

GNSS Ionosphere and Space Weather Fundamentals: Monitoring and new applications

*GNSS contributions to Space monitoring, EUREF2024, ICGC, June 4, 2024,
12h30-14h30m CET*

Manuel Hernández-Pajares (1,2), Germán Olivares-Pulido(1)
on behalf as well of many UPC-IonSAT colleagues & collaborators (see ref.)

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<http://scholar.google.es/citations?user=Tm-DcsMAAAAJ&hl=en&oi=ao>

4 June 2024



GNSS

Ionosphere
and Space

Weather Fundamentals:
Monitoring
and new
applications

Hernández-
Pajares et
al.

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RT ROTI global
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Other applications:
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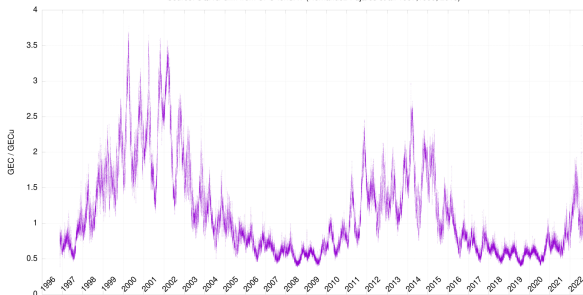
Fast and far-away
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GNSS ionosphere: *Effects and computation of the distribution of free electrons, located at the partially ionized part of the atmosphere above 50 km height, from the Global Navigation Satellite Systems (GNSS) multi-frequency measurements crossing it; and its applications, such as Space Weather monitoring, precise real-time positioning and, in general, precise geodetic modelling among others.*

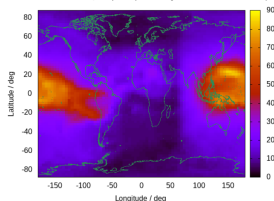
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Source: UQRG GIM from UPC-IonSAT (Hernández-Pajares et al. 1997,1999, 2018)

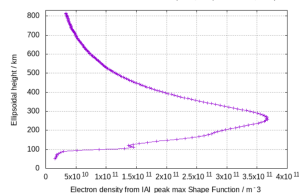


GPS time / years (from 15-Nov-1996 to 28-Sep-2022)

VTEC / TECUs 01h30m,18Sep2011 (source: UQRG GIMs from UPC-IonSAT)



RO GPS PRN17 from COSMIC-1 LEO (150E, 50°S) on 01h30m, 18Sep2011



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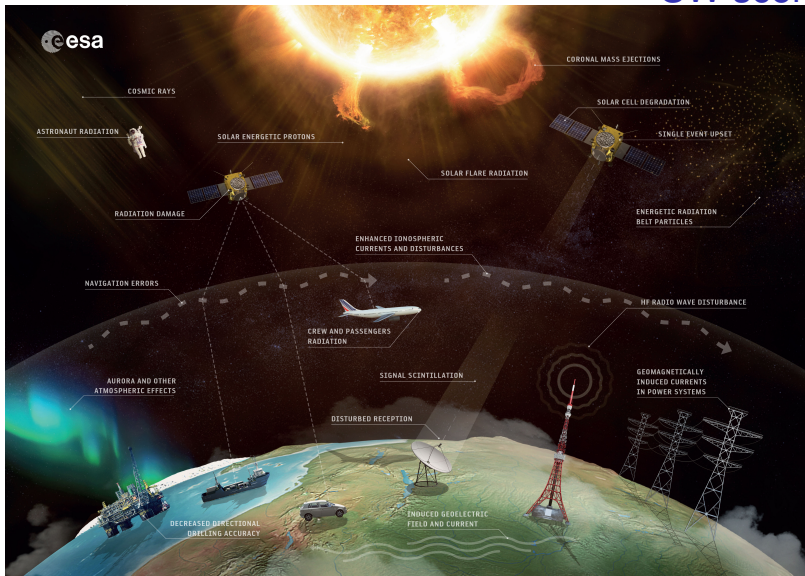
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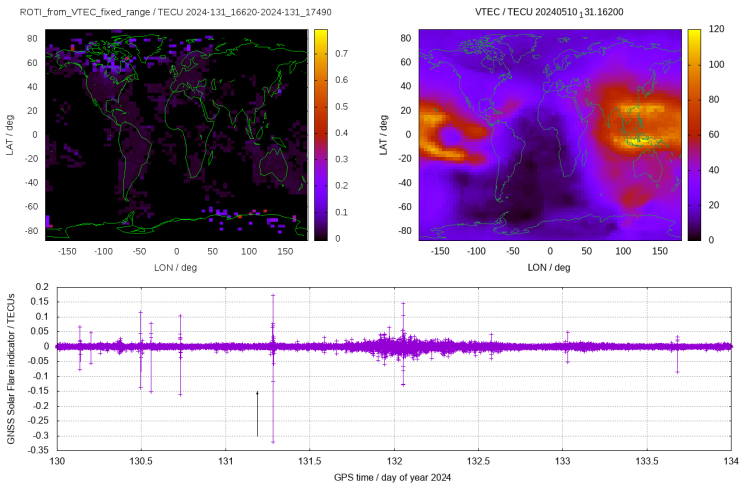
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SW scenario



(Reproduced from ESA Science Office, 2018)

Some RT-TOMION 10-11May24 outputs



Navigation controls:

"Whoever studies it learns it, whoever teaches it knows it, and whoever does it understands it"

Some contributions to such GNSS ionosphere applications to Space Weather monitoring:

- **Global Ionospheric Maps of Vertical Total Electron Content (GIMs):**¹, assessment, also in RT², Ionospheric Storm Scale GIM³ and VTEC gradient GIM⁴.
- **GNSS Solar EUV rate (SOLERA) proxy:**⁵, also in RT⁶.
- **Rate of Total Electron Content Index (ROTI):**⁷.

¹M 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](https://doi.org/10.1007/s00190-008-0266-1). URL: <https://doi.org/10.1007/s00190-008-0266-1>.

²Qi 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](https://doi.org/10.5194/essd-13-4567-2021). URL: <https://doi.org/10.5194/essd-13-4567-2021>.

³Qi 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.

⁴Qi 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.

⁵Talwinder 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](https://doi.org/10.1002/2015JA021824). URL: <https://doi.org/10.1002/2015JA021824>.

⁶Manuel Hernández-Pajares et al. "GNSS Solar Astronomy in real-time during more than one solar cycle". In: *Advances in Space Research* (2023).

⁷Enric Monte-Moreno et al. "Method for Forecasting Ionospheric Electron Content Fluctuations Based on the Optical Flow Algorithm.". In: *IEEE Transactions on Geoscience and Remote Sensing* (2021).

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Other applications of GNSS ionosphere that we have understood recently better:

- **GNSS Astronomy:** Hernández-Pajares & Moreno-Borràs (2020)⁸
- **Tsunami ionospheric signatures:** From the ground Alfonsi et al. 2024⁹, above LEOs Yang et al. (2022)¹⁰, Medium Scale Travelling Ionospheric Disturbances (MSTIDs) in gral.¹¹
- **Precise Positioning supported by Ionospheric Tomography and MSTIDs:** for low cost precise agriculture, Hernández-Pajares et al. (2022)¹², in an undifferenced uncombined common clock approach¹³, and mitigating the MSTID error¹⁴.

⁸Manuel Hernández-Pajares and David Moreno-Borràs. "Real-Time Detection, Location, and Measurement of Geoeffective Stellar Flares From Global Navigation Satellite System Data: New Technique and Case Studies". In: *Space Weather* 18.3 (2020), e2020SW002441. DOI: [10.1029/2020SW002441](https://doi.org/10.1029/2020SW002441). URL: <https://doi.org/10.1029/2020SW002441>.

⁹Lucilla Alfonsi et al. "Ionospheric response to the 2020 Samos earthquake and tsunami". In: *Earth, Planets and Space* 76.1 (2024), p. 13.

¹⁰Heng Yang et al. "Systematic detection of anomalous ionospheric perturbations above LEOs from GNSS POD data including possible tsunami signatures". In: *IEEE Transactions on Geoscience and Remote Sensing* 60 (2022), pp. 1–23.

¹¹Heng Yang, Enrique Monte-Moreno, and Manuel Hernández-Pajares. "Multi-TID detection and characterization in a dense GNSS receiver network". In: *Journal of Geophysical Research: Space Physics* (2017).

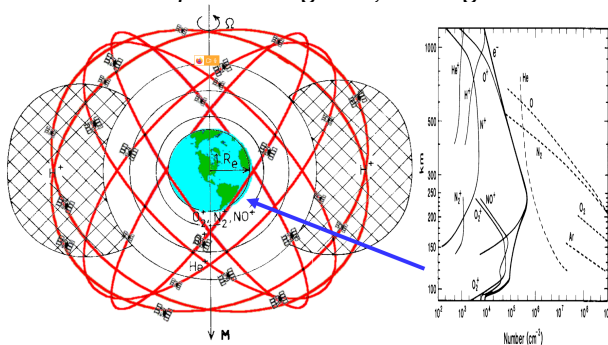
¹²Manuel Hernández-Pajares et al. "Wide-Area GNSS Corrections for Precise Positioning and Navigation in Agriculture". In: *Remote Sensing* 14.16 (2022), p. 3845.

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

¹⁴Manuel Hernández-Pajares et al. "Direct MSTID mitigation in precise GPS processing". In: *Radio Science* 52.3 (2017), pp. 321–337.

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¹⁵Manuel Hernández-Pajares. "GNSS Ionosphere". In: *Encyclopedia of Geodesy, Sideris, Michael G. (ed)., 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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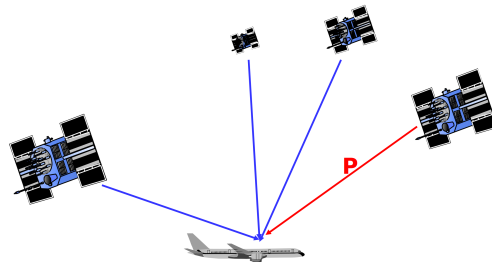
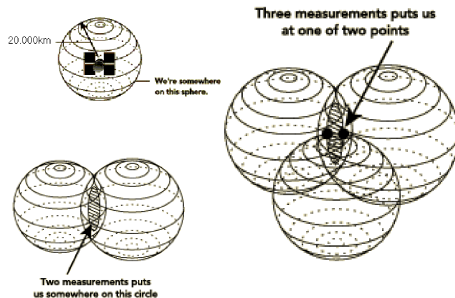
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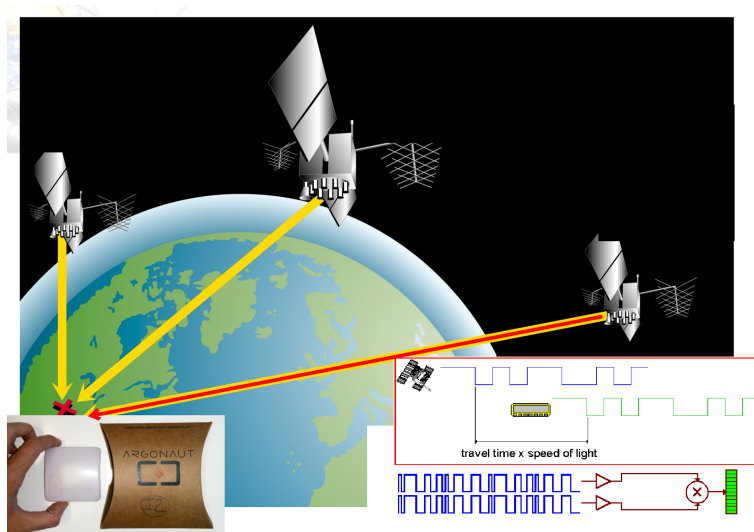
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Measuring the code



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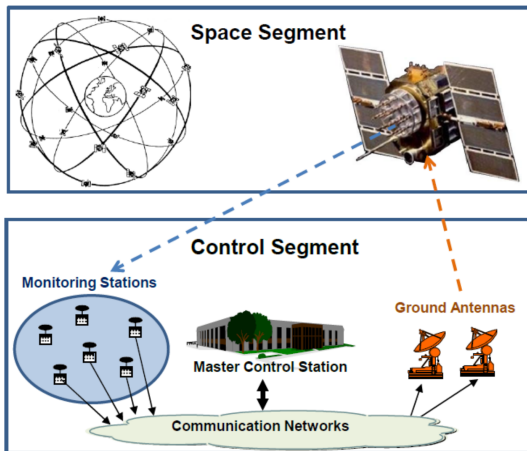
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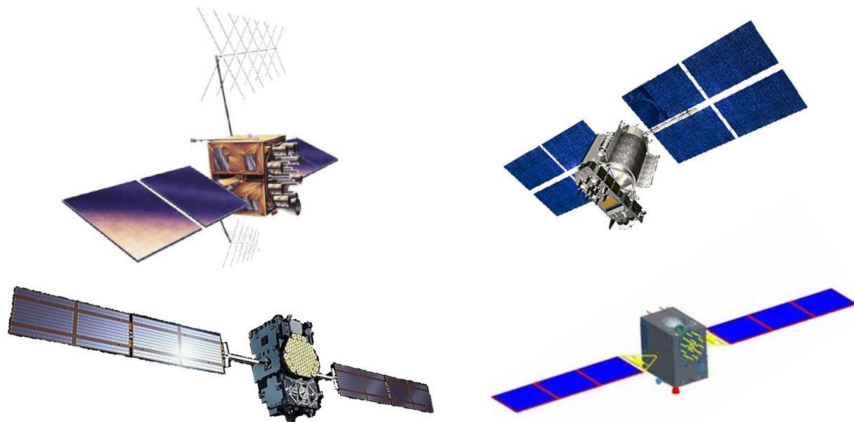
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GNSS segments



Satellites of GNSS constellations



GNSS satellites: GPS IIR-M (top left), Glonass-M (top right), Galileo IOV (bottom left) and Beidou-M (bottom right).

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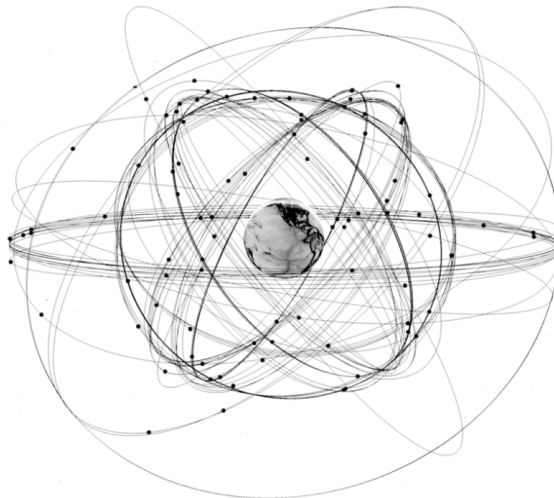
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Distribution of GNSS transmitters ($h > 19000$ km)



GNSS measurements: Code

The **basic GNSS measurements**, code and carrier phase, are defined as:

- **Code** (or pseudorange): from the apparent travel time τ of the EM signal propagated from GPS transmitter to receiver, scaled by the speed of light in the vacuum, c . Then this is a range proxy, i.e., a pseudorange:

$$P_j \equiv c\tau = \tilde{\rho} + \frac{40.309}{f_j^2} S + D_j + D'_j \quad (1)$$

where $\tilde{\rho} = \rho + c(dt - dt') + T$ is the non-frequency dependent term, with the distance between receiver and transmitter antenna, both receiver and transmitter clock errors, and slant tropospheric delay respectively; f_j , S , D_j , D'_j are the frequency of the carrier “j”, the Slant Total Electron Content and the receiver and transmitter delay code biases (DCBs).

P_j is obtained by correlating the received pseudorandom noise code (PRN; a binary function similar to random noise and with very good correlation properties) with a replica implemented in the receiver. In GPS, the “chip” length is $\simeq 300$ m for the Coarse Acquisition Code (C $\equiv$ C/A) and 30 m for the Precise Code (P), with associated measurement errors of $\simeq 1\%$ (i.e., at meter and decimeter levels for the C and P codes, respectively). This error can be significantly increased (up to several meters or more) due to the multipath.

GNSS measurements: Carrier phase

- **Carrier phase**, measured in the receiver by continuously integrating the frequency Doppler shift, mainly due to the relative velocity, but also to clocks, tropospheric and ionospheric drifts. This value is scaled in unit lengths to represent the pseudorange $\tilde{\rho}$ referring to the last time the carrier phase was locked by the receiver t_L :

$$L_j \equiv -\lambda_j \int_{t_L}^t \delta f_j \cdot dt = \tilde{\rho}(t) - \tilde{\rho}(t_L) = \tilde{\rho} - \frac{40.309}{f_j^2} S + \lambda_j \Phi + B_j, \quad (2)$$

where $\tilde{\rho}$ corresponds again to the non-frequency dependent pseudorange ($\tilde{\rho} = \rho + c(dt - dt') + T$), B_j is the carrier phase ambiguity for frequency f_j , $\lambda_j = c/f_j$ is its wavelength and Φ is the wind-up angle (in GPS $f_1 = 154f_0$ for L_1 and $f_2 = 120f_0$ for L_2 , with $f_0 = 10.23\text{MHz}$, i.e., $\lambda_1 \simeq 0.19\text{ m}$ and $\lambda_2 \simeq 0.24\text{ m}$). And their **ionospheric-free, geometry-free** (ionospheric, $P_1 = P_2 - P_1$, $L_1 = L_2 - L_1$) and widelane combinations.

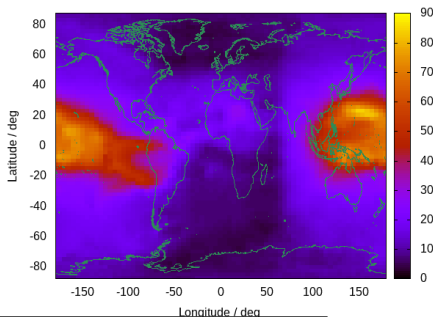
The measurement error is at millimeter level ($\simeq 0.01\lambda$), $10^2 - 10^3$ times smaller than the code measurement error. This fact, along

with a much smaller multipath (less than $\frac{\lambda}{4} \simeq 0.05\text{ m}$), makes this observable the most suitable for high-accuracy applications.

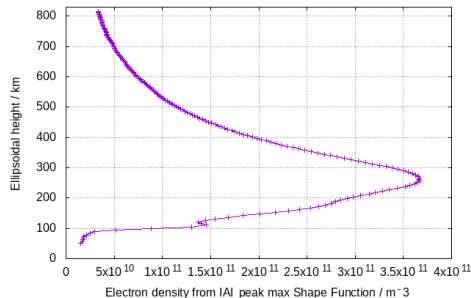
The ionosphere in brief seen by GNSS

- The **ionosphere** is typically distributed from around 50 km to 1000 km height, where some predominant air molecules, such as O_2 and NO at the very bottom and mostly O above, are partially ionized respectively by the x-ray and specially Extreme Ultraviolet (EUV) solar flux (see for instance¹⁶).

VTEC / TECUs 01h30m,18Sep2011 (source: UQRG GIMs from UPC-IonSAT)



RO GPS PRN17 from COSMIC-06 LEO (150E,50°S) on 01h30m,18Sep2011

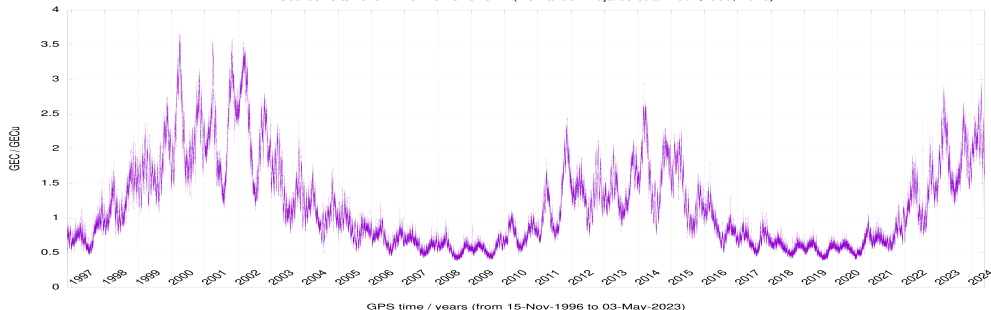


¹⁶Peter Teunissen and Oliver Montenbruck. *Springer handbook of global navigation satellite systems*. Springer, 2017, 1327. DOI: 10.1007/978-3-319-42928-1.

Global Electron Content (GEC)

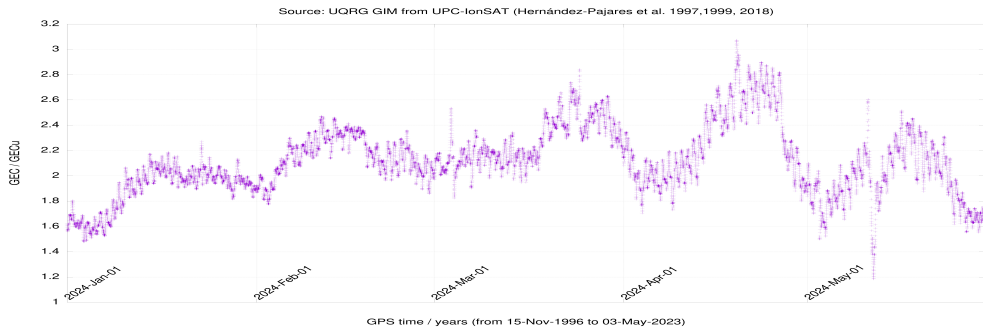
As consequence of its main origin, the total number of ionosphere free electrons (GEC) follows closely the solar activity, specially in normal (undisturbed) conditions: see the GEC time series obtained from the UQRG GIMs, computed every 15 minutes since end of 1996. The origin of features, like the semiannual and annual anomalies, are still under discussion (¹⁷).

Source: UQRG GIM from UPC-IonSAT (Hernández-Pajares et al. 1997, 1999, 2018)



¹⁷Francisco Azpilicueta and Claudio Brunini. "A new concept regarding the cause of ionosphere semiannual and annual anomalies". In: *Journal of Geophysical Research: Space Physics* 116.A1 (2011).

Ionospheric storms

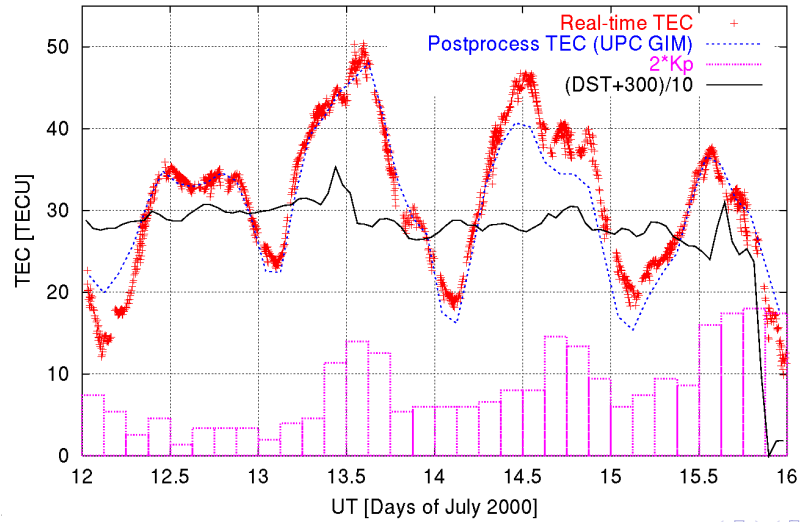


- In less frequent ionospheric disturbance conditions, such as **ionospheric storms**, the distribution of ionospheric **electron content** can significantly differ in space and time, at scales up to few thousands of km and hours, respectively (¹⁸).

¹⁸Claudia Borries et al. "Multiple ionospheric perturbations during the Saint Patrick's Day storm 2015 in the European-African sector". In: *Journal of Geophysical Research: Space Physics* 121.11 (2016), pp. 11–333.

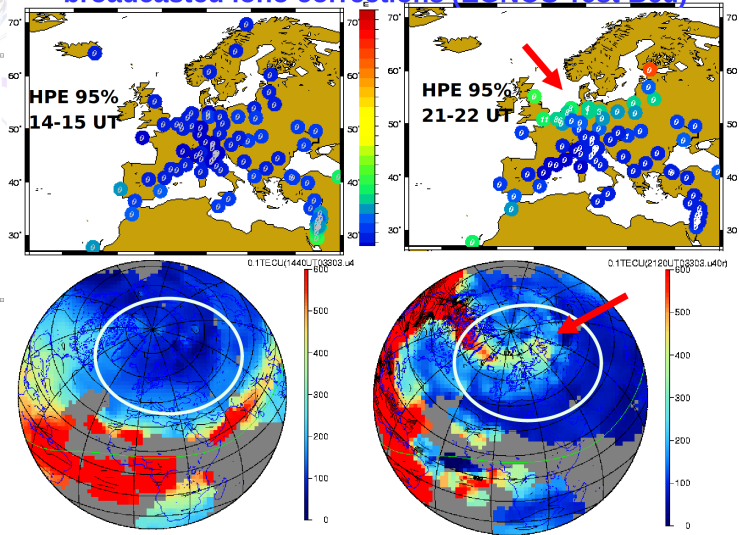
Example of VTEC under ionospheric storm

Real-time Total Electron Content: Brussels (Lon=4, Lat=51 deg.)



Ionospheric Storm during October 30th, 2003

Effects on single-frequency navigation based on broadcasted iono corrections (EGNOS Test Bed)



Ionospheric scintillation

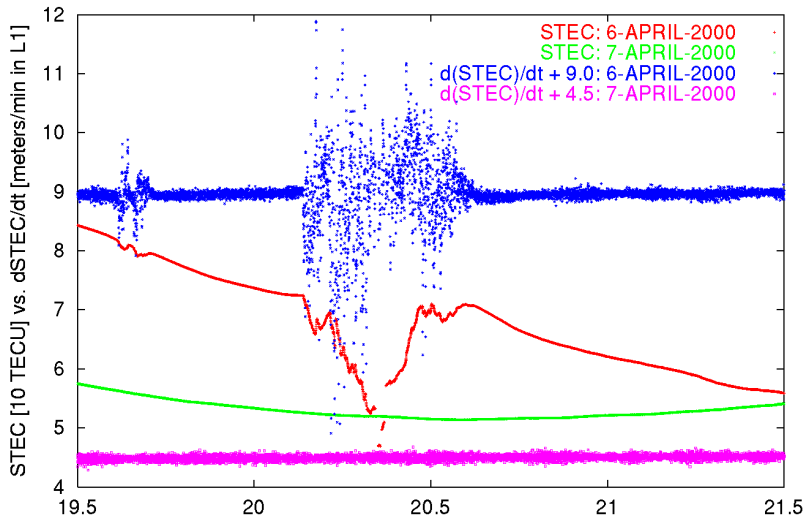
- The ionospheric storms can present associated enhanced or anomalous ionospheric scintillation, the rapid variation of the amplitude and phase of the GNSS received signal, with variability scales much smaller in space and time than the ones for ionospheric storms: up to hundreds of meters and below one second, respectively.
- In general the ionospheric scintillation is associated typically by high gradients or by patches of electron content, at low latitudes or close to the poles, respectively (e.g.¹⁹), but also at mid latitude in extreme geomagnetic storm events (e.g.²⁰ and associated plasma bubbles at mid-latitudes, see next viewgraph).

¹⁹Yannick Béniguel et al. "MONITOR Ionospheric Network: two case studies on scintillation and electron content variability". In: *Annales Geophysicae*. Vol. 35. 3. Copernicus GmbH. 2017, p. 377. DOI: [10.5194/angeo-35-377-2017](https://doi.org/10.5194/angeo-35-377-2017). URL: <https://doi.org/10.5194/angeo-35-377-2017>.

²⁰Zama Thobeka Katamzi-Joseph, John Bosco Habarulema, and Manuel Hernández-Pajares. "Midlatitude post sunset plasma bubbles observed over Europe during intense storms in April 2000 and 2001". In: *Space Weather* (2017).

Atypical mid. lat. plasma bubble & scintillation

Observed ambiguous STEC for PRN01 (UPC, Barcelona, Spain)



Medium Scale TIDs

- In between such variability scales of ionospheric storms and scintillation: the frequent **Medium Scale Travelling Ionospheric Disturbances** (MSTID), and the sudden overionization generated by solar flares.
- The **MSTIDs are ionospheric signatures of waves**, up to few TECUs of amplitude in solar cycle maximum conditions ($1 \text{ TECU} = 10^{16} \text{m}^{-3}$), which propagate with typical periods ranging from several minutes to less than one hour, velocities from 50 to 300 m/s, and associated wavelengths of 100 km. The **most prominent MSTIDs happen systematically during local fall and winter daytime, moving equatorward**²¹.
- The typical MSTID amplitudes in STEC are small ($< 1 \text{ TECU}$) BUT the **non-linear effect vs baseline can degrade applications** (e.g. precise GNSS positioning at $d \gtrsim \lambda/2 \simeq 10 \text{ km}$ far from the reference GNSS receivers,²²).

²¹ M Hernández-Pajares et al. "Propagation of medium scale traveling ionospheric disturbances at different latitudes and solar cycle conditions". In: *Radio Science* 47.6 (2012).

²² Manuel Hernández-Pajares et al. "Direct MSTID mitigation in precise GPS processing". In: *Radio Science* 52.3 (2017), pp. 321–337.

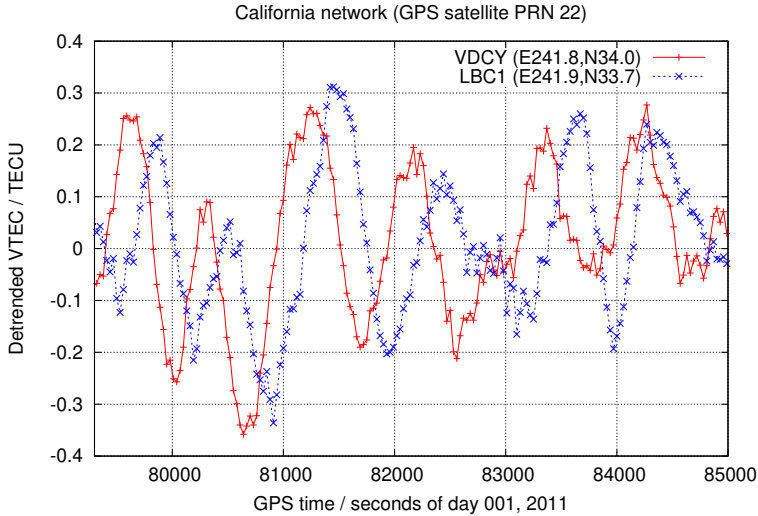
Potential origins of Travelling Ionospheric Disturbances

The origin of TIDs is not well established yet, but several potential sources have been pointed out (see²³ and mentioned references):

- The auroral zone, with the Lorentz force and Joule dissipation associated to particle precipitation, seems to be associated to Large Scale TIDs (LSTIDs), $\lambda \simeq 1000$ km and $v \simeq 400 - 1000$ m/s.
- The neutral atmosphere turbulence associated to meteorological activity and atmospheric winds. However, this is not a clear candidate to account for the repeatability of MSTIDs.
- The vertical irradiance gradient associated to the Solar Terminator at the given ionospheric region and its magnetic conjugate region, which seems to be a solid candidate to explain most part of the MSTID climatology.
- The Perkins instability, explaining the preferred westward propagation of local winter MSTIDs at night as the weakest damping direction.

²³M Hernández-Pajares et al. "Propagation of medium scale traveling ionospheric disturbances at different latitudes and solar cycle conditions". In: *Radio Science* 47.6 (2012).

Example of MSTID propagation over California



Solar flares

- Finally, the major **solar flares**, intense localized eruption of electromagnetic radiation in the Sun's atmosphere, can generate a direct ionospheric overionization during several minutes (with VTEC rates up to few TECUs in few minutes for those close to the apparent solar disk center).
- They affect to the sun illuminated Earth hemisphere, depending very well on the cosine of the solar-zenith angle and on the solar EUV flux rate, as it is predicted by a simple first principle based model ⁽²⁴⁾. But all of categories of solar flares, major, mid and minor, can be detected with GNSS ⁽²⁵⁾.
- Now the search of potential ionospheric signatures continues for super flares of close stars thanks to new very sensitive GNSS techniques²⁶.

²⁴Manuel 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](https://doi.org/10.1029/2012SW000826). URL: <https://doi.org/10.1029/2012SW000826>.

²⁵Talwinder 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](https://doi.org/10.1002/2015JA021824). URL: <https://doi.org/10.1002/2015JA021824>.

²⁶Manuel Hernández-Pajares and David Moreno-Borràs. "Real-Time Detection, Location, and Measurement of Geoeffective Stellar Flares From Global Navigation Satellite System Data: New Technique and Case Studies". In: *Space Weather* 18.3 (2020), e2020SW002441. DOI: [10.1029/2020SW002441](https://doi.org/10.1029/2020SW002441). URL: <https://doi.org/10.1029/2020SW002441>.

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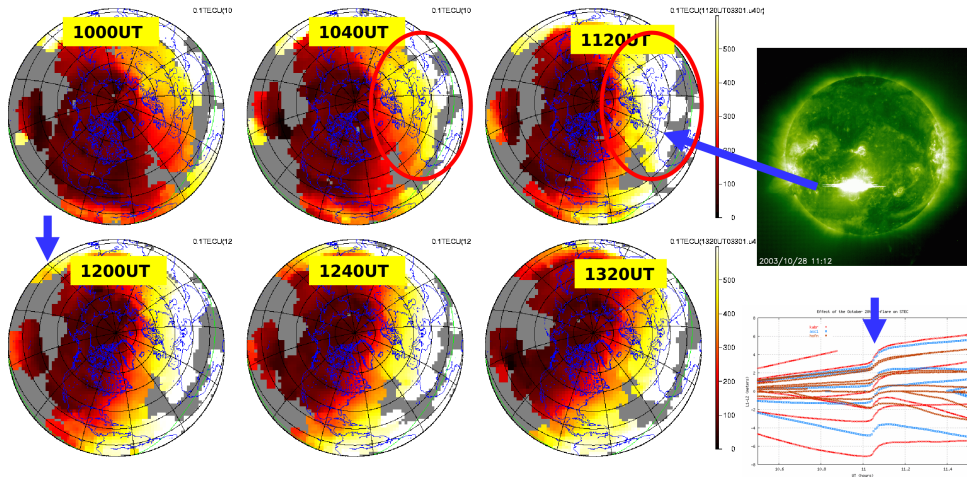
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TEC impact of Solar flare



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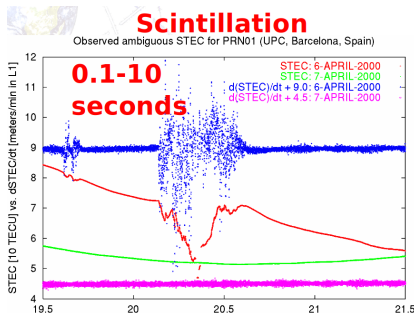
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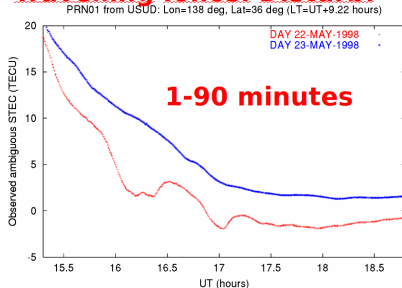
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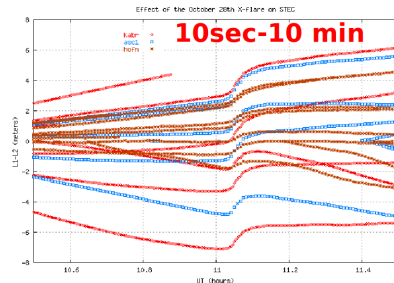
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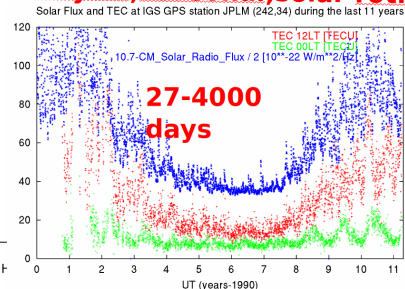
Travelling Ionos. Disturb.



Solar Flare sudden overioniz.

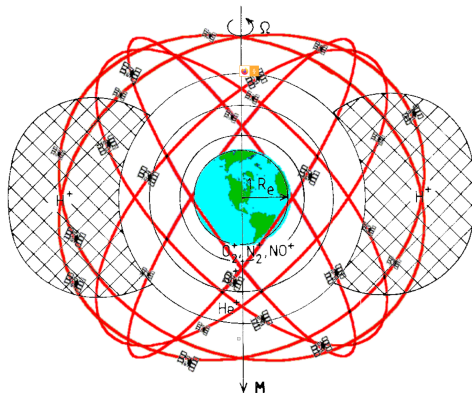


Solar-cycle,seasonal,solar rot.



Modelling

- The ionosphere **free electrons**, jointly with the ones at the next and outer partially ionized layer, the plasmasphere (also known as protonosphere), **are able to significantly affect the electromagnetic (EM) waves crossing it** (former definition of ionosphere as a whole, see²⁷).
- The free electrons react oscillating under the electric field of the crossing EM waves carrying the GNSS signals, generating secondary EM waves which overlap with the original ones. And this **slightly changes both the EM phase and group velocity depending on each given frequency**.



²⁷ Kenneth Davies. *Ionospheric radio propagation*. Vol. 80. US Department of Commerce, National Bureau of Standards, 1965. ▶

Electron density in main iono. GNSS effect

- The delay is **mainly proportional to the electron number density** (*electron density*) and **inversely proportional to the squared frequency** for GNSS signals (1-2GHz), see 9.4 in²⁸).
- Several pioneering works, such as^{29, 30, 31, 32, 33, 34, 35, 36}, opened the way.

²⁸G Petit and B Luzum. "The 2010 reference edition of the IERS conventions". In: *Reference Frames for Applications in Geosciences*. Springer, 2013, pp. 57–61.

²⁹John A Klobuchar. "Ionospheric time-delay algorithm for single-frequency GPS users". In: *IEEE Transactions on aerospace and electronic systems* 3 (1987), pp. 325–331.

³⁰Anthea J Coster, Edward M Gaposchkin, and Lorraine E Thornton. "Real-time ionospheric monitoring system using GPS". In: *Navigation* 39.2 (1992), pp. 191–204.

³¹Anthony J Mannucci, Brian D Wilson, and Charles D Edwards. "A new method for monitoring the Earth's ionospheric total electron content using the GPS global network". In: *Proceedings of the 6th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GPS 1993), Salt Lake City, UT, September 1993*. The Institute of Navigation (ION). 1993, pp. 1323–1332.

³²Esther Sardon, A Rius, and N Zarraoa. "Estimation of the transmitter and receiver differential biases and the ionospheric total electron content from Global Positioning System observations". In: *Radio science* 29.03 (1994), pp. 577–586.

³³N Jakowski et al. "Relationships between GPS-signal propagation errors and EISCAT observations". In: *Annales Geophysicae*. Vol. 14. 12. Copernicus GmbH. 1996, pp. 1429–1436.

³⁴CM Ho et al. "Global ionosphere perturbations monitored by the worldwide GPS network". In: *Geophysical Research Letters* 23.22 (1996), pp. 3219–3222.

³⁵Attila Komjathy and RB Langley. "An assessment of predicted and measured ionospheric total electron content using a regional GPS network". In: *Proceedings of the national technical meeting of the Institute of Navigation*. Citeseer. 1996, pp. 615–624.

³⁶EL Afraimovich, KS Palamartchouk, and NP Perevalova. "GPS Direct and Inverse Radiointerferometry—New Methods of Investigating Travelling Ionospheric Disturbances". In: *Acta Geodaetica et Geophysica Hungarica* 32.3 (1997), pp. 469–479.

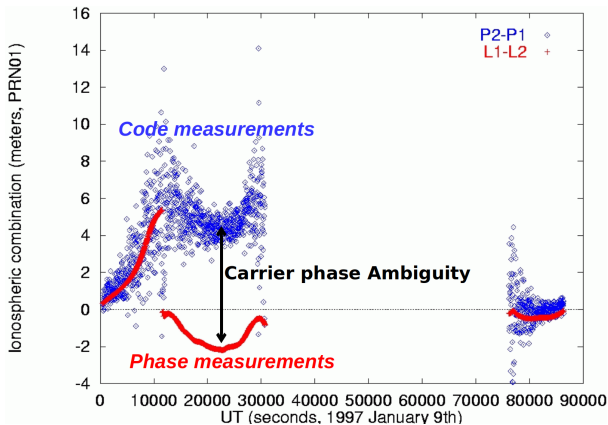
Slant total Electron Content

- For the signals travelling from the GNSS transmitters, above 19000 km height, to the receivers, the phase and group velocities increases/reduces in first order approximation (better than 99.9%³⁷) proportional to the *electron density* N_e and inversely proportional to the squared frequency f^2 .
- From these relationships the **integral of the electron density along the transmitter(τ)-receiver(ρ) GNSS signal path**, i.e. the **Slant Total Electron Content** (STEC, $S = \int_{\tau}^{\rho} N_e dl$), can be mostly deduced from the difference of simultaneous GNSS carrier phase L_1 and L_2 (or pseudorange P_2 and P_1), measurements at two different frequencies f_1 and f_2 , plus an unknown phase bias B_l and receiver and transmitter pseudorange instrumental delays D_l and D'_l (see more details in³⁸).

³⁷ M Hernández-Pajares et al. "Subchapter 9.4 Ionospheric model for radio techniques of IERS Conventions 2010". In: *IERS Technical Note 36* (2010).

³⁸ 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>.

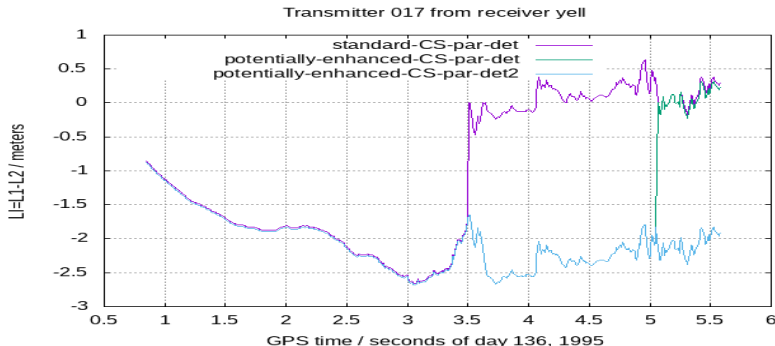
Ionospheric phase & code dual freq. comb.



where $\alpha = 40.309 \left(\frac{1}{f_2^2} - \frac{1}{f_1^2} \right)$,
 $\beta = c \left(\frac{1}{f_2} - \frac{1}{f_1} \right)$ (e.g. $\alpha = 1.051 \cdot 10^{-17} m^3$ and $\beta = 0.05392m$ for L_1 and L_2 GPS signals), ϕ is the angle (in radians) between the transmitter and receiver antenna boresights (corresponding to the **wind-up** term), $B_I = B_1 - B_2$, $D_I = D_2 - D_1$ and $D'_I = D'_2 - D'_1$, among the **multipath** code error, $\epsilon_M(P_I)$, and the **thermal noise** measurement error, $\epsilon_T(P_I)$.

$$\begin{aligned} L_I &\equiv L_1 - L_2 = \alpha \cdot S - \beta \cdot \phi + B_I, \\ P_I &\equiv P_2 - P_1 = \alpha \cdot S + D_I + D'_I + \epsilon_M(P_I) + \epsilon_T(P_I) \end{aligned} \quad (3)$$

Cycle slip detection with dual-freq. data



Example of detection of cycle slips in a geodetic multifrequency GNSS receiver, based on³⁹ with consecutive relaxation of the three thresholds (for double time diff. of L_1 , for single time diff. of Melbourne-Wübbena combination and for single diff. of time).

³⁹Geoffrey Blewitt. "An automatic editing algorithm for GPS data". In: *Geophysical research letters* 17.3 (1990), pp. 199–202.

Single freq. ionospheric comb.

When both **carrier phase** (L_j) and **pseudorange** (P_j) are available in a single-frequency f_j only, a estimation of S (affected by the **half of the pseudorange multipath** $\epsilon_M(L_j)$ and thermal noise $\epsilon_T(L_j)$) is still possible thanks to the so called **ionospheric-graphic combination** $I_{G,j}$ ⁽⁴⁰⁾:

$$I_{G,j} = \frac{1}{2} (P_j - L_j) = \alpha_j \cdot S + \frac{1}{2} (D_j + D'_j - B_j - \beta_j \cdot \phi + \epsilon_M(P_j) + \epsilon_T(P_j)) \quad (4)$$

where $\alpha_j = 40.309 \frac{1}{f_j^2}$, $\beta = c \frac{1}{f_j}$ (e.g. $\alpha = 1.624 \cdot 10^{-17} m^3$ and $\beta = 0.1903m$ for L_1 GPS signals). The carrier phase multipath and thermal noise terms, $\epsilon_M(L_j)$ and $\epsilon_T(L_j)$, can be neglected again: they are typically below 1 cm, i.e. around two order of magnitude smaller that the pseudorange ones.

⁴⁰Manuel Hernández-Pajares et al. "Precise ionospheric electron content monitoring from single-frequency GPS receivers". In: *GPS solutions* 22.4 (2018), p. 102.

Cycle slip det. & fixing improves mid cost navigation & ionospheric determination^{41 42}

GNSS

Ionosphere
and Space
Weather Fun-
damentals:
Monitoring
and new
applications

Hernández-
Pajares et
al.

Preface

GNSS Ionosphere

GNSS basics

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brief seen by GNSS

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Ionosphere for SW

RT GIMs

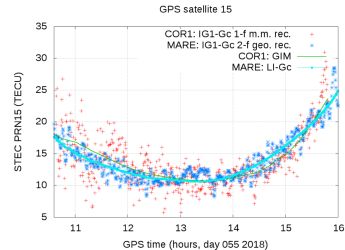
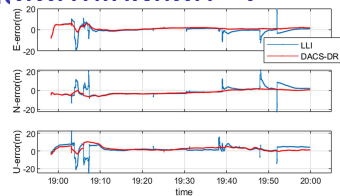
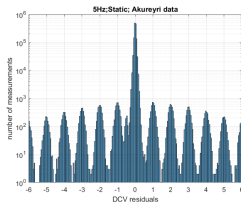
GNSS Ionosphere: a
solar 24/7 SW probe

RT ROTI global
maps

Other applications:
Tsunami warnings

Fast and far-away
precise RT GNSS
rover positioning

Conclusions



⁴¹ Manuel Hernández-Pajares et al. "Precise ionospheric electron content monitoring from single-frequency GPS receivers". In: *GPS solutions* 22.4 (2018), p. 102.

⁴² Jiaojiao Zhao et al. "High-rate Doppler-aided cycle slip detection and repair method for low-cost single-frequency receivers". In: *GPS Solutions* 24.80 (2020), p. 80.

Higher ionospheric order terms

- In Table 1 of⁴³ can be found an executive summary of the remaining higher ionospheric order effects slightly affecting GNSS measurements.
- The higher order ionospheric terms are the second order, STEC bending, third order and geometric bending terms, they can be typically neglected for the most part of GNSS applications. (see additional details in⁴⁴).
- The existence of thousands of permanent worldwide ground-based GNSS receivers with measurements openly available, hundreds of them in real-time (⁴⁵), gathering multi-frequency measurements from up to more than one hundred of GNSS transmitters belonging to the GPS, GLONASS, Galileo and Beidou constellations, allows to convert GNSS in a di facto giant 24/7 scanner of the ionosphere.

⁴³Manuel Hernández-Pajares et al. "Distribution and mitigation of higher-order ionospheric effects on precise GNSS processing". In: *Journal of Geophysical Research: Solid Earth* 119.4 (2014), pp. 3823–3837.

⁴⁴M Hernández-Pajares et al. "Subchapter 9.4 *Ionospheric model for radio techniques* of IERS Conventions 2010". In: *IERS Technical Note* 36 (2010).

⁴⁵Qi 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](https://doi.org/10.5194/essd-13-4567-2021). URL: <https://doi.org/10.5194/essd-13-4567-2021>.

GNSS as a giant 24/7 scanner of the ionosphere

- It allows to estimate the spatial and temporal distribution of **Vertical Total Electron Content (VTEC)** ⁽⁴⁶⁾ and either electron density ⁽⁴⁷⁾. It can be done as random processes, by properly considering the spatial and temporal correlations of the integrated GNSS measurements (e.g. based on carrier phase L_1 measurements only, ^{48, 49, 50, 51}), also in the interpolation ⁽⁵²⁾.

⁴⁶ Esther Sardon, A Rius, and N Zarraoa. "Estimation of the transmitter and receiver differential biases and the ionospheric total electron content from Global Positioning System observations". In: *Radio science* 29.03 (1994), pp. 577–586.

⁴⁷ George A Hajj et al. "Imaging the ionosphere with the Global Positioning System". In: *International Journal of imaging systems and Technology* 5.2 (1994), pp. 174–187.

⁴⁸ M Hernández-Pajares, JM Juan, and J Sanz. "New approaches in global ionospheric determination using ground GPS data". In: *Journal of Atmospheric and Solar-Terrestrial Physics* 61.16 (1999), pp. 1237–1247.

⁴⁹ 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](https://doi.org/10.1007/s00190-011-0508-5). URL: <https://doi.org/10.1007/s00190-011-0508-5>.

⁵⁰ 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.

⁵¹ Eren Erdogan et al. "Real-Time Monitoring of Ionosphere VTEC Using Multi-GNSS Carrier-Phase Observations and B-Splines". In: *Space Weather* 19.10 (2021), e2021SW002858.

⁵² R Orús et al. "Improvement of global ionospheric VTEC maps by using kriging interpolation technique". In: *Journal of Atmospheric and Solar-Terrestrial Physics* 67.16 (2005), pp. 1598–1609.

Electron content distribution and applications

The 24/7 estimation of the electron content has at least a two-fold benefit:

- 1 to estimate the ionosphere state, in terms of such electron content or electron density distribution, **contributing to the continuous Space Weather monitoring** (e.g.⁵³);
- 2 and to provide **accurate and fast ways of computing S for GNSS real-time users**, suitable when they are located up to few hundreds of km far from the nearest receiver of the permanent GNSS network, in order to **support precise GNSS positioning** (⁵⁴).

⁵³ 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; 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](https://doi.org/10.1029/2012SW000826). URL: <https://doi.org/10.1029/2012SW000826>.

⁵⁴ Manuel Hernández-Pajares et al. "Application of ionospheric tomography to real-time GPS carrier-phase ambiguities Resolution, at scales of 400–1000 km and with high geomagnetic activity". In: *Geophysical Research Letters* 27.13 (2000), pp. 2009–2012; M Hernandez-Pajares et al. "Wide-area RTK: High precision positioning on a continental scale". English. In: *Inside GNSS* 5.2 (2010), pp. 35–46. ISSN: 1559-503X.

STEC from carrier phase iono. comb. by geometric decorrelation

Typically from the geometry-free iono. comb. of meas. (eq. 3), by:

- Using the carrier phase measurements L_1 only, levelled by geometric decorrelation, i.e. by decomposing S in a certain basis functions (e.g. voxels distributed in some shells) to simultaneously estimate the electron density and the phase ambiguity and without using any background model, reducing the modelling errors^{55,56} (recently by B-splines (^{57,58})).

⁵⁵M Hernández-Pajares, JM Juan, and J Sanz. "New approaches in global ionospheric determination using ground GPS data". In: *Journal of Atmospheric and Solar-Terrestrial Physics* 61.16 (1999), pp. 1237–1247.

⁵⁶Manuel 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.

⁵⁷G Olivares-Pulido et al. "A 4 D tomographic ionospheric model to support PPP-RTK". In: *Journal of Geodesy* 93.9 (2019), pp. 1673–1683.

⁵⁸Eren Erdogan et al. "Real-Time Monitoring of Ionosphere VTEC Using Multi-GNSS Carrier-Phase Observations and B-Splines". In: *Space Weather* 19.10 (2021), e2021SW002858.

STEC from carrier phase-code iono. comb. by phase-code levelling

- Using phase-code levelling⁵⁹, affected by $\epsilon_M(P_I)$ and $\epsilon_T(P_I)$ as significant error sources⁶⁰, and requiring estimations of the inter-frequency instrumental delays D_I and D'_I values; this can be done simultaneously by expanding S in basis functions such as spherical harmonics or B-splines for the VTEC (see^{61, 62} respectively)

⁵⁹Anthony J Mannucci, Brian D Wilson, and Charles D Edwards. "A new method for monitoring the Earth's ionospheric total electron content using the GPS global network". In: *Proceedings of the 6th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GPS 1993)*, Salt Lake City, UT, September 1993. The Institute of Navigation (ION). 1993, pp. 1323–1332; AJ Mannucci et al. "A Global mapping technique for GPS-derived ionospheric total electron content measurements". In: *Radio science* 33.3 (1998), pp. 565–582.

⁶⁰Manuel 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](https://doi.org/10.1007/s00190-011-0508-5). URL: <https://doi.org/10.1007/s00190-011-0508-5>.

⁶¹S Schaer. "Mapping and predicting the earths ionosphere using the Global Positioning System. 1999. 205p". PhD thesis. Ph. D. dissertation. University of Bern, Bern, Switzerland, 1999.

⁶²Andreas Goss et al. "High-resolution vertical total electron content maps based on multi-scale B-spline representations". In: *Annales geophysicae*. Vol. 37. 4. Copernicus GmbH. 2019, pp. 699–717.

STEC from uncombined GNSS meas.

- From the uncombined carrier phase and pseudorange measurements, more simple to manage under so many different signals and frequency in the present GNSS context, by:
 - Considering S as an unknown to be directly estimated, in combination with other unknowns to avoid the rank deficiency, in the corresponding filter of the overall precise GNSS model (e.g.⁶³).
 - Expanding S in a basis functions, such as voxels in terms of electron density, in order to directly estimate the corresponding coefficients simultaneously with the geodetic GNSS model unknowns (e.g. Ionospheric Tomographic Common Clock -ITCC- model,⁶⁴).

⁶³Dennis Odijk et al. "On the estimability of parameters in undifferenced, uncombined GN network and PPP-RTK user models by means of S-system theory". In: *Journal of Geodesy* 90.1 (2016), pp. 15–44.

⁶⁴Germán Olivares-Pulido et al. "Ionospheric tomographic common clock model of undifferenced uncombined GNSS measurements". In: *Journal of Geodesy* 95.11 (2021), pp. 1–13.

RT GNSS Ionosphere for SW

Introduction

Why and **What** results and applications can we present so far?

- ① RT Global Ionospheric Maps of the ionosphere, as potential source for single-frequency GNSS usage in civil aviation, of:
 - Space Weather (SW) semaphor (ionospheric storm scale)
 - SW impact (electron content gradient) quantifier
 and, under collaboration:
 - Improving the RT VTEC interpolation.
 - Redundancy and reliability: the international collaborative effort of the combined RT and rapid IGS GIM.

② RT Solar Flare warnings.

③ Rate of TEC Index.

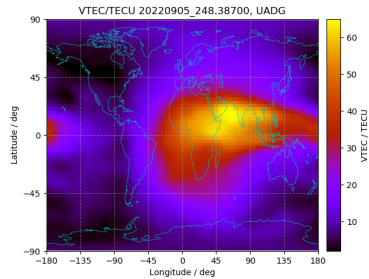
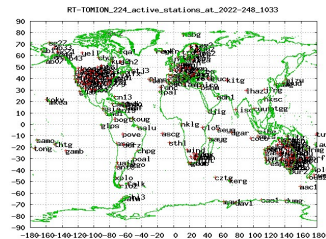
More applications:

① Potential RT / NRT tsunami warnings.

② Fast and far-away precise RT GNSS rover positioning.

- 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.

RT GIMs



(1) RT Global Ionospheric Maps of the Earth ionosphere as potential source in particular for single-frequency GNSS usage in civil aviation, of:

- Space Weather (SW) semaphor (ionospheric storm scale),
- and SW impact (electron content gradient) quantifier,

both working well from rapid UQRG GIMs, see⁶⁵ and⁶⁶, generated by the UPC-IonSAT inhouse software TOMION.

- TOMION is a tomographic data driven ionospheric model originally developed by MHP, in continuous development during the latest 25 years, including as well the geometric modelling and estimation (e.g. clocks and tropospheric parameters).
- TOMION is able, and typically estimates the electron density from GNSS carrier phase dual-frequency data only, without background model.

⁶⁵Qi 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.

⁶⁶Qi 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.

GNSS

Ionosphere
and Space
Weather Fundamentals:
Monitoring
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applications

Hernández-
Pajares et
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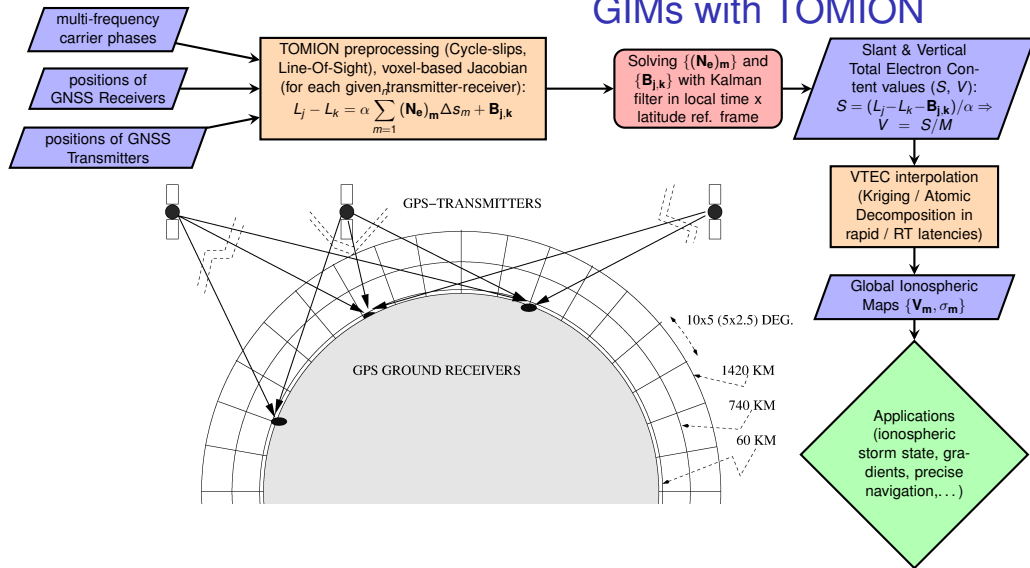
RT ROTI global
maps

Other applications:
Tsunami warnings

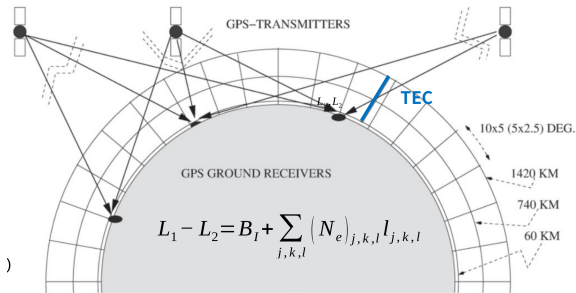
Fast and far-away
precise RT GNSS
rover positioning

Conclusions

GIMs with TOMION



Introduction to TOMION model (2 of 3)



UPC Quarter-of-an-hour time resolution Rapid GIM (UQRG)

- It incorporates a **Kalman filter** and a **kriging-based interpolation** for the vertically integrated electron density (the vertical total electron content, VTEC, see^{67, 68, 69}).

⁶⁷ M Hernández-Pajares, JM Juan, and J Sanz. "Neural network modeling of the ionospheric electron content at global scale using GPS data". In: *Radio Science* 32.3 (1997), pp. 1081–1089.

⁶⁸ M Hernández-Pajares, JM Juan, and J Sanz. "New approaches in global ionospheric determination using ground GPS data". In: *Journal of Atmospheric and Solar-Terrestrial Physics* 61.16 (1999), pp. 1237–1247.

⁶⁹ R Orús et al. "Improvement of global ionospheric VTEC maps by using kriging interpolation technique". In: *Journal of Atmospheric and Solar-Terrestrial Physics* 67.16 (2005), pp. 1598–1609.

Introduction to TOMION model (3 of 3)

- 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 (^{70,71,72}).
- The tomography performed by TOMION is able to combine different data and geometries (⁷³), in agreement with independent measurements and models (^{74,75}), also in the polar regions (⁷⁶).

⁷⁰M 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](https://doi.org/10.1007/s00190-008-0266-1). URL: <https://doi.org/10.1007/s00190-008-0266-1>.

⁷¹Manuel 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.

⁷²David 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.

⁷³Manuel 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.

⁷⁴DV 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.

⁷⁵DV 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.

⁷⁶Manuel 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.

GIM application: Ionospheric storm scale

In⁷⁷ 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 by⁷⁸:

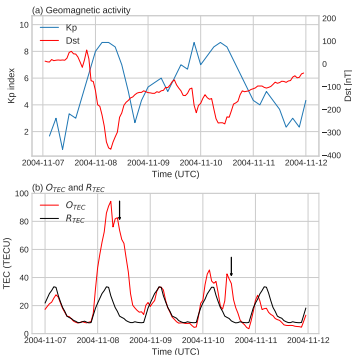
$$P_{TEC} = \frac{100 \times (O_{TEC} - R_{TEC})}{R_{TEC}} \implies \hat{P}_{TEC} = \frac{P_{TEC} - \mu}{\sigma} \quad (5)$$

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. The normalized $\hat{P}_{TEC}$ 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.

⁷⁷Qi 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.

⁷⁸Michi Nishioka et al. "A new ionospheric storm scale based on TEC and foF2 statistics". In: *Space Weather* 15.1 (2017), pp. 228–239.

Ionospheric storm scale from UQRG GIMs



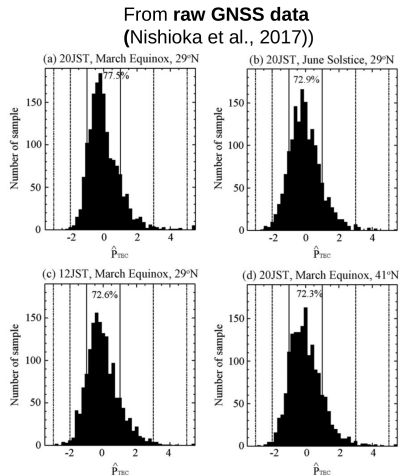
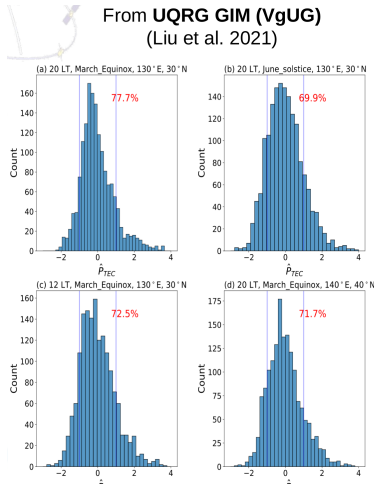
The evolution of O_{TEC} , R_{TEC} , Kp and Dst at [130°E, 30°N] from 7 to 10 November in 2004.

IsUG definition & occurrence (1997-2014).

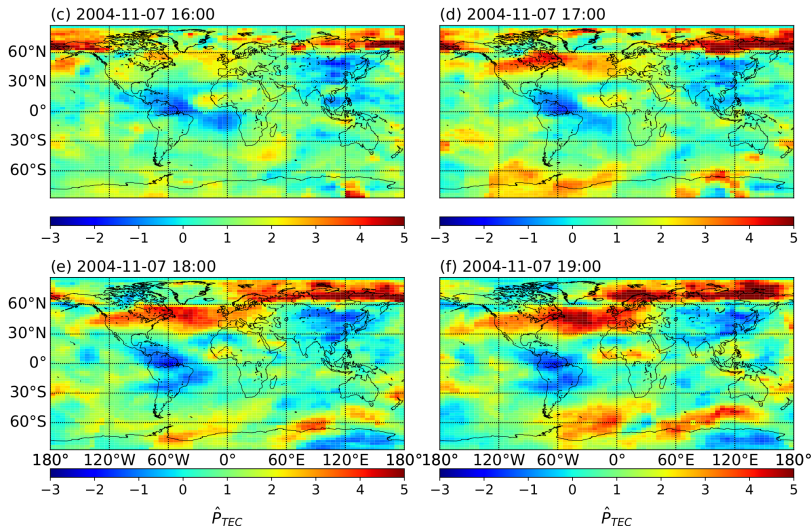
IsUG	Storm state	Definition	Global scale probability (%)
IP3	Severe positive	$5 < \hat{P}$	0.17
IP2	Strong positive	$3 < \hat{P} \leq 5$	0.72
IP1	Moderate positive	$1 < \hat{P} \leq 3$	12.43
I0	Quiet	$-1 < \hat{P} \leq 1$	73.96
IN1	Moderate negative	$-2 < \hat{P} \leq -1$	11.72
IN2	Strong negative	$-3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

Validation: IsUG vs original I-scale

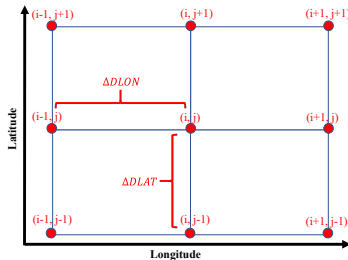
Comparison over Japan (1997-2014; each season: 3 months per year):



IsUG global map example (7-Nov-2004)



GIM application: VTEC gradient



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

$$\begin{aligned} \vec{\nabla} V_{i,j} &= (\nabla V_{x,i,j}, \nabla V_{y,i,j}) \Rightarrow \\ \Rightarrow \nabla V_{i,j} &\equiv \|\nabla V_{i,j}\| = \sqrt{\nabla V_{x,i,j}^2 + \nabla V_{y,i,j}^2} \end{aligned}$$

The VTEC gradient derived from UQRG GIMs (VgUG)⁷⁹ 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 effective height, $\Delta\lambda$ & $\Delta\phi$, separated 5° & 2.5° respectively, and the time difference between GIMs Δt (30 minutes, centered, 15 minutes, uncentered).

⁷⁹ 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.

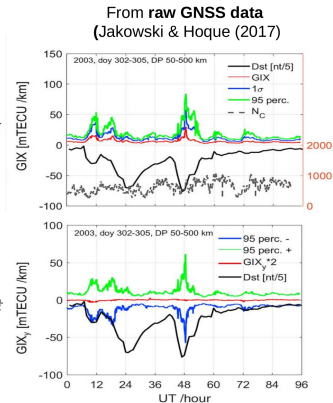
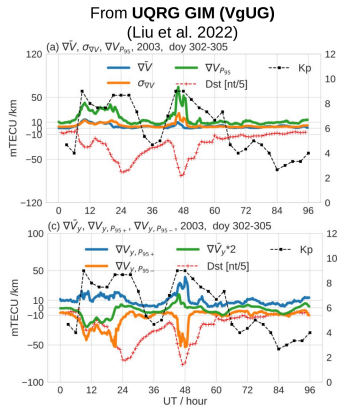
Validation of GIM-based $\nabla \vec{V}$ vs. raw-GNSS

DLR results

The UPC-IonSAT results from UQRG GIMs (Liu et al. 2022) are very similar to the DLR results from raw GNSS measurements (⁸⁰), as it can be seen during the Halloween Storm on Europe.

Spatial
gradient
norm

Latitudinal
gradient
component

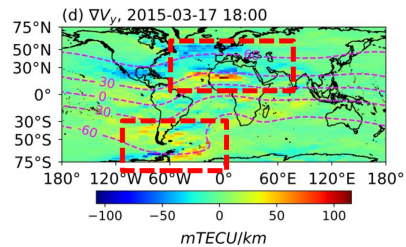
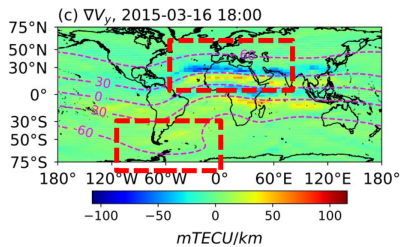
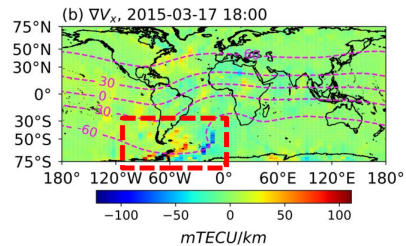
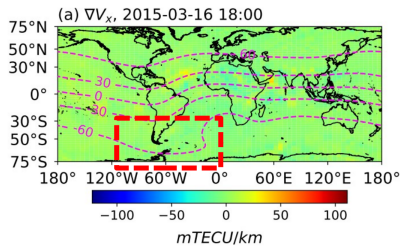


⁸⁰ Norbert Jakowski and Mohammed Mainul Hoque. "Estimation of spatial gradients and temporal variations of the total electron content using ground-based GNSS measurements" In: *Space Weather* 17.2 (2019) pp. 339–356

Example of $\nabla \vec{V}$ distribution from UQRG GIM

Quiet

St. Patrick's day storm



Improving the RT-GIMs

(1) Improving the RT VTEC interpolation

- VTEC interpolation need: the ionospheric measurements from GNSS satellites to stations are not distributed uniformly, with large gaps $\Rightarrow$ **iono. face recognition**.
- The new method ⁽⁸¹⁾ uses a high-quality historical database of post-processed GIMs, during more than two solar cycles: it calculates the GIM by weighted superposition on a subset of the database with the compatible solar condition.
- The linear combination of GIMs in the database was obtained by minimizing a L2 distance between collocated VTEC measurements and those from the database, adding a L1 penalization on the weights to assure a sparse solution.
- This method, in a Sun-fixed geomagnetic reference frame, uses the atomic decomposition/least absolute shrinkage and selection operator (LASSO), which will be denoted as atomic decomposition interpolator of GIMs (ADIGIM).
- As the computation is done in milliseconds, the interpolation is applied in RT.

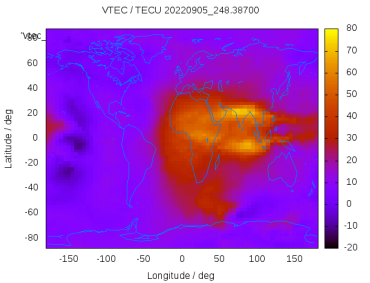
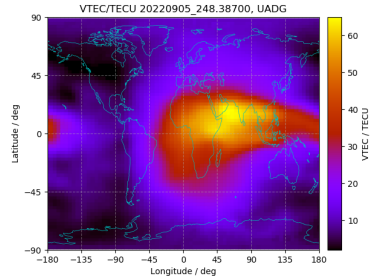
⁸¹ Heng Yang et al. "Systematic detection of anomalous ionospheric perturbations above LEOs from GNSS POD data including possible tsunami signatures". In: *IEEE Transactions on Geoscience and Remote Sensing* 60 (2022), pp. 1–23.

Improving the RT VTEC interpolation

Table 6 Summary of GIMs assessment by 4,253,502 common altimeter JASON3 VTEC measurement (in TECUs), for a period of +200 days, from day 258 of 2019 to day 155 of 2020

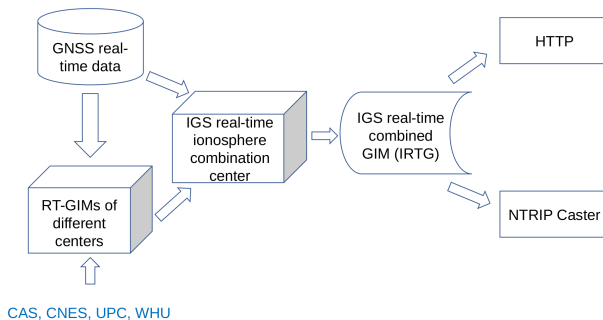
GIM Id	Latency	Bias	SD	RMS	ERR %
IGSG	> 15 days	-1.93	2.33	3.03	38.5
CODG	~5 days	-1.34	2.46	2.80	35.6
JPLG	~4 days	-3.34	2.45	4.15	52.7
UPCG	~15 h	-2.23	2.38	3.26	41.4
ESAG	~4 days	-0.87	2.83	2.96	37.6
WHUG	~4 days	-1.39	2.52	2.87	36.5
CASG	~4 days	-1.50	2.46	2.88	36.6
EMRG	~2 days	-1.69	2.61	3.11	39.5
CORG	~7 h	-1.29	2.64	2.94	37.4
JPRG	~7 h	-3.44	2.48	4.24	53.9
UQRG	~16 h	-2.14	2.30	3.14	39.9
ESRG	~2 h	-1.01	2.86	3.04	38.6
WHRG	~20 h	-1.35	2.55	2.89	36.6
CARG	~10 h	-1.51	2.59	3.00	38.1
EHRG	~3 h	-1.07	2.69	2.90	36.8
CASR	RT ^a	-1.14	2.80	3.02	38.4
CLK9	RT	-0.53	2.98	3.03	38.5
USRG	RT	-1.41	2.85	3.18	40.4
UARG	~20 h	-2.09	2.32	3.13	39.7
UADG	RT	-1.34	2.43	2.77	35.1

^aLatency of UADG is the delay for RT-GIM for each epoch



RT iono. electron content estimation: How?

(2) Redundancy, i.e. availability and reliability: the international collaborative effort of the combined RT IGS GIM (⁸²).



⁸²Qi 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](https://doi.org/10.5194/essd-13-4567-2021). URL: <https://doi.org/10.5194/essd-13-4567-2021>.

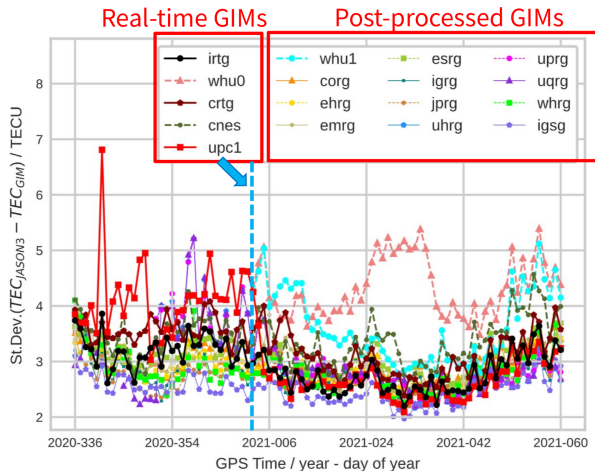
Broadcasting links



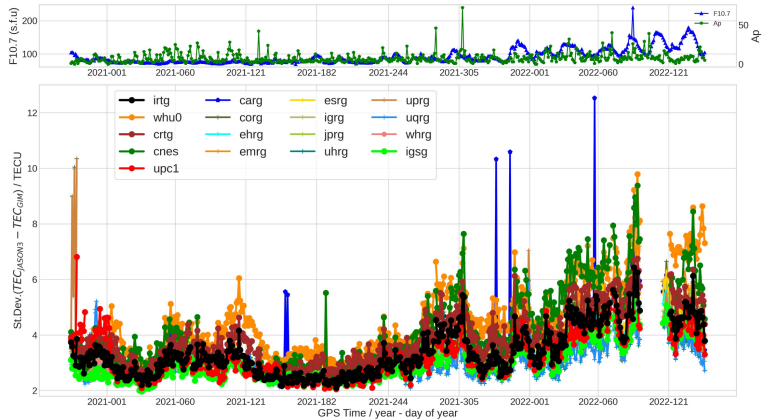
The broadcasting of IGS RT-GIMs

Agency	Temporal resolution	Broadcast frequency	Spherical harmonic degree	Mountpoints in NTRIP caster (in SSR format)	Real-Time IONEX files saved at FTP/HTTP
CAS	5 minutes	1 minute	15	59.110.42.14:2101/SSRA00CAS1 59.110.42.14:2101/SSRA00CAS0 59.110.42.14:2101/SSRC00CAS1 59.110.42.14:2101/SSRC00CAS0 182.92.166.182:2101/IONO00CAS1 182.92.166.182:2101/IONO00CAS0	ftp://ftp.gipp.org.cn/product/ionex/ (update at the end of day)
CNES	2 minutes	1 minute	12	products.igs-ip.net:2101/SSRA00CNE1 products.igs-ip.net:2101/SSRA00CNE0 products.igs-ip.net:2101/SSRC00CNE1 products.igs-ip.net:2101/SSRC00CNE0	No
UPC-IonSAT	15 minutes	15 seconds	15	products.igs-ip.net:2101/IONO00UPC1	http://chapman.upc.es/tomi/real-time/quick/ (update every 15 min)
WHU	5 minutes	1 minute	15	58.49.58.150:2106/IONO00WHU0	ftp://igs.gnsswhu.cn/pub/vh/MGEX/realtime-ionex/ (update every 30 min)
IRTG (IGS)	20 minutes	15 seconds	15	products.igs-ip.net:2101/IONO00IGS1	http://chapman.upc.es/irtg/ (update every 20 min)

Impact of new UPC-IonSAT RT iono. interpolation in combined RT-IGS GIM



More than one year of RT-IGS GIM assessment and combination



Summary of performances

Overall standard deviation of the GIM-VTEC versus measured Jason-3 VTEC in Jason-3 VTEC assessment (TECU)

GIM	From 1 December 2020 to 3 January 2021	From 4 January to 1 March 2021	From 4 January 2021 to 1 June 2022	From 4 January 2022 to 1 June 2022
corg	3.1	2.9	3.8	4.9
ehrg	3.0	2.8	3.6	4.5
emrg	3.2	2.9	3.9	5.1
esrg	3.2	3.0	3.8	4.9
igrgr	2.9	2.8	3.3	4.0
jprgr	2.8	2.7	3.4	4.2
uhrg	3.9	2.8	3.1	3.6
uprg	3.9	2.8	3.3	4.0
uqrg	3.5	2.8	3.1	3.7
igsg	2.6	2.5	3.2	4.0
crtg	3.6	3.2	4.1	5.2
cnes	3.5	3.4	4.7	6.2
upc1	4.3	2.7	3.4	4.2
whu0	4.3	4.4	5.0	6.5
irtg	3.3	2.8	3.5	4.5

The on-going collaboration in one picture

Earth Syst. Sci. Data, 13, 4567–4582, 2021
https://doi.org/10.5194/essd-13-4567-2021
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Earth System
Science
Data

The cooperative IGS RT-GIMs: a reliable estimation of the global ionospheric electron content distribution in real time

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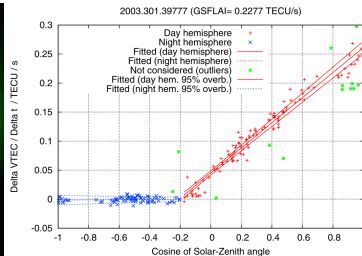
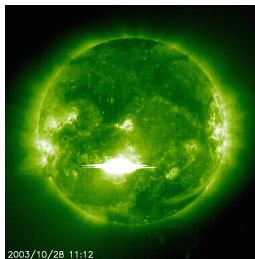
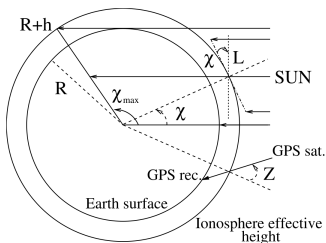
Correspondence: Manuel Hernández-Pajares (manuel.hernandez@upc.edu)

GNSS Ionosphere: a solar 24/7 SW probe

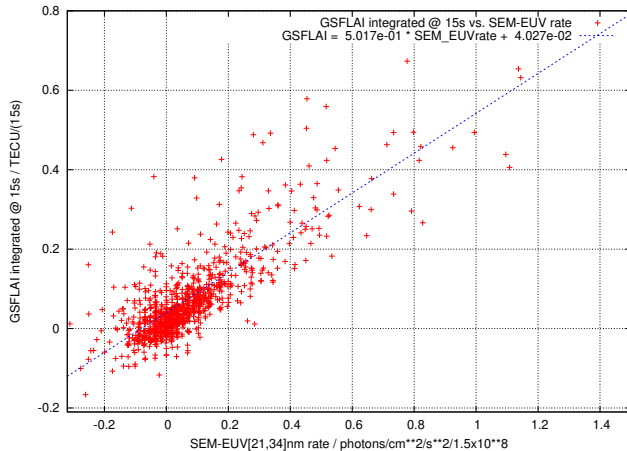
(2) RT Solar Flares warnings and potential NRT tsunami warnings

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:

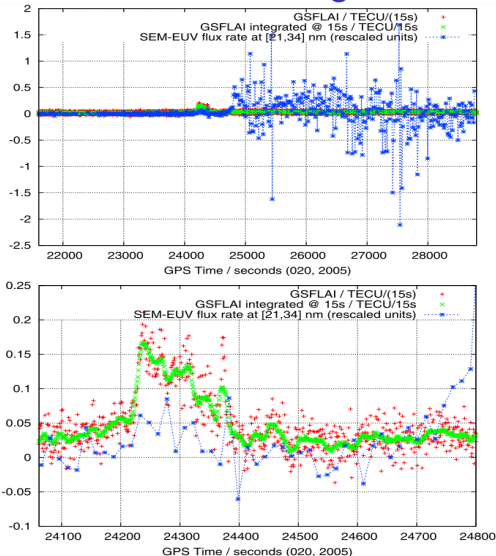
$$\dot{V} = \eta' \cdot C(\chi) \cdot \dot{I} \Rightarrow \frac{\partial V}{\partial t} = a(t) \cos \chi + b(t) \quad (6)$$



GNSS Ionosphere as a solar EUV photometer



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 $t = 24750$ s 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.

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		No. Points	Slope	Intercept	Corr. Factor	p values
C.	#	Peaks	Peaks	Peaks	Peaks	
<i>X</i>	59	53	159 ± 06	6.2 ± 1.5	0.73	0
<i>M</i>	323	219	152 ± 12	1.5 ± 0.3	0.64	0
<i>C</i>	390	58	159 ± 29	0.5 ± 0.4	0.59	1.9 * 10 ⁻⁶

(a) Units: *TECU/s* for GSFLAI & *photons · 10⁻⁹/cm²/s²* for EUV flux rate.

More details can be found in⁸³ and⁸⁴.

⁸³Manuel 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](https://doi.org/10.1029/2012SW000826). URL: <https://doi.org/10.1029/2012SW000826>.

⁸⁴Talwinder 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](https://doi.org/10.1002/2015JA021824). URL: <https://doi.org/10.1002/2015JA021824>.

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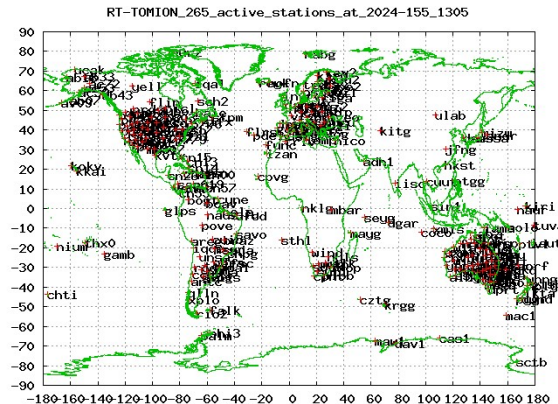
RT ROTI global
maps

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Tsunami warnings

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rover positioning

Conclusions

1-Hz GNSS networks overview



ROTI definition

$$\sigma_{\dot{T}}[r, s, \Delta t, \delta t](t) = \sqrt{\frac{\sum_{i=1}^n (\dot{T}_{r,i}^s)^2}{n} - \left(\frac{\sum_{i=1}^n \dot{T}_{r,i}^s}{n}\right)^2} \quad (7)$$

being

$$\dot{T}_{r,i}^s \equiv \dot{S}_{r,i}^s \simeq \frac{S_{r,i}^s(t + (i - n/2) * \delta t) - S_{r,i}^s(t + (i - n/2 - 1) * \delta t)}{\delta t} \quad (8)$$

where S represents the Slant TEC, and $(\Delta t, \delta t) = (300, 30)s$, see^{85, 86}. The Rate of Vertical TEC Index (ROVI) mitigates the influence of the geometry in the scintillation proxy index:

$$\dot{T}_{r,i}^s \equiv \dot{V}_{r,i}^s \simeq \frac{\dot{S}_{r,i}^s}{M_{r,i}^s} \quad (9)$$

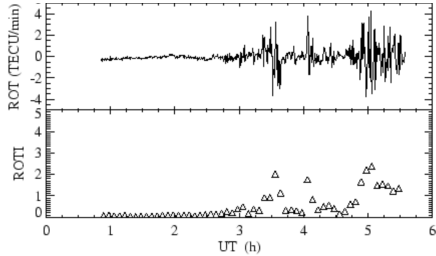
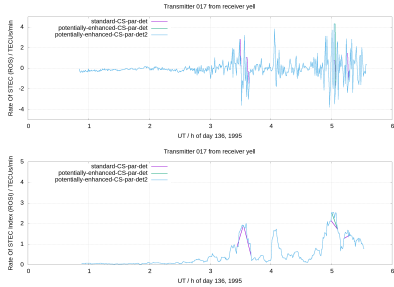
where $\dot{V}$ is the Rate of Vertical TEC (ROV), $M_{r,i}^s$ is the ionospheric mapping function (assuming thin spherical layer at a 450 km like IGS). ROTI can be predicted, with better performance than the frozen one, e.g.⁸⁷.

⁸⁵X Pi et al. "Monitoring of global ionospheric irregularities using the worldwide GPS network". In: *Geophysical Research Letters* 24.18 (1997), pp. 2283–2286.

⁸⁶Xiaoqing Pi et al. "Observations of global and regional ionospheric irregularities and scintillation using GNSS tracking networks". In: (2013).

⁸⁷Enric Monte-Moreno et al. "Method for Forecasting Ionospheric Electron Content Fluctuations Based on the Optical Flow Algorithm.". In: *IEEE Transactions on Geoscience and Remote Sensing* (2021).

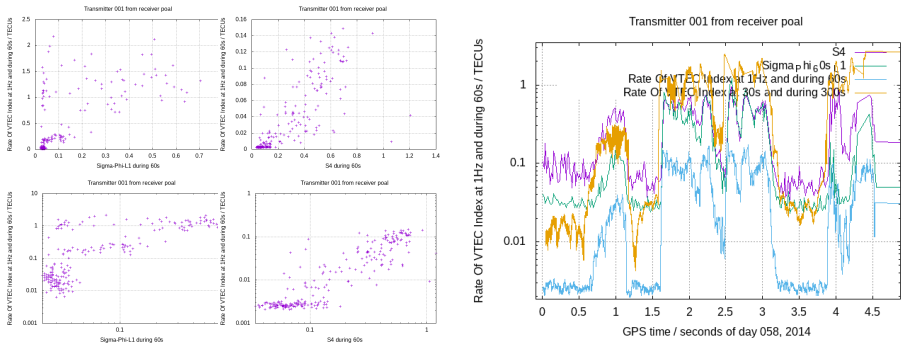
ROTI validation, vs original computation



Comparison of ROTI global computed by UPC-IonSAT with TOMION-v1 (top plot), ROT and ROTI computed in⁸⁸ (second and third plot) and ROTI computed by UPC-IonSAT (bottom plot), considering different cycle-slip detection thresholds (PRN17 measured from YELL GPS receiver during day 136, 1995).

⁸⁸Xiaoqing Pi et al. "Observations of global and regional ionospheric irregularities and scintillation using GNSS tracking networks". In: (2013).

ROTI comparison vs. σ_ϕ and S4



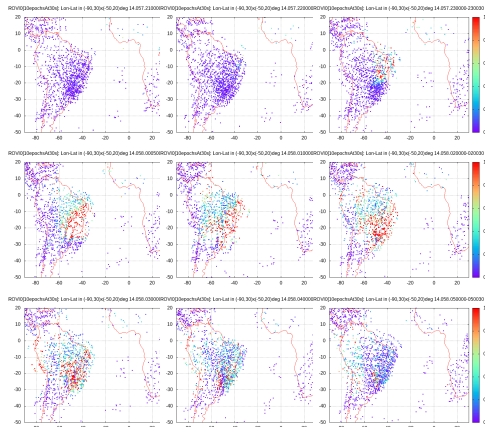
ROVI (in TECU/min), computed from POAL receiver (at 1/30s within 5 minutes at left column and at 1Hz within 1 minute at right column) of transmitter PRN001 during day 58 of year 2014, is represented vs σ_ϕ in first column and vs S4 in second column of first row. The corresponding plots, but in log-log scales, are included in the second row. Finally in bottom semi-log plot such scintillations indices are compared with the ROVI computed in a legacy way all of them vs time.

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Examples of multiGNSS ROTI maps



Worldwide view of the post-processed ROVI from multiGNSS data, including ground Brazilian GNSS network, computed by UPC-IonSAT every 30 sec.

Other applications: Tsunami warnings

- On 30 October, day 304 of year 2020 at 11:51 UT, a magnitude 7.0 earthquake occurred in the Dodecanese sea (37.84 °N, 26.81 °E, 10 km depth), producing a +1 meter height tsunami on the Turkish coasts.
- Both events produced acoustic and gravity waves that propagated upward, triggering co-seismic and co-tsunami ionospheric disturbances.
- We present the direct ionosphere tomography, exclusively based on GNSS carrier phase meas. gathered by ground-based permanent receivers, disclosing potential footprints of Samos 2020 tsunami.
- The GNSS ionospheric tomographic approach from the ground complements well recent techniques from GNSS LEO-based measurements (Yang et al. 2022⁸⁹).

⁸⁹Heng Yang et al. "Systematic detection of anomalous ionospheric perturbations above LEOs from GNSS POD data including possible tsunami signatures". In: *IEEE Transactions on Geoscience and Remote Sensing* 60 (2022), pp. 1–23.

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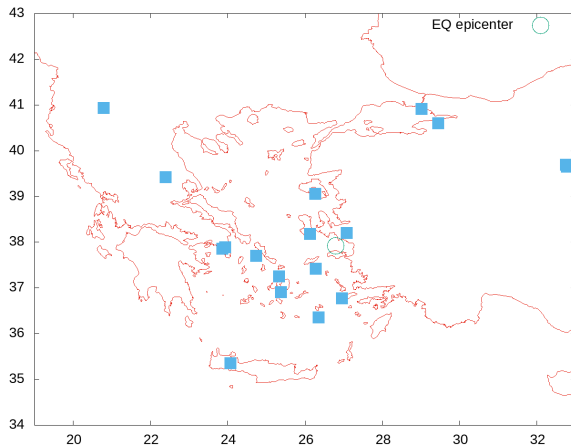
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**Other applications:
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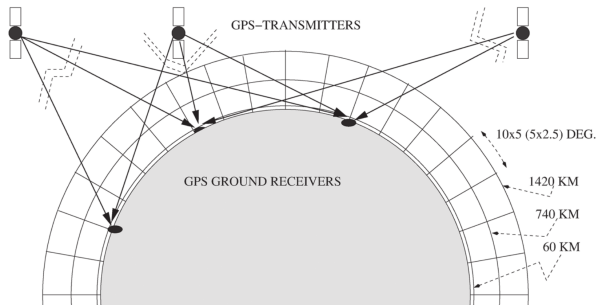
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Technique: Voxel-based 4D ED grad. est.



$$L_I - (\lambda_1 - \lambda_2) \cdot \phi = \alpha \sum_{i=1}^{M_I} \sum_{j=1}^{M_J} \sum_{k=1}^{M_K} (N_e)_{i,j,k} \cdot \Delta l_{i,j,k} + B_I$$

TOMION has been run in a high resolution mode from Samos EQ ground GPS data: assuming the electron density (N_e) distributed in voxels of 1 deg x 1 deg x 680 km (2 layers) x 30 sec in Right Ascension (α) x Latitude (ϕ) x Height (h) x Time (t) with random walk process noise a bit higher than the one used for computing the GIMs for IGS, where the UPC GIM UQRG is the

Technique: Voxel-based 4D ED grad. est.

Consistency of seven different GNSS global ionospheric mapping techniques during one solar. . .

Table 1 Summary of the different GIMs assessed in this work

GIM ID	Method	DCB computation	Shell model	Start date	References
IGSG	Weighted mean	Combined	Combined	1998.4	Hernández-Pajares et al. (2009)
CODG	Spherical harmonics	Same time as VTEC	Modified 2-D	1998.4	Schaer (1999)
ESAG ^a	Spherical harmonics	Same time as VTEC	2-D	1998.4	Feltens (2007)
JPLG	Three-shell model	Same time as VTEC	3-D	1998.4	Mannucci et al. (1998)
UPCG	Tomographic with splines	From VTEC	3-D	1998.4	Hernández-Pajares et al. (1999)
UQRG ^{b,c}	Tomographic with kriging	From VTEC	3-D	2011	Orús et al. (2005)
CASG	Spherical harmonics and generalized trigonometric series	Same time as VTEC	2-D	2016	Li et al. (2015)
EMRG ^c	Spherical harmonics	Same time as VTEC	2-D	1998.4, 2015.3	Ghoddousi-Fard (2014)
WHRG ^c	Spherical harmonics and inequality-constrained least squares	Same time as VTEC	2-D	2016	Zhang et al. (2013)
WHUG	Spherical harmonics and inequality-constrained least squares	Same time as VTEC	2-D	2016	Zhang et al. (2013)

^aA 3D multilayer assimilation model is currently under development by ESA. ^bThe time interval of UQRG is 15 min, in contrast with the other GIMs which have a time interval of 2 h. ^cUQRG, EMRG and WHRG are rapid GIMs with a latency of less than two days, in contrast with the other final GIMs which have a latency about 1 week

Technique: Voxel-based 4D ED grad. est.

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Table 2 Summary of the GIMs assessment versus +190 millions of altimeter VTEC measurements, including an overall period of up to almost 5000 days and a common period of 21 days (remarks: [*] For the newest period of EMRG product submission to IGS only, days 117-365, 2015; [**] Very limited sample)

GIM Id.	Up to more than 1 solar cycle, within days 180, 2001 to 007, 2016			21 common days, within 117, 2015 to 007, 2016	
	# days	Std. dev./TECU	Rel. error %	Std. dev. /TECU	Rel. error %
IGSG	4927	3.9	19.9	4.6	21.1
CODG	4934	4.3	22.0	4.8	21.8
ESAG	4926	5.3	26.6	5.6	25.5
JPLG	4912	4.1	21.2	4.8	21.9
UPCG	4925	3.9	19.7	4.2	19.1
CASG	4914	3.9	20.9	4.6	21.1
EMRG	255[*]	(4.8)	(26.2)	5.9	26.5
WHRG	4416	4.6	24.8	5.5	25.0
WHUG	42[**]	(5.9)	(26.9)	5.5	25.0
UQRG	3063	3.6	17.8	3.6	16.3

Technique: Voxel-based 4D ED grad. est.

Table 4 Summary of the dSTEC relative error for classical and new IGS GIMs, including the number of receiver * days available and processed in each case, within the + 50 independent GNSS receivers for days 082, 146, 280 and 330 of 2015, with Kp indices in the ranges 2.3–4.3, 0.3–2.3, 3.7–7.3 and 0.3–1.3, respectively (remarks: [*] number of available independent GNSS receivers significantly smaller than those of IGS, CODG, ESAG, UPCG and UQRG; [**] extremely limited number of independent GNSS receivers available for dSTEC assessment compared with the other GIMs)

GIM Id.	Rel. error dSTEC / %	# Rec. * days
IGSG	28.9	238
CODG	27.8	238
ESAG	33.0	238
JPLG	(31.0)	180[*]
UPCG	26.9	238
CASG	(28.0)	178[*]
EMRG	(33.6)	178[*]
WHRG	((30.7))	60[**]
WHUG	((30.7))	60[**]
UORG	20.5	233

Journal of Geodesy
<https://doi.org/10.1007/s00190-017-1088-9>

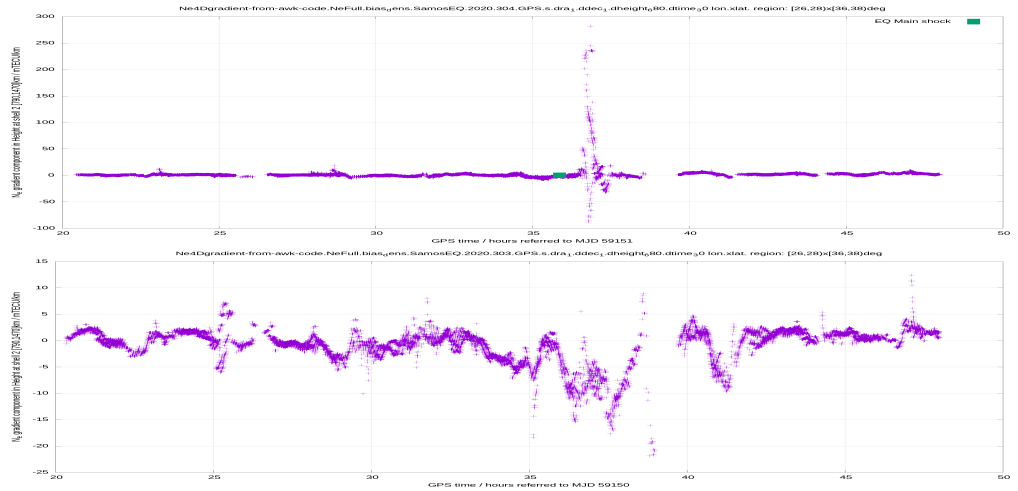
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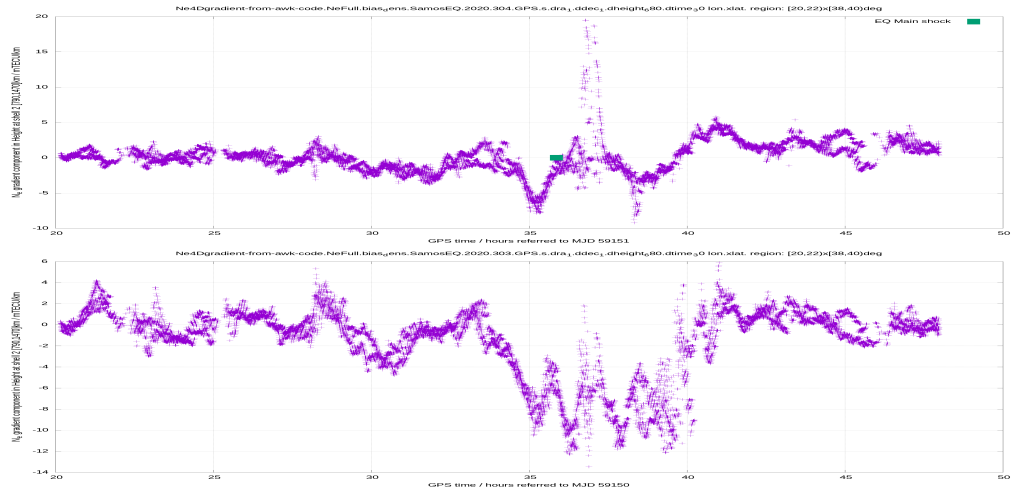
Consistency of seven different GNSS global ionospheric mapping techniques during one solar cycle

David Roma-Dollase^{1,2} · Manuel Hernández-Pajares¹ · Andrzej Krankowski³ · Kacper Kotulak³ · Reza Ghoddousi-Fard⁴ · Yunbin Yuan⁵ · Zishen Li⁶ · Hongping Zhang⁷ · Chuang Shi⁷ · Cheng Wang⁷ · Joachim Feltens⁸ · Panagiotis Vergados⁹ · Attila Komjathy⁹ · Stefan Schaer¹⁰ · Alberto Garcia-Rigo¹ · José M. Gómez-Cama²

$\frac{\partial N_e}{\partial h}$ vs time close to EQ (given & previous day)



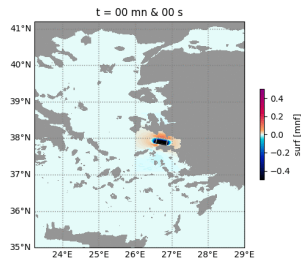
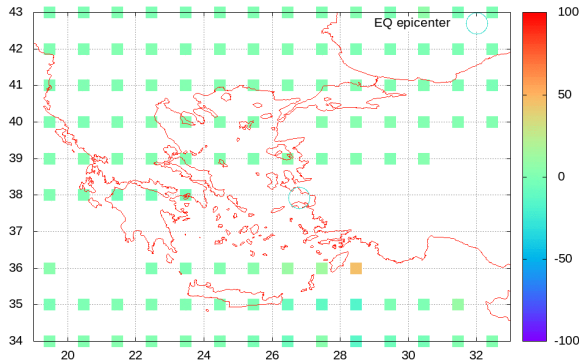
$\frac{\partial N_e}{\partial h}$ vs time far from EQ (given & previous day)



Animation of $\frac{\partial N_e}{\partial h}$ -41m30s & tsunami height

Animation after Samos 2020 EQ mainshock time of $\frac{\partial N_e}{\partial h}$ maps and tsunami height, using the TAITOKO code widely used for tsunami hazard prevention (Heinrich et al., 1998⁹⁰, Hébert et al., 2001⁹¹), shifted 41m30s.

Ne4Dgradient-dNedh-SamosEQ-tdjm59152.52291667 at height = 1130km (+ 41m 16s after EQ)



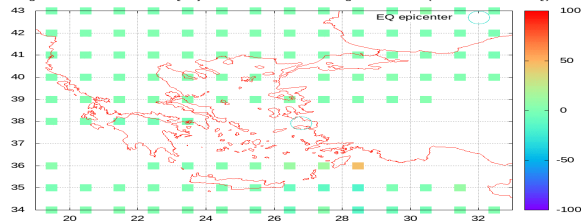
GNSS

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Monitoring
and new
applications

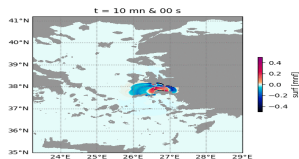
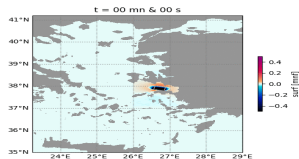
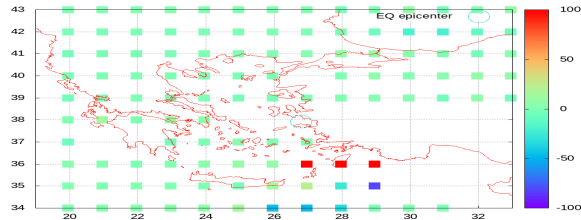
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al.

$\frac{\partial N_e}{\partial h}$ and tsunami height shifted 41m30s

Ne4Dgradient-dNedh-SamosEQ-tdjm59152.52291667 at height = 1130km (+ 41m 16s after EQ)



Ne4Dgradient-dNedh-SamosEQ-tdjm59152.52986111 at height = 1130km (+ 51m 16s after EQ)



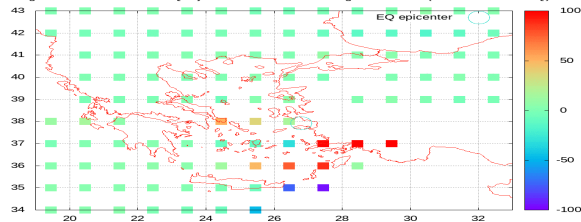
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Monitoring
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applications

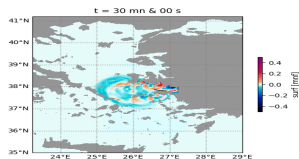
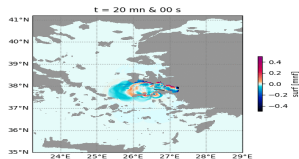
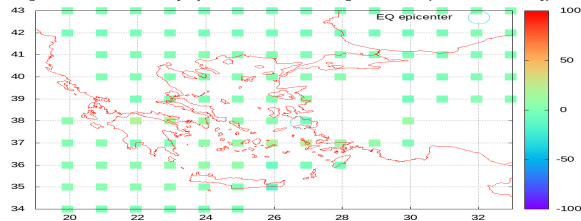
Hernández-
Pajares et
al.

$\frac{\partial N_e}{\partial h}$ and tsunami height shifted 41m30s

Ne4Dgradient-dNedh-SamosEQ-tdjm59152.53680556 at height = 1130km (+ 61m 16s after EQ)



Ne4Dgradient-dNedh-SamosEQ-tdjm59152.54375000 at height = 1130km (+ 71m 16s after EQ)



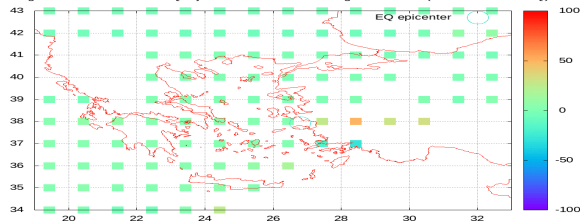
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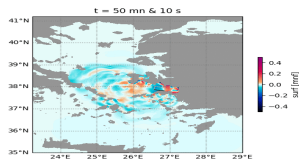
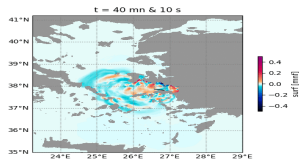
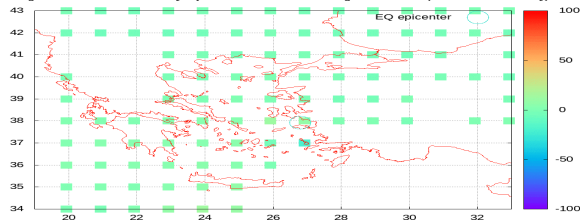
Hernández-
Pajares et
al.

$\frac{\partial N_e}{\partial h}$ and tsunami height shifted 41m30s

Ne4Dgradient-dNedh-SamosEQ-tdjm59152.55069444 at height = 1130km (+ 81m 16s after EQ)

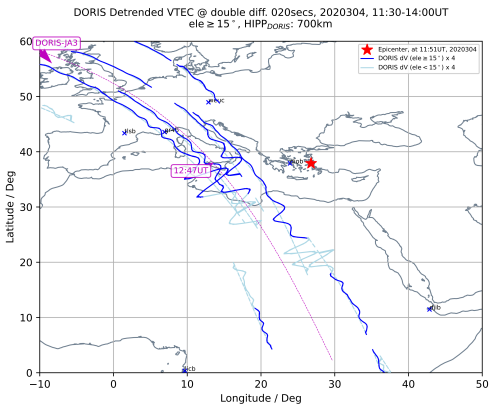


Ne4Dgradient-dNedh-SamosEQ-tdjm59152.55763889 at height = 1130km (+ 91m 16s after EQ)



Looking at JASON3 DORIS data

Considering Yang et al. (2022)⁹², and from the ground-to-JASON3 DORIS detrended VTEC, a compatible signature compatible has been also found.



⁹²Heng Yang et al. "Systematic detection of anomalous ionospheric perturbations above LEOs from GNSS POD data including possible

Summary of GNSS Ionosphere ground-based tsunami detection (1 of 3)

- The ionospheric electron density 4D gradient has been directly estimated from 20 GNSS receivers in the Samos region during the given day and previous day of October 30 2020 EQ.
- The larger values during these two days of the latitudinal component, $\frac{\partial N_e}{\partial \phi}$, but specially the height component of the gradient $\frac{\partial N_e}{\partial h}$ appears after starting the associated tsunami.
- An strong uplift of free electrons from the first shell to the second shell of the voxel-based tomographic model is detected since 42 min. up to 69 min. after the EQ main shock at the South-East of the epicenter, reaching values above 100 mTECU/km, and a late decrease up to 100 mTECU/km southward, which might be compatible with the tsunami evolution.

Summary of GNSS Ionosphere ground-based tsunami detection (2 of 3)

- A second uplift of free electrons, not so strong, has been detected towards the West of the EQ epicenter since 74 min. to 86 min. after the EQ main shock approximately.
- No significant vertical variations have been found to the North of the epicenter which might be compatible with a tsunami ionospheric signature *filtered* by the magnetic field.
- The evolution of the vertical gradient is compatible with the evolution of the tsunami height, after applying a delay of 41m30s and taking into account the geomagnetic field filtering effect⁹³.

⁹³Elvira Astafyeva. "Ionospheric detection of natural hazards". In: *Reviews of Geophysics* 57.4 (2019), pp. 1265–1288.

Summary of GNSS Ionosphere ground-based tsunami detection (3 of 3)

- Stronger signals are found: detrended VTEC below JASON3 from DORIS measurements at the part of the JASON3 footprint closer to the EQ epicenter, not found during previous day, and coinciding with a co-located increase of the detrended VTEC above SWARM from GNSS measurements.
- We interpret the plasma uplift as the signature of the propagation up to the thermosphere of the gravity waves generated by the Tsunami waves⁹⁴.

⁹⁴Sharon L Vadas et al. "Excitation of gravity waves by ocean surface wave packets: Upward propagation and reconstruction of the thermospheric gravity wave field". In: *Journal of Geophysical Research: Space Physics* 120.11 (2015), pp. 9748-9780.

LEO-based NRT tsunami warnings

Another potential GNSS application: geohazards monitoring. We have shown in⁹⁵ the feasibility of Near Real-Time (NRT) warnings from LEO POD GNSS data, with the new proposed approach *POD-GNSS LEO Detrended Ionospheric Electron Content Significant Deviations* (PIES).

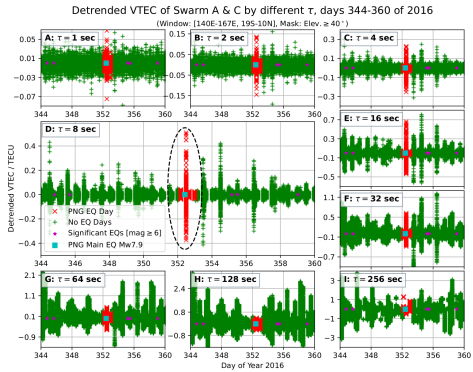


Fig. 3. The PIES detrended VTEC computed from Swarm A and C POD GPS data with an elevation mask of 40 deg is represented vs time during 17 days (in green) around the PNG earthquake, happened on 10h51m of day 352 of 2016 (with values marked in red), and for a spatial window (140°E–167°E vs. 19°S–10°N) around the epicentre. This is represented for different detrending time steps $\tau = 1, 2, 4, 8, 16, 32, 64, 128$, and 256 sec in subplots A to I. The common legends can be seen in plot D, in large size to emphasize that the larger detrended VTEC value happens very close to the earthquake main shock, and for $\tau = 8$ sec consistently with the expected values considering the high movement of the LEO and the expected wavelengths of the ionospheric waves. The blue star for location of the significant earthquakes ($\geq$ Mw 6).

⁹⁵Heng Yang et al. "Systematic detection of anomalous ionospheric perturbations above LEOs from GNSS POD data including possible tsunami signatures". In: *IEEE Transactions on Geoscience and Remote Sensing* 60 (2022), pp. 1–23.

Other applications: Tsunami warnings

PIES has been successfully applied to actual GNSS POD SWARM measurements co-located with a mid intensity earthquake and tsunami in Papua-New Guinea.

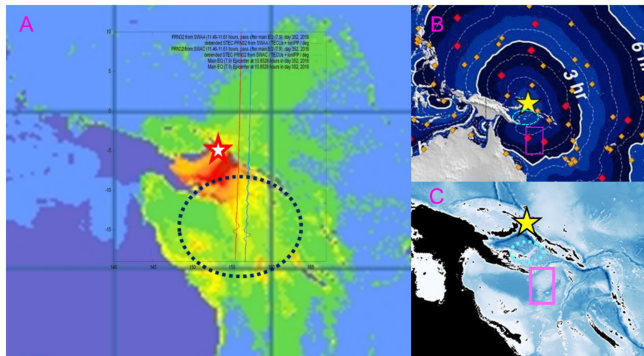
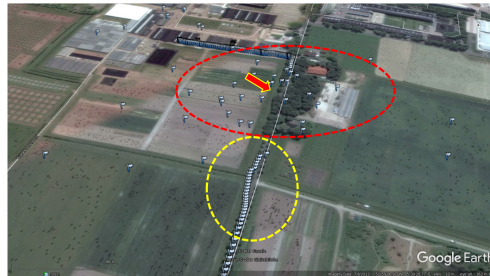
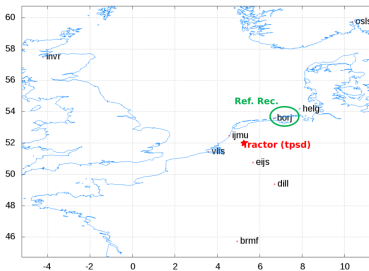


Fig. 6. A: The detrended VTEC overlapped on the trajectory of the ionospheric observing points regarding GPS satellite PRN 32 Swarm A & C, attached with the tsunami maximum amplitude graph, ranging from 0 (blue) to 100 cm (red), with intermediate growing values in green, yellow, and orange (source from [61]); B: Zoomed tsunami travel times, source from [61]; C: Zoomed Ocean Depth, white for the shallow part and blue for the deep sea (up to -8000 m in black), originating from the earth observatory of the U.S. NASA blue marble with topography and bathymetry, the yellow star for the epicentre, magenta rectangular for ionospheric observing points with higher detrended VTEC, and the cyan ellipse for the tsunami with the highest wave.

Fast and far-away precise RT GNSS rover positioning

It works thanks to the tomographically computed RT ionospheric LoS delays received by the user, at distances up to hundreds of km from the permanent receivers, by providing RT double differences (pair/receivers) of Slant Total Electron Content better than $\frac{1}{4}$ TECU, thanks to our inhouse software TOMIONv2, see Wide Area RTK (WARTK) application to agriculture in⁹⁶.

Rec. Id.	Distance to BORJ / km
HELG	104
<u>IJMU</u>	188
TPSD	190
VLIS	316
EIJS	321
DILL	468
OSLS	722
INVR	811
BRMF	882



⁹⁶Manuel Hernández-Pajares et al. "Wide-Area GNSS Corrections for Precise Positioning and Navigation in Agriculture". In: *Remote Sensing* 14.16 (2022), p. 3845.

WARTK experiments

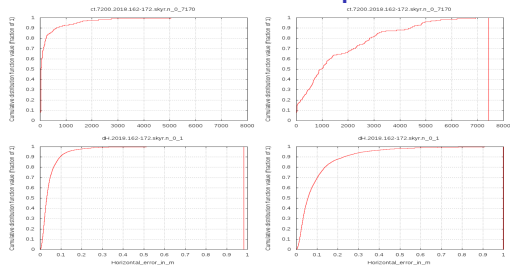
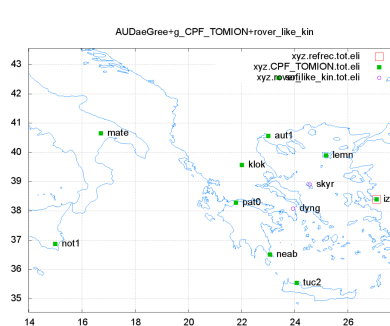
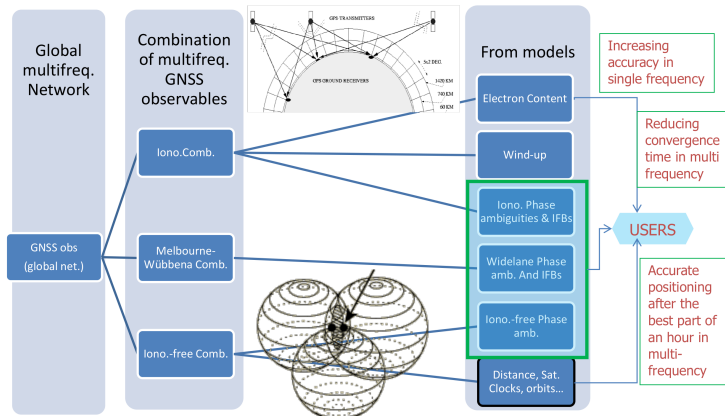


Figure 7. Summary of results for roving user SKYR. First row: Percentage of cumulative cases, over the 132 roving user resets between days 162 to 172, 2018, vs. convergence time for horizontal positioning error, in seconds. Second row: Corresponding final horizontal positioning error, in meters. First column: WARTK, constraining ambiguities updating them at every chance, and slightly estimating the permanent receivers coordinates; second column: no ambiguity constraining (i.e., without using the WARTK ionospheric corrections).

And the fast and far-away precise GNSS positioning can be done as well in an undifferenced and uncombined way (very suitable for multi-frequency multi-GNSS signals) thanks to the new TOMIONv2-uncomb software branch (see⁹⁷), opening both recent works new ways to affordable precise agriculture requiring sparse ground GNSS networks.

⁹⁷Germán Olivares-Pulido et al. "Ionospheric tomographic common clock model of undifferenced uncombined GNSS measurements". In: *Journal of Geodesy* 95.11 (2021), pp. 1–13.

WARTK: Symbiotic tomo-ionospheric & geodetic combined-undifferenced model



WARTK details can be found in⁹⁸.

⁹⁸Manuel Hernández-Pajares et al. "Wide-Area GNSS Corrections for Precise Positioning and Navigation in Agriculture". In: *Remote Sensing* 14.16 (2022), p. 3845.

Ionospheric Tomographic Common Clock uncombined undifferenced model (ITCC)

At the Central Processing Facility (CPF) from permanent GNSS receivers separated up to several hundreds of kilometers:

$$\begin{aligned}
 P(t)_{i,j}^k &= \rho(t)_j^k + c \cdot [dt(t)_j - dt(t)^k] + M_T(t)_j^k \cdot Z_T(t)_j + \\
 &\quad \frac{\beta}{f_i^2} \left[\sum_{p=1}^{n(t)_k^j} N_e(t)_{m(p)} \cdot \delta I(t)_{m(p),j}^k \right] + \frac{\beta}{f_i^2} [D(t)_j - D(t)^k] \\
 L(t)_{i,j}^k &= \rho(t)_j^k + c \cdot [dt(t)_j - dt(t)^k] + M_T(t)_j^k \cdot Z_T(t)_j \\
 &\quad - \frac{\beta}{f_i^2} \left[\sum_{p=1}^{n(t)_k^j} N_e(t)_{m(p)} \cdot \delta I(t)_{m(p),j}^k \right] + B_{i,j}^{k,m} + \frac{c}{f_i} \phi(t)_j^k,
 \end{aligned} \tag{10}$$

Model for the ITCC users

For any ITCC GNSS user (up to hundreds of kilometers from the nearest permanent GNSS receiver), with details in⁹⁹:

$$\begin{aligned}\tilde{P}(t)_{i,rov}^k &= -\hat{\rho}(t)_{rov,0}^k \cdot \Delta \vec{X} + c \cdot dt(t)_{rov} + M_T(t)_{rov}^k \cdot Z_T(t)_{rov} + \frac{\beta}{f_i^2} D(t)_{rov} \\ \tilde{L}(t)_{i,rov}^k &= -\hat{\rho}(t)_{rov,0}^k \cdot \Delta \vec{X} + c \cdot dt(t)_{rov} + M_T(t)_{rov}^k \cdot Z_T(t)_{rov} + B_{i,rov}^{k,m} + \frac{c}{f_i} \phi(t)_{rov}^k\end{aligned}\quad (11)$$

where

$$\begin{aligned}\tilde{P}(t)_{i,rov}^k &\equiv P(t)_{i,rov}^k - \rho(t)_{rov,0}^k + c \cdot dt(t)^k - \frac{\beta}{f_i^2} S(t)_{rov}^k + \frac{\beta}{f_i^2} D(t)^k \\ \tilde{L}(t)_{i,rov}^k &\equiv L(t)_{i,rov}^k - \rho(t)_{rov,0}^k + c \cdot dt(t)^k + \frac{\beta}{f_i^2} S(t)_{rov}^k,\end{aligned}\quad (12)$$

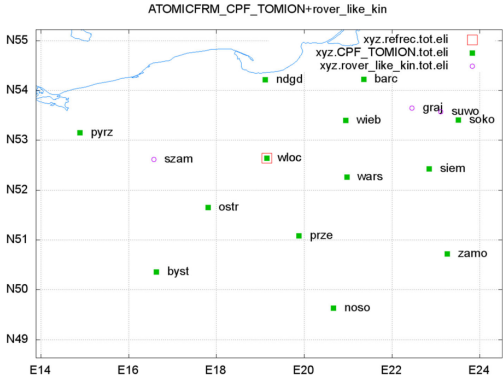
⁹⁹Germán Olivares-Pulido et al. "Ionospheric tomographic common clock model of undifferenced uncombined GNSS measurements". In: *Journal of Geodesy* 95.11 (2021), pp. 1–13.

ITCC experiment (1)

Table 1 Comparison of models in terms of their algebraic features and applicability in large networks (✓ and ✗ indicates whether the given condition is fulfilled or not, respectively)

Model	STEC-CC	VTEC-CC	ITCC
Rank fixed	✗	✓	✓
Large Network modelling	✓	✗	✓
Linear scaling of the Jacobian	✗	✗	✓
Estimable DCBs	✗	✓	✓

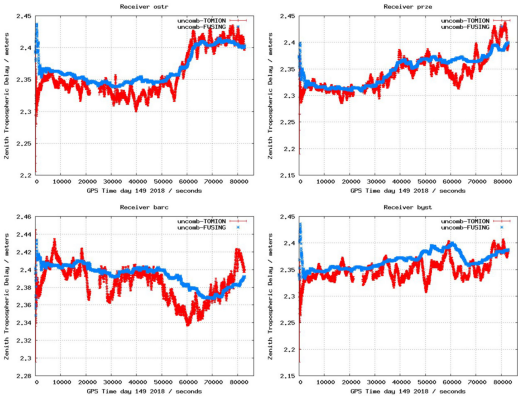
Fig. 1 Map representing the permanent receivers in Poland, containing the X-axis and Y-axis the longitude and latitude, respectively, in degrees. Data from days 249–255 in year 2018 (green squares) has been analysed in this work, as well as the reference receiver (red square) and permanent GPS ones treated as rover users (magenta circles)



ITCC experiment (2)

Table 2 Approximate percentile 95% of the convergence time in seconds of receiver SZAM treated as roving user to horizontal positioning error of 10 cm (first column), 20 cm (second column) and 30 cm (second column), performing a cold start every two hours during days 149-155 of year 2018

Rover SZAM	C.T. HPE 10 cm	C.T. HPE 20 cm	C.T. HPE 30 cm
WAPPP	4000 s	1200 s	700 s
ITCC	1350 s	450 s	250 s
WARTK+DDambFixing	750 s	200 s	125 s



Conclusions

- GNSS Ionosphere has become an excellent Space Weather monitor thanks to the precise and accurate real-time (RT) determination, from multi-frequency GNSS measurements, of the free electrons distribution in the ionosphere. In particular to compute in RT:
 - ① RT Global Ionospheric Maps, which can allow to estimate:
 - Global map of Space Weather (SW) semaphors (ionospheric storm scale)
 - SW impact (electron content gradient) quantifier
 - ② RT Solar Flare warnings and geoeffectiveness.
 - ③ RT global maps of ROTI.
- Other applications of RT-ionospheric estimation are:
 - ① Potential NRT tsunami warnings.
 - ② Fast, undifferenced, uncombined precise RT GNSS rover positioning.
- What are now the VTEC global map, the detrended solar EUV flux and the map of the ionospheric scintillation proxy? See^{100, 101, 102} **THANK YOU!**

¹⁰⁰ http://chapman.upc.es/tomion/real-time/quick/last_results.uadg/RT-VTEC-SNAPSHOT.gif

¹⁰¹ <http://chapman.upc.es/.monitor/solera-drift.latest.musf.gif>

¹⁰² http://chapman.upc.es/.monitor/2024/156/NRT/ROTI/global_plots/animation/roti.2024.156.mp4