GNSS Ionosphere: From Global Ionospheric Maps (GIMs) to Vertical Total Electron Content (VTEC) series

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Outline

Part 1- Visual introduction to GNSS Ionosphere

Part 2- Access to UPC-IonSAT Global Ionospheric Maps PITHIA-NRF registrations (AKA global VTEC maps every 15 minutes since end of 1996, i.e. ~1 million global VTEC maps & 5x10^9 VTECs computed so far)

Part 3- New applications of GIMs: gradient VTEC GIMs and Ionospheric Storm Scale GIMs

Part 4- Very basic introduction to Linux and to ionsat-tool "gim2vtec*.scr"

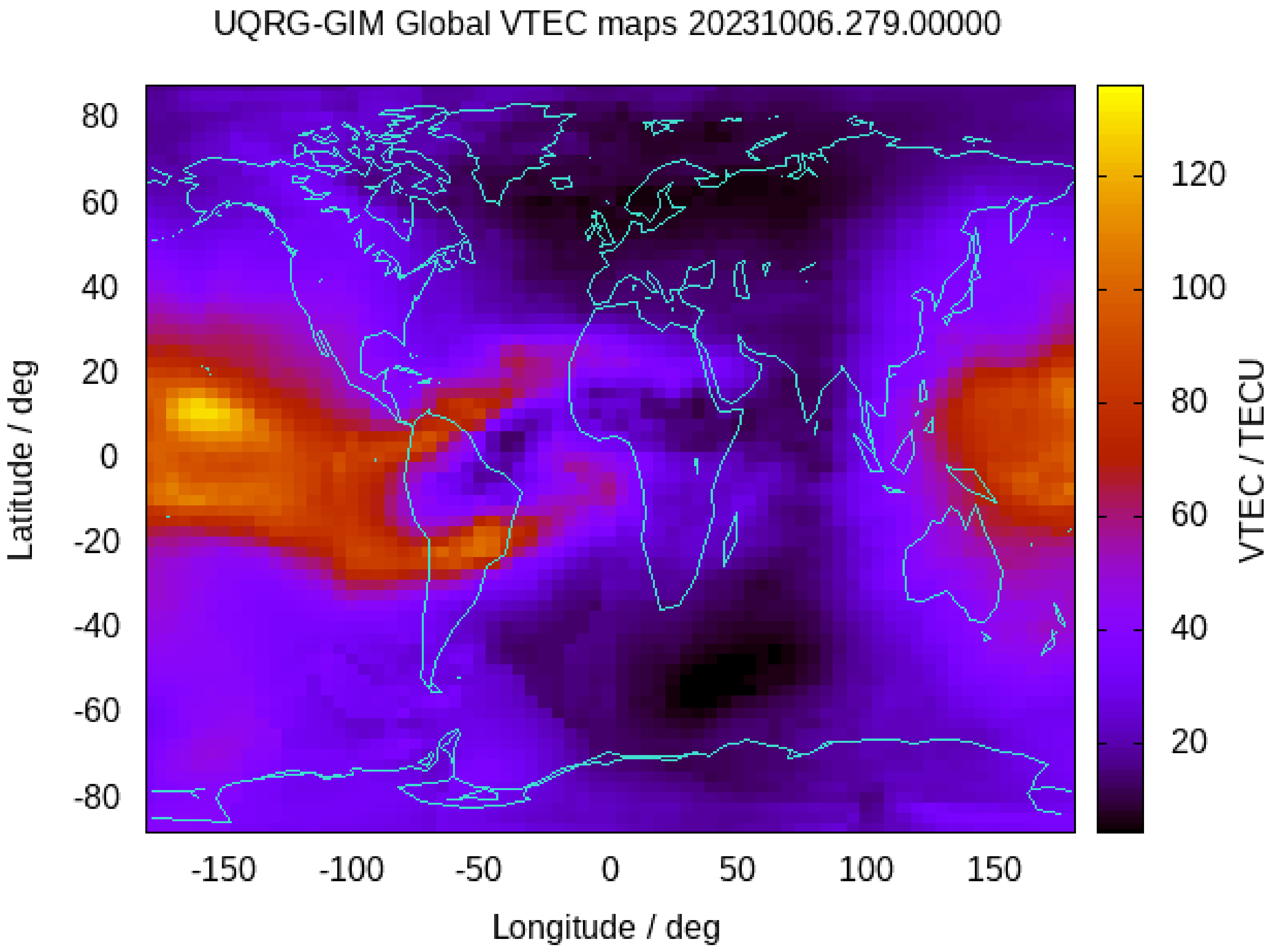
Part 5- Two case studies to work with:

(a) Total solar eclipse during 21-Aug-2017 in NorthAmerica
(b) Geomagnetic storm during 05-Nov-2023

Part 1

Visual introduction to GNSS Ionosphere

What is this?



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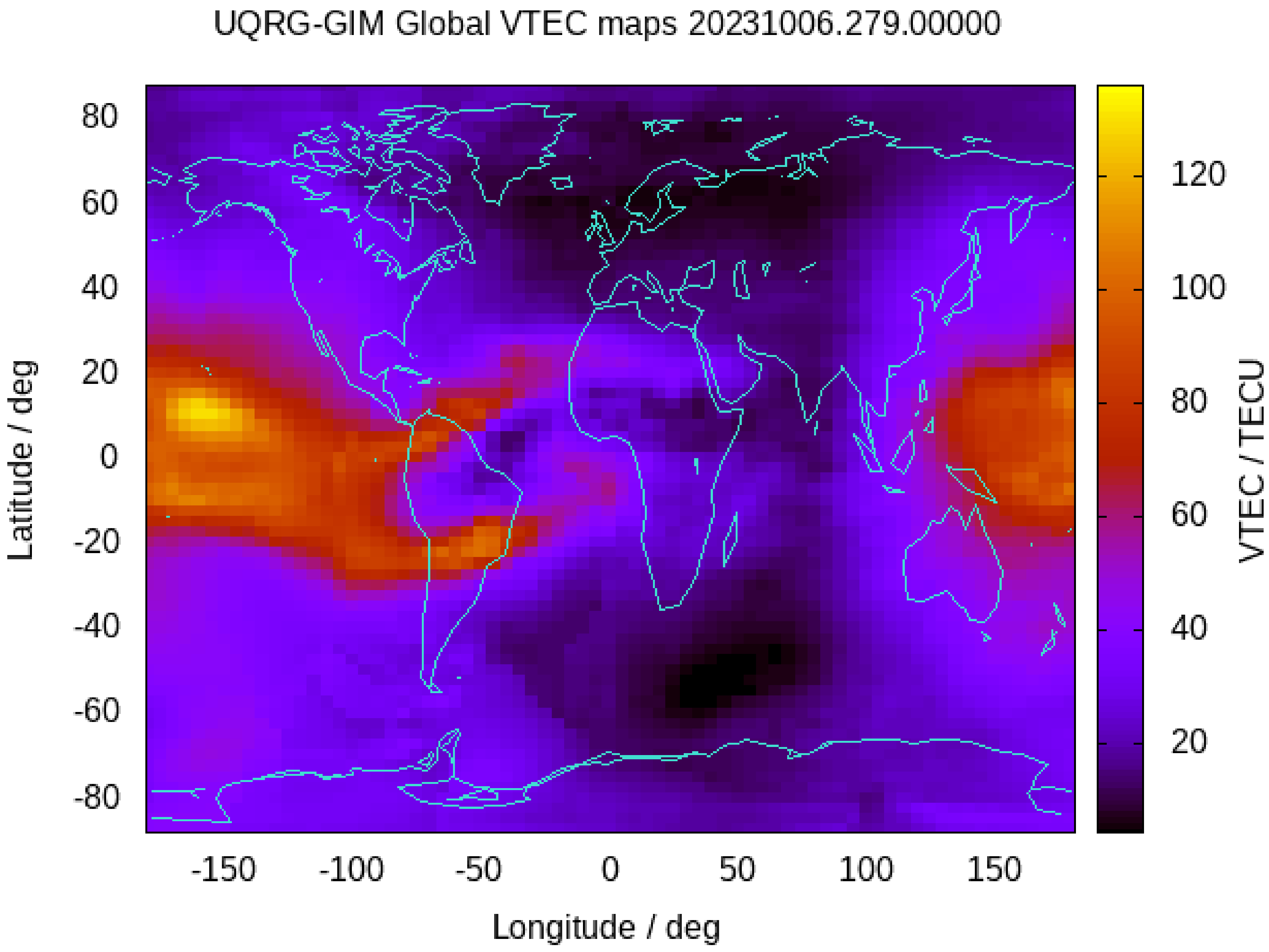
What is this?

Movie of the vertically integrated electron number density (AKA Vertical Total Electron Content, VTEC) of the partially ionized part of the Earth atmosphere (ionosphere) obtained from worldwide Global Navigation Satellite System (GNSS) multifrequency measurements

Do you wish to check the present global VTEC, from RT UPC-IonSAT GIMs? If yes:



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

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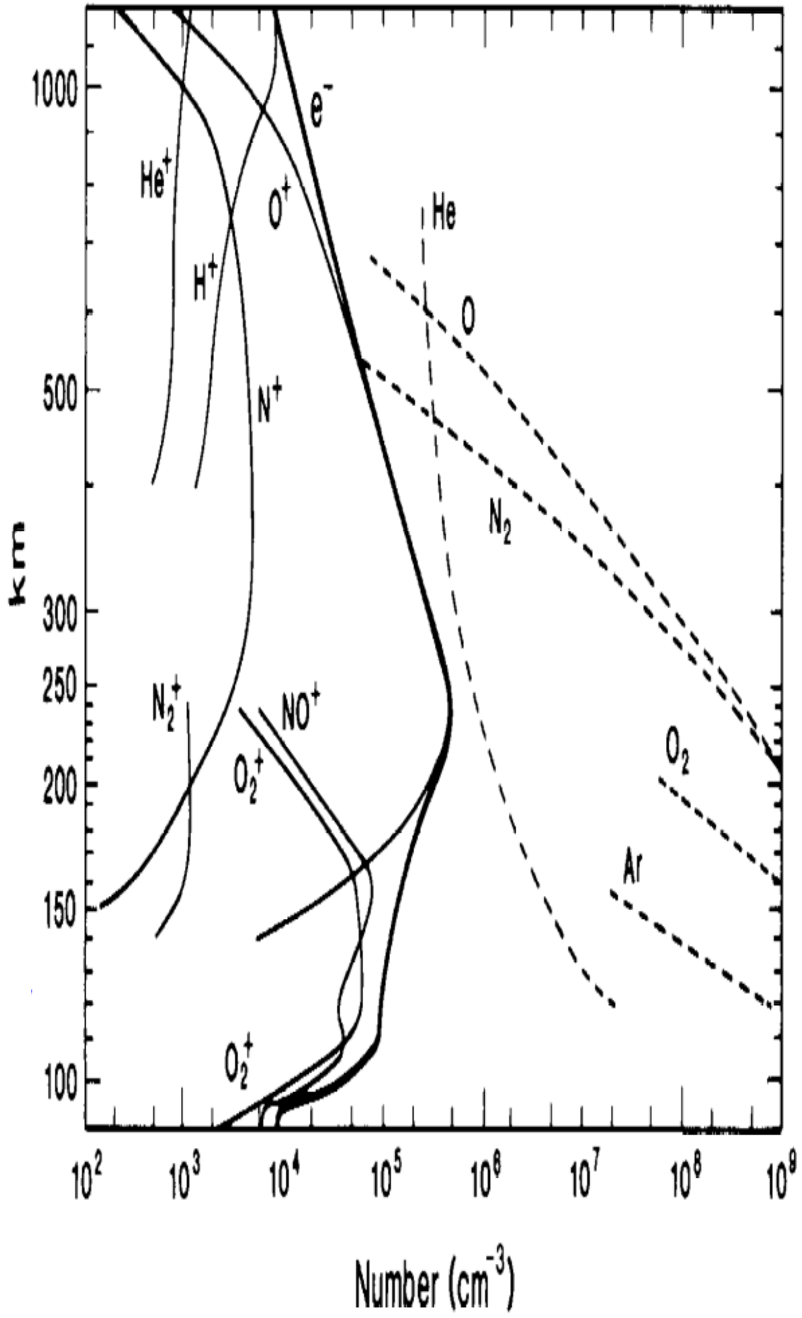
Why there are free electrons within the Earth atmosphere?



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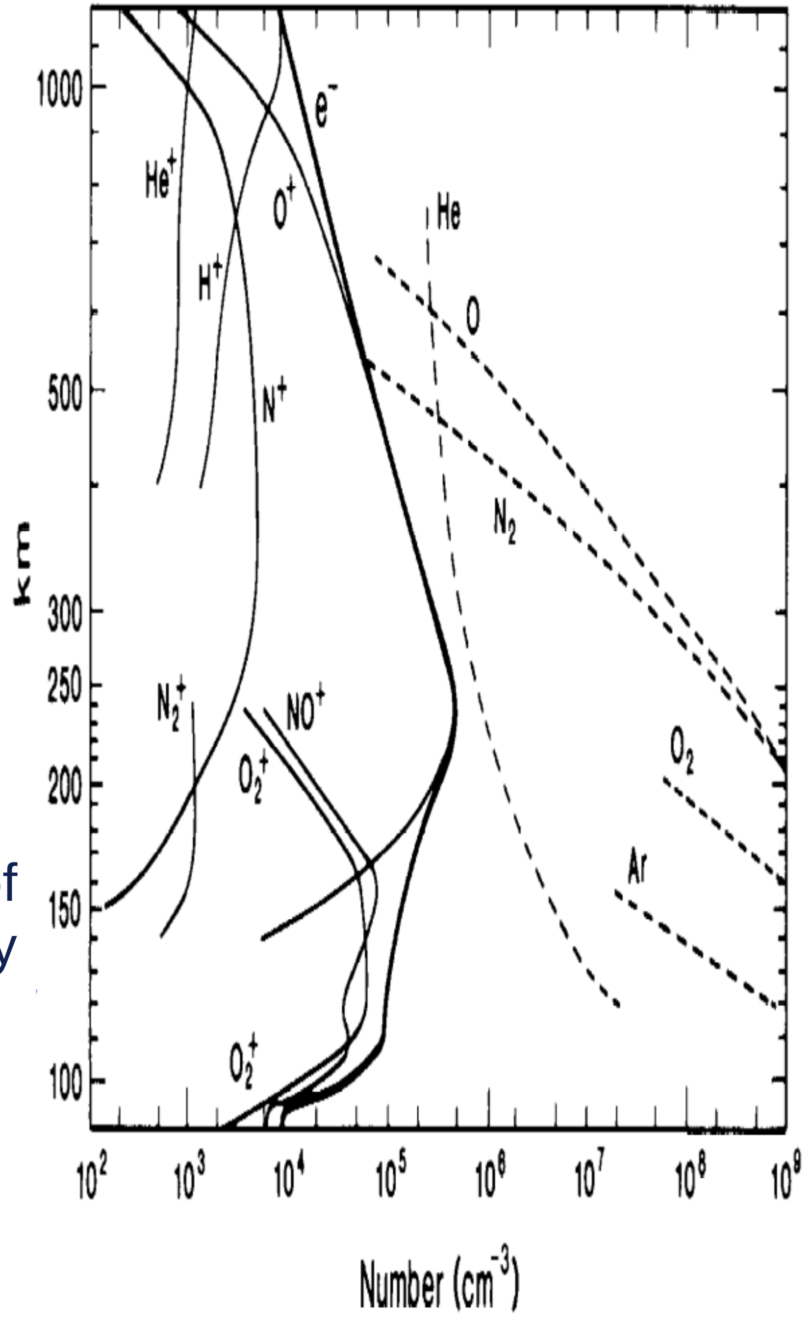
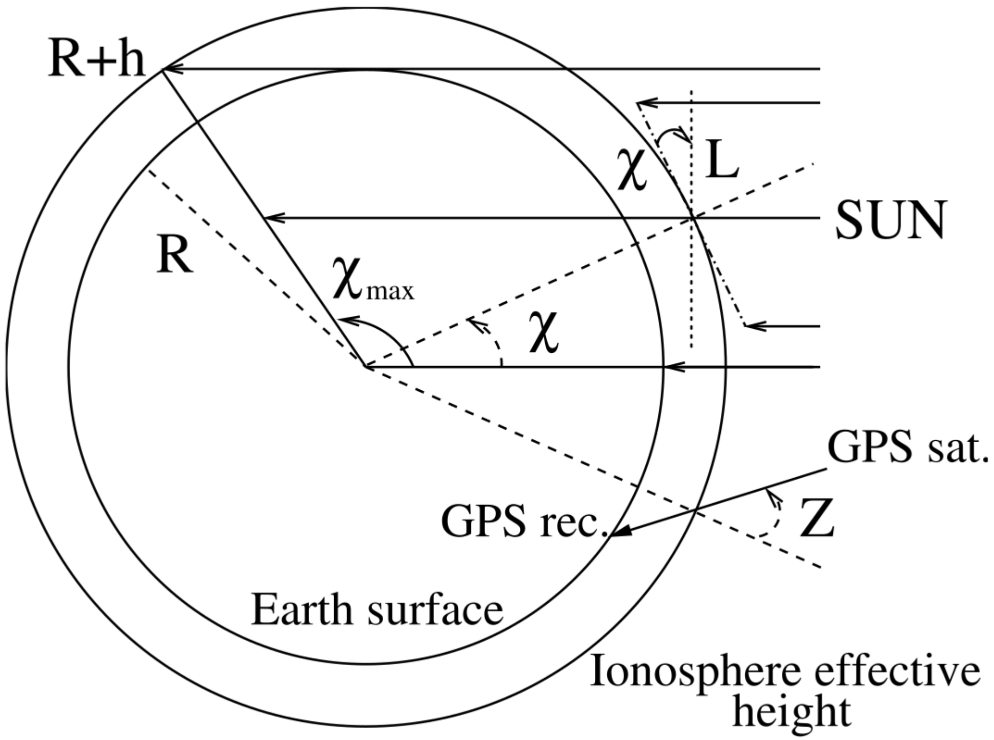
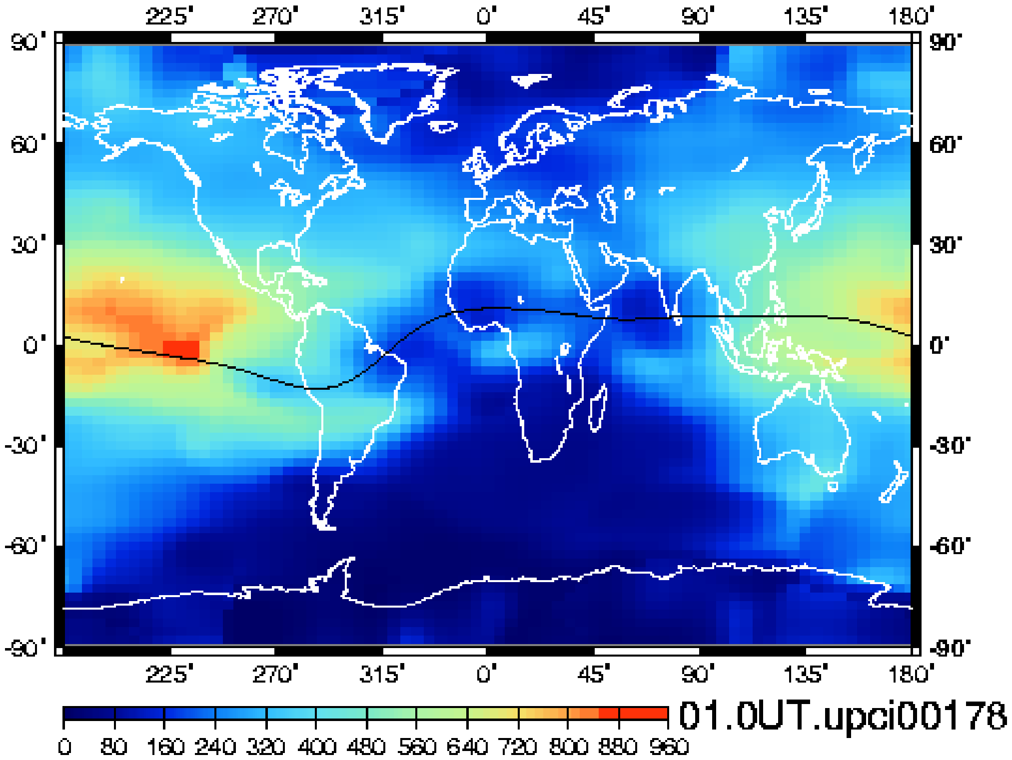
Why there are free electrons within the Earth atmosphere?

The chemical reactions on the Earth atmosphere of dissociation of different molecules at different heights by solar photons (mostly in EUV and X-ray bands).



How can the VTEC distribution be explained?





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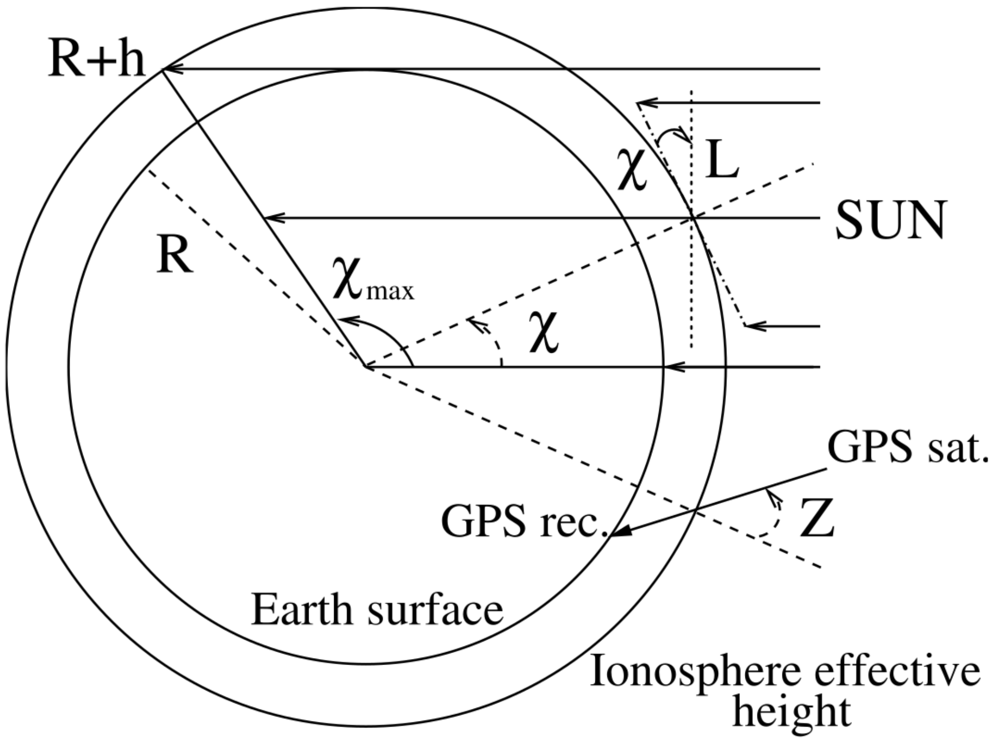
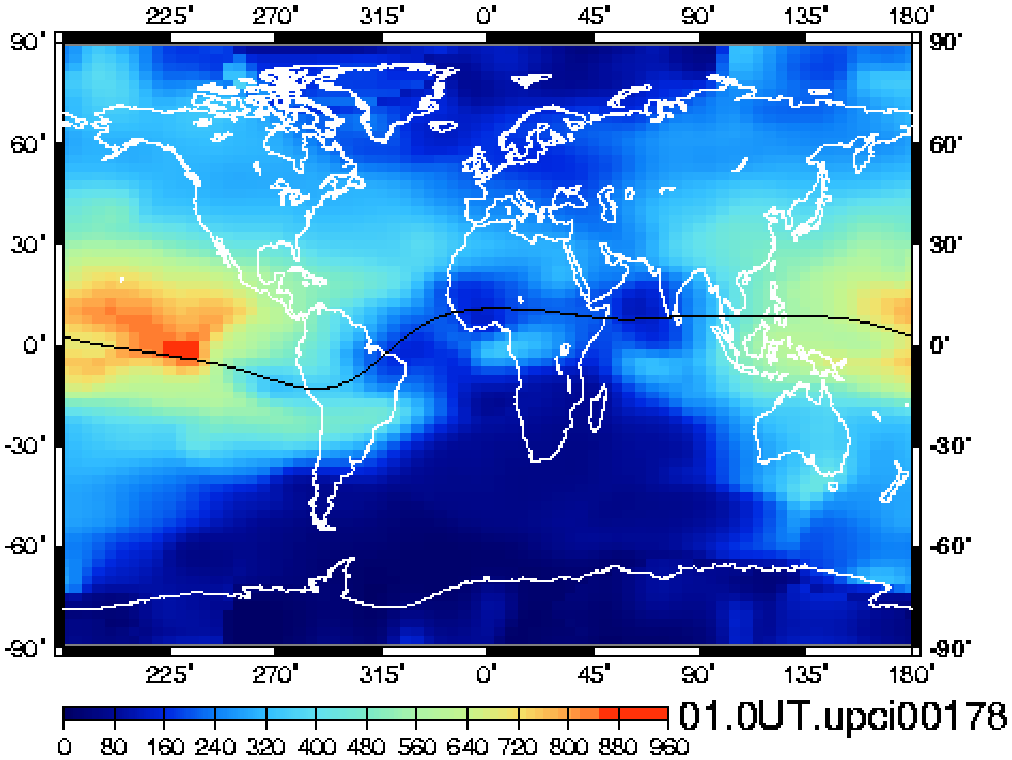
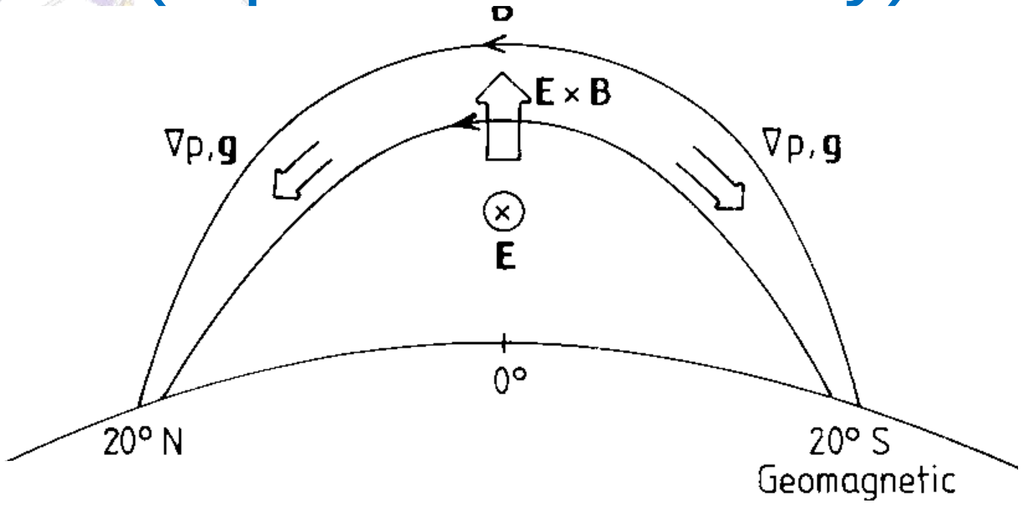


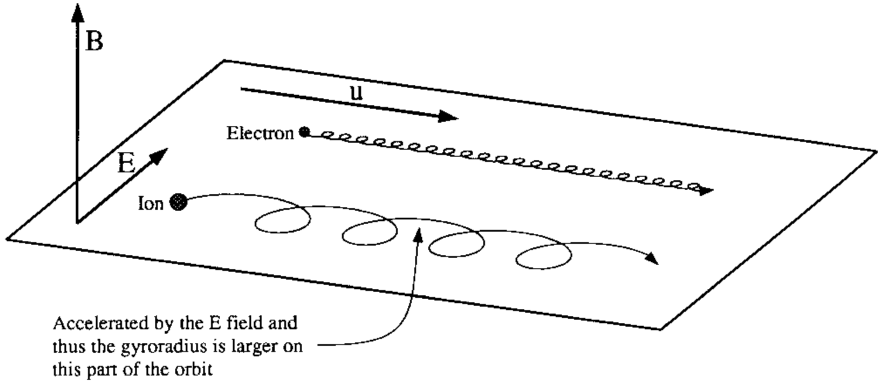


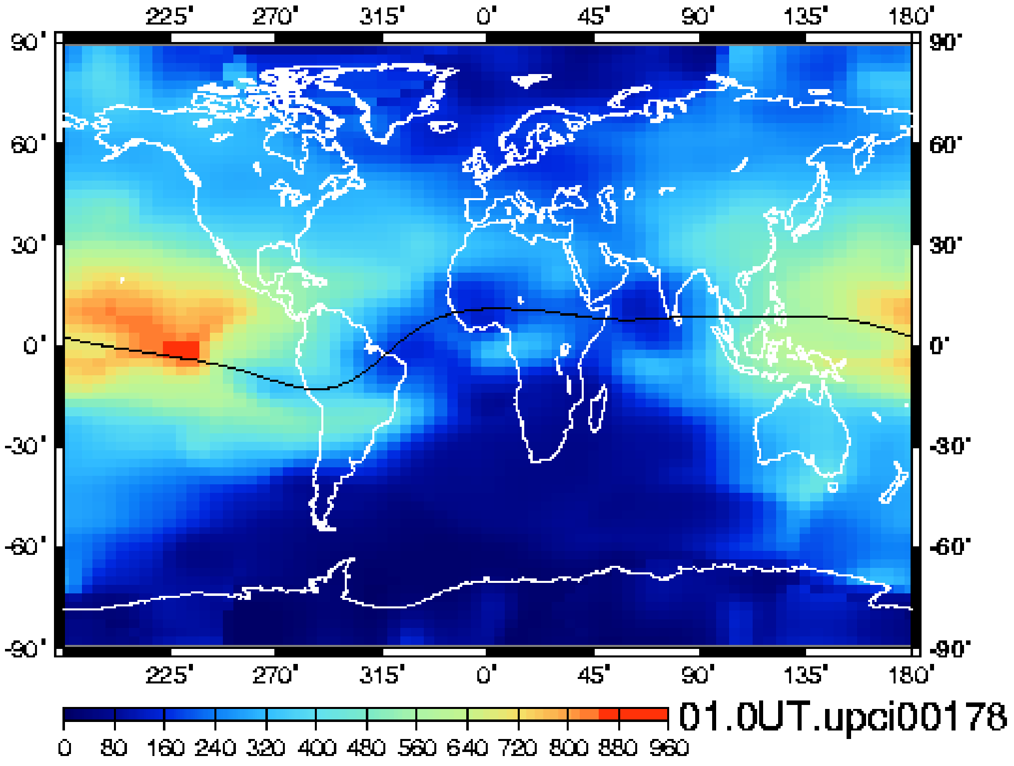
- In principle, taking into account with different solar irradiance in function of the latitude

- (And the Earth rotation!)

Anything else to be explained? What about the double VTEC peak (equatorial anomaly)?







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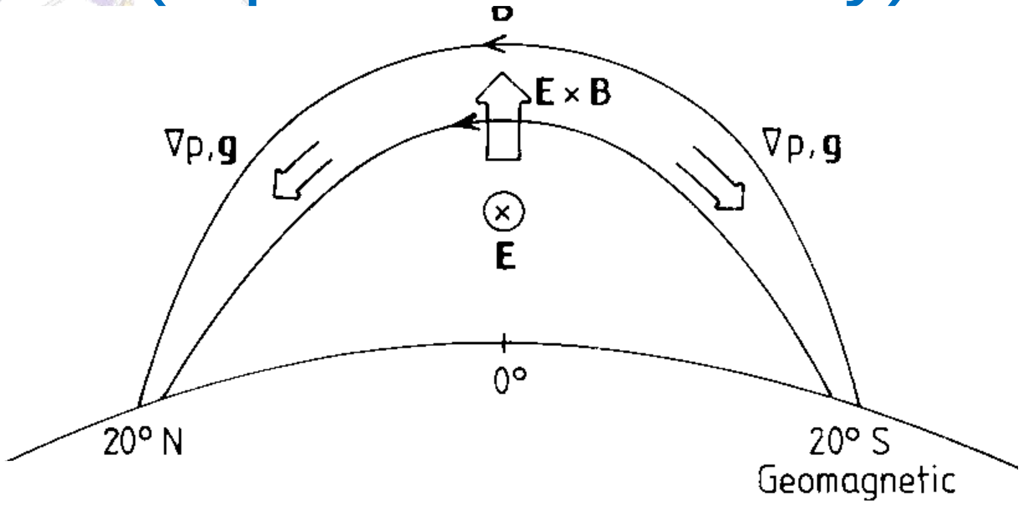
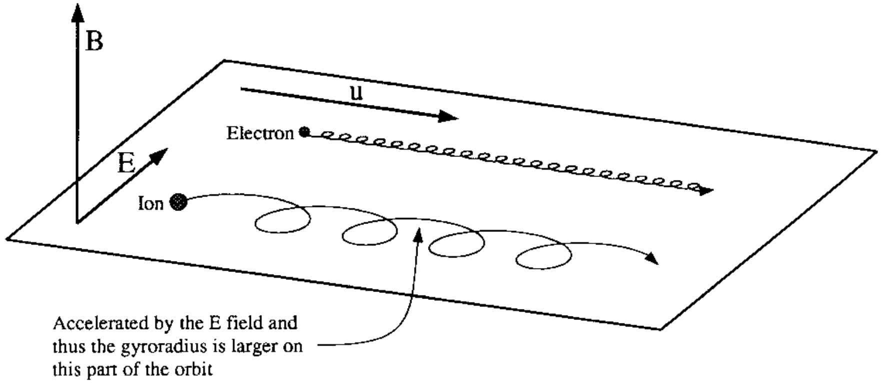
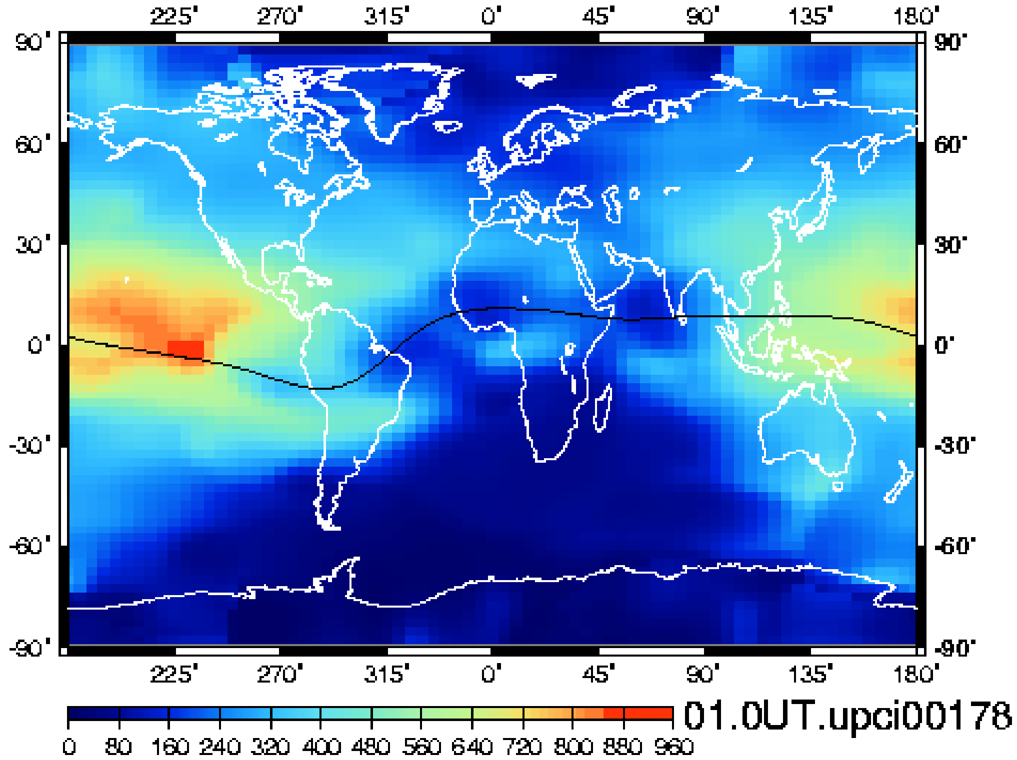
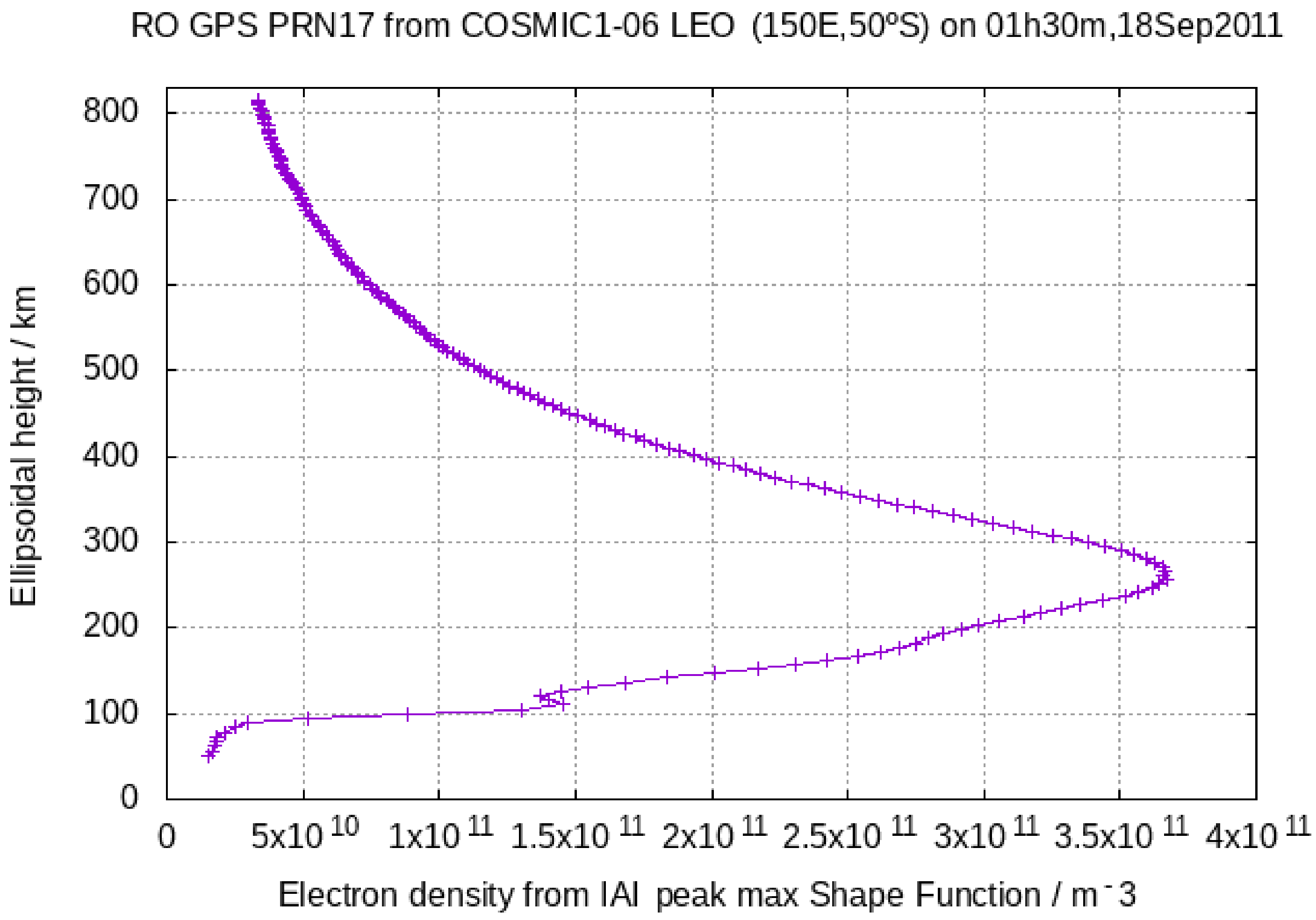






ExB drift, generates the fountain effect, and then, the equatorial anomaly and double peak, with a central role of the magnetic field, the magnetic equator in particular, in the distribution of the free electrons of the Earth ionosphere.

And this? How can it be explained?

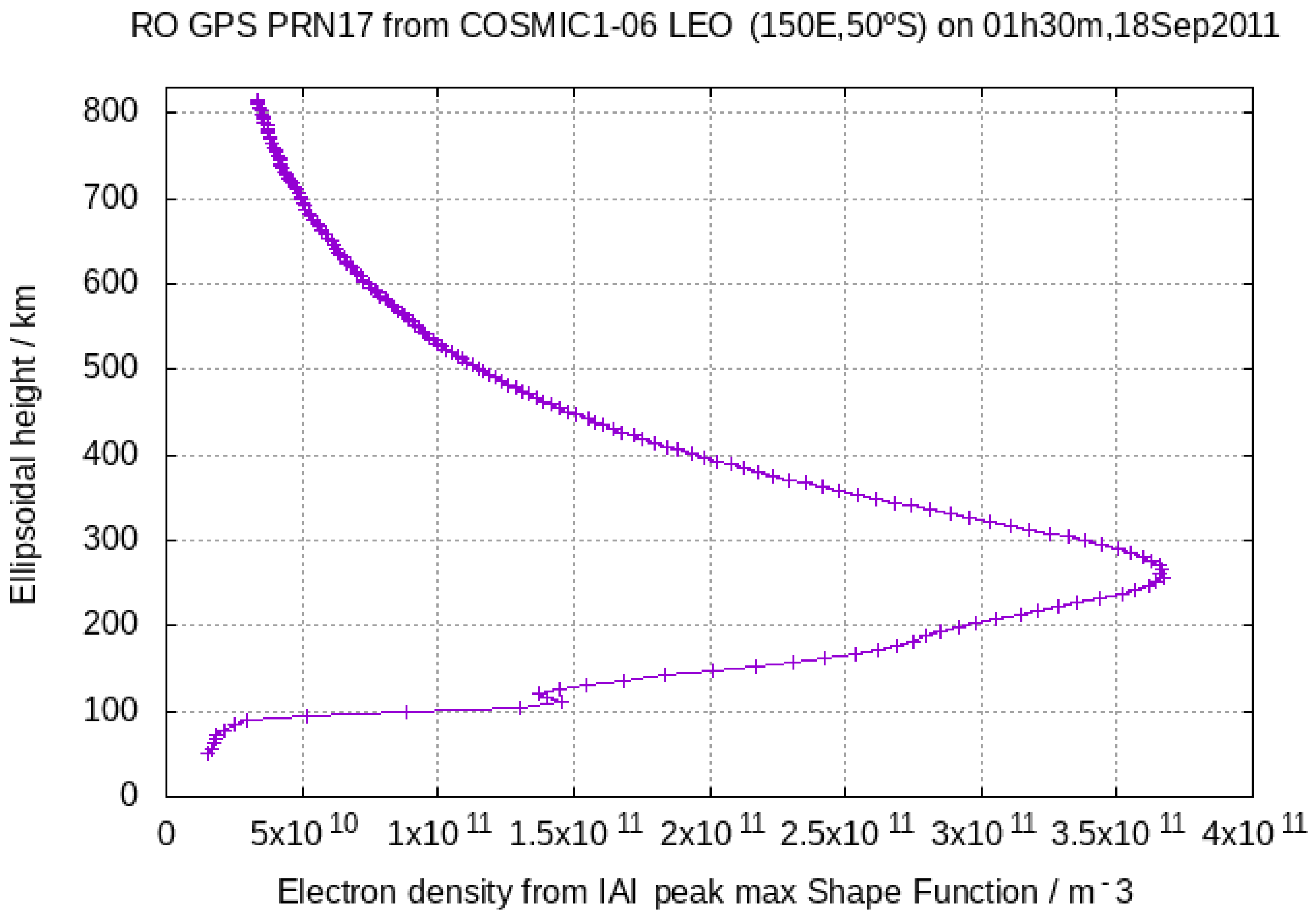


And this? How can it be explained?

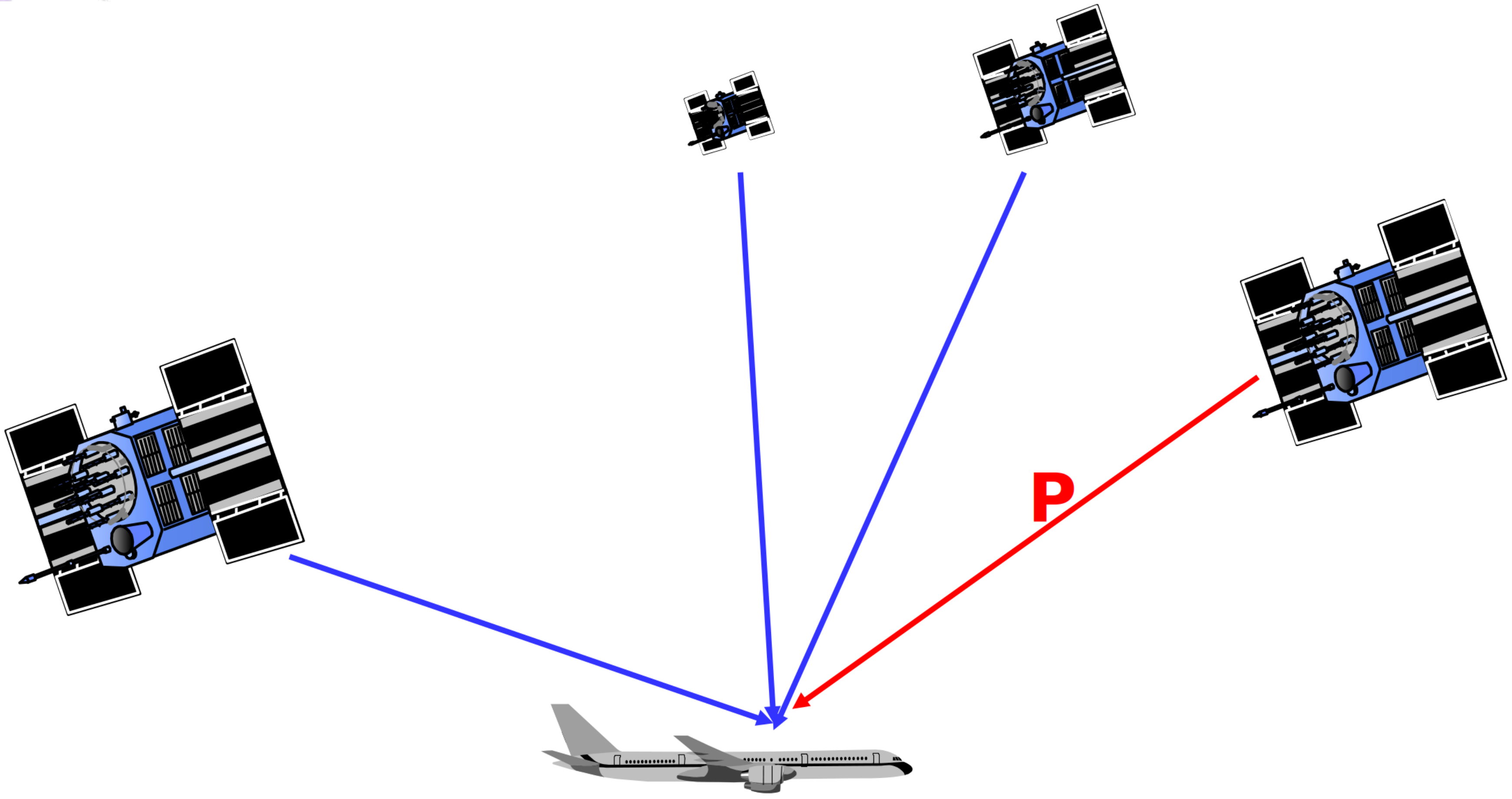
- The electron number density (hereinafter electron density) vs height(*).

- The intermediate electron density peak height can be understood as the optimal height of production of free electrons, a compromise between enough number of target molecules and enough ionizing solar radiation, specially in EUV.

(*) Estimated thanks to GNSS receivers flying on a Low Earth Orbiting satellite -in this case FORMOSAT-3/COSMIC- measuring multifrequency GNSS signals from transmitters below the LEO local horizon (radio-occultation scenario).



And what about this? Any guess?



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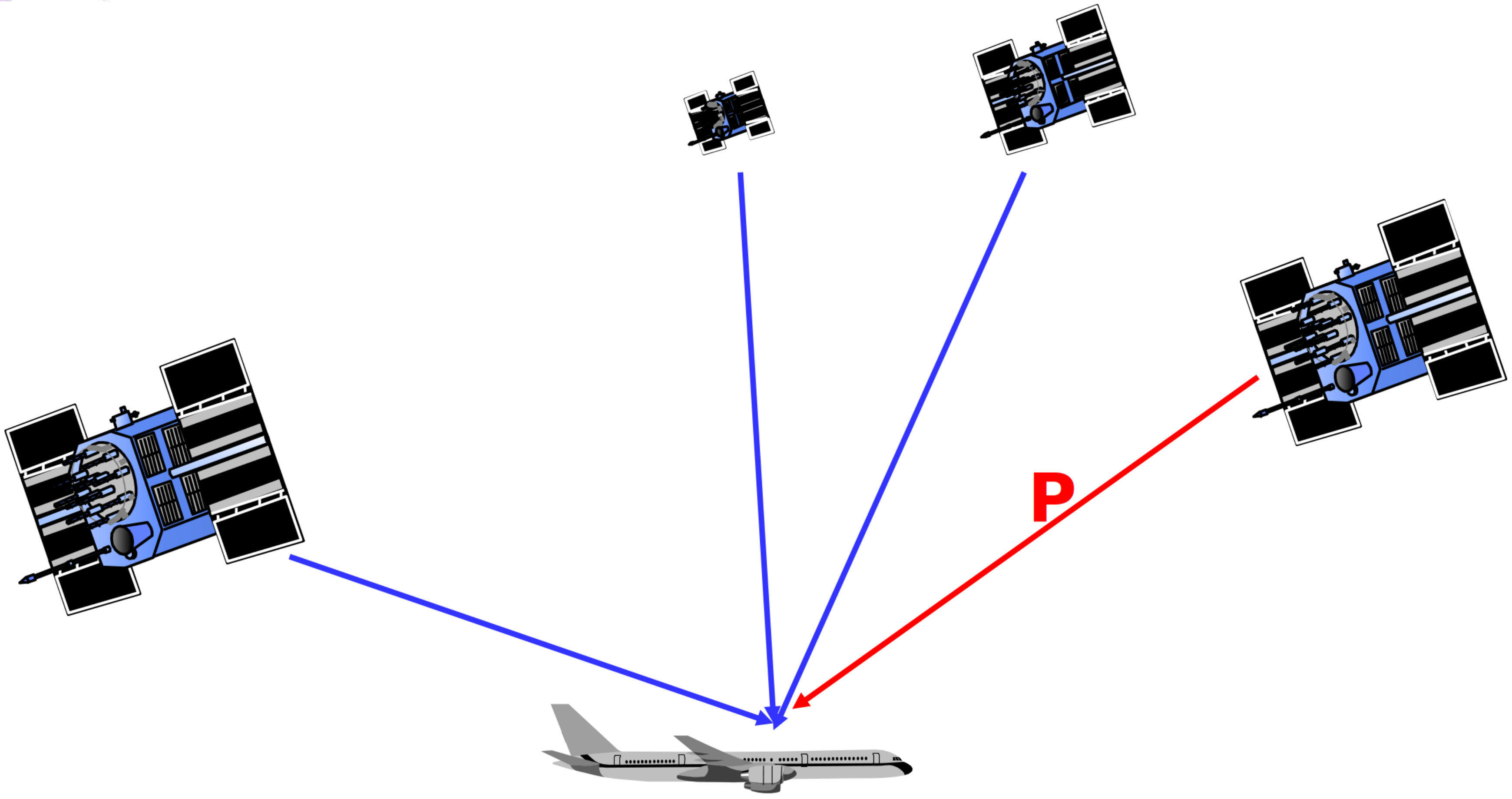
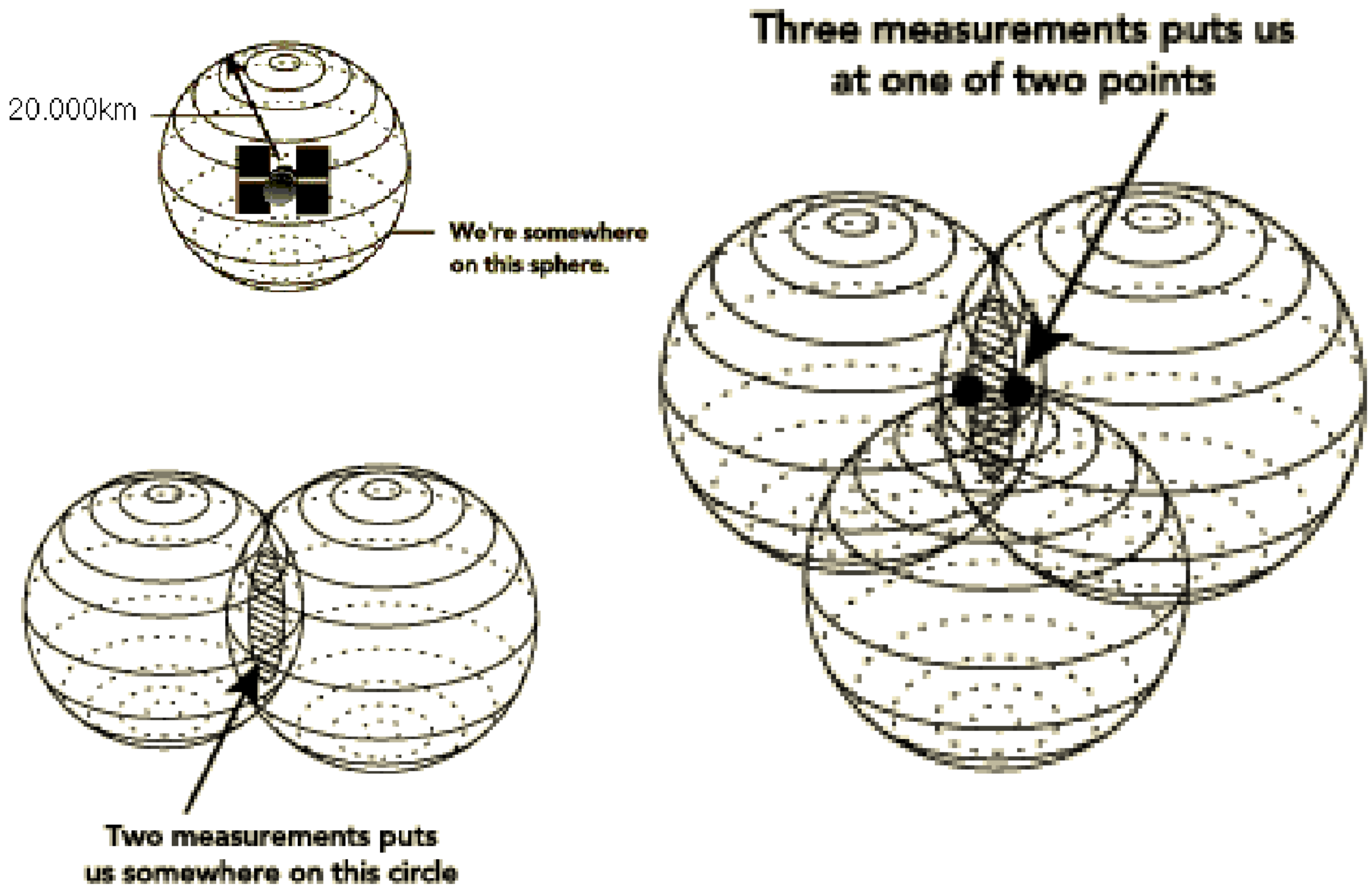


Yes, these are four Global Positioning System (GPS) transmitter providing pseudodistance signals to a receiver on board an airplane (this an “artistic” composition NOT following the real distance scale).

And now, who can explain these layouts?



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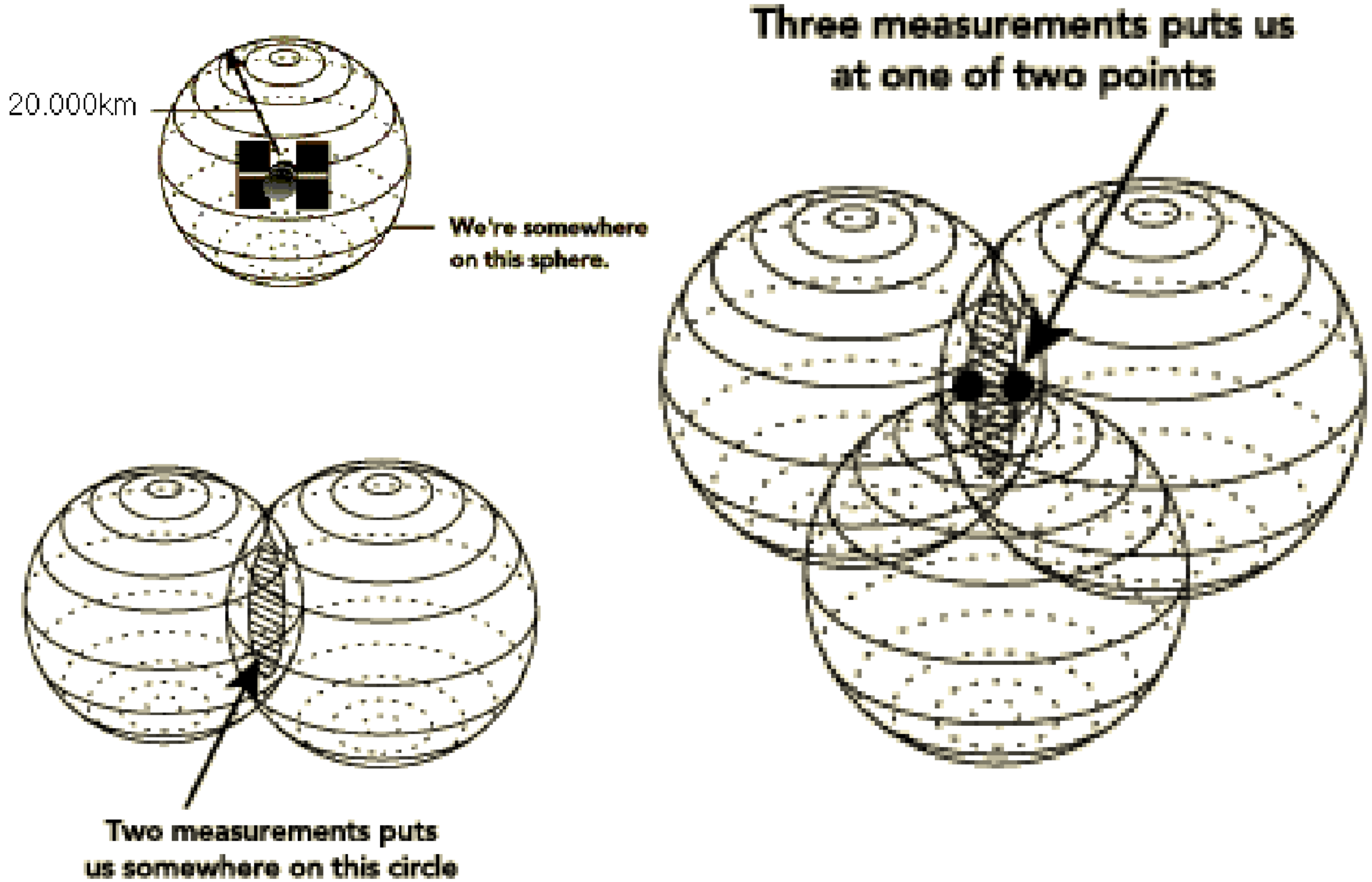
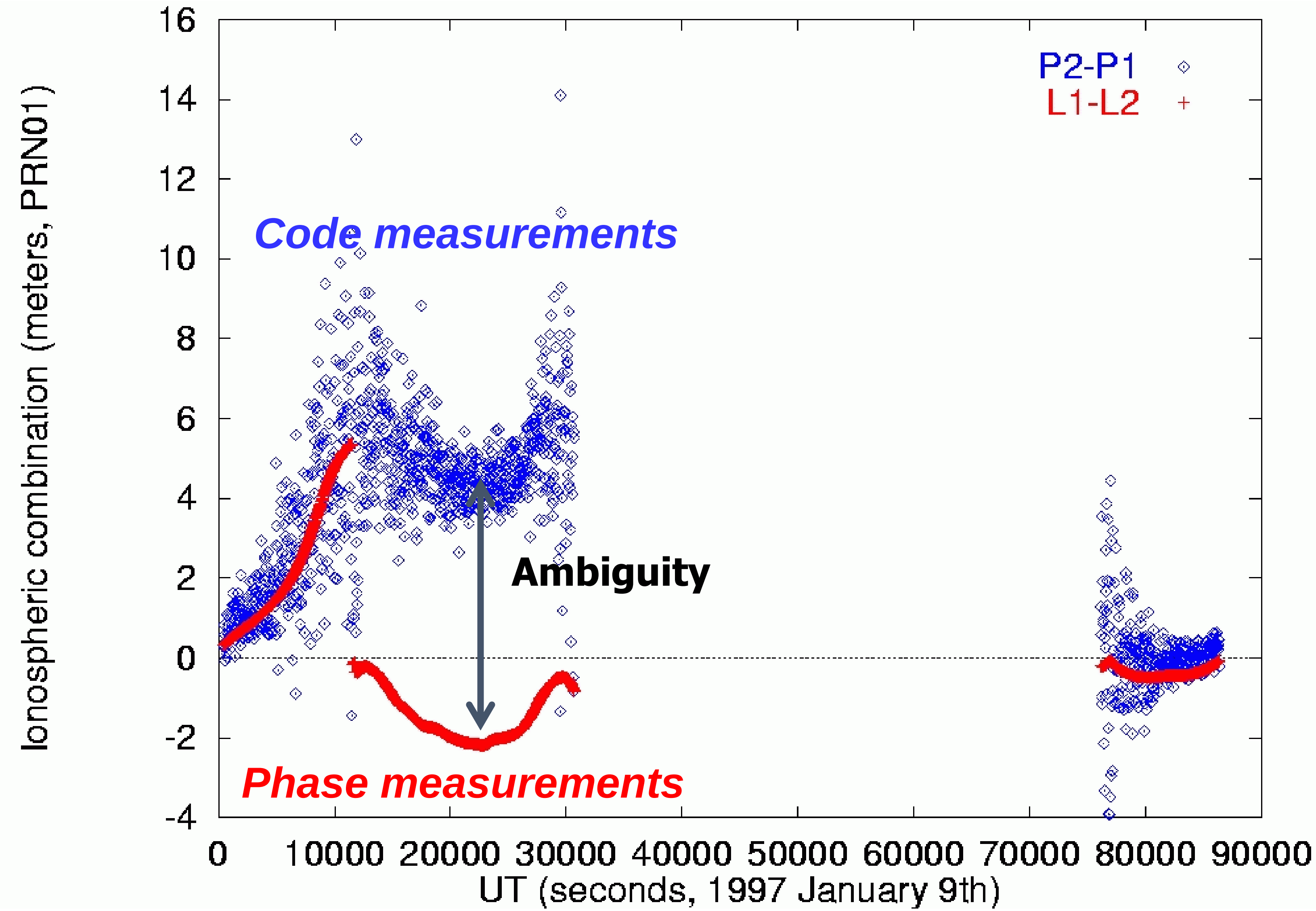


Yes, it illustrates the trilateration concept, foundation of GNSS for positioning: knowing the position of the center of at least three(*) spheres in different directions -GNSS transmitters on MEOs- and the radius of such spheres -from the pseudorange measurements-, we get the receiver position X,Y,Z -intersection-).

(*) at least four satellites are needed taking into account the receiver clock error

Now, any guess or comment about this plot?

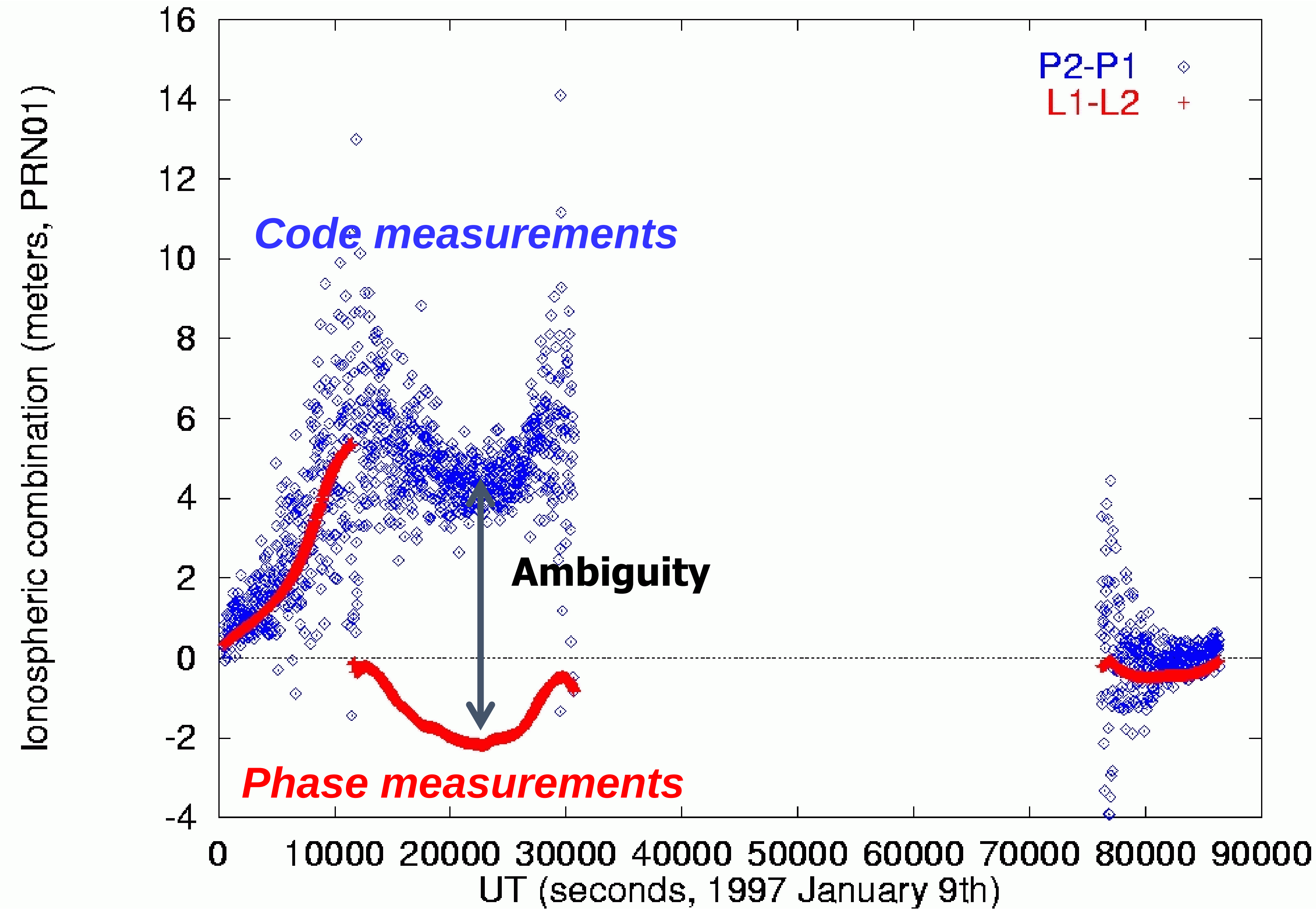


Now, any guess or comment about this plot?

-We can see how the code (i.e. pseudorange) and phase measurements ("ionospheric combination") of a given GPS transmitter ("PRN01") from a given receiver, complement each other very well:

-The code measurements are accurate (pseudorange) but not precise (measurement noise and multipath >~1 m).

-The carrier phase measurements are not accurate (unknown ambiguity = pseudorange at phase lock) but very precise (measurement noise and multipath < 1cm).



Finally, the electron content is inside GNSS measurements!

$$L_I \equiv L_1 - L_2 = \alpha \cdot S - \beta \cdot \phi + B_I, \qquad (17)$$

$$P_I \equiv P_2 - P_1 = \alpha \cdot S + D_I + D'_I + \epsilon_M + \epsilon_{\mathrm{T}}, \qquad (18)$$

where $\alpha = 40.309\left(\frac{1}{f_2^2} - \frac{1}{f_1^2}\right) = 1.05 \cdot 10^{-17}\, m^3$, $\beta = c\left(\frac{1}{f_2} - \frac{1}{f_1}\right) = 0.054\,\mathrm{m}$, $B_I = B_1 - B_2$, $D_I = D_2 - D_1$ and $D'_I = D'_2 - D'_1$.[2] In this case, we also made explicit the two main components of the measurement error, both corresponding to the code: the multipath code error ϵ_{M} and the thermal noise measurement error ϵ_{T}. Typically, the wind-up term $\beta \cdot \phi$ is a centimeter-level term. For the permanent receivers, this term can be corrected very accurately from their coordinates and orbital information, and it is not discussed explicitly herein.

Finally, the electron content is inside GNSS measurements!

-Then the highly variable ionospheric magnitude, STEC, is directly given by the ionospheric combination of dual-frequency carrier phases and pseudoranges (L & P): This is the main input data source for GNSS Ionosphere! (among the good performance of single-frequency measurements recently shown for certain ionospheric viewing problems such as plasma bubble detection).

-Other additional terms, are either constant at scales of hours (ambiguity BI, Differential Code Biases, DI, DI') or are small and can be very well modelled (wind-up term β*ϕ).

$$L_I \equiv L_1 - L_2 = \alpha \cdot S - \beta \cdot \phi + B_I, \quad (17)$$

$$P_I \equiv P_2 - P_1 = \alpha \cdot S + D_I + D_I' + \epsilon_M + \epsilon_\mathrm{T}, \quad (18)$$

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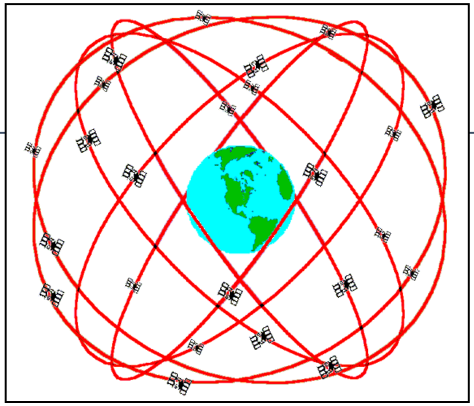
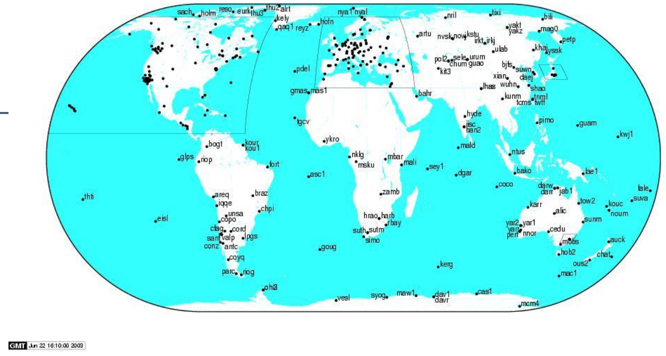
Conclusion: GNSS Ionosphere is well data-supported





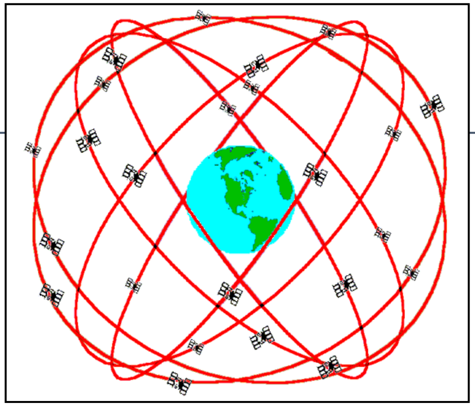
~ 100 GNSS trans. & +1000 24/7 static GNSS rec. (+100 in RT)

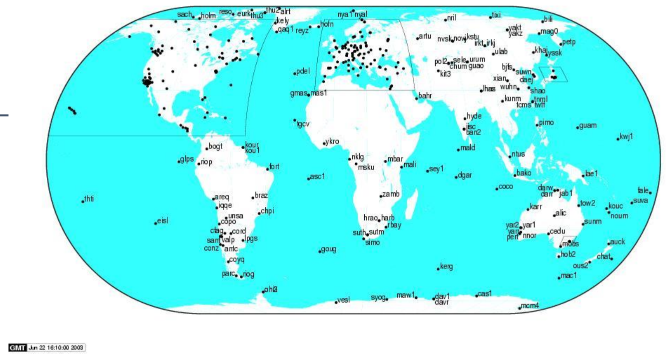
Worldwide *scanner* of the Ionosphere, an excellent input to generate ***Global Ionospheric Maps (GIMs) of VTEC maps*** (summarizing Big GNSS data), among **many other ways of modelling / studying the ionosphere**

Conclusion: GNSS Ionosphere is well data-supported

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) measurements, usually multi-frequency, 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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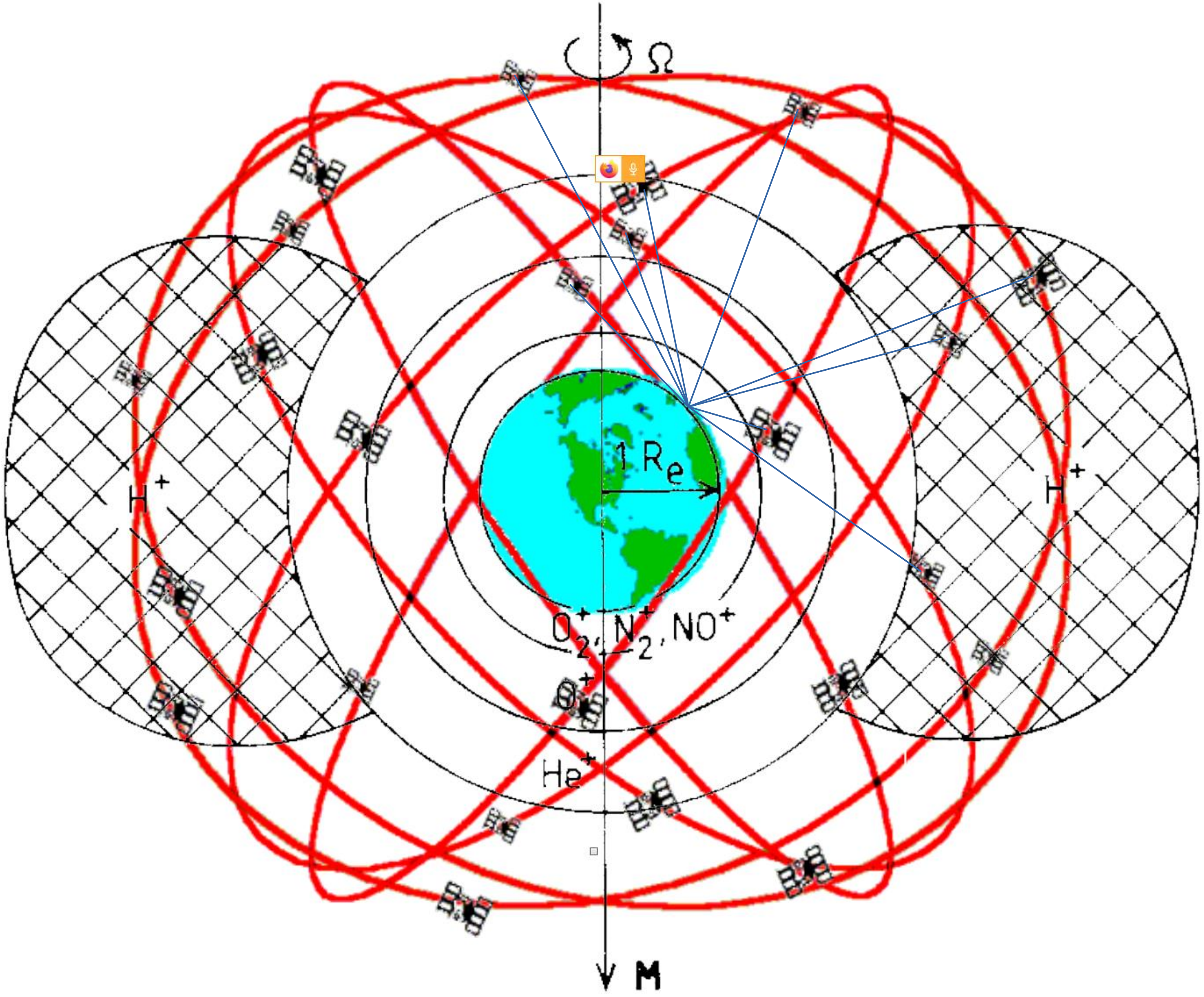

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Part 2

Access to UPC-IonSAT Global Ionospheric Maps PITHIA-NRF registrations

(AKA global VTEC maps every 15 minutes since end of 1996, i.e. ~1 million global VTEC maps & 5x10^9 VTECs computed so far)

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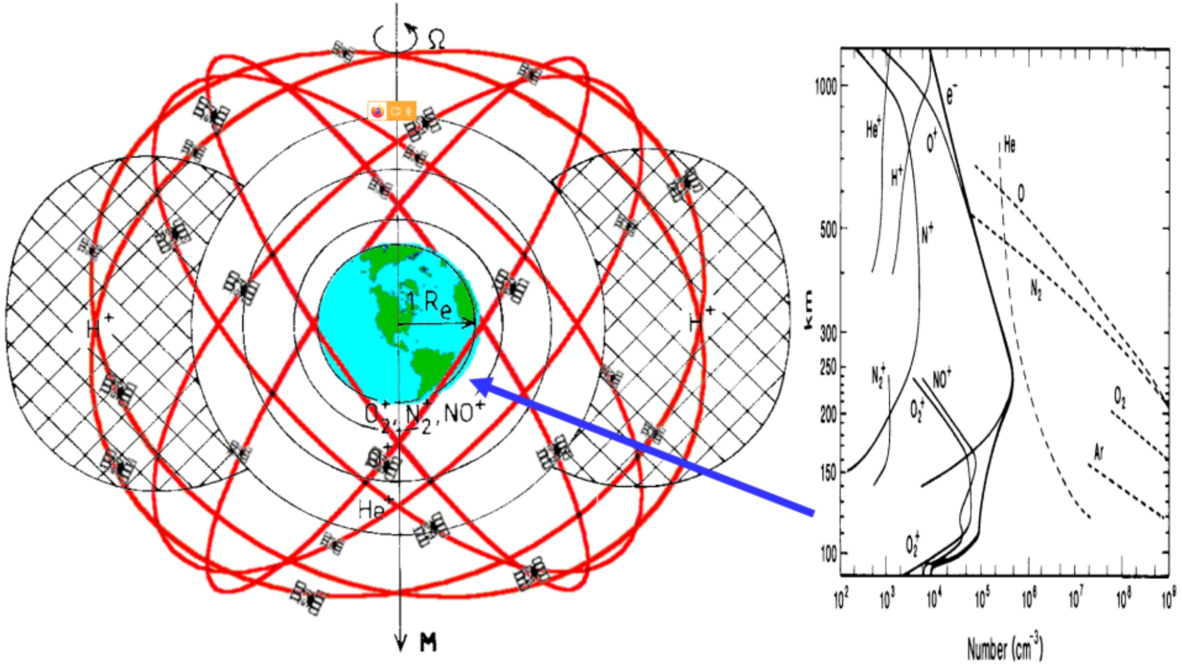
GNSS Ionosphere

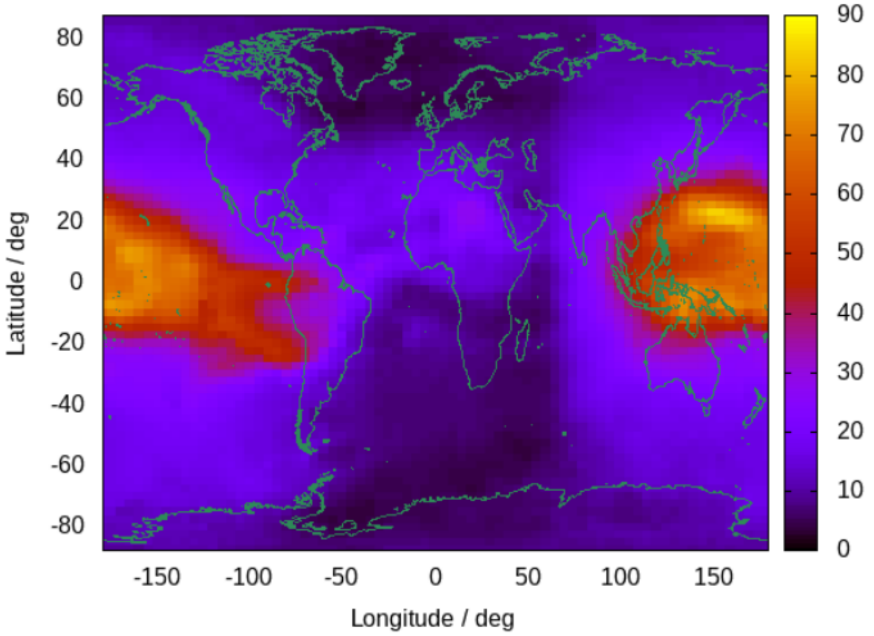
GNSS Ionosphere[1]: *Effects and computation of the distribution of free electrons, located at the partially ionized part of the atmosphere above 50 km height, from the Global Navigation Satellite Systems (GNSS) multi-frequency measurements crossing it; and its applications, such as Space Weather monitoring, precise real-time positioning and, among others.*

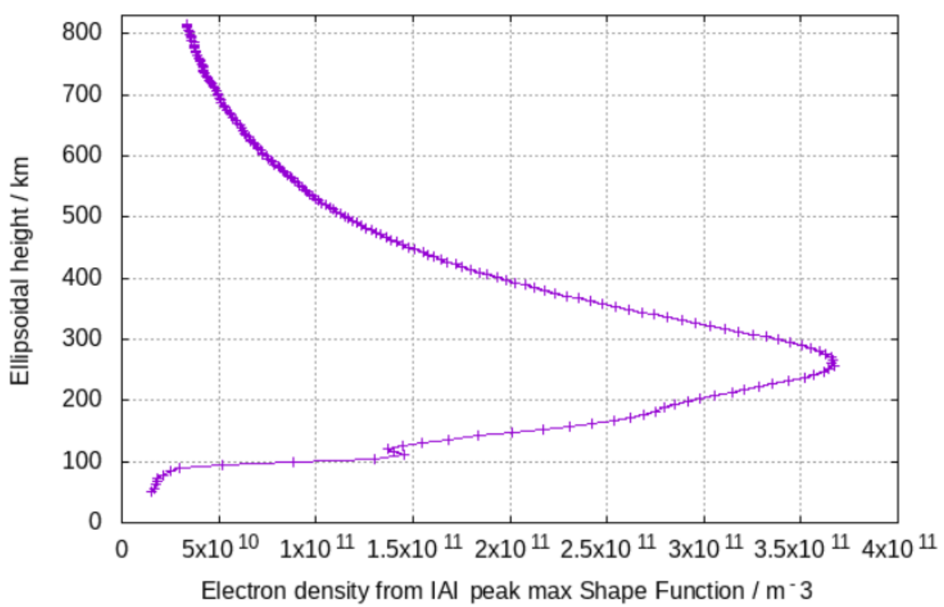


[1] Manuel Hernández-Pajares. “GNSS Ionosphere”. In: *Encyclopedia of Geodesy* (2022). Ed. by Michael G. Sideris, pp. 1–7.

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 instance[2]).

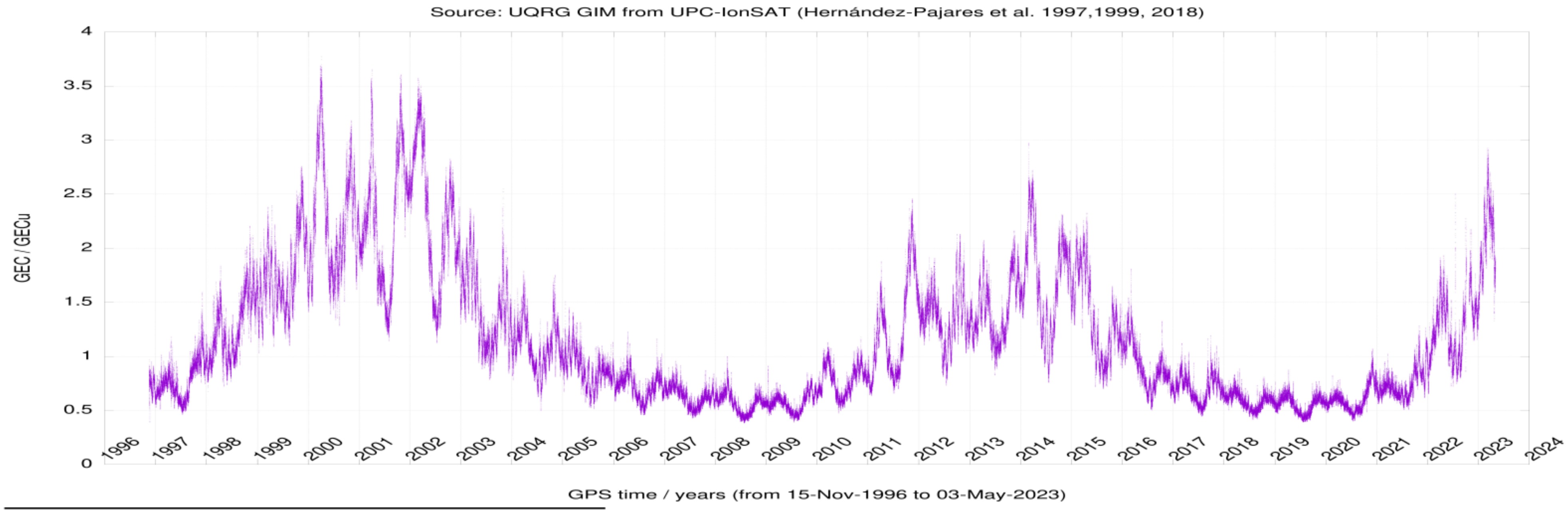




[2] Peter Teunissen and Oliver Montenbruck. *Springer handbook of global navigation satellite systems*. Springer, 2017, 1327, DOI: 10.1007/978–3–319–42928–1.

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 ([3]).



[3] Francisco 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).

GIMs with TOMION

multi-frequency carrier phases

positions of GNSS Receivers

positions of GNSS Transmitters

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

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

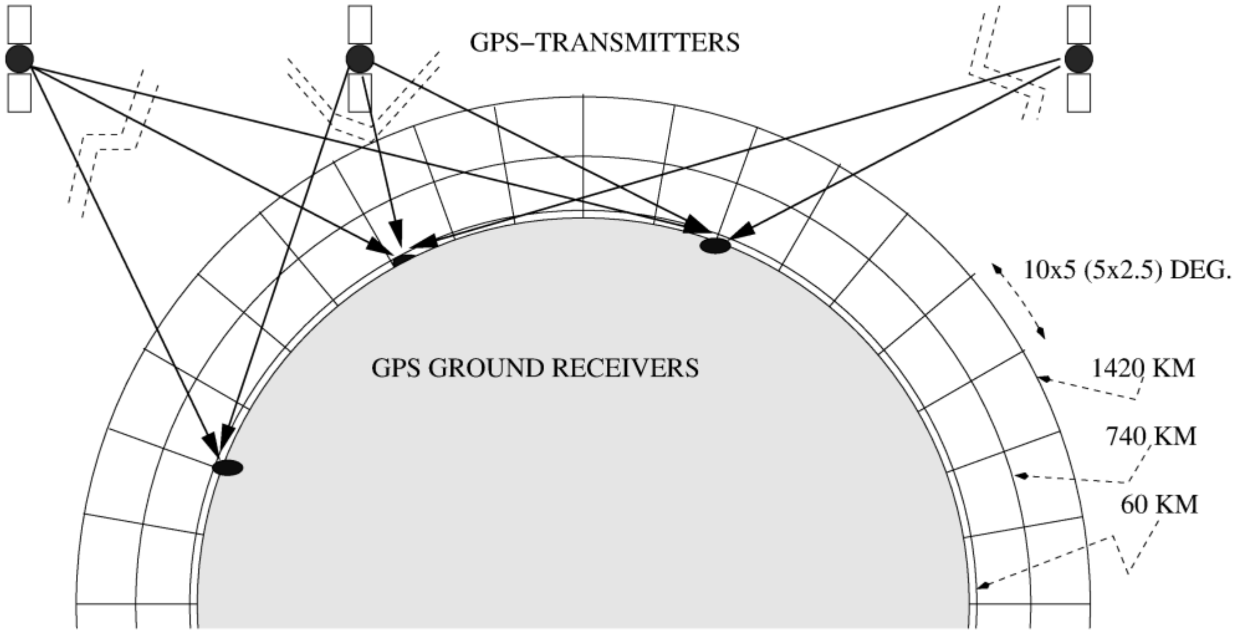
Solving $\{(\mathbf{N_e})_\mathbf{m}\}$ and $\{\mathbf{B_{j,k}}\}$ with Kalman filter in local time x latitude ref. frame

Slant & Vertical Total Electron Content values (S, V): $S = (L_j - L_k - \mathbf{B_{j,k}})/\alpha \Rightarrow V = S/M$

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

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

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



Introduction to TOMION model (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 ([9],[10],[11]).
- The tomography performed by TOMION is able to combine different data and geometries ([12]), in agreement with independent measurements and models ([13],[14]), also in the polar regions ([15]).

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

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

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

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

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

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

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

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Space Physics Ontology

Space Physics Ontology

Data Registration

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EIS foF2 Forecasts Over Digisonde Stations

EIS foF2 Long Term Prediction Maps

EIS foF2 Nowcast Maps

EIS hmF2 Nowcast Maps

EIS Ionospheric Alerts

EIS Near Real-Time TEC Maps

EPB_detectionTool

eSWua: Ionograms database, autoscaled records

eSWua: Ionograms database, manually scaled records

eSWua: Scintillation Indices and Total Electron Content (TEC) database

EUHFORIA: EUropean Heliospheric FORecasting Information Asset

GIM: Global Ionosphere Maps

hmF2_qModel

IAP-P Doppler sounder spectrograms

IPIM : Ionosphere-Plasmasphere IRAP Model

IRI: International Reference Ionosphere version 2001

IRTAM 3D global real-time assimilative model of ionospheric electron density

NOA Athens Digisonde (AT138) Data

RayTRIX-CQP: Oblique ionogram synthesizer with E, F1, F2 layer echo traces and MUFs, driven by IRTAM ionospheric nowcast

ROB-IONO Near-Real Time European Ionospheric Maps

SWIF Model

TechTIDE LSTID activity index

PITHIA-NRF
e-Science Centre

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Home / Browse Metadata / Data Collection-related Metadata / Data Collections / GIM: Global Ionosphere Maps

GIM: Global Ionosphere Maps

Global Vertical Total Electron Content 2D map computed using UPC Rapid Network of GPS receivers

Interact

Interaction Method	Description	Data Format	Link
Direct Link to Data Collection	The GIM landing page has the list of data the 15-minutes maps.	text/html (click the link to show information on this ontology term)	Open GIM Landing Page in new tab

Properties

Property	Value
Type (1/2)	Receiver of GNSS signals (click the link to show information on this ontology term)
Type (2/2)	Assimilative Model (click the link to show information on this ontology term)
Project	GIM: Global Ionospheric Maps (click the link to show information on this metadata registration)
Data Level	Level 3 (click the link to show information on this ontology term)
Result	*Not used*
Permission	Creative Commons Attribution-NonCommercial-ShareAlike (click the link to show information on this ontology term)

Identifier Properties

Local ID	DataCollection_UPC-RapidNetwork_GIM
Namespace	pithia
Version	1
Created	Tuesday 20th Dec. 2022, 09:30:00
Last Modified	Tuesday 20th Dec. 2022, 09:30:00

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IonSAT

Role *(from Related Party **(1/2)** > Responsible Party Info)*	Point of contact (click the link to show information on this ontology term)
Party *(from Related Party **(1/2)** > Responsible Party Info)*	Manuel Hernandez-Pajares (click the link to show information on this metadata registration)
Role *(from Related Party **(2/2)** > Responsible Party Info)*	Data Provider (click the link to show information on this ontology term)
Party *(from Related Party **(2/2)** > Responsible Party Info)*	UPC-IonSAT (click the link to show information on this metadata registration)
Result Time	*Not used*
Name *(from Collection Results > Source > Online Resource)*	GIM Landing Page
URL *(from Collection Results > Source > Online Resource > Linkage)*	http://cabrera.upc.es/upc_ionex_GPSonly-RINEXv3
Protocol *(from Collection Results > Source > Online Resource)*	HTTP
Data Format *(from Collection Results > Source > Online Resource)*	text/html (click the link to show information on this ontology term)
Description *(from Collection Results > Source > Online Resource)*	The GIM landing page has the list of the 15-minutes ionex files.

Index of /upc_ionex_GPSonly-RINEXv3

Name	Last modified	Size	Description
Parent Directory		-	
1996/	2022-10-09 15:56	-	
1997/	2020-04-08 10:56	-	
1998/	2020-04-08 10:56	-	
1999/	2020-04-08 10:56	-	
2000/	2020-04-08 10:56	-	
2001/	2020-04-08 10:56	-	
2002/	2022-10-09 16:23	-	
2003/	2020-04-08 10:56	-	
2004/	2020-04-08 10:56	-	
2005/	2020-04-08 10:56	-	
2006/	2022-10-09 16:22	-	
2007/	2020-04-08 10:56	-	
2008/	2020-04-08 10:56	-	
2009/	2020-04-08 10:56	-	
2010/	2020-04-08 10:56	-	
2011/	2020-04-08 10:56	-	
2012/	2020-04-08 10:56	-	
2013/	2020-04-08 10:56	-	
2014/	2020-04-08 10:56	-	
2015/	2020-04-08 10:56	-	
2016/	2020-04-08 10:56	-	

Index of /upc_ionex_GPSonly-RINEXv3/2010

Name	Last modified	Size	Description
Parent Directory		-	
001_100101.15min/	2020-04-08 10:56	-	
002_100102.15min/	2020-04-08 10:56	-	
003_100103.15min/	2020-04-08 10:56	-	
004_100104.15min/	2020-04-08 10:56	-	
005_100105.15min/	2020-04-08 10:56	-	
006_100106.15min/	2020-04-08 10:56	-	
007_100107.15min/	2020-04-08 10:56	-	
008_100108.15min/	2020-04-08 10:56	-	
009_100109.15min/	2020-04-08 10:56	-	
010_100110.15min/	2020-04-08 10:56	-	
011_100111.15min/	2020-04-08 10:56	-	
012_100112.15min/	2020-04-08 10:56	-	
013_100113.15min/	2020-04-08 10:56	-	
014_100114.15min/	2020-04-08 10:56	-	
015_100115.15min/	2020-04-08 10:56	-	
016_100116.15[illegible]	[illegible]020-04-08 10:56	-	
017_100117.15m[illegible]n/	[illegible]020-04-08 10:56	-	
018_100118.15min/	2020-04-08 10:56	-	
019_100119.15min/	2020-04-08 10:56	-	
020_100120.15min/	2020-04-08 10:56	-	
021_100121.15min/	2020-04-08 10:56	-	

Format: $\underbrace{\text{\$DOY}}_{\text{Day of Year}}$_$\underbrace{\text{\$YY}}_{\text{Year}}\underbrace{\text{\$MM}}_{\text{Month}}\underbrace{\text{\$DD}}_{\text{Day}}$.$\underbrace{\text{15min}}_{\text{Resolution}}$

Index of /upc_ionex_GPSonly-RINEXv3/2010/015_100115.15min

Name	Last modified	Size	Description
Parent Directory		-	
uqrg0150.10i.Z	2018-11-09 19:12	919K	

IONEX

Format (IGS): $\underbrace{\text{uqrg}}_{\text{Center}}\underbrace{\text{\$DOY}}_{\text{Day of Year}}\text{0.}\underbrace{\text{\$YY}}_{\text{Year}}\text{i.Z}$

Compressed

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Index of /upc_ionex_GPSonly-RINEXv3/2010/015_100115.15min

Name	Last modified	Size	Description
Parent Directory		-	
uqrg0150.10i.Z	2018-11-09 19:12	919K	

Apache/2.4.29 (Ubuntu) Server at cabrera.upc.es Port 80

Do you want to allow downloads on “cabrera.upc.es”?

You can change which websites can download files in Websites Preferences.

Cancel Al

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Terminal — more ◂ sh - /usr/bin/zmore

```
     1.0            IONOSPHERE MAPS     GPS                 IONEX VERSION / TYPE
tecrms2ionex_4.awk  UPC-IonSAT          11/09/18 1711UT     PGM / RUN BY / DATE
Global ionosphere maps for day  15, 2010 (15- 1-2010)       DESCRIPTION
Contact address: Manuel Hernandez-Pajares                   DESCRIPTION
                 IonSAT research group                      DESCRIPTION
                 Technical Univ. of Catalonia (UPC-IonSAT)  DESCRIPTION
                 Mod. C3 Campus Nord UPC                    DESCRIPTION
                 E08034-Barcelona, SPAIN                    DESCRIPTION
                 e-mail:  manuel@ma4.upc.edu                DESCRIPTION
                                                            DESCRIPTION
                                                            DESCRIPTION
P1-P2 DCBs(UPC3-BRDC)  15 2010: Bias=  0.000 RMS= 0.855 [ns]DESCRIPTION
                                                            DESCRIPTION
  2010     1    15     0     0     0                        EPOCH OF FIRST MAP
  2010     1    15    23    59    24                        EPOCH OF LAST MAP
   900                                                      INTERVAL
    97                                                      # OF MAPS IN FILE
  COSZ                                                      MAPPING FUNCTION
     0.0                                                    ELEVATION CUTOFF
   300                                                      # OF STATIONS
    32                                                      # OF SATELLITES
  6371.0                                                    BASE RADIUS
     2                                                      MAP DIMENSION
   450.0 450.0   0.0                                        HGT1 / HGT2 / DHGT
    87.5 -87.5  -2.5                                        LAT1 / LAT2 / DLAT
  -180.0 180.0   5.0                                        LON1 / LON2 / DLON
    -1                                                      EXPONENT
TEC values in  0.1 TECUs; 9999 if no value available        COMMENT
IGS GPS stations used in the computations:                  COMMENT
019b ab02 ab07 ab08 ab11 ab14 ab25 ab27 ab37 ab39 ab41 ab43 COMMENT
ab44 abmf abpo ac03 ac12 ac60 ac61 acor acso acu5 ade1 adks COMMENT
agmt ahid aira ajac alac alam albh algo alic allg alon alrt COMMENT
amc2 ankr antc areq arli artu asky aspa auck autf baie bake COMMENT
bako bamo ban2 barh bcyi bdos bell bjfs bla1 blmm bluf boav COMMENT
bogt bomj brft brib brip brmu brst brus bshm bsmk bucu bue1 COMMENT
buri bysp cabl cagl call cand cant cas1 casc ccj2 cedu cefe COMMENT
cfag chan chat chiz chme chum chur cjtr ckis clrk cmbl cnmr COMMENT
coco cont copo cosa coyq crao crar cuib cusv daej dane darw COMMENT
dav1 devi dgar dgjg dksg drao dres dum1 dupt ecsd edoc eur2 COMMENT
faa1 falk fall flin flrs func g101 g107 g117 g124 g201 g202 COMMENT
ganp gisb glps glsv gmas gmma guat harb hdil helg her2 hil1 COMMENT
hilb hlfx hmbg hnlc hob2 hobu hofn holm howe hrst hueg hugo COMMENT
hvlk hvwy hyde ifr1 impz ineg invk iqal iqqe irkj isba ispa COMMENT
ista jct1 joen karr kerg khaj khar kir0 kiri kit3 kouc kour COMMENT
ksnb kuaq kunm kuuj kvtx lafe lamt laut lhaz lpal lthw mac1 COMMENT
```

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2014/	2020-04-08 10:56	-
2015/	2020-04-08 10:56	-
2016/	2020-04-08 10:56	-
2017/	2020-04-08 10:56	-
2018/	2023-09-04 16:57	-
2019/	2023-09-04 16:59	-
2020/	2023-09-04 17:05	-
2021/	2023-09-04 17:08	-
2022/	2023-01-01 20:40	-
2023/	2023-09-05 06:14	-
tmp/	2023-03-05 21:19	-
uqrg.latest.Z	2023-09-05 05:00	1.1M
uqrg.latest.rms.gif	2023-09-05 07:45	4.5M
uqrg.latest.tec.gif	2023-09-05 07:45	4.8M

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Part 3

New applications of GIMs: gradient VTEC GIMs and Ionospheric Storm Scale GIMs

0. Motivation

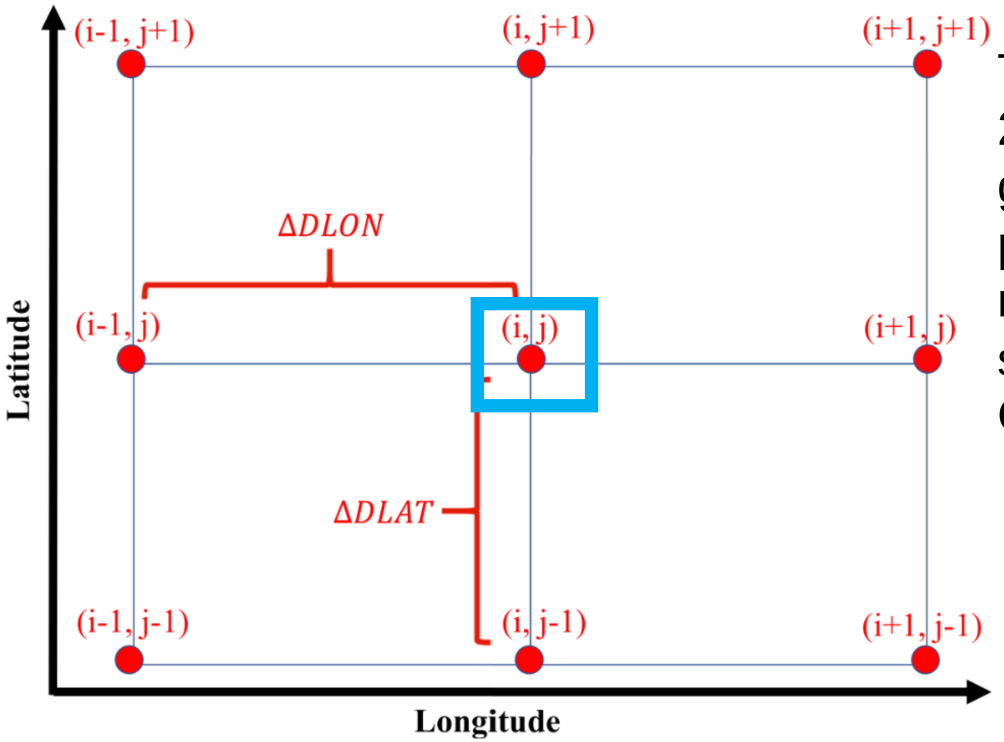
In this work we summarize the approach, results and answer to the question that we did ourselves almost two years ago:

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

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

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

2. Defining the components of VTEC gradient from the GIM



The **spatial and temporal components of VTEC gradient at grid points of** UQRG **GIM** on a global scale are introduced.

The VTEC gradient derived from UQRG GIMs (VgUG, Liu et al. 2022), **allows** to obtain full (non-relative) values of TEC spatial gradients and temporal variations **separately at any worldwide grid point**, considering the distances on the corresponding parallels and meridians at the ionospheric efective height, ΔDLON & ΔDLAT, separated 5º & 2.5º respectively, and the time difference between GIMs Δt (30 minutes, centered, 15 minutes, uncentered).

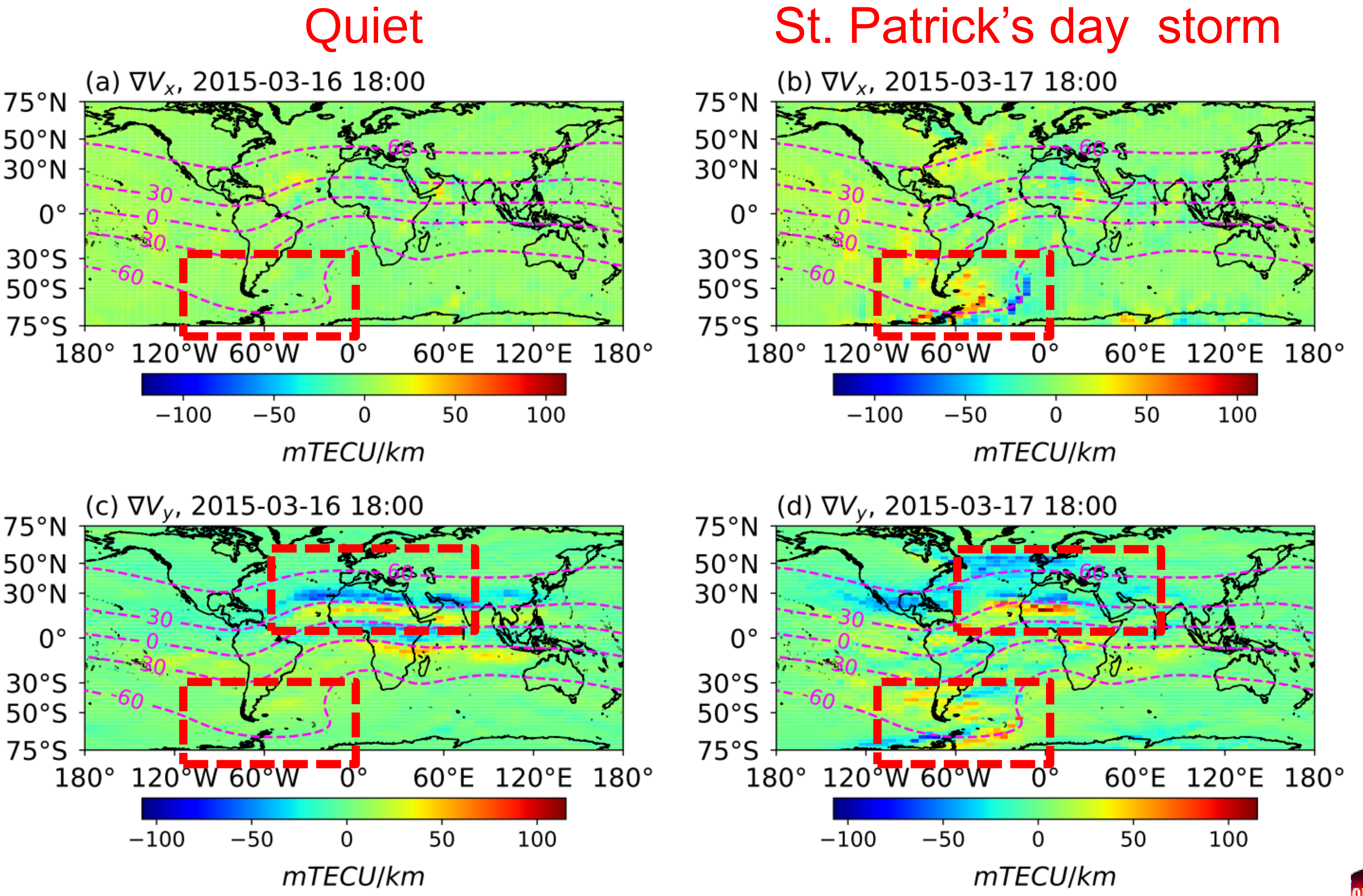
$$\begin{cases} \nabla V_{x,i,j} = (VTEC_{i,j} - VTEC_{i-1,j})/\Delta DLON \\ \nabla V_{y,i,j} = (VTEC_{i,j} - VTEC_{i,j-1})/\Delta DLAT \\ \nabla V_{i,j} = \sqrt{\nabla V_{x,i,j}^2 + \nabla V_{y,i,j}^2} \\ \vec{\nabla V} = (\nabla V_{x,i,j}, \nabla V_{y,i,j}) \end{cases}$$

$$\dot{V}_{i,j} = \Delta VTEC_{i,j}/\Delta t = (VTEC_{i,j,t} - VTEC_{i,j,t-1})/\Delta t$$

2.1 Example of global distribution of VTEC spatial gradient

Compared with the quiet ionospheric state, the VTEC spatial and temporal gradient directly derived from the GIM are able to capture the extraordinary VTEC variations during the disturbed ionospheric state, splitted in north, east and time components.

St. Patrick's Day 2015 Geomagnetic Storm



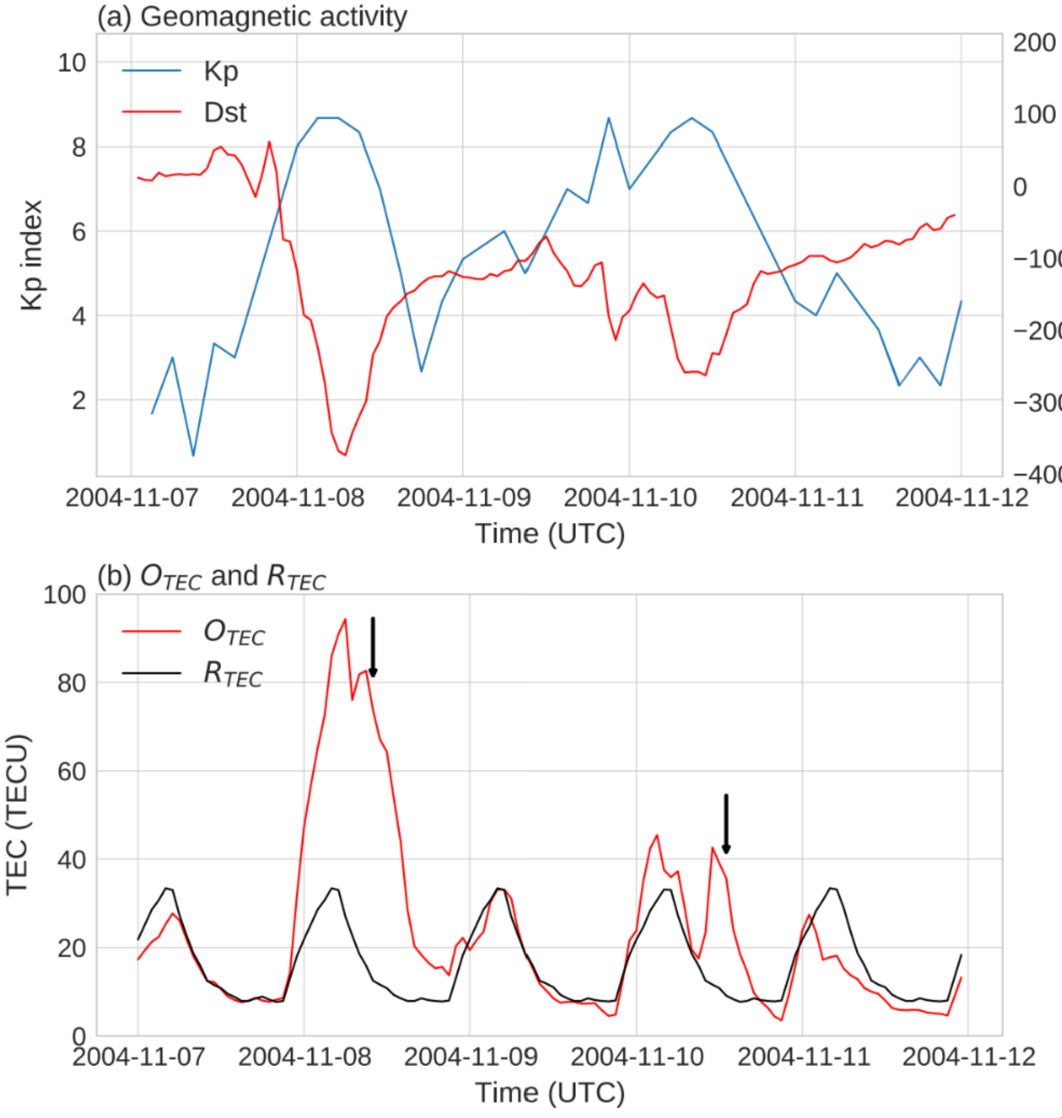
4. Extending the definition of the Ionospheric storm scale index to GIMs (IsUG)

We propose the Ionospheric Storm Scale Index Based on UQRG (IsUG) as a direct extension of the I-scale index proposed at regional level (Japan) and from raw GNSS data by Nishioka et al. (2017):

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

It is defined as the standardized Ptec, $\hat{P}_{TEC}$, where Ptec is the percentage deviation of VTEC, Otec is the hourly median VTEC derived at grid points of GIM. The hourly median VTEC is the median of the five VTEC values during 1-h interval, under the GIM VTEC temporal resolution of 15 min. The hourly median VTEC is calculated every hour (for example, 0, 1, 2 UT). Rtec is the reference median value at the same local time and geographic location in the past 27 days.

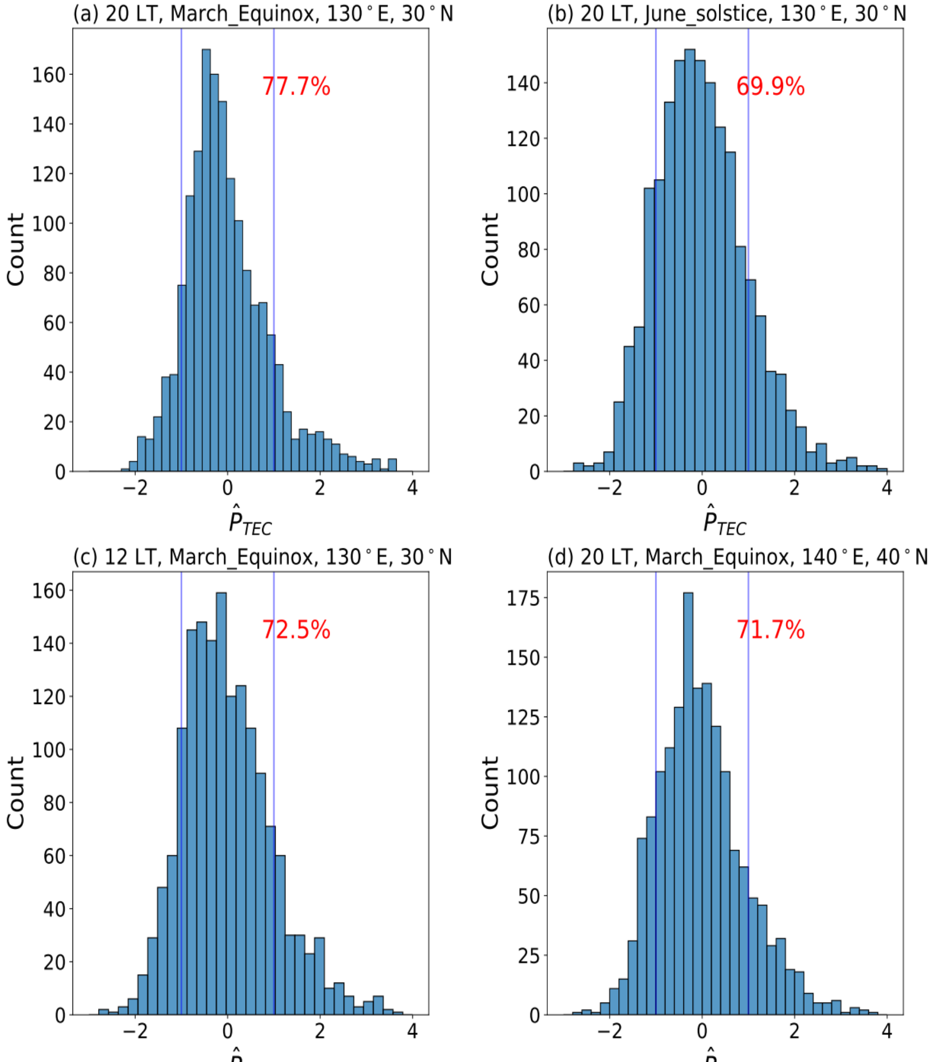
IsUG	Description	Definition	Probability on a global scale (%)
IP3	Severe positive storm	$5 < \hat{P}$	0.17
IP2	Strong positive storm	$3 < \hat{P} \leq 5$	0.72
IP1	Moderate positive storm	$1 < \hat{P} \leq 3$	12.43
I0	Quiet	$-1 < \hat{P} \leq 1$	73.96
IN1	Moderate negative storm	$-2 < \hat{P} \leq -1$	11.72
IN2	Strong negative storm	$-3 < \hat{P} \leq -2$	0.95
IN3	Severe negative storm	$\hat{P} < -3$	0.06



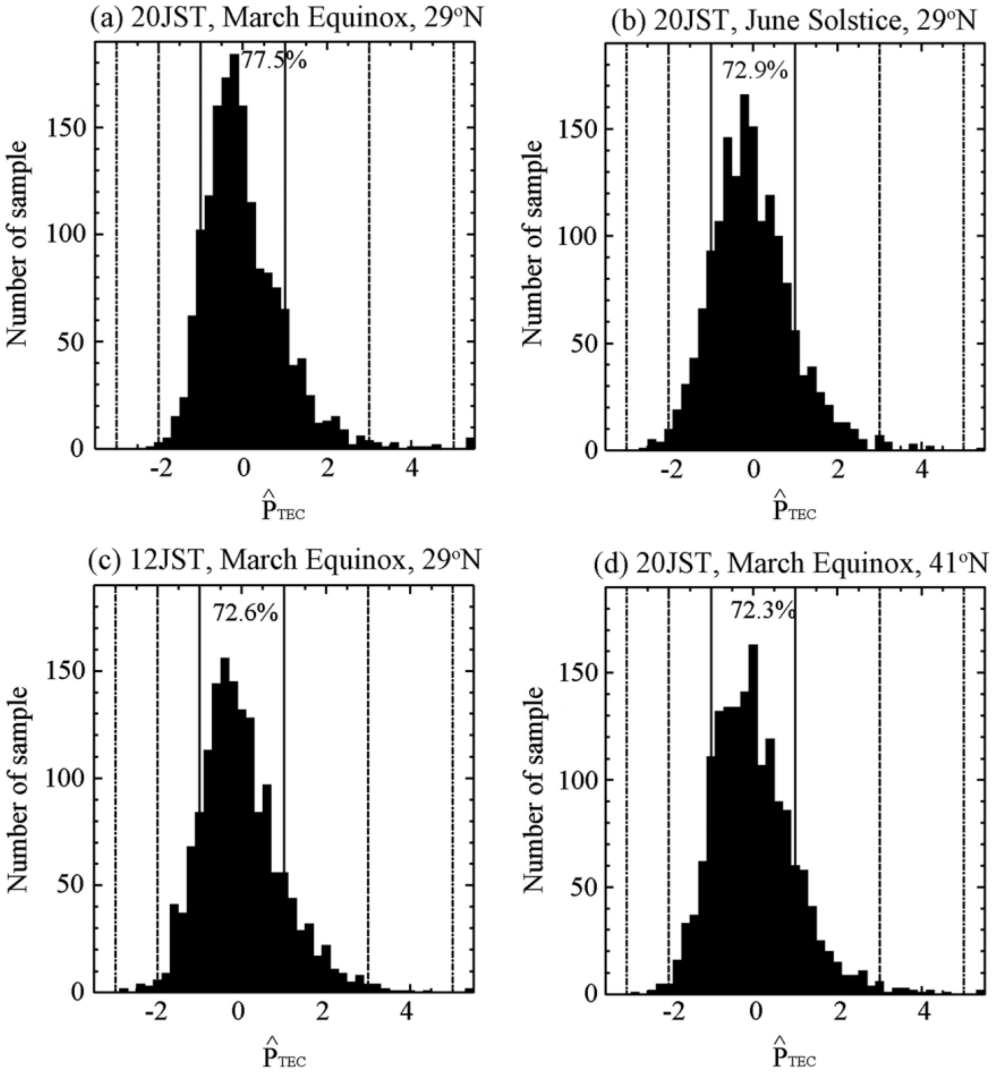
(130°E, 30°N)

4.2 Comparing $\hat{P}_{TEC}$ from GIM $\hat{P}_{TEC}$ from raw GNSS data over Japan since 1997 to 2014 (3 months of seasonal data per year)

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



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



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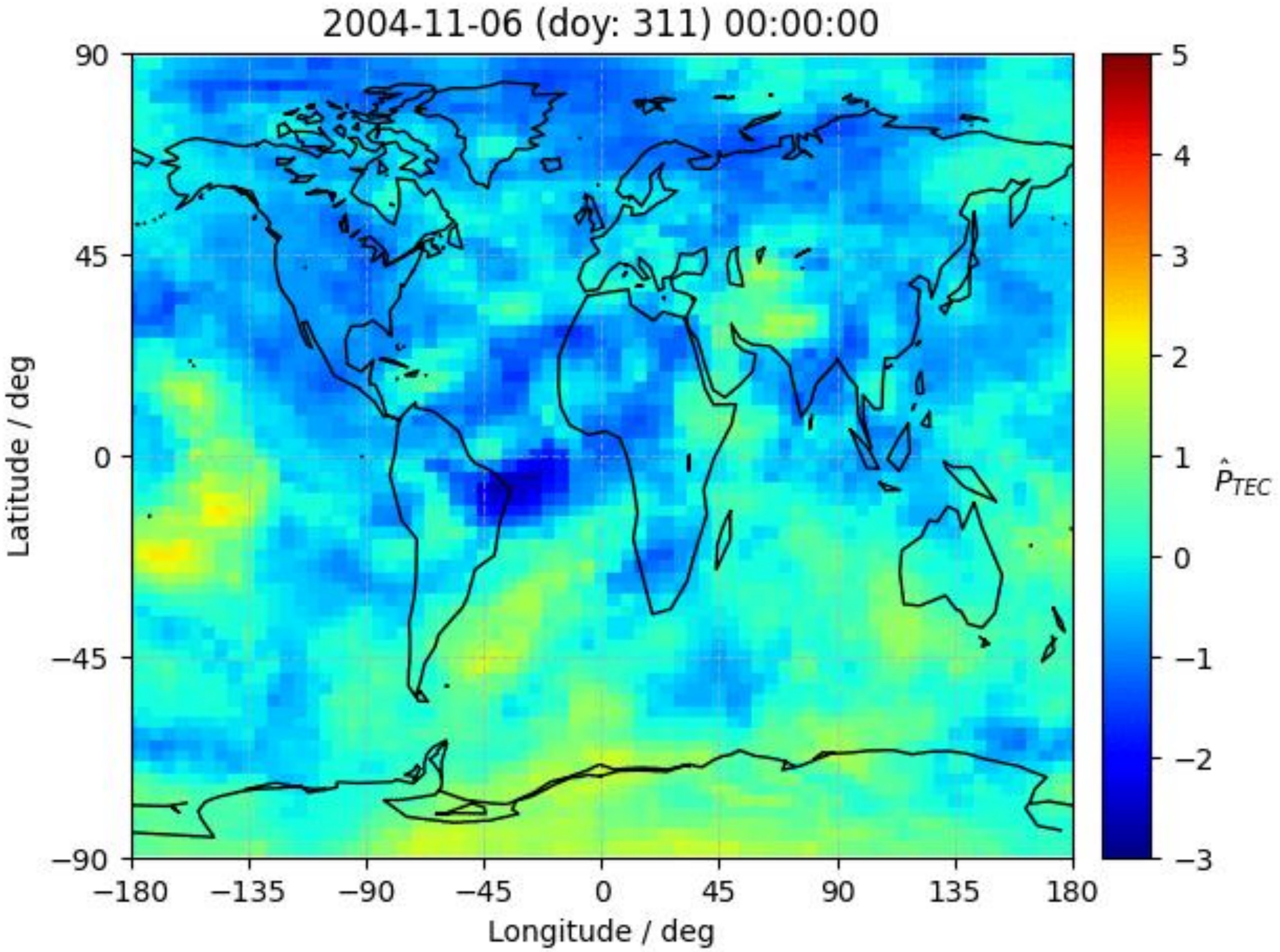
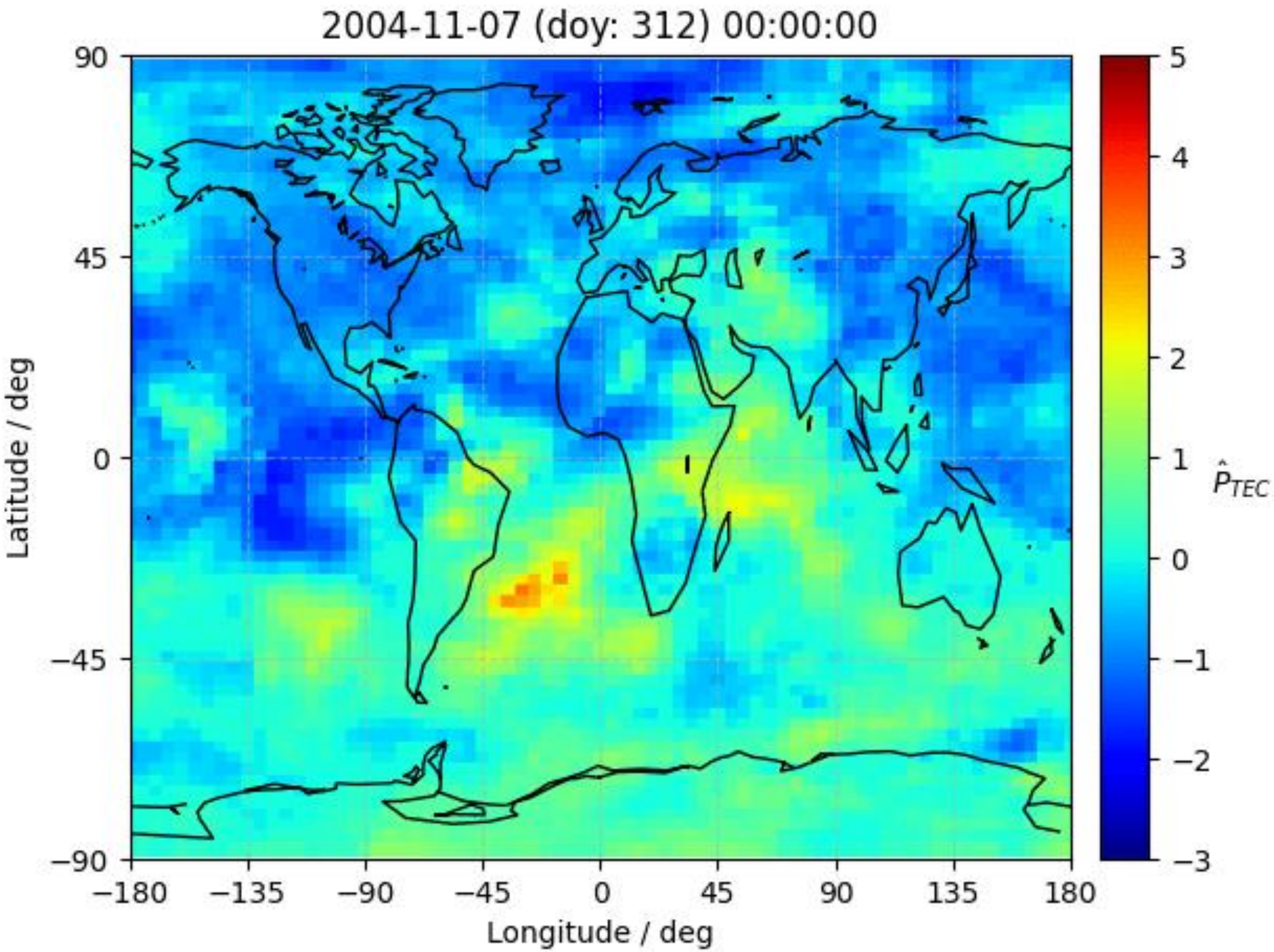
4.6 Animation of IsUG maps during a quiet period



4.6 Animation of IsUG maps during a ionospheric storm period



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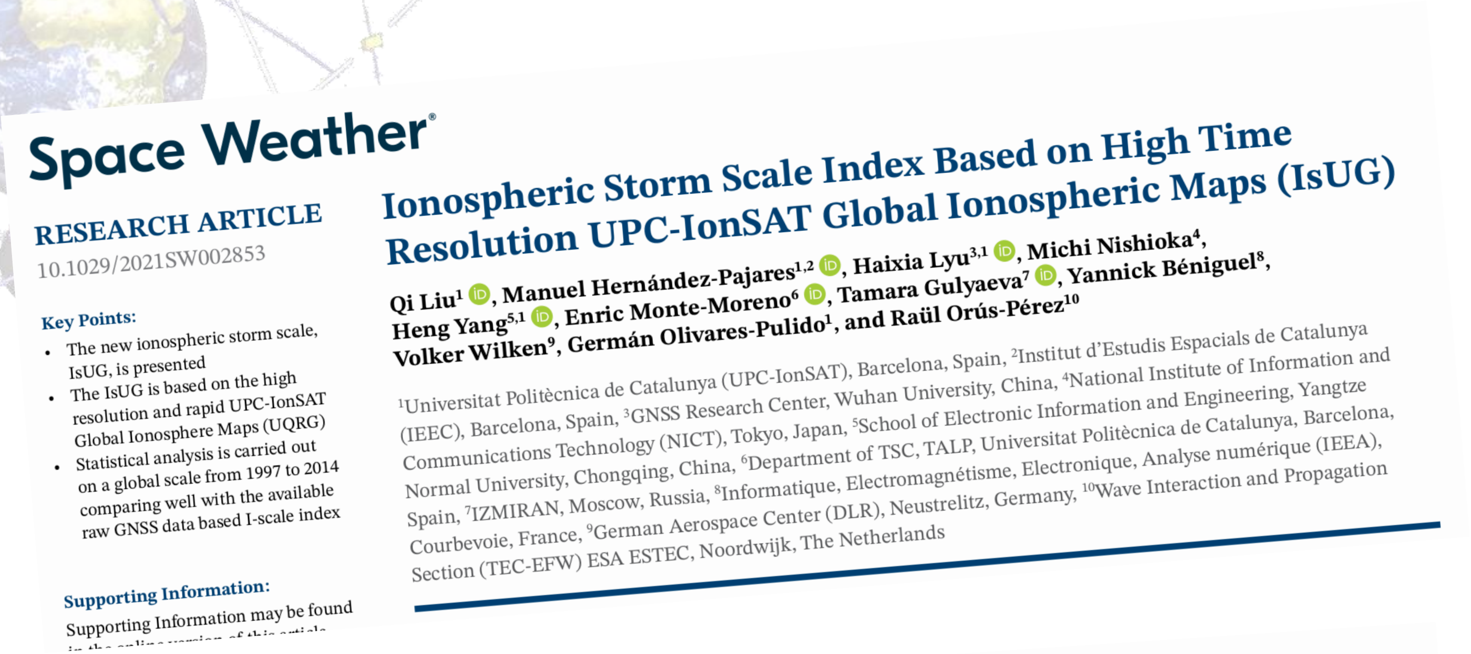


Space Weather®

RESEARCH ARTICLE

10.1029/2021SW002853

Key Points:

- The new ionospheric storm scale, IsUG, is presented
- The IsUG is based on the high resolution and rapid UPC-IonSAT Global Ionosphere Maps (UQRG)
- Statistical analysis is carried out on a global scale from 1997 to 2014 comparing well with the available raw GNSS data based I-scale index

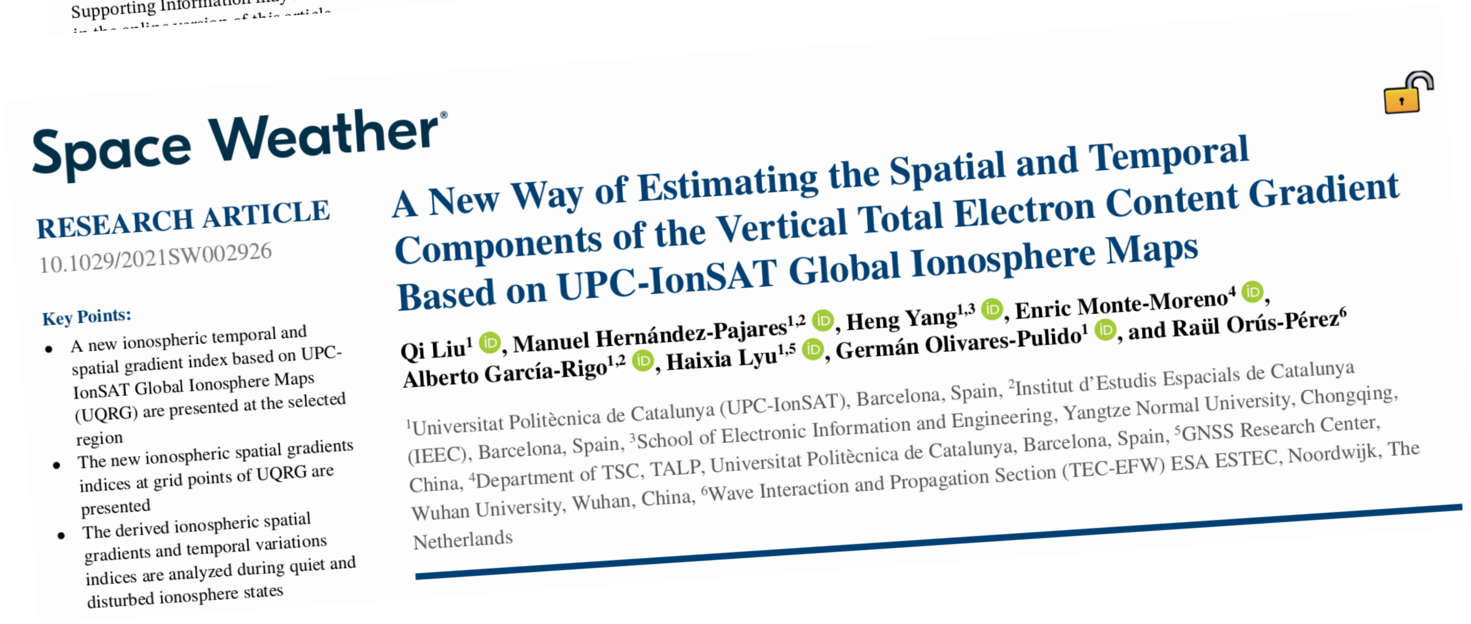
Supporting Information:

Supporting Information may be found

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]

[1]Universitat Politècnica de Catalunya (UPC-IonSAT), Barcelona, Spain, [2]Institut d'Estudis Espacials de Catalunya (IEEC), Barcelona, Spain, [3]GNSS Research Center, Wuhan University, China, [4]National Institute of Information and Communications Technology (NICT), Tokyo, Japan, [5]School of Electronic Information and Engineering, Yangtze Normal University, Chongqing, China, [6]Department of TSC, TALP, Universitat Politècnica de Catalunya, Barcelona, Spain, [7]IZMIRAN, Moscow, Russia, [8]Informatique, Electromagnétisme, Electronique, Analyse numérique (IEEA), Courbevoie, France, [9]German Aerospace Center (DLR), Neustrelitz, Germany, [10]Wave Interaction and Propagation Section (TEC-EFW) ESA ESTEC, Noordwijk, The Netherlands



Space Weather®

RESEARCH ARTICLE

10.1029/2021SW002926

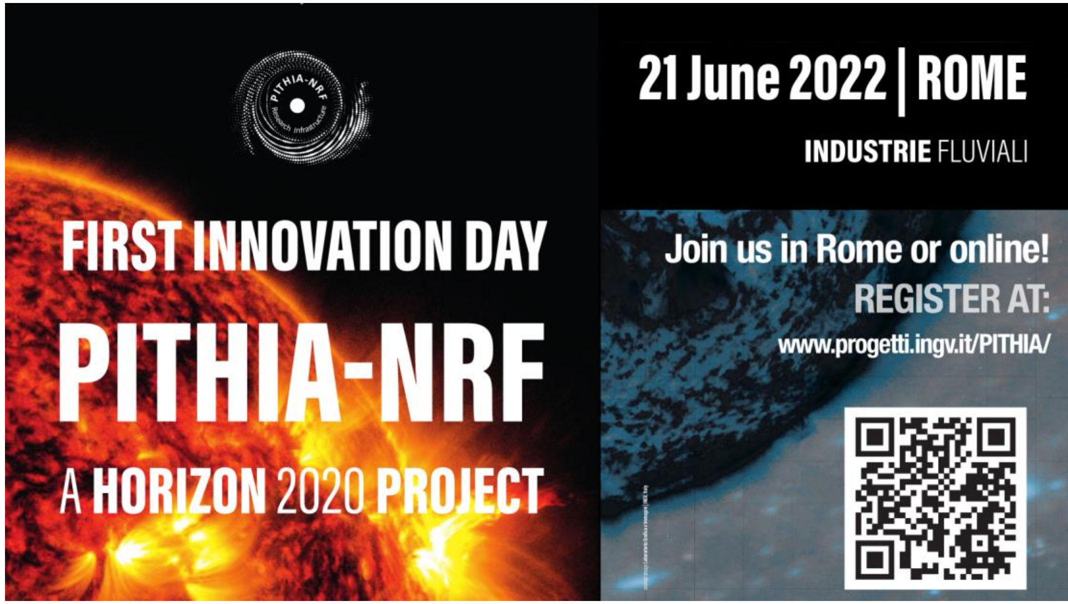
Key Points:

- A new ionospheric temporal and spatial gradient index based on UPC-IonSAT Global Ionosphere Maps (UQRG) are presented at the selected region
- The new ionospheric spatial gradients indices at grid points of UQRG are presented
- The derived ionospheric spatial gradients and temporal variations indices are analyzed during quiet and disturbed ionosphere states

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], Germán Olivares-Pulido[1], and Raül Orús-Pérez[6], Alberto García-Rigo[1,2], Haixia Lyu[1,5]

[1]Universitat Politècnica de Catalunya (UPC-IonSAT), Barcelona, Spain, [2]Institut d'Estudis Espacials de Catalunya (IEEC), Barcelona, Spain, [3]School of Electronic Information and Engineering, Yangtze Normal University, Chongqing, China, [4]Department of TSC, TALP, Universitat Politècnica de Catalunya, Barcelona, Spain, [5]GNSS Research Center, Wuhan University, Wuhan, China, [6]Wave Interaction and Propagation Section (TEC-EFW) ESA ESTEC, Noordwijk, The Netherlands



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IonSAT

Part 4

Very basic introduction to Linux and to ionsat-tool “gim2vtec*.scr”

Layout:

1) [**Motivation**] Precise Agriculture (PA) presentation (EU AUDITOR experiment)

1) [**Background**]: Brief introduction to main identified points of the presentation:
   a) GPS fundamentals: pseudoranges and carrier phases (optional)
   b) Ionospheric electron content
   c) Wide Area Real-Time Kinematic
   d) The International GNSS Service (*optional*)

3) [**One efficient operative system**] Quick introduction to Linux (*optional*)

3) [**New tools for learning and research**] IonSAT Tools (IT), emulating Real-Time (RT) as much as possible (presented on the PA AUDITOR experiment):
   a) *gim2vtec.v2.scr*
   b) *gimrnx2stec.v2.scr*

5) [**IT application to ECLIPSE, FLARE & GSTORM scenarios**] (*optional*).

5) [**Example of RT GPS-ionospheric system**]: UPC-IonSAT since 2012.

5) [**Monitoring of co-seismic generated ionospheric signals]:** Application of RT ionospheric sounding for potential Tsunami warnings), with GNSS dense (Tohoku and mid earthquakes, EQ) and sparse networks (Chile 2015 EQ).

Connection to server (from xterm or similar)

- ssh –X ionsat-tools-userYY@chapman.upc.es

- Where YY is the User Id. # (starting on 01), and the password, should be given to you at the beginning of the corresponding laboratory session.

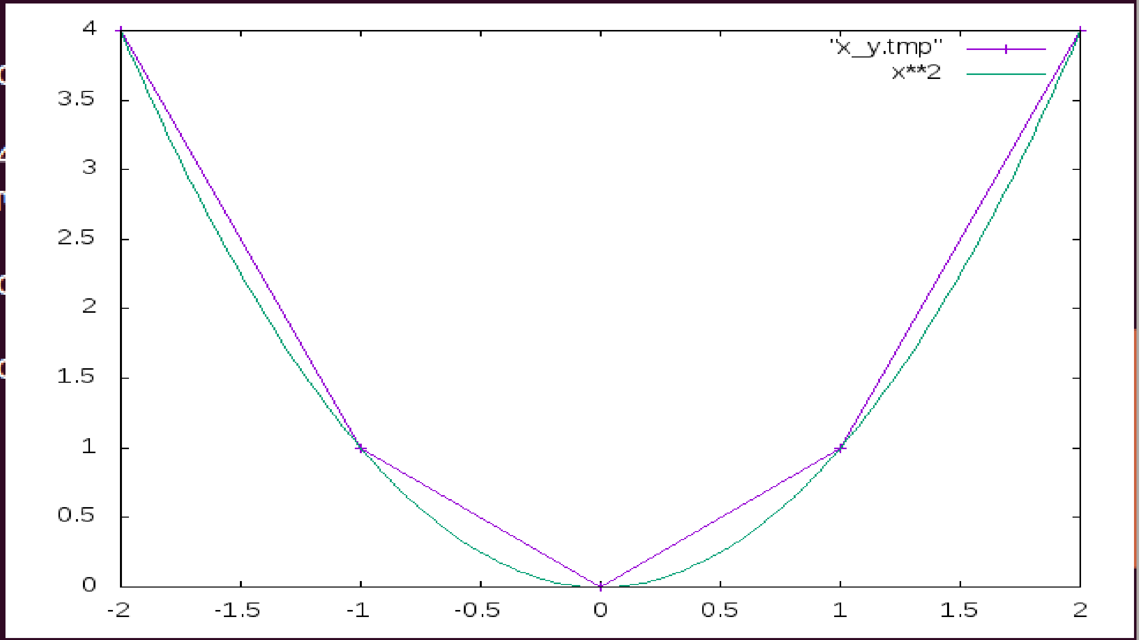
You will find in the next few slides a quick introduction to very basic Linux, the open-source, reliable and high performance operative system for computers.

manuel@manuel-HP-ENVY-Notebook-13-ab0XX: ~

File Edit View Search Terminal Help

```
manuel@manuel-HP-ENVY-Notebook-13-ab0XX:~$ ssh -X user01@localhost
user01@localhost's password:
Welcome to Ubuntu 16.04.2 LTS (GNU/Linux 4.10.0-37-generic x86_64)

 * Documentation:  https://help.ubuntu.com
 * Management:     https://landscape.canonical.com
 * Support:        https://ubuntu.com/advantage

272 packages can be updated.
20 updates are security updates.

Last login: Sat Nov  4 23:33:39 2017 from 127.0.0.1
manuel-HP-ENVY-Notebook-13-ab0XX:~> pwd
/home/user01
manuel-HP-ENVY-Notebook-13-ab0XX:~> mkdir ionsat-lab-01
manuel-HP-ENVY-Notebook-13-ab0XX:~> cd ionsat-lab-01/
manuel-HP-ENVY-Notebook-13-ab0XX:~/ionsat-lab-01> pwd
/home/user01/ionsat-lab-01
manuel-HP-ENVY-Notebook-13-ab0XX:~/ionsat-lab-01> echo -2 4 > x_y.tmp
manuel-HP-ENVY-Notebook-13-ab0XX:~/ionsat-lab-01> echo -1 1 >> x_y.tmp
manuel-HP-ENVY-Notebook-13-ab0XX:~/ionsat-lab-01> echo 0 0 >> x_y.tmp
manuel-HP-ENVY-Notebook-13-ab0XX:~/ionsat-lab-01> echo 1 1 >> x_y.tmp
manuel-HP-ENVY-Notebook-13-ab0XX:~/ionsat-lab-01> echo 2 4 >> x_y.tmp
manuel-HP-ENVY-Notebook-13-ab0XX:~/ionsat-lab-01> more x_y.tmp
-2 4
-1 1
0 0
1 1
2 4
```

```
2 4
manuel-HP-ENVY-Notebook-13-ab0XX:~/ionsat-lab-01> wc -l x_y.tmp
5 x_y.tmp
manuel-HP-ENVY-Notebook-13-ab0XX:~/ionsat-lab-01> ls -l x_y.tmp
-rw-rw-r-- 1 user01 user01 22 nov  4 23:36 x_y.tmp
manuel-HP-ENVY-Notebook-13-ab0XX:~/ionsat-lab-01> gnuplot

        G N U P L O T
        Version 5.0 patchlevel 3    last mo

        Copyright (C) 1986-1993, 1998, 2004
        Thomas Williams, Colin Kelley and m

        gnuplot home:     http://www.gnuplo
        faq, bugs, etc:   type "help FAQ"
        immediate help:   type "help"  (plo

Terminal type set to 'qt'
gnuplot> plot "x_y.tmp"
gnuplot> plot "x_y.tmp" w lp
gnuplot> plot "x_y.tmp" w lp,x**2
gnuplot> set term png
Terminal type set to 'png'
Options are 'nocrop enhanced size 640,480 font "/usr/share/fonts/truetype/libera
tion/LiberationSans-Regular.ttf,12" '
gnuplot> set output "x_y.png"
gnuplot> replot
gnuplot> quit
```



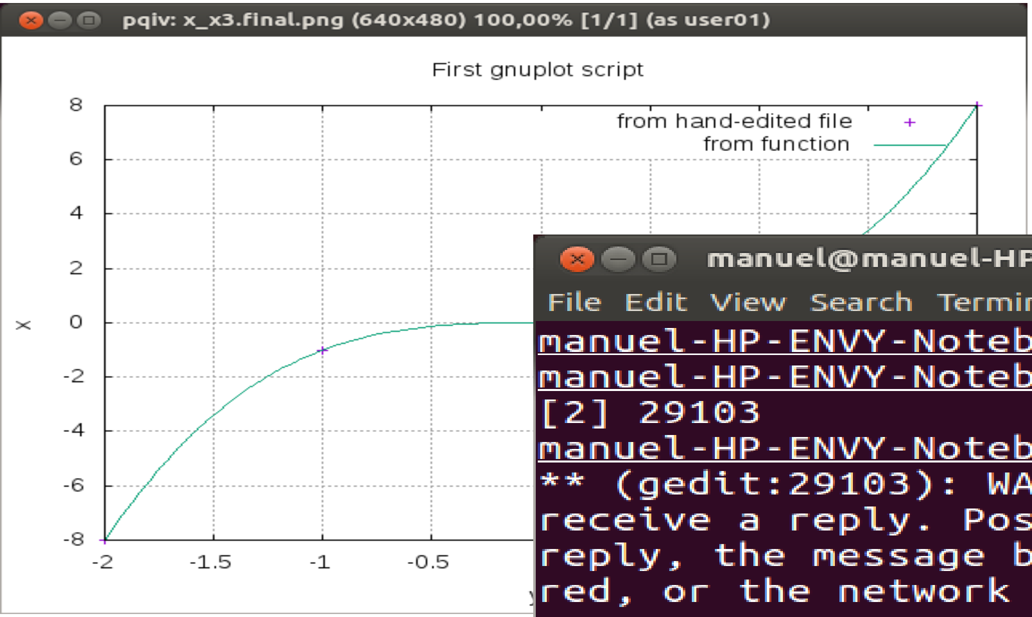
manuel@manuel-HP-ENVY-Notebook-13-ab0XX: ~

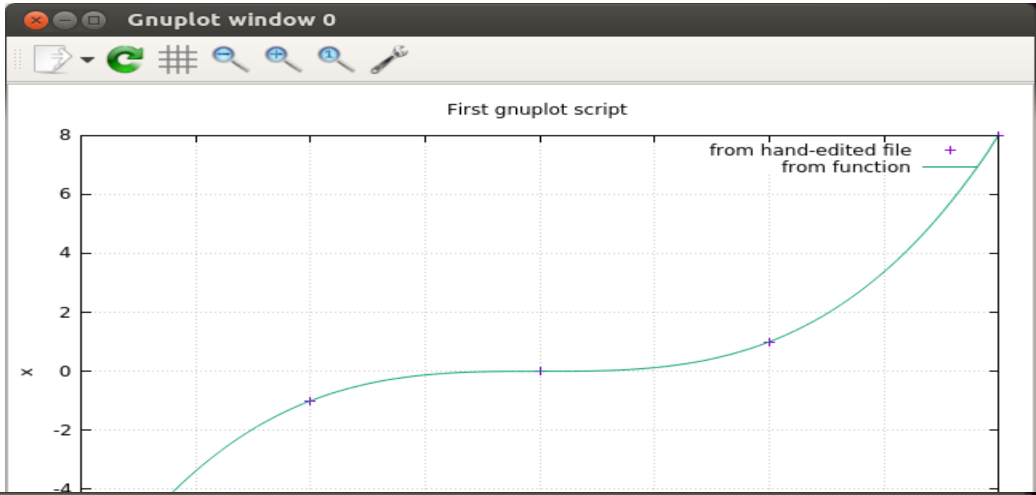
File Edit View Search Terminal Help

```
manuel-HP-ENVY-Notebook-13-ab0XX:~/ionsat-lab-01> pqiv -i x_y.png

** (pqiv:18405): WARNING **: Couldn't register with accessibility bus: Did not r
eceive a reply. Possible causes include: the remote application did not send a r
eply, the message bus security policy blocked the reply, the reply timeout expir
ed, or the network connection was broken.
^Z
Suspended
manuel-HP-ENVY-Notebook-13-ab0XX:~/ionsat-lab-01> bg
[1]    pqiv -i x_y.png &
manuel-HP-ENVY-Notebook-13-ab0XX:~/ionsat-lab-01> gawk '{print $1,$1**3}' x_y
x_y.png  x_y.tmp
manuel-HP-ENVY-Notebook-13-ab0XX:~/ionsat-lab-01> gawk '{print $1,$1**3}' x_y.tm
p > x_x3.tmp
manuel-HP-ENVY-Notebook-13-ab0XX:~/ionsat-lab-01> gnuplot

        G N U P L O T
        Version 5.0 patchlevel 3    last modified 2016-02-21

        Copyright (C) 1986-1993, 1998, 2004, 2007-2016
        Thomas Williams, Colin Kelley and many others

        gnuplot home:     http://www.gnuplot.info
        faq, bugs, etc:   type "help FAQ"
        immediate help:   type "help"  (plot window: hit 'h')

Terminal type set to 'qt'
gnuplot> plot "x_x3.tmp" w lp
gnuplot> plot "x_x3.tmp" w lp,x**3
gnuplot> set term png
Terminal type set to 'png'
Options are 'nocrop enhanced size 640,480 font "/usr/share/fonts/truetype/libera
tion/LiberationSans-Regular.ttf,12" '
gnuplot> set output "x_x3.png"
gnuplot> replot
gnuplot> quit
manuel-HP-ENVY-Notebook-13-ab0XX:~/ionsat-lab-01> pqiv -i x_*.png
```

x_x3.gnu
~/ionsat-lab-01

```
set xlabel "y"
set ylabel "x"
set grid
set title "First gnuplot script"
plot "x_x3.final" t "from hand-edited file",x**3 t "from function"
pause(-1)
set term png
set output "x_x3.final.png"
replot
```





manuel@manuel-HP-ENVY-Notebook-13-ab0XX: ~

```
manuel-HP-ENVY-Notebook-13-ab0XX:~/ionsat-lab-01> cp x_x3.tmp x_x3.final
manuel-HP-ENVY-Notebook-13-ab0XX:~/ionsat-lab-01> gedit x_x3.gnu &
[2] 29103
manuel-HP-ENVY-Notebook-13-ab0XX:~/ionsat-lab-01>
** (gedit:29103): WARNING **: Couldn't register with accessibility bus: Did not receive a reply. Possible causes include: the remote application did not send a reply, the message bus security policy blocked the reply, the reply timeout expired, or the network connection was broken.

manuel-HP-ENVY-Notebook-13-ab0XX:~/ionsat-lab-01> gnuplot x_x3.gnu

manuel-HP-ENVY-Notebook-13-ab0XX:~/ionsat-lab-01> pqiv -i x_x3.final.png &
[3] 29176
manuel-HP-ENVY-Notebook-13-ab0XX:~/ionsat-lab-01>
** (pqiv:29176): WARNING **: Couldn't register with accessibility bus: Did not receive a reply. Possible causes include: the remote application did not send a reply, the message bus security policy blocked the reply, the reply timeout expired, or the network connection was broken.
```

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Layout:

1) [**Motivation**] Precise Agriculture (PA) presentation (EU AUDITOR experiment)

1) [**Background**]: Brief introduction to main identified points of the presentation:
   a) GPS fundamentals: pseudoranges and carrier phases (optional)
   b) Ionospheric electron content
   c) Wide Area Real-Time Kinematic
   d) The International GNSS Service (*optional*)

3) [**One efficient operative system**] Quick introduction to Linux (*optional*)

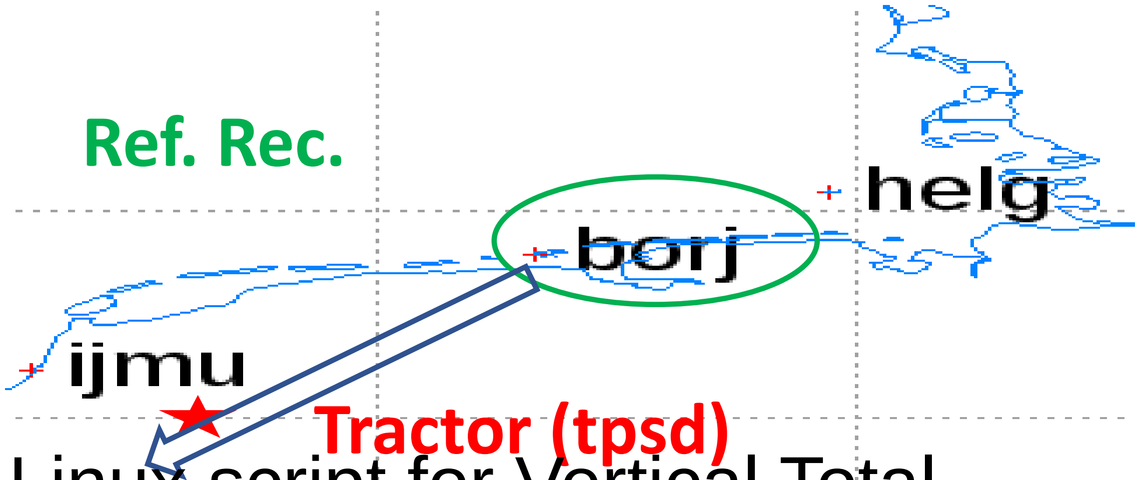
3) [**New tools for learning and research**] IonSAT Tools (IT), emulating Real-Time (RT) as much as possible (presented on the PA AUDITOR experiment):
   a) *gim2vtec.v2.scr*
   b) *gimrnx2stec.v2.scr*

5) [**IT application to ECLIPSE, FLARE & GSTORM scenarios**] (*optional*).

5) [**Example of RT GPS-ionospheric system**]: UPC-IonSAT since 2012.

5) [**Monitoring of co-seismic generated ionospheric signals]:** Application of RT ionospheric sounding for potential Tsunami warnings), with GNSS dense (Tohoku and mid earthquakes, EQ) and sparse networks (Chile 2015 EQ).

New IonSAT tools:
gim2vtec.v2.scr & gimrnx2stec.v2.scr



- ➢IonSAT tool gim2vtec.v2.scr : New Linux script for Vertical Total Electron Content (VTEC) extraction from Global Ionospheric Maps (GIM).

- ➢IonSAT tool gimrnx2stec.v2.scr: New Linux script for Slant TEC (STEC) computation from GIM-calibrated GPS meas. Carrier phase prepro.

- ➢The first suggested application is for the *motivating* AUDITOR experiment (June 13th, 2017) described in section 1, and for the baseline between reference and permanent receiver, similar to the

gim2vtec.v2.scr & gimrnx2stec.v2.scr @ AUDITOR

- ssh –X ionsat-tools-userYY@chapman.upc.es

- Where YY the User Id. # (from 01), and the password is given to you at the beginning of the laboratory session

```
 Editar  Ver  Buscar  Terminal  Ayuda
man:~% whoami
at-tools-user00
man:~% pwd
e/ionsat-tools-user00
man:~% cd ils
man:~/ils% ~/w/bin/gim2vtec.v2.scr
                        => (VTECvsTIME)  year0 (e.g. 2017)  month0 (e.g. 6)  day_of_month0 (e.g. 12)  ye
 (e.g. 2017)  month1 (e.g. 6)  day_of_month1 (e.g. 14)  GIM_IONEX_ID (e.g. uqrg)  dtsec_GIM_VTEC (e.g. 120
unID (e.g. Tractor_exp)  view_final_plots (y/n)  run_level (VTECvsTIME_extraction, VTECvsTIME_plots)  rec
rID_1 (e.g. borj) ... receiverID_N (e.g. ijmu)
                       //
e: gim2vtec.v2.scr runmode
                       \\
                        => (VTECvsLAT)  year (e.g. 2017)  month0 (e.g. 6)  day_of_month0 (e.g. 12)  mont
e.g. 6)  day_of_month1 (e.g. 14)  longitude (e.g. 4.556064337)  GIM_IONEX_ID (e.g. uqrg)  runID (e.g. Tra
_exp)  view_final_plots (y/n)  run_level (VTECvsLAT_extraction, VTECvsLAT_movie)
man:~/ils% ~/w/bin/gimrnx2stec.v2.scr
e: gimrnx2stec.v2.scr year0 (e.g. 2017)  month0 (e.g. 6)  day_of_month0 (e.g. 12)  year1 (e.g. 2017)  mon
 (e.g. 6)  day_of_month1 (e.g. 14)  GIM_IONEX_ID (e.g. uqrg)  rinex_sampling_time_in_seconds (e.g. 30)  ru
 (e.g. Tractor_exp)  generate_plots (y/n)  view_overall_plot_STECvsTIME  (y/n)  run_level (STEC_computatio
TEC_extraction, overall_STECvsTIME)  receiverID_1 (e.g. borj) ... receiverID_N (e.g. ijmu)
man:~/ils% 
```

gim2vtec.v2.scr & gimrnx2stec.v2.scr @ AUDITOR

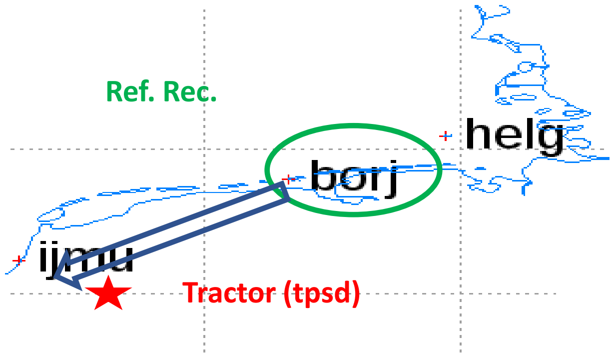
- An to get more productivity:

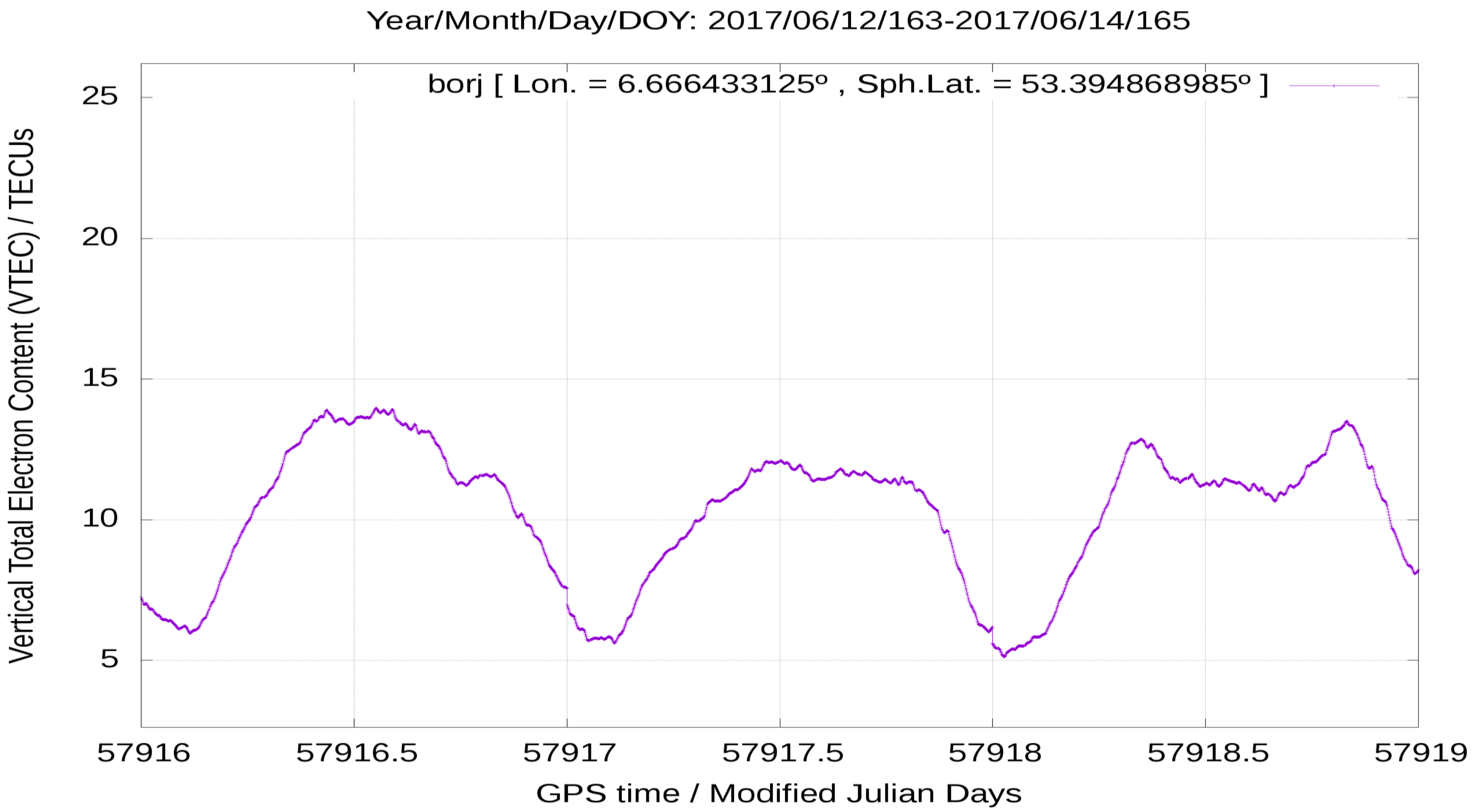
- chapman:~% whoami
- chapman:~% cd ~/ils
- chapman:~% pwd
- chapman:~% ls -l
- chapman:~% xedit run.IonSAT-lab_sessions.v4b.scr &

- Uncomment (remove the first leading #) the three command lines for AUDITOR block, save and run the script:

- chapman:~% ./run.IonSAT-lab_sessions.v4b.scr >& log.1 < /dev/null &

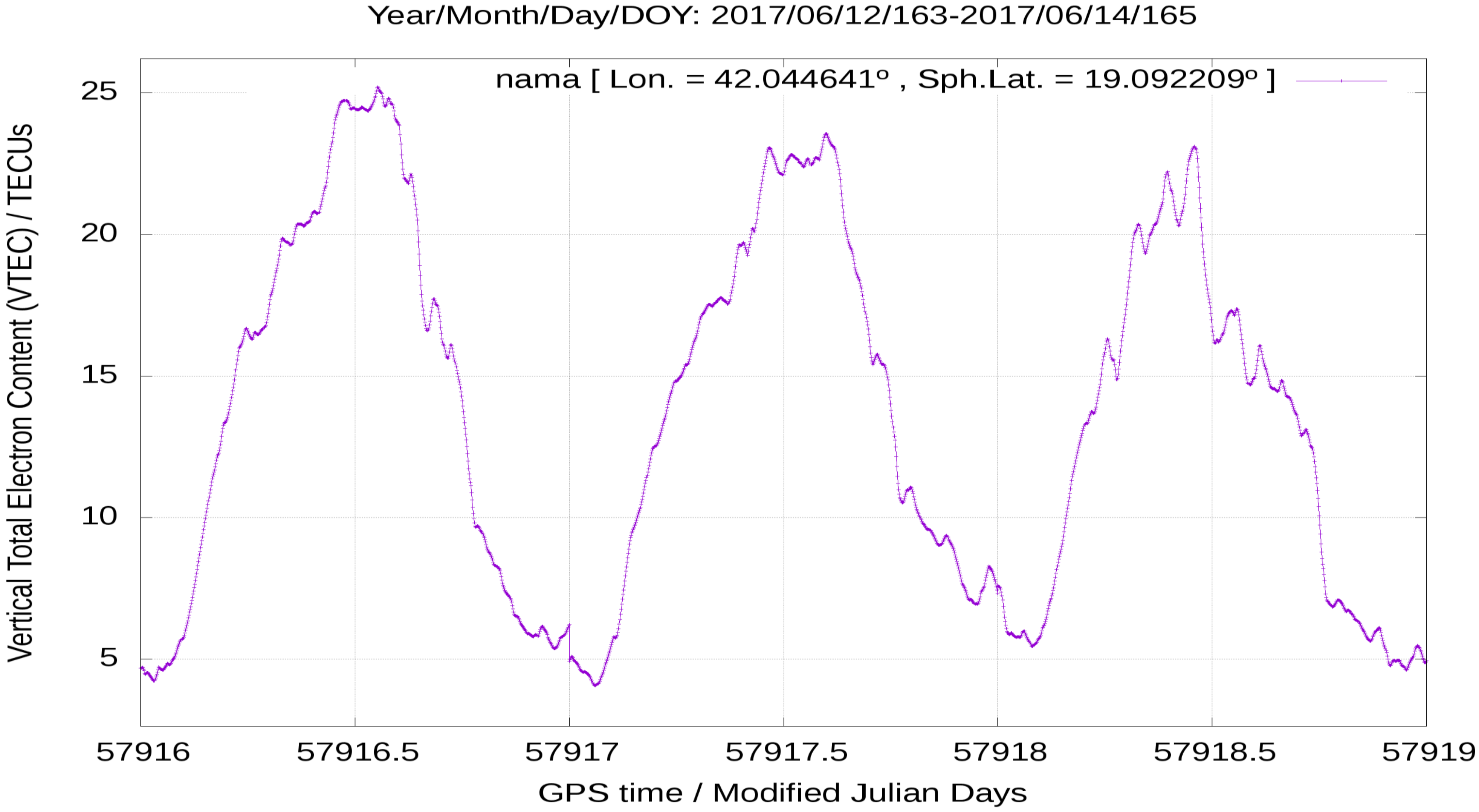
VTEC over BORJ from GIM UQRG





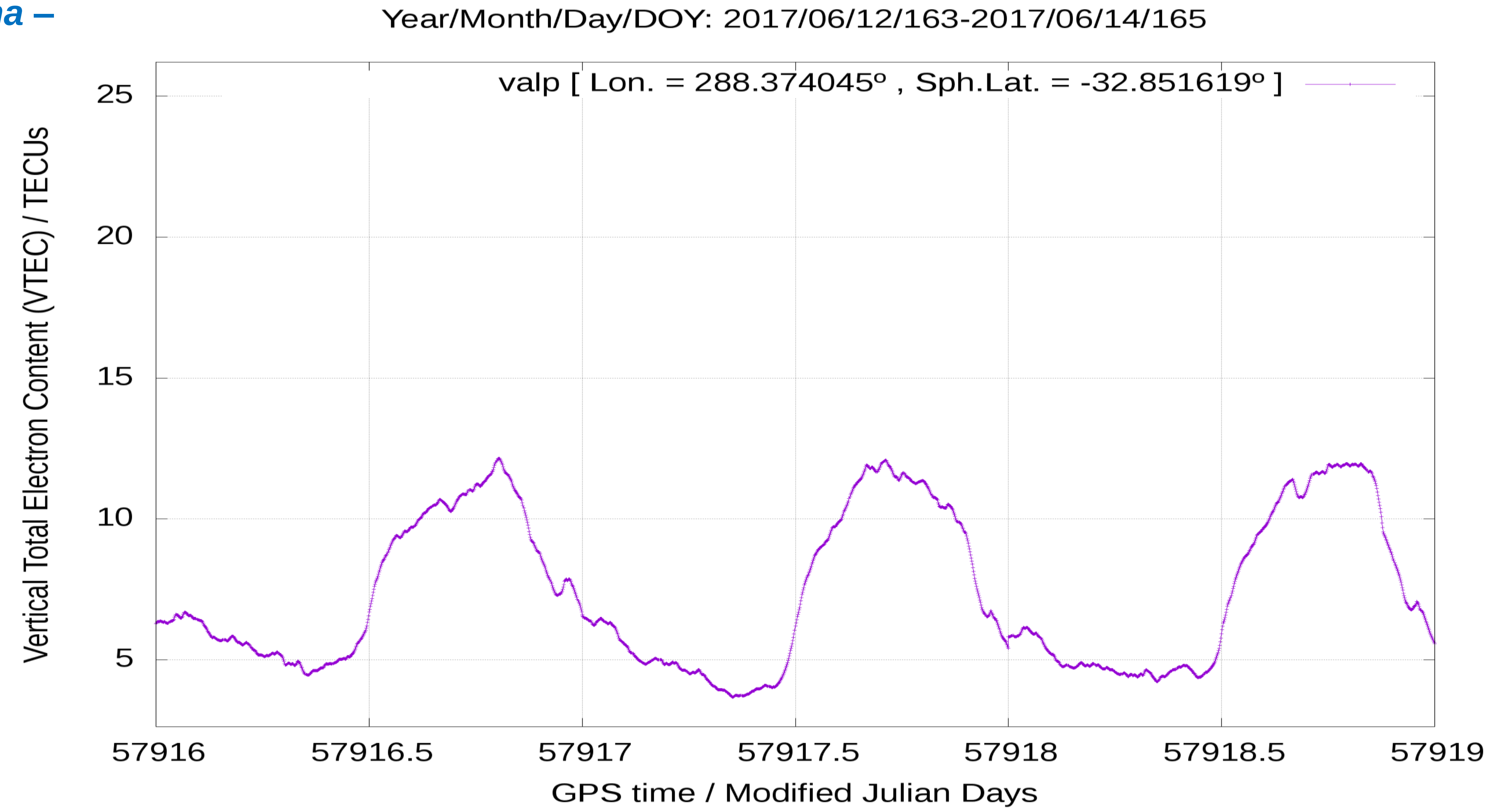
NAMA-TMP1 is a similar baseline to BORJ-IJMU but now at low latitude (Saudi Arabia)

VTEC over NAMA from GIM UQRG



RGAO-VALP is a similar baseline to BORJ-IJMU but now at mid-low latitude in South Hemisphere (Argentina – Chile border)

VTEC over VALP from GIM UQRG



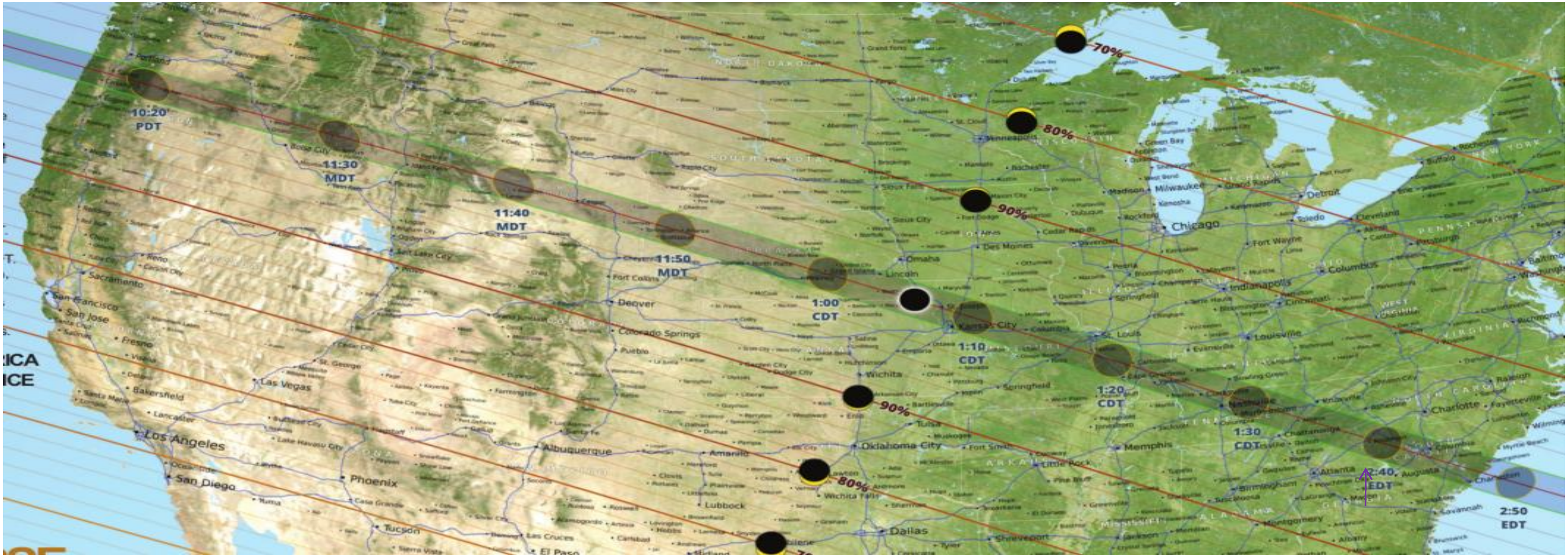
Part 5

Two case studies to work with:

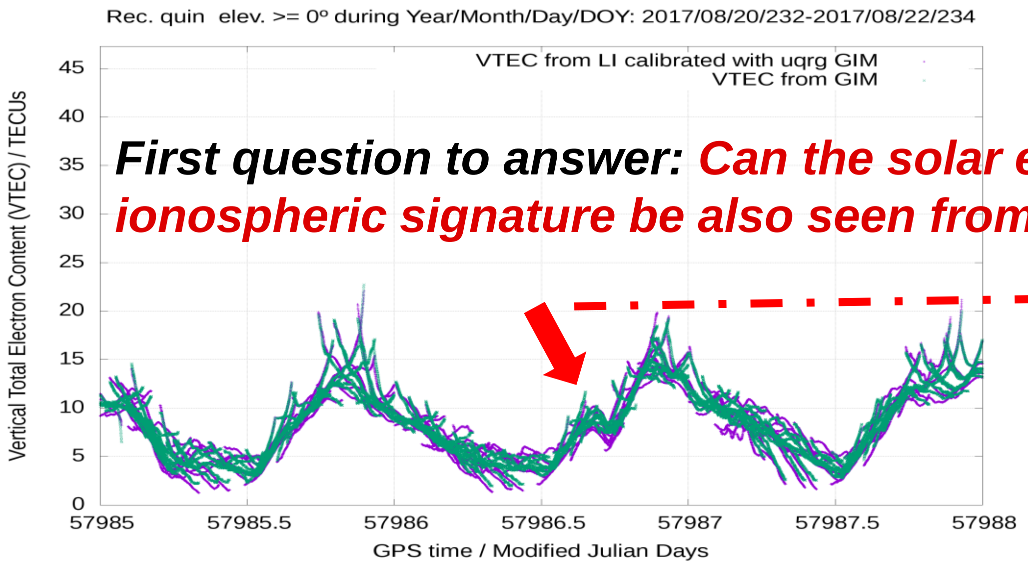
(a) Total solar eclipse during 21-Aug-2017 in NorthAmerica

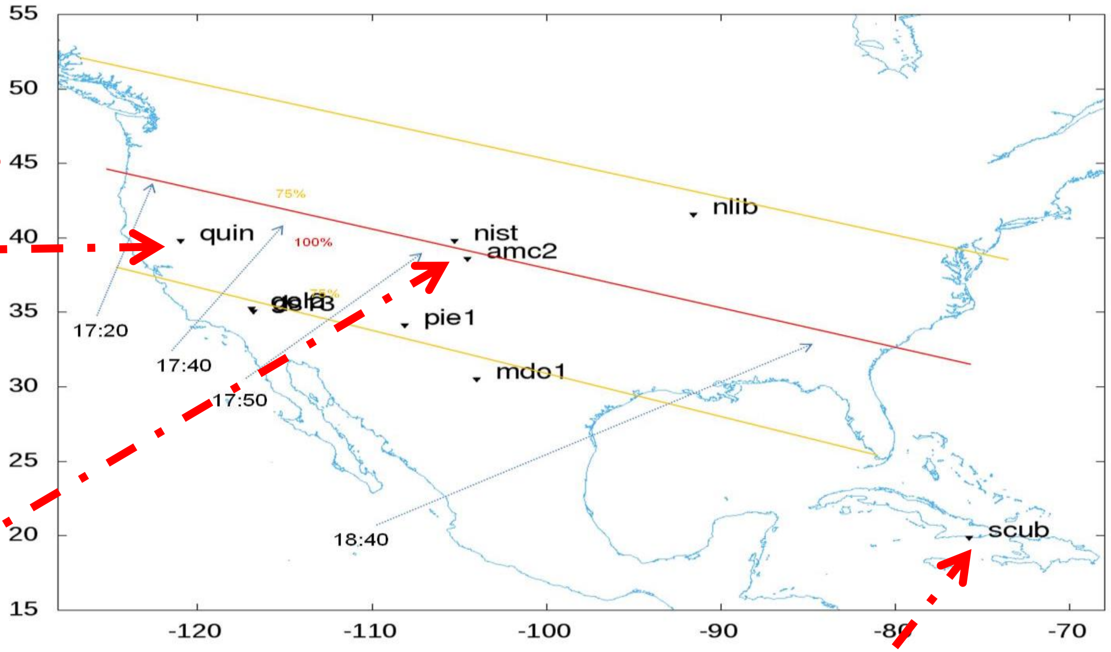
(b) Geomagnetic storm during 05-Nov-2023

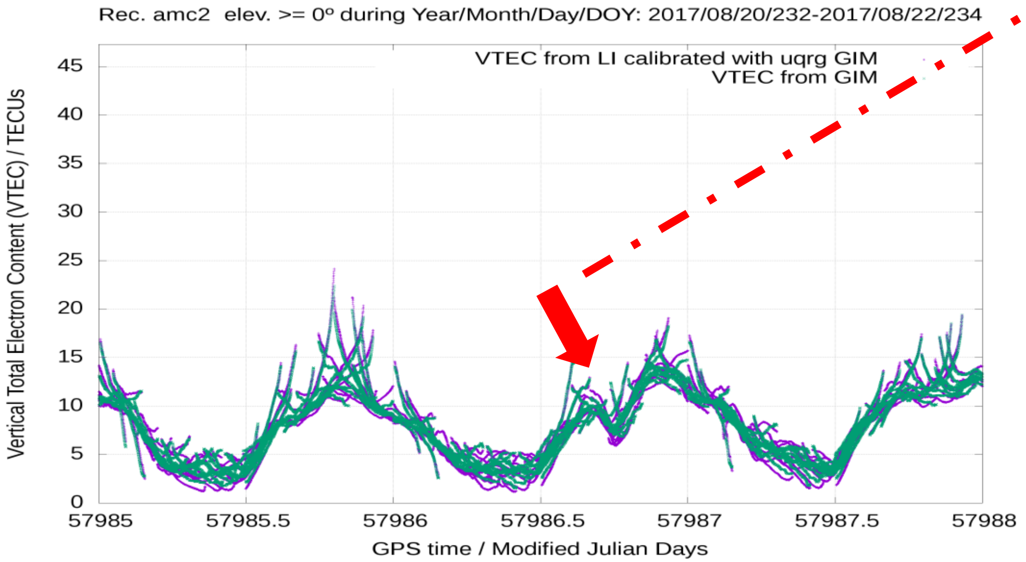
First case to study: Solar Eclipse 21 August 2017

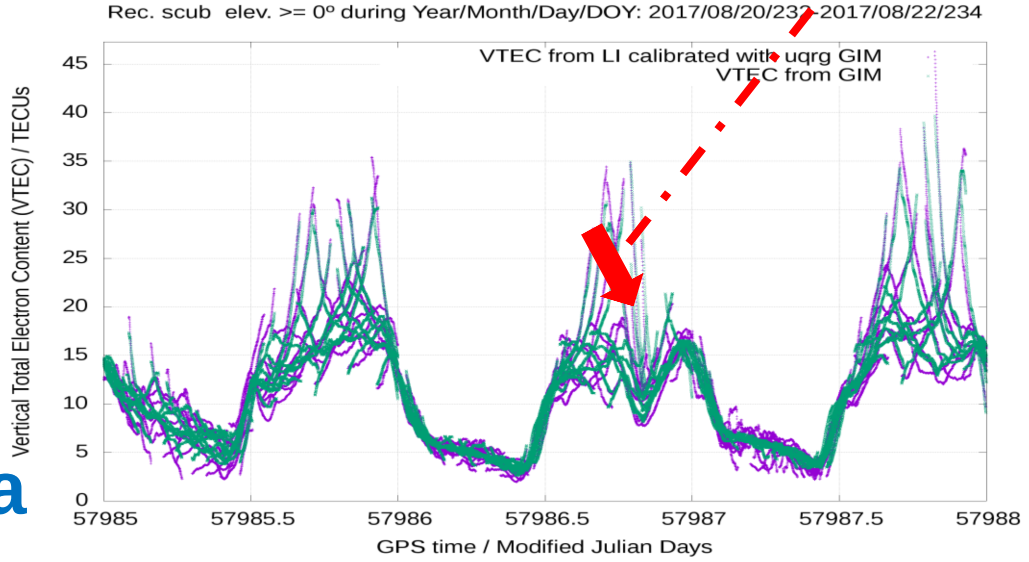


First question to answer: Can the solar eclipse ionospheric signature be also seen from VTEC GIMs?



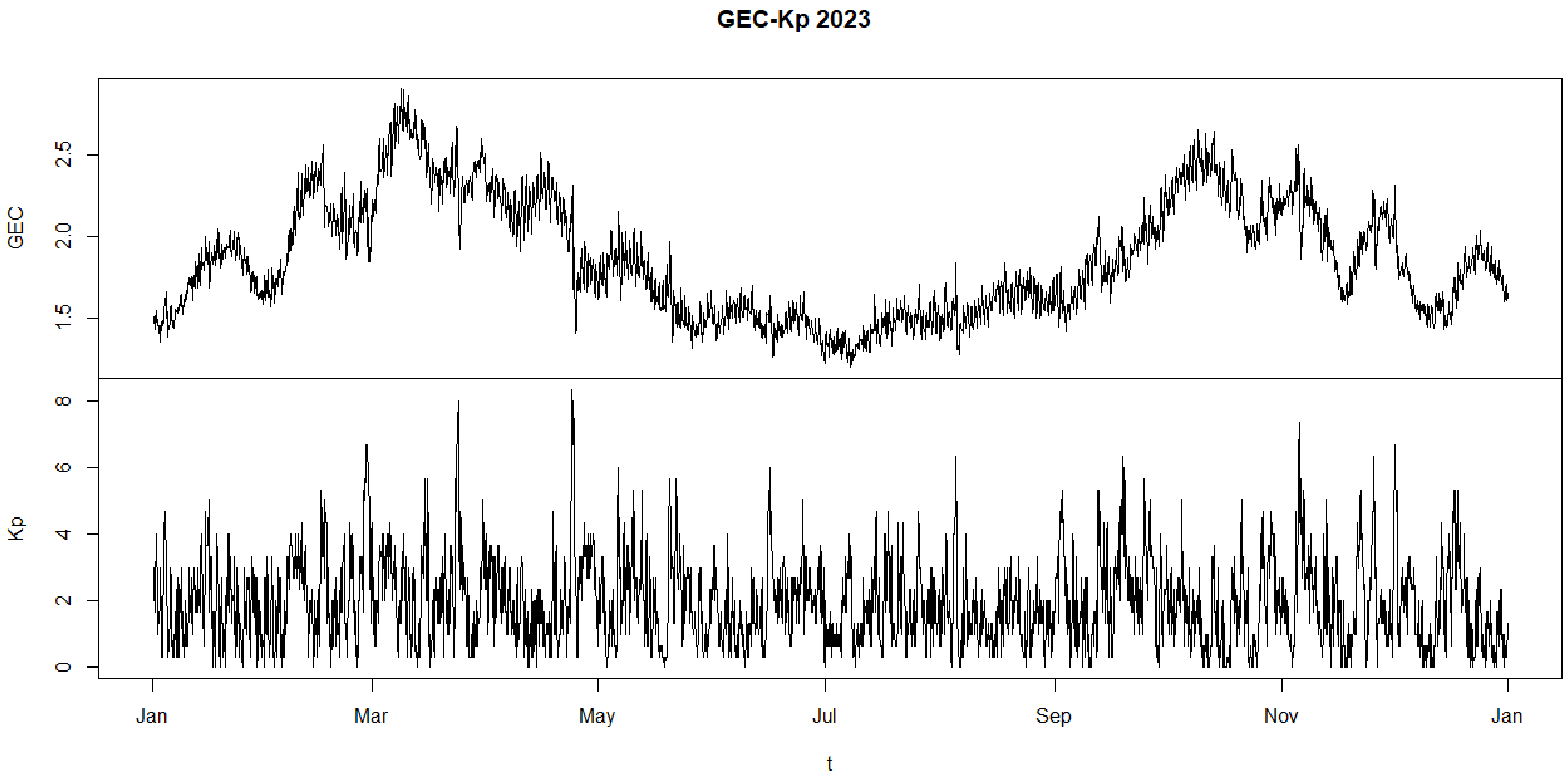




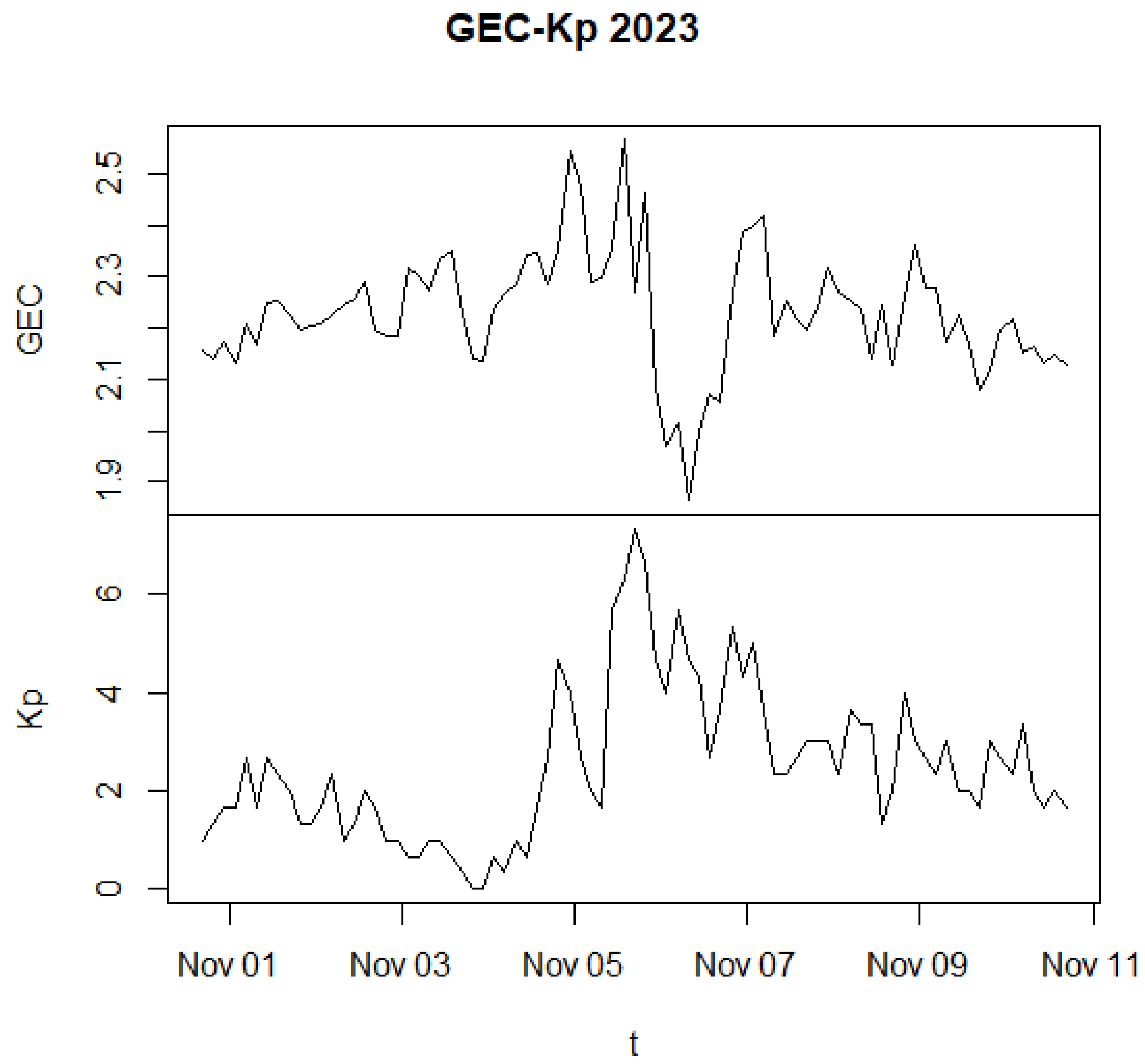


Depletion in agreement with Moon shadow timing from raw GNSS data

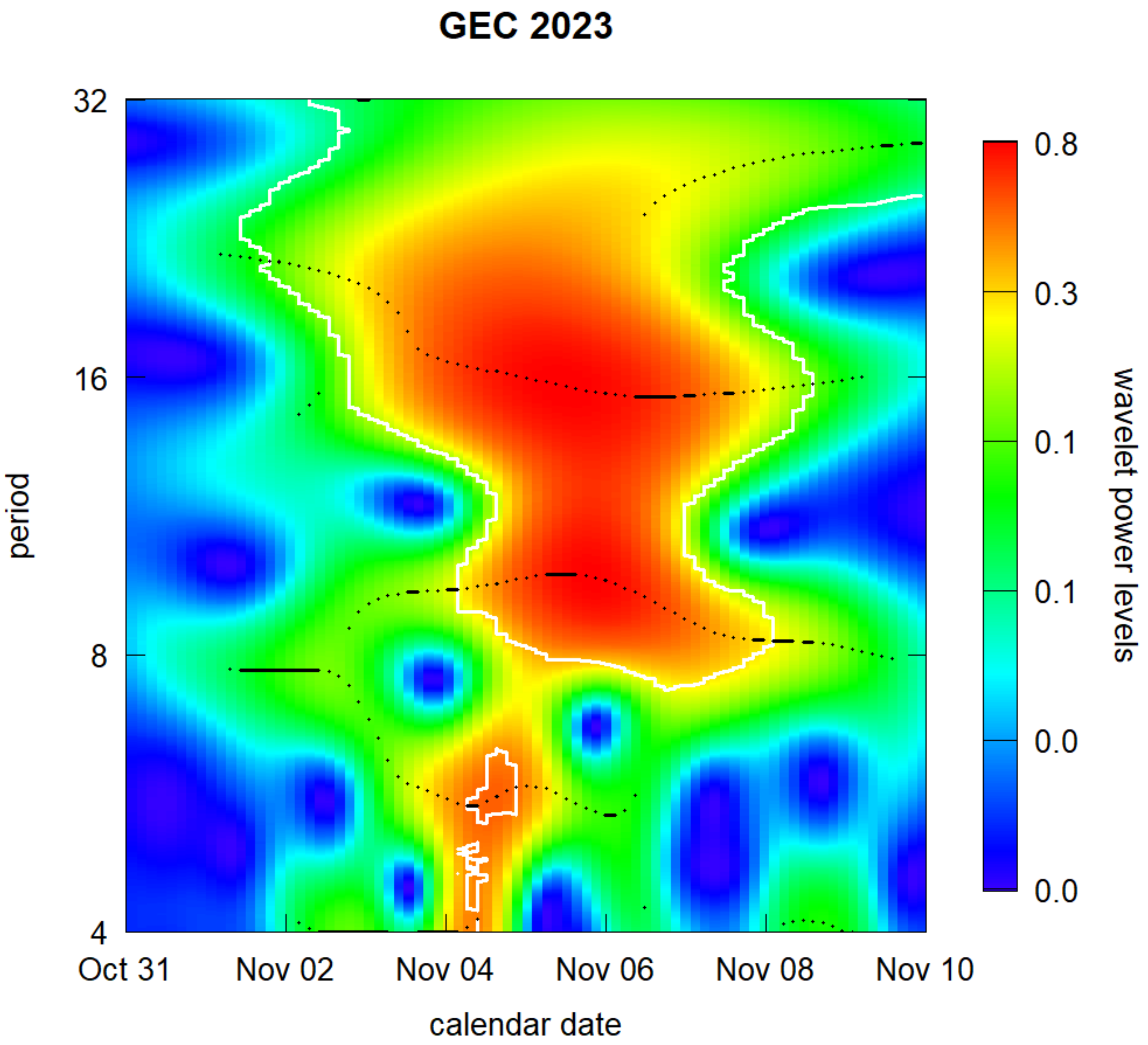
Second case to study: Geomagnetic storm during 5 Nov 2023

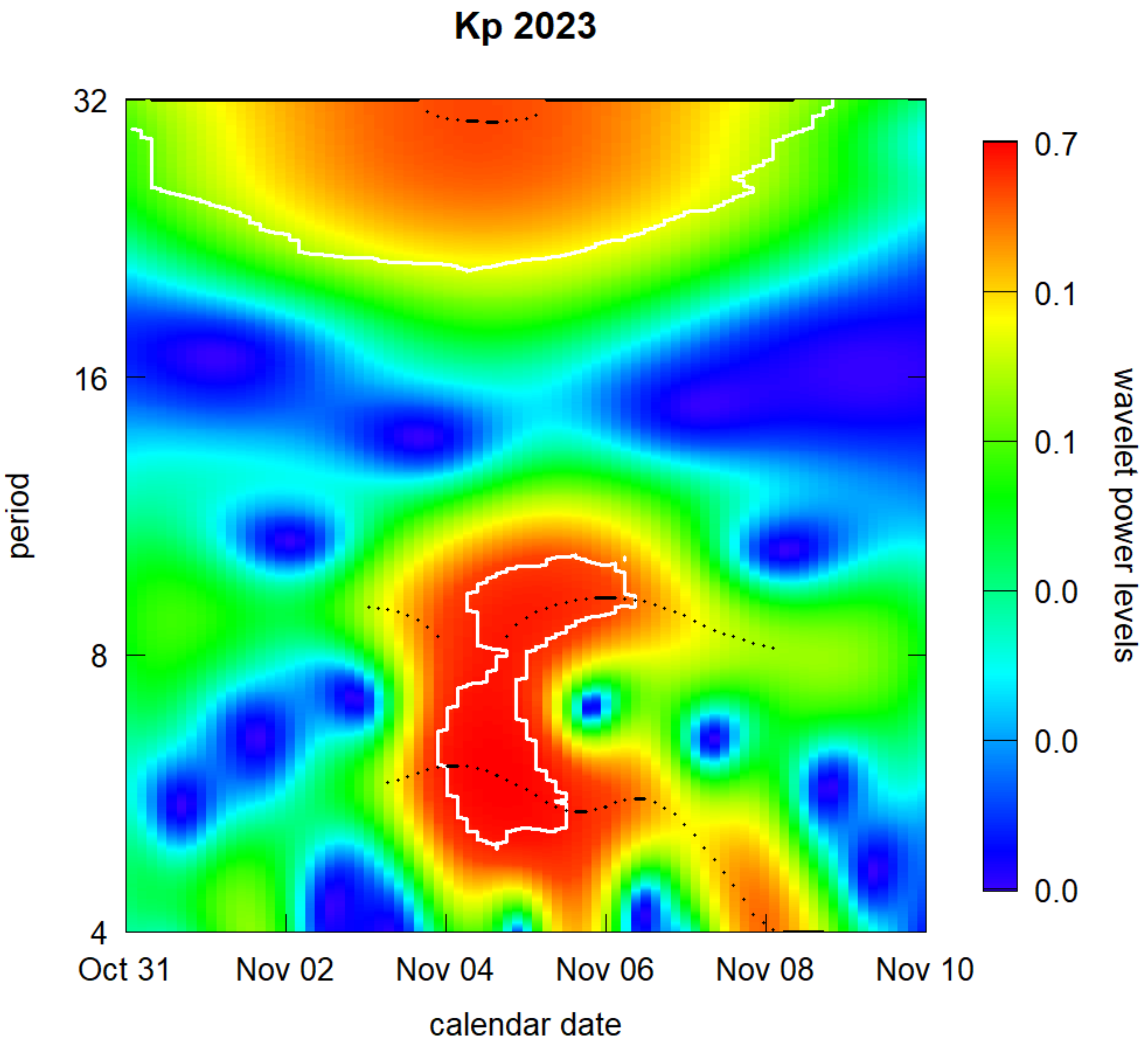


Zoom of GEC and Kp time evolution



Both GEC and Kp spectra becomes excited within the storm





Such GEC and Kp spectrum correlation is not new:

sensors

MDPI

Communication

The Spectrum of Global Electron Content: A New Potential Indicator of Space Weather Activity

Josep Maria Aroca-Farrerons [1], Manuel Hernández-Pajares [1,2,*], Haixia Lyu [1,3,4], David Roma-Dollase [2,5], Raul Orus-Perez [6], Alberto García-Rigo [1,2], Victoria Graffigna [1,2], Germán Olivares-Pulido [1], Enric Monte-Moreno [7], Heng Yang [1,7,8] and Qi Liu [1,9]

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2 IEEC, 08034 Barcelona, Spain; roma@ieec.cat
3 GNSS Research Center, Wuhan University, Wuhan 430079, China
4 Department of Physics and Mathematics, University of Alcalá, 28801 Alcalá de Henares, Spain
5 Instituto de Ciencias del Espacio (ICE-CSIC, IEEC), Campus Universitat d'Autonoma de Barcelona, Carrer de Can Magrans, 08193 Cerdanyola del Vallès, Spain
6 ESA, ESTEC, 2201 AZ Noordwijk, The Netherlands; raul.orus.perez@esa.int
7 UPC-TALP, 08034 Barcelona, Spain; enric.monte@upc.edu
8 School of Electronic Information and Engineering, Yangtze Normal University, Chongqing 408100, China
9 College of Geography and Environmental Science, Henan University, Kaifeng 475004, China
* Correspondence: manuel.hernandez@upc.edu

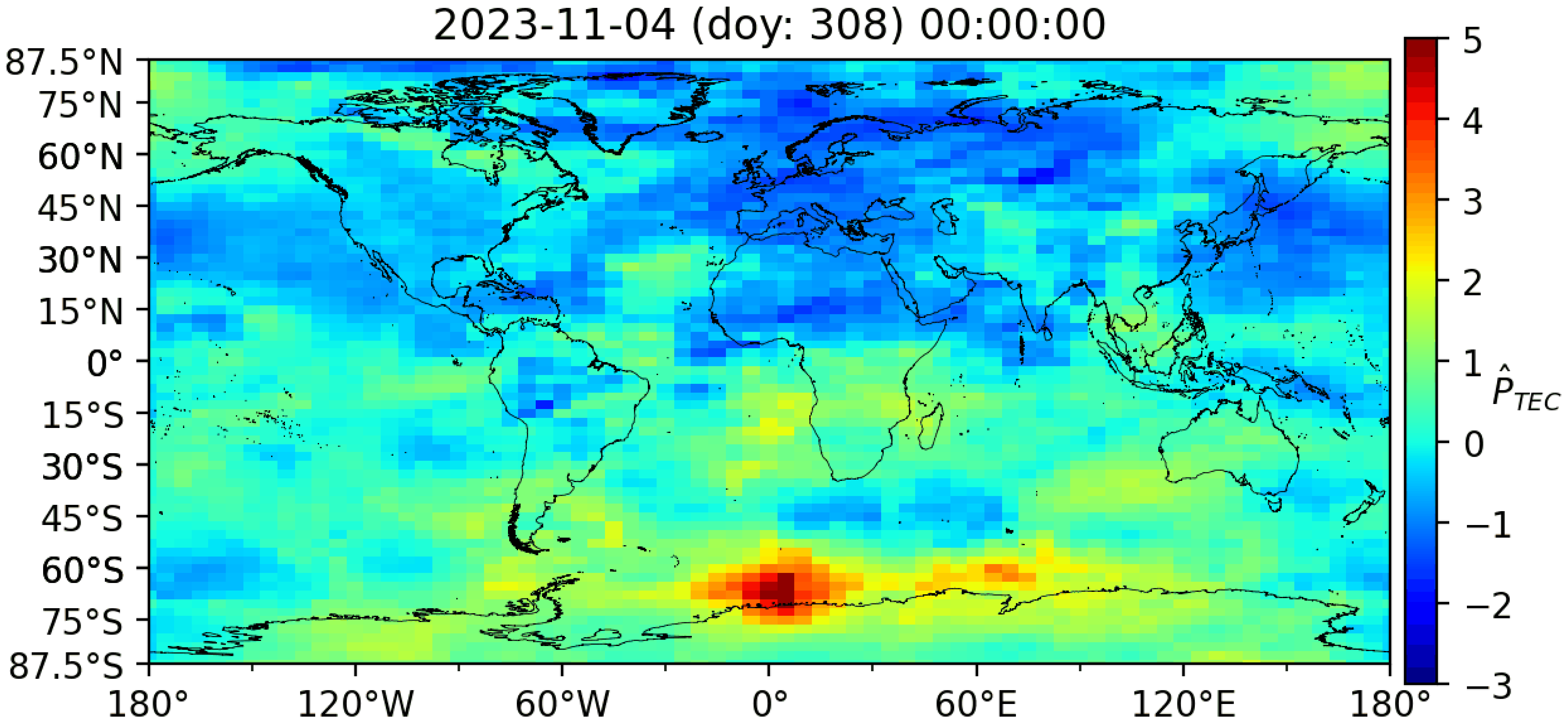
Abstract: The time evolution of the total number of free electrons in the Earth's ionosphere, i.e., the Global Electron Content (GEC), during more than two solar cycles is analyzed in this work. The GEC time series has been extracted from the Global Ionospheric Maps (GIMs) of Vertical Total Electron Content (VTEC) estimated by UPC-IonSAT with TOMION-v1 software from global GPS measurements since the end of 1996. A dual-layer voxel-based tomographic model solved with a forward Kalman scalar filter, from dual-frequency carrier GPS data only, provides the so-called UQRG GIM after VTEC kriging interpolation, with a resolution of 15 min in time, 5° in longitude and 2.5° in latitude. UQRG is one of the best behaving GIMs in the International GNSS Service (IGS).In this context, the potential application of the GEC spectrum evolution as a potential space weather index is discussed and demonstrated.

Keywords: global electron content; space weather index; global navigation satellite systems

check for updates

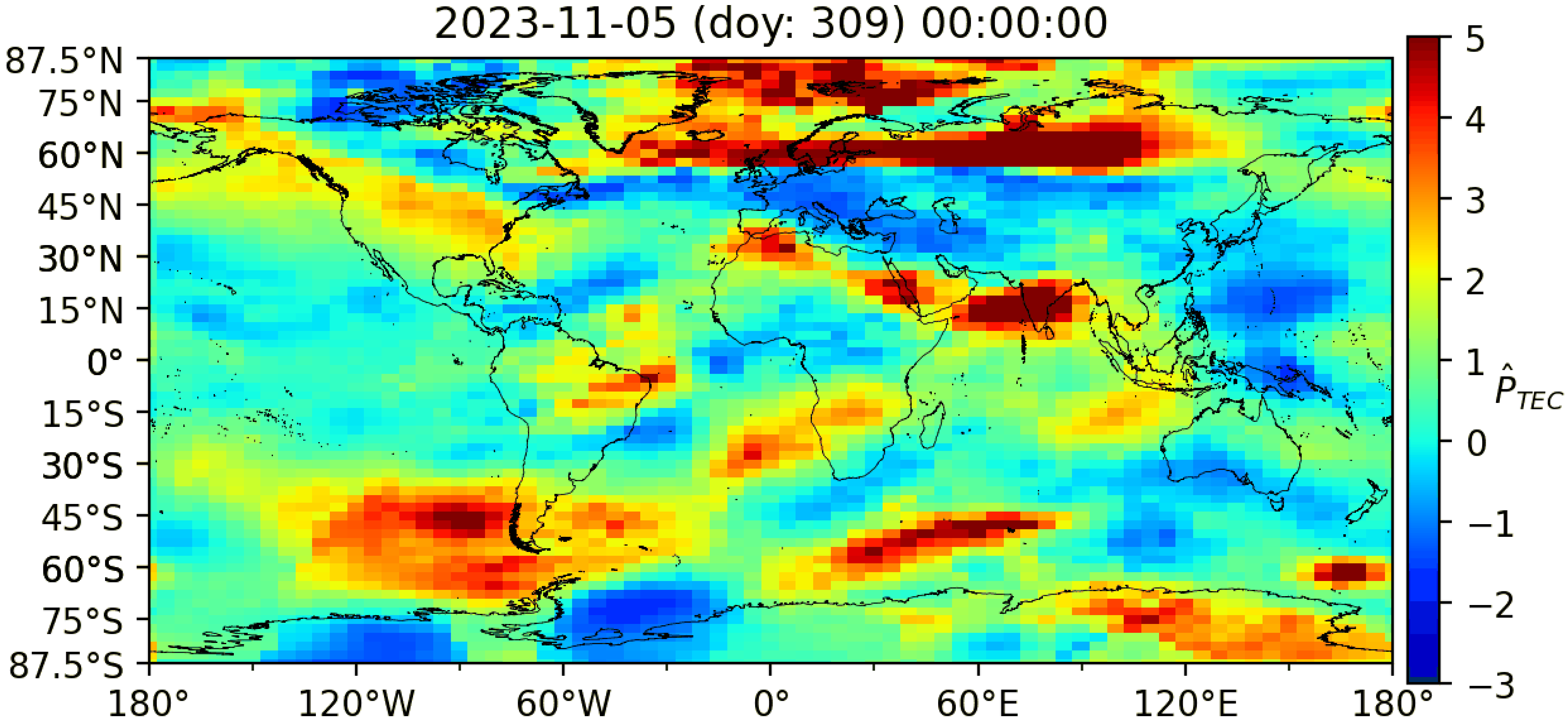
Citation: Aroca-Farrerons, J.M.; Hernández-Pajares, M.; Lyu, H.; Roma-Dollase, D.; Orus-Perez, R.; García-Rigo, A.; Graffigna, V.; Olivares-Pulido, G.; Monte-Moreno, E.; Yang, H.; et al. The Spectrum of Global Electron Content: A New Potential Indicator of Space Weather Activity. *Sensors* **2024**, *24*, 393. https://doi.org/10.3390/s24020393

Ionospheric Storm Scale GIM (IsUG) for previous day

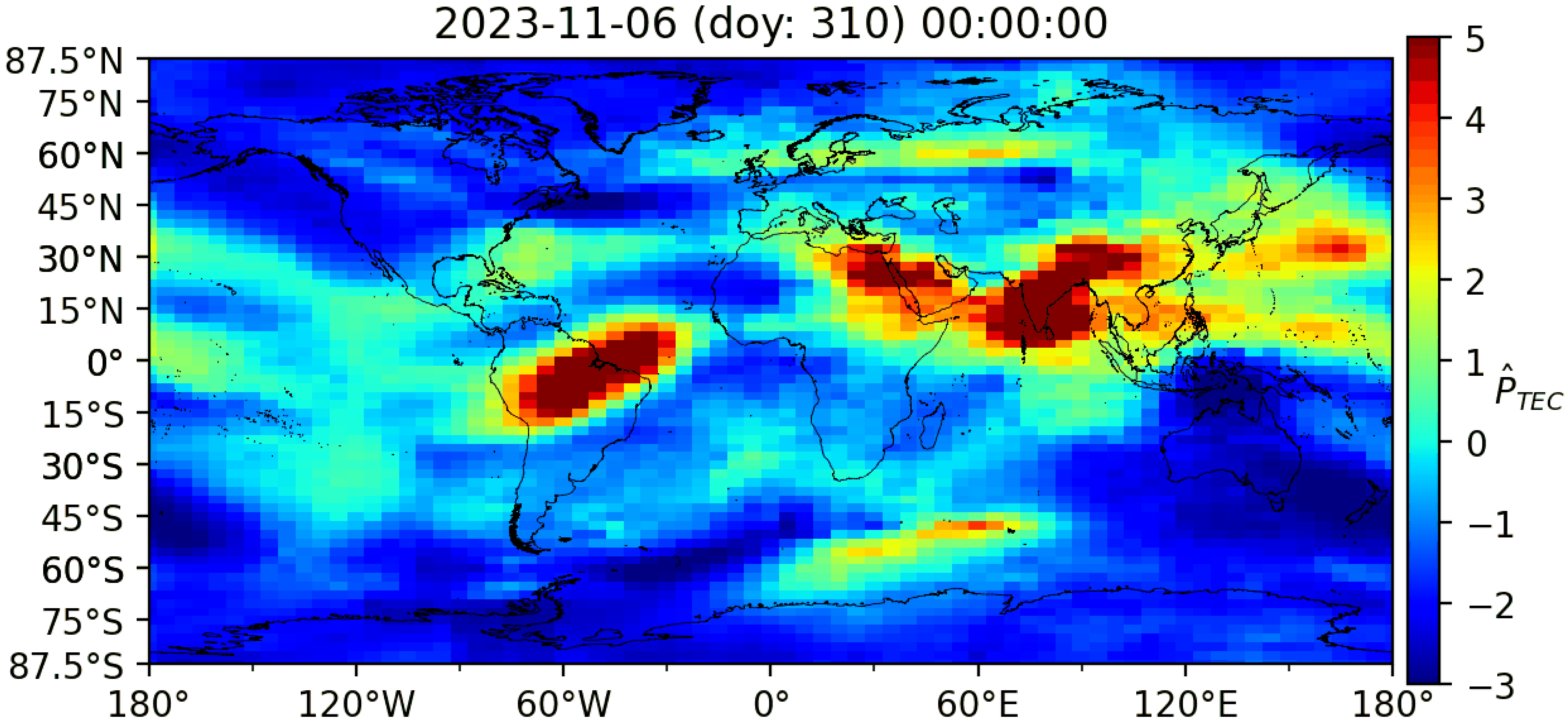


http://cabrera.upc.es/MoNEWIC/2023/

Ionospheric Storm Scale GIM (IsUG) for given day



Ionospheric Storm Scale GIM (IsUG) for next day



Second question to answer: ***Can we see corrresponding GIM VTEC time evolutions for different locations?***

Outline

Part 1- Visual introduction to GNSS Ionosphere

Part 2- Access to UPC-IonSAT Global Ionospheric Maps PITHIA-NRF registrations (AKA global VTEC maps every 15 minutes since end of 1996, i.e. ~1 million global VTEC maps & 5x10^9 VTECs computed so far)

Part 3- New applications of GIMs: gradient VTEC GIMs and Ionospheric Storm Scale GIMs

Part 4- Very basic introduction to Linux and to ionsat-tool "gim2vtec*.scr"

Part 5- Two case studies to work with:

(a) Total solar eclipse during 21-Aug-2017 in NorthAmerica

(b) Geomagnetic storm during 05-Nov-2023

More details in GIM WG with the study with gim2vtec*scr

IonSAT-tool of 2017 Solar eclipse & recent geomag. storm!

THANK YOU!!

4. References

- Hernandez-Pajares, M., Juan, J. M., & Sanz, J. (1997). Neural network modeling of the ionospheric electron content at global scale using GPS data. Radio Science, 32(3), 1081-1089.
- Hernández-Pajares, M., Juan, J. M., & Sanz, J. (1999). New approaches in global ionospheric determination using ground GPS data. Journal of Atmospheric and Solar-Terrestrial Physics, 61(16), 1237-1247.
- Hernández-Pajares, M., García-Rigo, A., Juan, J. M., Sanz, J., Monte, E., & Aragón-Àngel, A. (2012). GNSS measurement of EUV photons flux rate during strong and mid solar flares. Space Weather, 10(12).
- Hernández-Pajares, M., Juan, J. M., Sanz, J., Orus, R., Garcia-Rigo, A., Feltens, J., ... & Krankowski, A. (2009). The IGS VTEC maps: a reliable source of ionospheric information since 1998. Journal of Geodesy, 83(3), 263-275.
- Hernández-Pajares, M., Roma-Dollase, D., Krankowski, A., García-Rigo, A., & Orús-Pérez, R. (2017). Methodology and consistency of slant and vertical assessments for ionospheric electron content models. Journal of Geodesy, 91(12), 1405-1414.
- Hernández-Pajares, M., Lyu, H., Aragón-Àngel, À., Monte-Moreno, E., Liu, J., An, J., & Jiang, H. (2020). Polar Electron Content From GPS Data-Based Global Ionospheric Maps: Assessment, Case Studies, and Climatology. Journal of Geophysical Research: Space Physics, 125(6), e2019JA027677.
- Hernández-Pajares, M., Lyu, H., Garcia-Fernandez, M., & Orus-Perez, R. (2020). 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. Journal of Geodesy, 94(8), 1-16.
- Jakowski, N., & Hoque, M. M. (2019). Estimation of spatial gradients and temporal variations of the total electron content using ground-based GNSS measurements. Space Weather, 17, 339–356. https://doi.org/10.1029/2018SW002119.

4. References

- Kotov, D. V., Richards, P. G., Truhlík, V., Bogomaz, O. V., Shulha, M. O., Maruyama, N., ... & Chepurnyy, Y. M. (2018). 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. Geophysical Research Letters, 45(16), 8062-8071.
- Kotov, D. V., Richards, P. G., Truhlík, V., Maruyama, N., Fedrizzi, M., Shulha, M. O., ... & Domnin, I. F. (2019). Weak magnetic storms can modulate ionosphere-plasmasphere interaction significantly: Mechanisms and manifestations at mid-latitudes. Journal of Geophysical Research: Space Physics, 124(11), 9665-9675.
- Liu, Q., Hernández-Pajares, M., Lyu, H., Nishioka, M., Yang, H., Monte-Moreno, E., ... & Orús-Pérez, R. (2021). Ionospheric Storm Scale Index Based on High Time Resolution UPC-IonSAT Global Ionospheric Maps (IsUG). Space Weather, 19(11), e2021SW002853.
- Liu, Q., Hernández-Pajares, M., Yang, H., Monte-Moreno, E., García-Rigo, A., Lyu, H., ... & Orús-Pérez, R. (2022). A New Way of Estimating the Spatial and Temporal Components of the Vertical Total Electron Content Gradient Based on UPC-IonSAT Global Ionosphere Maps. Space Weather, 20(2), e2021SW002926.
- Nishioka, M., T. Tsugawa, H. Jin, and M. Ishii (2017), A new ionospheric storm scale based on TEC and f o F 2 statistics, Space Weather, 15, 228–239, doi:10.1002/2016SW001536.
- Orús R., Hernández-Pajares, M., Juan, J. M., & Sanz, J. (2005). Improvement of global ionospheric VTEC maps by using kriging interpolation technique. Journal of atmospheric and solar-terrestrial physics, 67(16), 1598-1609.
- Roma-Dollase, D., Hernández-Pajares, M., Krankowski, A., Kotulak, K., Ghoddousi-Fard, R., Yuan, Y., ... & Gómez-Cama, J. M. (2018). Consistency of seven different GNSS global ionospheric mapping techniques during one solar cycle. Journal of Geodesy, 92(6), 691-706.