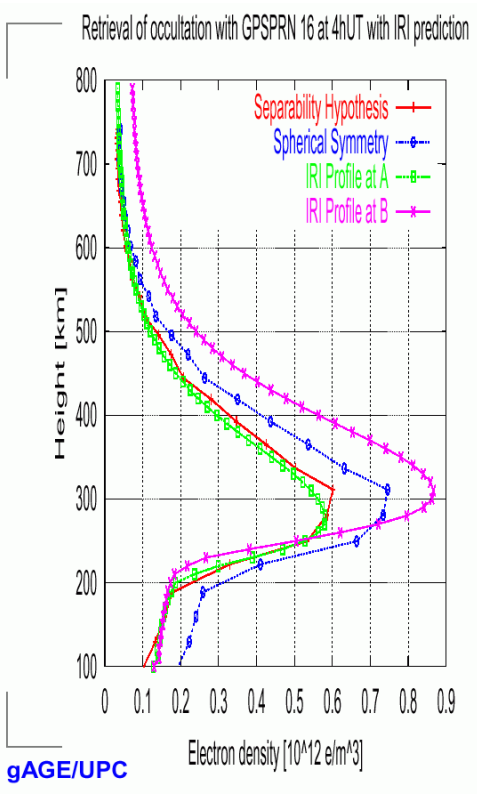
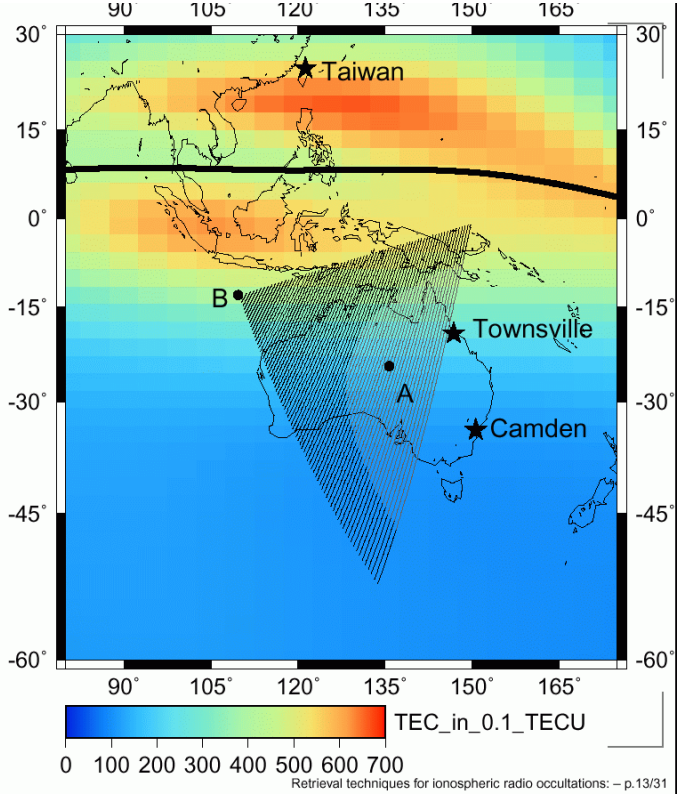
Global Ionospheric Maps





Germán Olivares-Pulido (1) and Manuel Hernandez-Pajares (1)
(1) UPC-IonSAT Research Group, IGS Associate Analysis Center, Spain

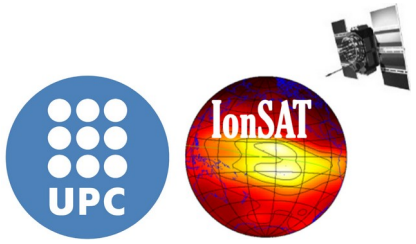
Tomography of the Ionosphere with GNSS Measurements & Global Ionospheric Maps

GNSS Space Weather monitoring: from solar flares to global maps of activity proxy

Manuel Hernández-Pajares*(1,2), Germán Olivares-Pulido(1), Victoria Graffigna(1,2), David Moreno-Borràs(1), Alejandro Pérez-Conesa(1), Alberto García-Rigo(2,1), Enric Monte-Moreno(3), Qi Liu(4), Heng Yang(5), Josep Maria Aroca-Farrerons(1), David Roma-Dollase(6) & Raul Orus-Perez(7)

IWGI2026, Neustrelitz, Germany, 31 August - 3 September 2026

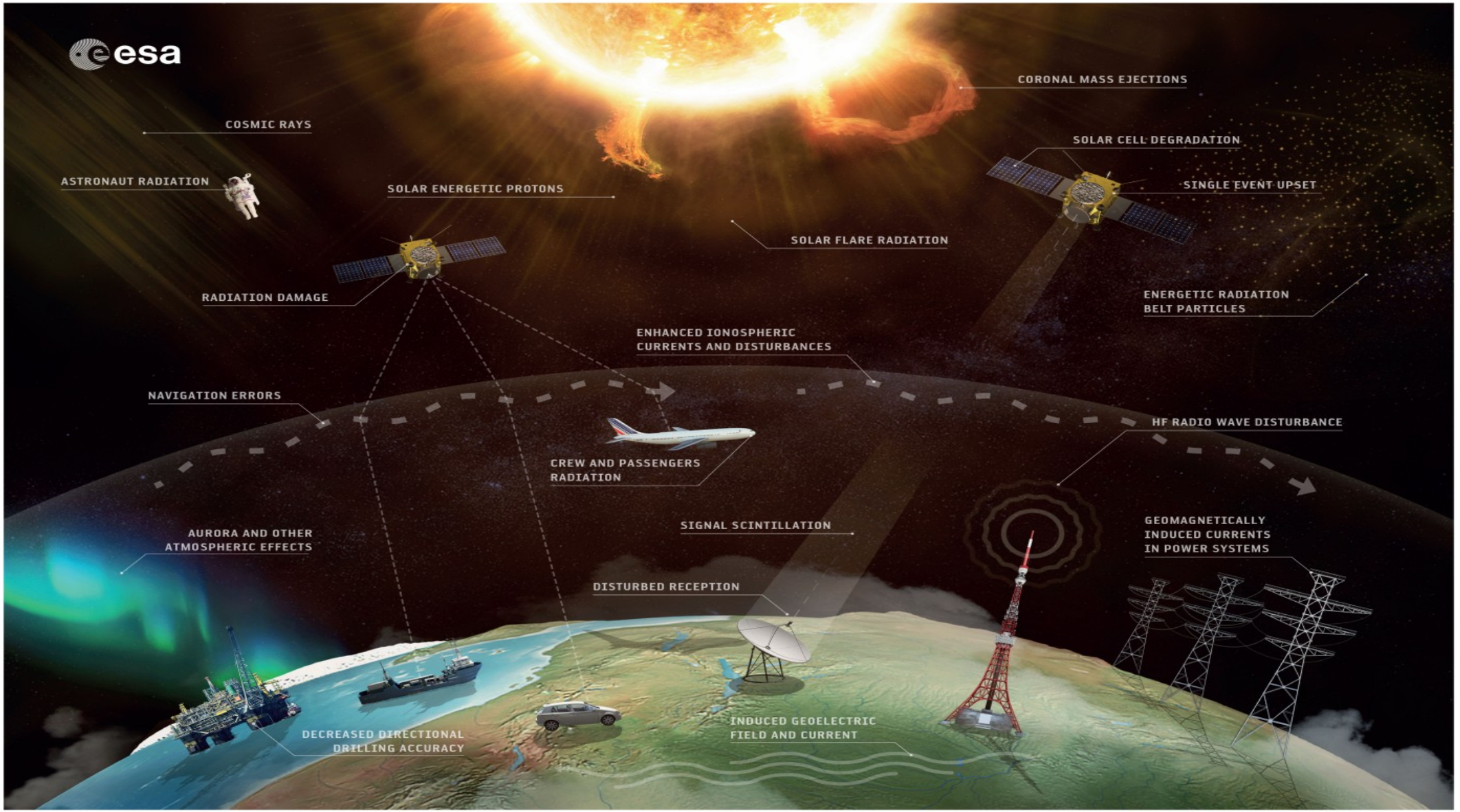
(1) UPC-IonSAT, Barcelona, Spain; (2) IEEC, Barcelona, Spain; (3) UPC-TALP, Barcelona, Spain; (4) Henan University, Kaifeng, China; (5) Yangtze Normal University, Chongqing, China; (6) ICE/IEEC/CSIC, Cerdanyola del Vallès, Spain; (7) ESA, Noordwijk, The Netherlands



Outline

- Visual summary of Space Weather
- (I) Measuring solar flares with GNSS Ionosphere
- (II) The VTEC GIMs contribute to Space Weather monitoring
- (III) Global Maps of VTEC gradients
- (IV) Global Maps of Ionospheric Storm Scale Index
- (V) Global Electron Content (GEC) & Space Weather
- Conclusions

Visual summary of Space Weather



(Reproduced from ESA Science Office, 2018)

(I) Measuring solar flares with GNSS Ionosphere

What? **The EUV flux from solar flares generates a sudden overionization in the illuminated ionosphere** (at main layer F2).

How? GNSS Ionosphere, with **global and continuous coverage**.

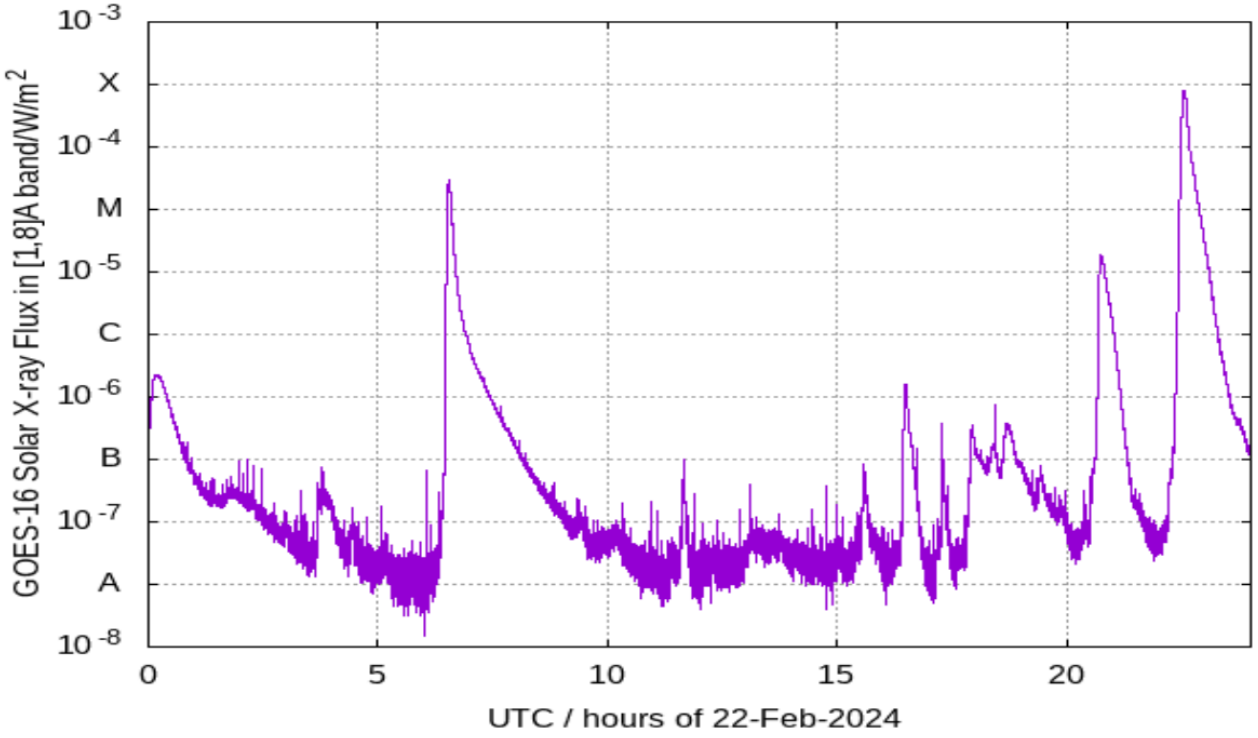
Why? *Original idea: (conceived & implemented as UPC-IonSAT RT products for ESA I-ESC)* **to transform the Earth ionosphere crossed by GNSS multi-frequency signals in a giant RT 24/7 solar EUV flux rate sensor & flare warning** system, i.e. *GNSS Astronomy*.

Application? **24/7 RT monitoring and warning of solar flares** since 2011.

Extension? This technique has been adapted to potentially detect and validate the Earth ionospheric footprint of **super flares of nearby stars** and **extremely energetic events of distant astronomical sources**, with recent improvement conceived and implemented in ***GNSS Astronomy* ESA-funded project**.

What is a solar flare?

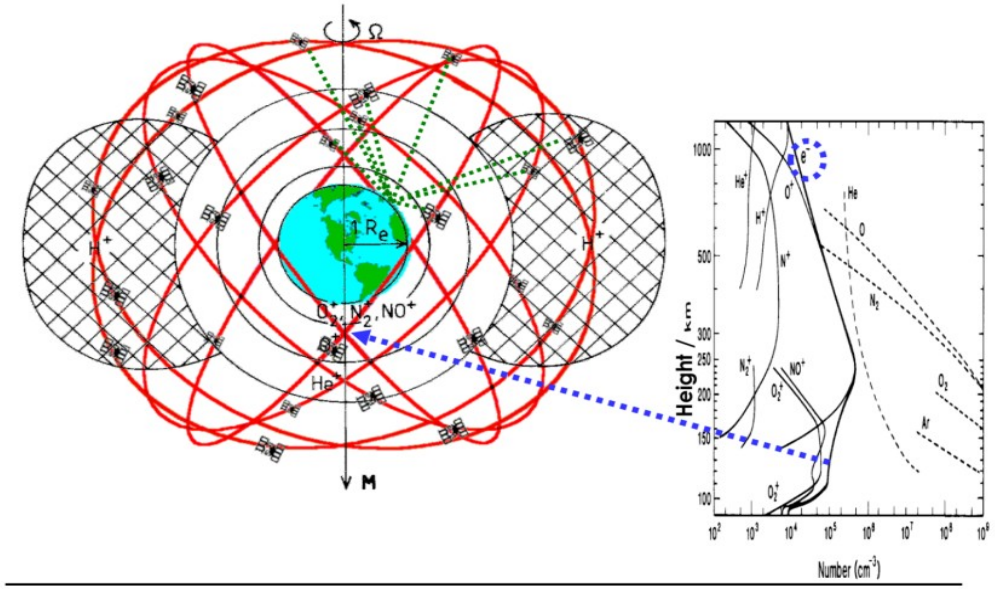
- A solar flare is a burst of electromagnetic radiation on the Sun (from radio waves to EUV-, x- and gamma-rays) that happens when energy stored in twisted magnetic fields (usually above sunspots) is suddenly released.
- The solar flares are classified by their x-ray brightness in [1,8]Å comprising the five categories: X -major-,M -mid-,C -small-, B, and A (see example from GOES spacecraft during solar flares on February 22, 2024):

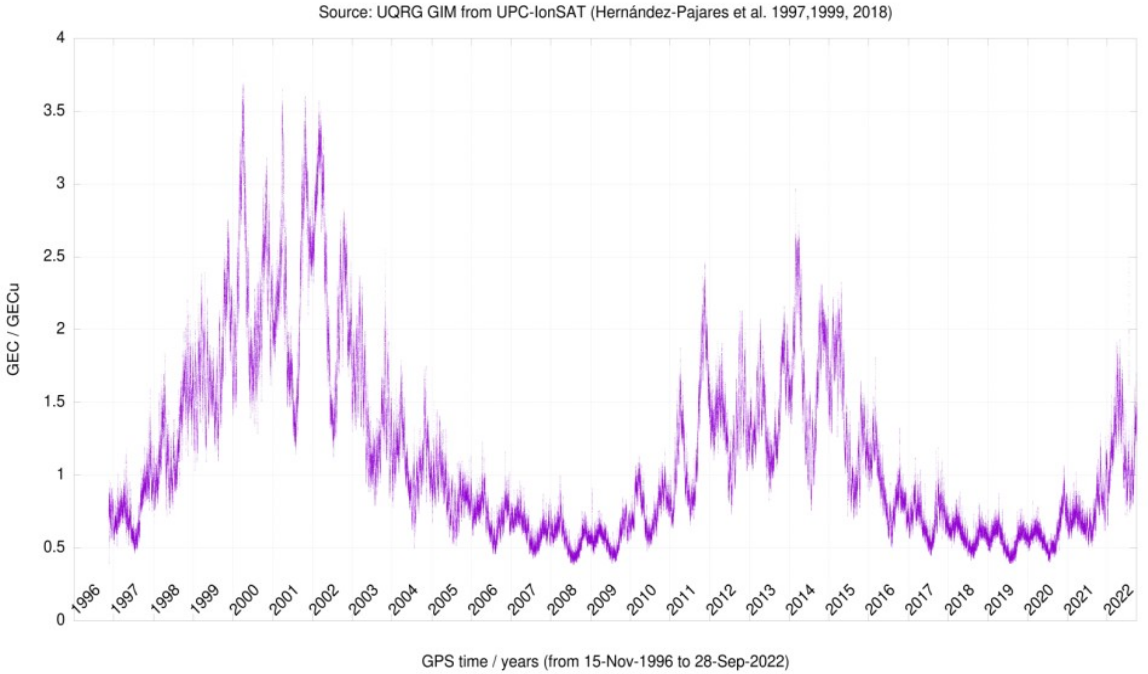


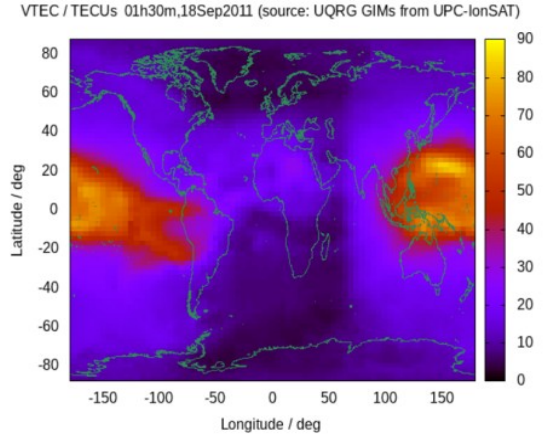
Flare type	PeakFlux([1,8]Å) / W/m^2
A	$< 10^{-7}$
B	$10^{-7} - 10^{-6}$
C	$10^{-6} - 10^{-5}$
M	$10^{-5} - 10^{-4}$
X	$> 10^{-4}$

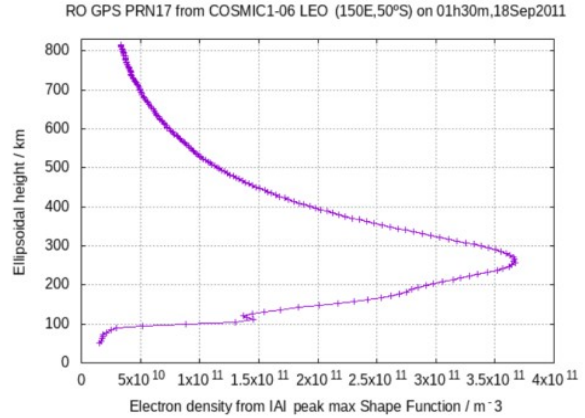
What is GNSS Ionosphere?

GNSS Ionosphere*[1] *studies the effects and computation of the distribution of free electrons, located at the partially ionized part of the atmosphere above 50 km height, from the Global Navigation Satellite Systems (GNSS) multi-frequency measurements crossing it; and its applications...



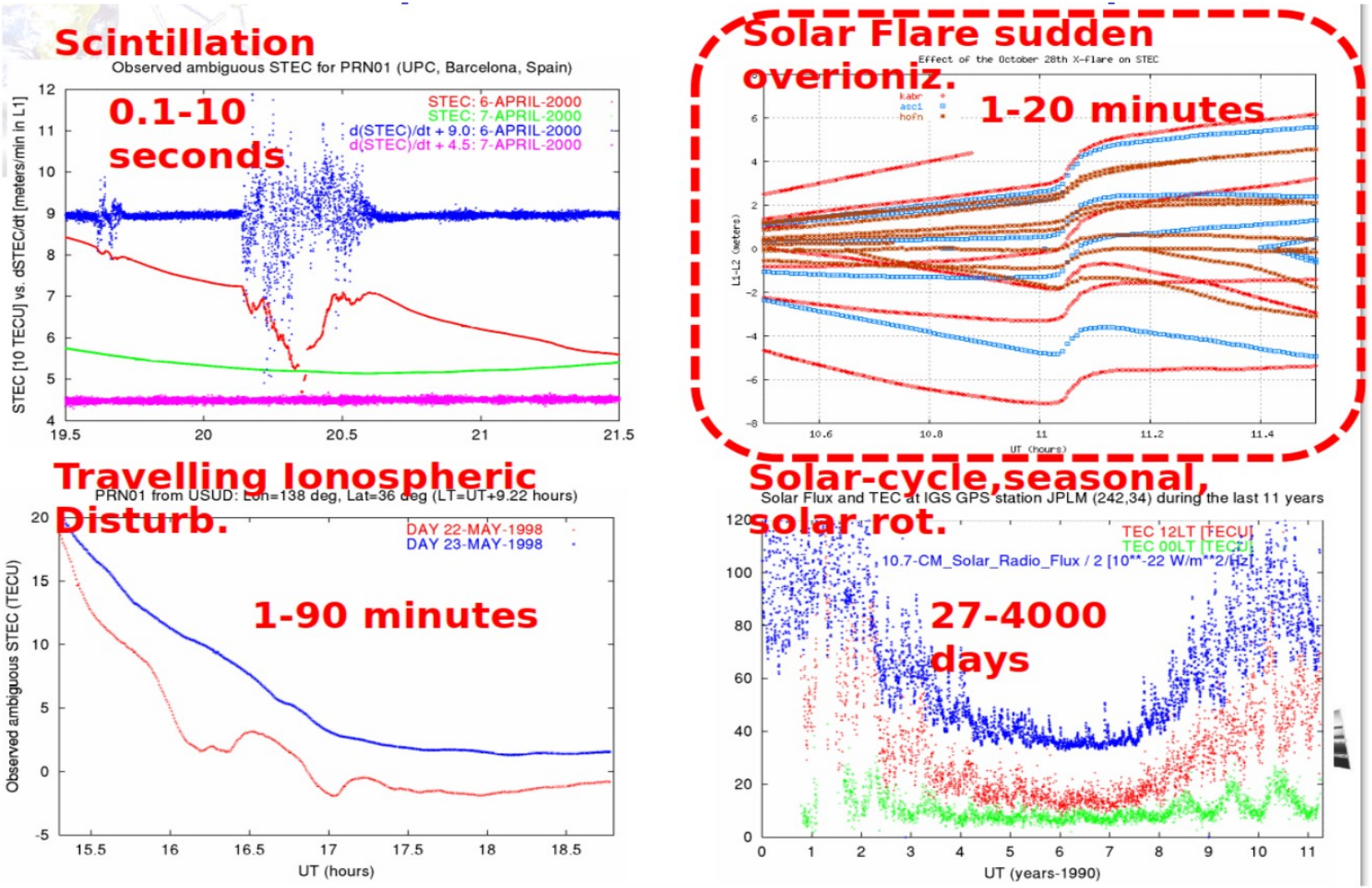






[1] Manuel Hernández-Pajares. "GNSS Ionosphere (subchapter in Encyclopedia of Geodesy, Sideris, Michael G. ed.)". In: Springer International Publishing, New York City, 2022, pp. 1–7. ISBN: 978-3-319-02370-0. DOI: 10.1007/978-3-319-02370-0_172-1. URL: https://doi.org/10.1007/978-3-319-02370-0_172-1.

Example of solar flare footprint on GNSS obs.



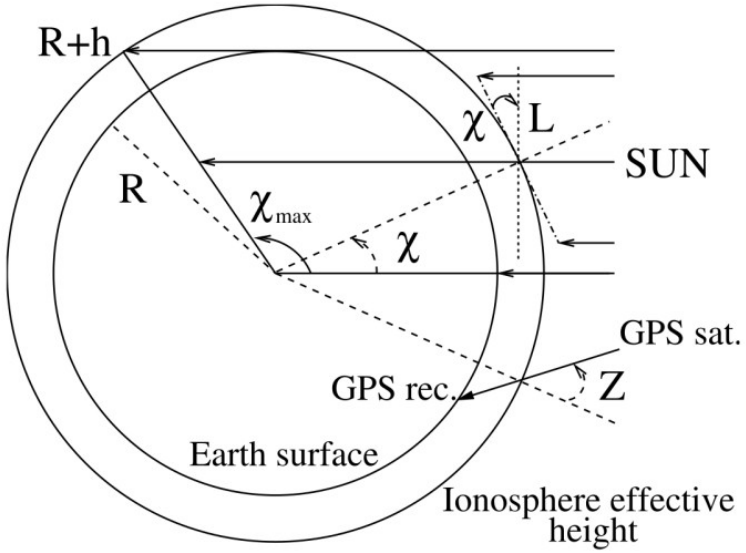
More details can be found, e.g., in[2]

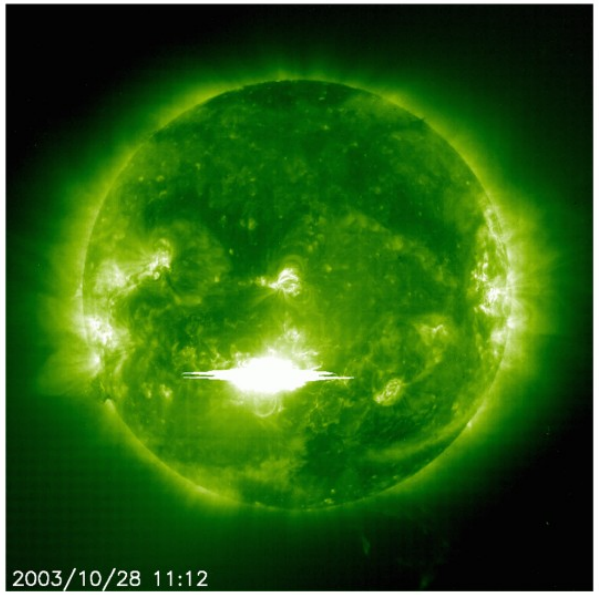
[2] Manuel Hernández-Pajares et al. "The ionosphere: effects, GPS modeling and the benefits for space geodetic techniques". In: *Journal of Geodesy* 85.12 (2011), pp. 887–907. DOI: 10.1007/s00190-011-0508-5. URL: https://doi.org/10.1007/s00190-011-0508-5.

From First Principles to a GNSS solar EUV photometer

The VTEC rate associated to the sudden overionization of the Earth ionosphere due to a solar flare, $\dot{V}$, for a given Solar zenith angle χ, can be related with the source solar EUV flux rate, $\dot{I}$, by means of the geo-effectiveness, η', which depends on physical constants (see[3] &[4]):

$$\dot{V} = \eta' \cdot C(\chi) \cdot \dot{I} \implies \frac{\partial V}{\partial t} = a(t)\cos\chi + b(t) \tag{1}$$



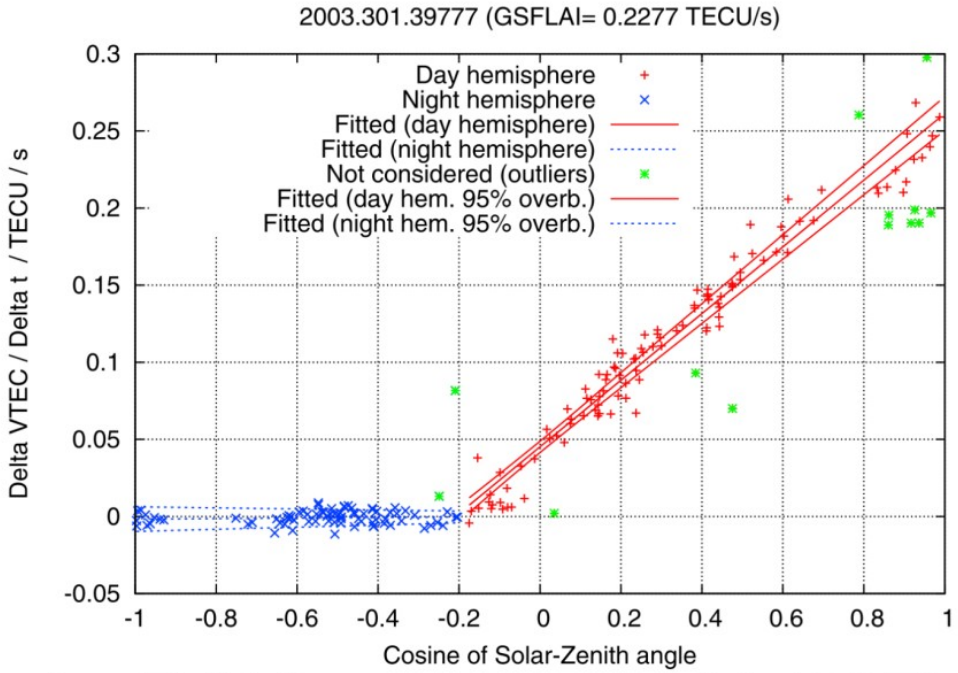


[3] Weixing Wan et al. "The sudden increase in ionospheric total electron content caused by the very intense solar flare on July 14, 2000". In: *Science in China Series A: Mathematics* 45.1 (2002), p. 142. DOI: 10.1007/BF02889695. URL: https://doi.org/10.1007/BF02889695.

[4] Manuel Hernández-Pajares et al. "GNSS measurement of EUV photons flux rate during strong and mid solar flares". In: *Space Weather* 10.12 (2012), pp. 1–16. DOI: 10.1029/2012SW000826. URL: https://doi.org/10.1029/2012SW000826.

The solar flare overionization model behaves well

How well does the model fit? Example: major (X17.2) solar flare preceding the Halloween ionospheric storm, day 301 of year 2003, 39777s.



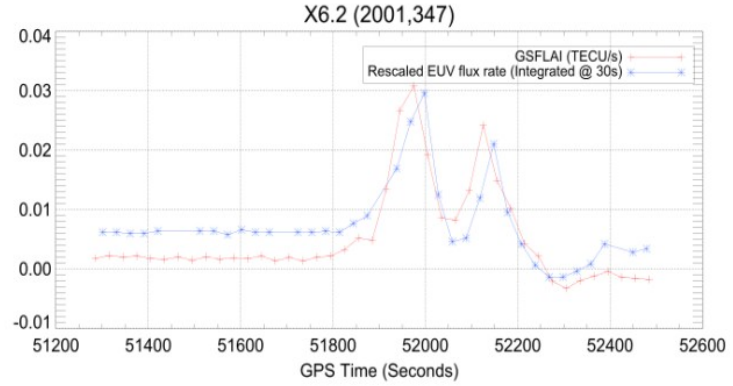
$$\dot{V} = a(t)\cos\chi + b(t)$$

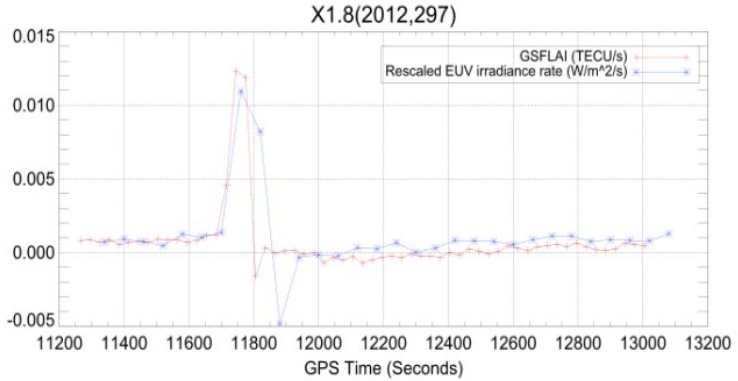
The GNSS solar EUV flux rate proxy $a(t)$ (GSFLAI, AKA SOLERA) was presented in Hernández-Pajares et al. (2012)[5], besides the solar flare detector SISTED (evolved from García-Rigo et al. (2007)[6]).

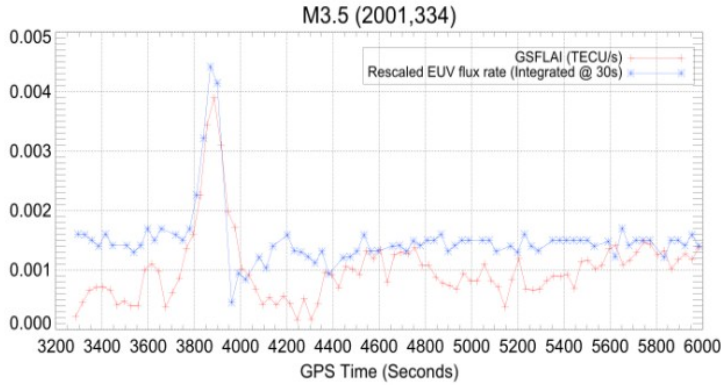
[5] Manuel Hernández-Pajares et al. "GNSS measurement of EUV photons flux rate during strong and mid solar flares". In: *Space Weather* 10.12 (2012), pp. 1–16. DOI: 10.1029/2012SW000826. URL: https://doi.org/10.1029/2012SW000826.

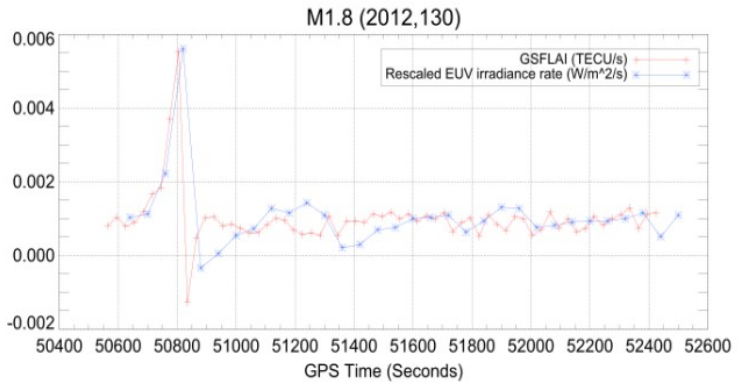
[6] A. García-Rigo et al. "Solar flare detection system based on global positioning system data: First results". In: *Advances in Space Research* 39.5 (2007), pp. 889–895. DOI: 10.1016/j.asr.2006.09.031. URL: https://doi.org/10.1016/j.asr.2006.09.031.

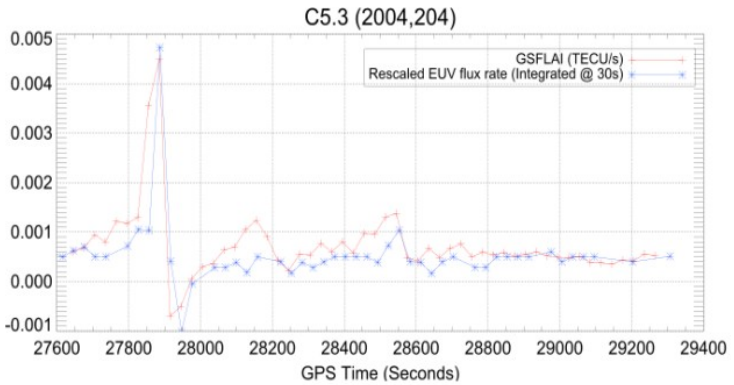
Examples for strong, mid and weak solar flares

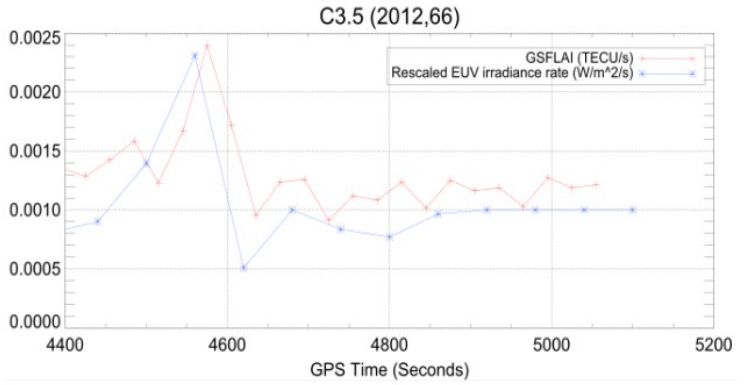








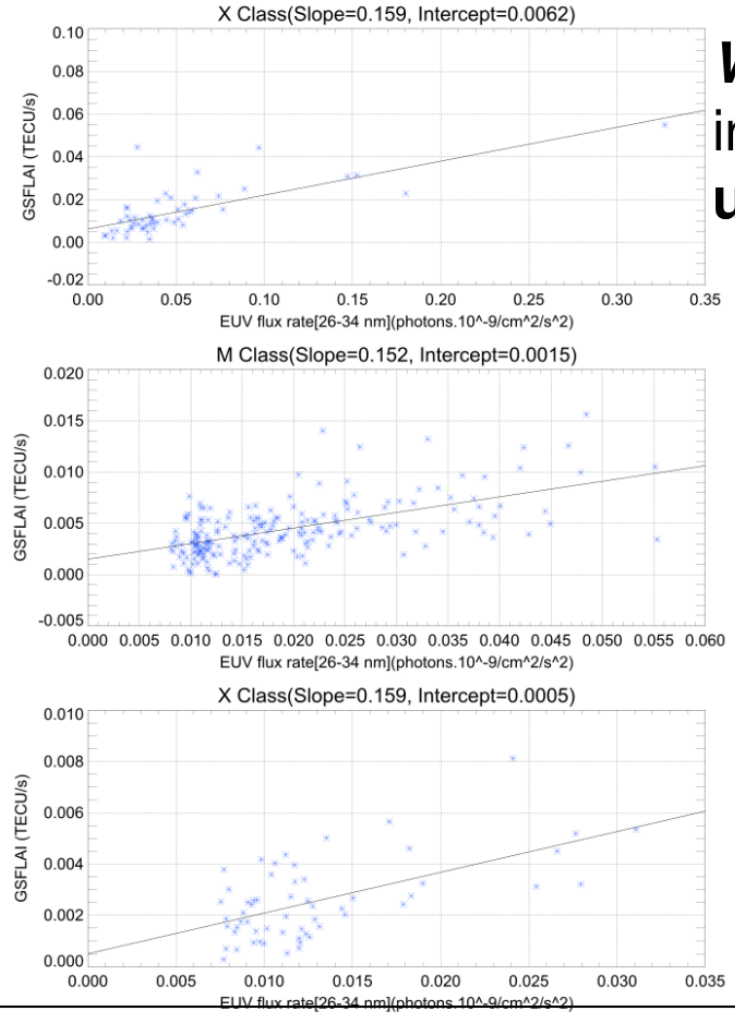




Examples of time series of GS-FLAI vs time series of EUV flux rate from SOHO-SEM space borned photometer, from top to bottom & left to right:

1. X6.2 flare, day 347, 2001
2. M3.5 flare, day 334, 2001
3. C5.3 flare, day 204, 2004
4. X1.8 flare, day 297, 2012
5. M1.8 flare, day 130, 2012
6. C3.5 flare, day 66, 2012

Why? *GNSS Solar Astronomy* works very well



Why should this indirect way (GSFLAI/SOLERA) of measuring the EUV flux rate be considered? **It works very well, using existing (GNSS) infrastructures**:

- GSFLAI versus EUV flux rate data provided by SOHO/SEM in the 26-34 nm range for peak values: X, M, and C class flares respectively (2001-2015).
- **The X-, M- & C- class flares regression lines slopes agrees +95%, confirming the consistency of the first-principles model**, Singh et al. (2015)[7].
- We have **applied SOLERA to confirm solar flare time series have a long tail distribution** in amplitude and time corr. (Monte-Moreno et al. 2014)[8].

[7] Talwinder Singh et al. "GPS as a solar observational instrument: Real-time estimation of EUV photons flux rate during strong, medium, and weak solar flares". In: *Journal of Geophysical Research: Space Physics* 120.12 (2015), pp. 1–11. DOI: 10.1002/2015JA021824. URL: https://doi.org/10.1002/2015JA021824.

[8] Enrique Monte-Moreno and Manuel Hernández-Pajares. "Occurrence of solar flares viewed with GPS: Statistics and fractal nature". In: *Journal of Geophysical Research: Space Physics* 119.11 (2014), pp. 9216–9227. DOI: 10.1002/2014JA020206. URL: https://doi.org/10.1002/2014JA020206.

The EUV extinction of solar atmosphere is clearly seen

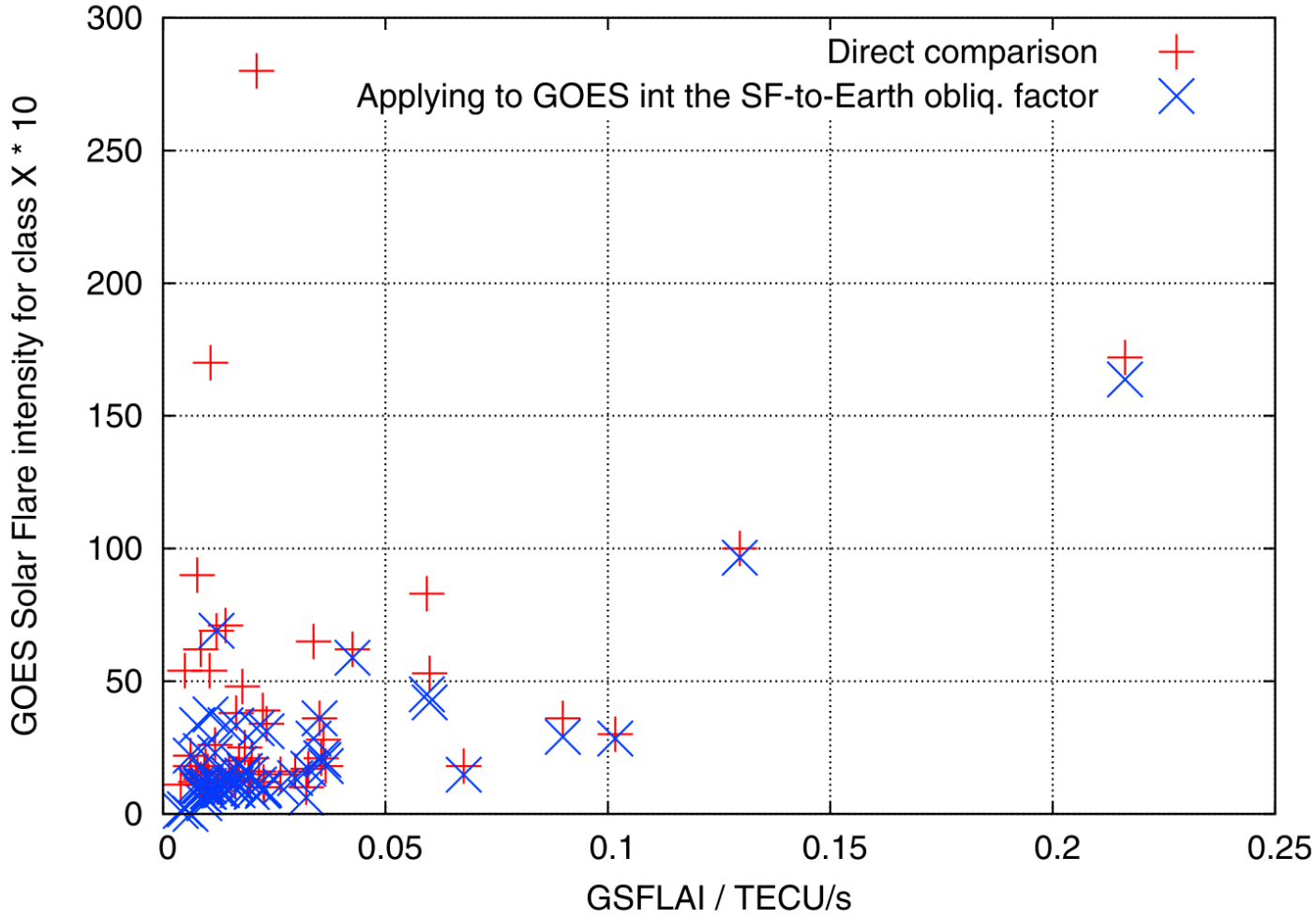
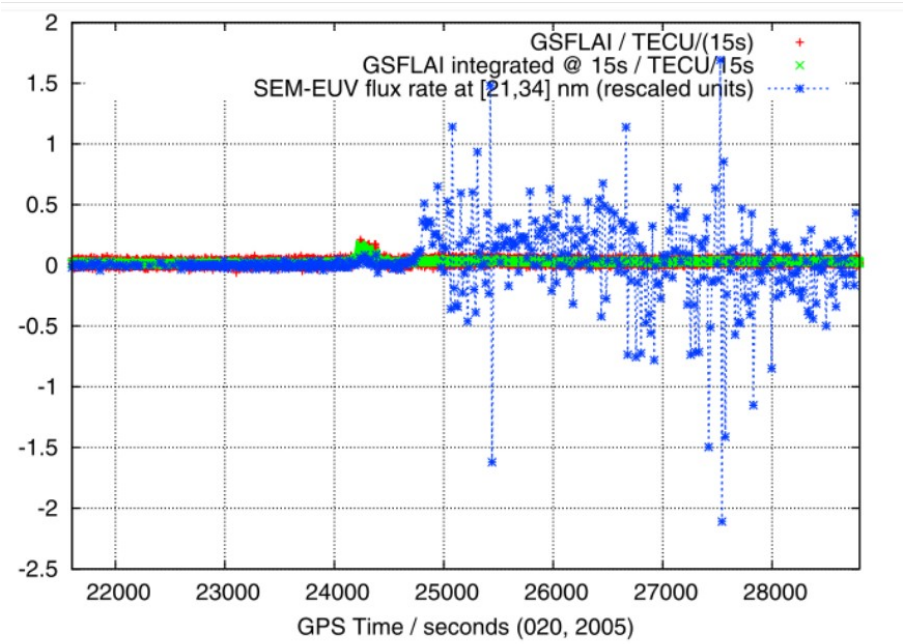
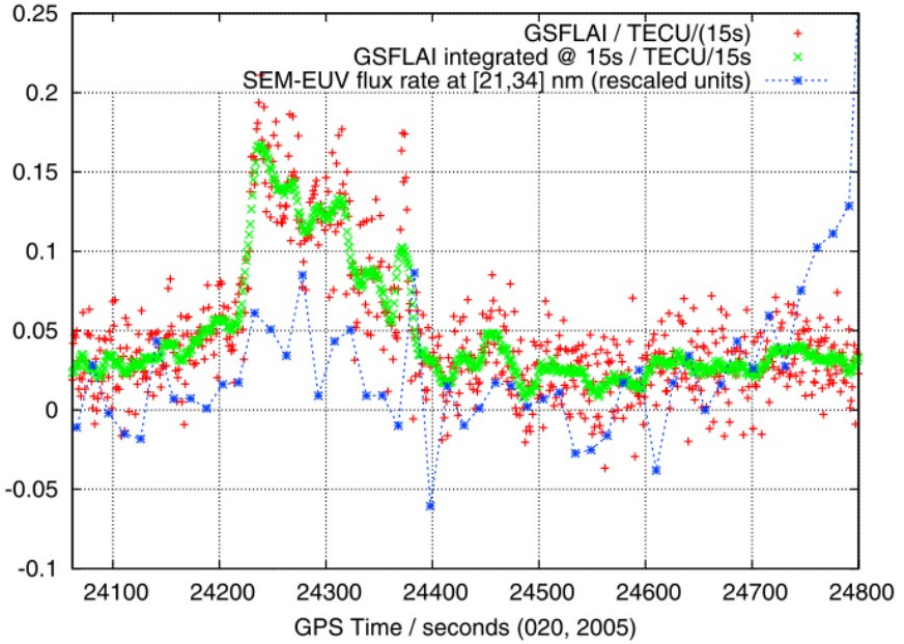


Figure 9. X-ray band solar flare intensity, corresponding to the GOES index for all the X-class flares analyzed in this work (those with available data between 2001 and 2011) represented versus the GSFLAI value at the corresponding peak. The red points represent the direct comparison, and the blue points the comparison after applying a solar-earth deprojecting factor, in terms of the solar flare occurrence location in the surface of the Sun.

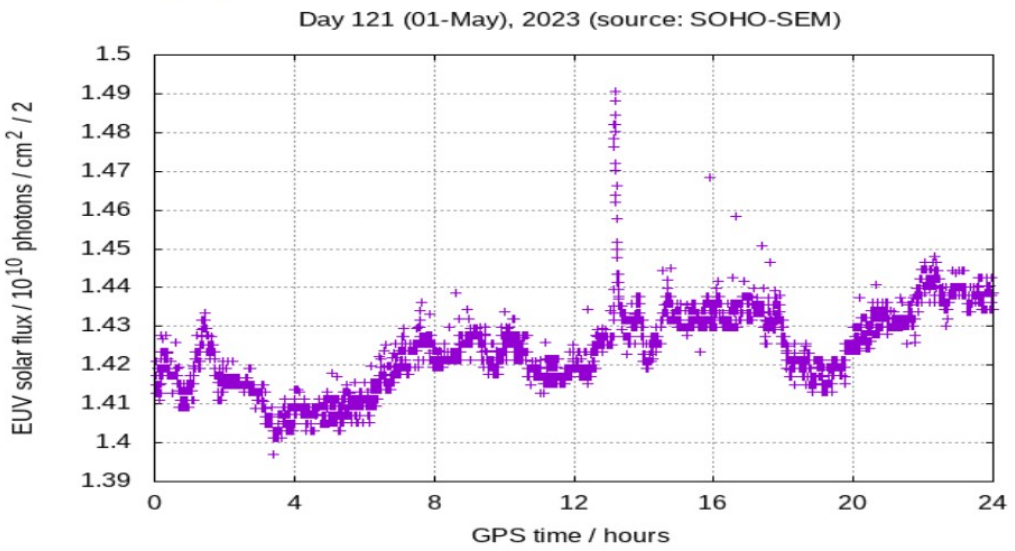
GNSS Solar Astronomy is unaffected by relativistic e-

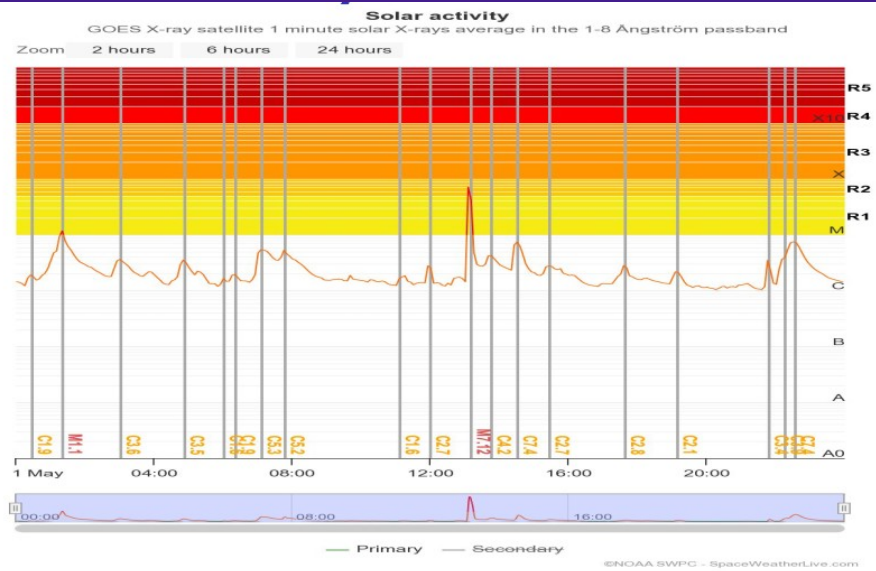


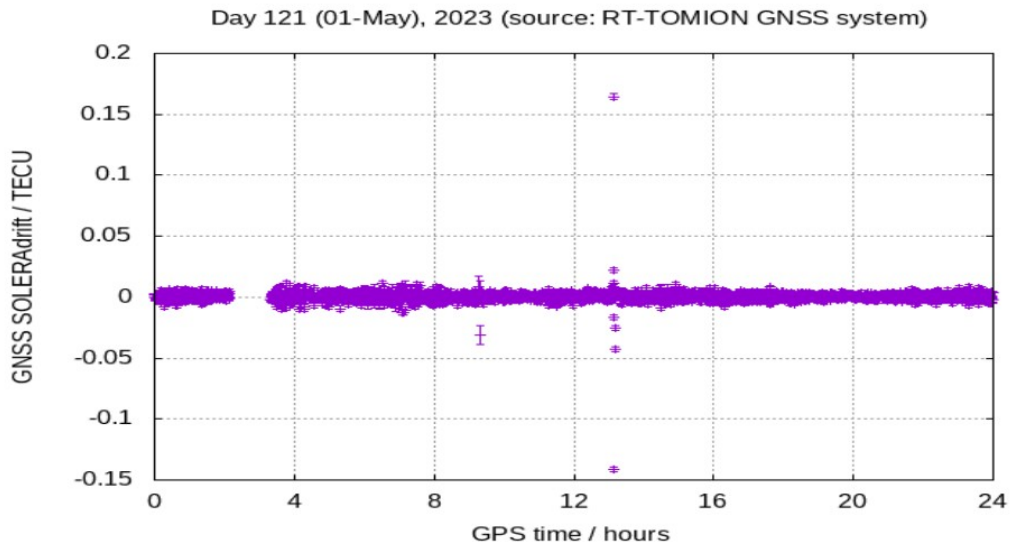


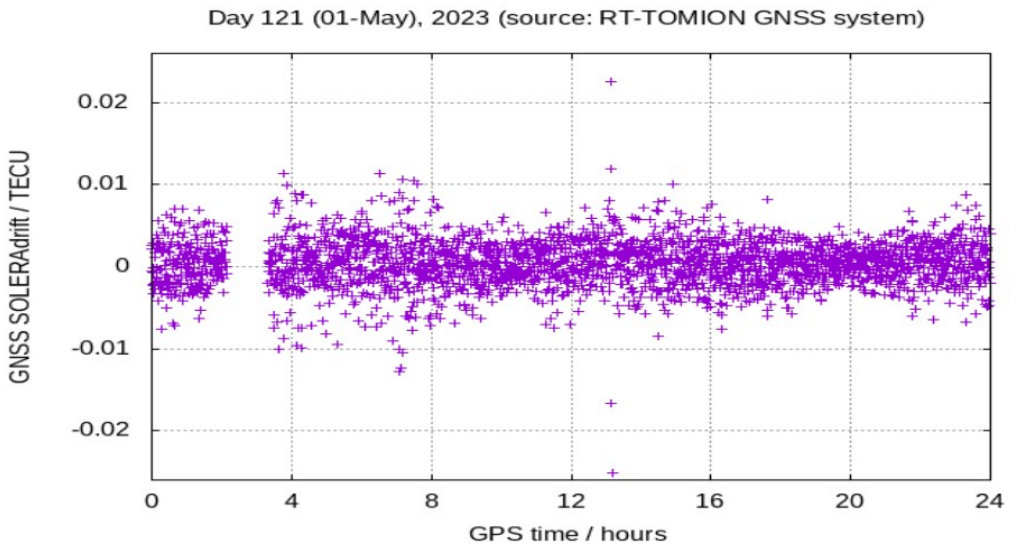
And the indirect ionosphere-GNSS solar EUV sensor can work better than the direct conventional spacecraft-based measurements: The X7.1 solar flare, reported by GOES on January 20th, 2005, is of special interest because of the **relativistic electrons that reached the Earth less than 10 min later**, produced a contamination of the SOHO/SEM detector with wrong readings of EUV starting from t = 24750s of GPS time. However GSFLAI remains unaffected due to its definition as solar-zenith angle gradient of VTEC rate (see above) generated by the photons enhancement, since it filters out any influence of relativistic electrons.

RT 24/7 GNSS Solar Astronomy started in 2011









More details can be found, e.g., in[9]

[9] Manuel Hernández-Pajares et al. "GNSS Solar Astronomy in real-time during more than one solar cycle". In: *Advances in Space Research* 74.6 (2024), pp. 2593–2598.

(II) The VTEC GIMs contribute to Space Weather monitoring

In next slides we summarize the approach, results and answer to the question that we did ourselves almost six years ago:

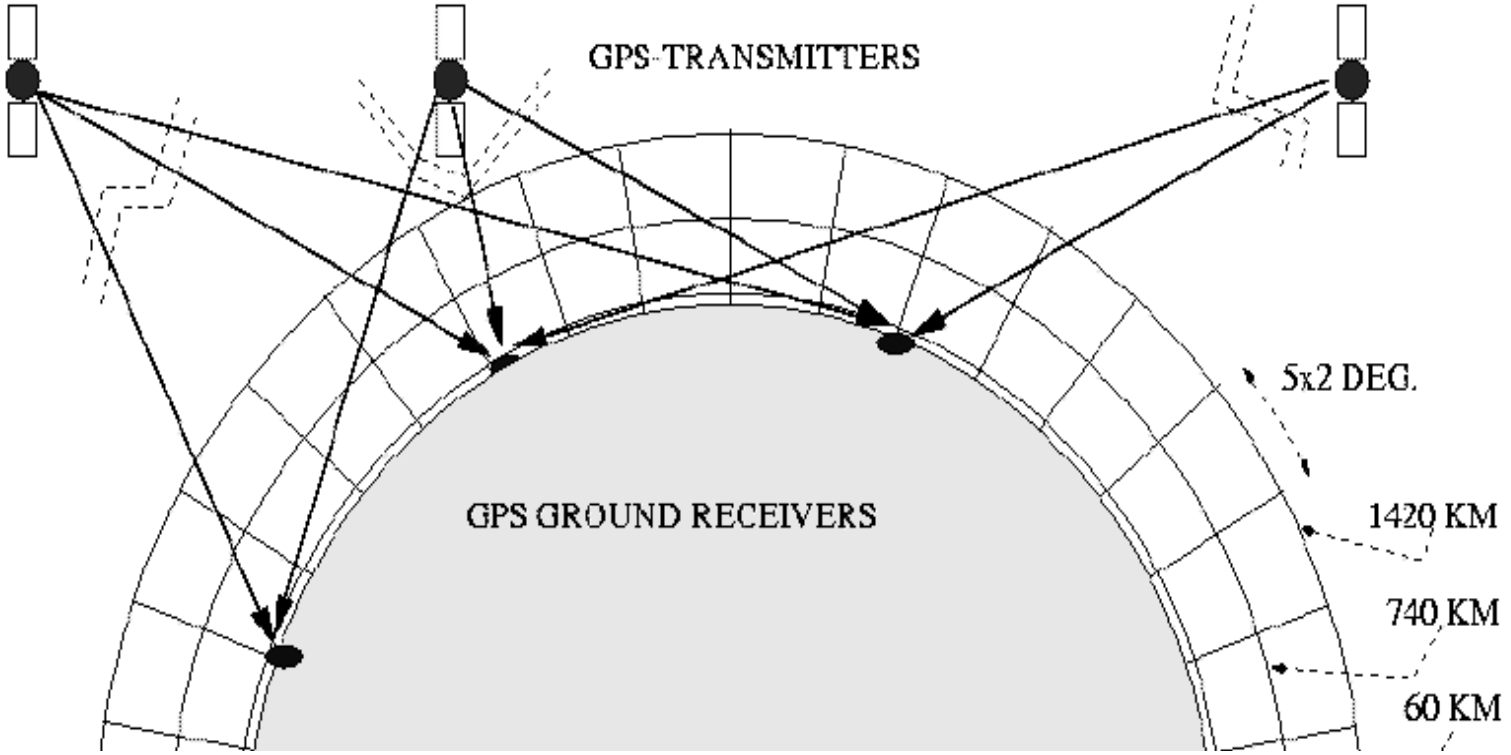
Can the high temporal resolution VTEC Global Ionospheric Maps (GIM, such as UQRG generated by UPC-IonSAT since end 1996) directly provide **reliable estimation** of the spatial and temporal components of the **VTEC gradients**, and of a sensitive **Ionospheric storm scale index**, with **comparable results** to the corresponding indices proposed and generated by other colleagues from **raw GNSS data** (respectively Jakowski & Hoque 2019, and Nishioka et al. 2017)?

Jakowski, N., & Hoque, M. M. (2019). Estimation of spatial gradients and temporal variations of the total electron content using ground-based GNSS measurements. Space Weather, 17, 339–356. https://doi.org/10.1029/2018SW002119.

Nishioka, M., T. Tsugawa, H. Jin, and M. Ishii (2017), A new ionospheric storm scale based on TEC and f o F 2 statistics, Space Weather, 15, 228–239, doi:10.1002/2016SW001536.

Baseline: Global ionospheric tomography

- UPC-IonSAT TOMION software package estimates the averaged Ne for each voxel alongside with the ambiguity B_l linked to the Geometry-free combination of GNSS L_1 and L_2 carrier-phase measurements.
- The output is a two-layer grid with Ne estimates in voxels with GNSS measurements.
- No thin-shell approach, thus reducing gradient mismodelling.
- The ambiguity term does not depend on the transmitter-receiver relative geometry, whereas STEC does. This difference is the key for decorrelation of both terms (using a Kalman filter).



$$L_1\text{-}L_2 = \alpha \cdot STEC + B_l$$

$$STEC = \sum Ne_i \cdot d_i$$

i: voxel index
d: path of the signal along the voxel
α: scale factor

GIMs with TOMION

multi-frequency carrier phases

positions of GNSS Receivers

positions of GNSS Transmitters

TOMION preprocessing (Cycle-slips, Line-Of-Sight), voxel-based Jacobian (for each given transmitter-receiver):

$$L_j - L_k = \alpha \sum_{m=1} (\mathbf{N_e})_{\mathbf{m}} \Delta s_m + \mathbf{B_{j,k}}$$

Solving $\{(\mathbf{N_e})_{\mathbf{m}}\}$ and $\{\mathbf{B_{j,k}}\}$ with Kalman filter in local time x latitude ref. frame

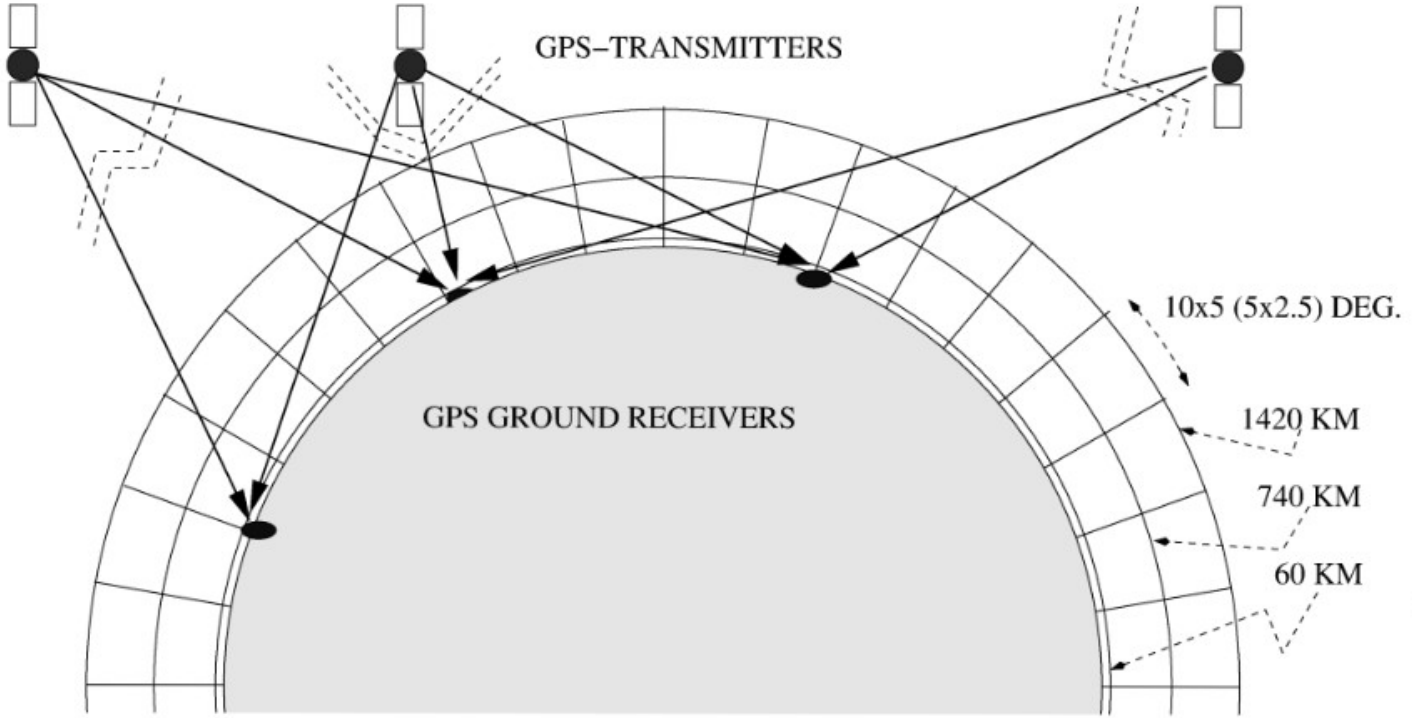
Slant & Vertical Total Electron Content values (S, V):

$$S = (L_j - L_k - \mathbf{B_{j,k}})/\alpha \Rightarrow$$
$$V = S/M$$

VTEC interpolation (Kriging / Atomic Decomposition in rapid / RT latencies)

Global Ionospheric Maps $\{\mathbf{V_m}, \sigma_{\mathbf{m}}\}$

Applications (ionospheric storm state, gradients, precise navigation,...)



Introduction to TOMION model

- TOMION is the software used in the generation of UPC-IonSAT GIMs of VTEC for the International GNSS Service (IGS), such as the UQRG one, one of the best behaving GIMs in IGS ([9],[10],[11]).
- The tomography performed by TOMION is able to combine different data and geometries ([12]), in agreement with independent measurements and models ([13],[14]), also in the polar regions ([15]).

[9] M Hernández-Pajares et al. "The IGS VTEC maps: a reliable source of ionospheric information since 1998". In: *Journal of Geodesy* 83.3-4 (2009), pp. 263–275.

[10] Manuel Hernández-Pajares et al. "Methodology and consistency of slant and vertical assessments for ionospheric electron content models". In: *Journal of Geodesy* 91.doi:10.1007/s00190-017-1032-z (2017), pp. 1405–1414.

[11] David Roma-Dollase et al. "Consistency of seven different GNSS global ionospheric mapping techniques during one solar cycle". In: *Journal of Geodesy* 92.6 (2018), pp. 691–706.

[12] Manuel Hernández-Pajares et al. "A new way of improving global ionospheric maps by ionospheric tomography: consistent combination of multi-GNSS and multi-space geodetic dual-frequency measurements gathered from vessel-, LEO-and ground-based receivers". In: *Journal of Geodesy* 94.8 (2020), pp. 1–16.

[13] DV Kotov et al. "Coincident observations by the Kharkiv IS radar and ionosonde, DMSP and Arase (ERG) satellites, and FLIP model simulations: Implications for the NRLMSISE-00 hydrogen density, plasmasphere, and ionosphere". In: *Geophysical Research Letters* 45.16 (2018), pp. 8062–8071.

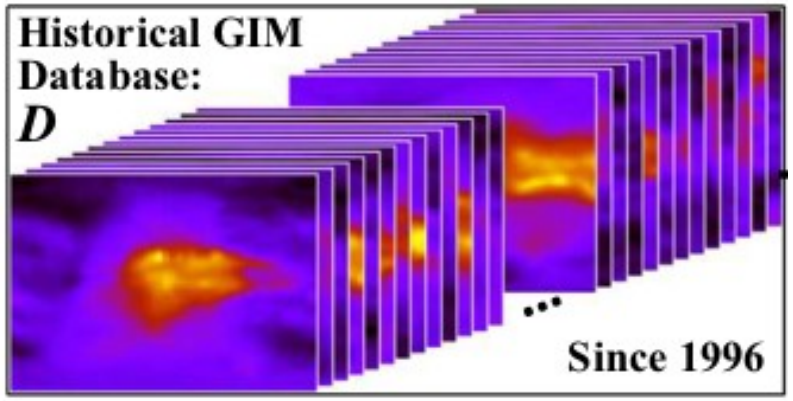
[14] DV Kotov et al. "Weak magnetic storms can modulate ionosphere-plasmasphere interaction significantly: Mechanisms and manifestations at mid-latitudes". In: *Journal of Geophysical Research: Space Physics* 124.11 (2019), pp. 9665–9675.

[15] Manuel Hernández-Pajares et al. "Polar Electron Content From GPS Data-Based Global Ionospheric Maps: Assessment, Case Studies, and Climatology". In: *Journal of Geophysical Research: Space Physics* 125.6 (2020), e2019JA027677.

Historical data sets derived from TOMION

- The **UPC-IonSAT historical data** set contains **UQRG GIMs** (Global Ionospheric Maps) computed every 15 mins since end of 1996, derived from daily tomographic TOMION runs for the International GNSS Service, and the **electron densities of the illuminated voxels**, previously estimated to the GIM.
- GIMs are 71 (lat) x 73 (lon) pixel-size images of the ionosphere.

Generation of data sets with TOMION software & GNSS data.



❖ Historical Data Sets (since 1997*[*]*).

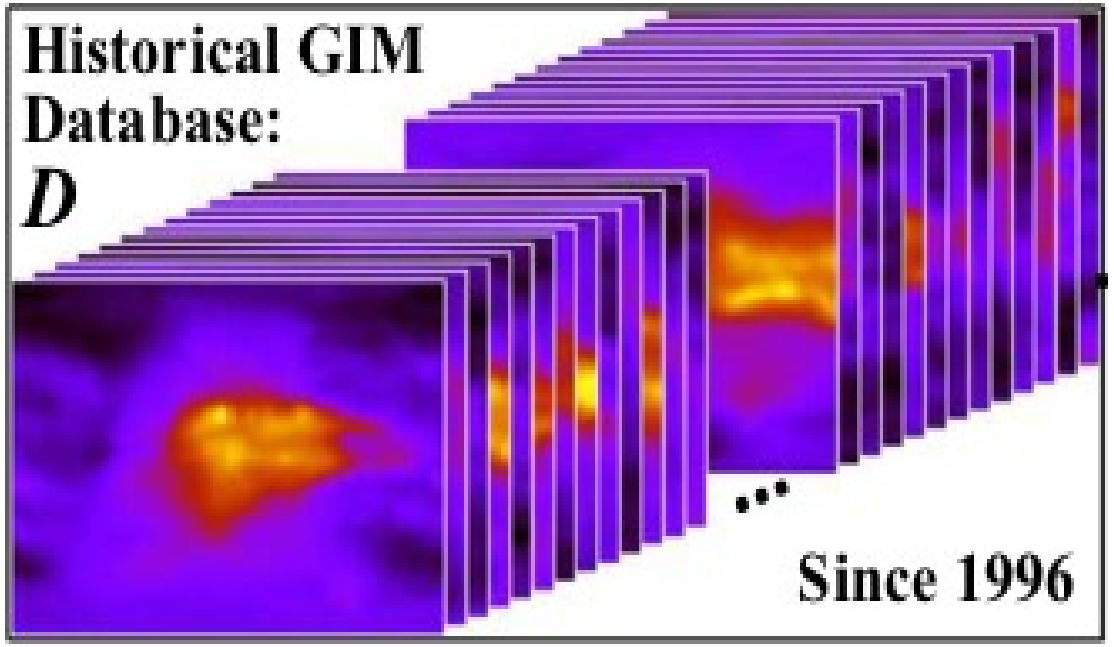
- ➢ VTEC global maps
- ➢ Differential Code Biases
- ➢ **VTEC gradient global maps**
- ➢ **Global maps of Ionospheric Storm Scale**
- ➢ **Ne and Ne (v) gradient datasets**
- ➢ **Global Electron Content time series**

https://chapman.upc.es/tomion/DISPEC/SDA4/

[*] Products obtained in DISPEC after one year of continuous parallel computations at UPC-IonSAT linux servers.

VTEC Global Ionospheric Maps (GIMs) and DCBs

The historical **UQRG Vertical Total Electron Content (VTEC) Global Ionospheric Map** (GIM) and **GPS Differential Code Biases (DCB)** data base is the main output of TOMION ionospheric tomographic model (see for instance Hernández-Pajares et al. 2019 and Roma-Dollase et al. 2020, and references inside). It covers since the end of 1996, (+5. 10^9 VTEC estimations within more than one million of corresponding maps) and it is directly available (also via PITHIA-NRF eScience center) at:



https://chapman.upc.es/tomion/DISPEC/SDA4/VTEC_GIMs_and_DCBs/

Hernández-Pajares, M., Roma-Dollase, D., Krankowski, A., García-Rigo, A. and Orús-Pérez, R., 2017. Methodology and consistency of slant and vertical assessments for ionospheric electron content models. Journal of Geodesy, 91(12), pp.1405-1414.

Roma-Dollase, D., Hernández-Pajares, M., Krankowski, A., Kotulak, K., Ghoddousi-Fard, R., Yuan, Y., Li, Z., Zhang, H., Shi, C., Wang, C. and Feltens, J., 2018. Consistency of seven different GNSS global ionospheric mapping techniques during one solar cycle. Journal of Geodesy, 92(6), pp.691-706.

One decade of cooperative real-time GIMs in IGS

☐ Real-Time GIM Is a Powerful Support for Enhancing GNSS Positioning

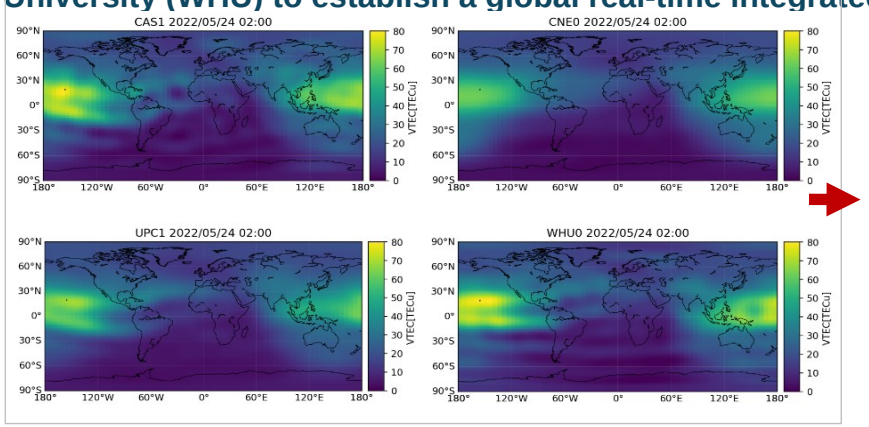
Modeling Bias → Single-organization products inherently suffer from biases in processing strategies and modeling methods.

Data Limitations → The distribution and stability of real-time monitoring stations vary significantly among institutions in different countries, leading to objective differences in accuracy across regions.

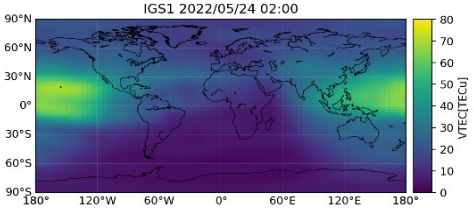
Product Interruption → Single-organization products face risks of interruption in real-time station data reception and processing.

Real-Time Global Ionospheric Model Integration Method Based on RT-dSTEC

Collaborating with the French Space Agency CNES, the Polytechnic University of Catalonia (UPC) in Spain, the Chinese Academy of Sciences (CAS), and Wuhan University (WHU) to establish a global real-time integrated ionospheric model.



IGS combined Product



Effectively combines the strengths and advantages of ionospheric models from different institutions.

By extracting the ionospheric variation representation capabilities of different organization products based on real-time ionospheric reference data, real-time weights are precisely determined. A robust global ionospheric integrated model product is formed according to these weights, making it one of the important development directions for global real-time ionospheric monitoring in the coming years.

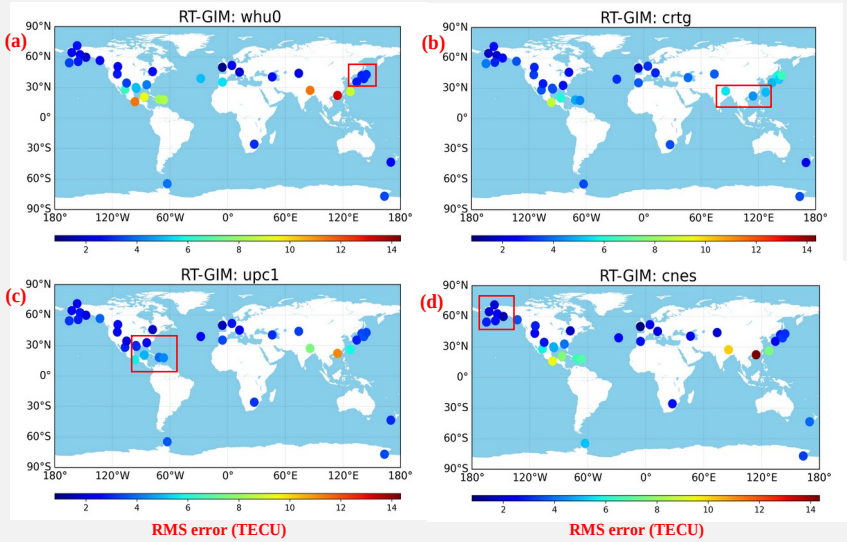
Liu Q, Hernández-Pajares M*, et al. The cooperative IGS RT-GIMs: A reliable estimation of the global ionospheric electron content distribution in real time[J]. **Earth System Science Data**, 2021.

RT assessment & comb.: different GIMS & conditions

- **The current capabilities of various institutions in characterizing the spatiotemporal (regional and temporal) variations of real-time ionospheric TEC, as well as the anomalies**

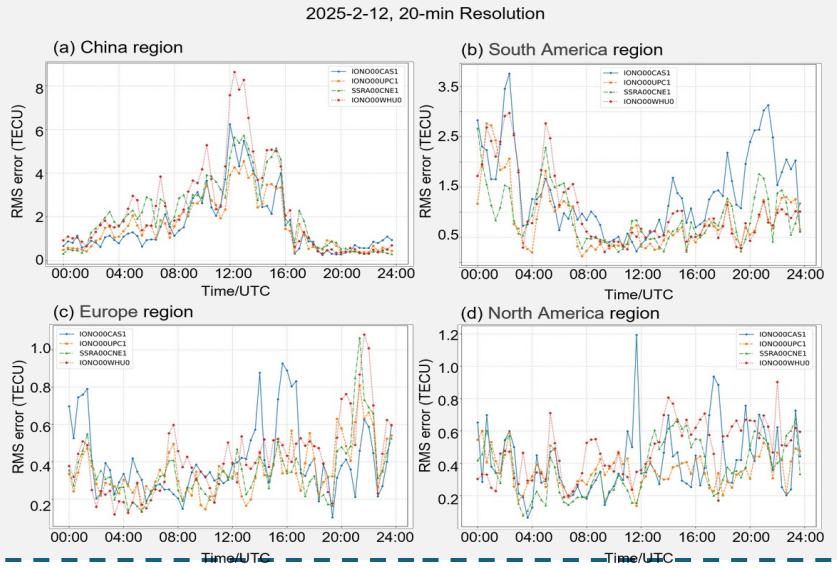
The accuracy is unstable

The precision of a single institution's Real-Time Global Ionospheric Map (RT-GIM) exhibits fluctuations across temporal scales ranging from minutes to days



Regional heterogeneity

RT-GIMs produced by different institutions exhibit inconsistent performance across various global regions, resulting in significant spatial variations in accuracy



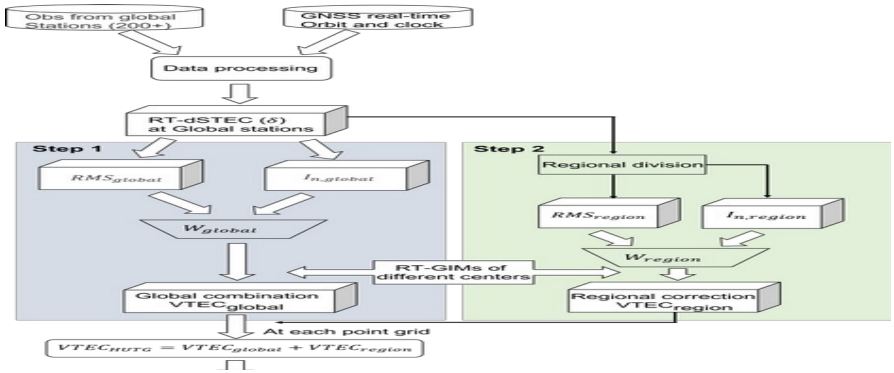
Robustness

Under extreme space weather conditions, RT-GIM products are prone to exhibit performance degradation or even anomalies



New RT assessment & combination strategies

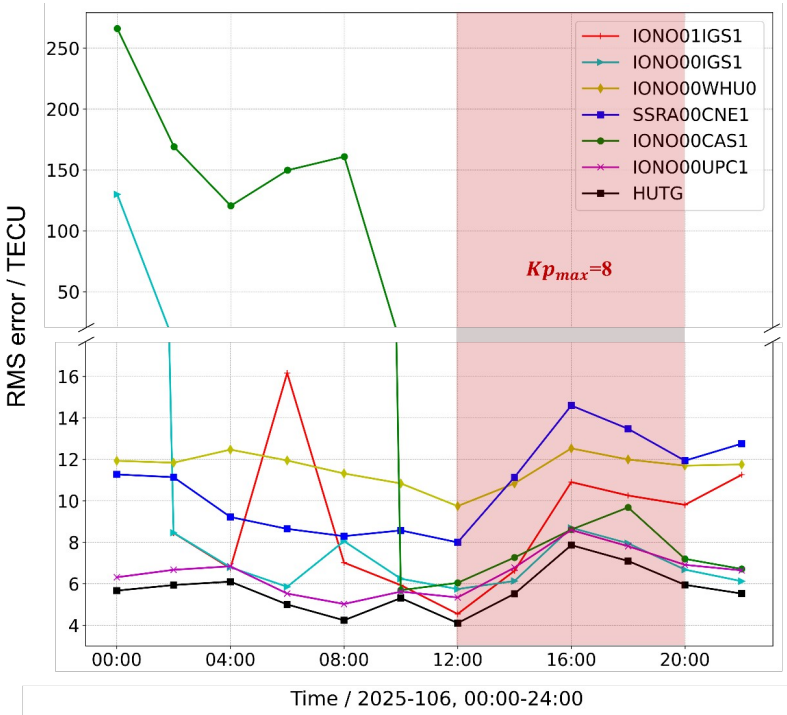
HUTG: a next-generation IGS real-time combined GIM via two-step global and regional correction with robust weighting from HENU and UPC-IonSAT



Kualong Xu, Liu Q*, Hernández-Pajares Manuel et al. HUTG: A next-generation IGS real-time combined GIM via two-step global and regional correction with robust weighting from HENU and UPC-IonSAT [J]. GPS Solutions, 2025

For the period of January 1 to April 15, 2025

RT-GIM	Jason-3 VTEC	dSTEC-GPS
SSRA00CNE1	11.13	14.14
IONO00CAS1	8.10	8.35
IONO00IGS1	7.58	8.89
IONO00UPC1	7.23	9.08
IONO00WHU0	11.38	13.68
IONO01IGS1	7.57	8.21
HUTG	6.78	7.40



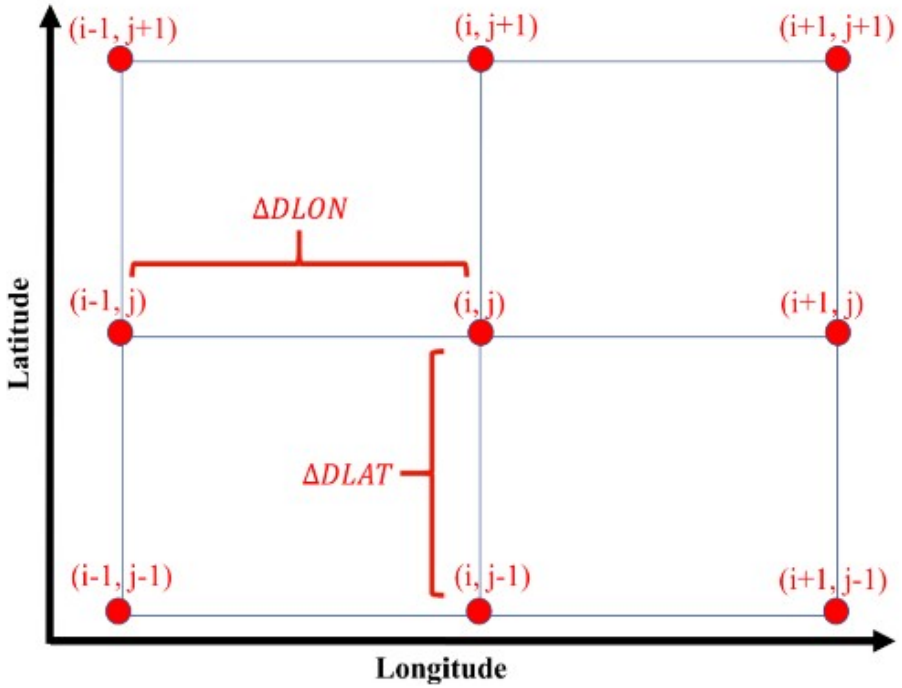
- ✓ **Based on the Jason-3 VTEC evaluation, the standard deviation of HUTG is reduced by approximately 0.8 TECU compared to the original IGS combined RT-GIM (IRTG)**
- ✓ **According to the dSTEC-GPS evaluation, the standard deviation of HUTG is reduced by approximately 1.5 TECU relative to IRTG**
- ✓ **Furthermore, during geomagnetic storms, HUTG demonstrates superior performance compared to all currently available IGS RT-GIM products**

(III) Global Maps of VTEC gradients

- **Computation of VTEC gradient maps from VTEC GIMs**

The **VTEC gradient** derived from GIMs **allows** to obtain full (non-relative) values of TEC spatial gradients and temporal variations **separately at any worldwide grid point**, considering the distances on the corresponding parallels and meridians at the ionospheric effective height, ΔDLON & ΔDLAT, separated 5º & 2.5º respectively, and the time difference between GIMs Δt (30 minutes, centered, computed each 15 minutes). **See Liu Q. et al. (2022) for further details, including validation vs. Jakowski & Hoque (2017).**

Now, under DISPEC, The GIMs of VTEC gradient components, in longitude, latitude and time, have been computed since 1997 (+1.5x10^{10} VTEC gradient component estimations within more than three millions of corresponding maps), and stored, publicly available in IONEX-like format at:



https://chapman.upc.es/tomion/DISPEC/SDA4/gradVTEC_GIMs/

Jakowski, N., & Hoque, M. M. (2019). Estimation of spatial gradients and temporal variations of the total electron content using ground-based GNSS measurements. Space Weather, 17(2), 339–356.

Liu, Q., Hernández-Pajares, M., Yang, H., Monte-Moreno, E., García-Rigo, A., Lyu, H., ... & Orús-Pérez, R. (2022). A New Way of Estimating the Spatial and Temporal Components of the Vertical Total Electron Content Gradient Based on UPC-IonSAT Global Ionosphere Maps. Space Weather, 20(2), e2021SW002926.

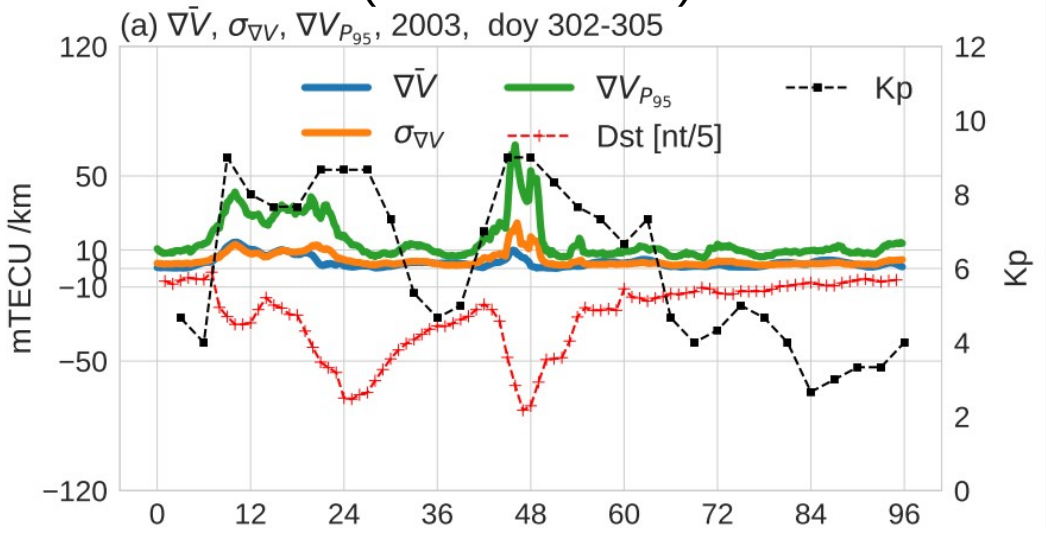
Example of comparison of GIM- vs raw-GNSS data- based regional **spatial** indices over Europe: **Halloween storm** (28 Oct -1 Nov 2003)

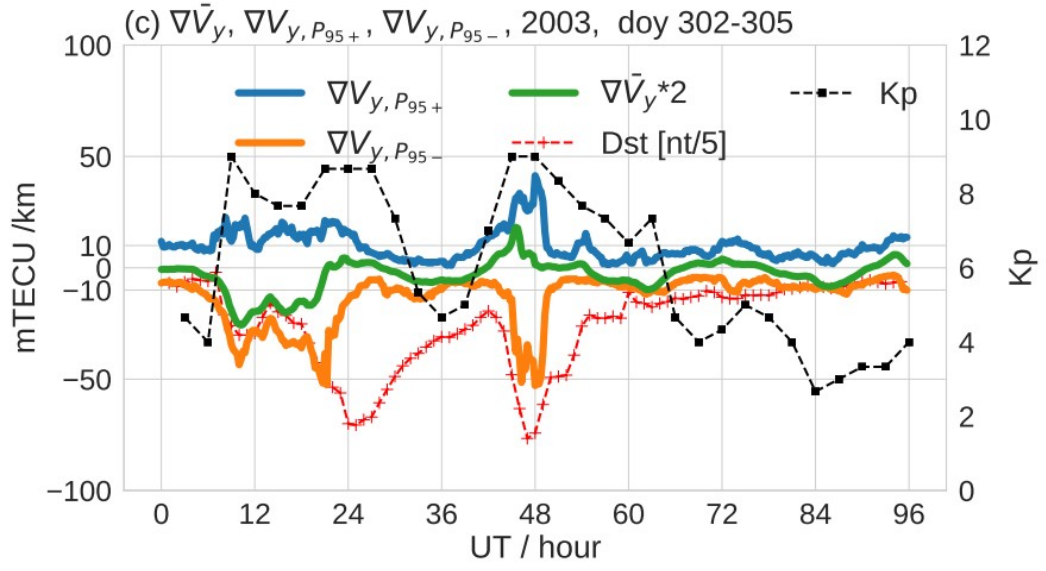
From **UQRG GIM (VgUG)** (Liu et al. 2022)

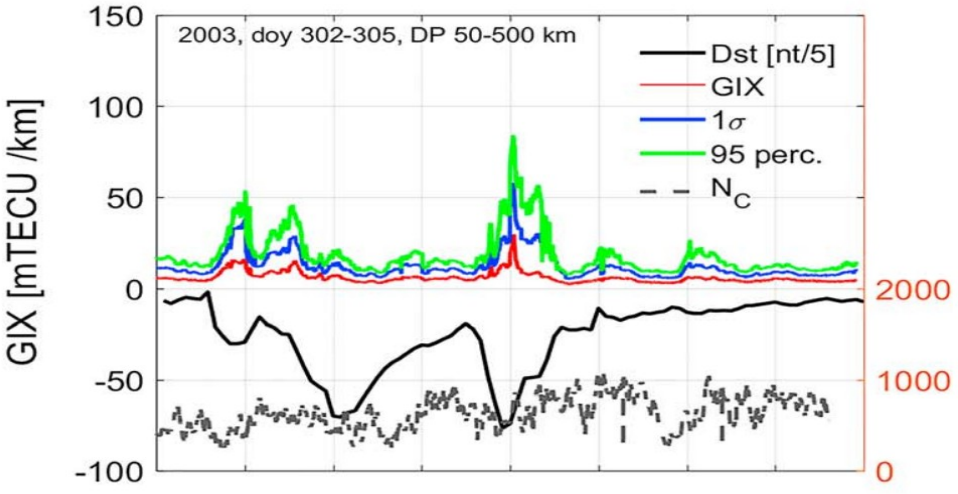
From **raw GNSS data** (Jakowski & Hoque (2017)

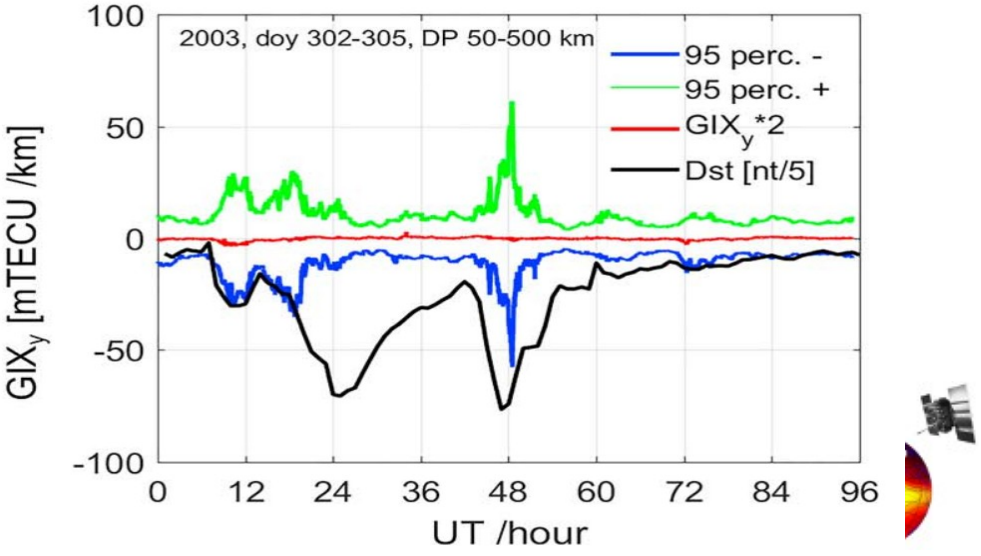
Spatial gradient norm

Latitudinal gradient component









Recent comparison of GIM gradients, including the RT-ones

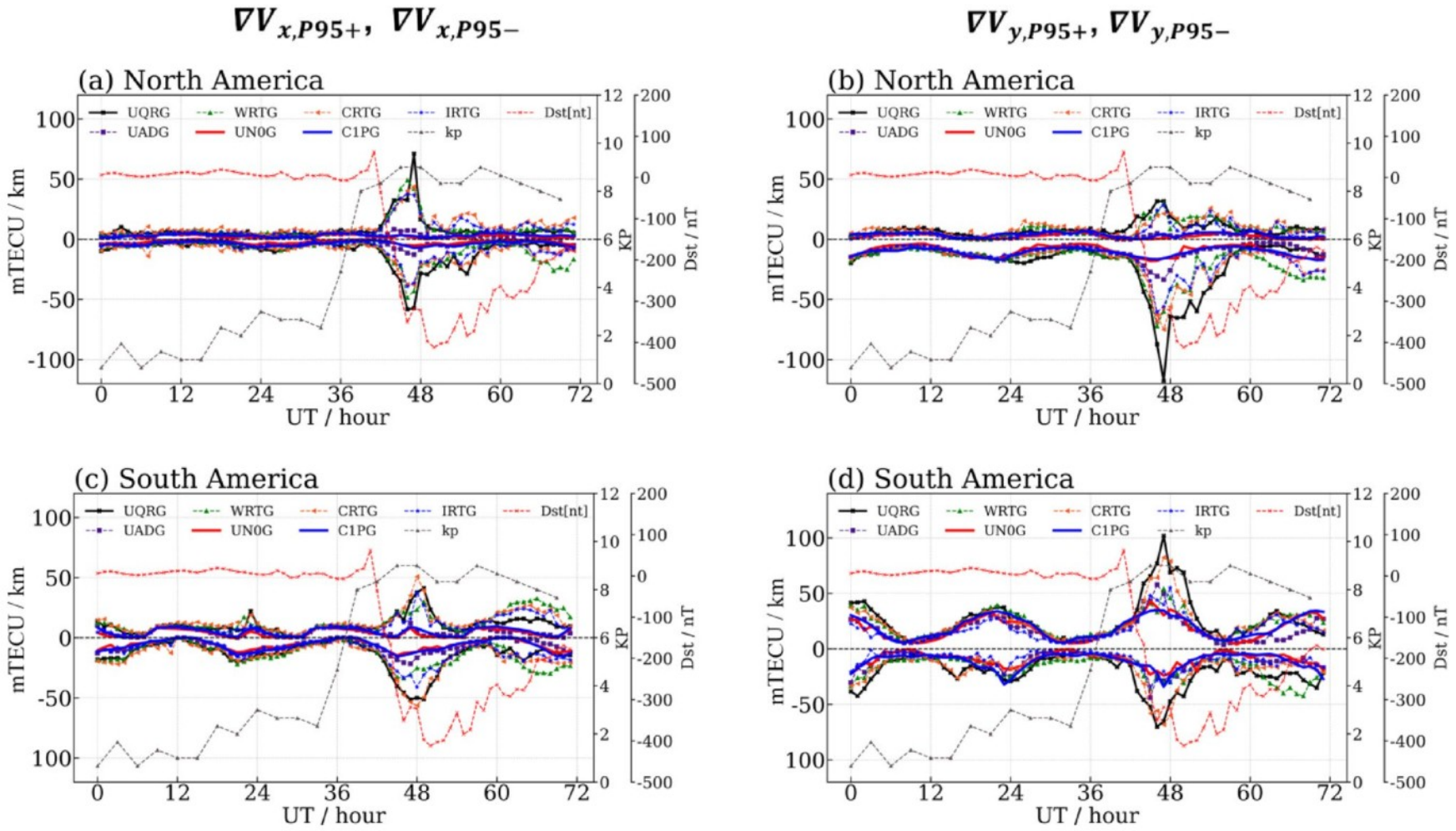


Fig. 5 Comparison of the regional spatial gradient indices ($\nabla V_{x,P_{95\pm}}$ and $\nabla V_{y,P_{95\pm}}$) based on different GIMs during the severe geomagnetic storm period from day 130 to 132 of 2024

Xu, K., Liu, Q., Monte-Moreno, E., Yang, H., Hernández-Pajares, M., Olivares-Pulido, G., ... & Zhang, C. (2026). Monitoring and prediction of ionospheric spatial gradients from global ionosphere maps: a comparative analysis. GPS solutions, 30(1), 17.

(IV) Global Maps of Ionospheric Storm Scale Index

- **Computation of Iscale (^P_{TEC}) from VTEC GIMs.**

The **Ionospheric Storm Scale Index** (or IsUG) was defined in Nishioka et al. (2017) as the standardized $\mathbf{P_{tec}}$, $\hat{P}_{TEC}$, where P_{tec} is the percentage deviation of VTEC, $\mathbf{O_{tec}}$ is the hourly median VTEC derived at grid points of GIM. The hourly median VTEC is the median of the five VTEC values during 1-h interval, under the GIM VTEC temporal resolution of 15 min. The hourly median VTEC is calculated every hour (for example, 0, 1, 2 UT). $\mathbf{R_{tec}}$ is the reference median value at the same local time and geographic location in the past 27 days.

$$P_{TEC} = \frac{100 \times (O_{TEC} - R_{TEC})}{R_{TEC}}$$

$$\hat{P}_{TEC} = \frac{P_{TEC} - \mu}{\sigma}$$

Now, under DISPEC, the IsUG GIM historical dataset starting on 1997 (+1.2 10^9 IsUG estimations within a quarter of million of corresponding maps) is publicly available , in IONEX format, at:

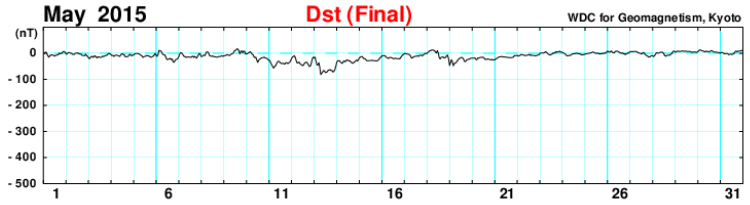
https://chapman.upc.es/tomion/DISPEC/SDA4/IonoStormScale_GIMs/

Liu, Q., Hernández-Pajares, M., Lyu, H., Nishioka, M., Yang, H., Monte-Moreno, E., Gulyaeva, T., Béniguel, Y., Wilken, V., Olivares-Pulido, G. and Orús-Pérez, R., 2021. Ionospheric storm scale index based on high time resolution UPC-IonSAT global ionospheric maps (IsUG). Space Weather, 19(11), p.e2021SW002853.

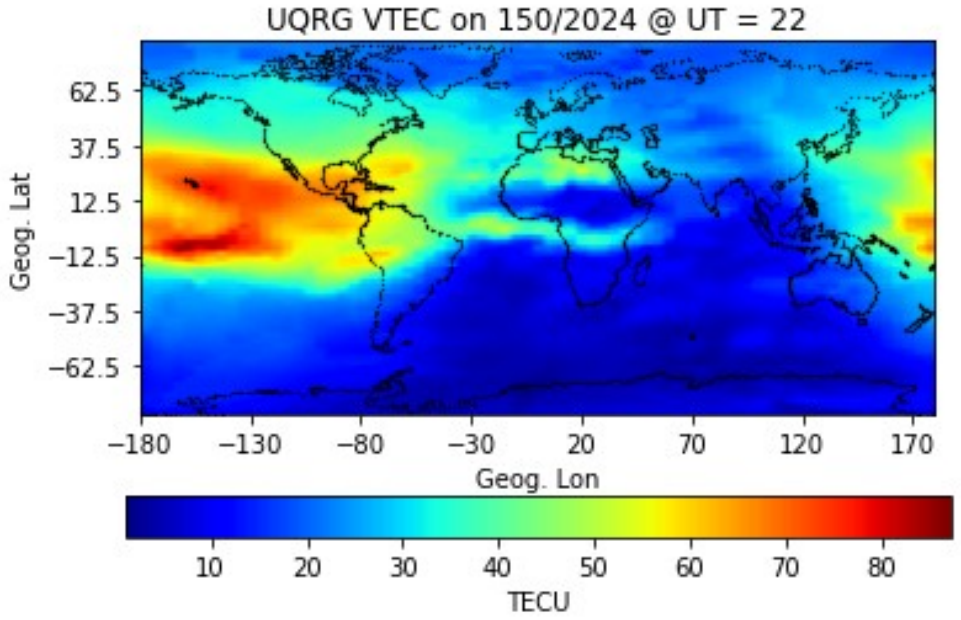
Nishioka, M., Tsugawa, T., Jin, H., & Ishii, M. (2017). A new ionospheric storm scale based on TEC and foF2 statistics. Space Weather, 15(1), 228–239.

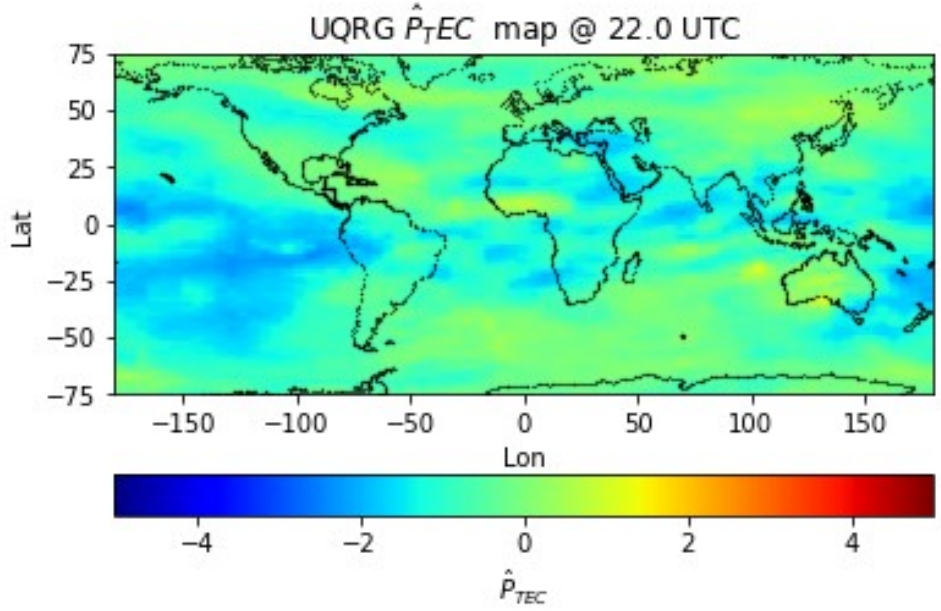
Ionospheric Storm Scale Index GIMs (IsUG)

- **Iscale Index Maps.** GIMs can be used to characterize the state of the ionosphere.
- Example for quiet conditions. May 30th 2015



$$P_{TEC} = \frac{100 \times (G_{TEC} - R_{TEC})}{R_{TEC}} \qquad \hat{P}_{TEC} = \frac{P_{TEC} - \mu}{\sigma}$$

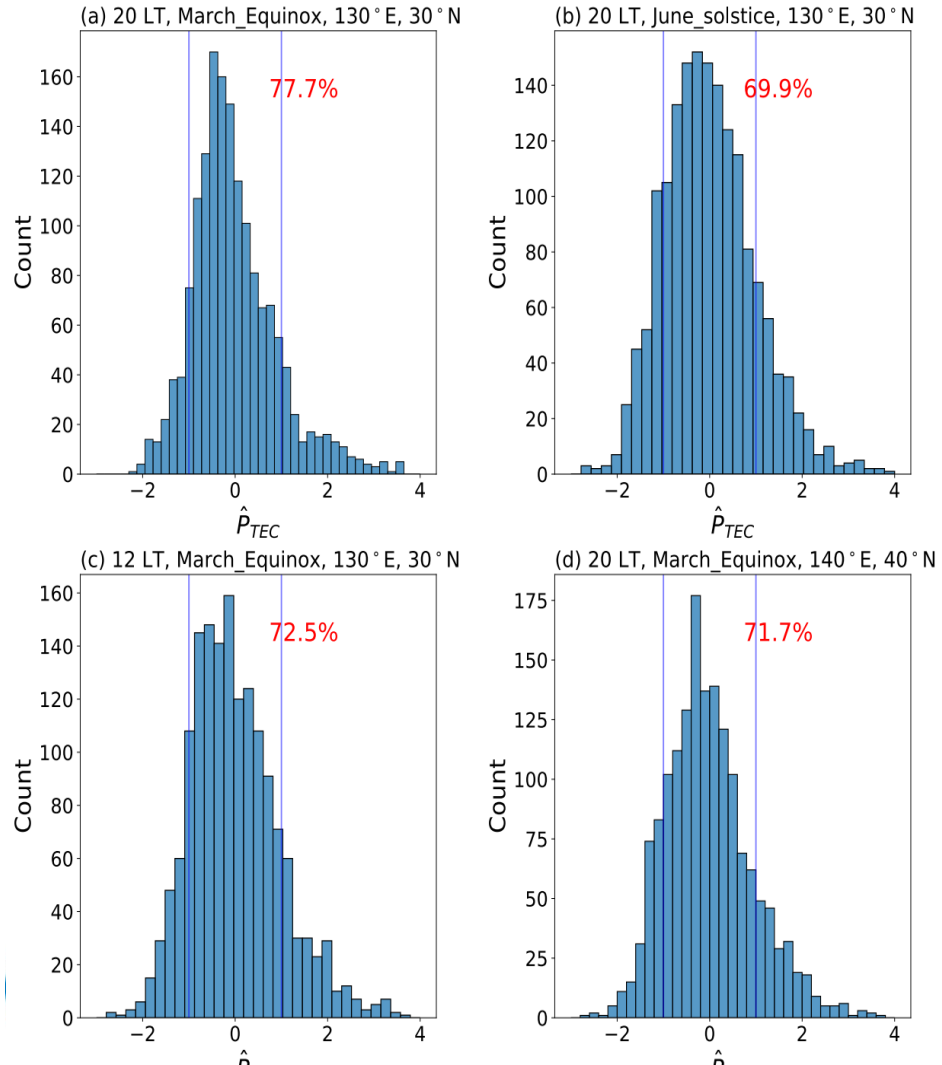




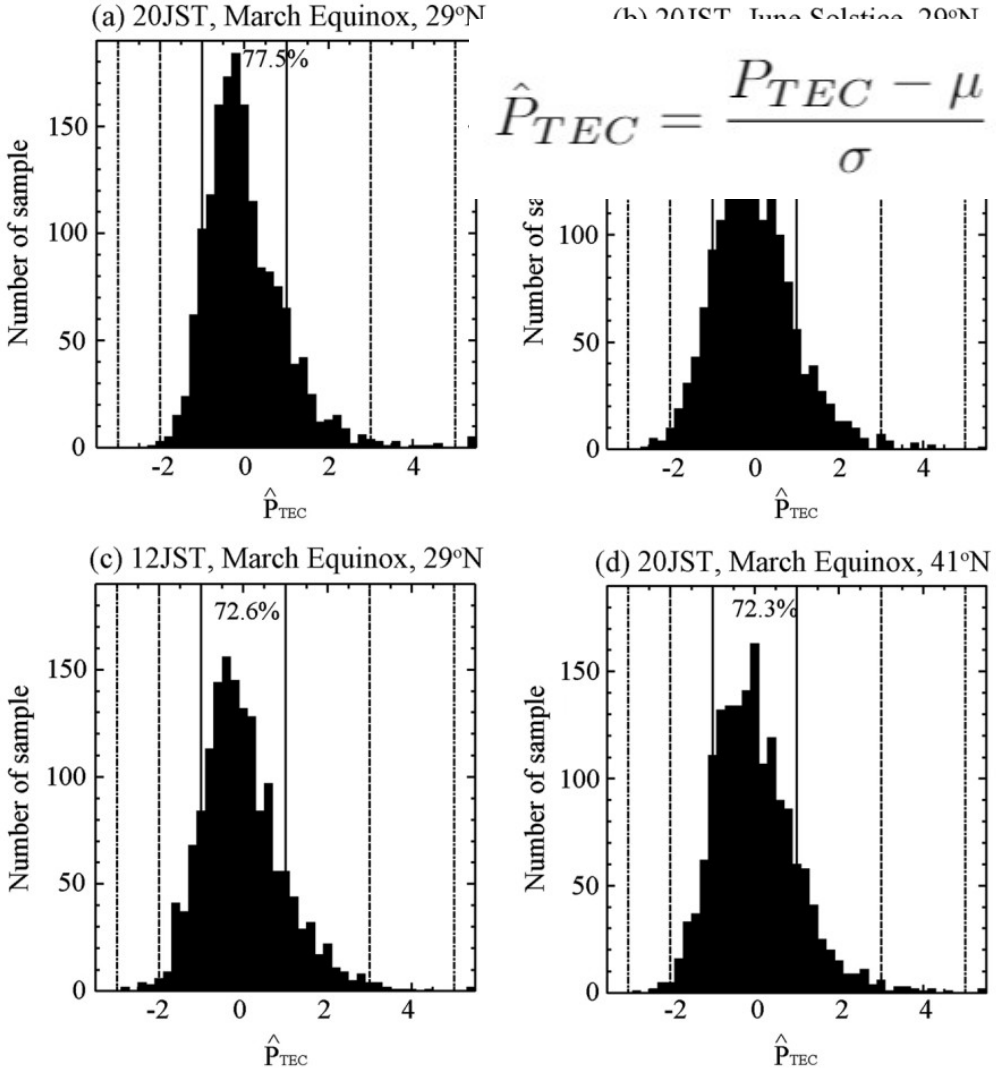
- G_{TEC}: Hourly VTEC
- R_{TEC}: Median of the G_{TEC} for the last 27 days @ the same local time and geographical location.

Comparing ^Ptec from GIM with ^Ptec from raw GNSS data over Japan since 1997 to 2014 (3 months of seasonal data per year)

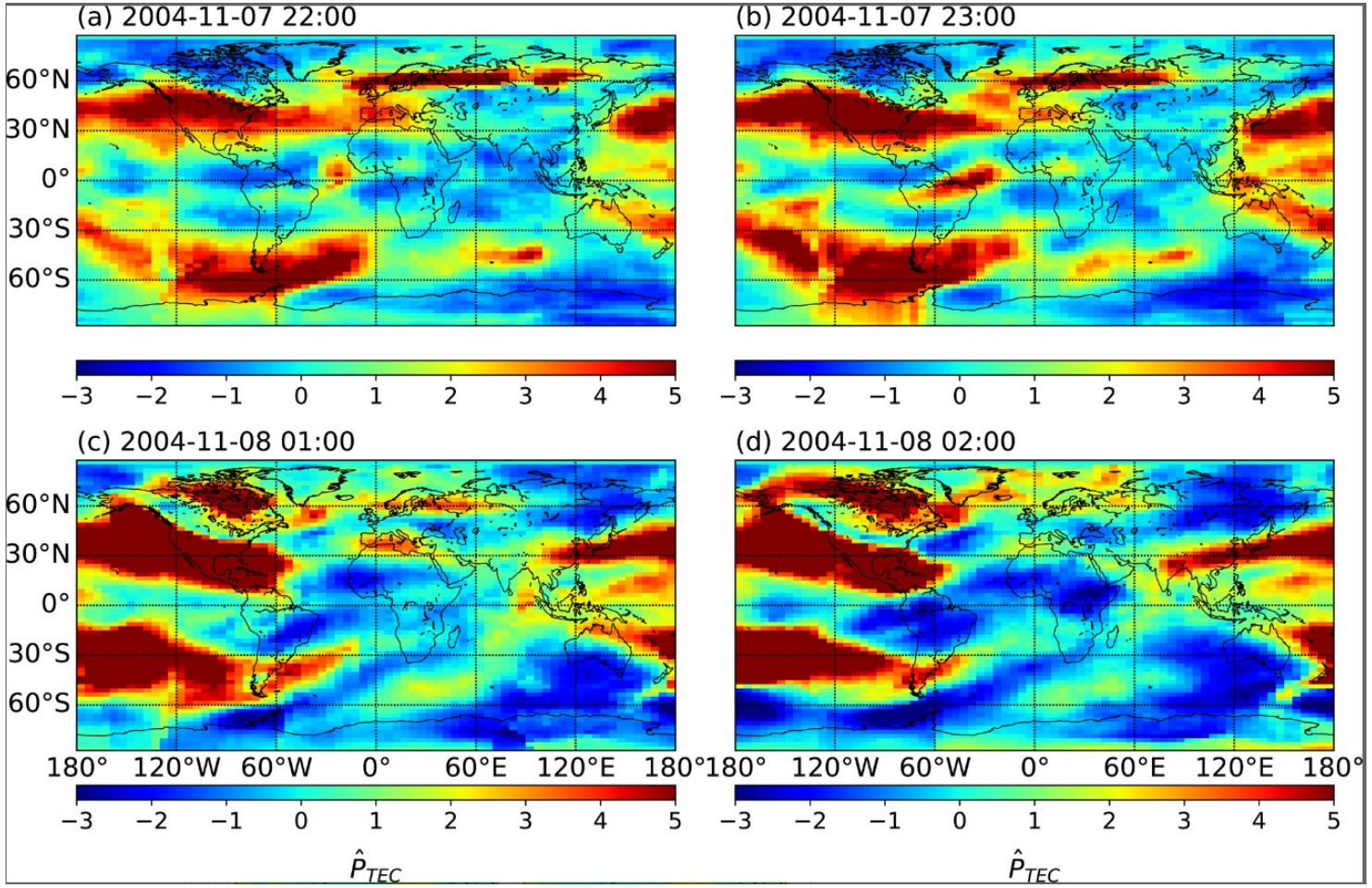
From **UQRG GIM (VgUG)**
(Liu et al. 2021)



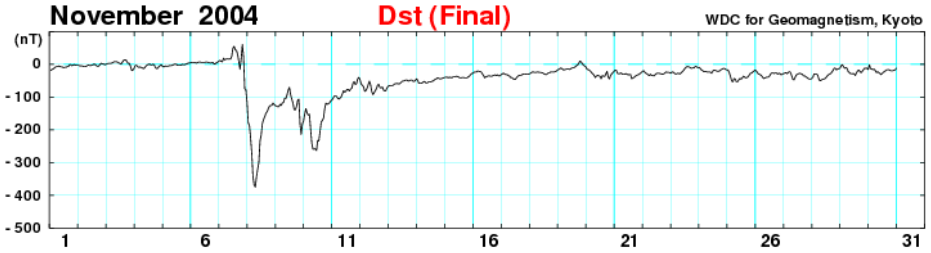
From **raw GNSS data**
(Nishioka et al., 2017))



Ionospheric Storm Scale Index GIMs (IsUG)



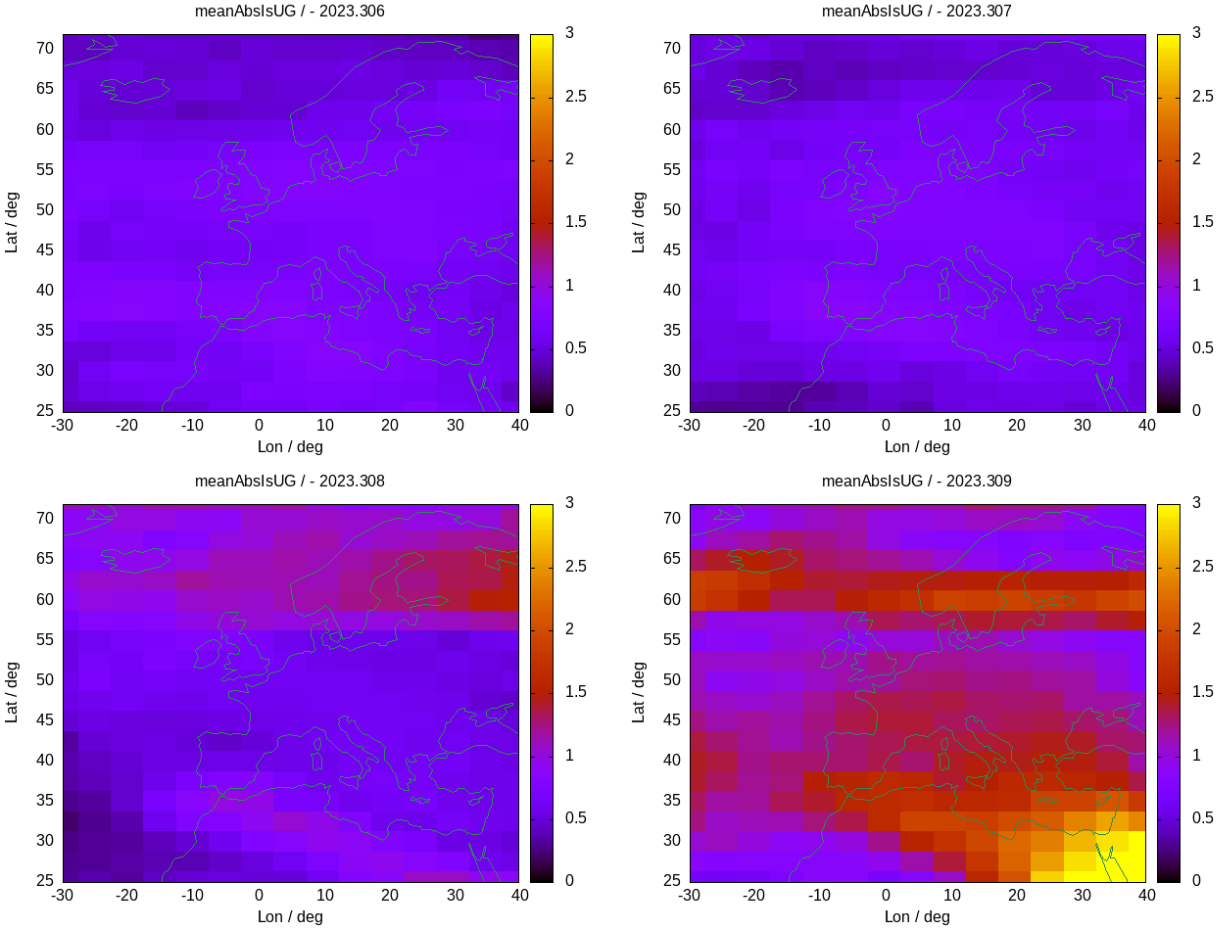
- November 2004 G5 geomagnetic storm. Kp 9
- Displacement of the EIA lobes.



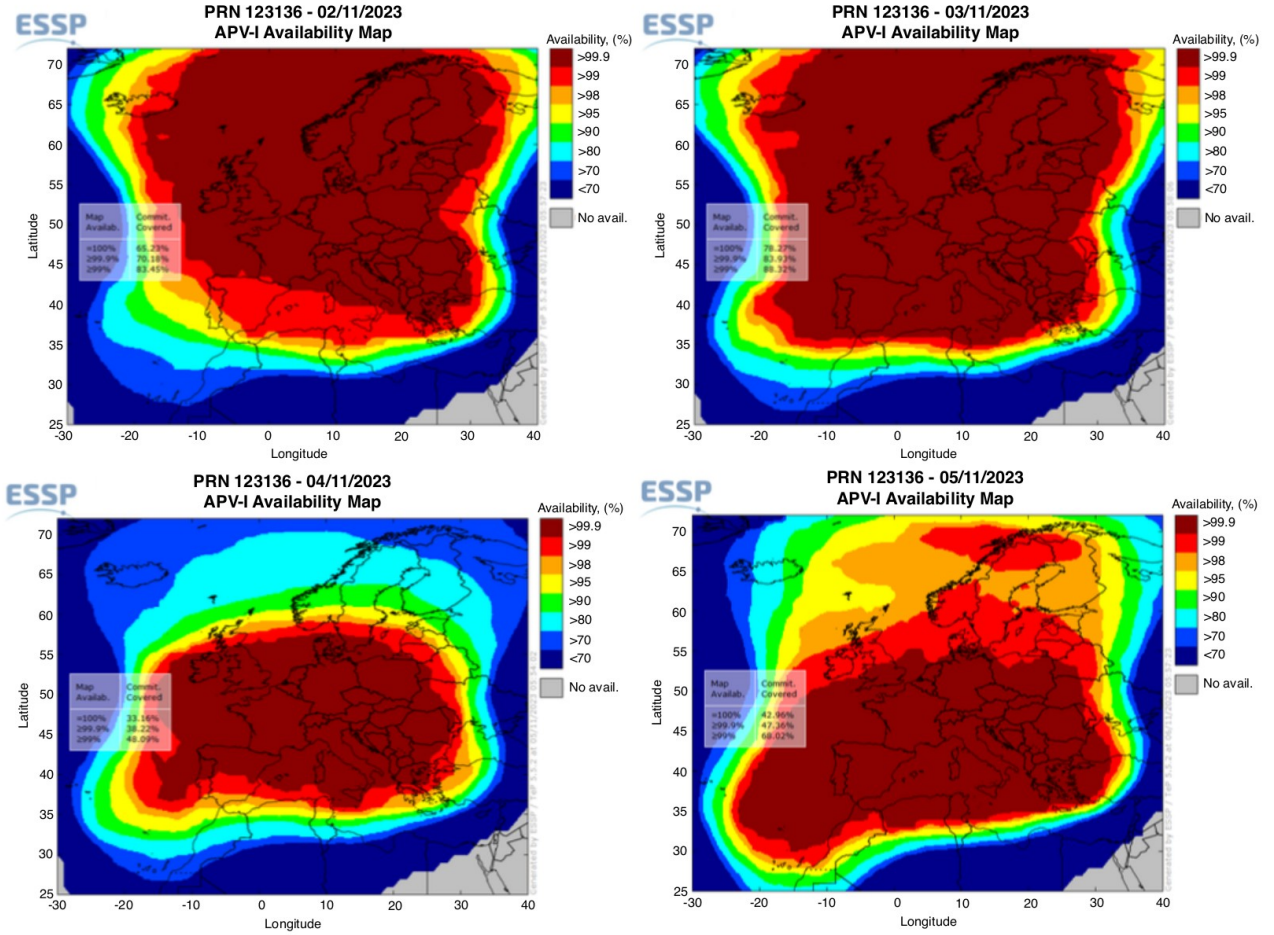
- From Liu, Q., Hernández-Pajares, M., Lyu, H., Nishioka, M., Yang, H., Monte-Moreno, E., Gulyaeva, T., Béniguel, Y., Wilken, V., Olivares-Pulido, G. and Orús-Pérez, R., 2021. Ionospheric storm scale index based on high time resolution UPC-IonSAT global ionospheric maps (IsUG). *Space Weather*, *19*(11), p.e2021SW002853.

<|IsUG|> vs EGNOS APV-I daily availability map over Europe (02, 03, 04 & 05 Nov 2023)

Daily IsUG mean maps over Europe



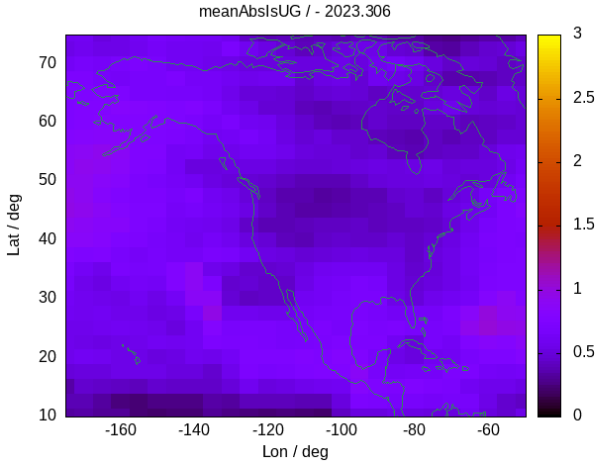
Daily EGNOS APV-I Availability maps (i.e. over Europe)

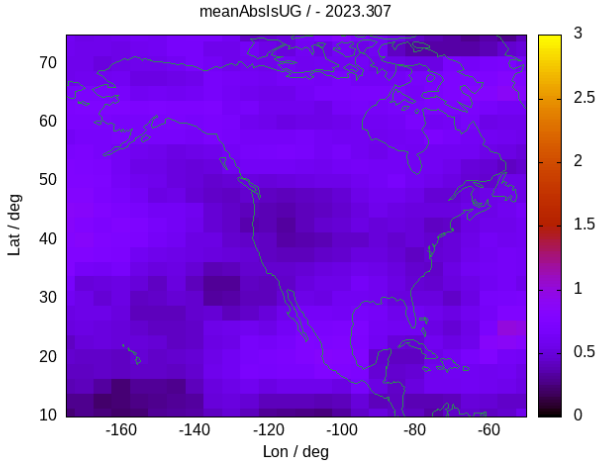


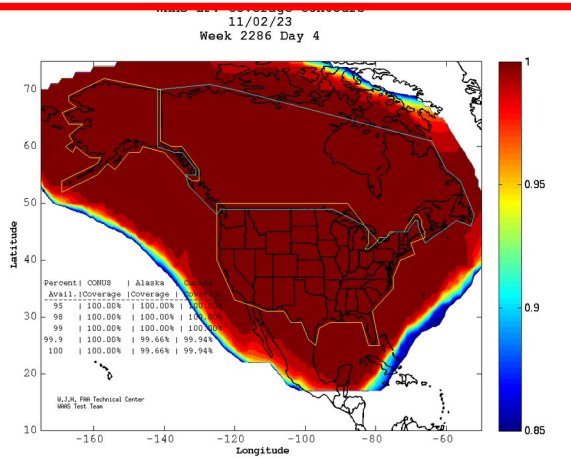
<|IsUG|> vs WAAS LPV daily availability map over NorthAmerica (02 Nov to 05 Nov 2023)

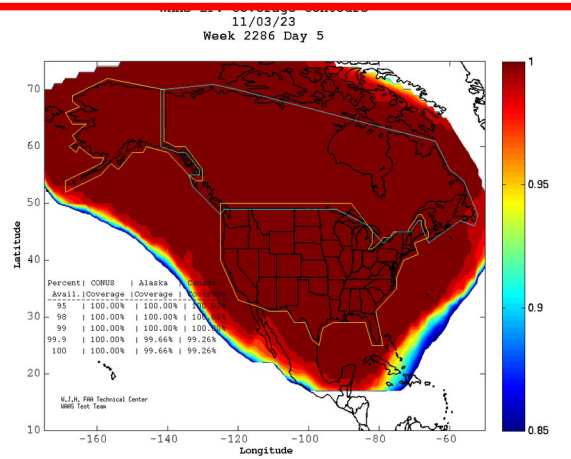
Daily IsUG mean maps over North-America

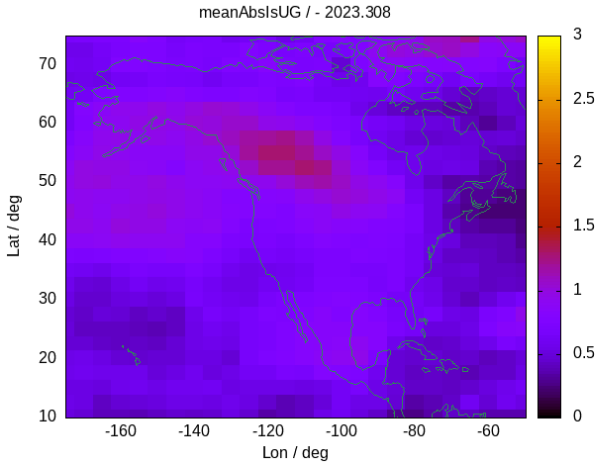
Daily WAAS LPV coverage maps (i.e. over North-America)

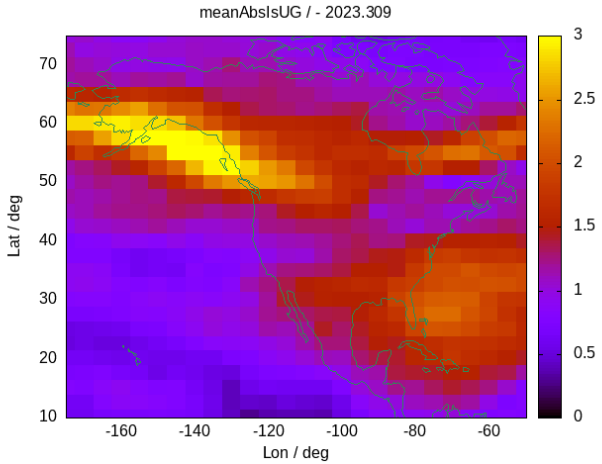


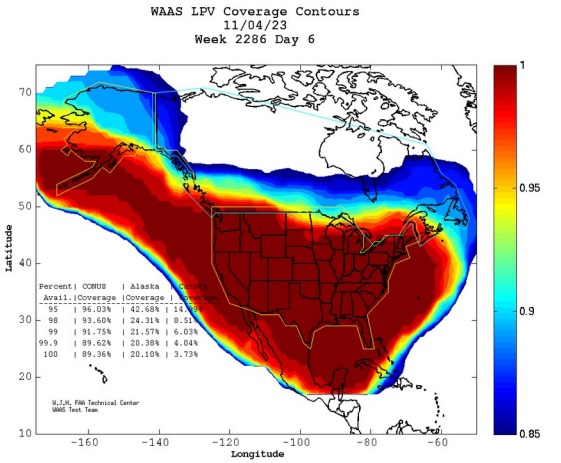


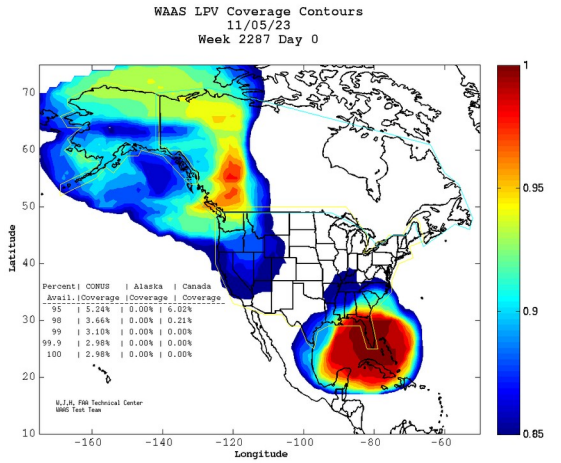




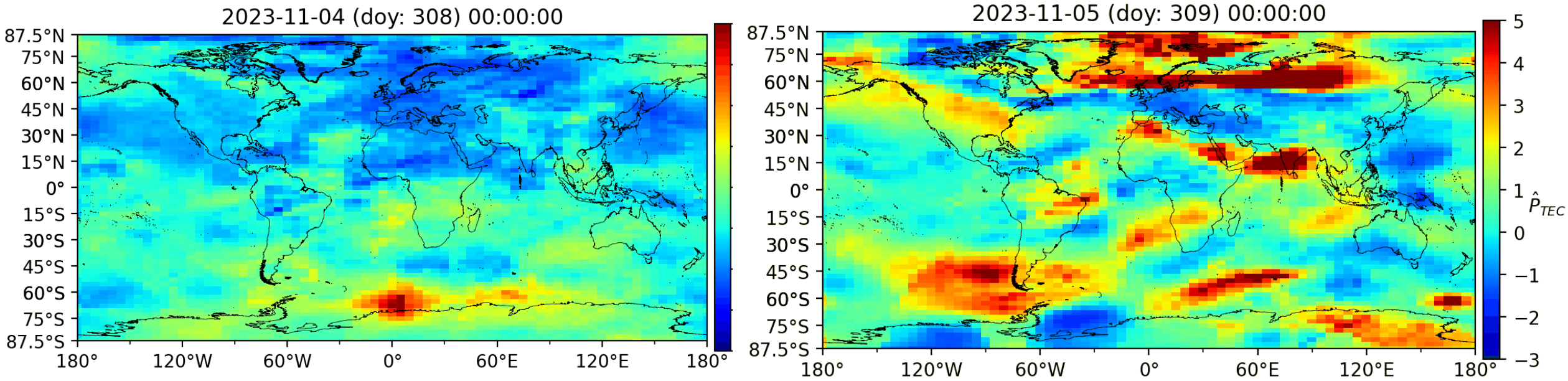








Movies of IsUG GIMs on 04 & 05 Nov 2023



The validation of IsUG vs different types of ionospheric parameters within the 4-5 Nov 2023 ionospheric storm, is summarized in the manuscript recently published:

Smirnov, A., Asamoah, E. N., Navas-Portella, V., Kronberg, E. A., Lühr, H., Liu, Q., & Hernández-Pajares, M. (2026). Global IsUG index maps for tracking ionospheric variability: a case study of the 4–5 November 2023 geomagnetic storm. Journal of Space Weather and Space Climate, 16, 17.

J. Space Weather Space Clim. 2026, **16**, 17
© A. Smirnov et al., Published by EDP Sciences 2026
https://doi.org/10.1051/swsc/2026008

JSWSC

Available online at:
www.swsc-journal.org

RESEARCH ARTICLE OPEN ACCESS

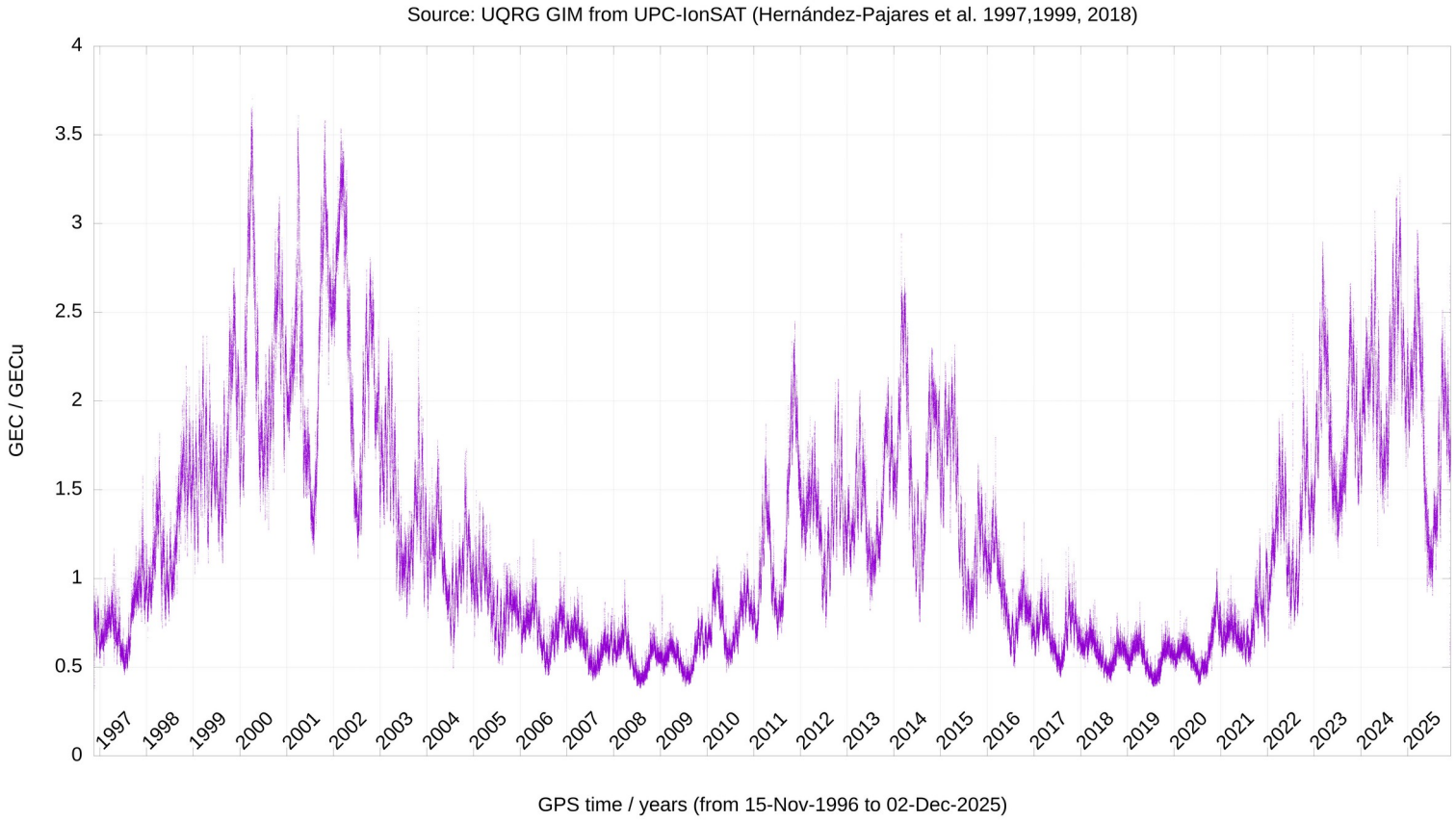
Global IsUG index maps for tracking ionospheric variability: a case study of the 4–5 November 2023 geomagnetic storm

Artem Smirnov[1,2,*], Eric Nana Asamoah[3,4], Víctor Navas-Portella[5,6], Elena A. Kronberg[1], Hermann Lühr[2], Qi Liu[7], and Manuel Hernández-Pajares[8,9]

Abstract – In this study, we analyze ionospheric and thermospheric changes during a composite geomagnetic storm on 4–5 November 2023 with two activity periods. On 4 November, the corotating interaction region (CIR) compression resulted in moderate activity (SYM-H = −60 nT), while on 5 November the arrival of two Coronal Mass Ejections (CMEs) embedded into the ongoing CIR caused intense geomagnetic disturbances (SYM-H = −188 nT). Using global observations of vertical total electron content (VTEC) from the Universitat Politècnica de Catalunya (UPC) Global Ionosphere Maps (GIMs) and the normalized Ionospheric storm scale from UPC GIMs (IsUG) storm-time index, we examine ionospheric anomalies during these events. The IsUG index reveals that both events began with positive VTEC changes, but their delayed responses differed significantly. During the 4 November event, the negative phase did not develop, while the 5 November storm produced severe negative VTEC anomalies. Using complementary satellite observations of thermospheric composition, temperature and density, along with ionosonde-derived large-scale traveling ionospheric disturbances (LSTIDs) velocities, we show that these contrasting responses were caused by differences in thermospheric heating and composition. On 4 November, high-latitude heating was weak, while in the 5 November storm it was significant and led to the development of global disturbance winds and strong O/N_2 decreases, causing severe negative VTEC anomalies. Despite the complicated morphology, the IsUG index could track these dynamics in agreement with the underlying physical processes, and can be used for monitoring of complex ionospheric storms.

(V) Global Electron Content (GEC) & Space Weather

Introduced in Afraimovich et al. (2008), we showed in Aroca-Farrerons et al. (2024) that the GEC presents a frequent high (or extremely high) similarity to Kp, in the spectral domain. We have computed the GEC vs time series, each 15 minutes, since end of 1996 (+1 million GEC values):



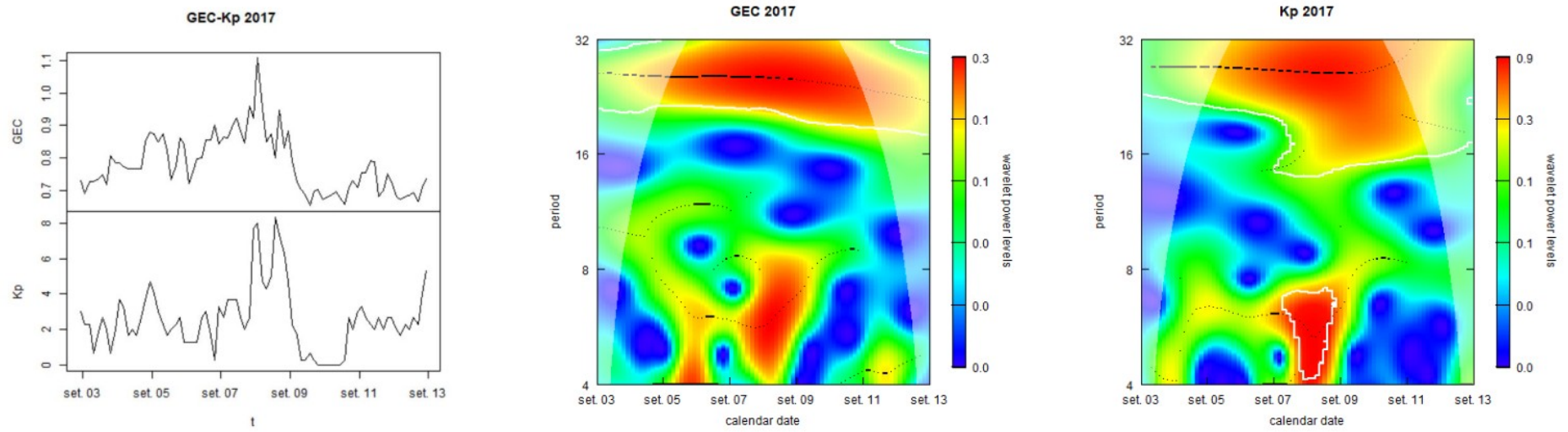
https://chapman.upc.es/tomion/DISPEC/SDA4/GEC/

Afraimovich, E.; Astafyeva, E.; Oinats, A.; Yasukevich, Y.V.; Zhivetiev, I. Global electron content: A new conception to track solar activity. Ann. Geophys. 2008, 26, 335–344.

Aroca-Farrerons, J. M., Hernández-Pajares, M., Lyu, H., Roma-Dollase, D., Orus-Perez, R., García-Rigo, A., ... & Liu, Q. (2024). The Spectrum of Global Electron Content: A New Potential Indicator of Space Weather Activity. Sensors, 24(2), 393.

Correlation of GEC vs Kp

Aroca-Farrerons et al. (2024) showed that the GEC and Kp geomagnetic index spectrograms typically present a high or extremely high similarity, compared during 10 days around the 34 geomagnetic events (Kp ≥ 7.5) from 2000 to 2020.



Example of **extremely high** **similarity between GEC and Kp spectrograms**, as the **29%** of geomagnetic events with $Kp \geq 7.5$ in 2000-2020 (10 of 34).

Summary and Conclusions

The global RT processing of GNSS multifrequency measurements and the rapid Global Ionospheric Maps of VTEC generated by UPC-IonSAT **over 2.5 solar cycles**, since end of 1996 (+5x10^9 VTEC values), allows to derive products for the **RT detection and characterization of Space Weather**, **part of them derived from VTEC GIMs** that are also computed, **assessed and combined in RT** by different IGS centers:

1) The **GNSS Ionosphere proxy of EUV solar flux variation during solar flares**, that is working in RT 24/7 provinding warnings during more than one solar cycle.

2) The global maps of latitudinal and longitudinal components of **VTEC gradient are derived from VTEC GIMs consistently** with those derived from raw measurements.

2) The **Ionospheric Storm Scale (IsUG) maps,** with a first example remarkable correlation of daily mean over Europe and North-America vs. the daily availability maps of GNSS supported precise landing provided, respectively, by EGNOS and WAAS Satellite Based Augmentation Systems (SBAS), during the 02-05 Nov 2023 storm.

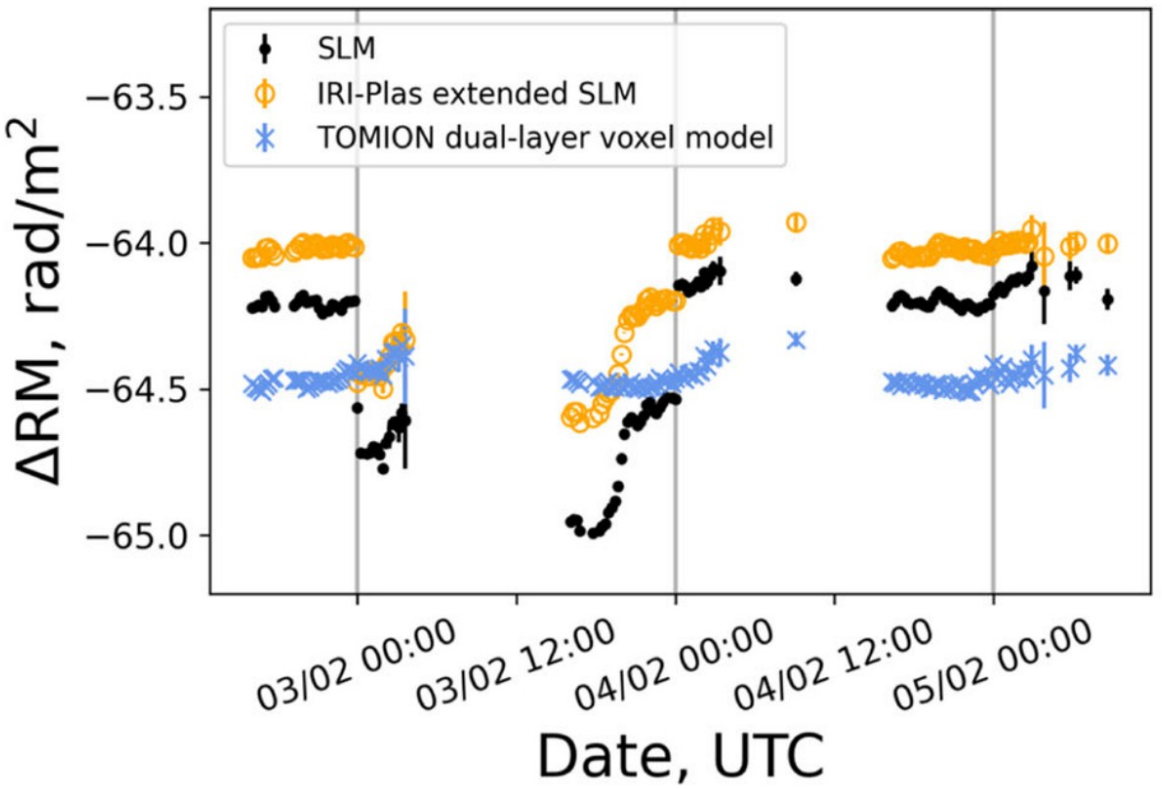
3) The **GEC** and its **remarkable correlations with Kp geomagnetic activity index in spectral domain** during major geomagnetic storms.

Thank you for your attention

Backup slides

Electron density (Ne) from global tomography

The electron density Ne is estimated with a tomographic Kalman filter on the illuminated voxels in the daily TOMION runs from global multi-frequency GNSS receiver data, for generating the UQRG GIMs. The high accuracy of this product has been shown in different works, e.g. recently in terms of the improvement of the Faraday rotation (ionospheric second order) correction in radio-astronomical LOFAR observations (Porayko et al. 2023). We have computed Ne of illuminated voxels up to each 15 minutes, since end of 1996 (+663 millions of Ne values):

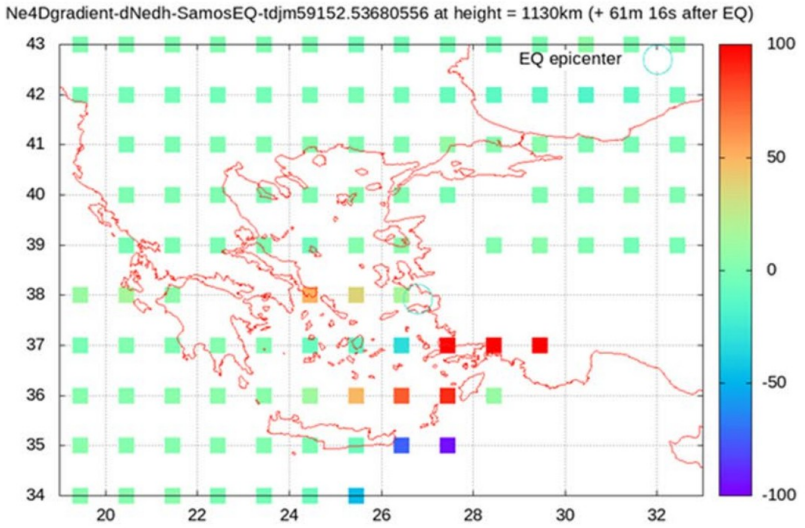


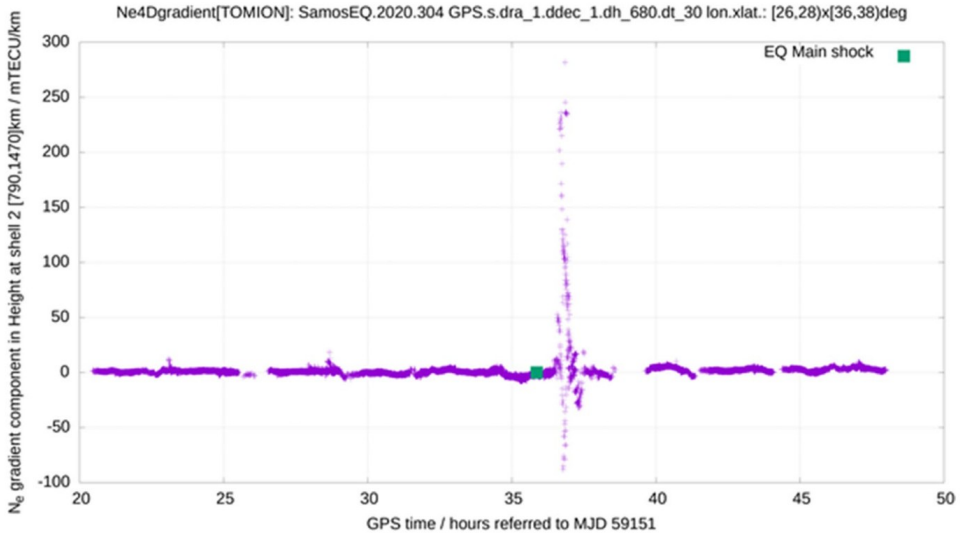
https://chapman.upc.es/tomion/DISPEC/SDA4/Ne/

Porayko, N. K., Mevius, M., Hernández-Pajares, M., Tiburzi, C., Olivares Pulido, G., Liu, Q., ... & Wucknitz, O. (2023). Validation of global ionospheric models using long-term observations of pulsar Faraday rotation with the LOFAR radio telescope. Journal of Geodesy, 97(12), 116.

Electron density vertical gradient (dNe/dz)

The electron density vertical gradient, dNe/dz is directly estimated from the electron density estimations in the illuminated voxels, Ne, generated in the daily TOMION runs from global multi-frequency GNSS permanent receiver data, for generating the UQRG GIMs. The high sensitivity of this new product has been recently shown in the detection, from regional network of GNSS ground receivers, of tsunami signatures in the ionosphere (Alfonsi et al. 2024). We have computed dNe/dz up to each 15 minutes, since end of 1996 (+320 millions values of dNe/dz values):





https://chapman.upc.es/tomion/DISPEC/SDA4/dNedz/

Alfonsi, L., Cesaroni, C., Hernandez-Pajares, M., Astafyeva, E., Bufféral, S., Elias, P., ... & Guerra, M. (2024). Ionospheric response to the 2020 Samos earthquake and tsunami. Earth, Planets and Space,76(1), 13.