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GIM application: VTEC gradient (example)
Conclusions

Some UPC-IonSAT contributions to GNSS Space Weather monitoring

Space Weather for Spain, ESA-ESAC, Madrid, Spain, 8-9 June 2026

Manuel Hernández-Pajares(1,2,+), Germán Olivares-Pulido(1,+), Victoria Graffigna(1), David Moreno-Borràs(1), Alejandro Pérez-Conesa(1), Alberto García-Rigo(2,1), Enric Monte-Moreno(3), Qi Liu(4), Heng Yang(5), Josep Ma. Aroca-Farrerons(1), David Roma-Dollase(6) and Raul Orus-Perez(7), among many other colleagues (see cited papers)

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8 June 2026

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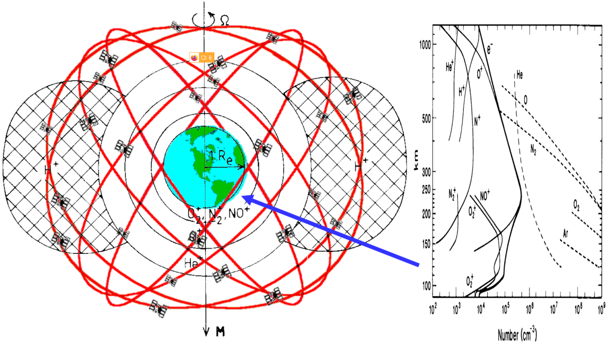
GNSS Ionosphere

GNSS Ionosphere[1]: *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, such as Space Weather monitoring, precise real-time positioning, among others.*



[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.

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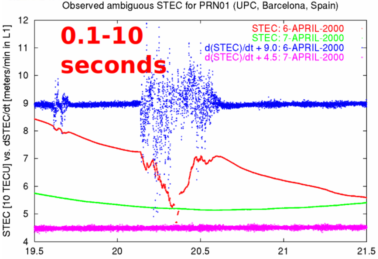
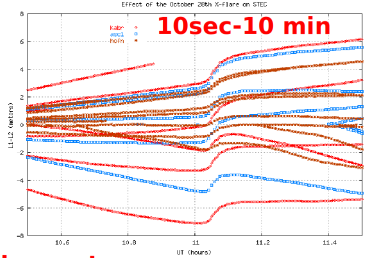
Space Weather from single GNSS receivers

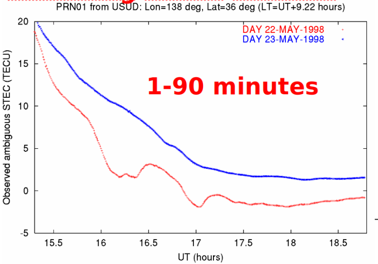
Scintillation



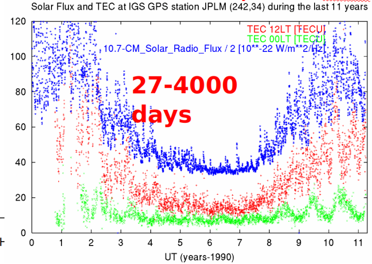
Solar Flare sudden overioniz.



Travelling Ionos. Disturb.



Solar-cycle,seasonal,solar rot.



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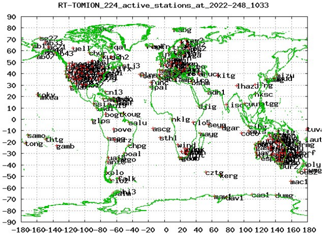
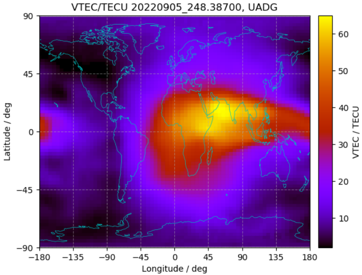
Space Weather from global GNSS networks

- Presently a high and increasing number of regional and worldwide distributed permanent Global Navigation Satellite System (GNSS) receivers is providing raw multi-frequency measurements in real-time (RT, $\lesssim$ 2 seconds) from several tens of GNSS transmitters.
- This has opened the door to an accurate real-time determination of the distribution of the ionospheric electron content, either at global scale (RT-GIMs) facilitated by the International GNSS Service (IGS) RT working group with hundreds of receivers.





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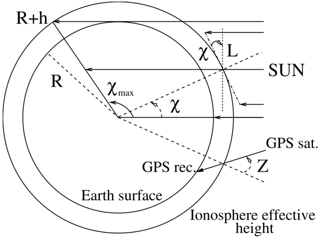
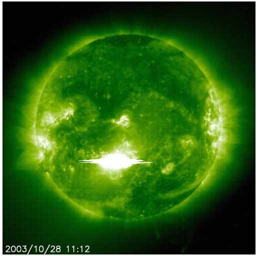
GNSS Ionosphere for Solar Astronomy

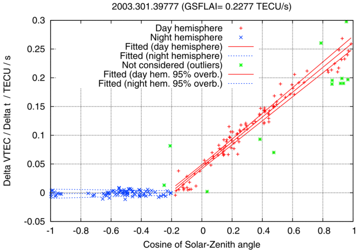
RT Solar Flares warnings and potential NRT tsunami warnings

The VTEC rate at 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 of the considered spectral range, η', following[2]:

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







[2] 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.

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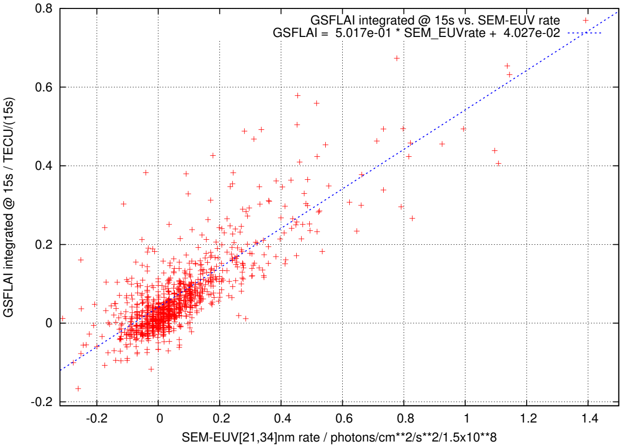
GNSS Ionosphere as a solar EUV photometer



It is working in real-time since 2011[3] at UPC-IonSAT.

[3] 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.

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Sensitivity & consistency of GNSS-based solar EUV flux rate

Table: Slope, intercept and correlation of linear fitting of GSFLAI vs SOHO/SEM Solar EUV flux rate when only GSFLAI peaks are taken, for X, M and C class flares$^{(a)}$.
GSFLAI (AKA SOLERA-drift) is being produced in RT 24/7 by UPC-IonSAT during the latest years for the European SSA follow-on projects.

Flares C.	Flares #	No. Points Peaks	Slope Peaks	Intercept Peaks	Corr. Factor Peaks	p values
X	59	53	**159** $\pm$ 06	6.2 ± 1.5	0.73	0
M	323	219	**152** $\pm$ 12	1.5 ± 0.3	0.64	0
C	390	58	**159** $\pm$ 29	0.5 ± 0.4	0.59	$1.9 * 10^{-6}$

(a) Units: $TECU/s$ for GSFLAI & $photons \cdot 10^-9/cm^2/s^2$ for EUV flux rate.

~~More details can be found in[4] and[5].~~

[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.

[5] 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.

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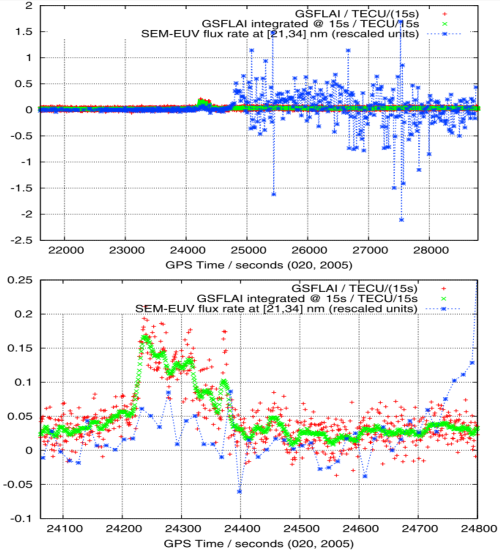
One advantage of GNSS-based EUV solar flux



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.

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GIMs with TOMION-V1

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

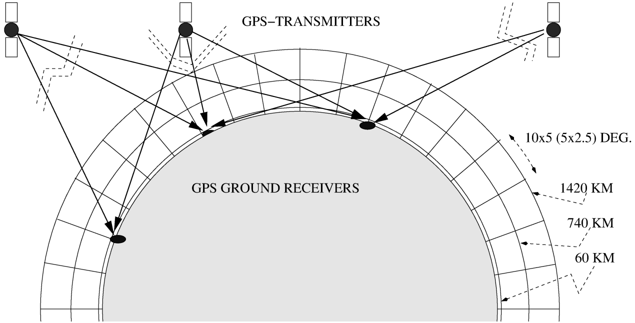
Solving $\{(\mathbf{N_e})_\mathbf{m}\}$ and $\{\mathbf{B_{j,k}}\}$ with Kalman filter in local time x latitude ref. frame

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 UPC-IonSAT soft which generates VTEC GIMs for IGS, among the best behaving rapid / real-time ones, UQRG / UADG ([6],[7],[8]),[9].
- TOMION tomography can combine different data and geometries ([10]), in agreement vs other data and models ([11], also in polar regions ([12]). It estimates precise GNSS RT positioning faster and further away ([13]).

[6] 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. DOI: 10.1007/s00190-008-0266-1. URL: https://doi.org/10.1007/s00190-008-0266-1.

[7] Heng Yang et al. "Real-time interpolation of global ionospheric maps by means of sparse representation". In: *Journal of Geodesy* 95.6 (2021), pp. 1–20.

[8] 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.

[9] Qi Liu et al. "The cooperative IGS RT-GIMs: a reliable estimation of the global ionospheric electron content distribution in real time". In: *Earth System Science Data* 13.9 (2021), pp. 4567–4582. DOI: 10.5194/essd-13-4567-2021. URL: https://doi.org/10.5194/essd-13-4567-2021.

[10] 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.

[11] 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.

[12] 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.

[13] Germán Olivares-Pulido et al. "Ionospheric tomographic common clock model of undifferenced uncombined GNSS measurements". In: *Journal of Geodesy* 95.11 (2021), pp. 1–13.

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GIM application: Maps of Iono. storm scale

In[14] the Ionospheric Storm Scale Index Based on UQRG (IsUG) was proposed as a direct extension of the I-scale index proposed at regional level (Japan) and from raw GNSS data by[15]:

$$P_{TEC} = \frac{100 \times (O_{TEC} - R_{TEC})}{R_{TEC}} \Longrightarrow \hat{P}_{TEC} = \frac{P_{TEC} - \mu}{\sigma} \qquad (2)$$

Where P_{TEC} is the percentage deviation of VTEC: O_{TEC} is the hourly median VTEC derived at grid points of GIM (five VTEC values during 1-hour interval), under the UQRG GIM time resolution of 15 minutes. And R_{TEC} is the reference median value of O_{TEC} at the same local time and geographic location in the past 27 days.

The normalized P_{TEC} removes, at each grid point and with mean value μ and standard deviation σ from 1997 to 2014 at the given season, the dependence of P_{TEC} on season, local time and geographical location.

[14] Qi Liu et al. "Ionospheric Storm Scale Index Based on High Time Resolution UPC-IonSAT Global Ionospheric Maps (IsUG)". In: *Space Weather* 19.11 (2021), e2021SW002853.

[15] Michi Nishioka et al. "A new ionospheric storm scale based on TEC and foF2 statistics". In: *Space Weather* 15.1 (2017), pp. 228–239.

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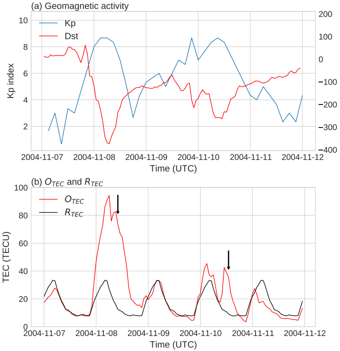
Ionospheric storm scale: *semaphor* values



The evolution of O_{TEC}, R_{TEC}, Kp and Dst at [130°E, 30°N] from 7 to 10 November in 2004.

IsUG definition & occurrence (1997-2014).

IsUG	Storm state	Definition	Global scale probability (%)
IP3	Severe positive	$5 < \hat{P}$	0.17
IP2	Strong positive	$3 < \hat{P} \leq 5$	0.72
IP1	Moderate positive	$1 < \hat{P} \leq 3$	12.43
I0	Quiet	$-1 < \hat{P} \leq 1$	73.96
IN1	Moderate negative	$-2 < \hat{P} \leq -1$	11.72
IN2	Strong negative	$-3 < \hat{P} \leq -2$	0.95
IN3	Severe negative	$\hat{P} < -3$	0.06

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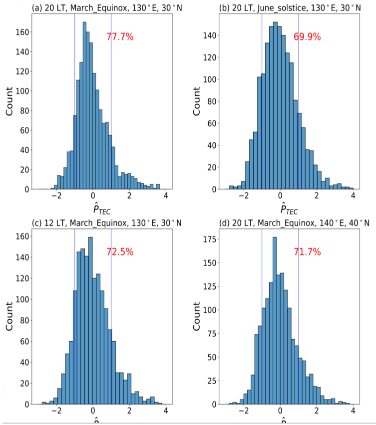
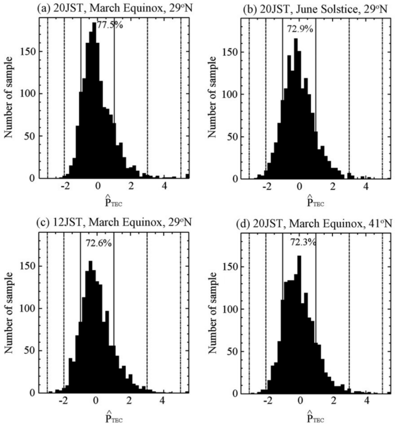
Comparison over Japan (1997-2014;each season: 3 months per year):

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



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



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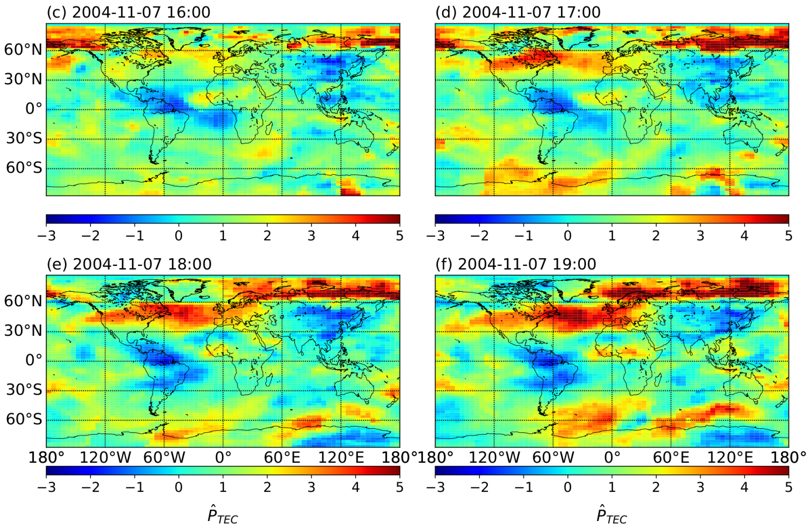
IsUG global map example (7-Nov-2004)



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IsUG SW monitoring capabilities: New results[16]

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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]

"(...) 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. (...) 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."

[16] Artem Smirnov et al. "Global IsUG index maps for tracking ionospheric variability: a case study of the 4–5 November 2023 geomagnetic storm". In: *Journal of Space Weather and Space Climate* 16 (2026), p. 17.

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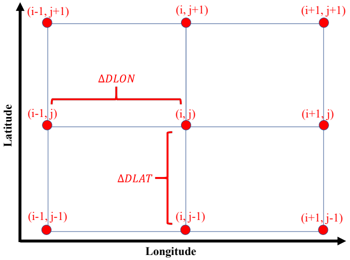
GIM application: VTEC gradient



$$\begin{cases} \nabla V_{x,i,j} = (V_{i,j} - V_{i-1,j})/\Delta d_\lambda \\ \nabla V_{y,i,j} = (V_{i,j} - V_{i,j-1})/\Delta d_\phi \\ \dot{V}_{i,j}(t) = \Delta V i,j(t)/\Delta t = \\ = (V_{i,j}(t-\Delta t) - V_{i,j}(t+\Delta t))/\Delta t \end{cases}$$

$$\vec{\nabla} V_{i,j} = (\nabla V_{x,i,j}, \nabla V_{y,i,j}) \Longrightarrow$$

$$\Longrightarrow \nabla V_{i,j} \equiv \|\nabla V_{i,j}\| = \sqrt{\nabla V_{x,i,j}^2 + \nabla V_{y,i,j}^2}$$

The VTEC gradient derived from UQRG GIMs (VgUG)[17] is a full (non-relative) and direct estimation of the VTEC partial derivatives (spatial and temporal separately) at any worldwide grid point, considering the distances on the corresponding parallels and meridians at the ionospheric efective height, $\Delta\lambda$ & $\Delta\phi$, separated 5° & 2.5° respectively, and the time difference between GIMs Δt (30 minutes, centered, 15 minutes, uncentered).

[17] Qi Liu et al. “A new way of estimating the spatial and temporal components of the Vertical Total Electron Content gradient based on UPC-IonSAT Global Ionosphere Maps”. In: *Space Weather* (2022), e2021SW002926.

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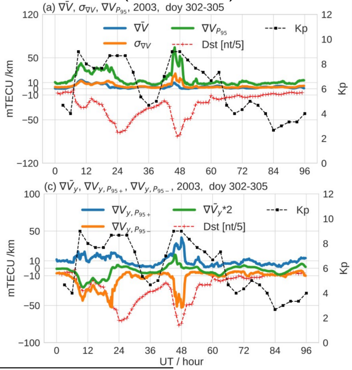
The UPC-IonSAT results from UQRG GIMs (Liu et al. 2022) are very similar to the DLR results from raw GNSS measurements ([18]), as it can be seen during the Halloween Storm on Europe.

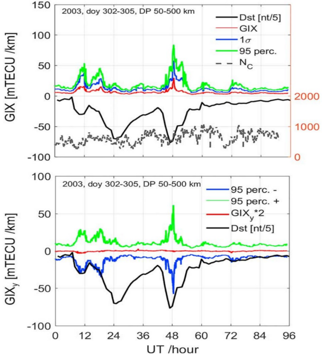
From **UQRG GIM (VgUG)** (Liu et al. 2022)

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

Spatial gradient norm

Latitudinal gradient component





[18] Norbert Jakowski and Mohammed Mainul Hoque. “Estimation of spatial gradients and temporal variations of the total electron content using ground-based GNSS measurements”. In: *Space Weather* 17.2 (2019), pp. 339–356.

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GIM application: VTEC gradient (example)
Conclusions

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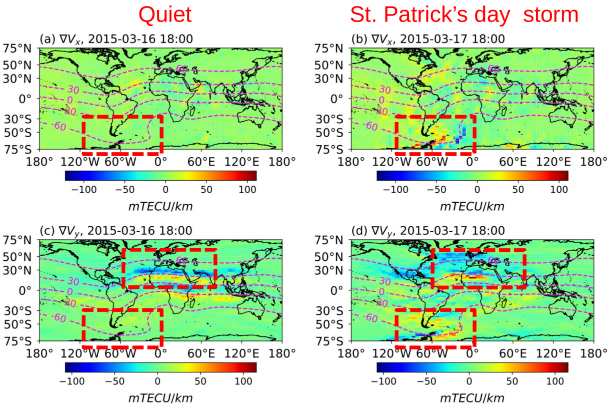
([19],[20])



[19] Qi Liu et al. "A new way of estimating the spatial and temporal components of the Vertical Total Electron Content gradient based on UPC-IonSAT Global Ionosphere Maps". In: *Space Weather* (2022), e2021SW002926.

[20] Norbert Jakowski and Mohammed Mainul Hoque. "Estimation of spatial gradients and temporal variations of the total electron content using ground-based GNSS measurements". In: *Space Weather* 17.2 (2019), pp. 339–356.

GNSS Ionosphere
Space Weather from single GNSS receivers
Space Weather from global GNSS networks
GNSS Ionosphere for Solar Astronomy
GIMs with TOMION-V1
GIM application: Maps of Iono. storm scale
Validation: IsUG vs original I-scale
Validation: GIM-based vs DLR obs-based $\nabla\vec{V}$
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Conclusions

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The accurate 24/7 real-time (RT) determination of the free electrons distribution in the ionosphere based on global GNSS networks, add new potential global Space Weather (SW) products for different users to the existing ones:

- EUV solar flux rate RT estimation and **solar flares warnings** since 2011.
- Global maps on Vertical Total Electron Content (VTEC) in RT since 2011, opening the RT door to:
  - **Global maps of SW semaphor**: ionospheric storm scales (IsUG), one per 5ºx2.5º pixel in lon. x lat.
  - **Global maps of SW impact quantification**: electron content gradient (VgUG).

More details at:


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GNSS Solar Astronomy in real-time during more than one solar cycle

Manuel Hernández-Pajares[a,b,*], Alberto García-Rigo[b,a], Enric Monte-Moreno[c], Qi Liu[d,a], David Roma-Dollase[b,a], Heng Yang[e,a], Yannick Béniguel[f], David Moreno-Borràs[a], Octavi Fors[g], Haixia Lyu[h,a], Raul Orus-Perez[i], Javier Ventura-Traveset[j]

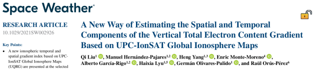

Space Weather

RESEARCH ARTICLE
10.1029/2021SW002853

Ionospheric Storm Scale Index Based on High Time Resolution UPC-IonSAT Global Ionospheric Maps (IsUG)

Qi Liu[1], Manuel Hernández-Pajares[1,2], Haixia Lyu[3,1], Michi Nishioka[4], Heng Yang[5,1], Enric Monte-Moreno[6], Tamara Gulyaeva[7], Yannick Béniguel[8], Volker Wilken[9], Germán Olivares-Pulido[1], and Raül Orús-Pérez[10]

Key Points:
- The new ionospheric storm scale, IsUG, is presented
- The IsUG is based on the high


Space Weather

RESEARCH ARTICLE
10.1029/2021SW002926

A New Way of Estimating the Spatial and Temporal Components of the Vertical Total Electron Content Gradient Based on UPC-IonSAT Global Ionosphere Maps

Qi Liu[1], Manuel Hernández-Pajares[1,2], Heng Yang[1,3], Enric Monte-Moreno[4], Alberto García-Rigo[1,2], Haixia Lyu[1,5], Germán Olivares-Pulido[1], and Raül Orús-Pérez[6]

Key Points:
- A new ionospheric temporal and spatial gradient index based on UPC-IonSAT Global Ionosphere Maps (UQRG) are presented at the selected

THANK YOU!