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Space Weather studies with the NeQuick ionospheric electron density model

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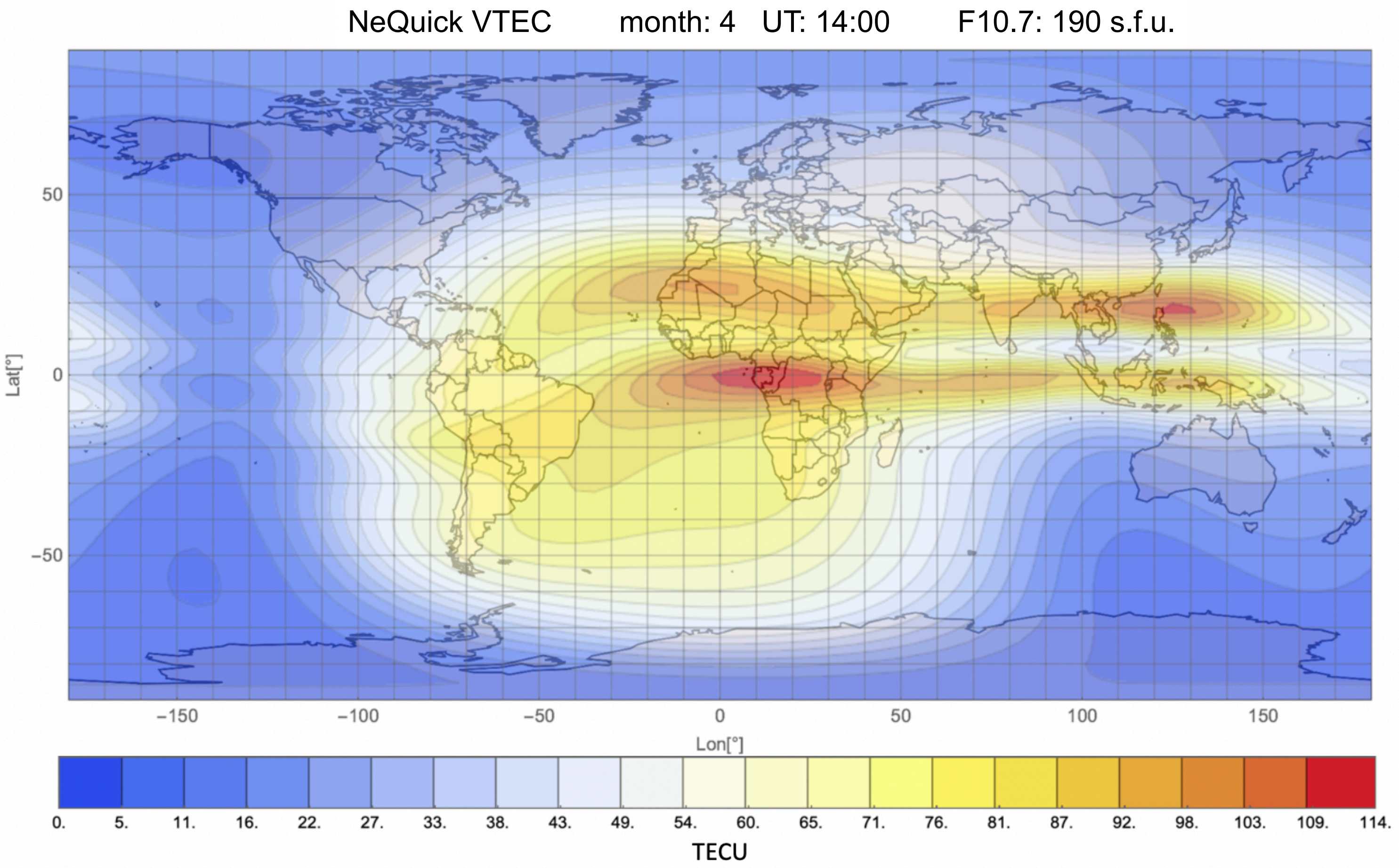
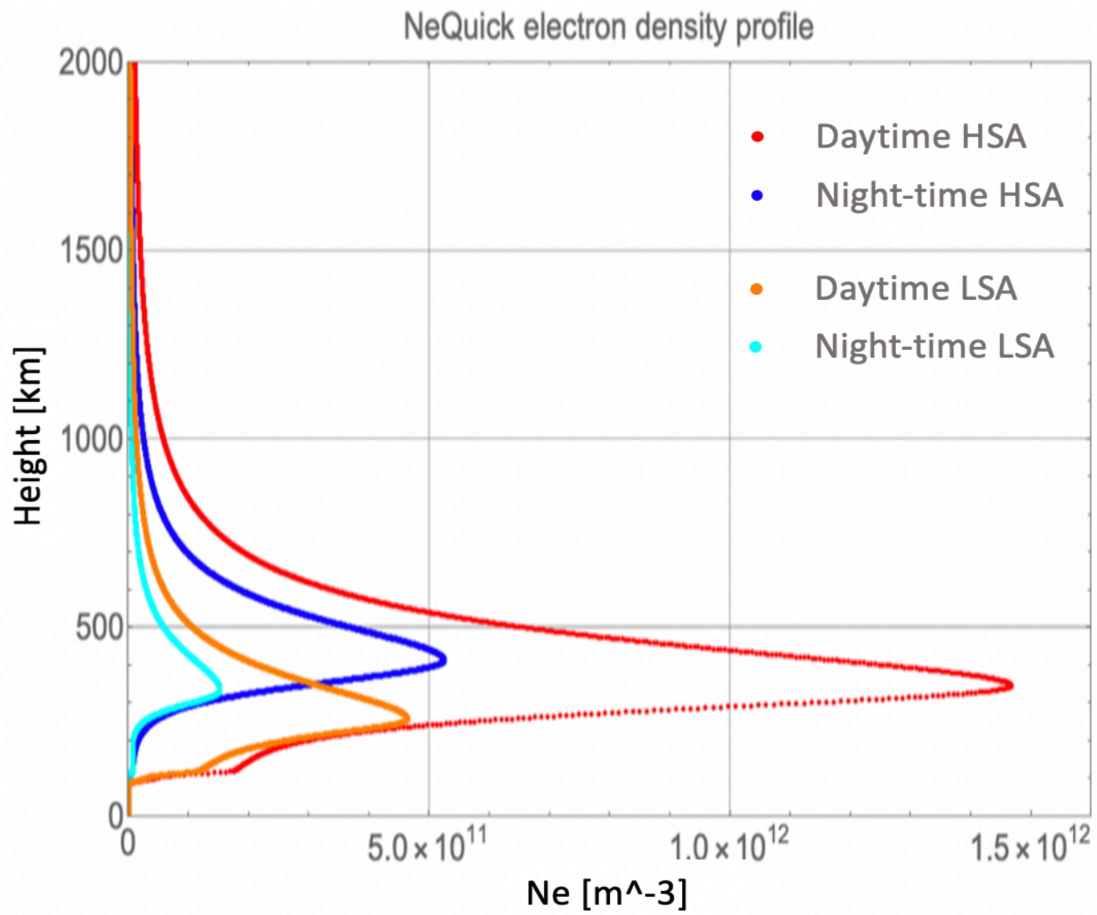
NeQuick

- The **NeQuick 2** (Nava et al., 2008) is an ionospheric electron density model developed at the Abdus Salam International Centre for Theoretical Physics (ICTP), Trieste, Italy, in collaboration with the University of Graz, Austria.
- It is a quick-run empirical model particularly designed for trans-ionospheric propagation applications, conceived to reproduce the median behavior of the ionosphere.
- NeQuick inputs are: position, time and solar flux; the output is the electron concentration at the given location and time.





NeQuick

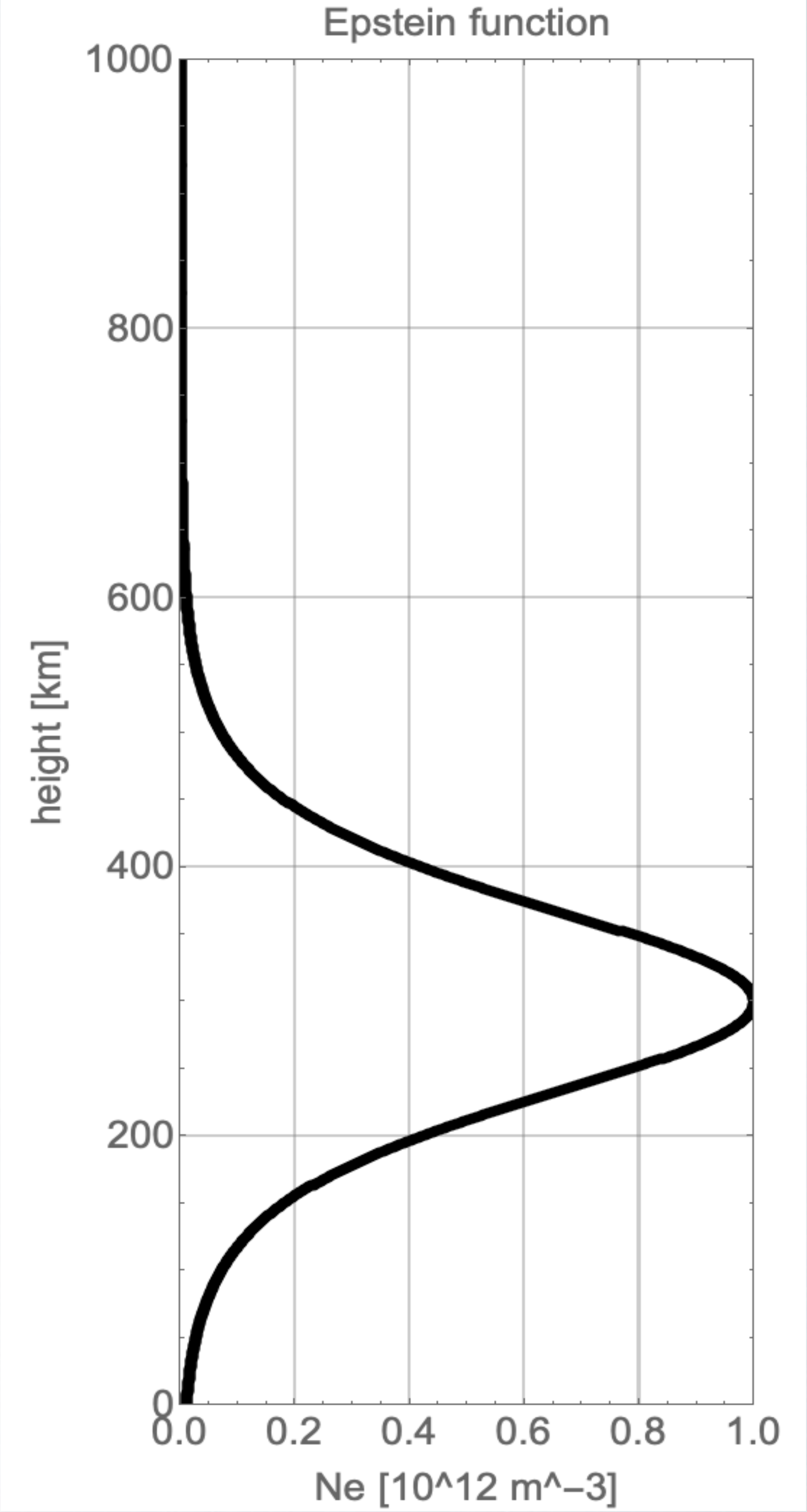
- The model profile formulation includes 6 semi-Epstein layers with modeled thickness parameters and is based on anchor points defined by foE, foF1, foF2 and M(3000)F2 values.
- These values can be modeled (ITU-R coefficients for foF2, M(3000)F2) or experimentally derived.

$$N_E(h) = \frac{4Nm^*E}{\left(1+\exp\left(\frac{h-hmE}{BE}\xi(h)\right)\right)^2} \exp\left(\frac{h-hmE}{BE}\xi(h)\right)$$

$$N_{F1}(h) = \frac{4Nm^*F1}{\left(1+\exp\left(\frac{h-hmF1}{B1}\xi(h)\right)\right)^2} \exp\left(\frac{h-hmF1}{B1}\xi(h)\right)$$

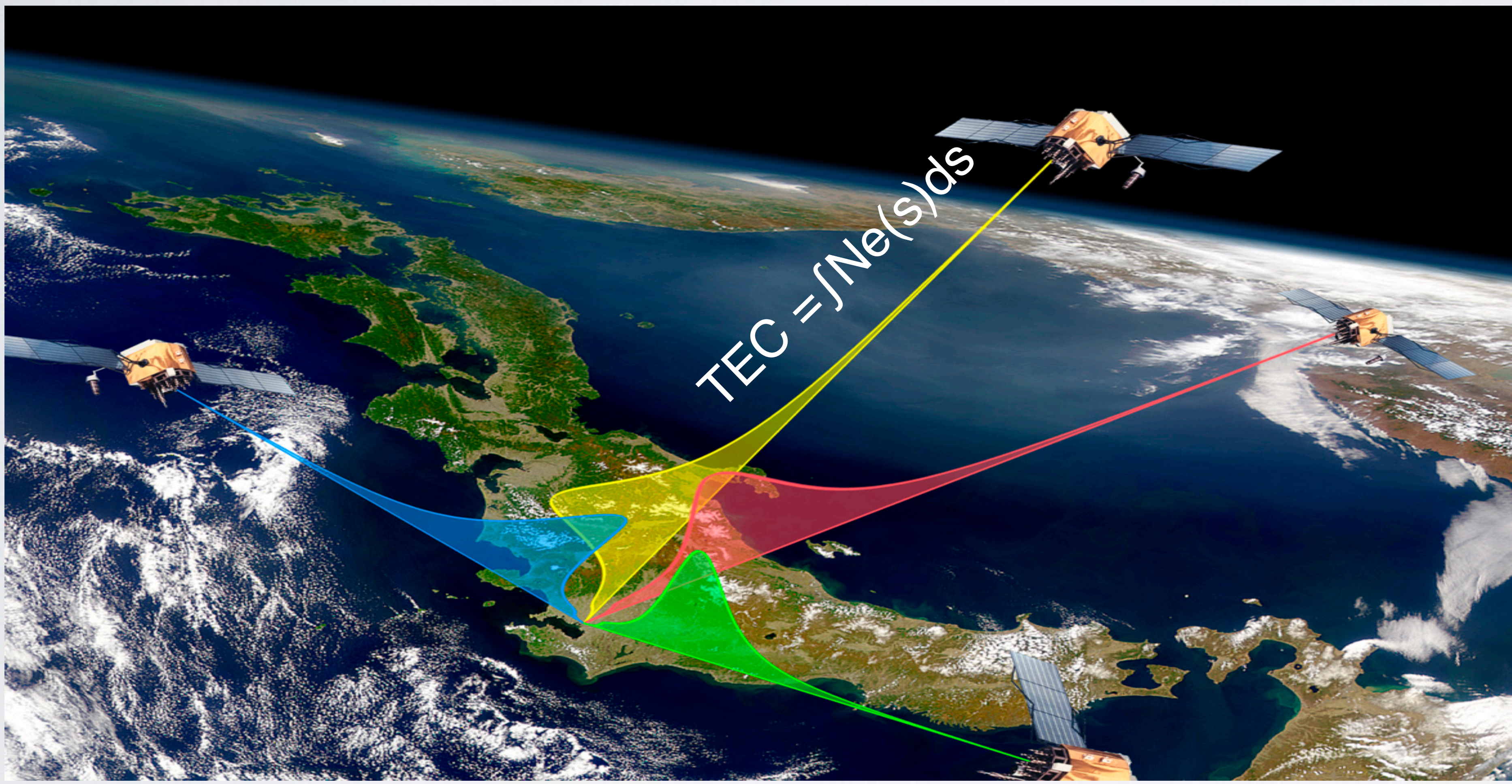
$$N_{F2}(h) = \frac{4NmF2}{\left(1+\exp\left(\frac{h-hmF2}{B2}\right)\right)^2} \exp\left(\frac{h-hmF2}{B2}\right)$$

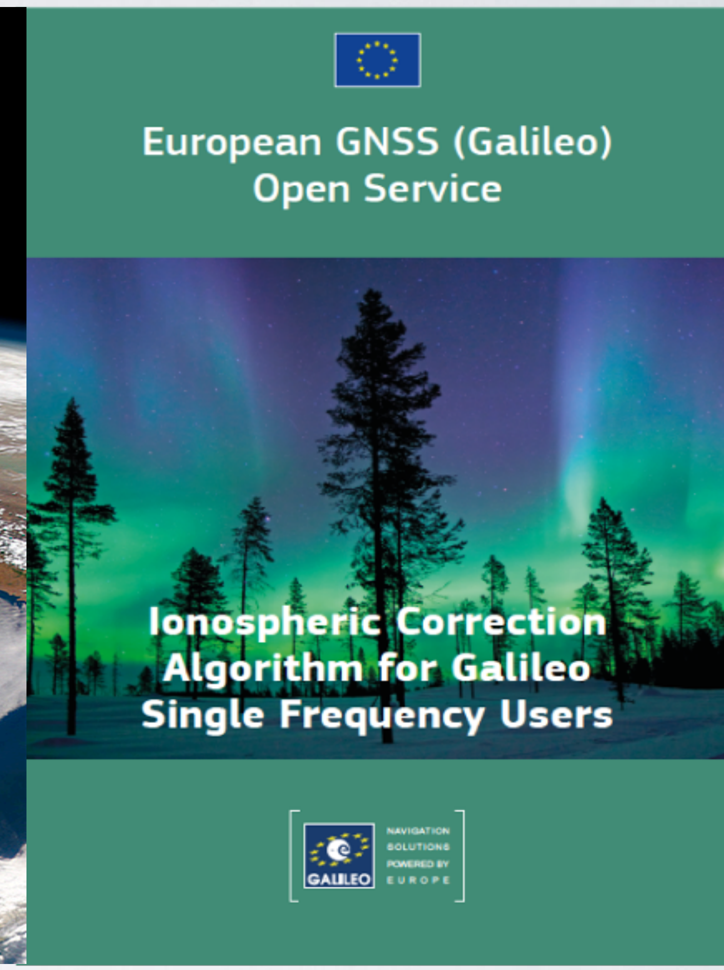
where $$\xi(h) = \exp\left(\frac{10}{1+1|h-hmF2|}\right)$$



NeQuick

- NeQuick package includes routines to evaluate the electron density along any "ground-to-satellite" ray-path and the corresponding Total Electron Content (TEC) by numerical integration.



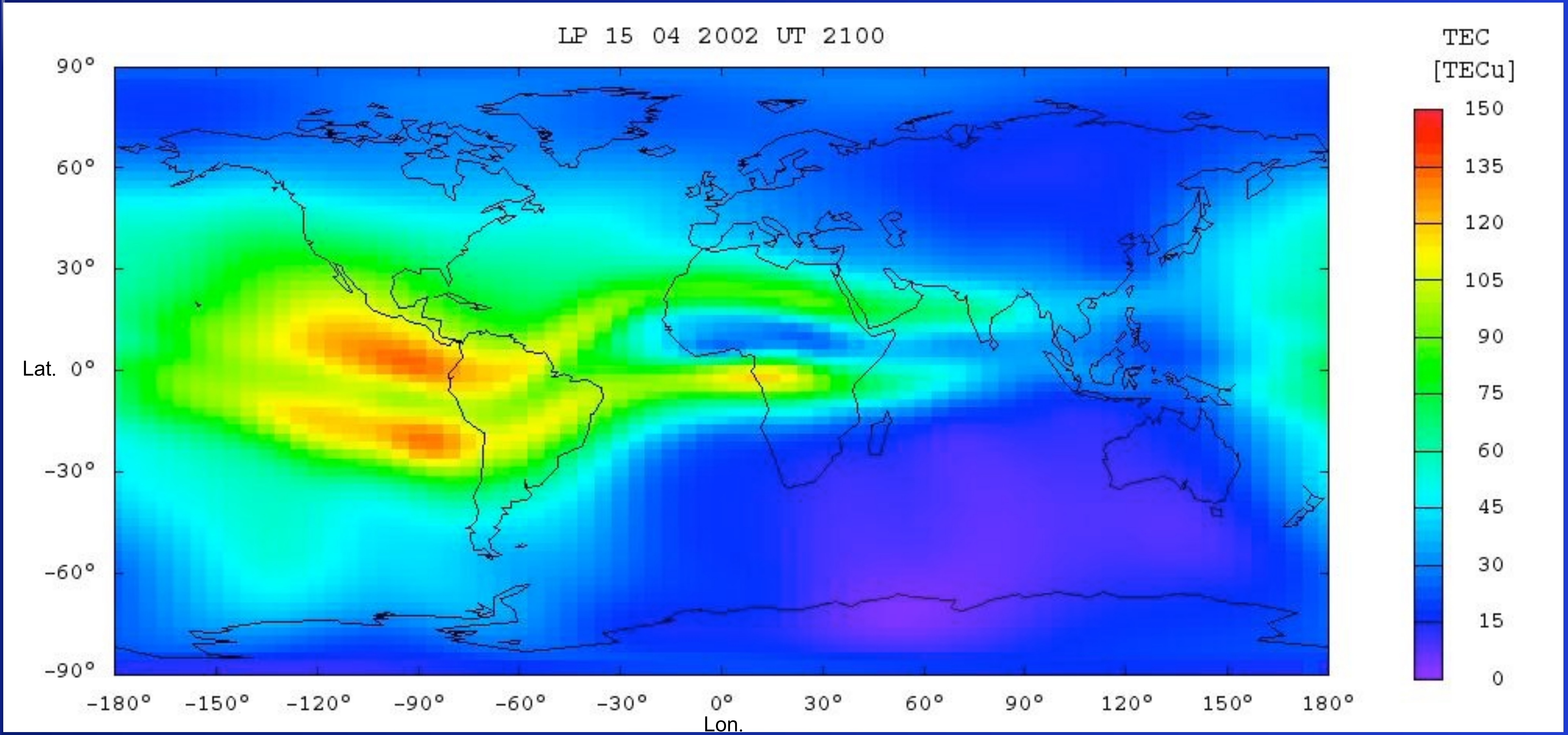


- A specific version of NeQuick (NeQuick G, implemented by ESA) has been adopted as Galileo Single-Frequency Ionospheric Correction Algorithm (EC, 2016) and its performance has been confirmed during In-Orbit Validation.

From climate to weather

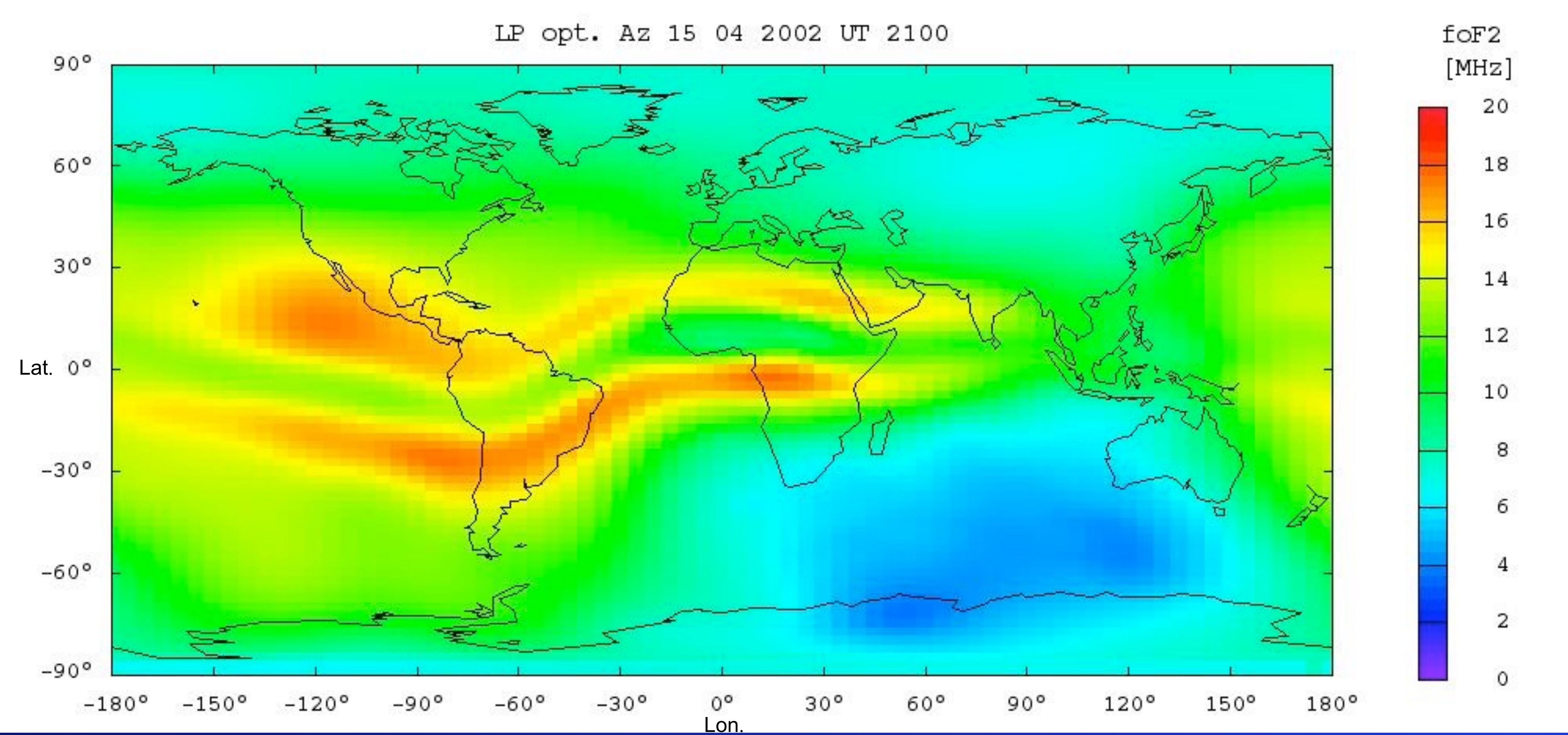
- Empirical models like NeQuick have been conceived to reproduce the median behavior (“climate”) of the ionosphere.
- To estimate the 3-D electron density of the ionosphere for current conditions ("weather") several assimilation schemes have been developed. They are of different complexity and rely on different kinds of data.
- In the case of NeQuick, (multiple) effective parameters and the BLUE algorithm have been utilised to adapt the model to GNSS-derived TEC data (and ionosonde measured peak parameters values).
- In the following, specific examples and case studies will be considered.

Vertical TEC data ingestion



grid points:
lat.=-90°, 90° step 2.5°
lon.=-180°, 180° step 5°

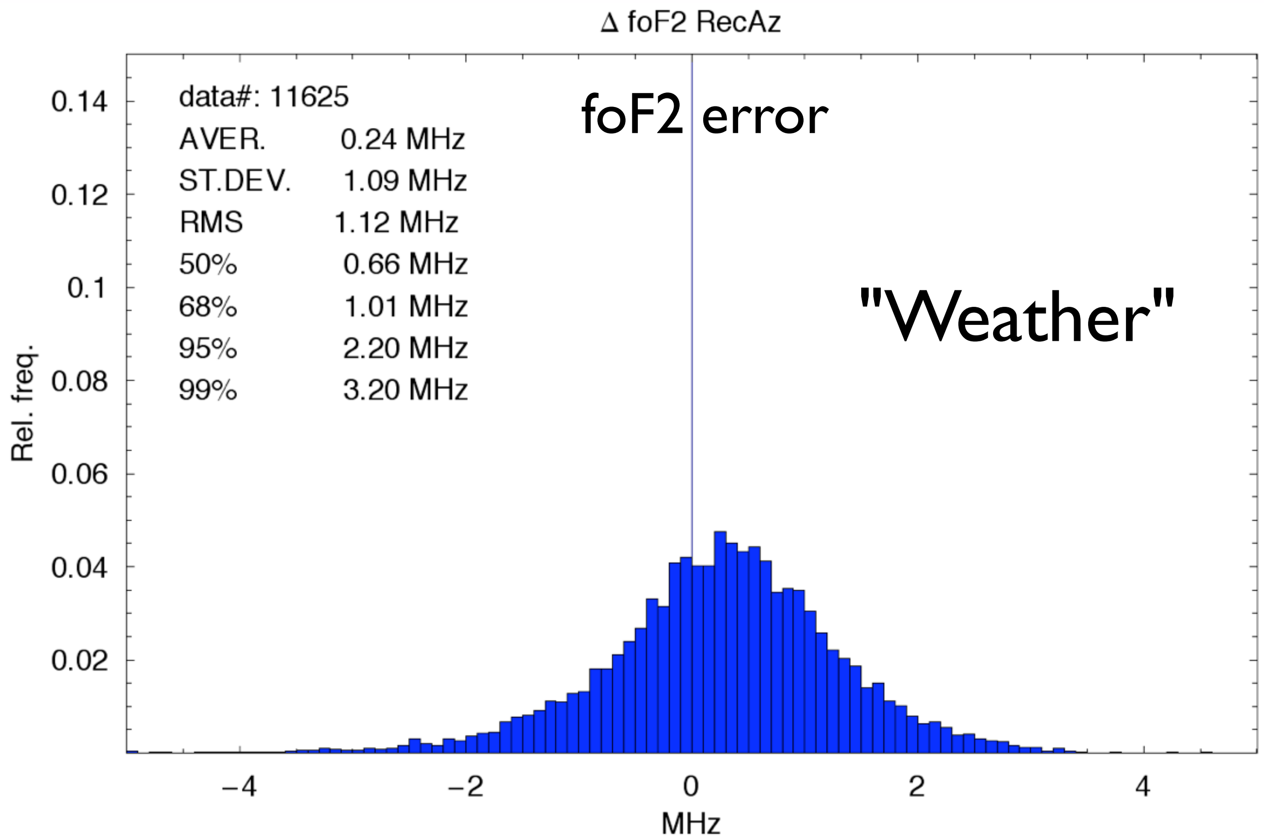
Reconstructed foF2 map

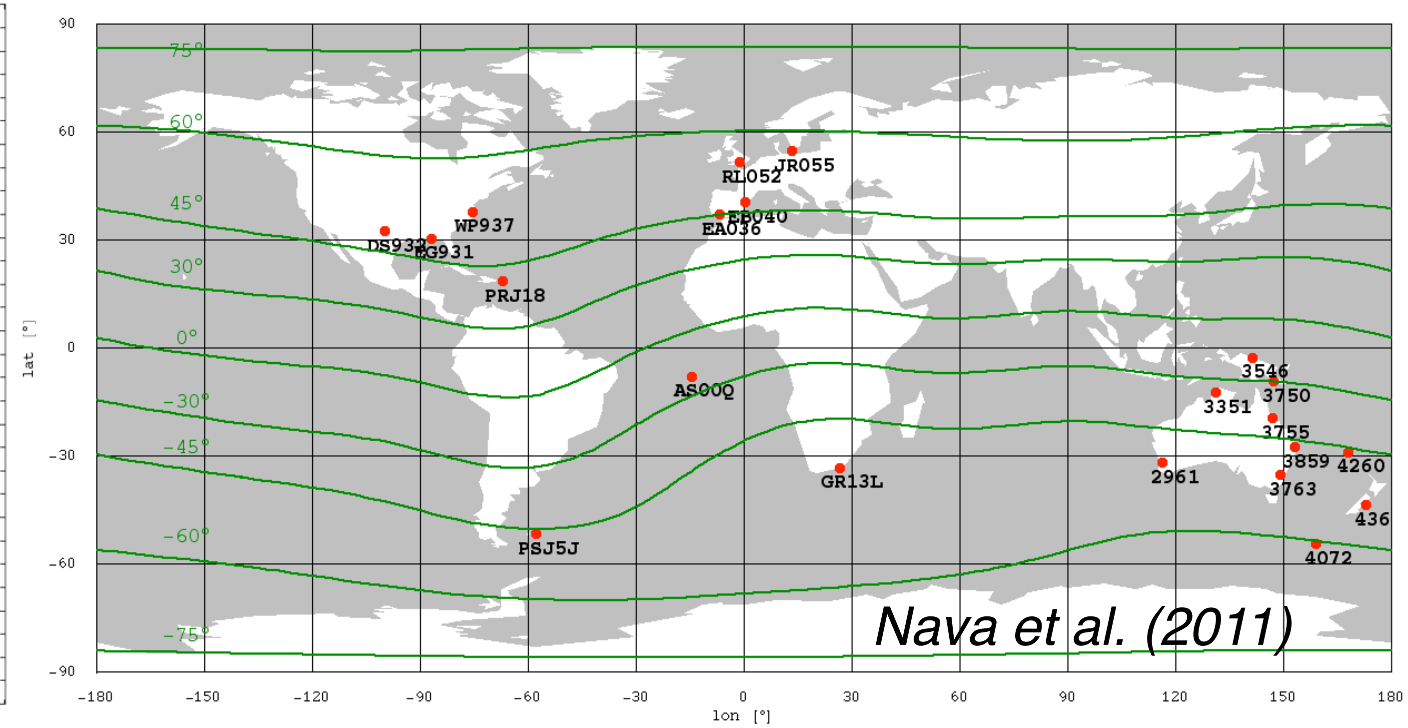


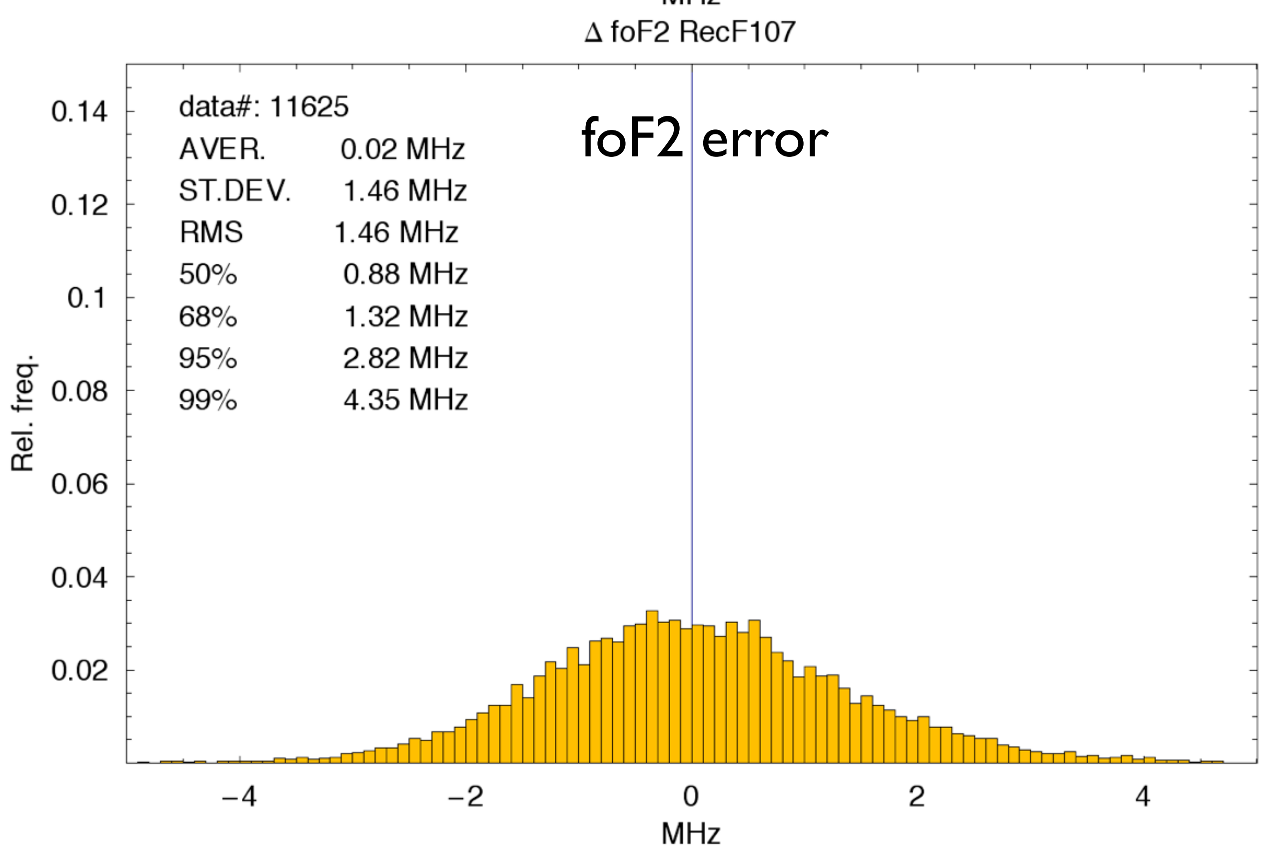
grid points:
lat.=-90°, 90° step 2.5°
lon.=-180°, 180° step 5°

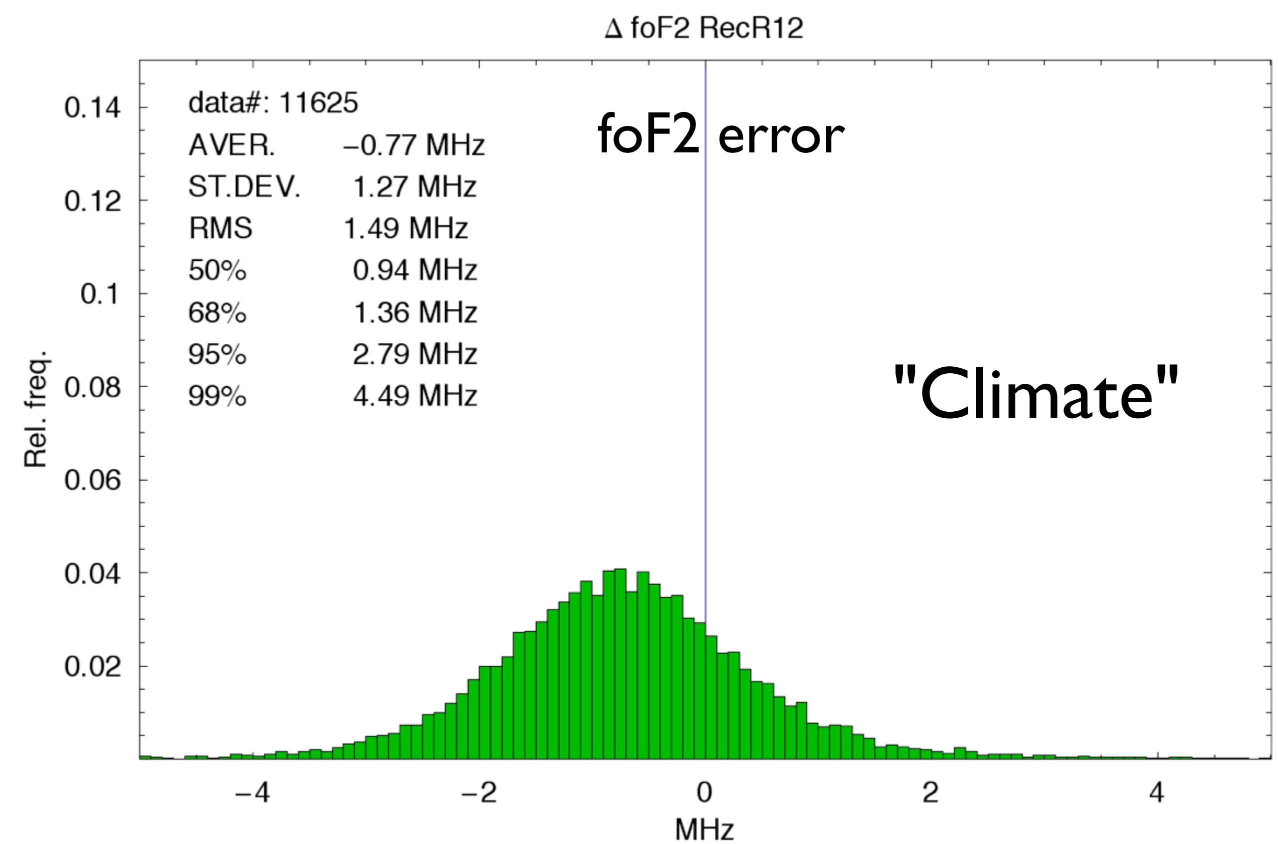
Vertical TEC data ingestion

High Solar Activity (Apr. 2000)

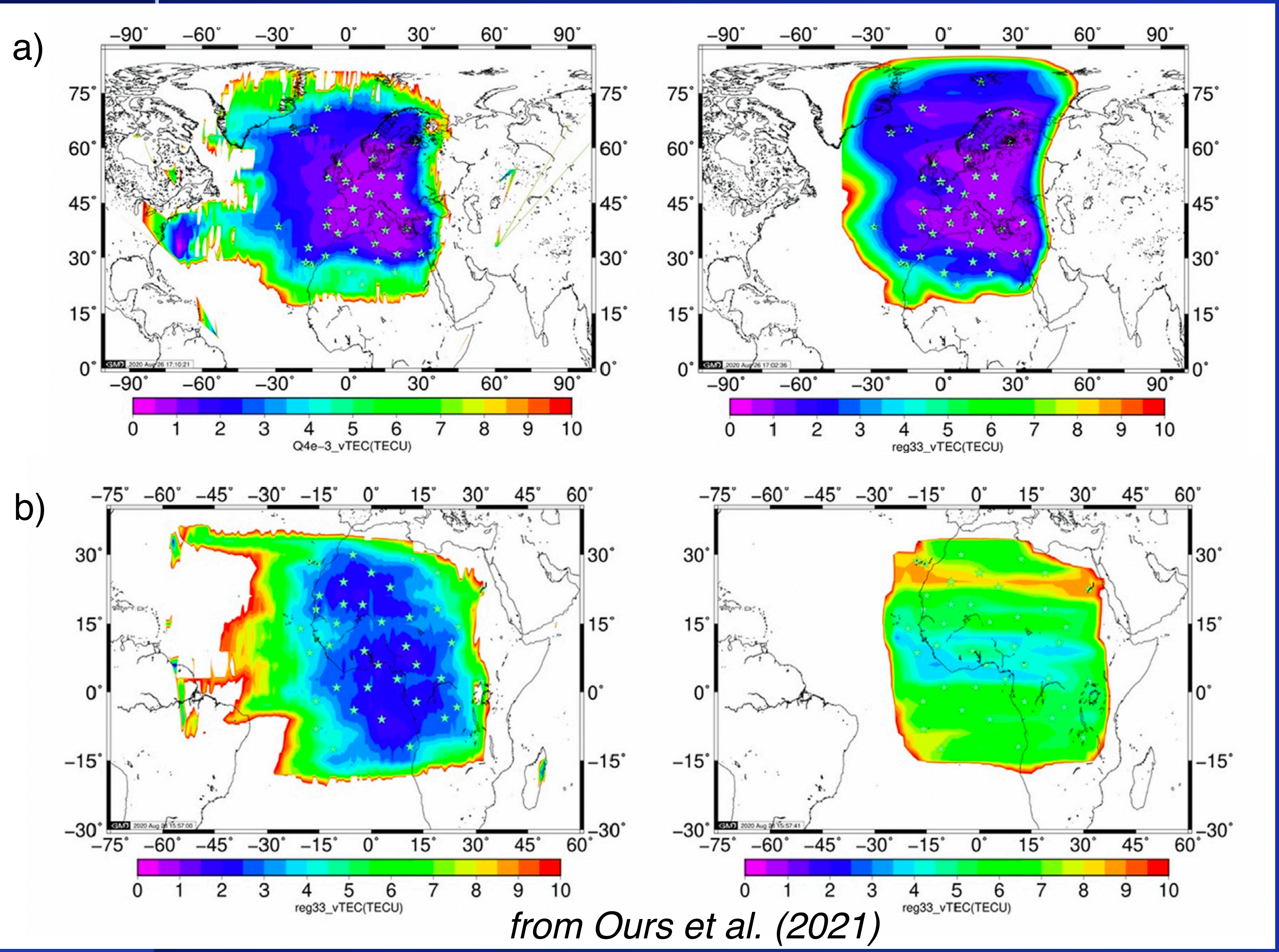








NeQuick for assessment studies

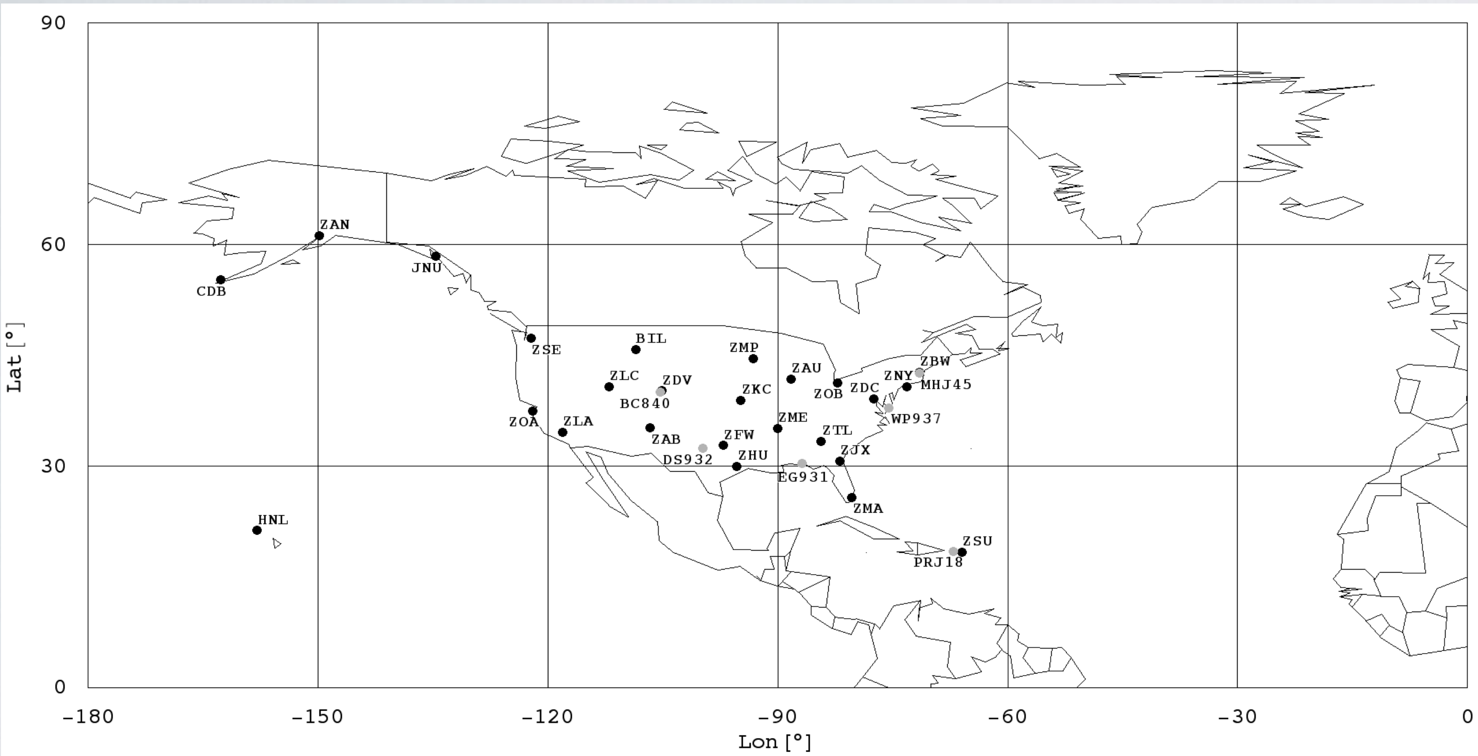


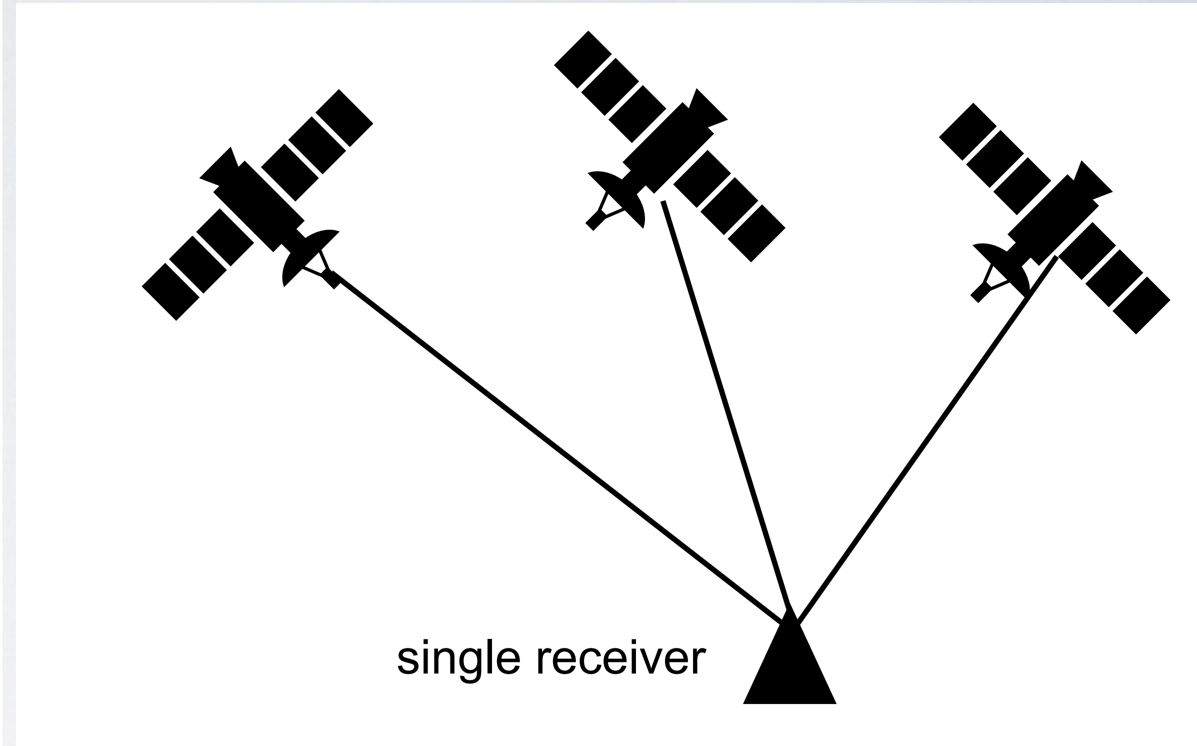
RMS TEC error for the voxel (left) and spherical harmonics (right) models used over European (a) and African (b) region.

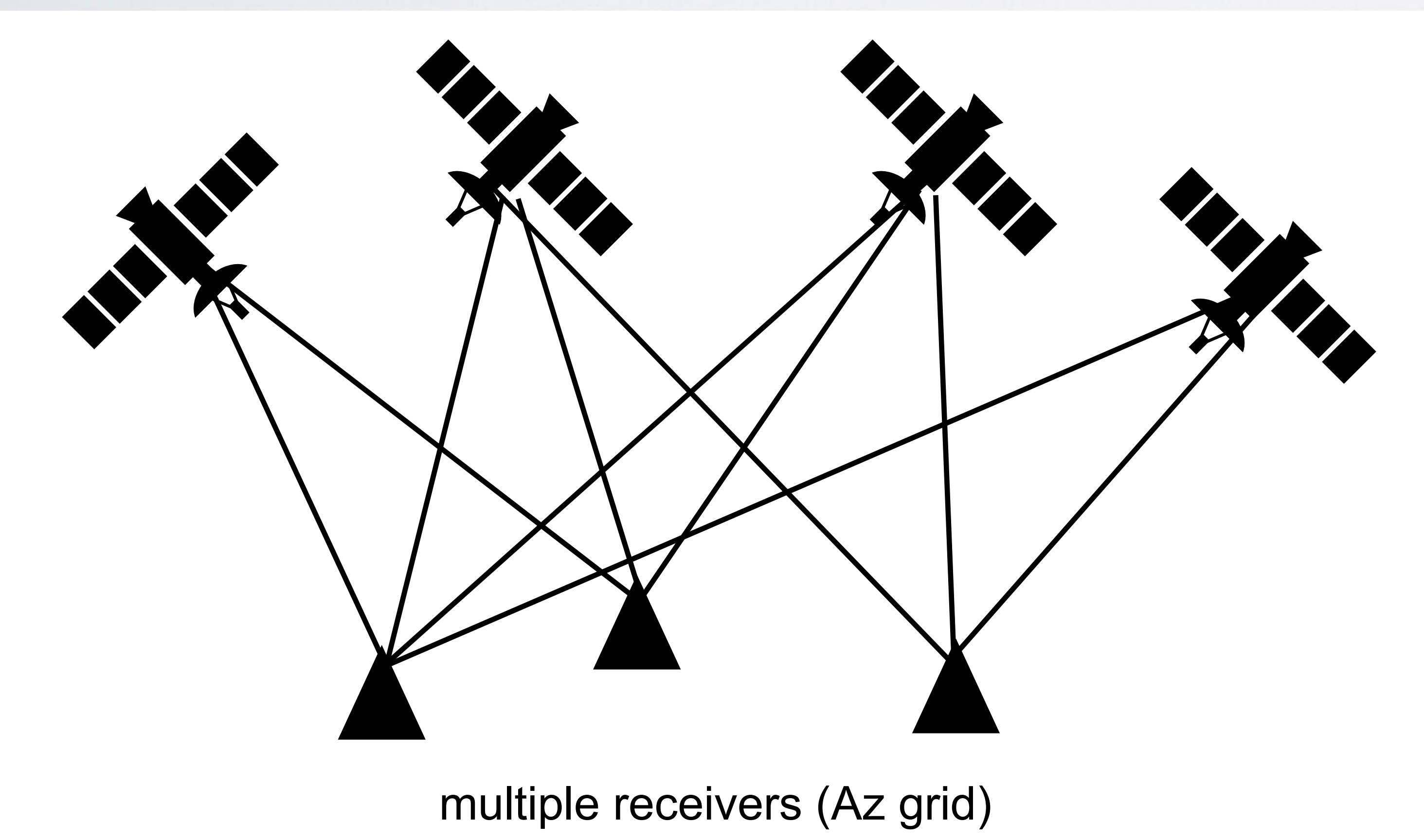
- The previously mentioned ingestion methodology has been used by Orus et al. (2021) to construct realistic representations of the ionosphere.
- This allowed evaluating different algorithms/ models aimed at estimating vertical TEC from GNSS dual frequency observables, including the relevant Inter Frequency Biases (also called Differential Code Biases) and phase ambiguities.

Slant TEC data ingestion

Using the effective parameter Az (effective ionisation level)





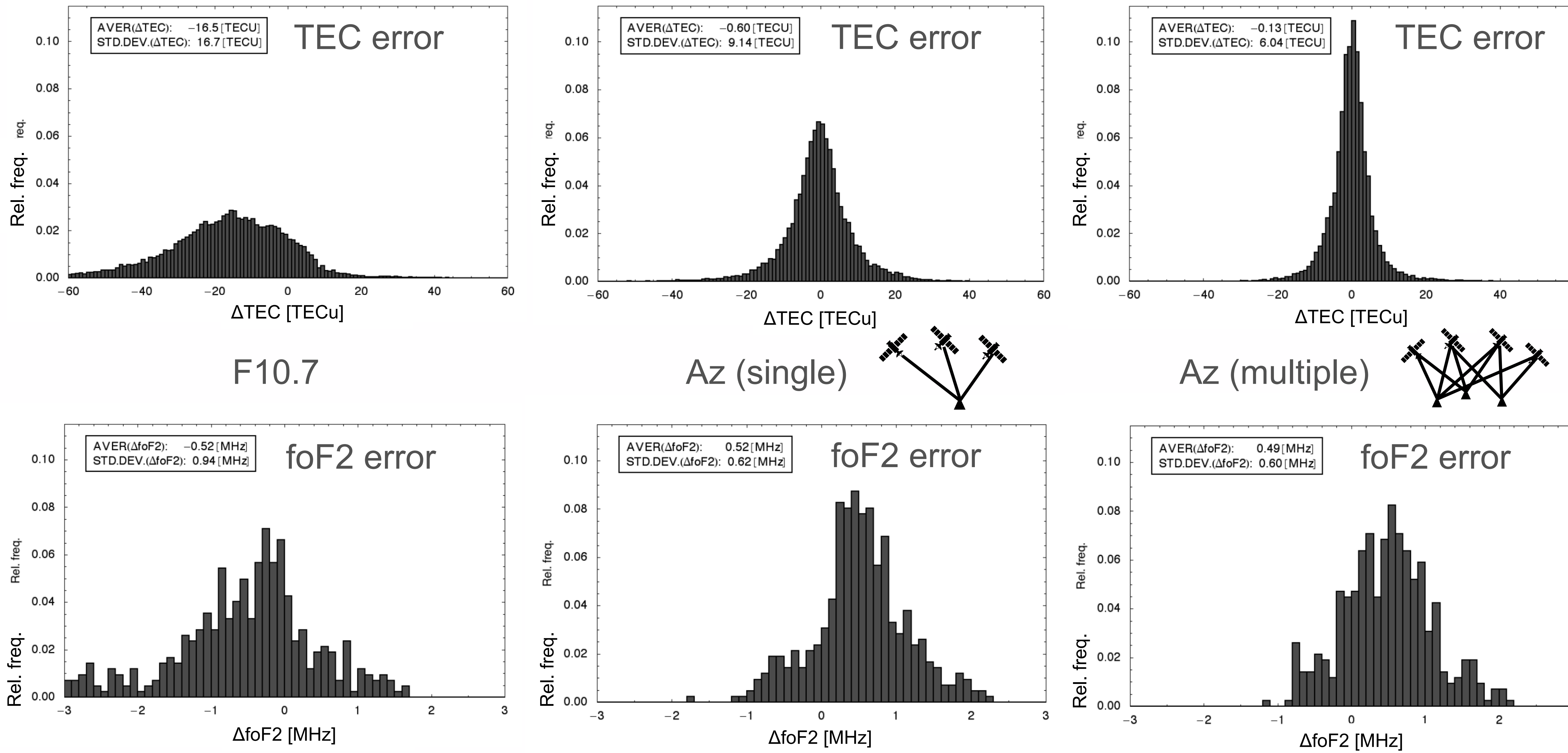


Adapting NeQuick model to experimental slant TEC data at a given location

Adapting NeQuick model to experimental slant TEC data at several locations

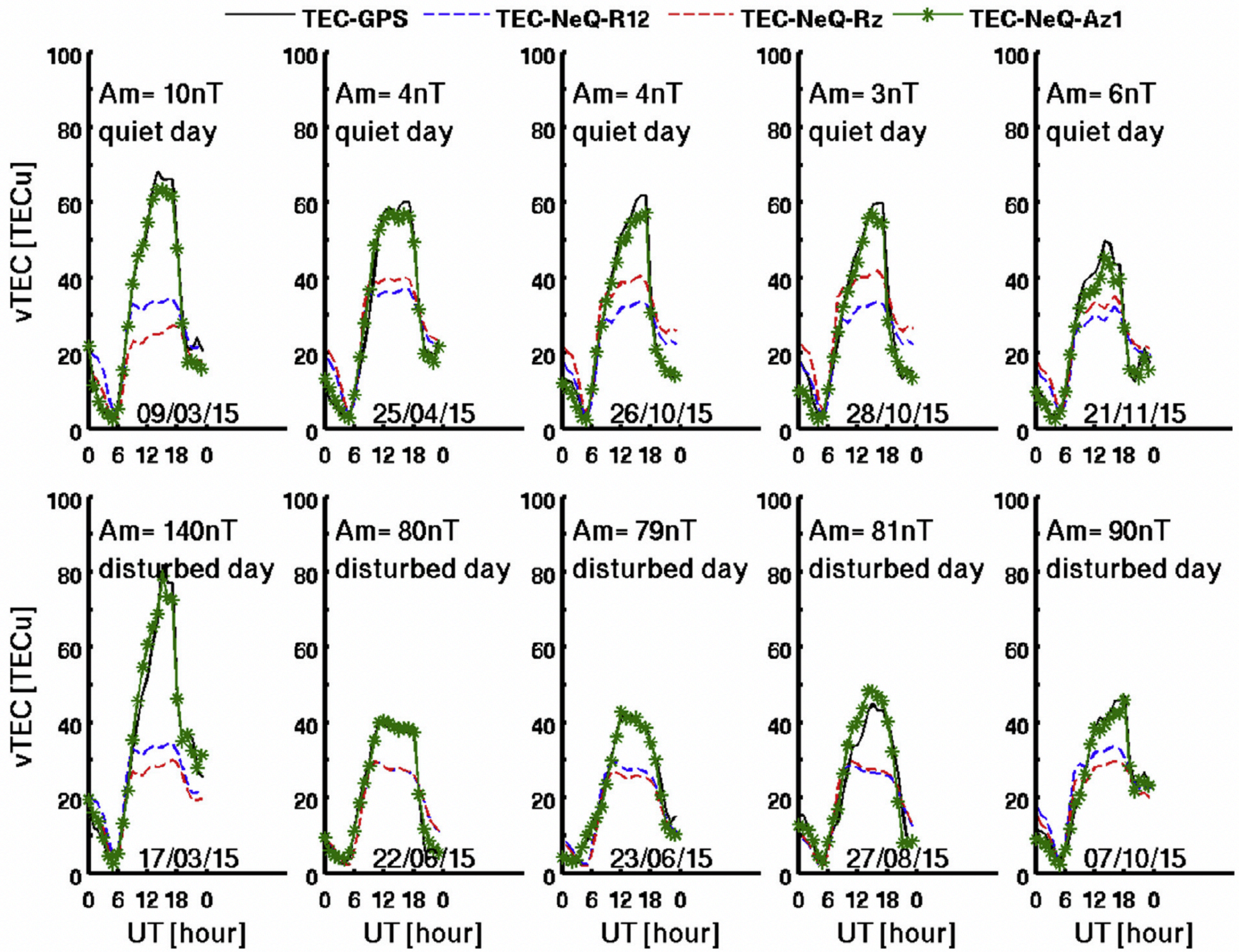
Slant TEC data ingestion

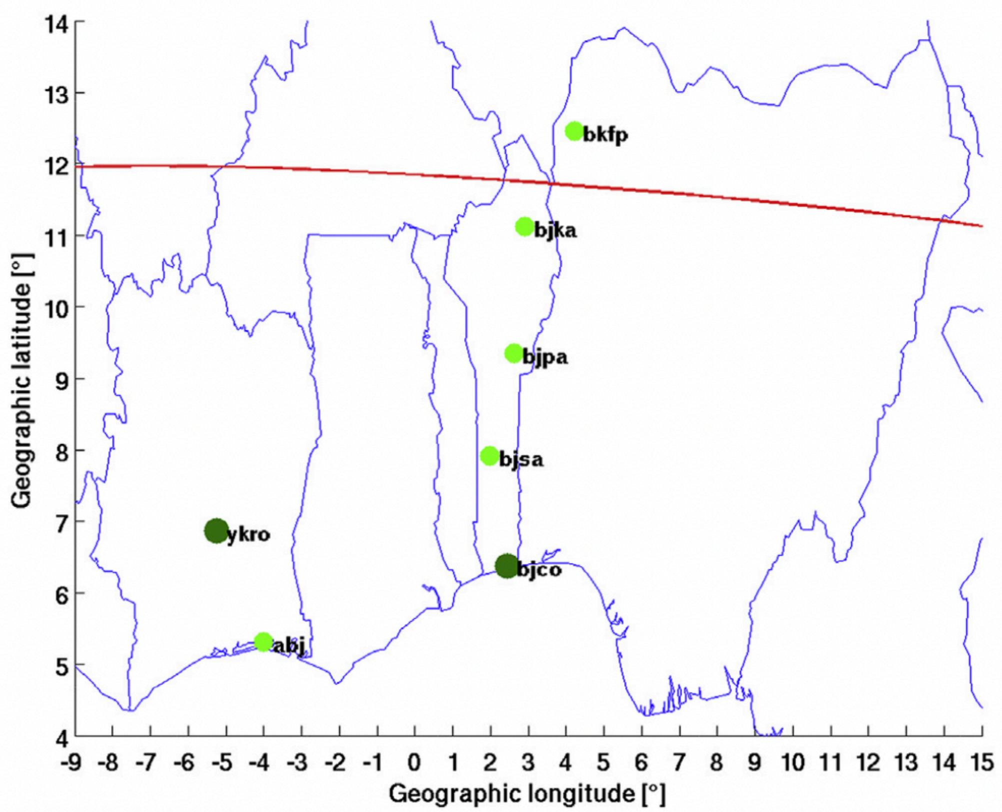
Nava et al. (2006)



Distribution of the differences between modeled and experimental slant TEC data for 25 ground stations (top panels) and between modeled and experimental foF2 data for six ionosondes (bottom panels) when NeQuick is driven by F10.7 (first column), Az computed using the single (second column) and multiple (third column) station technique.

vTEC ingestion; geomagnetically disturbed period

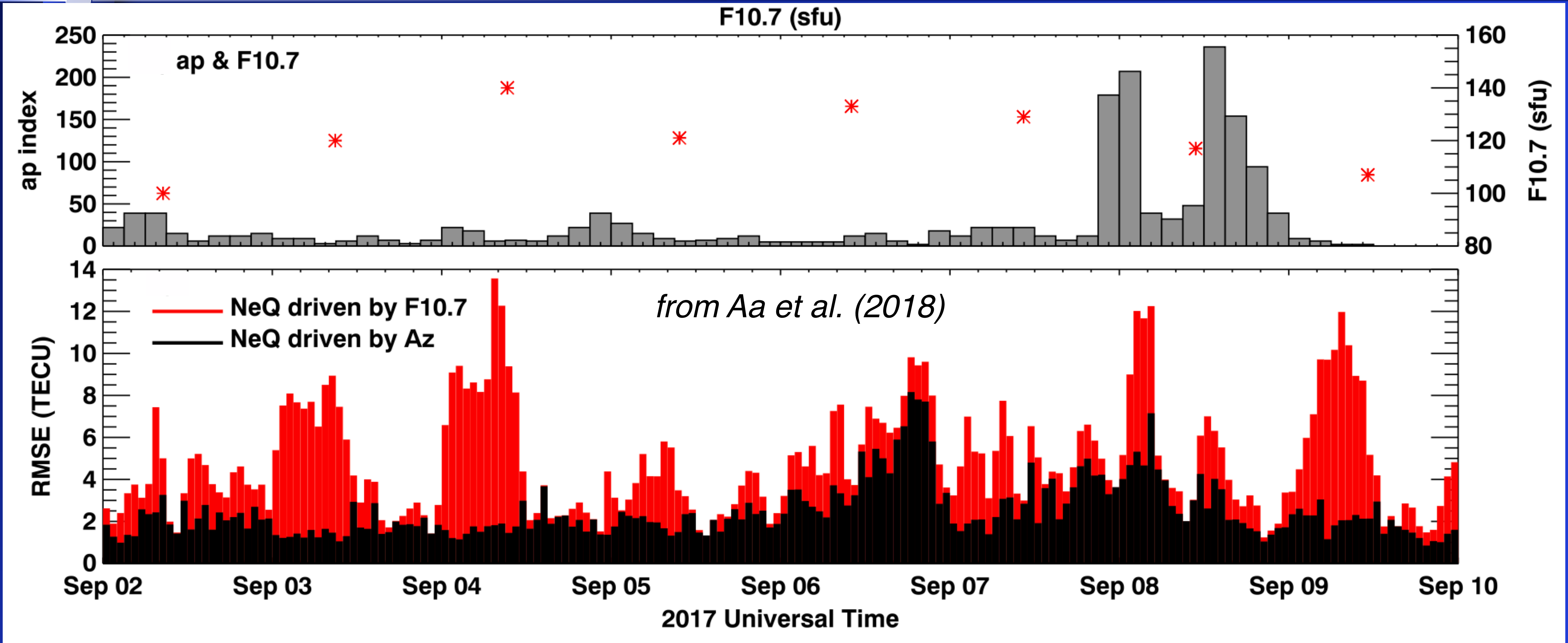




Yao et al., 2018

vTEC at abj station during 5 quietest days (top) and 5 disturbed days (bottom) in 2015. TEC-GPS: black line; TEC-NeQuick 2 driven by R12: dashed blue line; TEC-NeQuick 2 driven by Rz: dashed red line; TEC-NeQuick 2 driven by the effective f10.7 as inferred from ykro data: green line with star symbol.

TEC ingestion; geomagnetically disturbed period

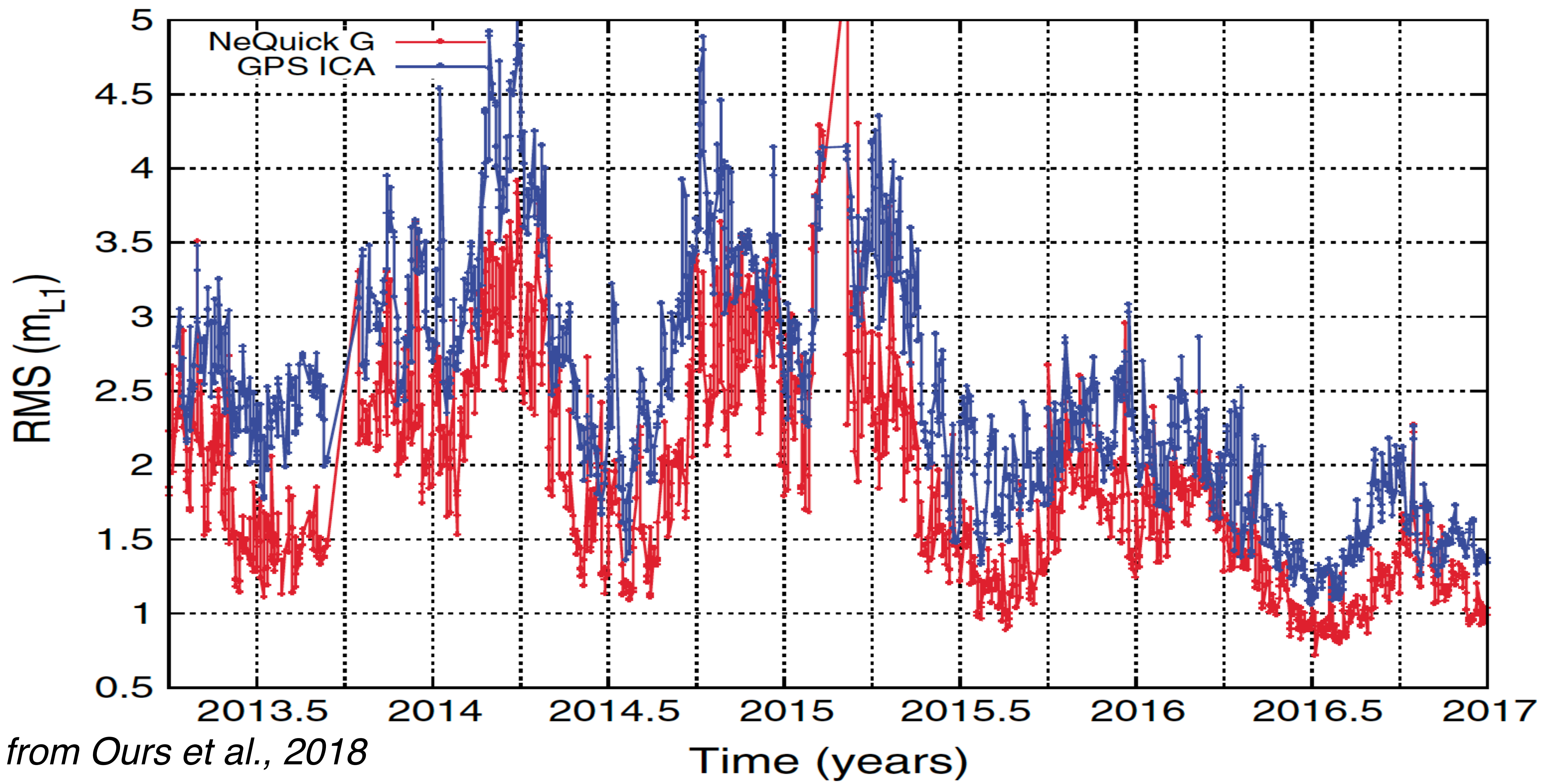


(Top) Temporal variation of Ap index and F10.7 during 02–10 September 2017. (Bottom) Root Mean Square Error comparison between NeQuick 2 driven by F10.7 (red) and driven by Az (black) at BJFS station (39.4◦N, 115.9◦E).

The authors further developed this data ingestion method using the empirical orthogonal function (EOF) analysis technique to construct a parameterized time-varying global Az model.

NeQuick G performance

Ours et al. (2018) have performed a full analysis of the NeQuick G performance in the period 2013 - 2017 (including the most relevant ionospheric storms occurred during the same period).

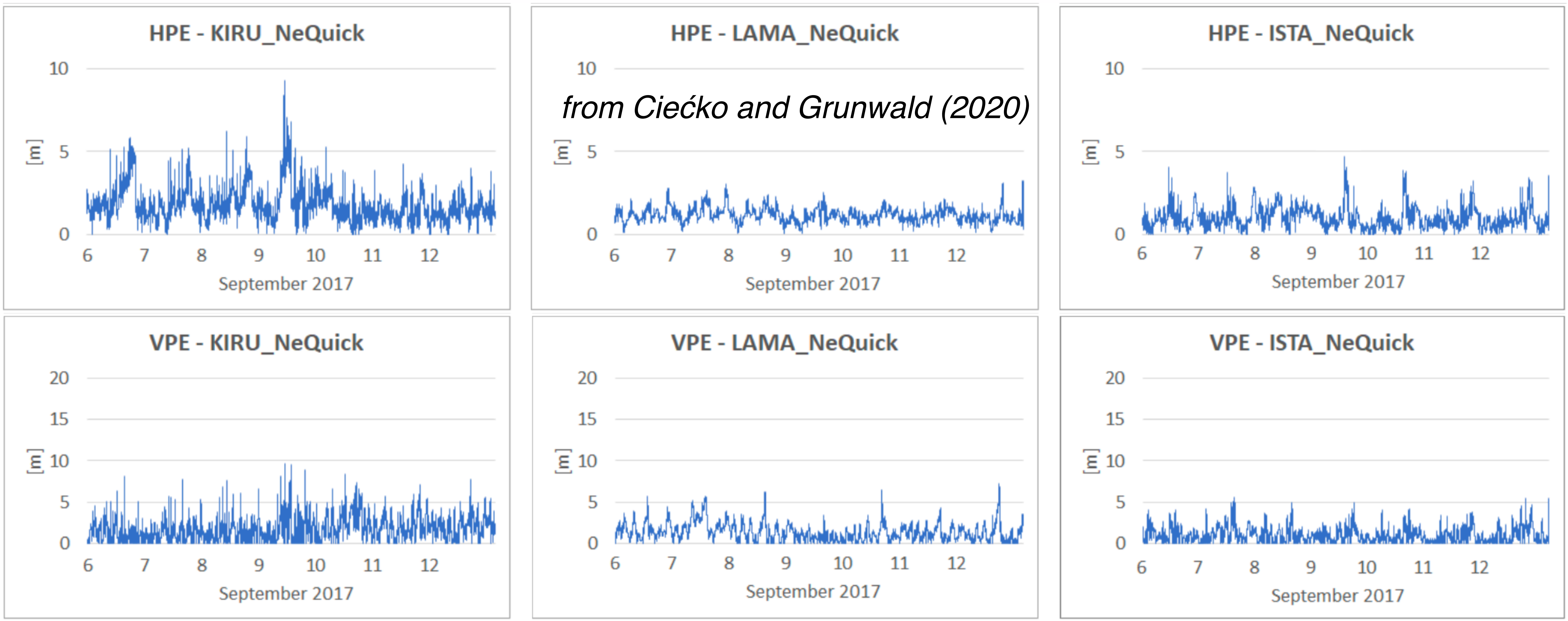


from Ours et al., 2018

Global root-mean-square error from March 2013 to December 2016 for NeQuick G and Global Positioning System Ionospheric Correction Algorithm.

NeQuick G performance

Ciećko and Grunwald (2020) have examined the performance in single-frequency positioning of different model corrections, including NeQuick G.



Horizontal (top) and vertical (bottom) position error during 6-12 Sep 2017 (geomagnetically disturbed period) at Kiruna (Finland), Lamkówko (Poland), Istanbul (Turkey).

Slant TEC Data Assimilation

Best Linear Unbiased Estimator (BLUE)*

$\mathbf{x}_t$ true model state (dimension n)

$\mathbf{x}_b$ background model state (dimension n)

$\mathbf{x}_a$ analysis model state (dimension n)

$\mathbf{y}$ vector of observations (dimension p)

$\boldsymbol{H}$ observation operator (dimension p x n)

B covariance matrix of background errors $\boldsymbol{\varepsilon}_b=(\mathbf{x}_b-\mathbf{x}_t)$ (dimension n x n)

R covariance matrix of observation errors $\boldsymbol{\varepsilon}_o=(\mathbf{y}-H[\boldsymbol{x}_t])$ (dimension p x p)

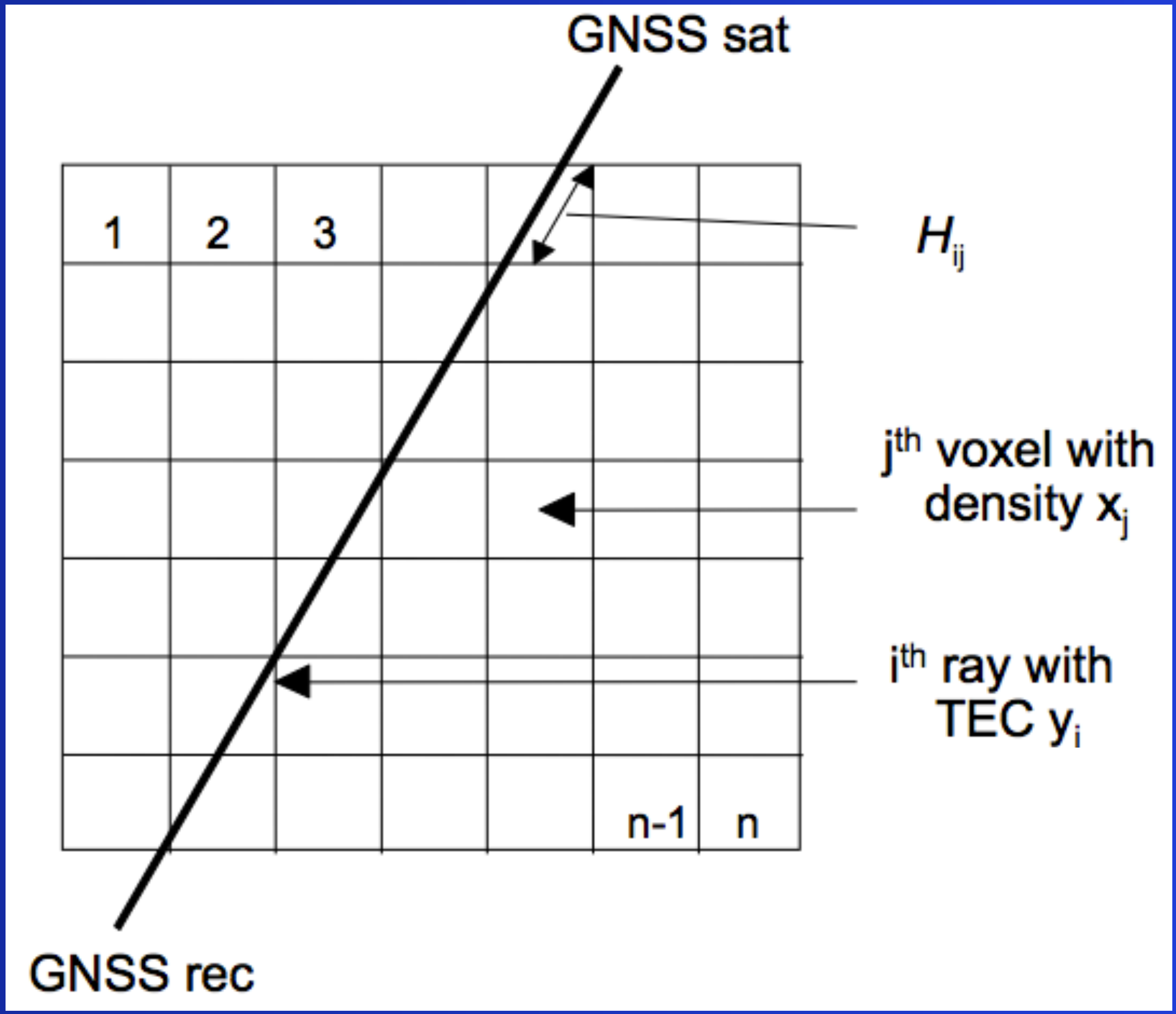
A covariance matrix of analysis errors $\boldsymbol{\varepsilon}_a=(\mathbf{x}_a-\mathbf{x}_t)$ (dimension n x n)

*https://www.ecmwf.int/sites/default/files/elibrary/2002/16928-data-assimilation-concepts-and-methods.pdf

The BLUE algorithm

The optimal least-square estimator (BLUE analysis) is defined by

$$\mathbf{x_a = x_b + K\,(y - Hx_b)}$$
$$\mathbf{K = BH^T(HBH^T + R)^{-1}}$$
$$\mathbf{A = (I\text{-}KH)B}$$



In our case:

y = GNSS sTEC
$\mathbf{x_b}$ = NeQuick electron density
$\mathbf{x_a}$ = retrieved electron density
H -> “crossing lengths” in “voxels”

Voxels dimensions:
(2° x 3°) in (lat x lon); 25 - 500 km in height, depending on height

The BLUE algorithm

R is diagonal

$R_{ij}=c_R\,\delta_{ij}\,y_i^2$ (measurements are independent*)

Simple formulation for **B** has been adopted

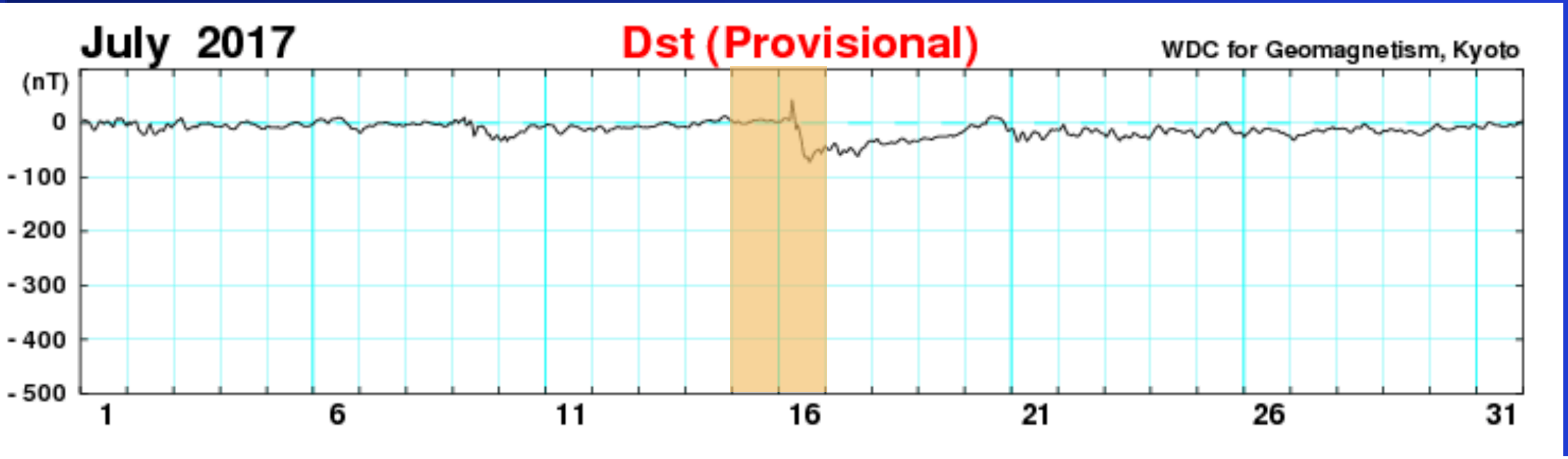
$B_{ij}=c_B\,x_{bi}\,x_{bj}\,\mathrm{Exp}[-(z_{ij}/Lz)^2]\,\mathrm{Exp}[-(\alpha_{ij}/L\alpha)^2]$
(V & H correlations are separable)

z_{ij} ~ height difference between voxels i and j
α_{ij} ~ angular (great circle) distance between voxels i and j

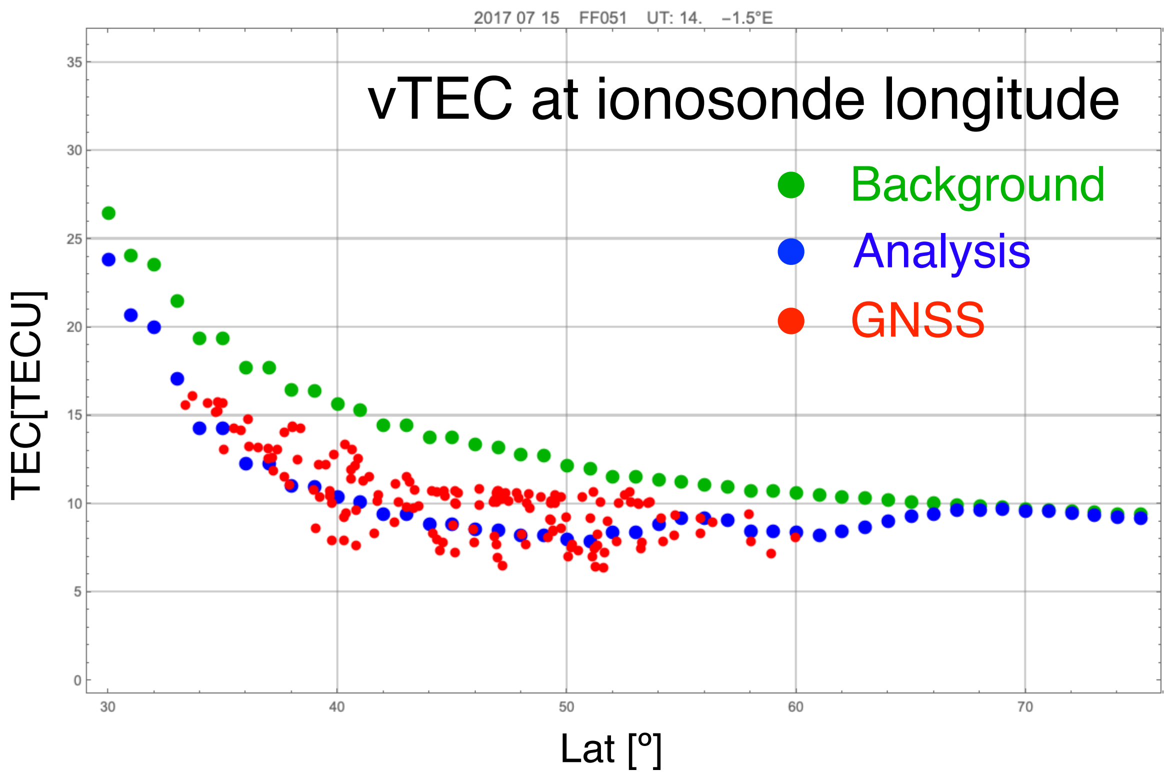
Lz ~ correl. distance in vert. direction (depends on height)
$L\alpha$ ~ correl. distance in hor. direction (different in lat. & lon.)

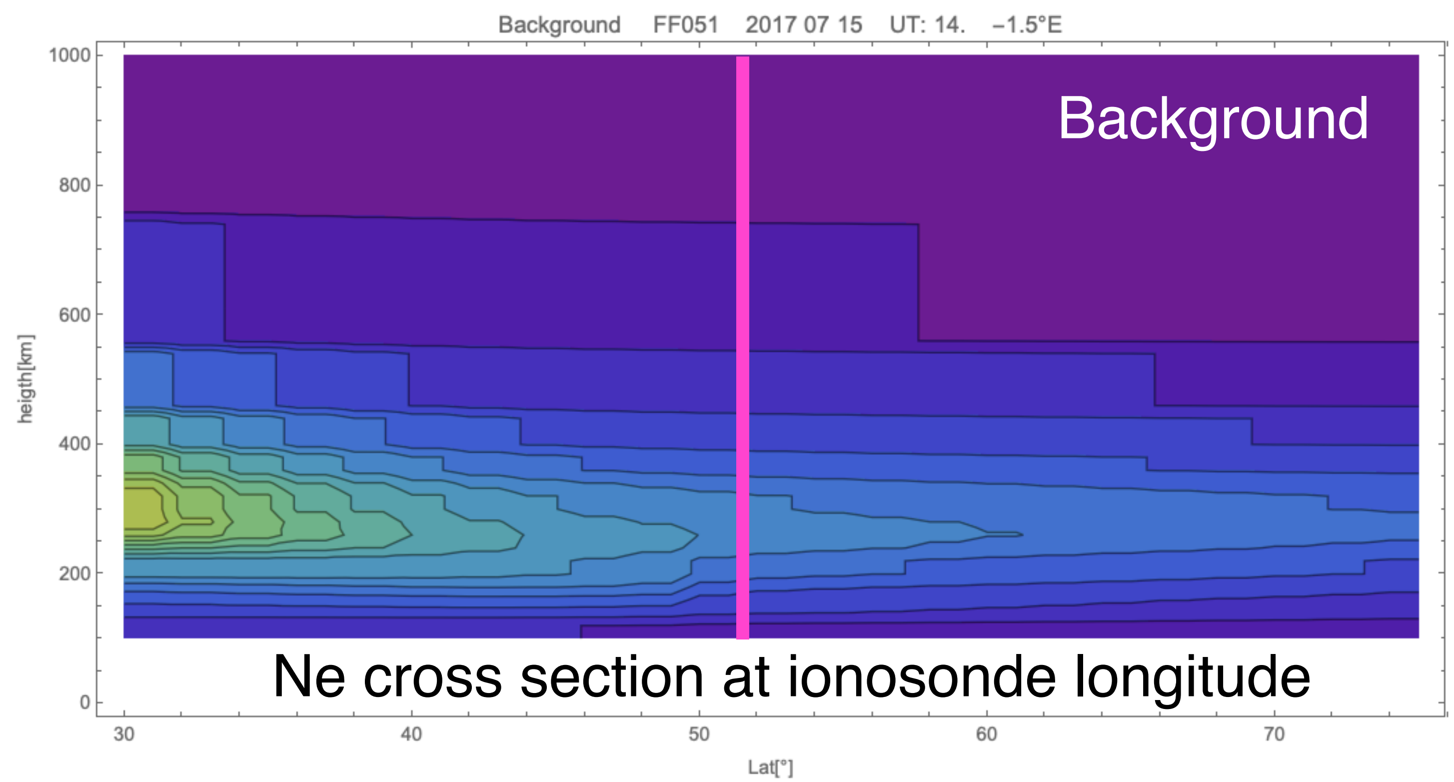
GNSS TEC DA

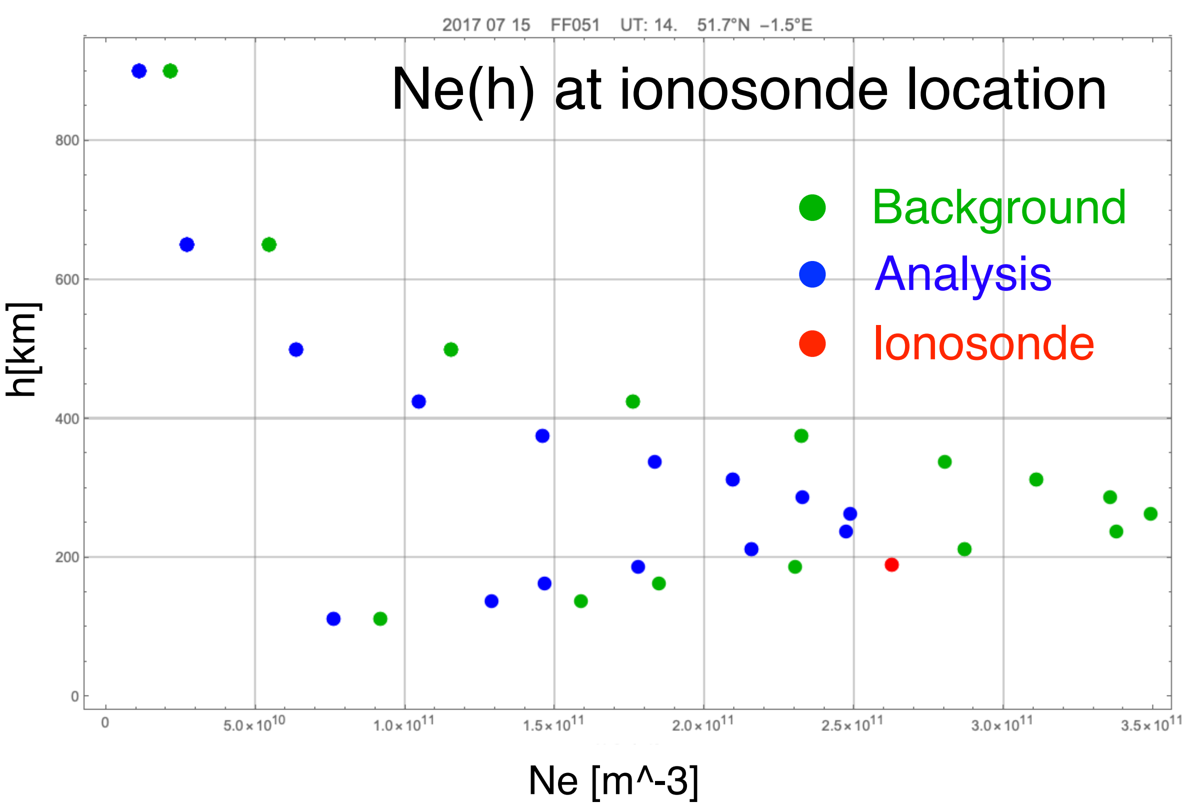
- For the assimilation
  - Calibrated (as in Themens et al. 2015) ground-based GNSS-derived slant TEC data from about 300 receivers located in the European region and about 150 receivers located in South America (Madrigal database).
- For the validation
  - Manually scaled foF2 data at 1 hour time interval obtained from 11 ionosondes in Europe and 3 in Brazil (only the result corresponding to Fairford and Boa Vista will be illustrated).
- The data correspond the period 15-16 July 2017

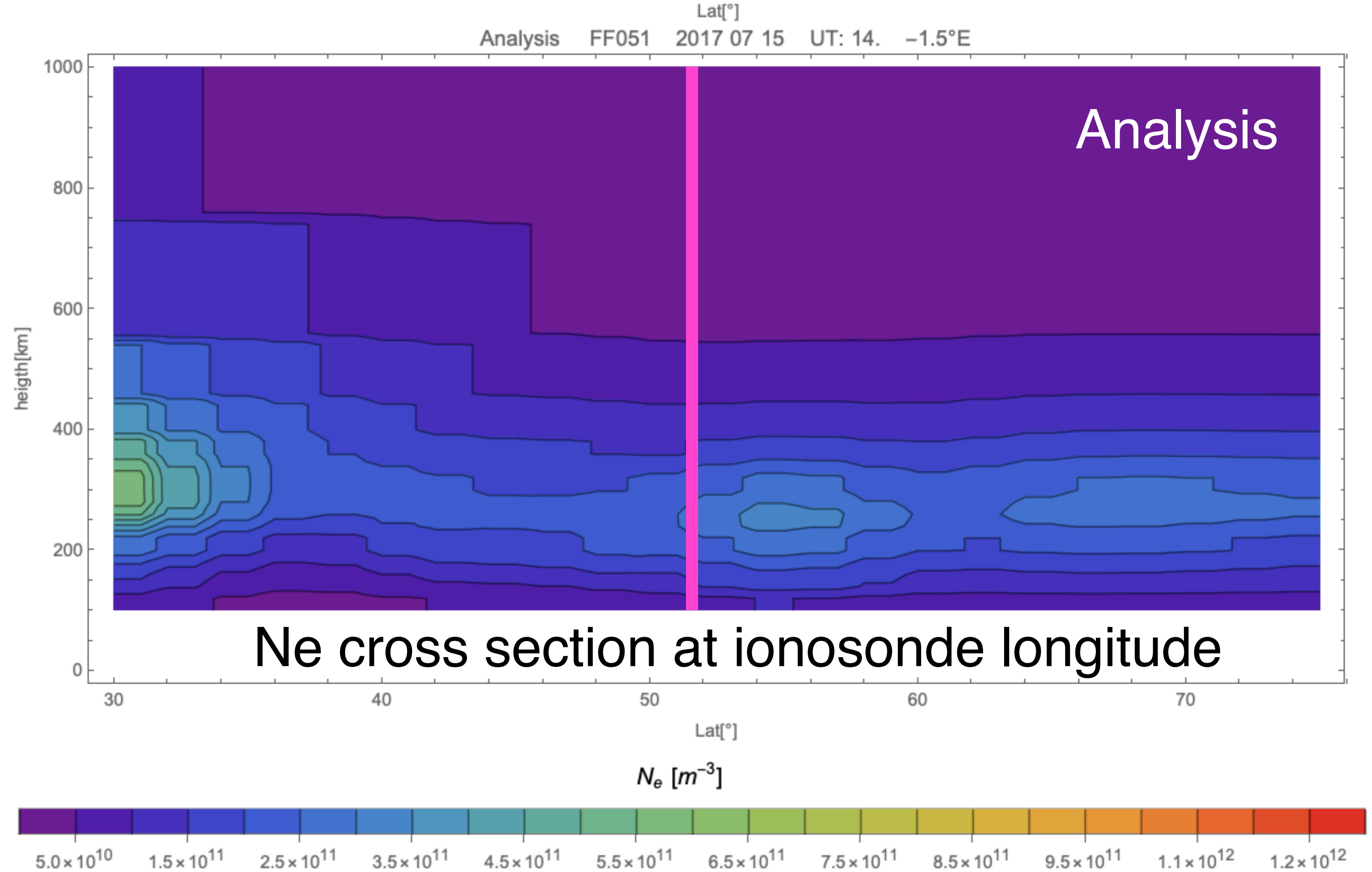


Results: 15 July 2017; 14:00UT; FF051

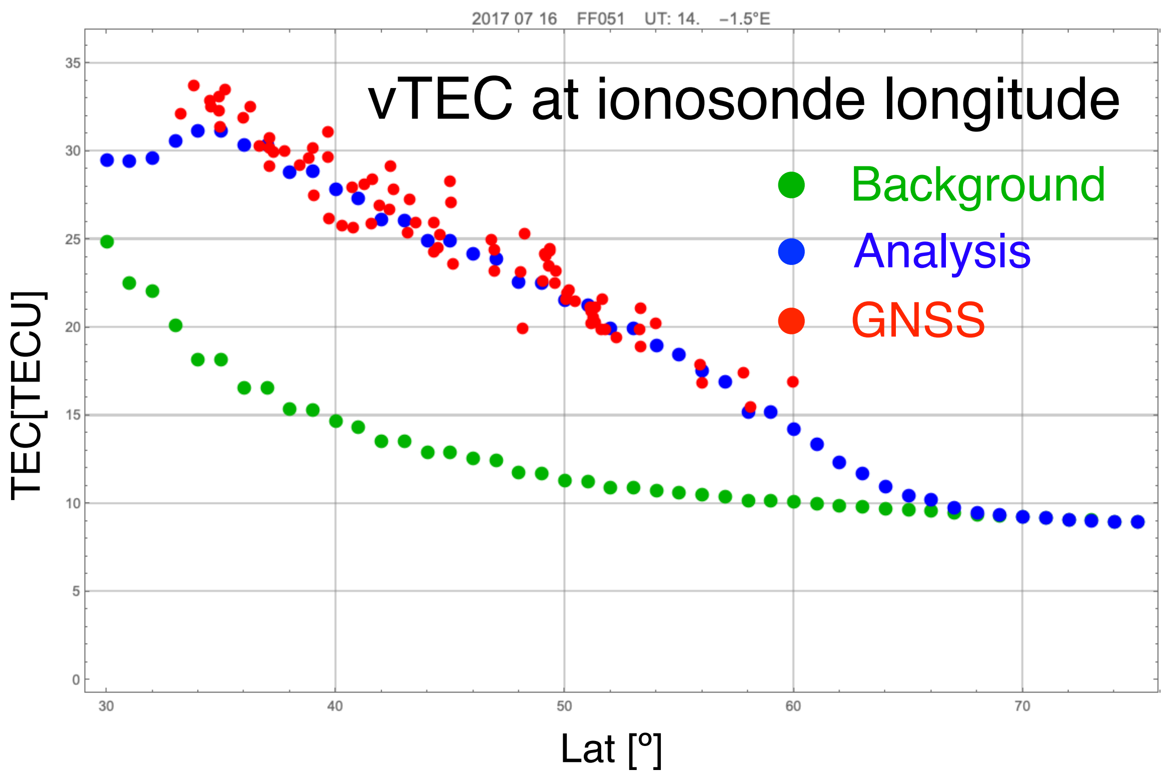


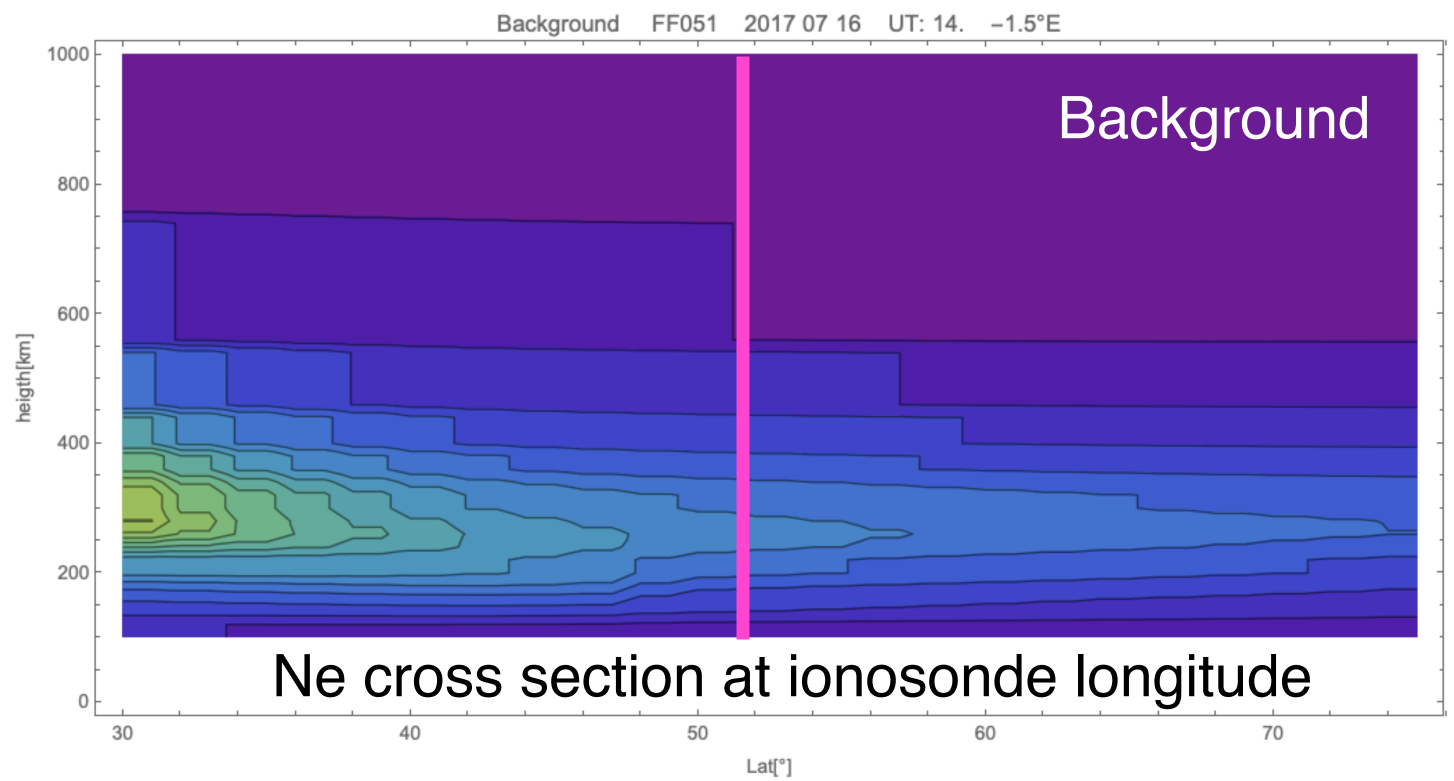


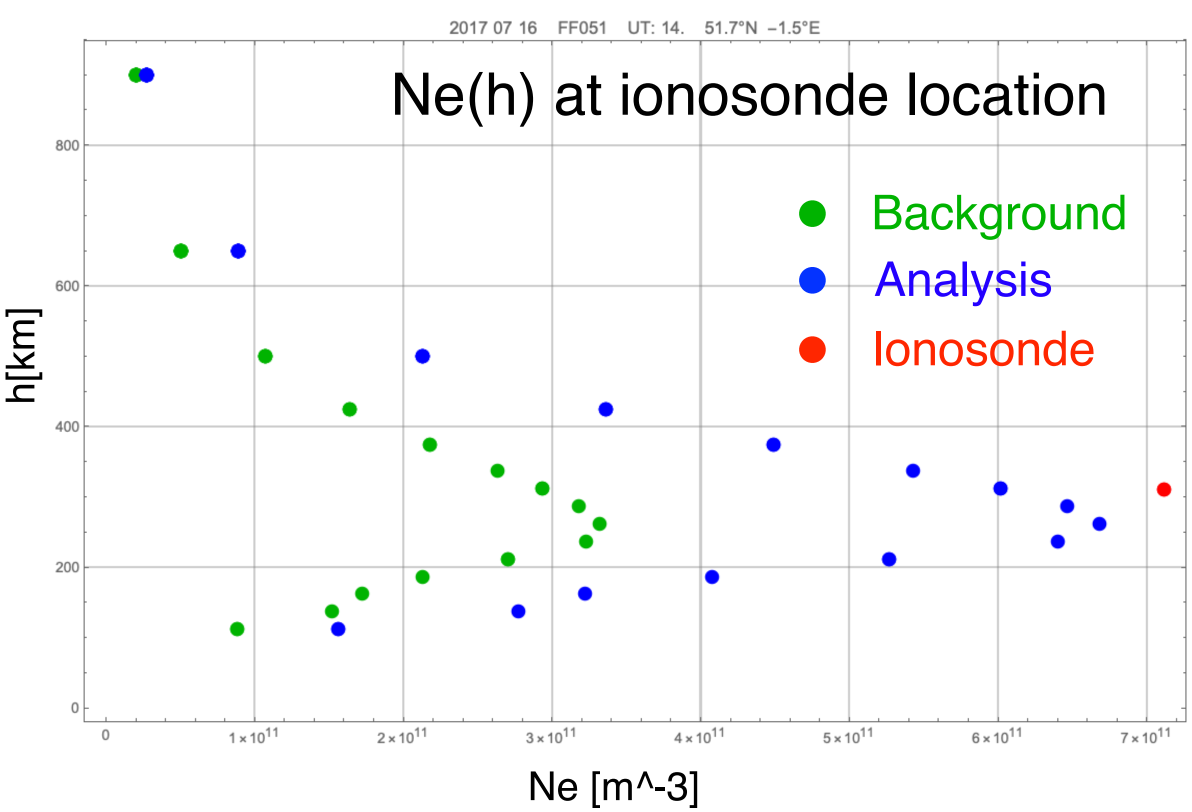


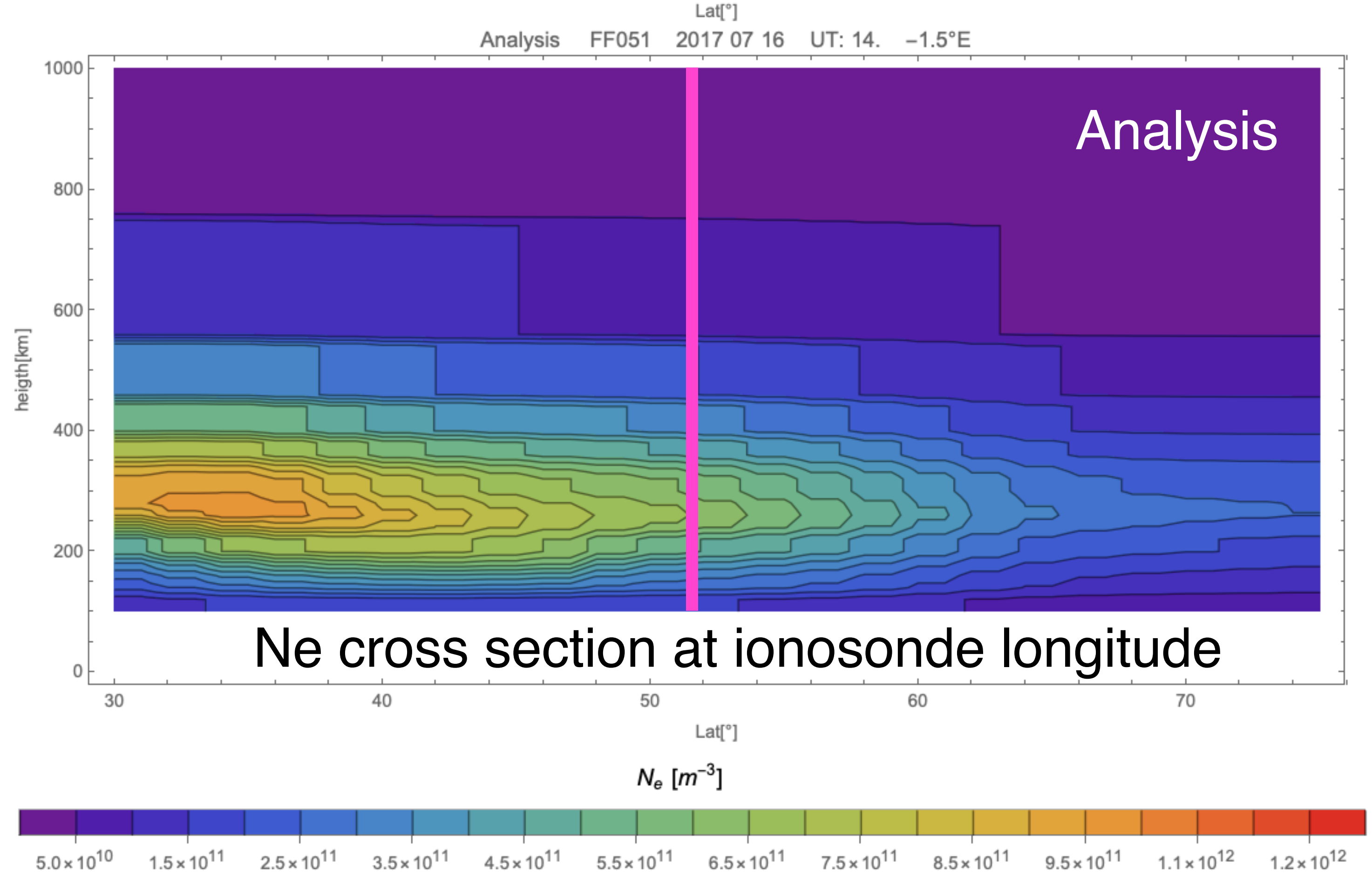


Results: 16 July 2017; 14:00UT; FF051

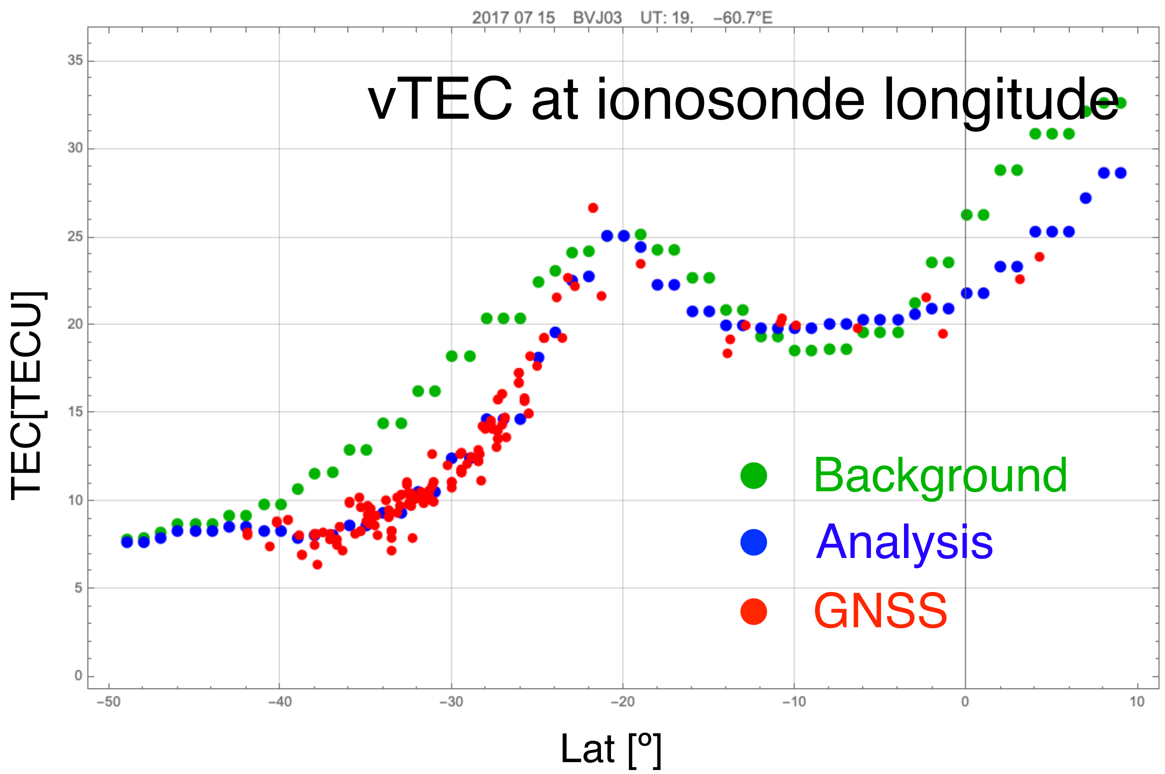


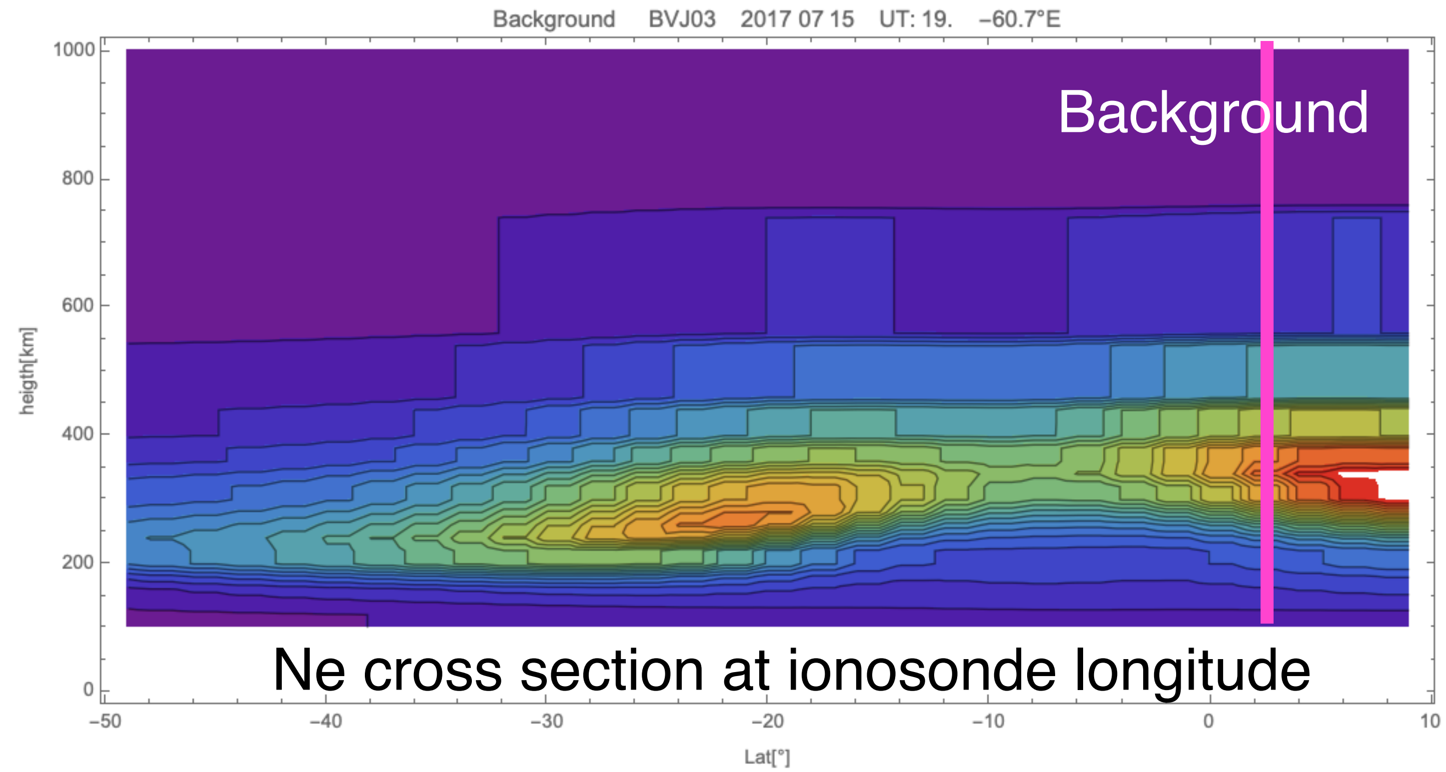


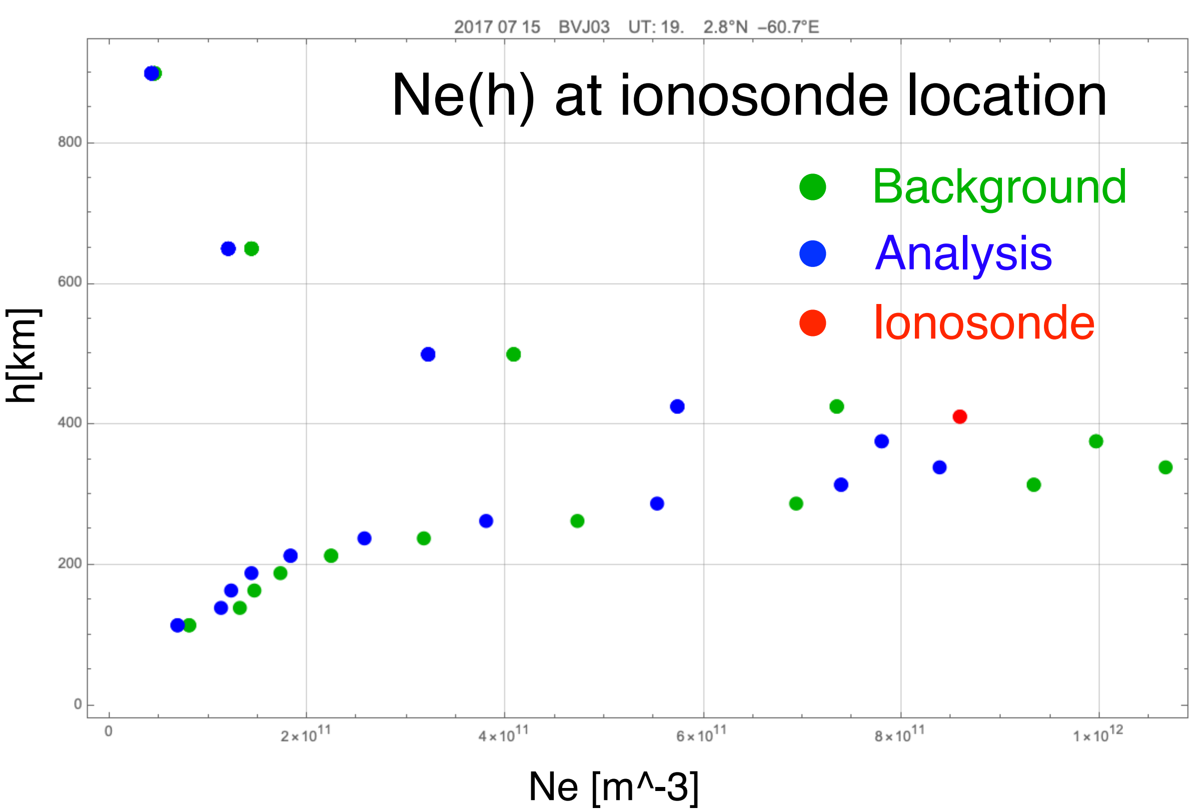


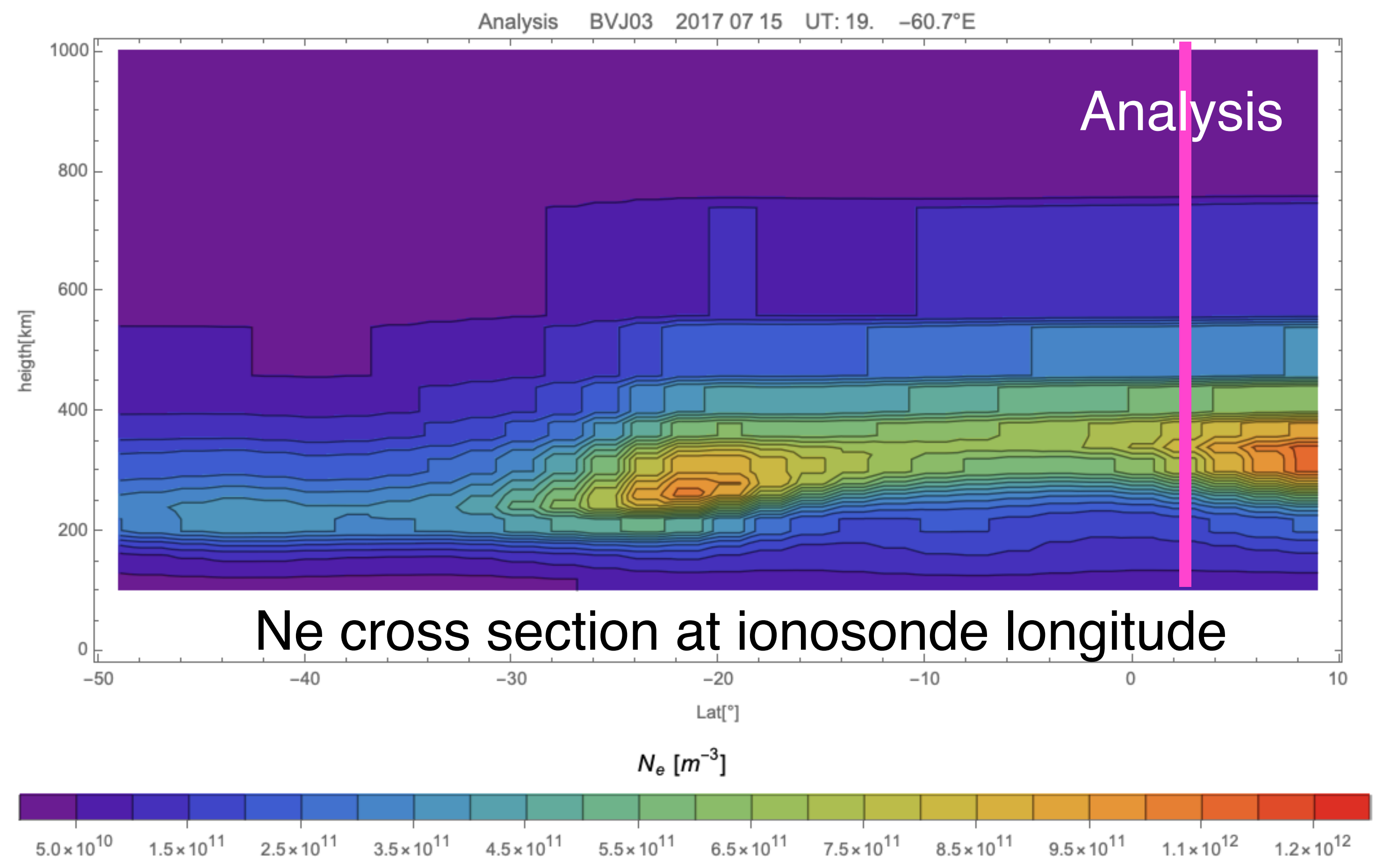


Results: 15 July 2017; 19:00UT; BVJ03

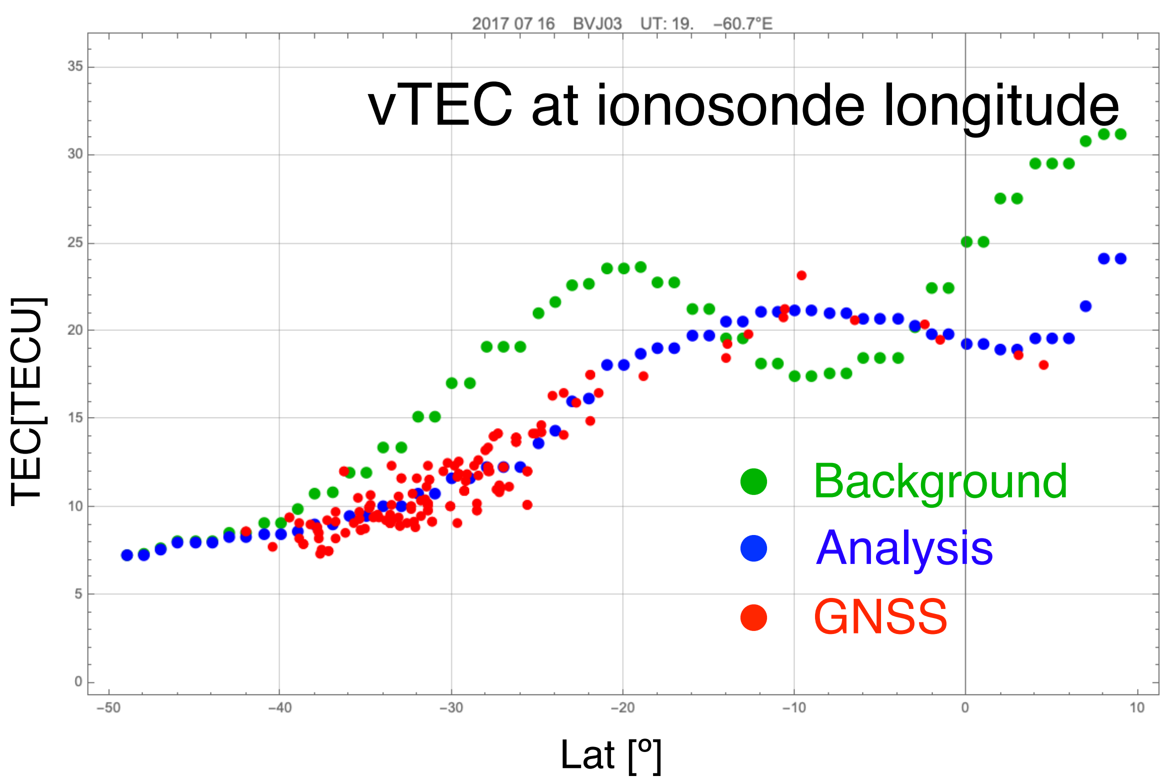


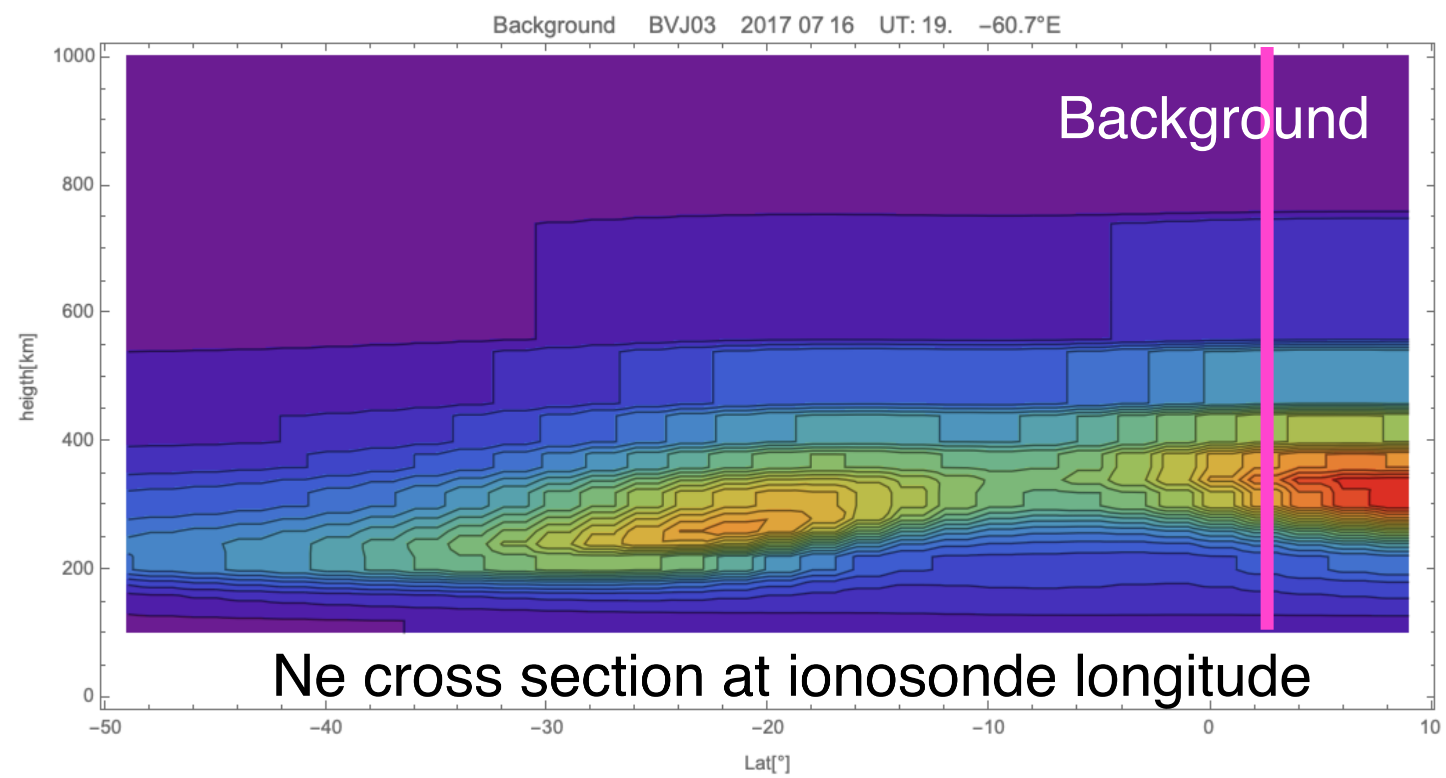


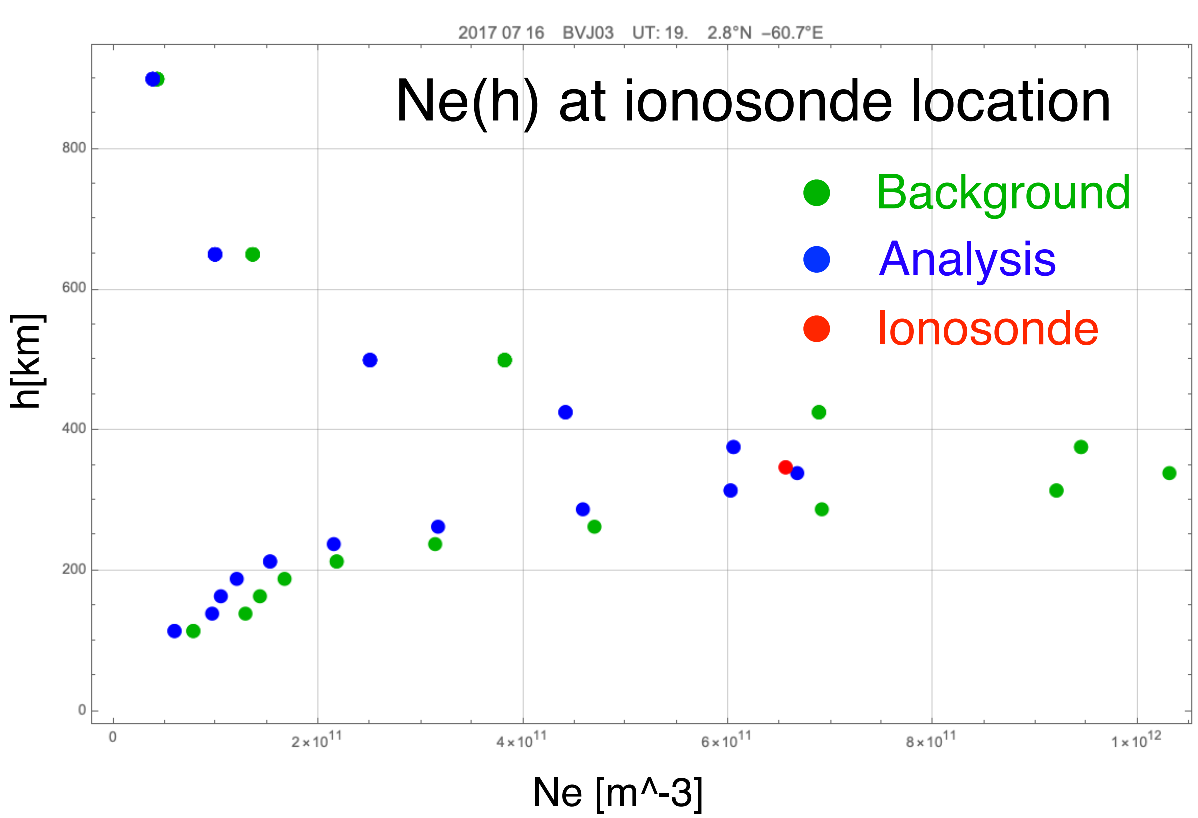


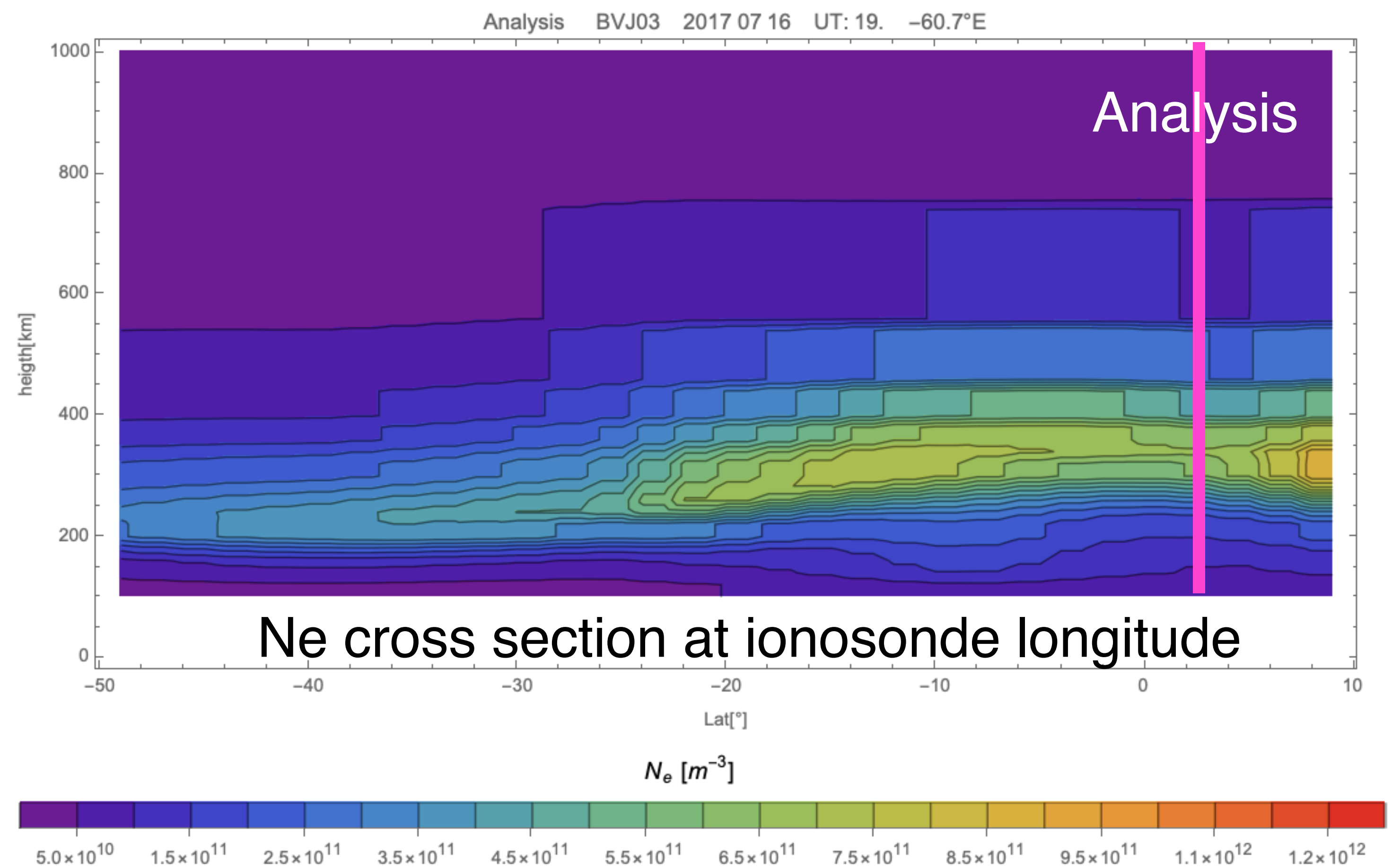


Results: 16 July 2017; 19:00UT; BVJ03

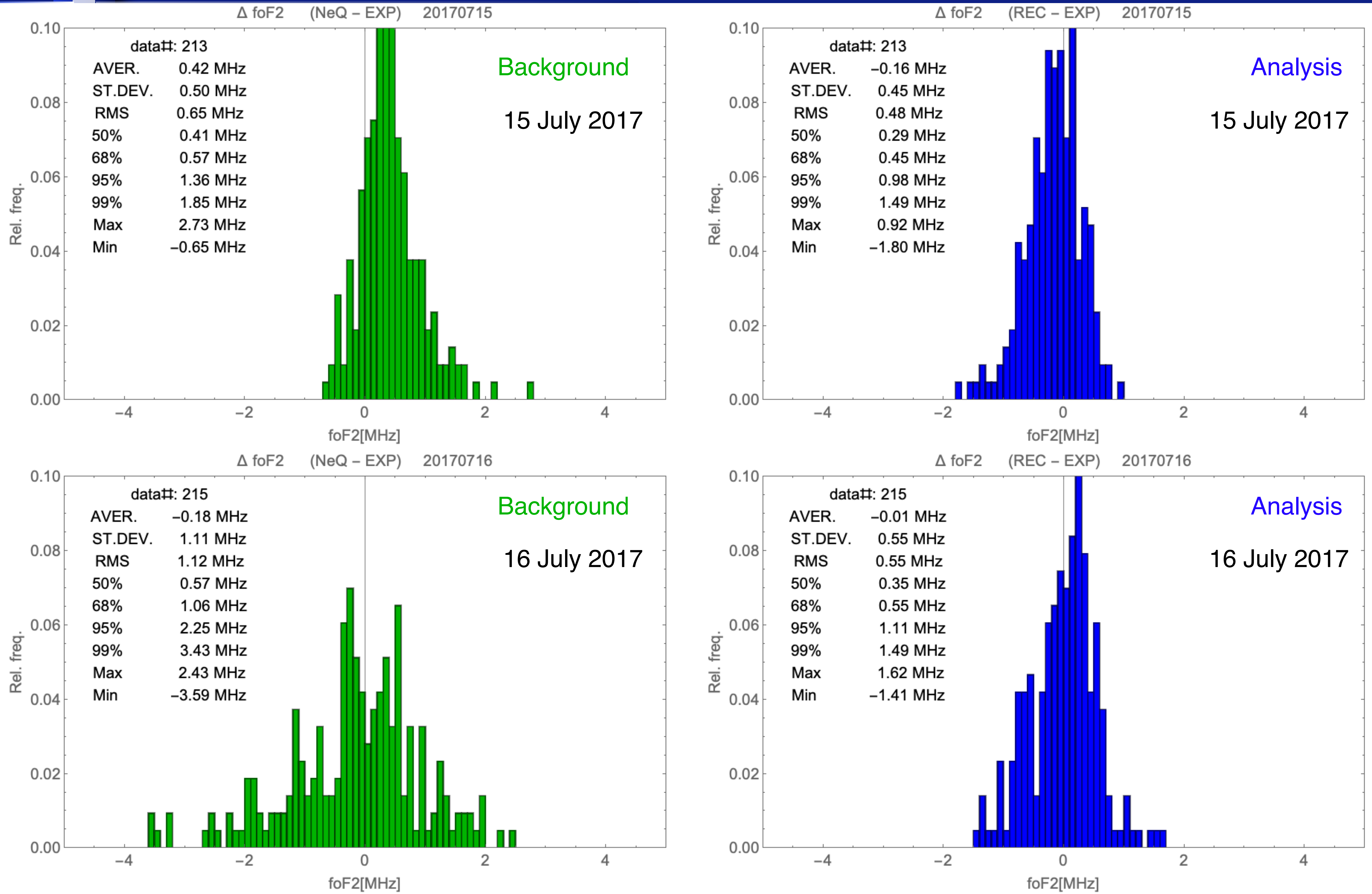




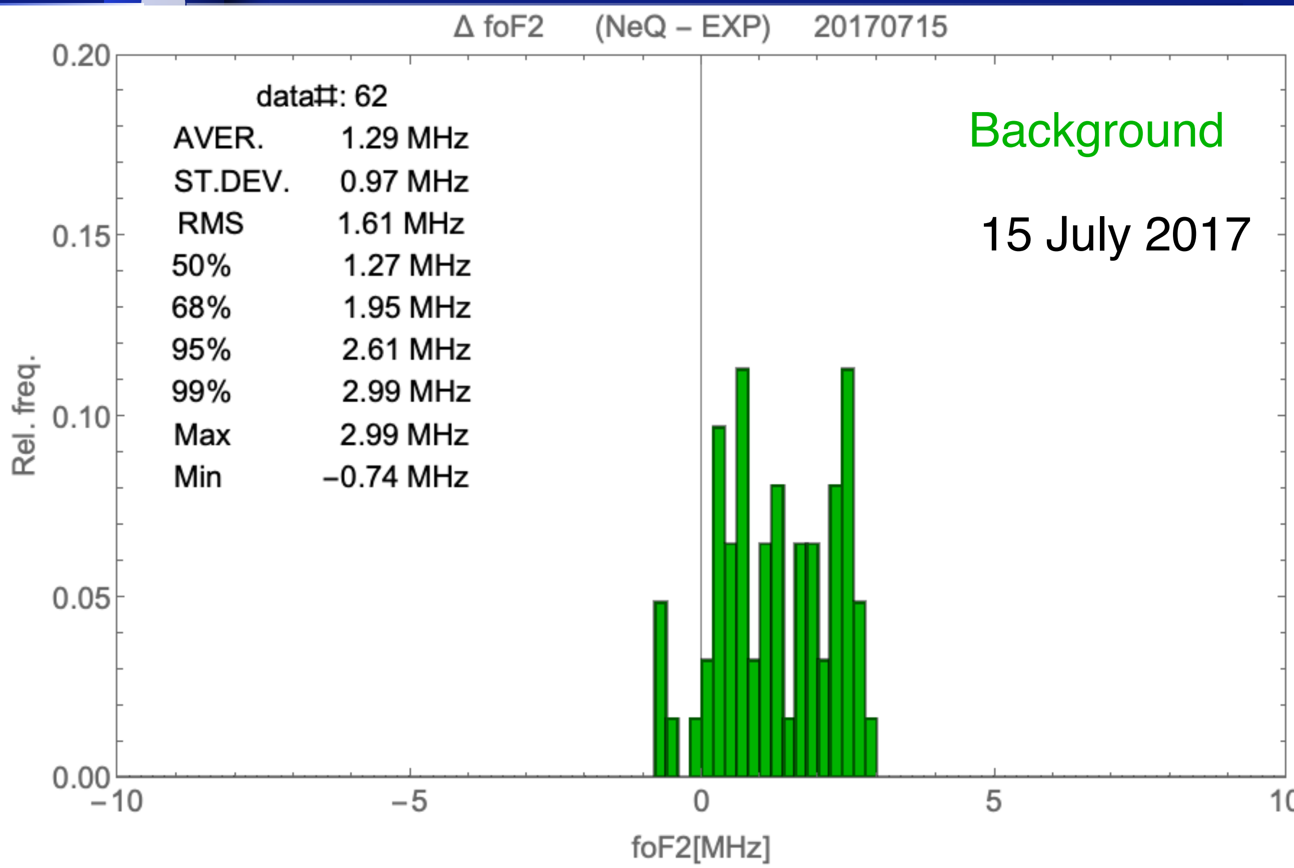


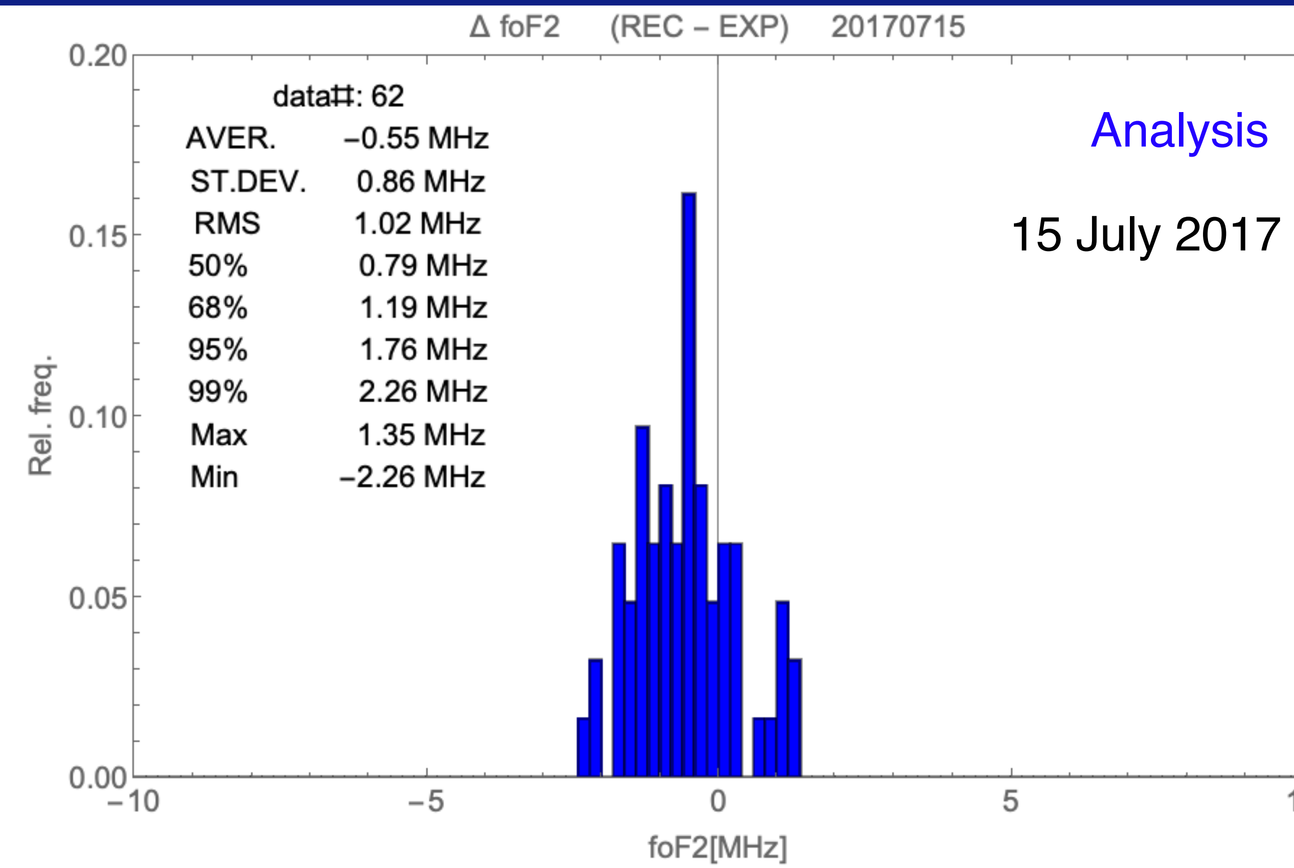


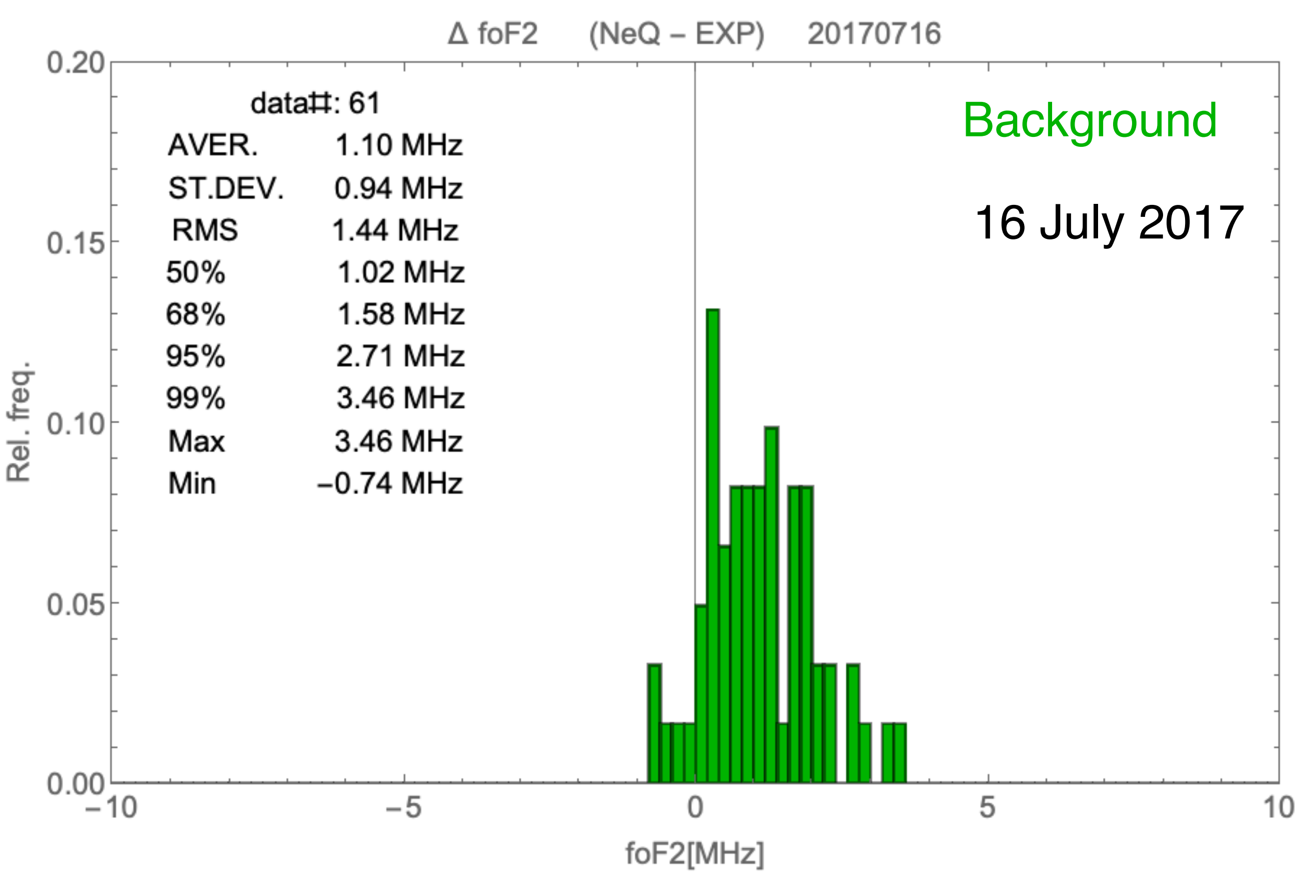
foF2 errors (11 ionosondes; mid-lat.)

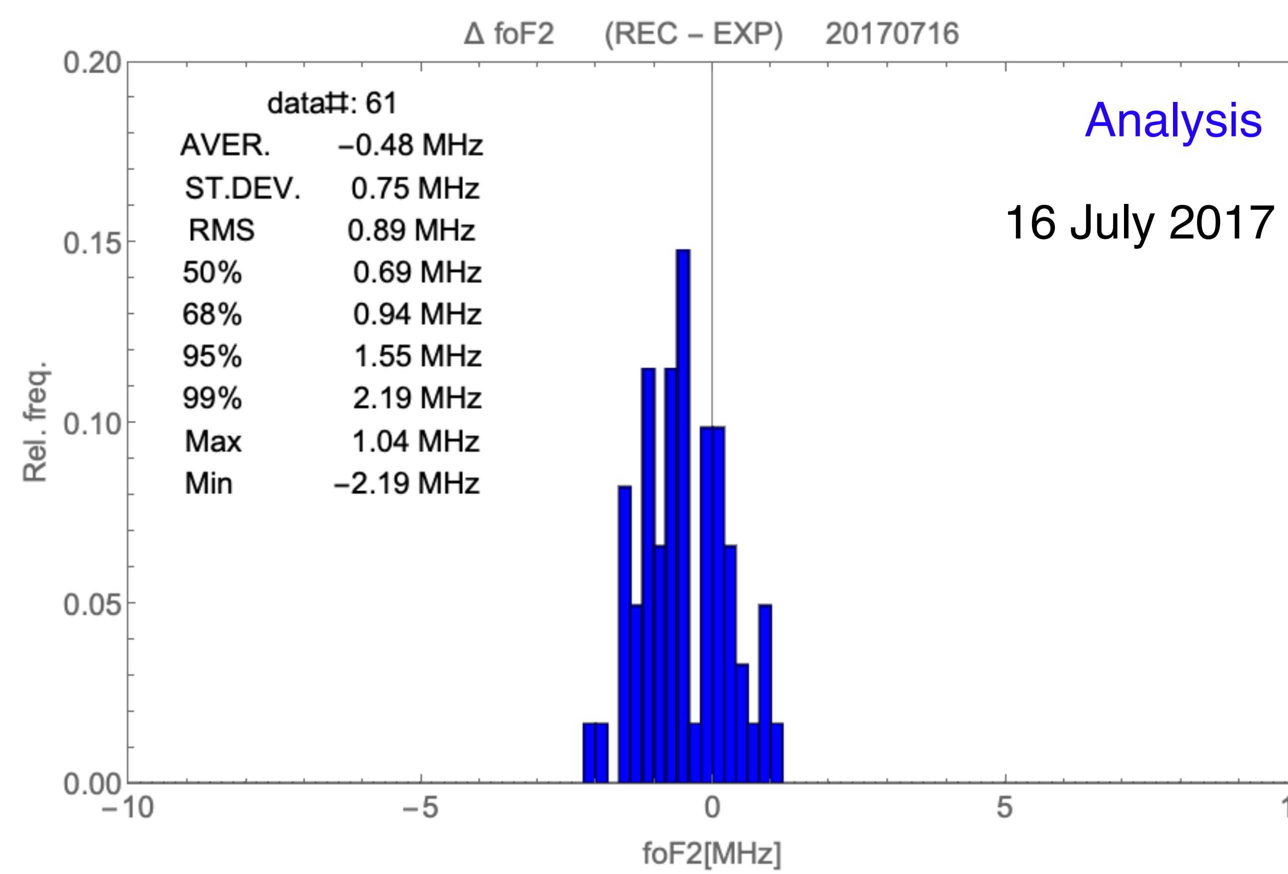


foF2 errors (3 ionosondes; low lat.)









Conclusions

- Specific examples related to the use of the NeQuick model in Space Weather studies have been presented.
- They have indicate that the NeQuick model can provide realistic “weather-like” descriptions of the 3-D electron density of the ionosphere, if suitable data ingestion and assimilation techniques are used.
- The ingestion techniques relying on the use of effective parameters allow NeQuick model to describe the storm-time space weather effects in terms of TEC and NeQuick G to reduce the errors in position estimation.
- The analysis results have confirmed the effectiveness of the sTEC data assimilation method based on the BLUE algorithm in reconstructing the ionospheric electron density, especially during geomagnetically disturbed conditions.

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Thank you for your attention