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Real-Time Central Processing Facility for High Accuracy Navigation (IONO4HAS)

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A tutorial elaborated in the framework of the SpaceSUITE ERASMUS+ Blueprint Project, Funded by the European Union.

EUREF Symposium 2024, Barcelona, Spain.

gAGE

Outline

1. Introduction
2. IONO4HAS ionospheric correction tool
3. Assessment of the IONO4HAS ionospheric corrections
4. Results from the user perspective
5. gAGE RT-products portal

1

Introduction

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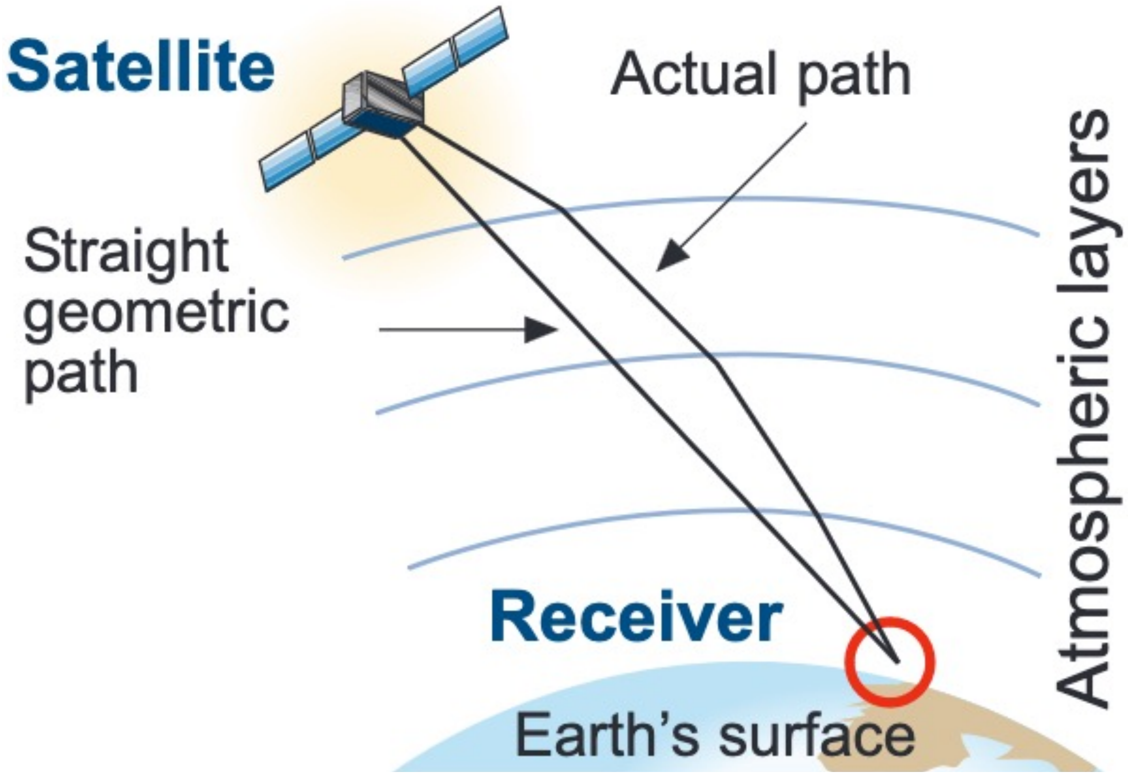
1. Introduction

Ionospheric delay on GNSS

- The total electron content (TEC) in the atmosphere affects the GNSS signals:
  - **Double-frequency** receivers can apply a linear combination of measurements at different frequencies to reduce the ionospheric error up to 99.9%
  - **Single-frequency** receivers require external information to mitigate the ionospheric effects.
    - ✓ Klobuchar (GPS)
    - ✓ NeQuick-G (Galileo)



Source: "GNSS data processing, Vol. I: fundamentals and algorithms" (2013)

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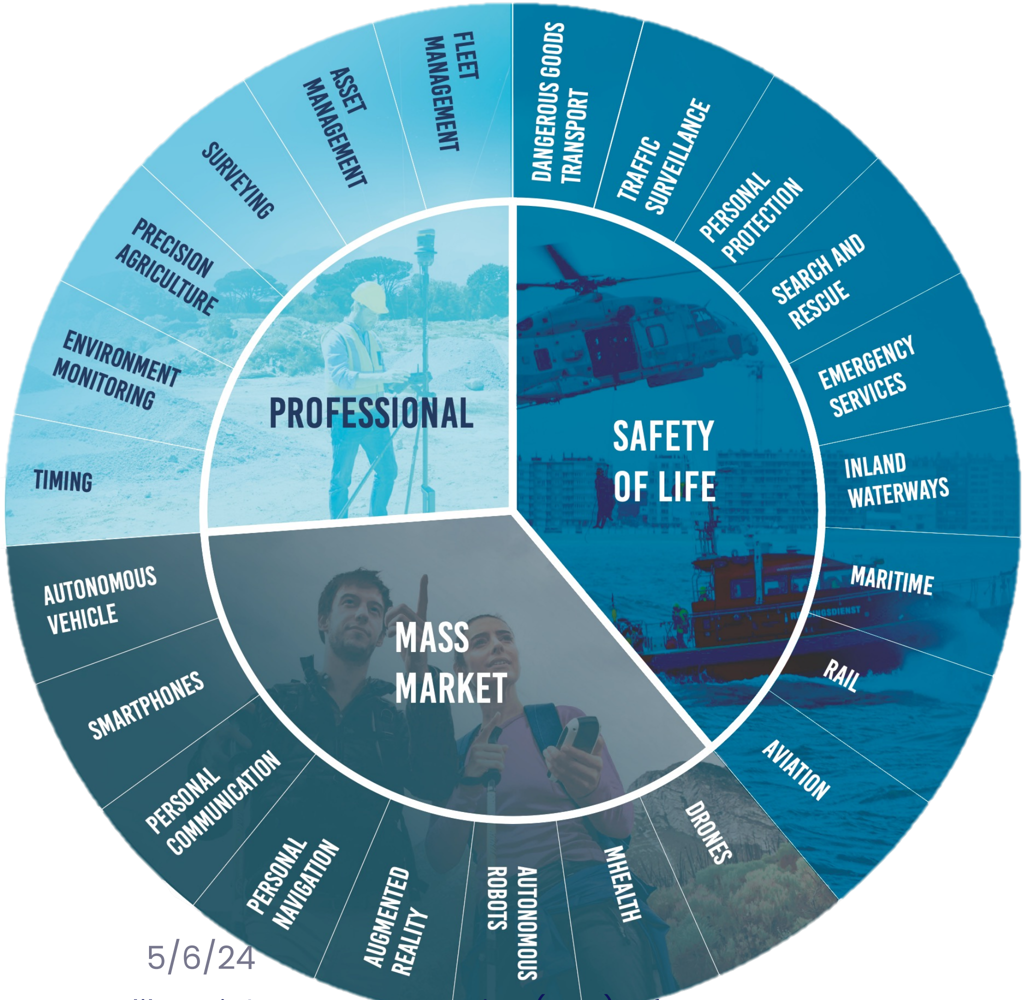
1. Introduction

Galileo HAS



Source: Galileo High Accuracy Service (HAS) Info Note

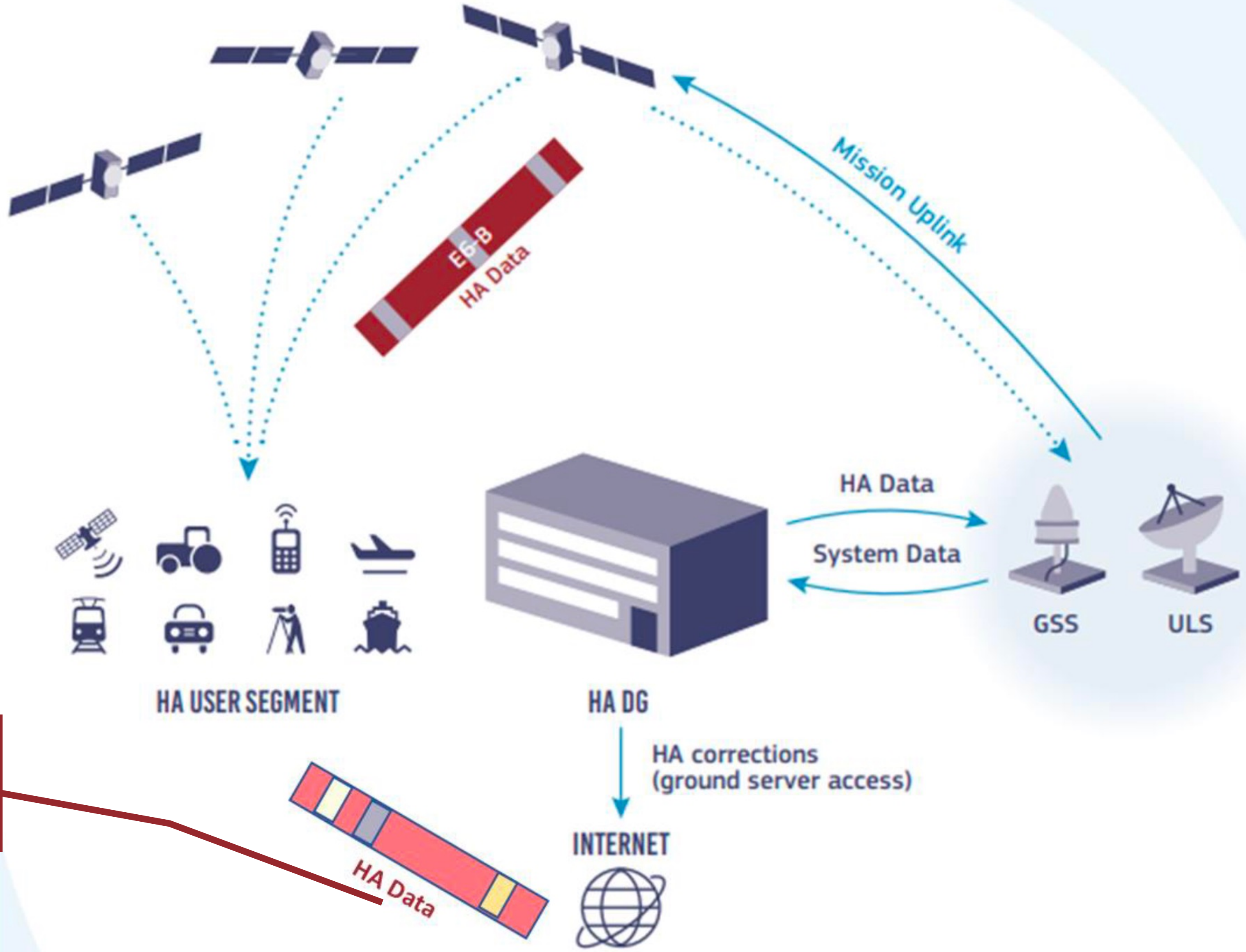
GALILEO High Accuracy Service (HAS)

Enabling Precise Point Positioning (PPP) on a global scale

	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**

1. Introduction

Galileo HAS architecture



RTCM format
NTRIP protocol

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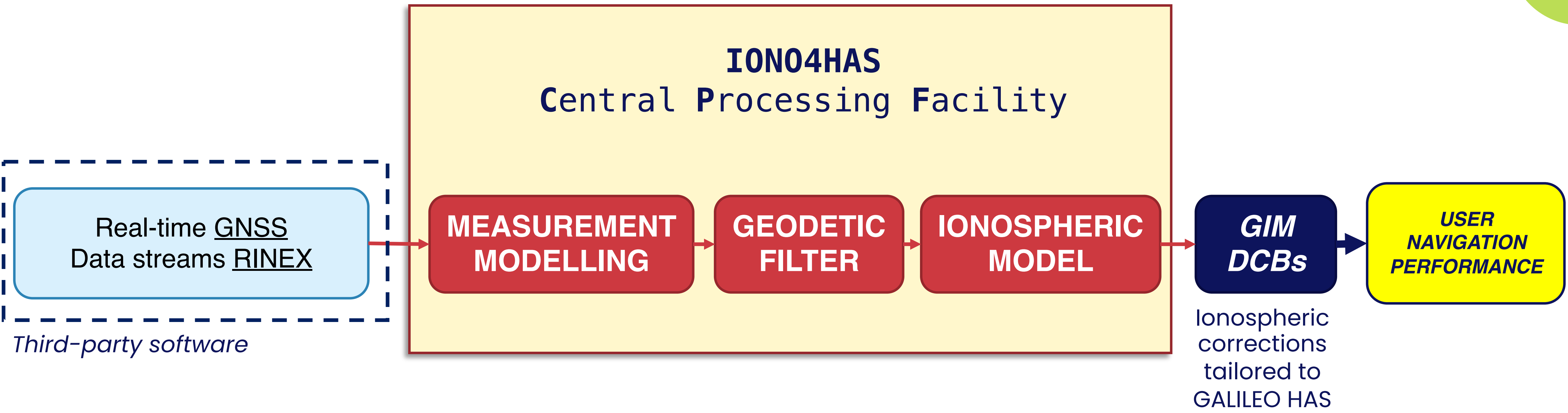
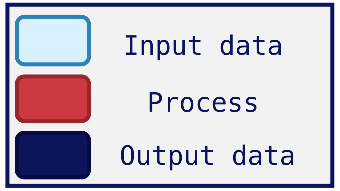
1. Introduction

IONO4HAS: a real-time implementation of the ionospheric correction model for Galileo HAS SL2





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2

IONO4HAS ionospheric correction tool

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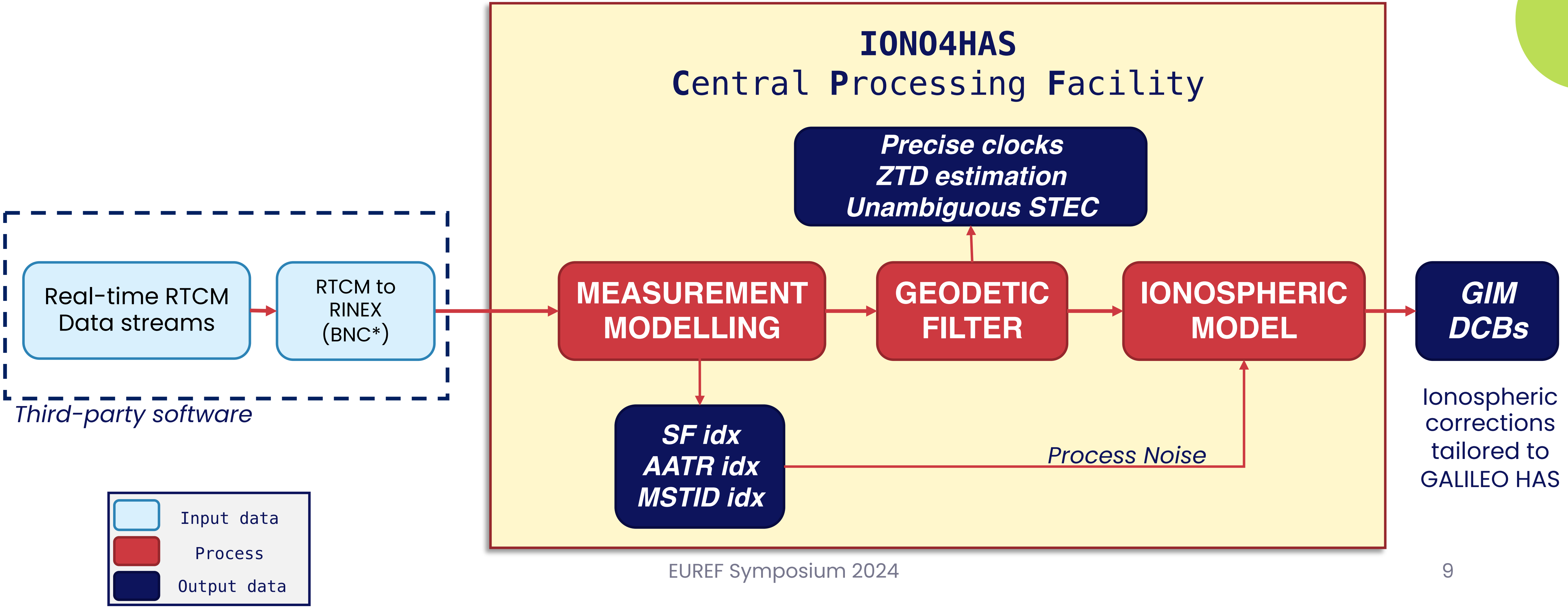
IONO4HAS ionospheric correction tool

General overview



2.1

Measurement Modelling Module

IONO4HAS ionospheric correction tool

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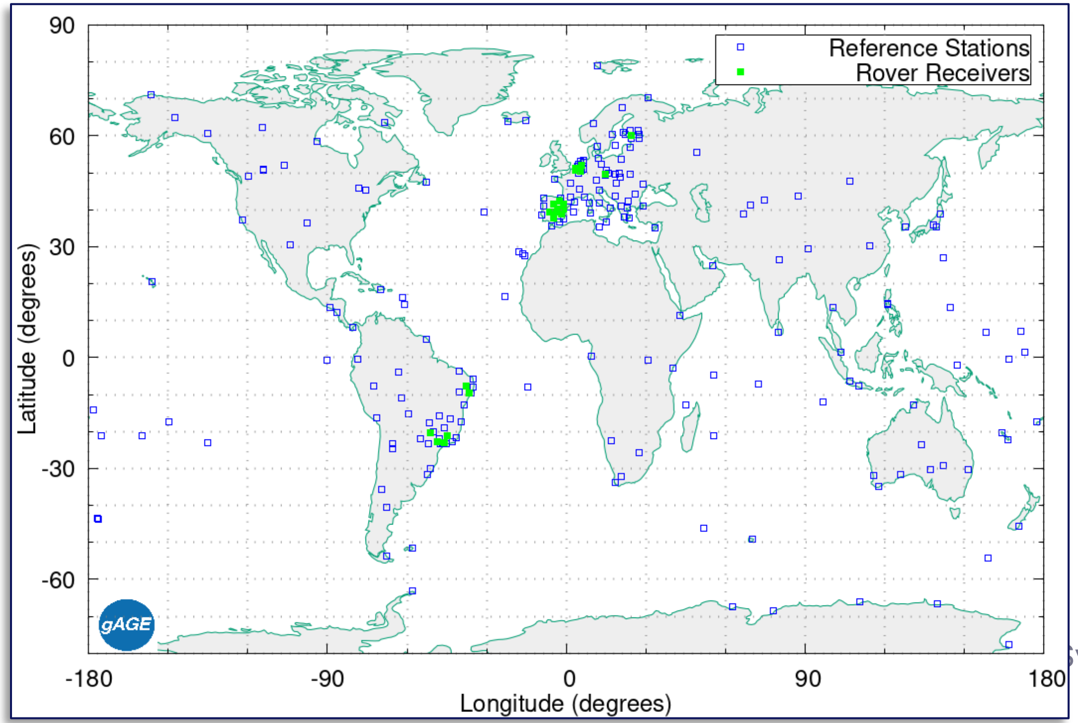
2. IONO4HAS tool

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
- ✓ Multiconstellation: **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°)

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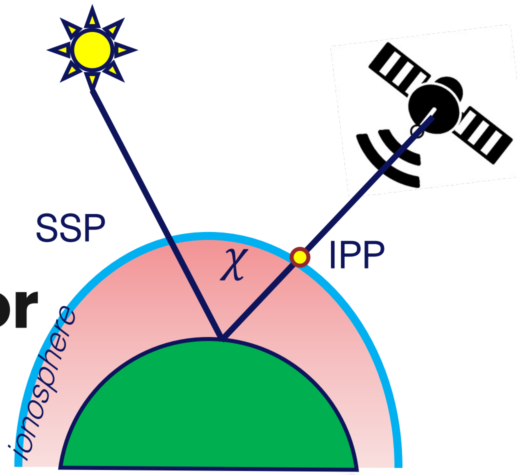
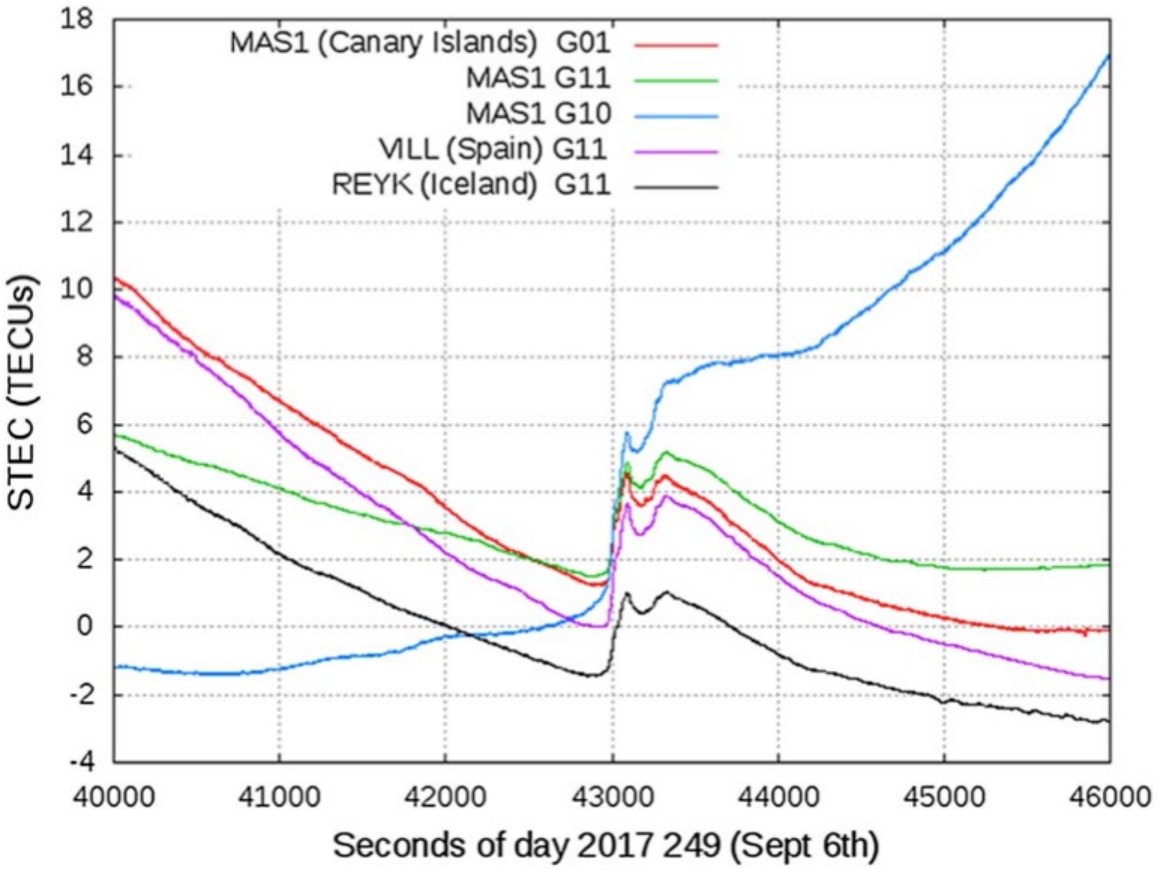
2. IONO4HAS tool

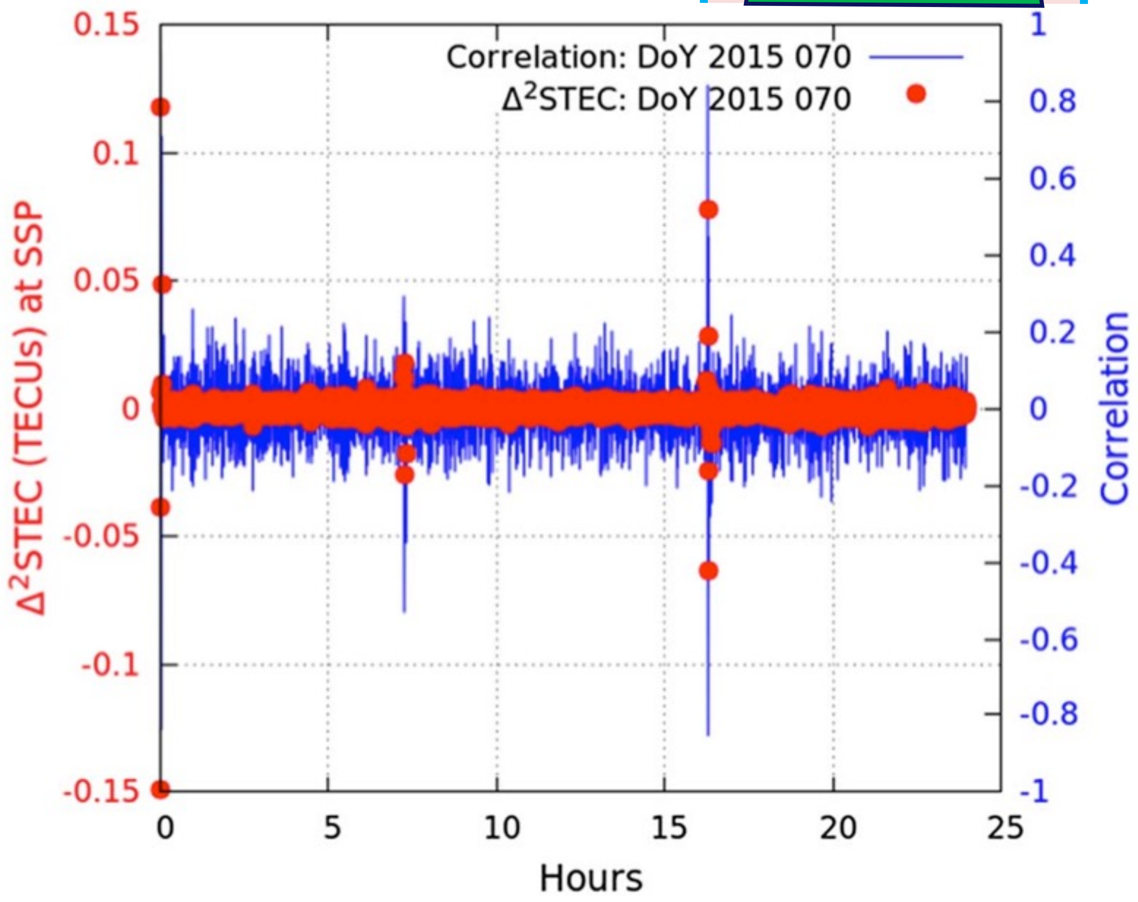
Ionospheric monitoring indexes: **GNSS solar flares detector**

$L_{GF} = L1 - L2$

Geometry-free: only frequency-dependent effects







Symposiur

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Recent Solar activity

Forbes

FORBES > INNOVATION > SCIENCE

Watch Issued: Solar Storm May Overload Electric Grid, Put On Aurora Show

Los Angeles Times

SCIENCE & MEDICINE

Solar storm heading to Earth could disrupt communications and bring northern lights to California

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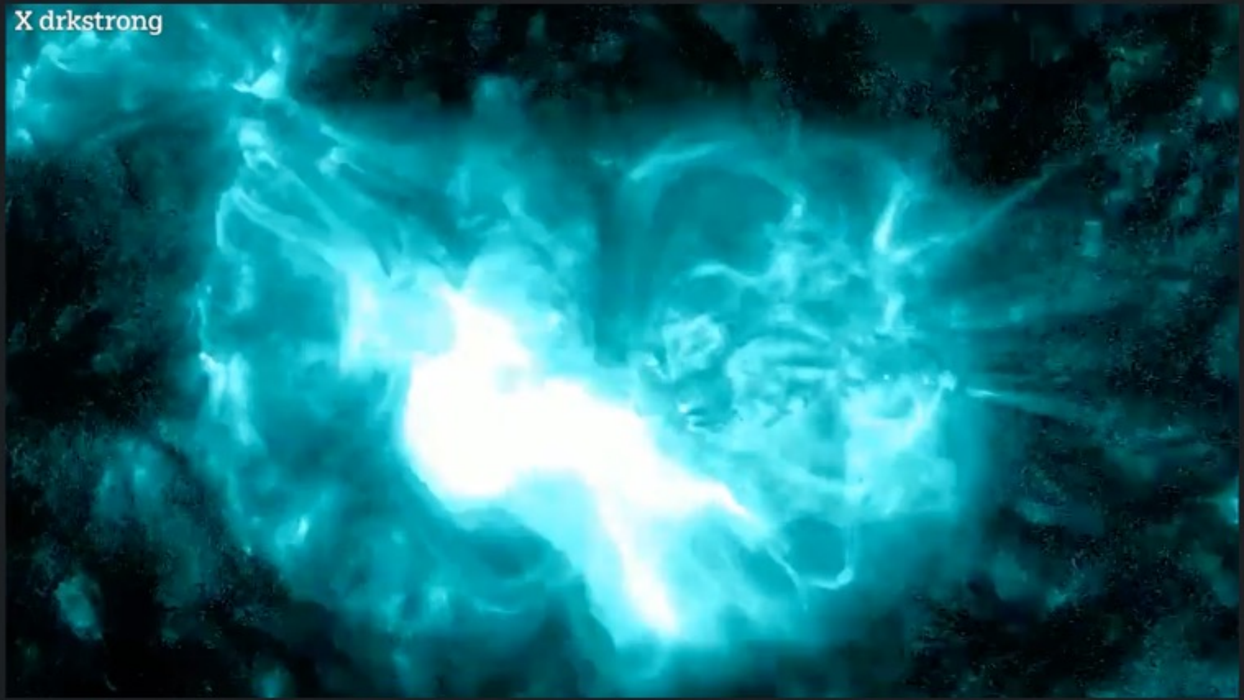

Tech

SPACE 'ATTACK' Biggest solar storm in 19 years could cripple internet, phones & power grids TODAY as rare 'severe' flare warning issued

Co-funded by the European Union

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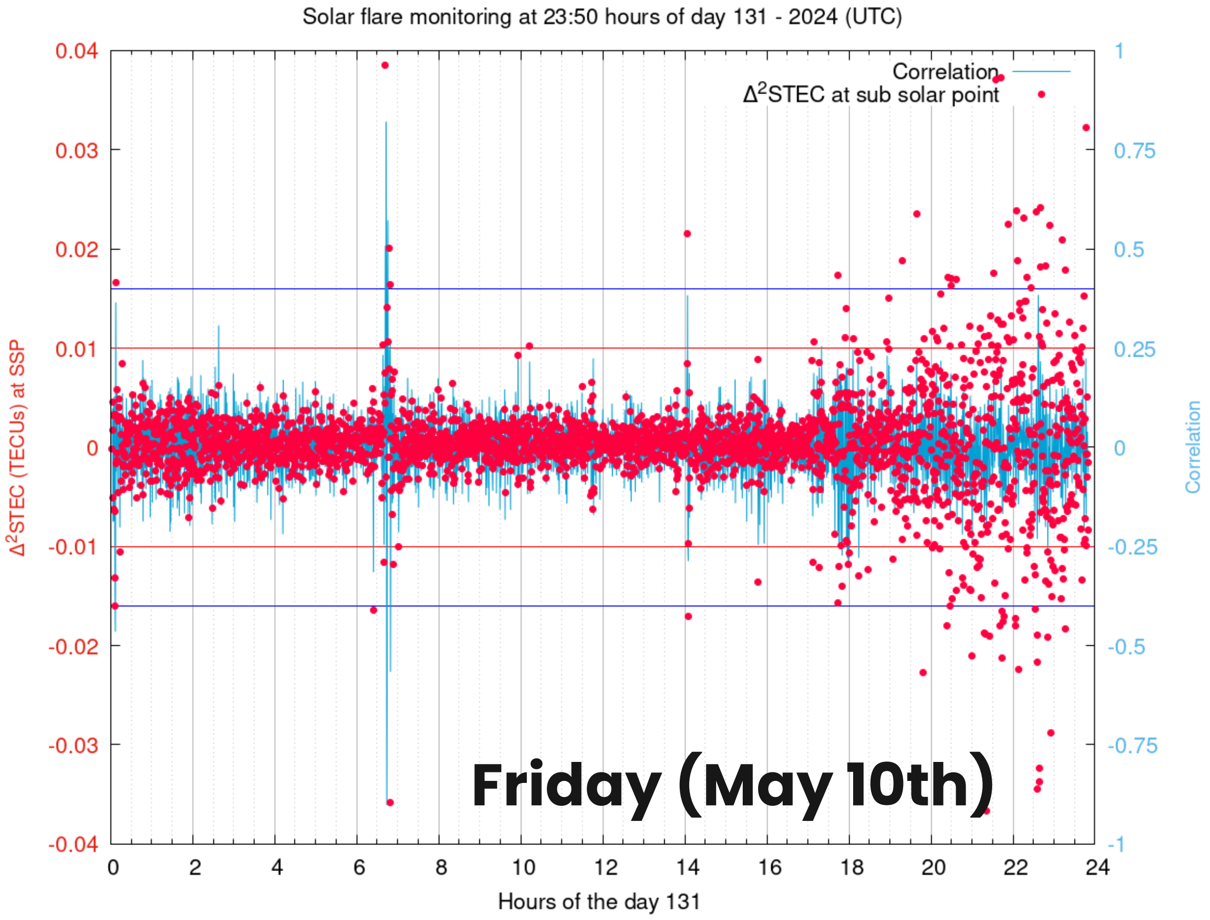
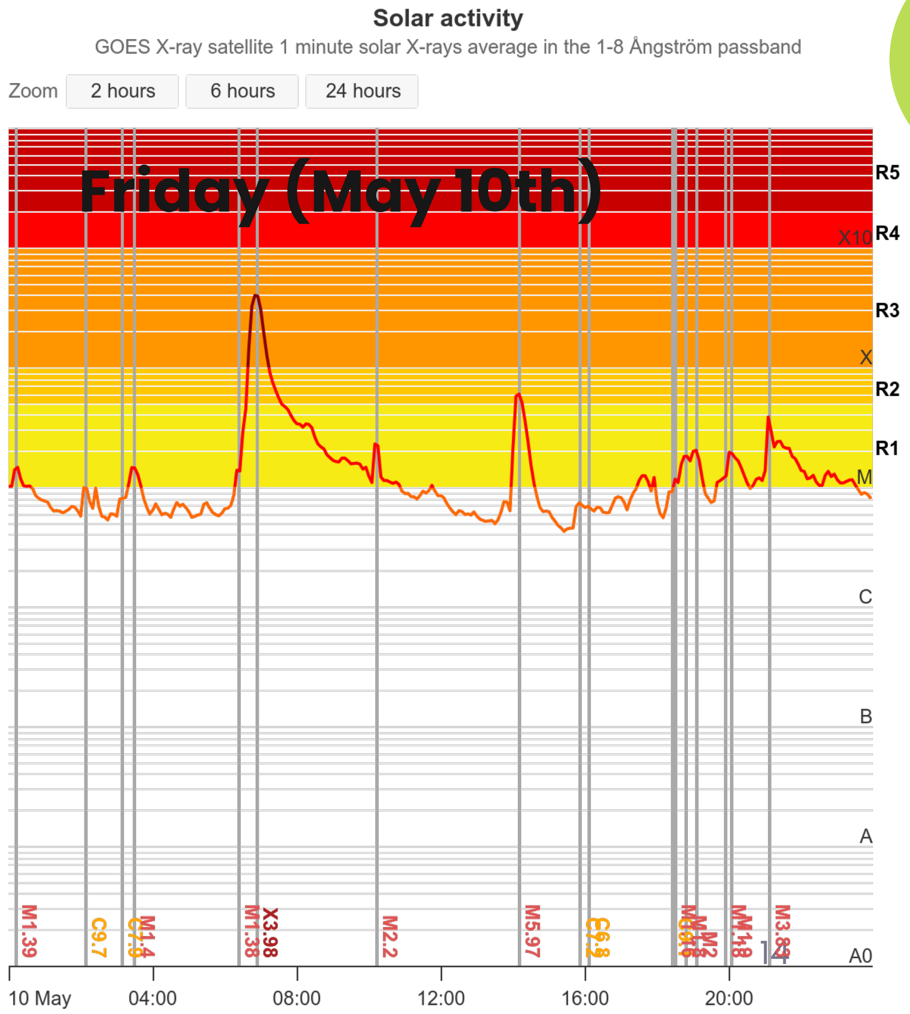
2. IONO4HAS tool

Curto JJ, Juan JM, Timote CC (2019) "[Confirming geomagnetic Sfe by means of a solar flare detector based on GNSS](#)" Journal of Space Weather and Space Climate 9:A42:1-15. [DOI 10.1051/swsc/2019040](#)

Ionospheric monitoring indexes: **GNSS solar flares detector**





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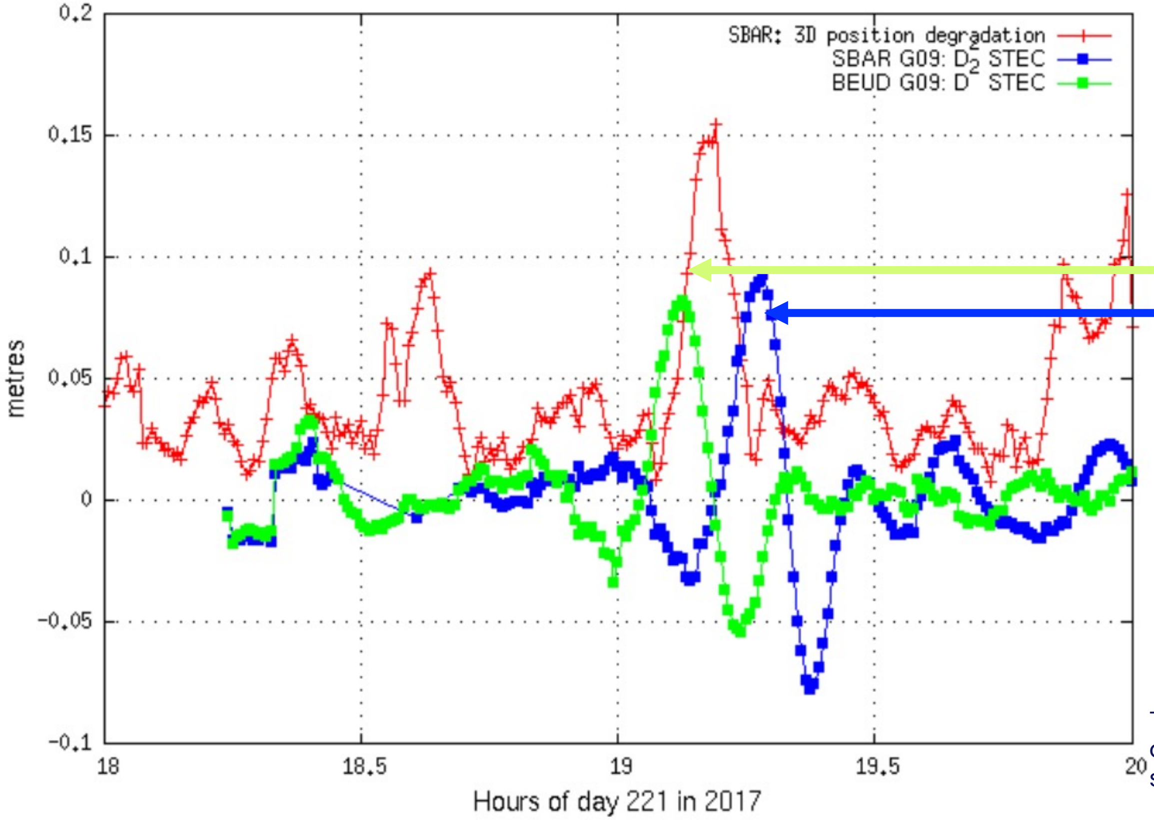
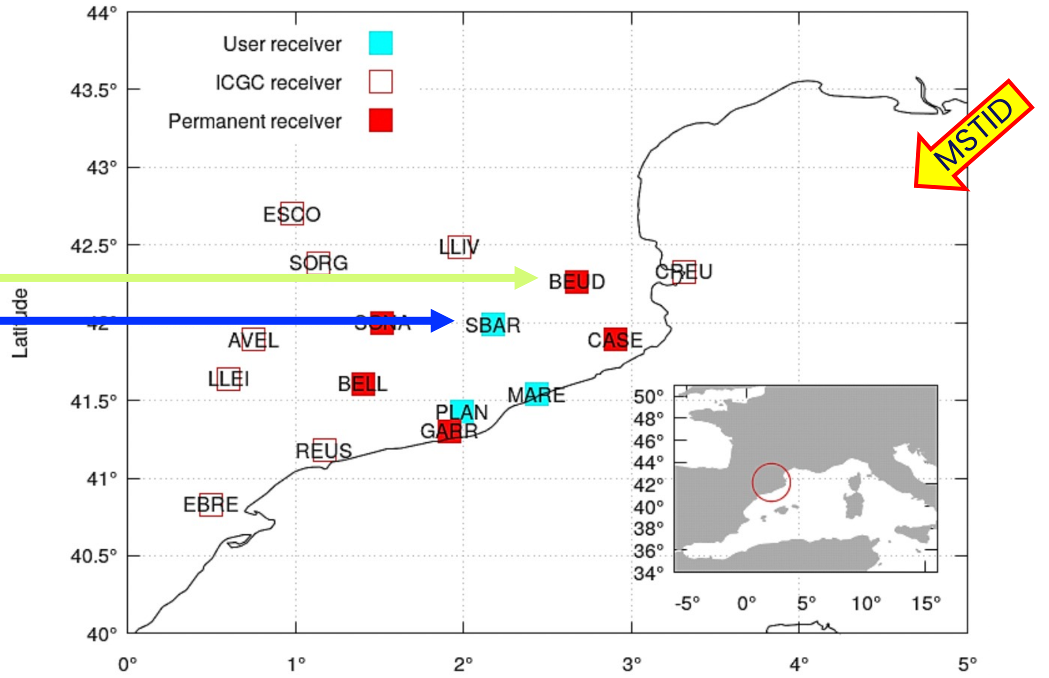
Timoté CC, Juan JM, Sanz J, González-Casado G, Rovira-Garcia A, Escudero M (2020) "[Impact of medium-scale traveling ionospheric disturbances on network real-time kinematic services: CATNET study case](#)" Journal of Space Weather Space Climate 10:A29:1-13. [DOI 10.1051/swsc/2020030](#)

2. IONO4HAS tool

Ionospheric monitoring indexes: **MSTID index**

Medium Scale Traveling Ionospheric Disturbances (**MSTID**) **potentially degrade** ionospheric mitigation of single-frequency users of **RTK** and **NRTK** services





Timoté, C. C., Juan, J. M., Sanz, J., González-Casado, G., Rovira-García, A., & Escudero, M. (2020). Impact of medium-scale traveling ionospheric disturbances on network real-time kinematic services: CATNET study case. *Journal of Space Weather and Space Climate*, *10*, 29.

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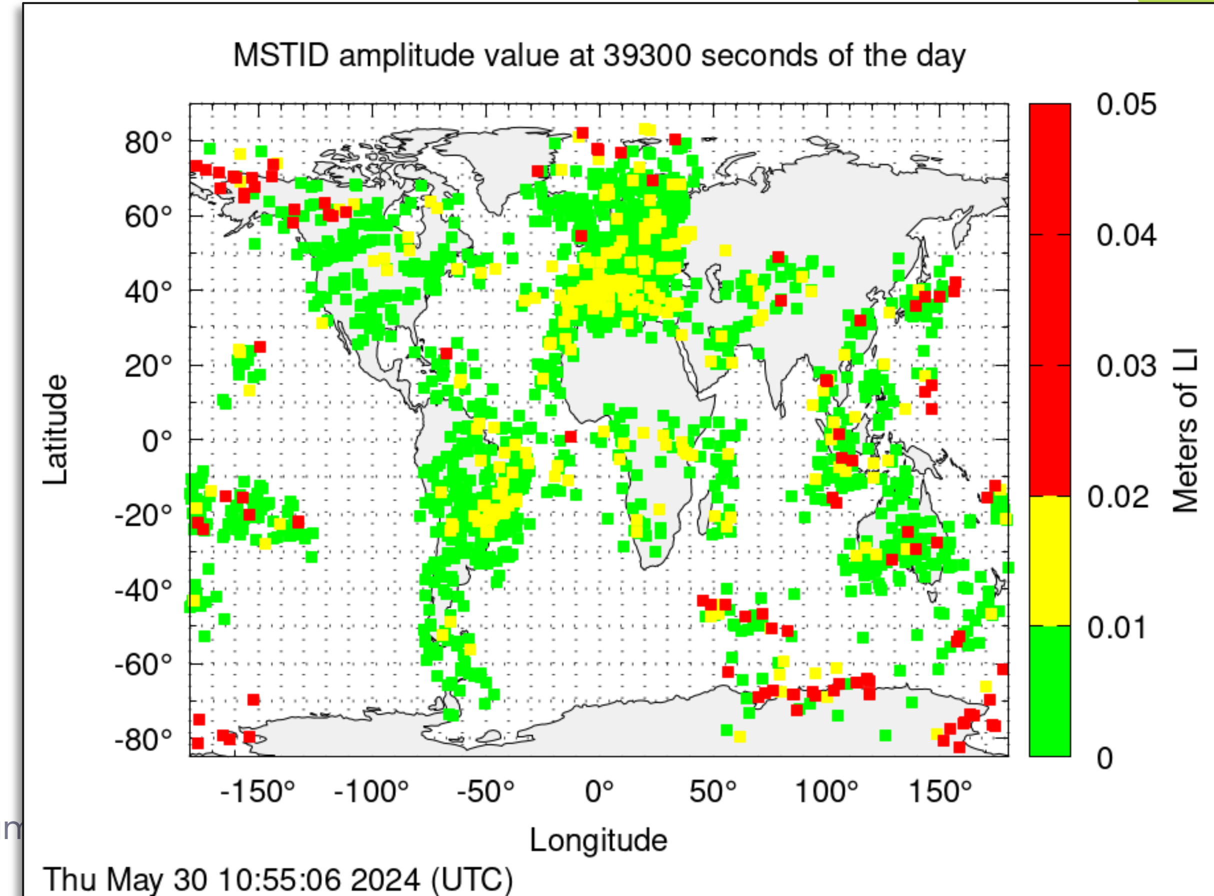
2. IONO4HAS tool

Ionospheric monitoring indexes: **MSTID index**

$L_{GF} = L1 - L2$	Geometry-free: only frequency-dependent effects

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

$\Delta^2 STEC(t)$: $0.5 \bullet \left(STEC(t+\tau) + STEC(t-\tau) - 2 \cdot STEC(t)\right)$
τ : tuning parameter (MSTID periods of 10 min)
$M(\epsilon)$ is an obliquity factor for mitigating larger values of $\Delta^2 STEC$



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Recent Solar activity

The New York Times

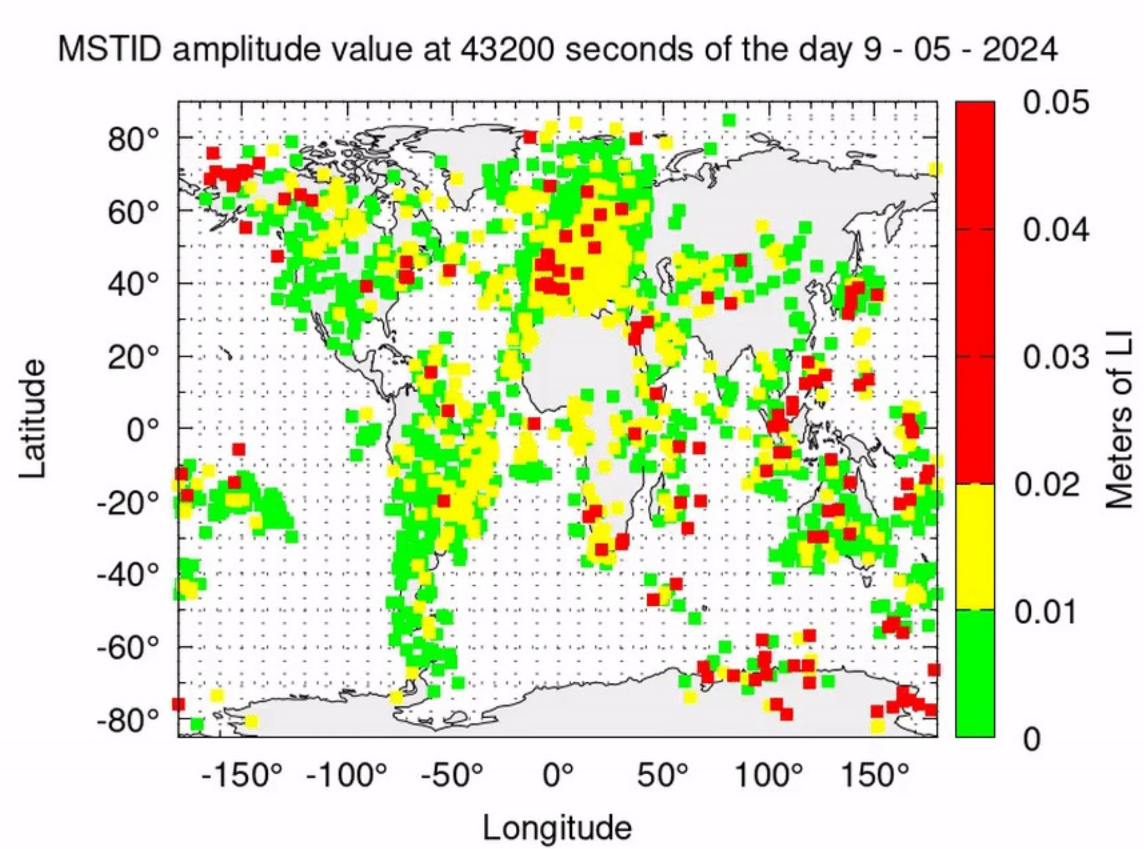
Solar Storm Intensifies, Filling Skies With Northern Lights

Officials warned of potential blackouts or interference with navigation and communication systems this weekend, as well as auroras as far south as Southern California or Texas.

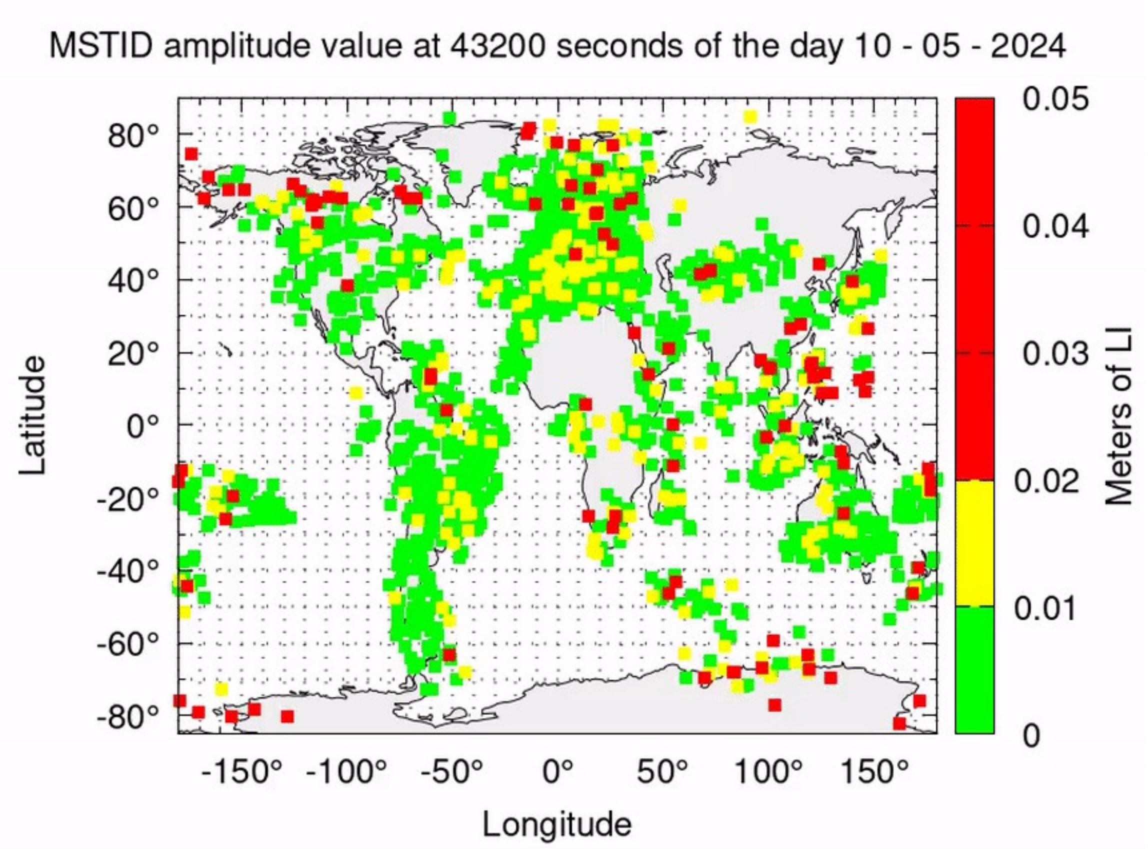
2. IONO4HAS tool

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)



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Juan JM, Sanz J, Rovira-Garcia A, González-Casado G, Ibáñez-Segura D, Orus R (2018) "AATR an Ionospheric Activity Indicator Specifically based on GNSS Measurements" Journal of Space Weather Space Climate 8:A14:1-11. DOI 10.1051/swsc/2017044

2. IONO4HAS tool

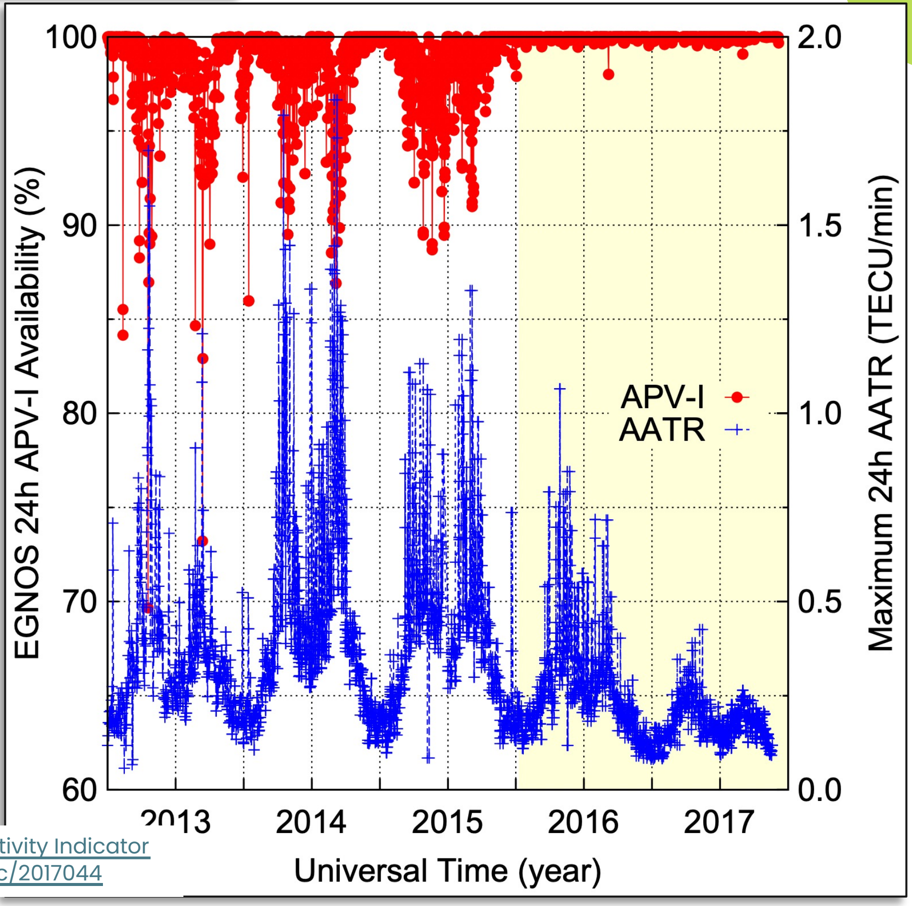
Ionospheric monitoring indexes: **AATR computation**

$L_{GF} = L1 - L2$ | Geometry-free: only frequency-dependent effects

Along-Arc TEC Ratio is defined as:

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

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



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2. IONO4HAS tool

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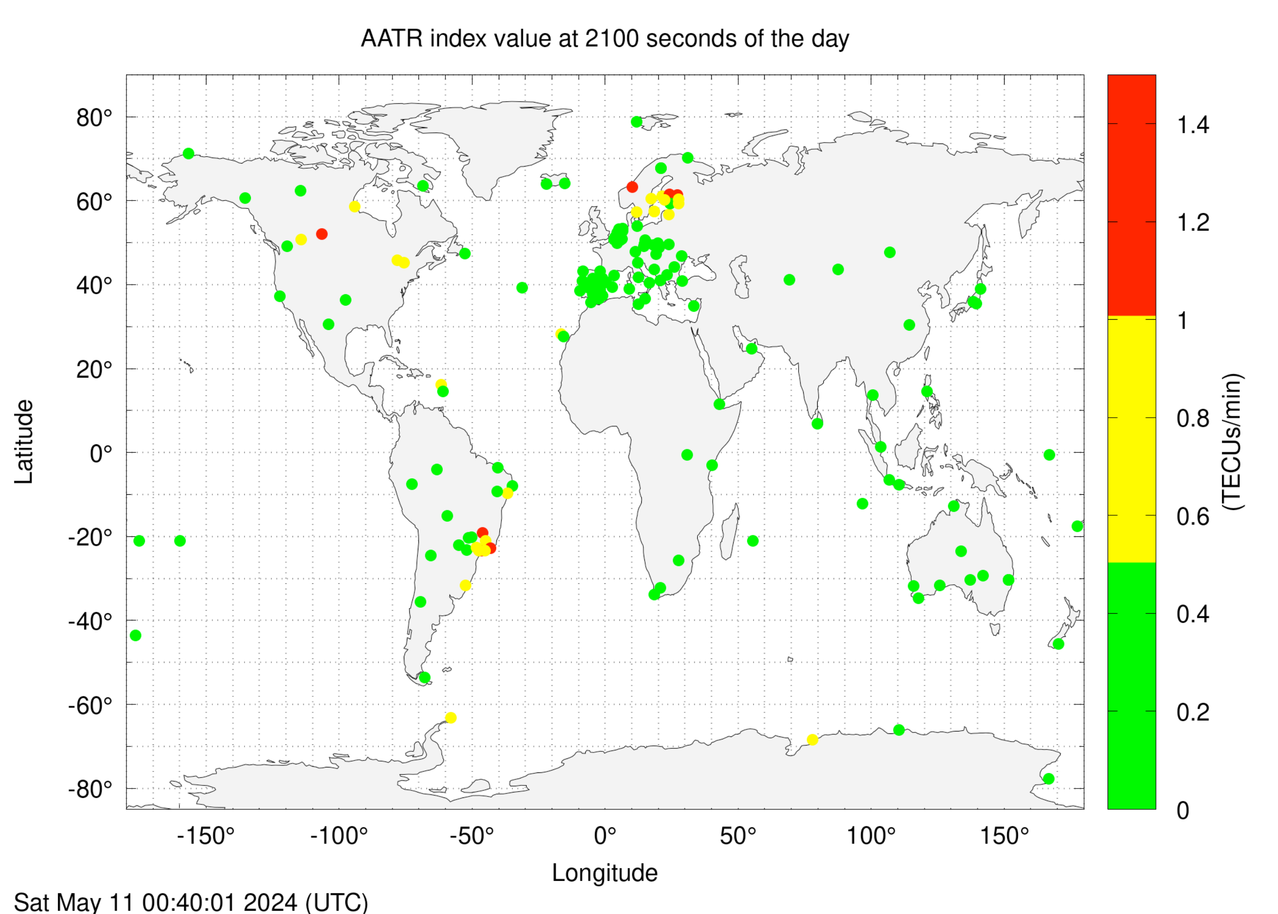

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Recent Solar activity

EL PAÍS

SUSCRÍBETE INICIAR SESIÓN

Aurora boreal en Sabadell (Barcelona), en una imagen cedida por la usuaria @LaValiente_ en la red social X.
@LAVALIENTE_

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2. IONO4HAS tool

Ionospheric monitoring indexes: **AATR index**

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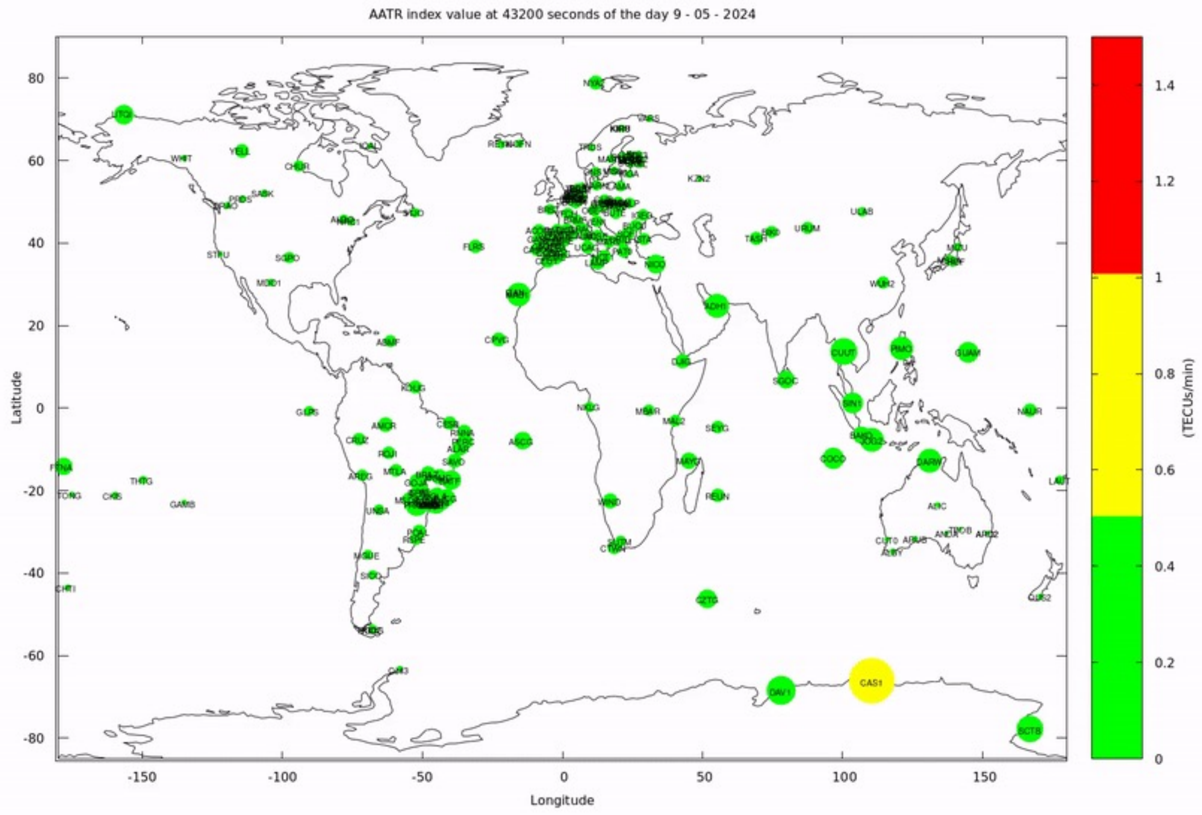

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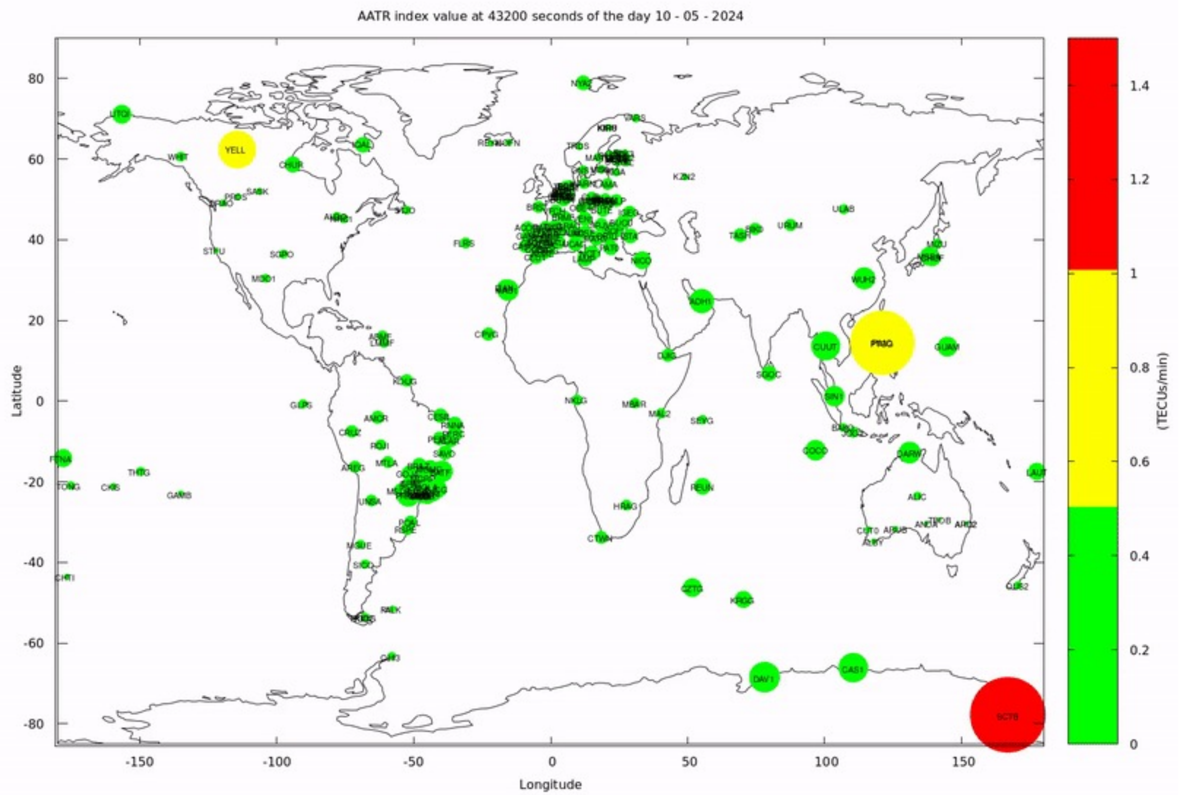
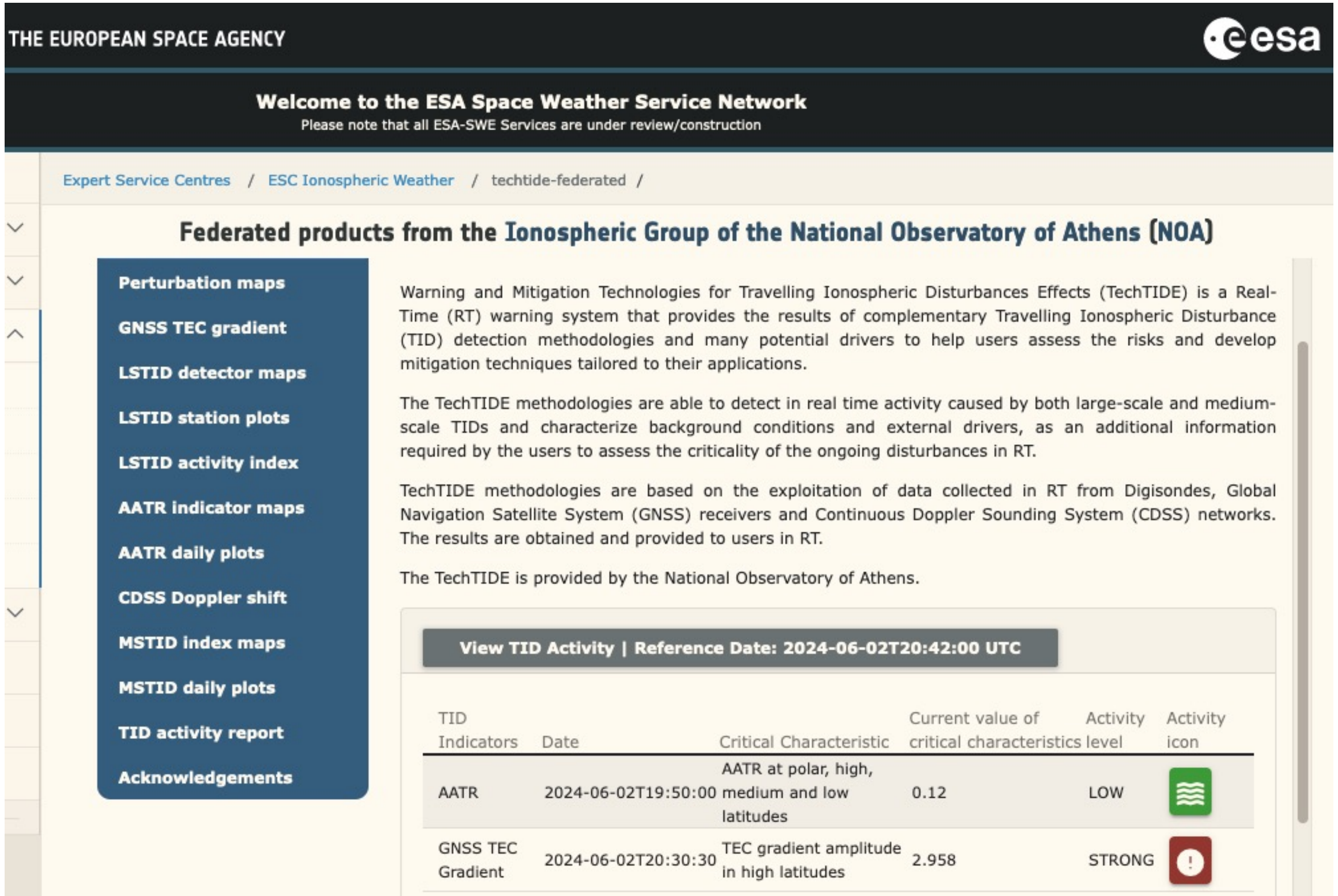


2. IONO4HAS tool

ESA Space Weather Service Network https://swe.ssa.esa.int/



2.2

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Geodetic Filter

IONO4HAS ionospheric correction tool

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2. IONO4HAS tool

Geodetic Filter

Measurements Modelling → **Geodetic Filter** | Ionospheric Filter

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

1

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

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

2

B_{GF} ambiguity in the Geometry-free combination $\quad B_{GF} = \alpha[B_{WL} - B_{IF}]$

Main input of the ionospheric module

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

Unambiguous carrier phases

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2.3

Ionospheric Modelling Module

IONO4HAS ionospheric correction tool

2. IONO4HAS tool

Ionospheric Modelling

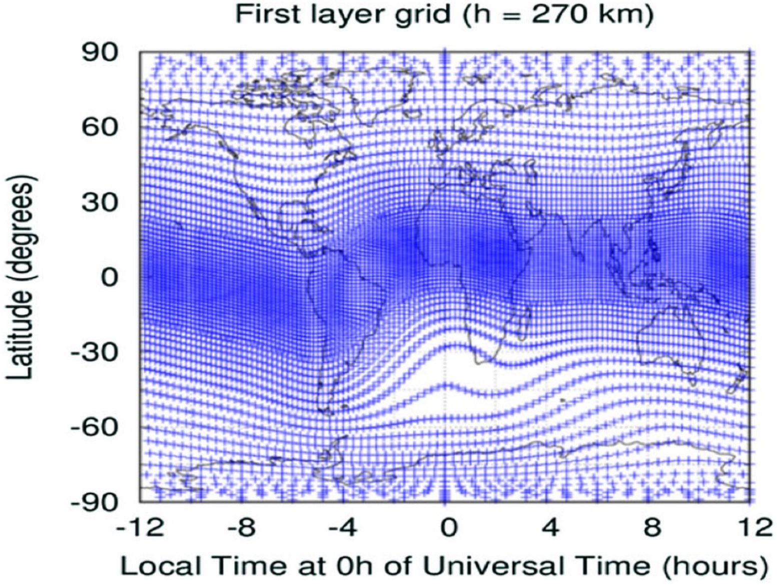
Measurements Modelling → Geodetic Filter → **Ionospheric Model**

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

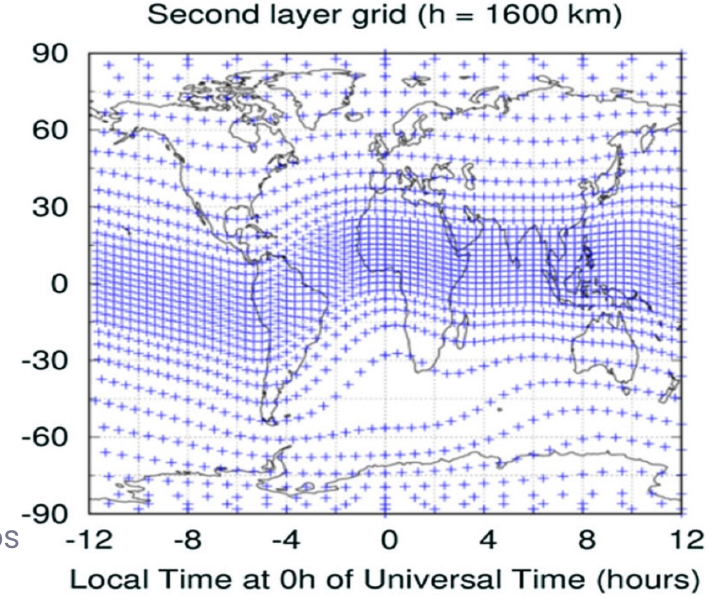
- ✓VTEC
- ✓DCBs

A <u>two-layer</u> model of the ionosphere feed with **<u>unambiguous carrier phases</u>**

First layer
main ionospheric content



Second layer
plasmapheric content



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2. IONO4HAS tool

Ionospheric Modelling

Measurements Modelling → Geodetic Filter → **Ionospheric Model**

- ✓VTEC
- ✓DCBs

The unambiguous carrier-phase measurements can be separated in the ionospheric delay term (STEC) and a constant part (hardware biases).

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

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

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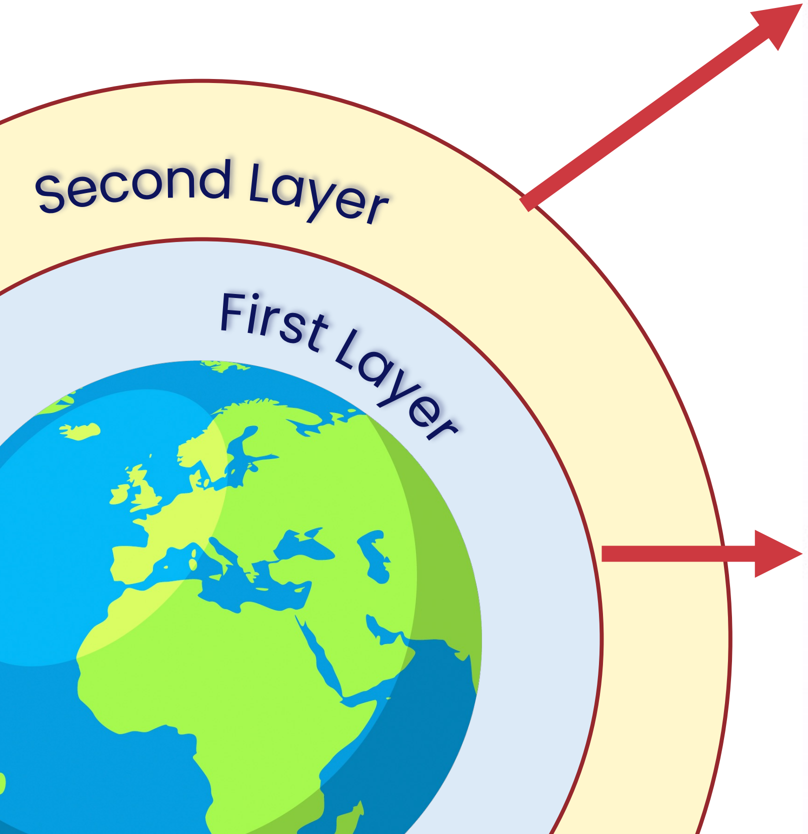
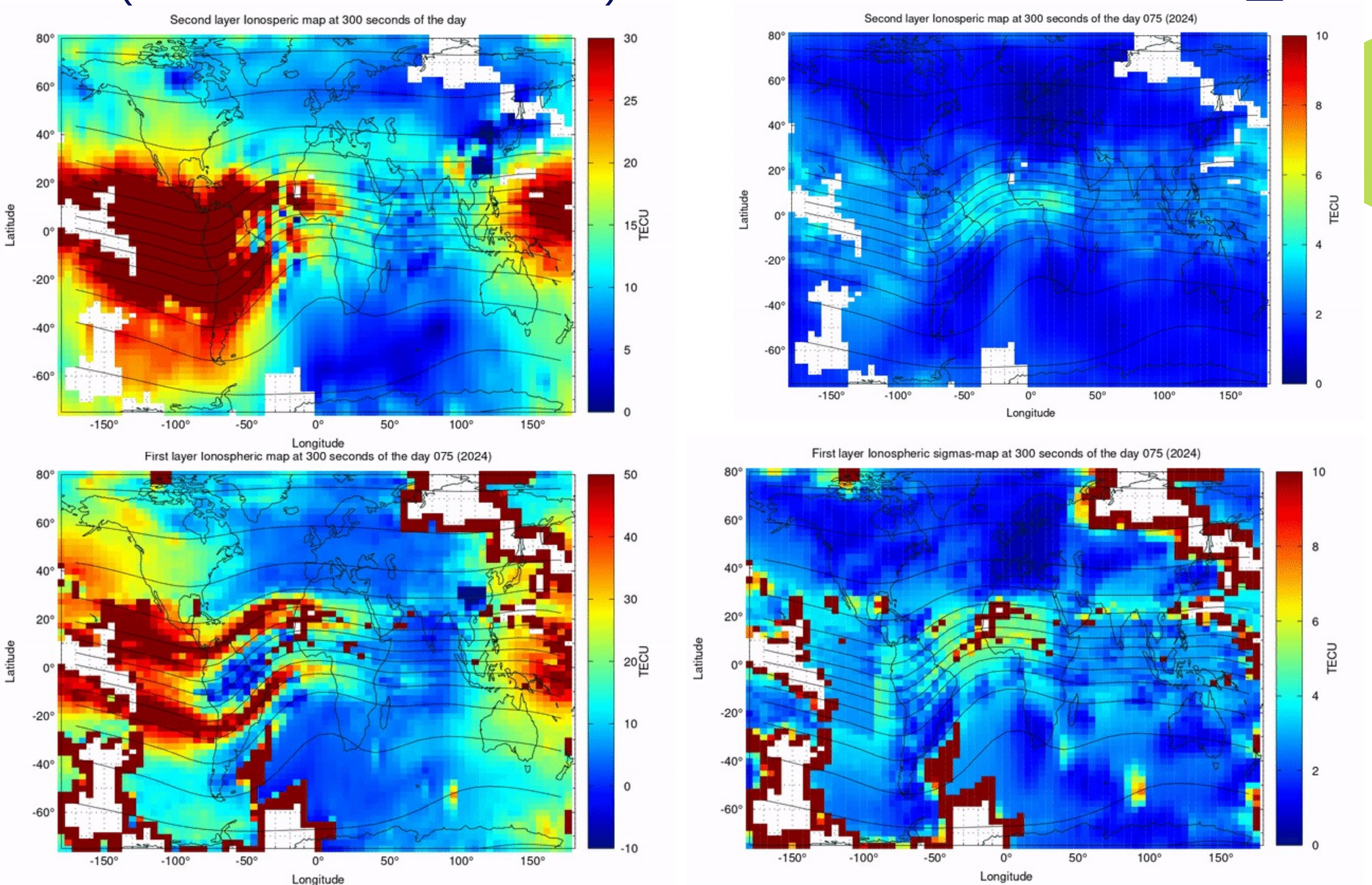
2. IONO4HAS tool

Ionospheric Modell

V (Vertical Electron Content)

SIGMA_V





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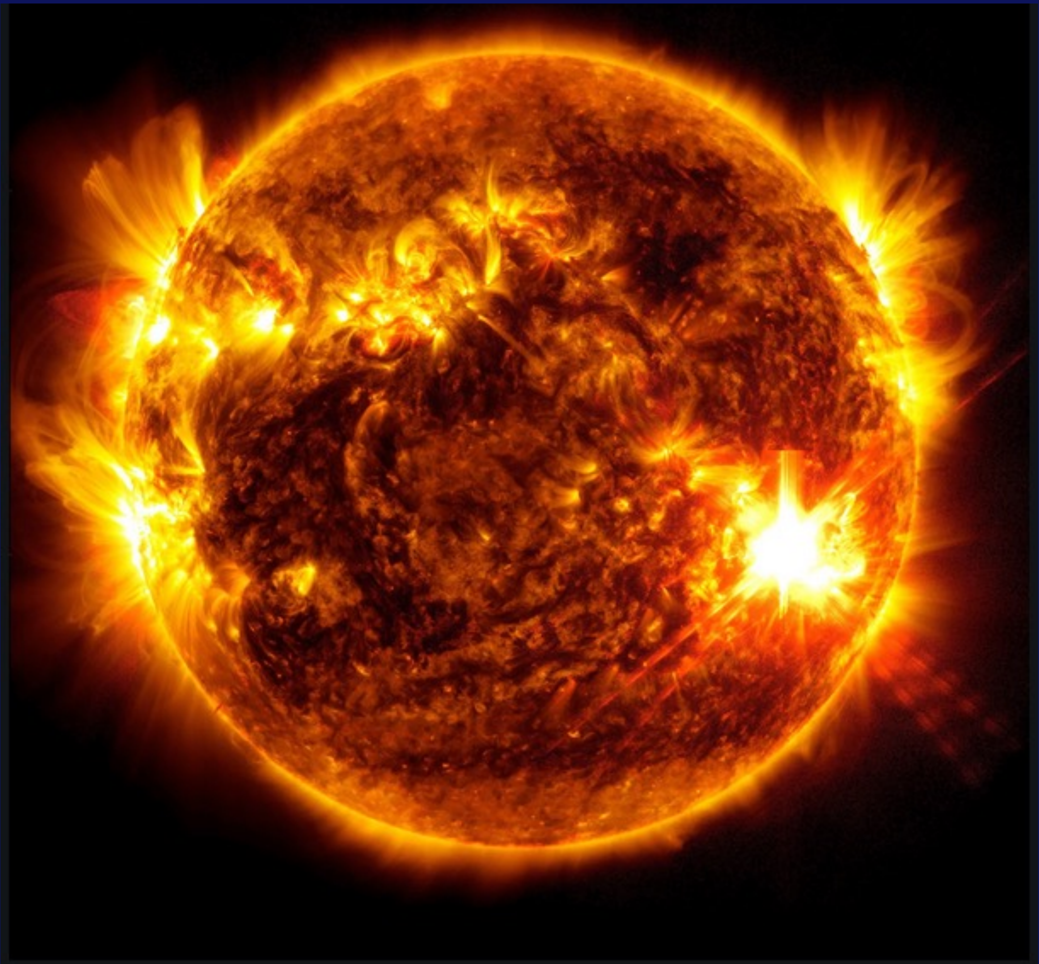
Recent Solar activity



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

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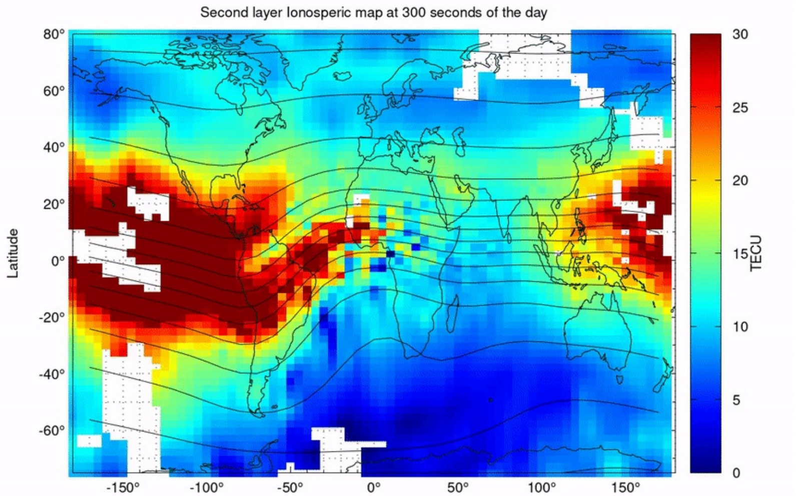
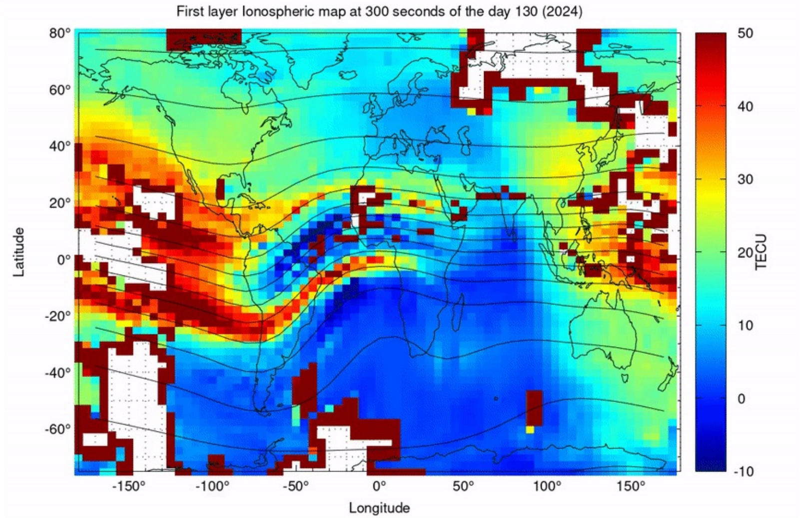
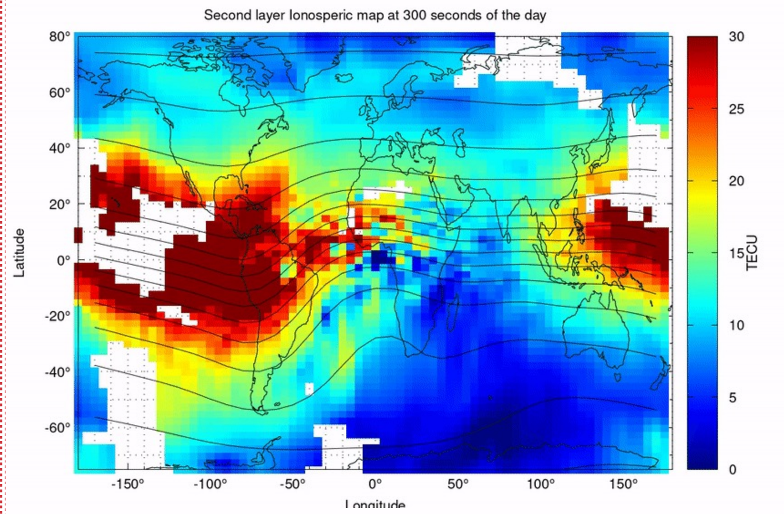
2. IONO4HAS tool

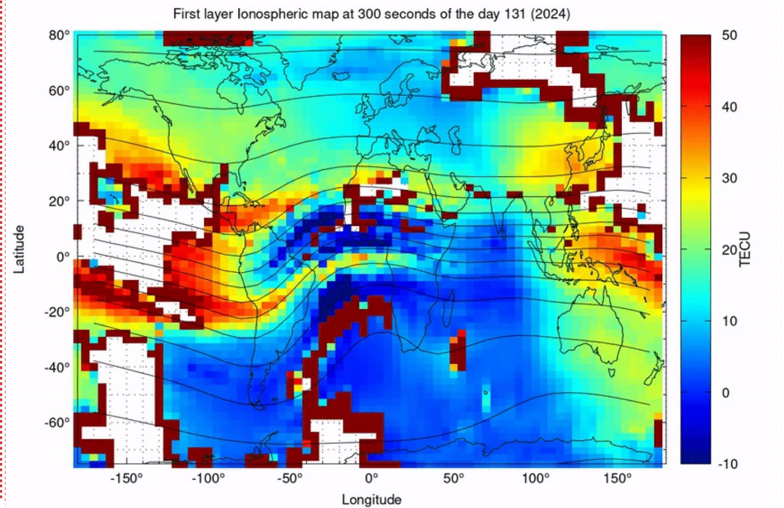
Thursday (09-05)



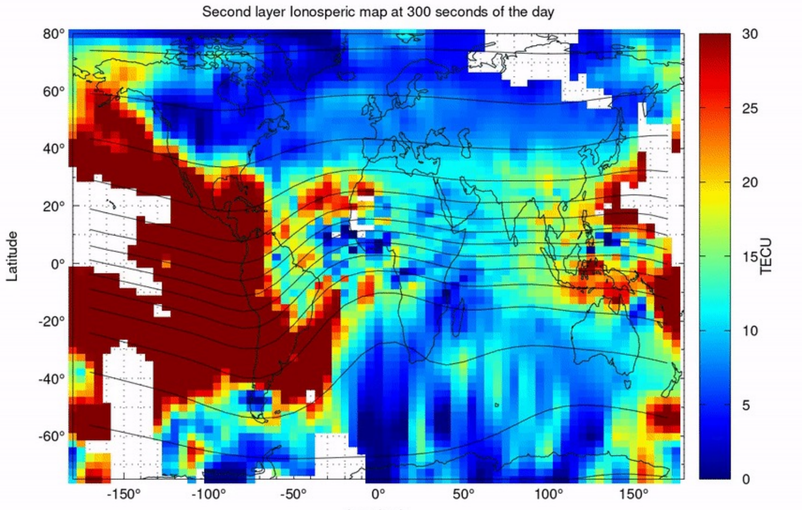


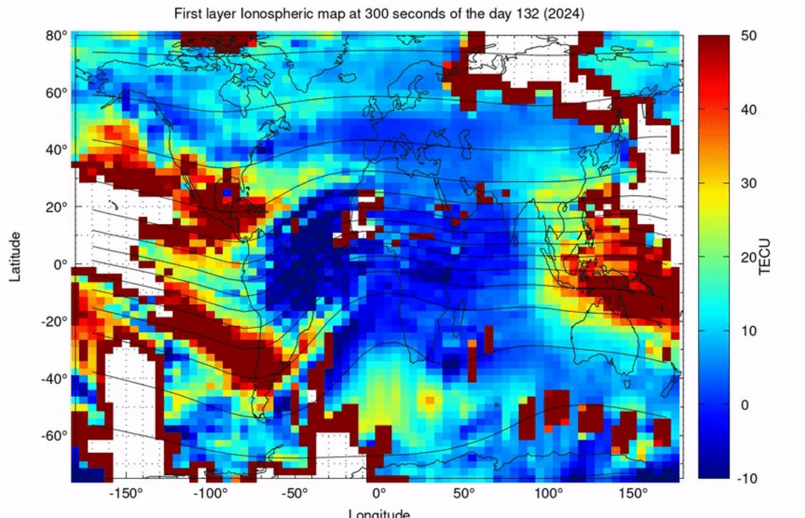
Friday (10-05)





Saturday (11-05)





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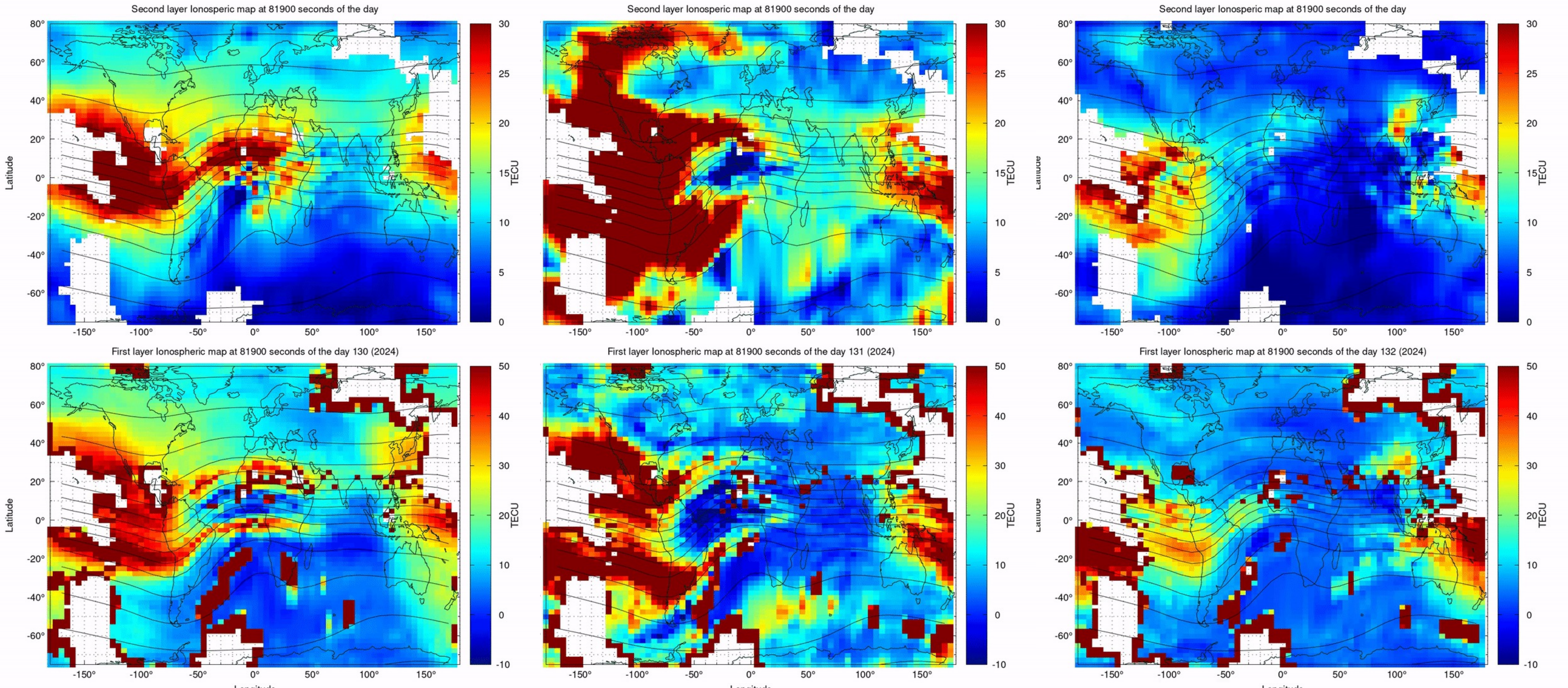
2. IONO4HAS tool



3

Assessment of the IONO4HAS ionospheric corrections

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3. Assessment of the IONO4HAS

Main goal: To define a **single-epoch positioning test** to link the user error positioning directly to ionospheric corrections.

Wide-lane combination

$$L_{W\,rcv}^{\;sat} = \frac{f_i L_{i\,rcv}^{\;sat} - f_j L_{j\,rcv}^{\;sat}}{f_i - f_j}$$

$$L_{W\,rcv}^{\;sat} = \rho_{rcv}^{sat} + c(T_{rcv} - T^{sat}) + Trop_{rcv}^{sat} + \alpha_W (I_{rcv}^{sat} + DCB_{rcv} + DCB^{sat}) + \lambda_W \left(N_{W\,rcv}^{\;sat} + \delta_{W\,rcv} + \delta_W^{\;sat}\right) + \epsilon_{LW}$$

- ρ_{rcv}^{sat}: Geometric Range
- $c(T_{rcv} - T^{sat})$: Sat. and Rec. clock offsets
- $Trop_{rcv}^{sat}$: Trop. delay
- $\alpha_W (I_{rcv}^{sat} + DCB_{rcv} + DCB^{sat})$: Iono. delay, sat. and rec. Differential Code Biases
- $\lambda_W \left(N_{W\,rcv}^{\;sat} + \delta_{W\,rcv} + \delta_W^{\;sat}\right)$: Carrier Phase Ambiguity: 1 integer, 2 real.
- ϵ_{LW}: noise and other non-modelled terms.

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3. Assessment of the IONO4HAS

Main goal: To define a **single-epoch positioning test** to link the user error positioning directly to ionospheric corrections.

$$\boldsymbol{L}_{\boldsymbol{w}}{}_{rcv}^{sat} = \rho_{rcv}^{sat} + c\left(\underline{\hat{T}_{rcv}} - T^{sat}\right) + Trop_{rcv}^{sat} + \alpha_W\left(I_{rcv}^{sat} + DCB_{rcv} + DCB^{sat}\right) + \lambda_W\left(\underline{N_W{}_{rcv}^{sat}} + \delta_{W\,rcv} + \underline{\delta_W{}^{sat}}\right) + \epsilon_{LW}$$

$$\rho_{rcv}^{sat} = \rho_0{}_{rcv}^{sat} + \boldsymbol{G}\Delta\mathrm{r} \qquad Trop_{rcv}^{sat} = Trop_0{}_{rcv}^{sat} + \underline{M(e)ZTrop_{rcv}}$$

$$\Delta\mathrm{r} = \mathrm{r}_{\mathrm{rcv}} - \mathrm{r}_{0_{rcv}}$$

Terms computed by the Geodetic Filter

$$\boxed{\Delta L_{w}{}_{rcv}^{sat} - \boldsymbol{\alpha}\left(\boldsymbol{I}_{\boldsymbol{rcv}}^{\boldsymbol{sat}} + \boldsymbol{DCB}^{\boldsymbol{sat}}\right) = \boldsymbol{G\Delta r} + c\hat{T}_{rcv} + M(e)_{rcv}^{sat} \cdot ZTrop_{rcv} + \epsilon_{Lw}}$$

Direct link between ionospheric corrections and rover positioning error.

Note that $c\hat{T}_{rcv} = cT_{rcv} + \delta_{w_{rcv}} + \alpha_W DCB_{rcv}$

4

Results

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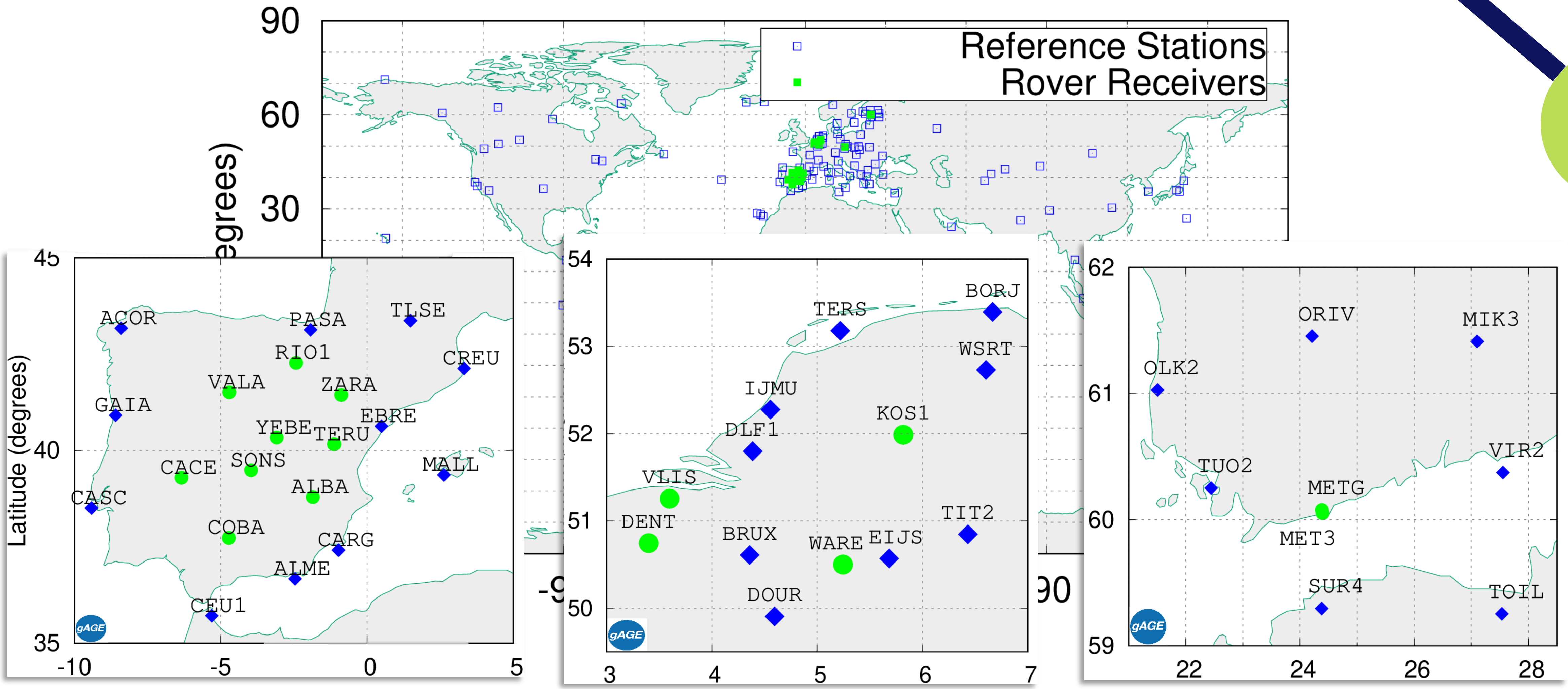
4. Results



100 – 400 km

30 – 100 km

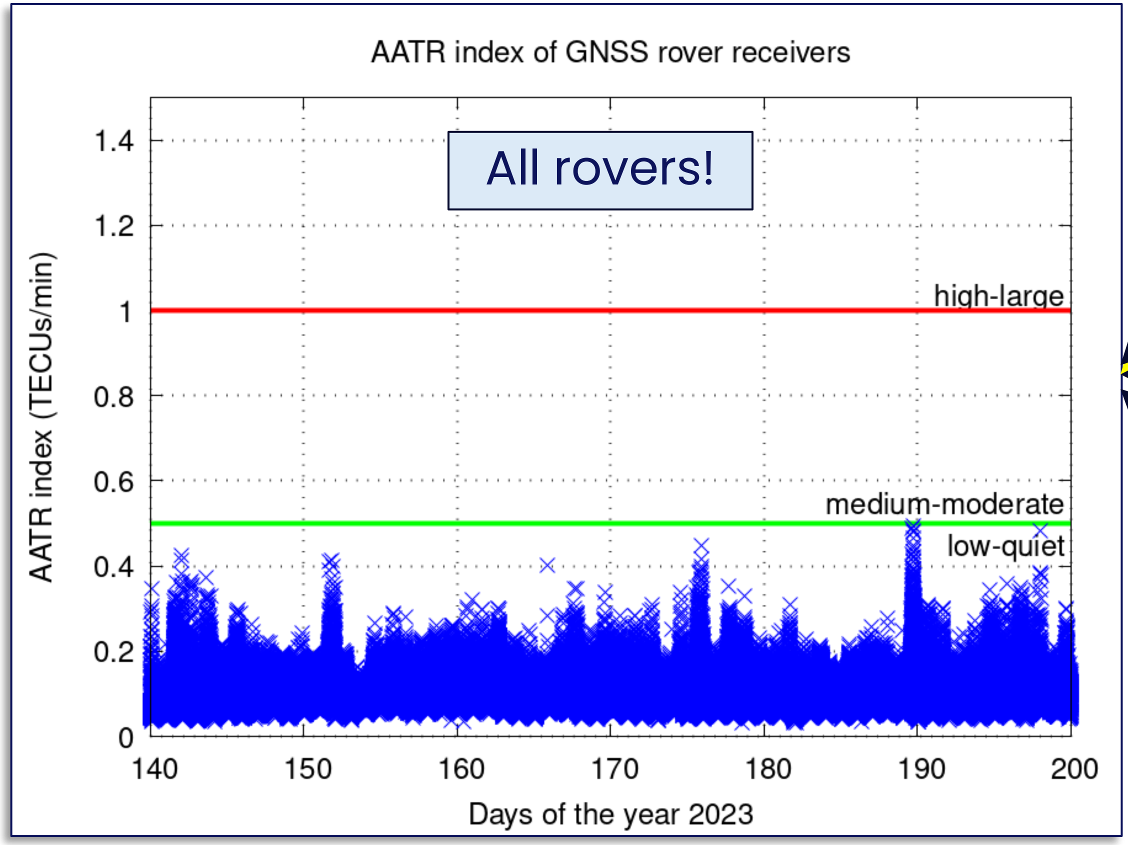
85 km

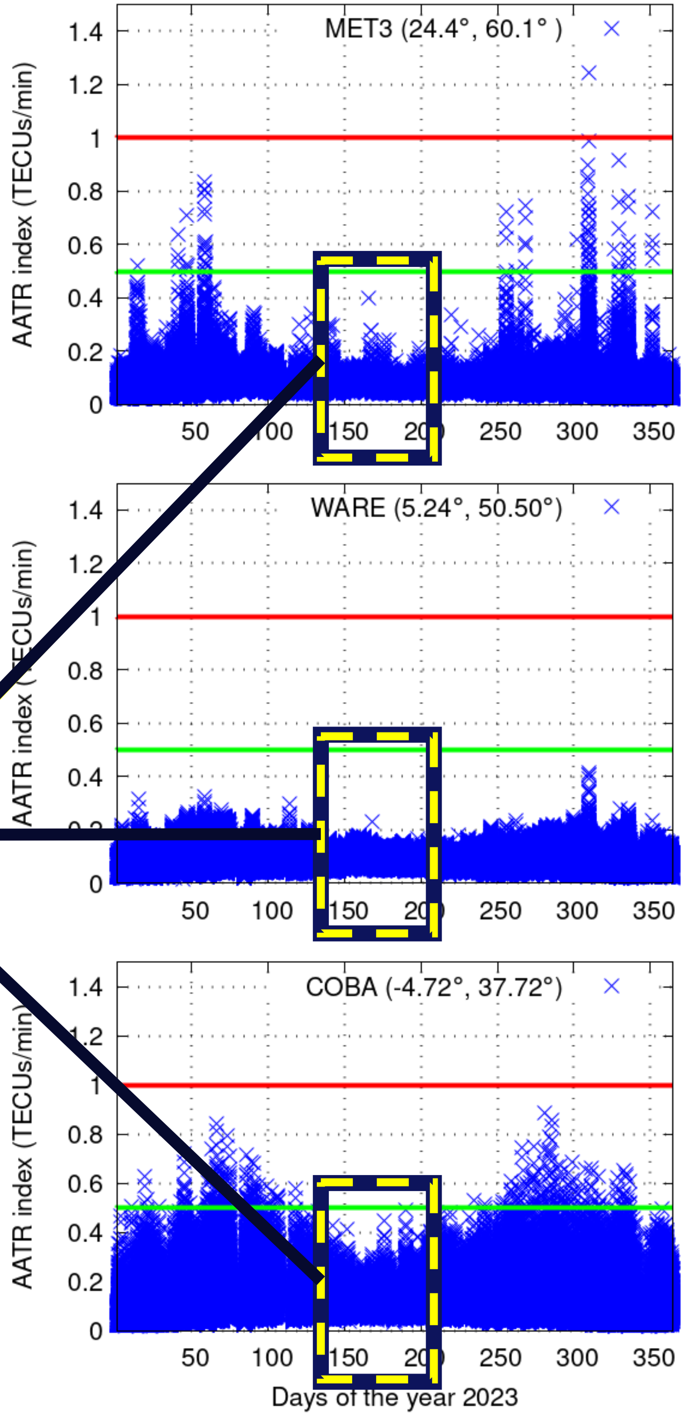
4. Results

Data window: from DoY 140 up to 200 (2023)

Ionospheric activity characterization using the Along Arc TEC Ratio (AATR index)

*A period with **nominal ionosphere** is selected to test the prototype*





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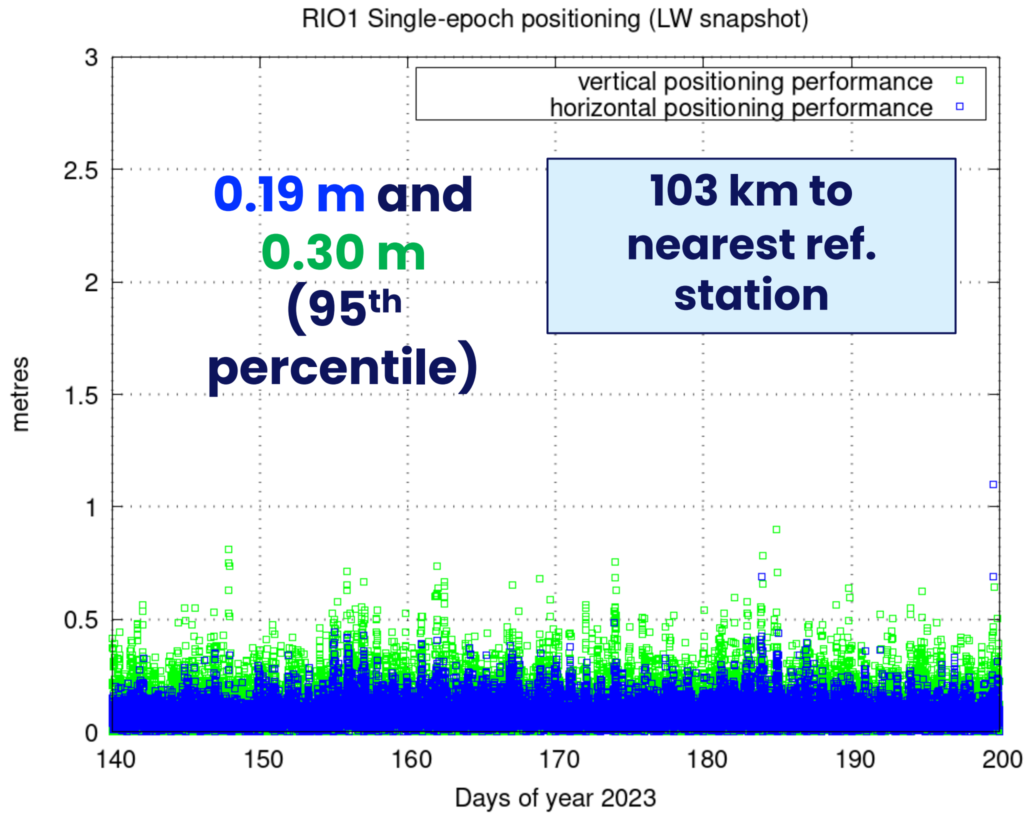
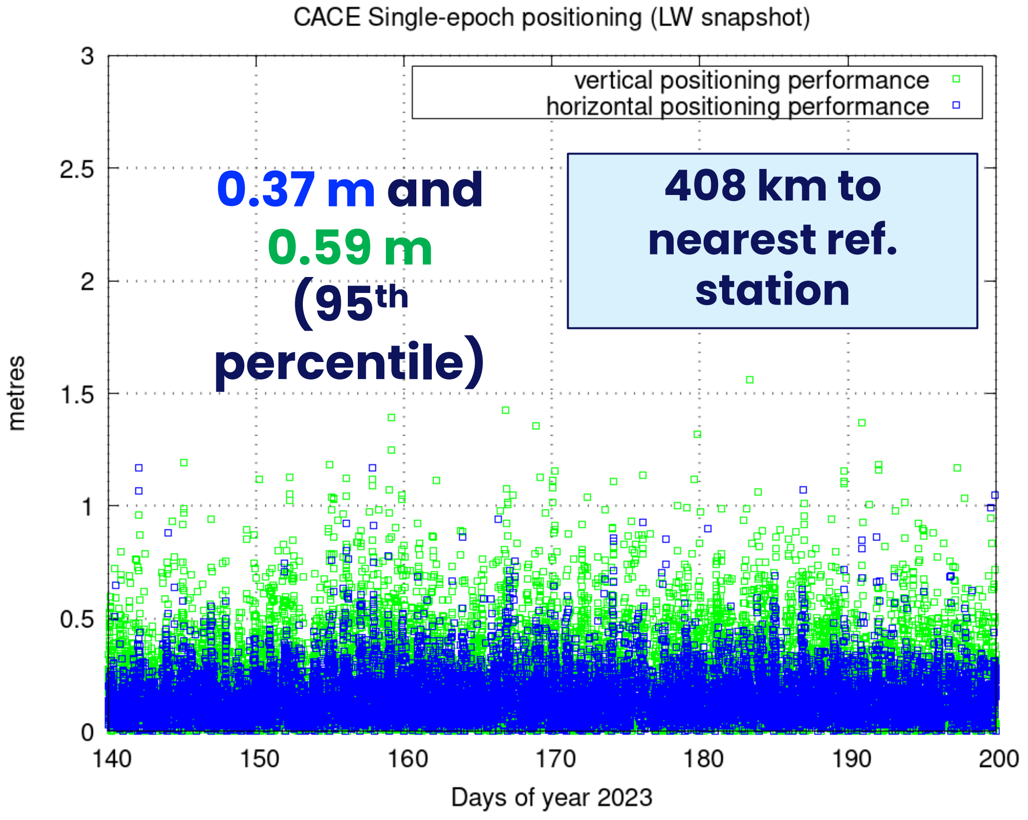
4. Results

Real-time validation of ionospheric corrections

Position error due strictly to ionospheric mismodelling

Instantaneous positioning error (no convergence time)



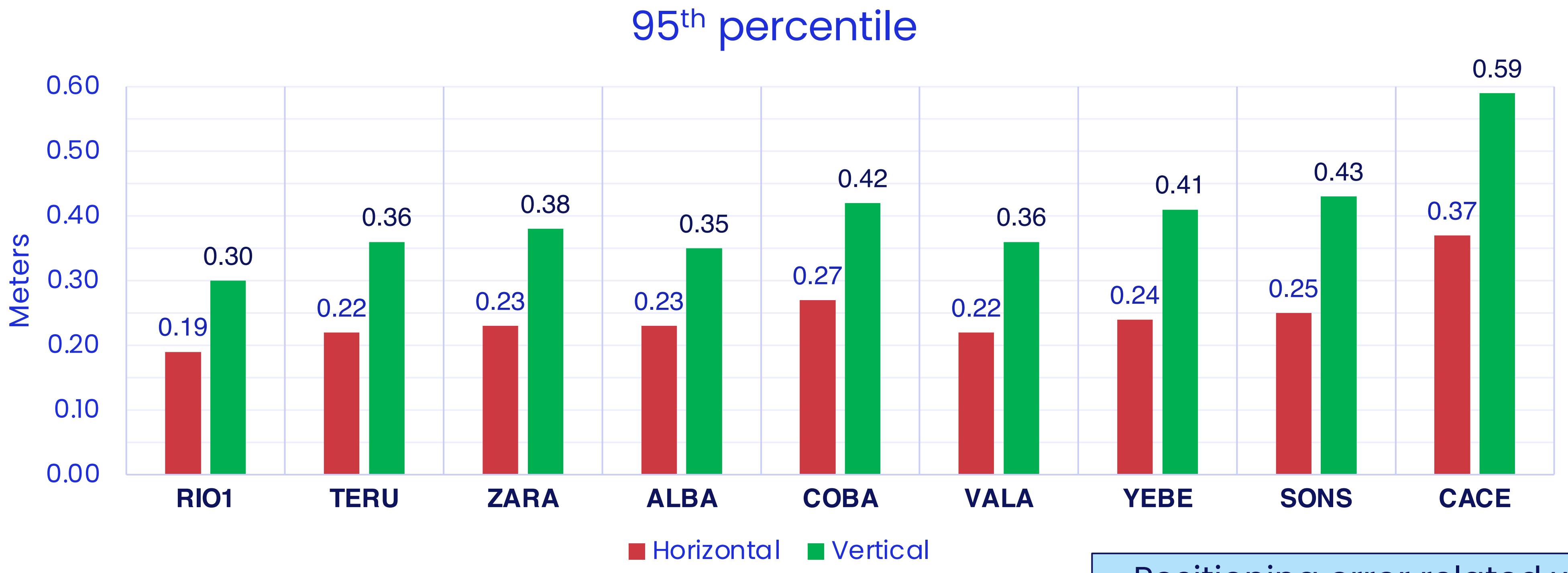


4. Results

Requirement GALILEO HAS
hor. 20 cm
ver. 40 cm
In 100 s

Real-time validation of ionospheric corrections through the 95th percentile

Instantaneous positioning error (no convergence time): **10 to 30 cm (hor)**, **20 to 50 cm (ver)**.



Network Baseline: **100 – 400 km**

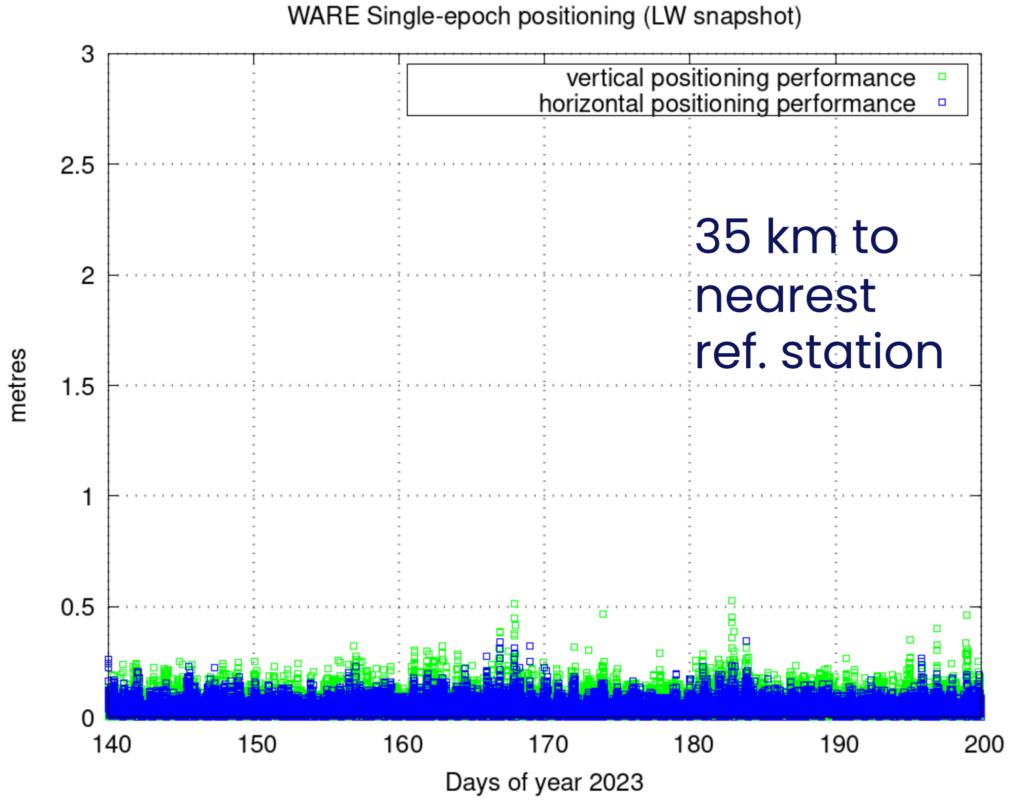
Positioning error related with distance of the user receiver to nearest ref. receiver

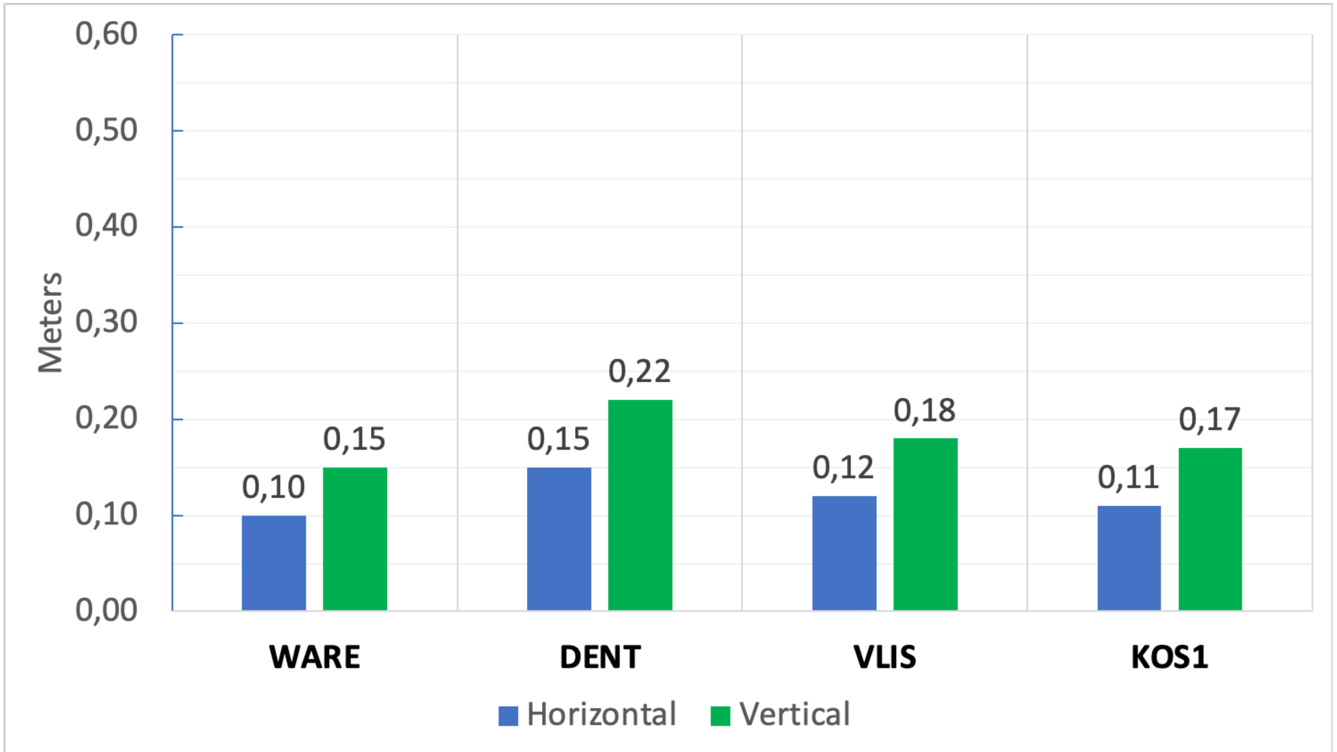
Requirement GALILEO HAS
hor. 20 cm
ver. 40 cm
In 100 s

4. Results

Real-time validation of ionospheric corrections through the 95th percentile

Instantaneous positioning error (no convergence time): **10 to 15 cm (hor)**, **15 to 22 cm (ver)**





Network Baseline: **30 – 100 km**

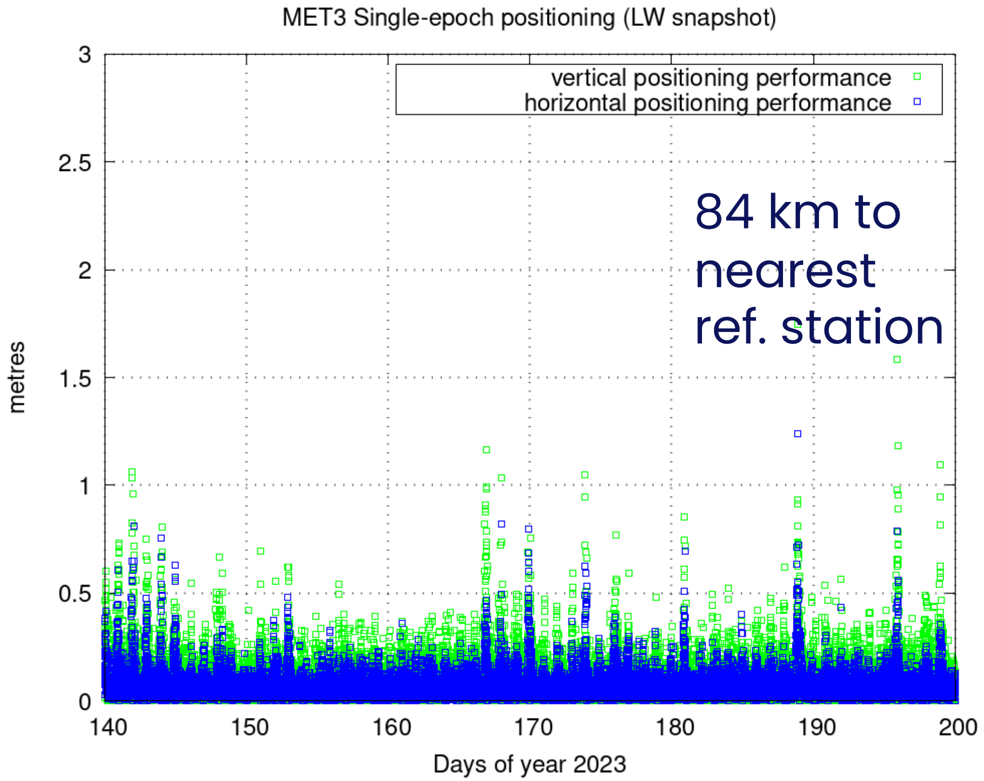
SpaceSUITE

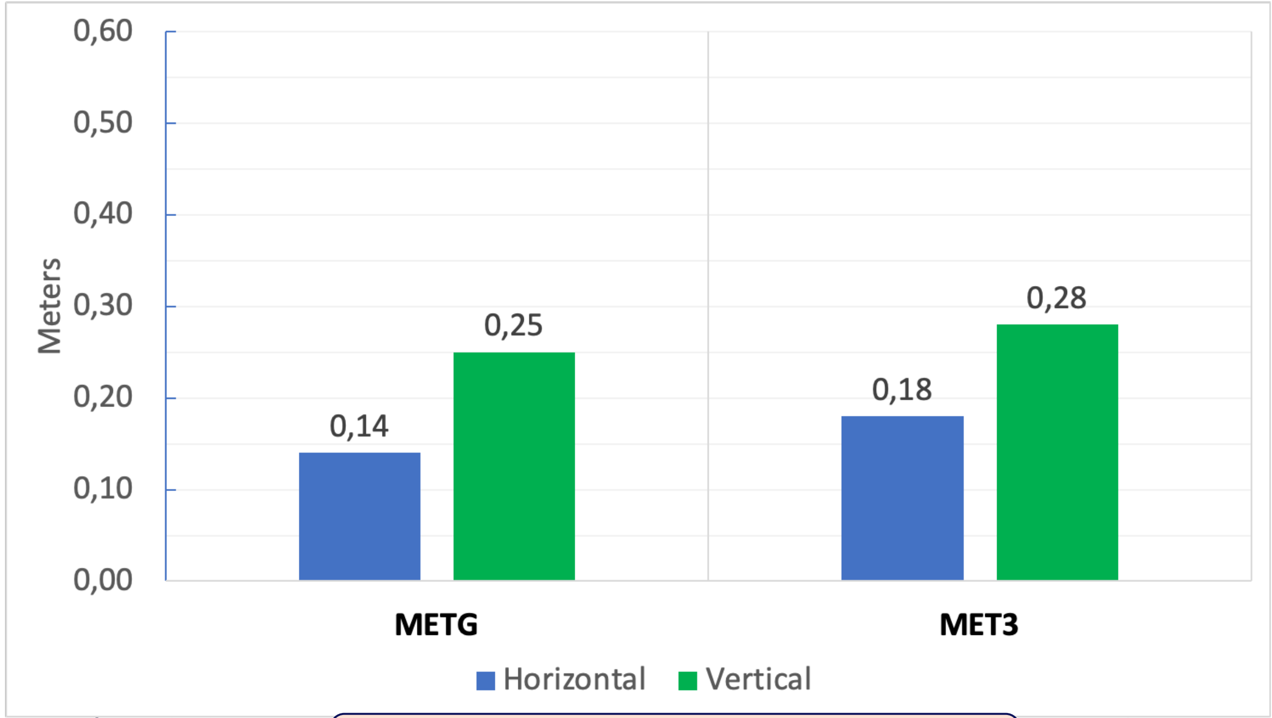
Requirement
GALILEO HAS
hor. 20 cm
ver. 40 cm
In 100 s

4. Results

Real-time validation of ionospheric corrections through the 95th percentile

Instantaneous positioning error (no convergence time): **14 to 18 cm (hor)**, **25 to 28 cm (ver)**





Network Baseline: **85 km**

4. Results

Timote, C. C., Juan, J. M., Sanz, J., Rovira-Garcia, A., González-Casado, G., Orús-Pérez, R., ... & Blonski, D. (2024). Ionospheric corrections tailored to Galileo HAS: validation with single-epoch navigation. *GPS Solutions*, *28*(2), 93.

Single-epoch (first epoch) comparison strategies:

$$\Delta P_{IF} = \boldsymbol{G\Delta r} + c(T_{rcv}) + M(e)_{rcv}^{sat} \cdot ZTrop_{rcv} + E_{IF}$$
$$\Delta L_{IF} = \boldsymbol{G\Delta r} + c(T_{rcv}) + M(e)_{rcv}^{sat} \cdot ZTrop_{rcv} + \lambda_N w^{sat} + B_c^j + \epsilon_{IF}$$

NO-IONO

Classical PPP

Single-epoch solution is driven the **Code IF**

$$\Delta L_{w\,rcv}^{\;sat} - \boldsymbol{\alpha}(\boldsymbol{I_{rcv}^{sat}} + \boldsymbol{DCB^{sat}}) = \boldsymbol{G\Delta r} + cT_{rcv} + M(e)_{rcv}^{sat} \cdot ZTrop_{rcv} + \epsilon_{L_W}$$

IGRG

IGS corrections

$$\Delta L_{w\,rcv}^{\;sat} - \boldsymbol{\alpha}(\boldsymbol{I_{rcv}^{sat}} + \boldsymbol{DCB^{sat}}) = \boldsymbol{G\Delta r} + cT_{rcv} + M(e)_{rcv}^{sat} \cdot ZTrop_{rcv} + \epsilon_{L_W}$$

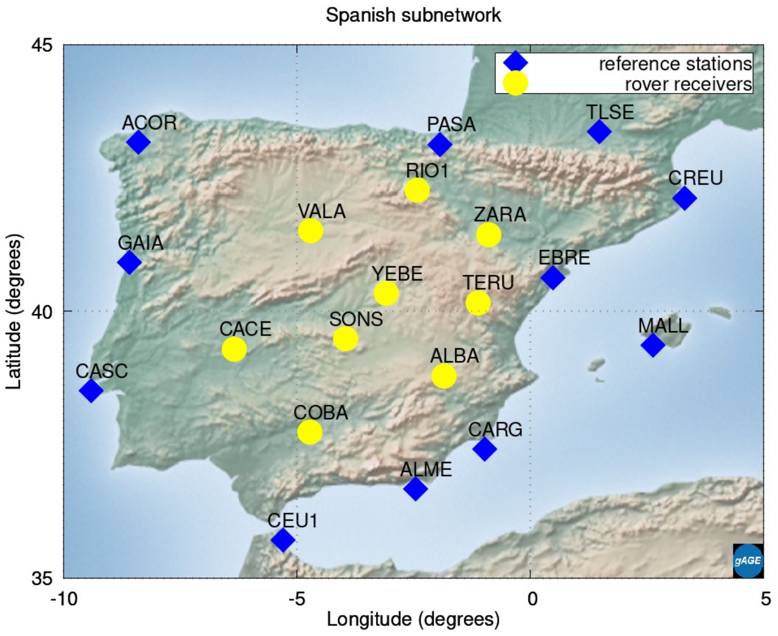
IONO4HAS

IONO4HAS corrections

4. Results

Validation with other products in single-epoch PPP

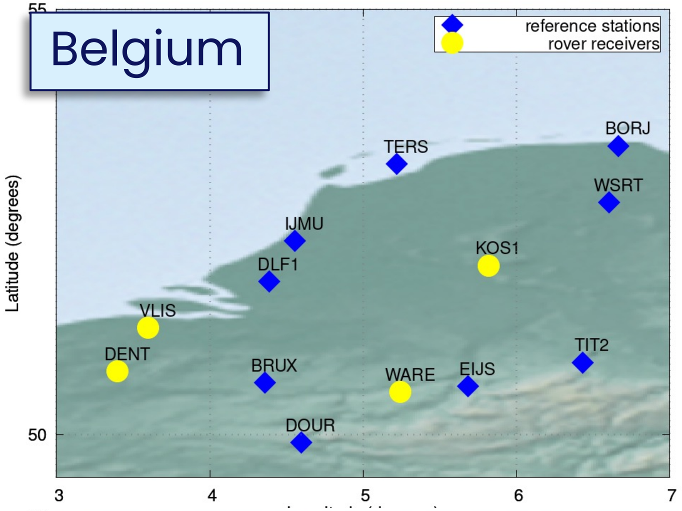
Iberian Peninsula



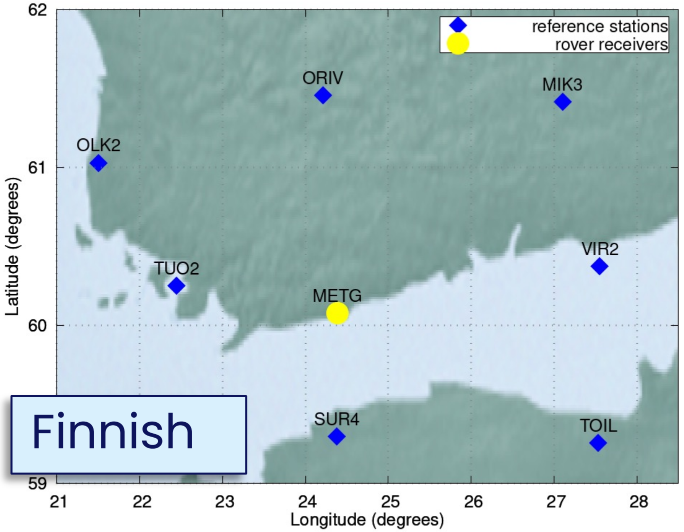
	95th percentile horizontal error (m)			95th percentile vertical error (m)		
	NO-IONO	IGRG	IONO4HAS	NO-IONO	IGRG	IONO4HAS
RIO1	2.05	0.58	0.19	3.06	0.91	0.32
TERU	1.70	0.61	0.21	2.59	1.07	0.41
ZARA	1.83	0.60	0.19	3.04	1.00	0.32
ALBA	2.20	0.56	0.23	3.46	0.95	0.37
COBA	1.65	0.61	0.25	2.72	1.06	0.41
VALA	1.53	0.57	0.22	2.33	0.90	0.37
YEBE	2.06	0.65	0.22	3.29	1.15	0.46
SONS	1.77	0.62	0.25	2.95	1.10	0.45
CACE	2.32	0.71	0.32	3.98	1.22	0.52

4. Results

Validation with other products in single-epoch PPP



	95th percentile horizontal error (m)			95th percentile vertical error (m)		
	NO-IONO	IGRG	IONO4HAS	NO-IONO	IGRG	IONO4HAS
WARE	1.25	0.56	0.12	1.94	0.92	0.18
VLIS	1.61	0.54	0.13	2.50	0.85	0.20
DENT	1.23	0.57	0.14	1.97	0.94	0.21
KOS1	1.23	0.59	0.12	2.07	1.00	0.19



	95th percentile horizontal error (m)			95th percentile vertical error (m)		
	NO-IONO	IGRG	IONO4HAS	NO-IONO	IGRG	IONO4HAS
METG	0.86	0.37	0.18	1.30	0.59	0.26
MET3	1.59	0.61	0.19	2.70	1.08	0.29

5

gAGE RT products portal

SpaceSUITE

SpaceSUITE

5. gAGE RT products portal

https://server.gage.upc.edu/iono4has/

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gAGE

SpaceSUITE

Thank you!

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www.spacesuite-project.eu

Co-funded by the European Union

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