Three decades of continuous monitoring of ionospheric electronic content on a global scale and new derived products

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URSI GASS, Wroclaw, Poland, 18 August 2026

(1)UPC-IonSAT; (2) ICE/IEEC & CSIC; (3)IEEC ; (4) TEC-EFW, ESA; (5) Henan Univ.; (6)Yangtze Normal Univ.; (7) UPC-TALP; (8) IAASARS, NOAA; (9) Borealis Global; (10) University of Warmia and Mazury; (11) DEMR, ONERA

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Outline

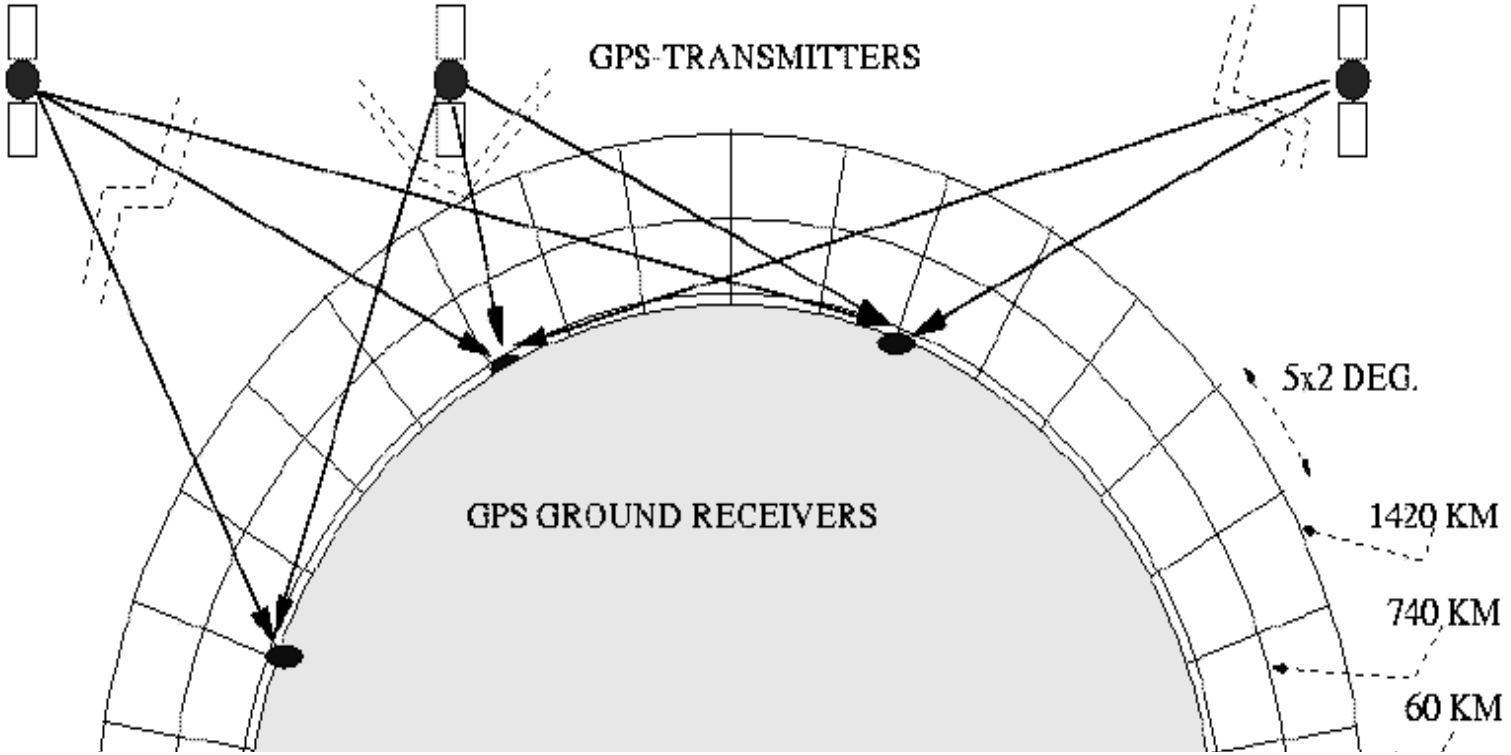
- Ionospheric tomography and VTEC GIM with TOMION
- Historical datasets of VTEC GIMs & DCBs
- VTEC gradient GIMs
- GIMs of Ionospheric Storm Scale index
- Global Electron Content
- Dual-layer global ionospheric tomography and associated vertical gradients of electron content
- Conclusions

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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):

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

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

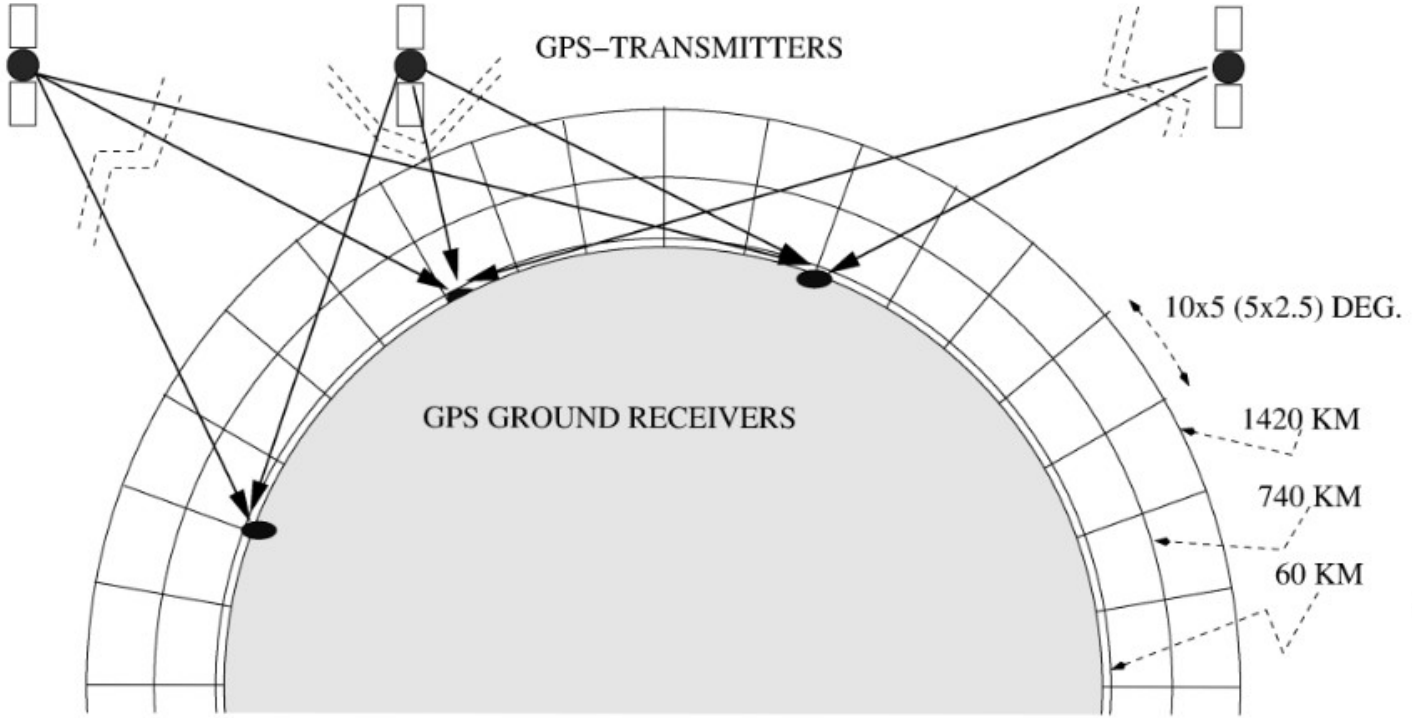
Slant & Vertical Total Electron Content values (S, V):

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

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,. . .)



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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.

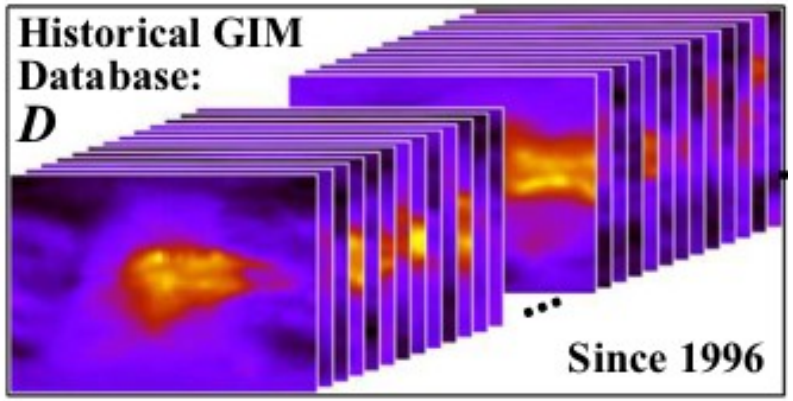
[14] DV Kotov et al. "Weak magnetic storms can modulate ionosphere-plasmasphere interaction significantly: Mechanisms and manifestations at mid-latitudes". In: *Journal of Geophysical Research: Space Physics* 124.11 (2019), pp. 9665–9675.

[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/

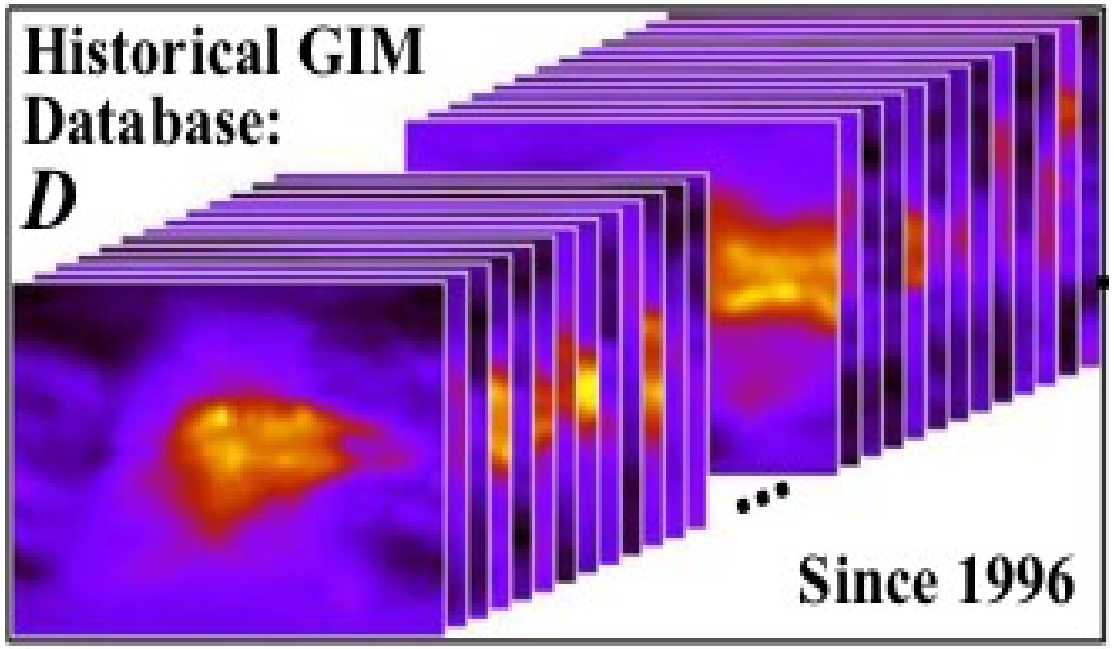
[*] Products obtained in DISPEC after one year of continuous parallel computations at UPC-IonSAT linux servers.

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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.

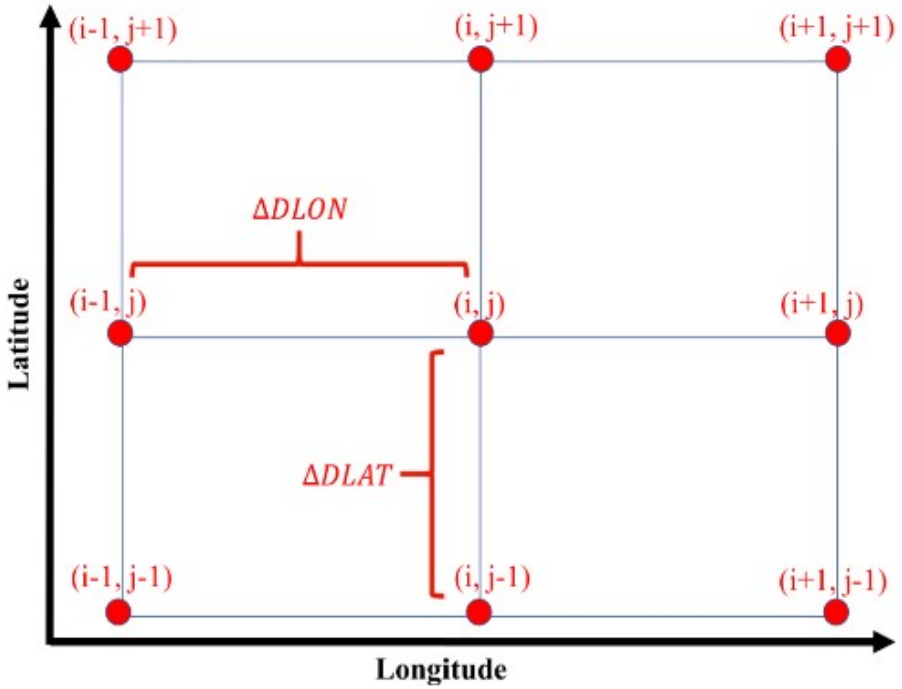
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VTEC gradient GIMs

- **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.**

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/

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),

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Ionospheric Storm Scale Index GIMs (IsUG)

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

The **Ionospheric Storm Scale Index** (or IsUG) is defined as the standardized **P_{tec}**, $\hat{P}_{TEC}$, where P_{tec} is the percentage deviation of VTEC, **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). **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/

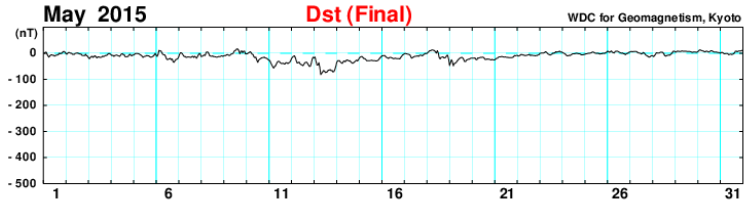
Liu, Q., Hernández-Pajares, M., Lyu, H., Nishioka, M., Yang, H., Monte-Moreno, E., Gulyaeva, T., Béniguel, Y., Wilken, V., Olivares-Pulido, G. and Orús-Pérez, R., 2021. Ionospheric storm scale index based on high time resolution UPC-IonSAT global ionospheric maps (IsUG). Space Weather, 19(11),

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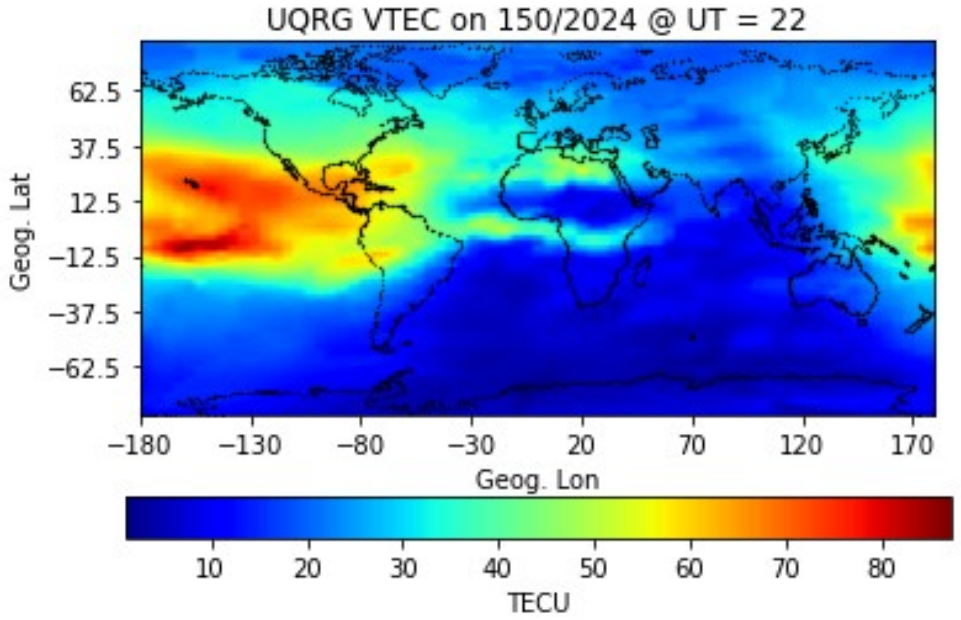
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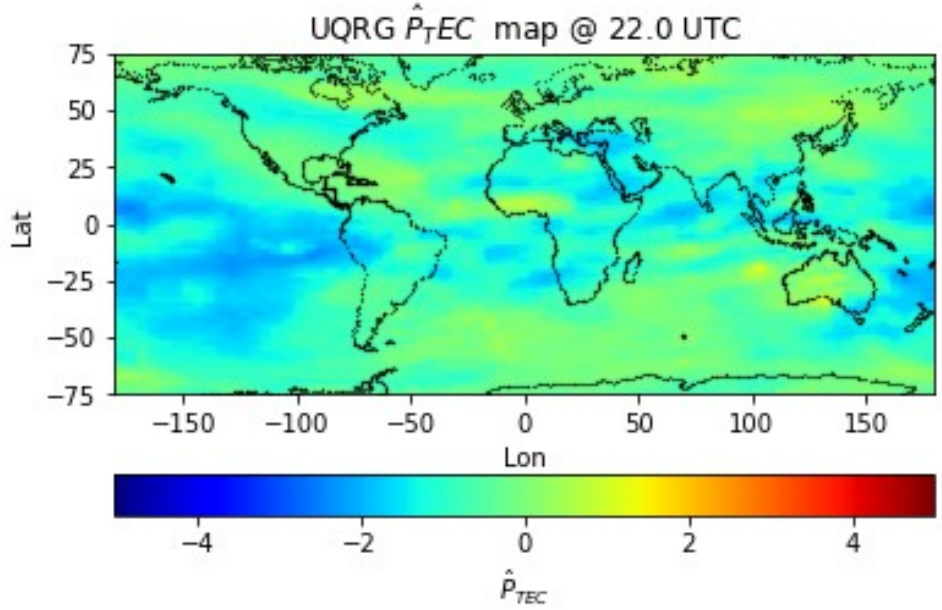
Ionospheric Storm Scale Index GIMs (IsUG)

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



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



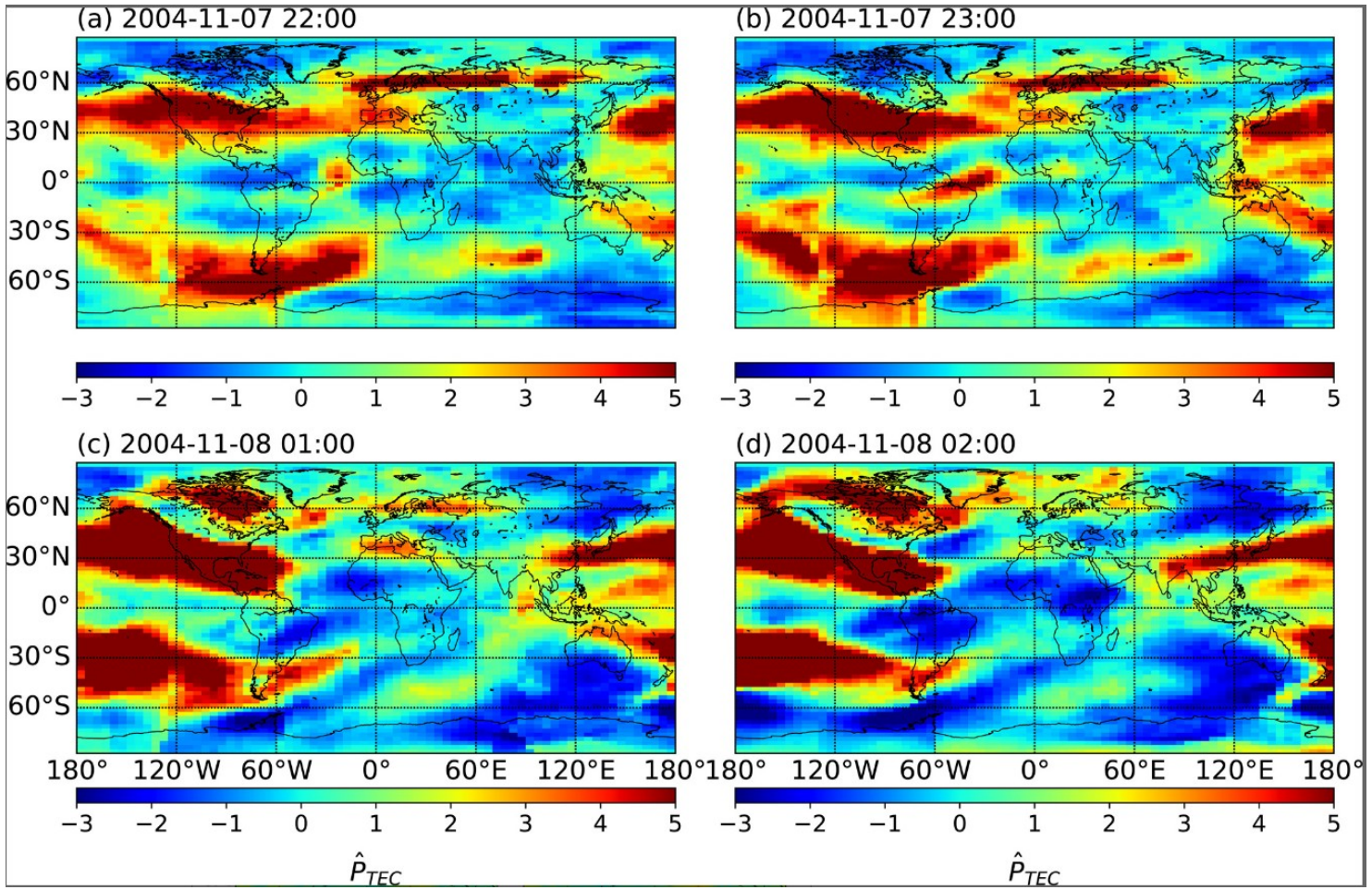


- G_{TEC}: Hourly VTEC
- R_{TEC}: Median of the G_{TEC} for the last 27 days @ the same local time and geographical location.

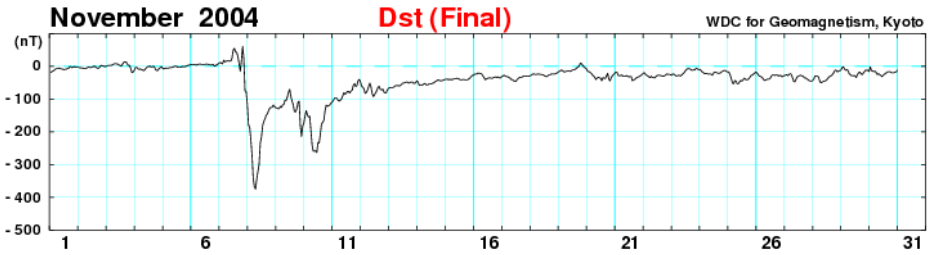
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Ionospheric Storm Scale Index GIMs (IsUG)



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



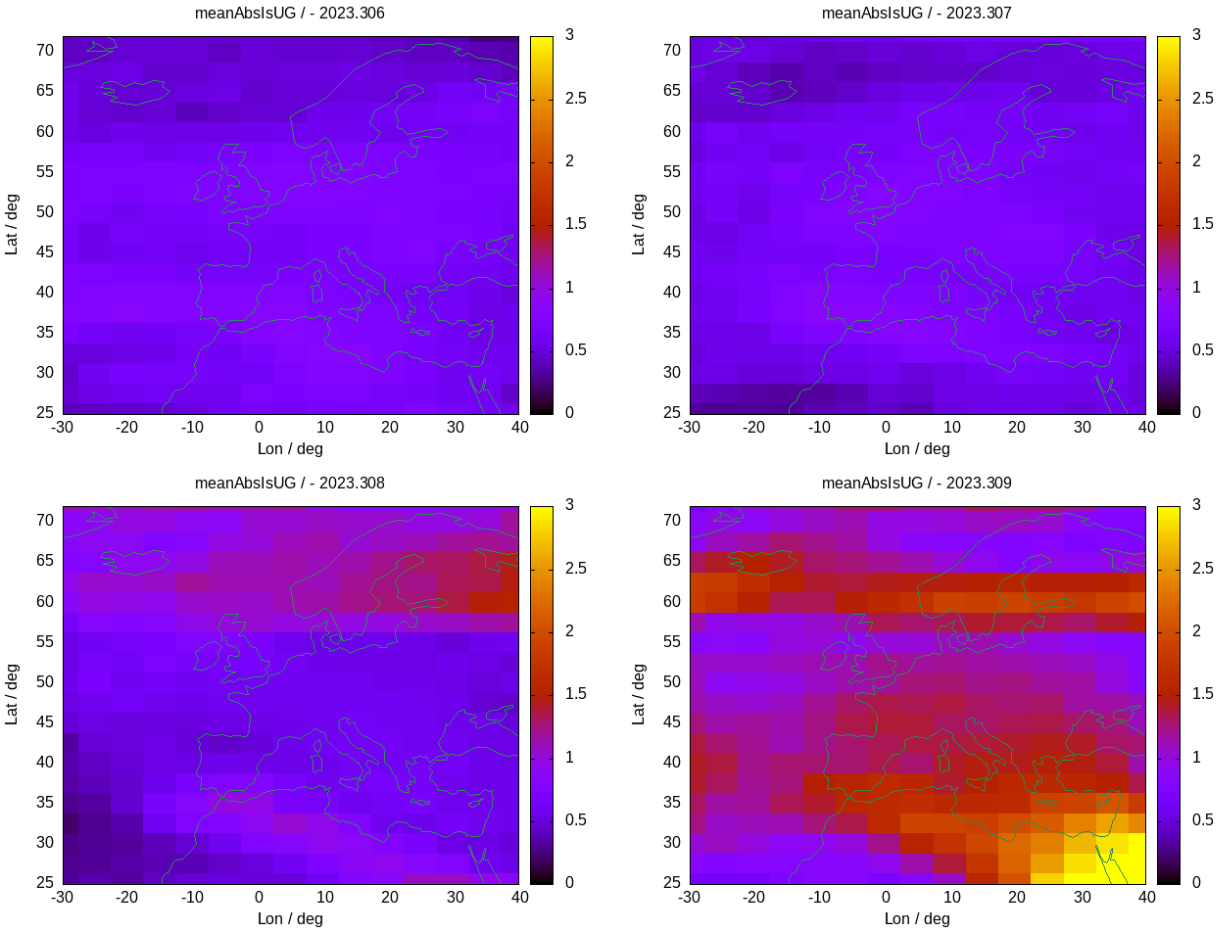
- From Liu, Q., Hernández-Pajares, M., Lyu, H., Nishioka, M., Yang, H., Monte-Moreno, E., Gulyaeva, T., Béniguel, Y., Wilken, V., Olivares-Pulido, G. and Orús-Pérez, R., 2021. Ionospheric storm scale index based on high time resolution UPC-IonSAT global ionospheric maps (IsUG). *Space Weather*, *19*(11),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

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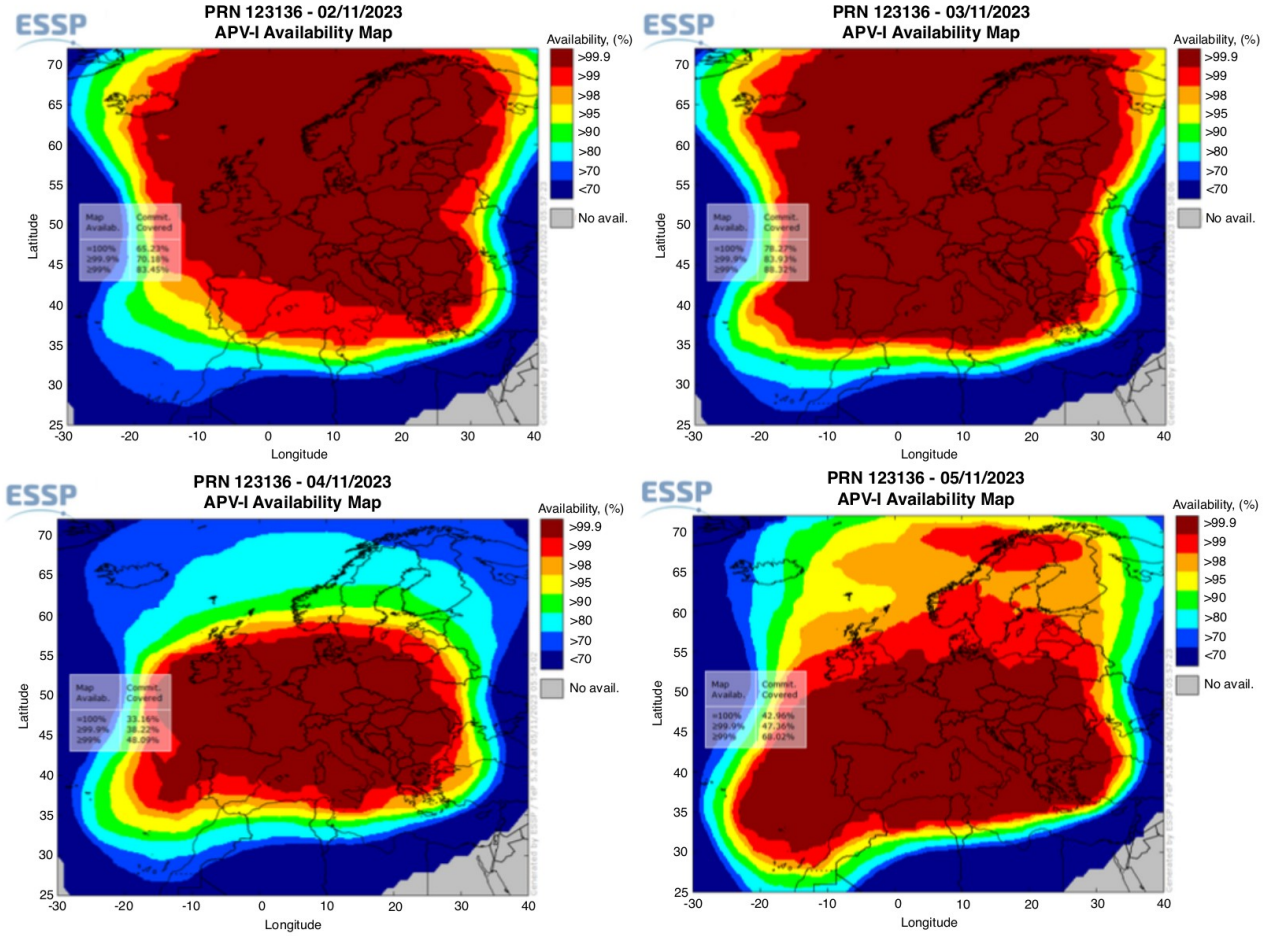
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<|IsUG|> vs EGNOS APV-I daily availability map over Europe (02, 03, 04 & 05 Nov 2023)

Daily IsUG mean maps over Europe



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



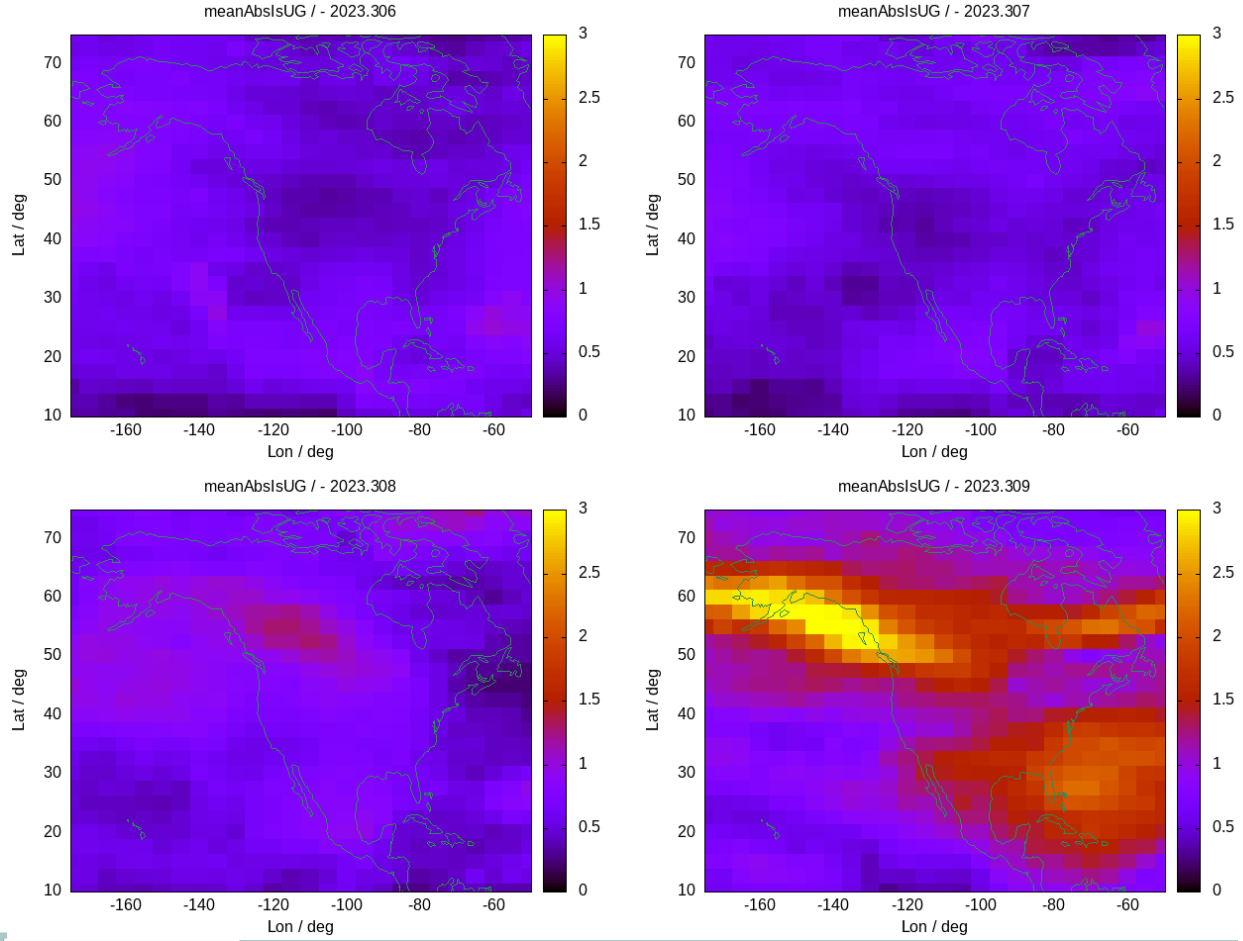
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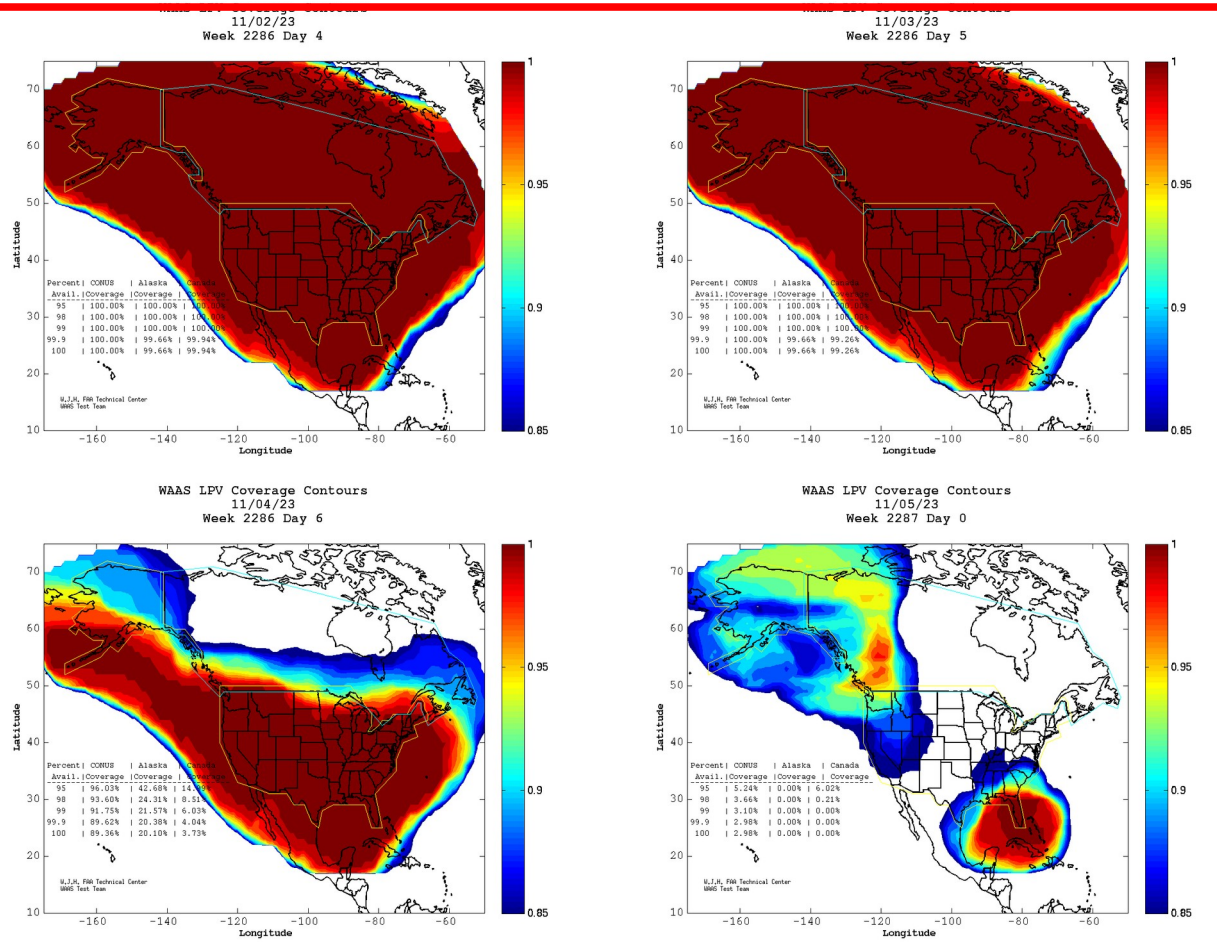
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<|IsUG|> vs WAAS LPV daily availability map over NorthAmerica (02 Nov to 05 Nov 2023)

Daily IsUG mean maps over North-America

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

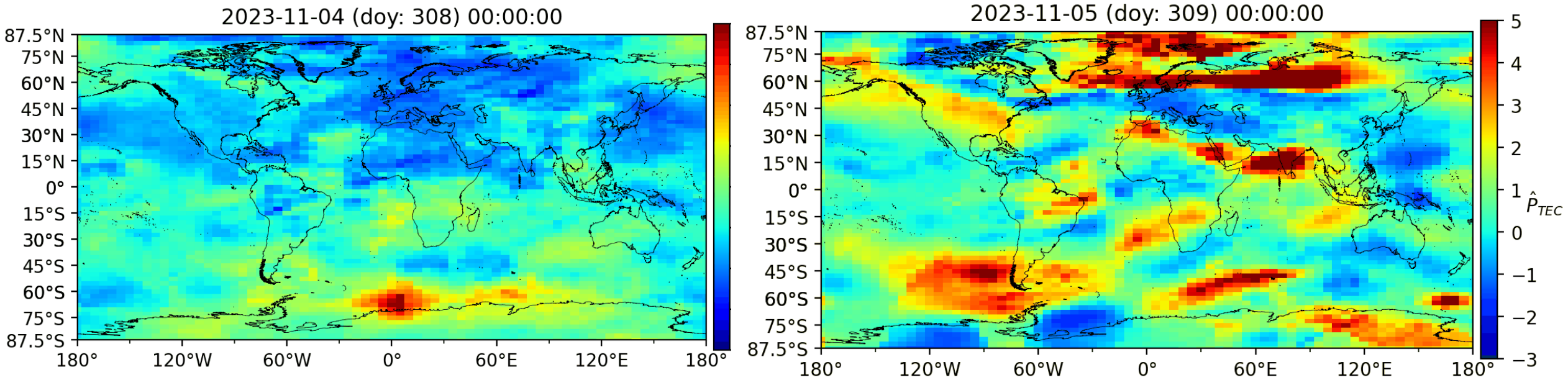




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Movies of IsUG GIMs on 04 & 05 Nov 2023



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.

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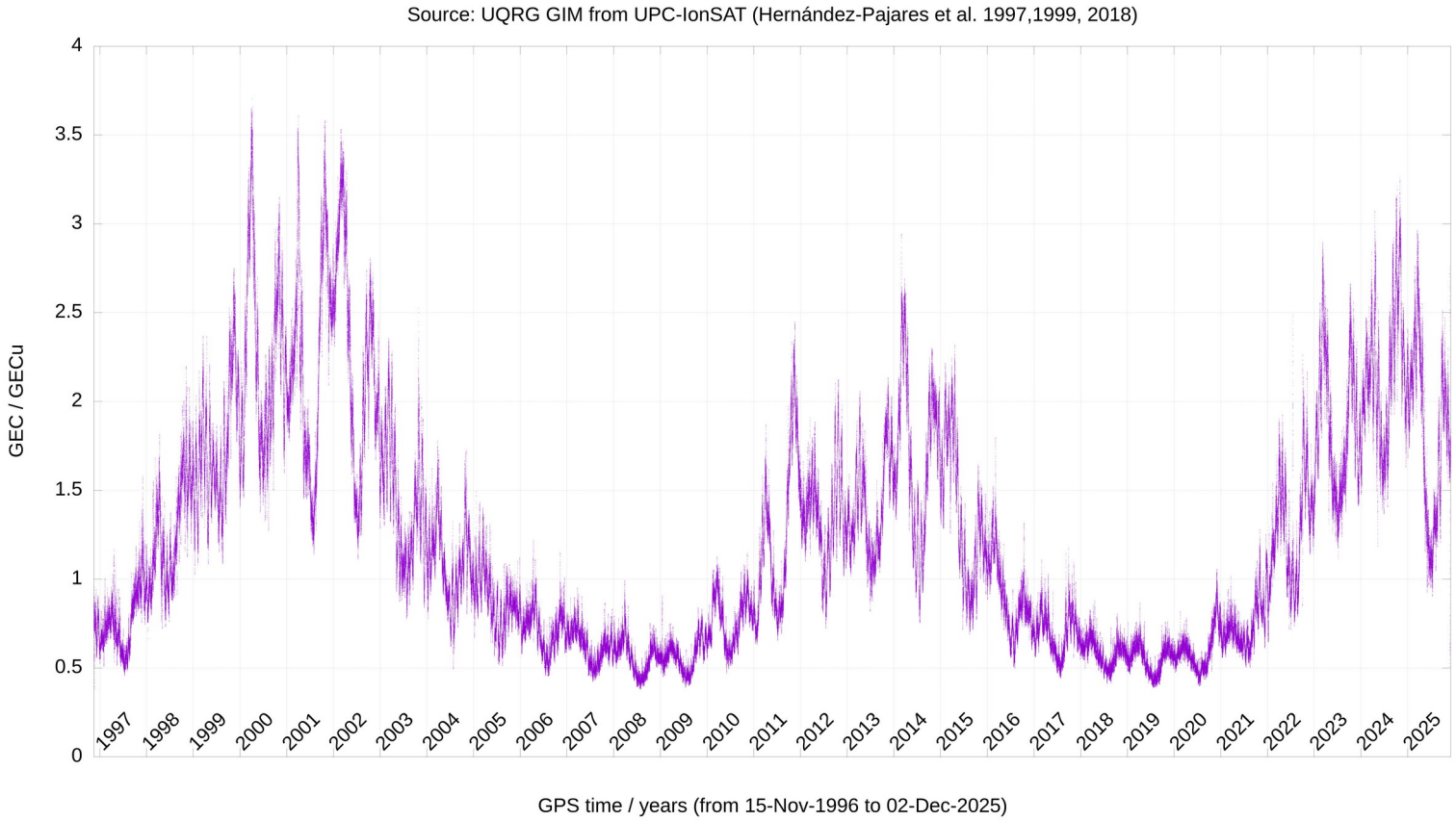
Global IsUG index maps for tracking ionospheric variability: a case study of the 4–5 November 2023 geomagnetic storm

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.

Global Electron Content (GEC) time series

We showed in Aroca-Farrerons et al. (2024) that the GEC and Kp geomagnetic index spectrograms typically present a high or extremely high similarity. We have computed the GEC times series, each 15 minutes, since end of 1996 (+1 million GEC values):



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

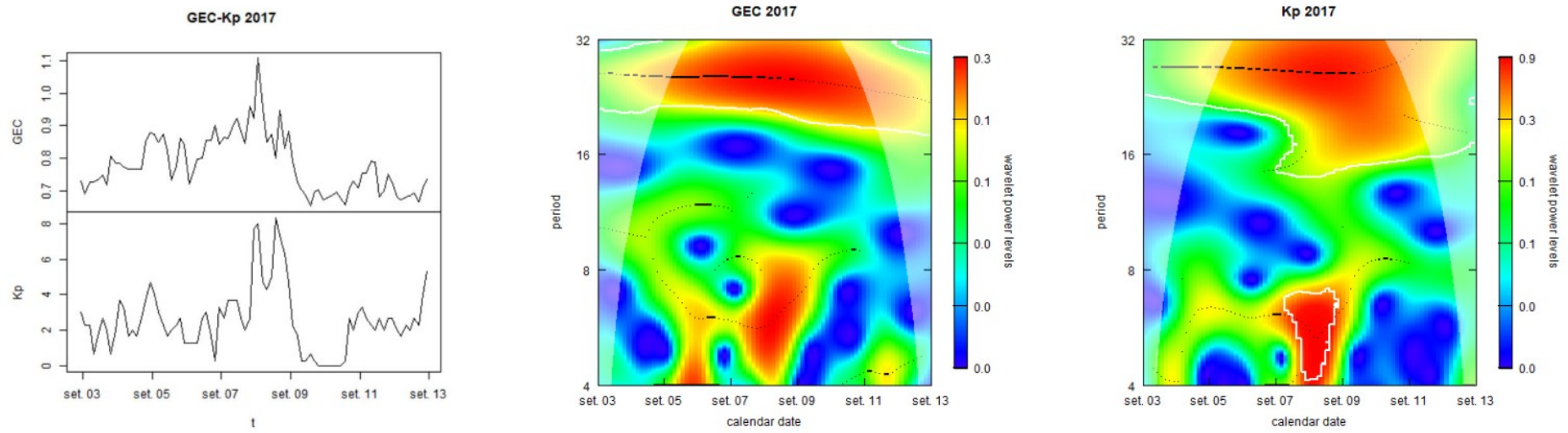
Aroca-Farrerons, J. M., Hernández-Pajares, M., Lyu, H., Roma-Dollase, D., Orus-Perez, R., García-Rigo, A., ... & Liu, Q. (2024). The Spectrum of Global Electron Content: A New Potential Indicator of Space Weather Activity. Sensors, 24(2), 393.

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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.



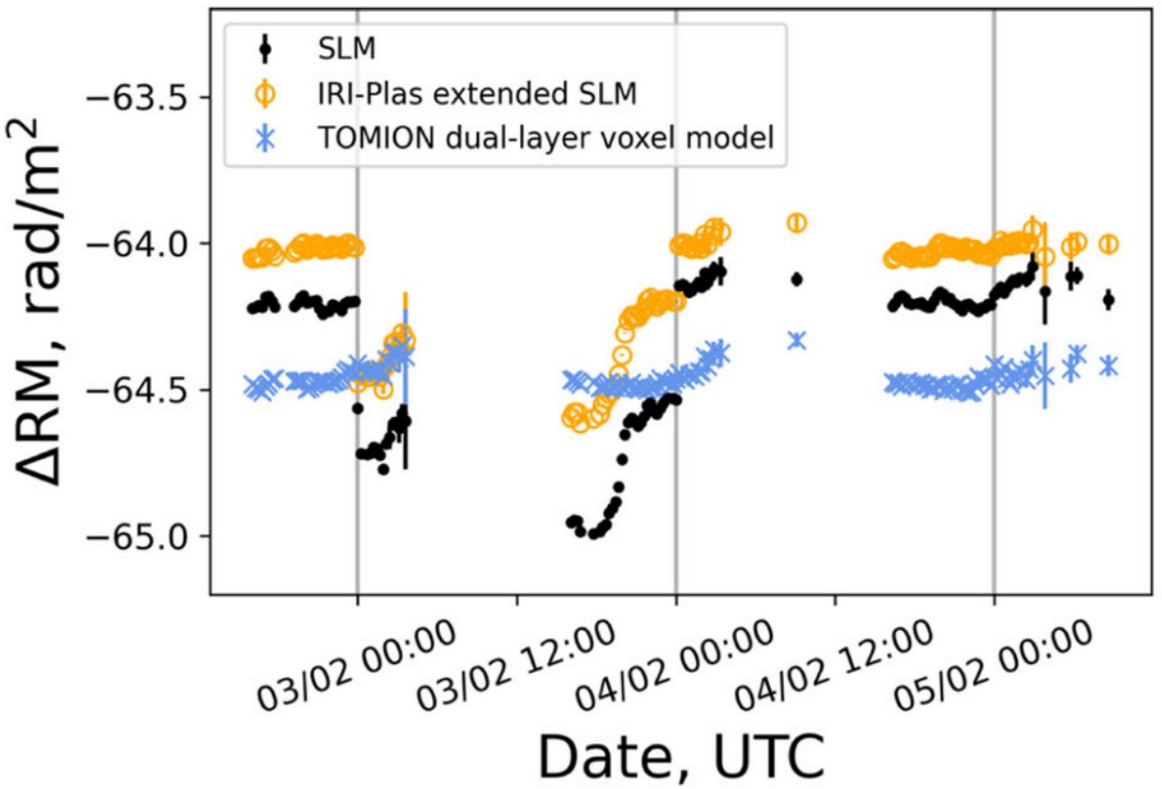
Example of **extremely high** **similarity between GEC and Kp spectrograms**, as the **29%** of geomagnetic events with $Kp \geq 7.5$ in 2000-2020 (10 of 34).

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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/

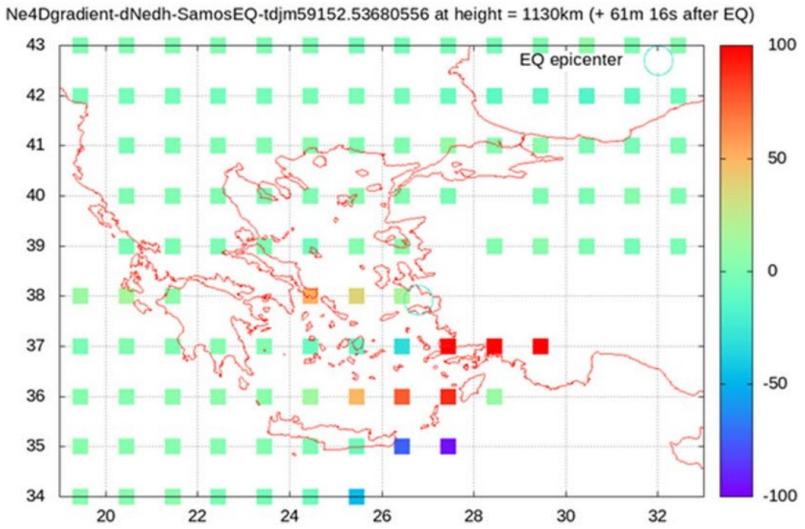
Porayko, N. K., Mevius, M., Hernández-Pajares, M., Tiburzi, C., Olivares Pulido, G., Liu, Q., ... & Wucknitz, O. (2023). Validation of global ionospheric models using long-term observations of pulsar Faraday rotation with the LOFAR radio telescope. Journal of Geodesy, 97(12), 116.

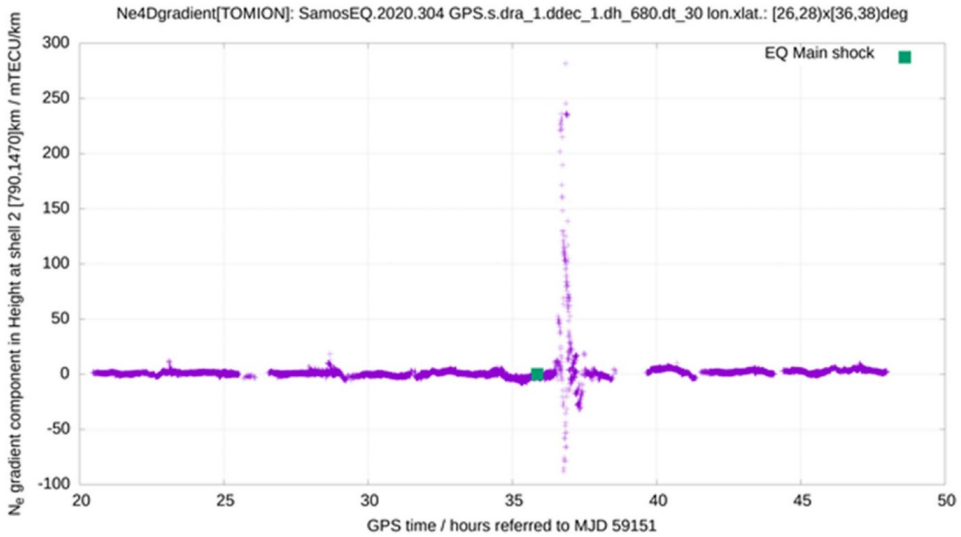
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Electron density vertical gradient (dNe/dz)

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.

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Summary and Conclusions

1) The computation of **seven historical data sets** (namely VTEC GIMs, DCBs, VTEC gradients GIMs, Iono. Storm Scale GIMs, Electron Density Ne, Vertical Ne gradient d Ne/dz and GEC), **over 2.5 solar cycles**, since end of 1996 (+10^{10} values), has been completed under the DISPEC EU Horizon project.

2) The products generated allow the **detection and characterization of Natural hazards and Space Weather** (with first results in civil aviation):

- 2a) **Ne and dNe/dz provides information about** the interaction between the top and bottom atmosphere layers, e.g. **IGW generated by tsunamis**.
- 2b) Remarkable **correlations of GEC and Kp geomagnetic activity index in spectral domain** during major geomagnetic storms.
- 2c) Remarkable **correlation of daily mean Ionospheric Storm Scale (IsUG) maps 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.

***Future improvements?**: Interest of UPC-IonSAT and maybe other **analysis centers to generate, assess and combine dual-layer Global Ionospheric Maps** for the community **(also in RT ?)**.*

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Thank you for your attention!

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