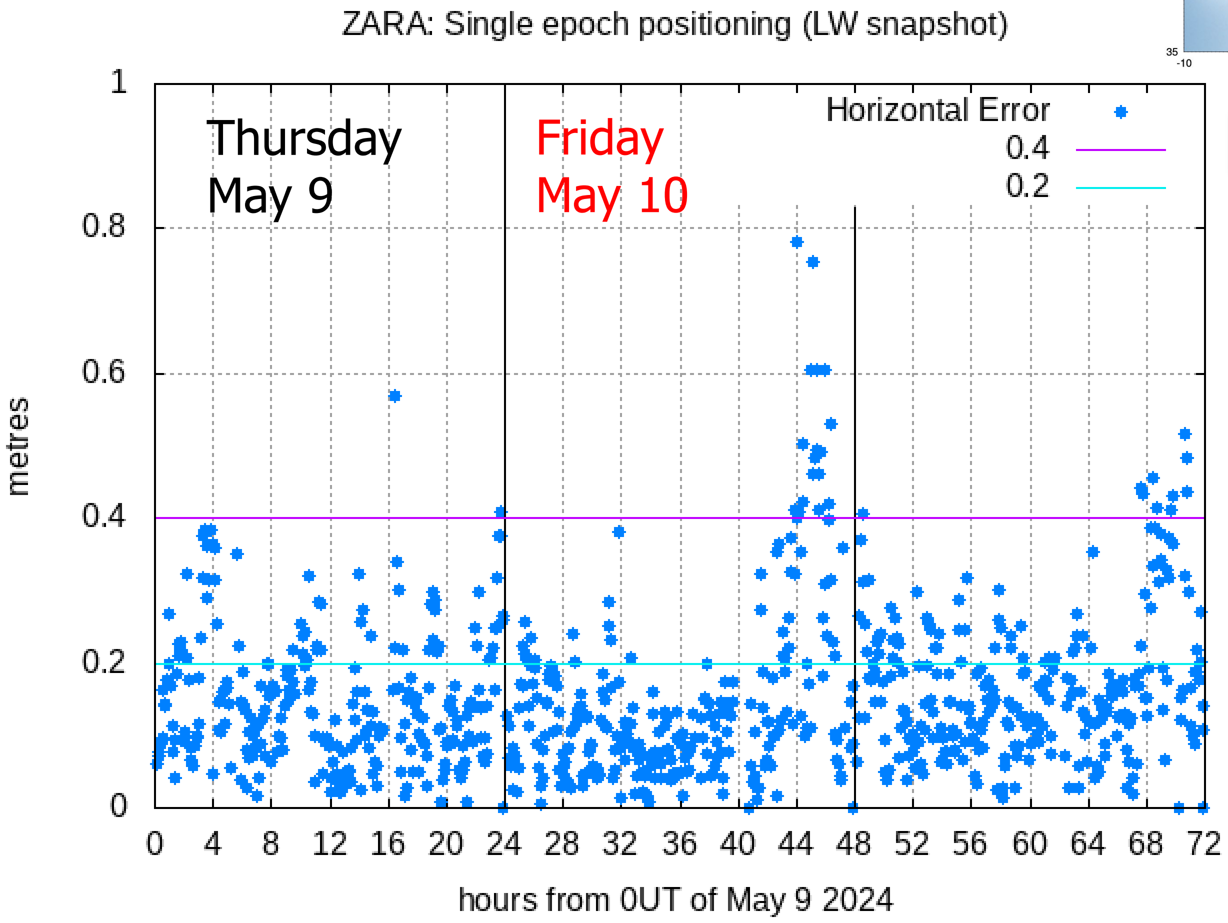
1. Satellite orbit corrections to the broadcast ephemeris
2. Satellite clock corrections to the broadcast ephemeris
3. Satellite biases (code and phase)



RTCM format
NTRIP protocol

# IONO4HAS





Iberian Peninsula

# The linear observation model $\mathbf{y}=\mathbf{G}\,\mathbf{x}$ for the code and carrier measurements in PPP can be written as follows:

$$
\begin{bmatrix}
Prefit(Pc)^1\\
Prefit(Lc)^1\\
\cdots\cdots\\
Prefit(Pc)^n\\
Prefit(Lc)^n
\end{bmatrix}
=
\begin{bmatrix}
\frac{x_{o,rec}-x^1}{\rho^1_{0,rec}} & \frac{y_{o,rec}-y^1}{\rho^1_{0,rec}} & \frac{z_{o,rec}-z^1}{\rho^1_{0,rec}} & 1 & M^1_{wet} & 0 & \cdots & \cdots & 0\\
\frac{x_{o,rec}-x^1}{\rho^1_{0,rec}} & \frac{y_{o,rec}-y^1}{\rho^1_{0,rec}} & \frac{z_{o,rec}-z^1}{\rho^1_{0,rec}} & 1 & M^1_{wet} & 1 & \cdots & \cdots & 0\\
\cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots\\
\frac{x_{o,rec}-x^n}{\rho^n_{0,rec}} & \frac{y_{o,rec}-y^n}{\rho^n_{0,rec}} & \frac{z_{o,rec}-z^n}{\rho^n_{0,rec}} & 1 & M^n_{wet} & 0 & \cdots & \cdots & 0\\
\frac{x_{o,rec}-x^n}{\rho^n_{0,rec}} & \frac{y_{o,rec}-y^n}{\rho^n_{0,rec}} & \frac{z_{o,rec}-z^n}{\rho^n_{0,rec}} & 1 & M^n_{wet} & 0 & \cdots & \cdots & 1
\end{bmatrix}
\begin{bmatrix}
\Delta x_{rec}\\
\Delta y_{rec}\\
\Delta z_{rec}\\
cdt_{rec}\\
\Delta Tr_{Z,wet}\\
B_C^{\,1}\\
\cdots\\
B_C^{\,n}
\end{bmatrix}
$$

Carrier ambiguities

$$\boxed{Prefit(P_C)^k} = P_C{}^k - \rho_0^k + cdt^k - Trop_0^k$$

$$\boxed{Prefit(L_C)^k} = L_C{}^k - \rho_0^k + cdt^k - Trop_0^k - \lambda_N \omega^k$$

# How the ionosphere helps the filter convergence in Fast-PPP?

➔**In the classical PPP, the navigation filter convergence is driven by the convergence of the floated iono-free ambiguity ($B_C$), which, at the beginning, depends on the code noise.**

**1) There is a constraint between the wide-lane ambiguity ($B_w$), the iono-free ambiguity ($B_C$) and the ionospheric refraction ($STEC$) and $DCB$.**

$$B_C = B_W - 1.98\,(L_1 - L_2 - STEC - DCB)$$

**2) The wide-lane ambiguity ($B_w$) is estimated/fixed quickly**
(less than 1 minute with 2-freq and in single epoch with 3-freq. signals).

**3) The ionosphere ($STEC$) is the bridge (through the mentioned constraint) to transfer the quick accuracy achieved in the wide-lane ambiguity ($B_w$) computed value to the iono-free ambiguity ($B_C$) estimation, accelerating in this way the filter convergence.**

➔**Thence, in Fast-PPP the convergence time is strongly reduced thanks to the** quick wide-lane ambiguity fixing and the accurate ionospheric corrections. It allows to achieve High Accuracy quickly (< 1 minute with 2-freq & single epoch with 3-freq).

**The ionosphere helps provided that its quality (noise/error) is better than the code**