The Abdus Salam
International Centre
for Theoretical Physics
www.ictp.it
Trieste, Italy

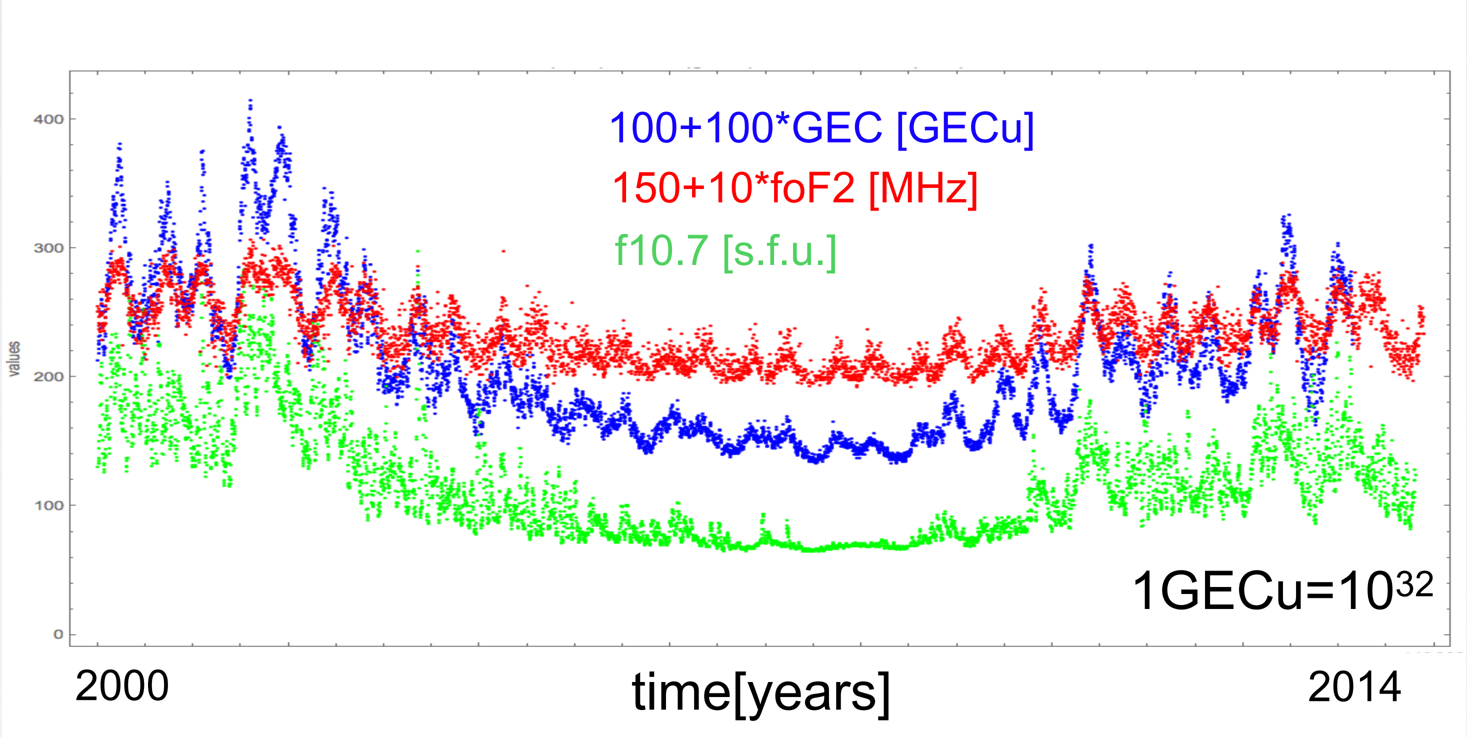
Introduction to Ionospheric Modeling

Bruno Nava
ICTP, Trieste, Italy

Regional Workshop on GNSS and Space Weather
Rabat, 9 - 13 May 2021

The Earth’s Ionosphere

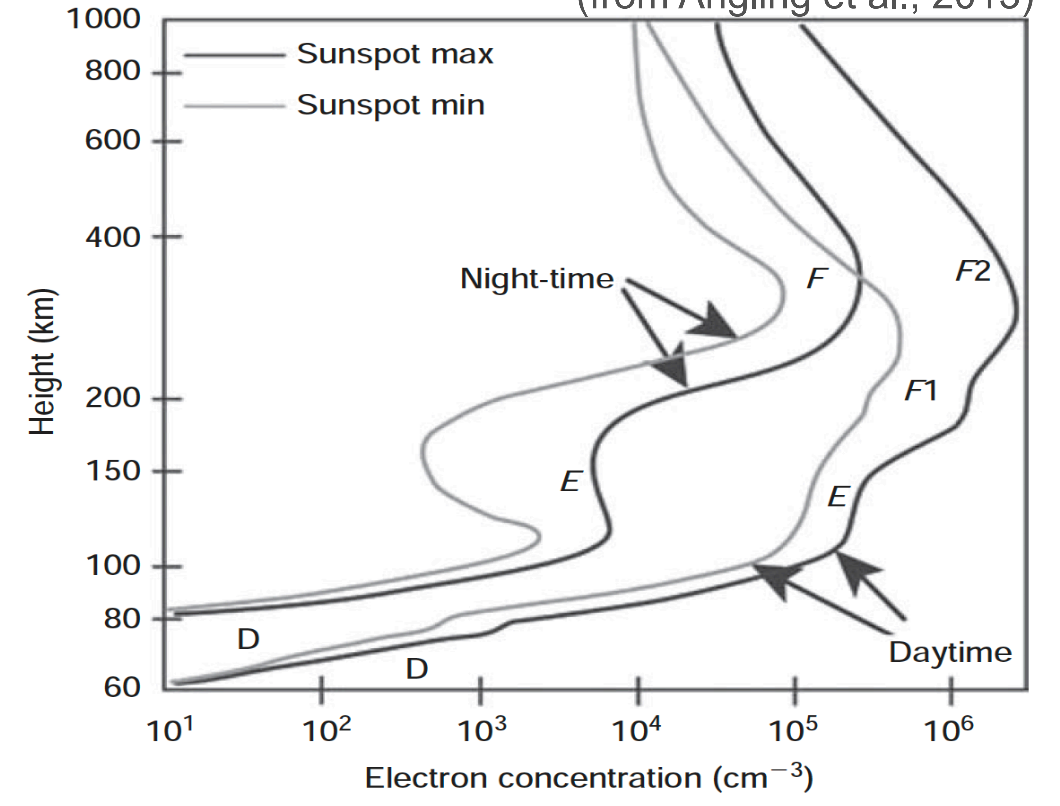
- Part of the upper atmosphere where sufficient free electrons and ions exist to affect the propagation of radio waves
- Between 80-1000 km height (Plasmasphere > 1000 km)
- Produced by solar X, UV radiation
- NO^+, O_2^+, O^+, H^+
- Stratified in D,E,F layers
- Strong variability (daily, seasonal, solar activity); geomagnetic field



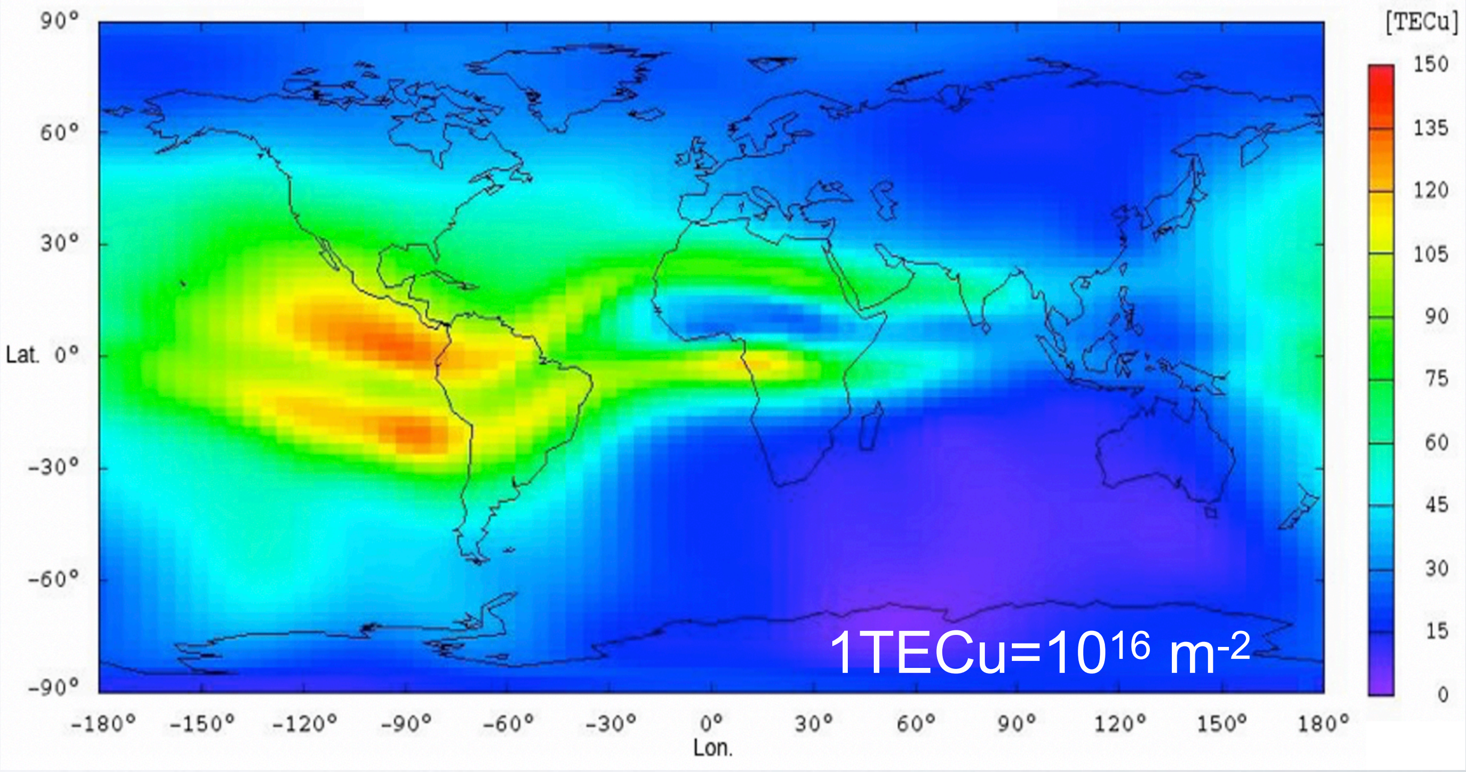
1GECu=10^{32}

time[years]

(from Angling et al., 2013)



VTEC 15 04 2002 21:00 UT



1TECu=10^{16} m^{-2}

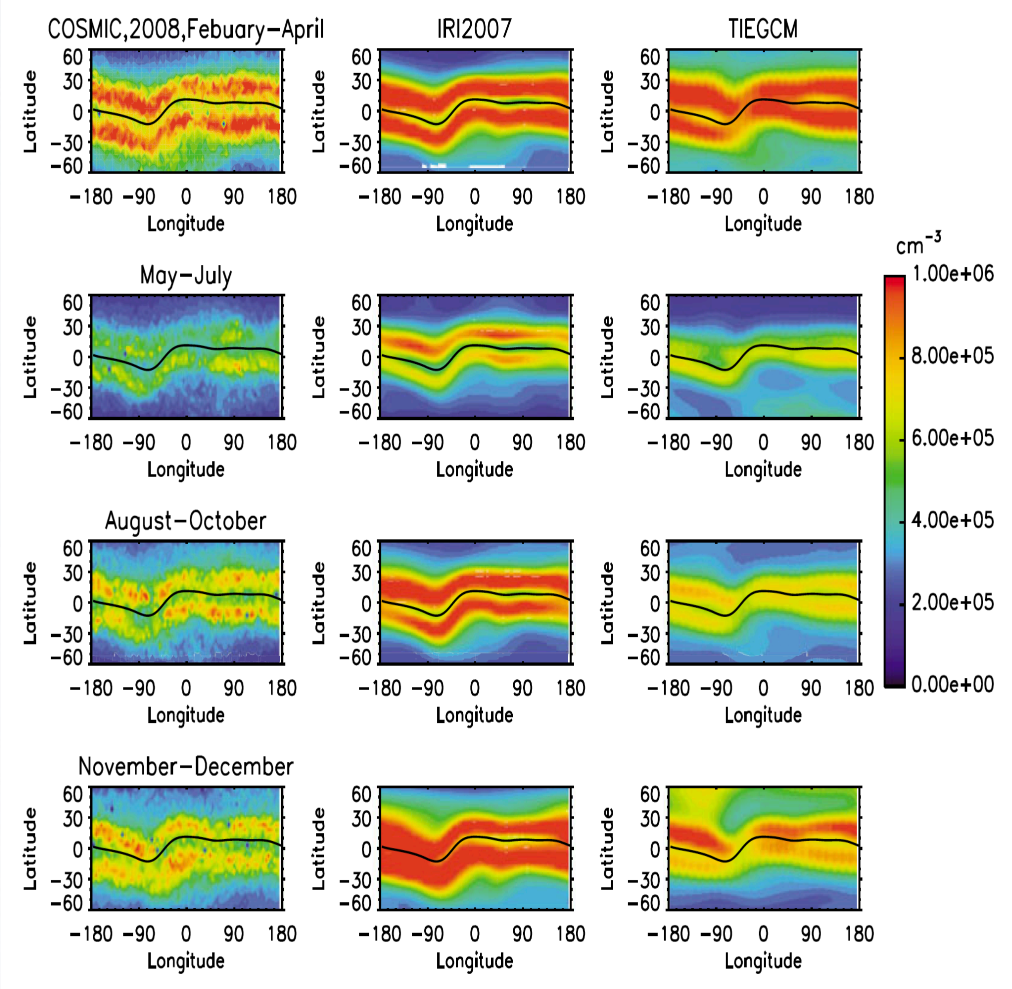
Ionospheric models

The understanding of the ionosphere behaviour is determined by the ability to model at least the height, geographic and time distributions of the electron density.

- Physics-based models
  - Conservation (continuity, momentum, energy, etc.) equations are solved numerically as a function of spatial and time coordinates to calculate plasma densities
  - Highly demanding in terms of implementation and computational costs
  - Effective for understanding the physical processes of the upper atmosphere
- Empirical models
  - Based on an analytical description of the ionosphere with functions obtained from experimental data or adapted from physic-based models
  - Relatively simple
  - Very good performance in reproducing the “climatological” behaviour of the ionosphere (median models)
- Data assimilation models
  - Use specific mathematical techniques to incorporate experimental data into physics-based or empirical background models

TIE-GCM

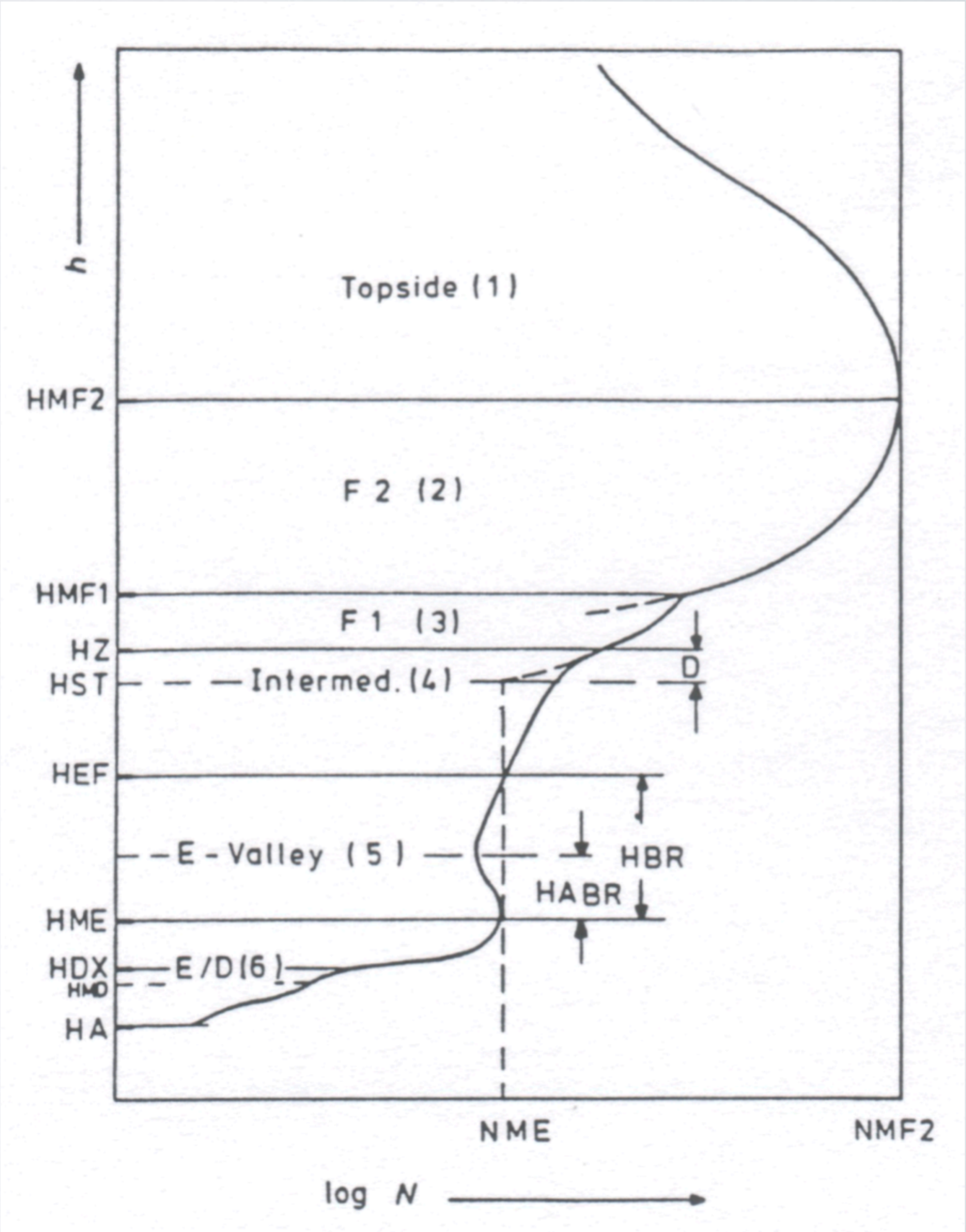
- The Thermosphere-Ionosphere-Electrodynamics General Circulation Model (TIE-GCM), is developed at the National Center for Atmospheric Research High-Altitude Observatory.
- It is a global 3-D numerical model that simulates the coupled thermosphere/ionosphere system from 95 to 600 km altitude.
- The TIE-GCM self-consistently solves the fully coupled, nonlinear, hydrodynamic, thermodynamic, and continuity equations of the neutral gas, the ion and electron energy and momentum equations, the ion continuity equation, and neutral wind dynamo.
- It is an open-source community model and is also available for runs-on-request at the NASA Community Coordinated Modeling Center.



NmF2 observed by COSMIC, IRI, TIE-GCM, during 2008. NmF2 is averaged over 10:00–13:00 LT and over the months shown in each panel; from: Qian et al. (2014).

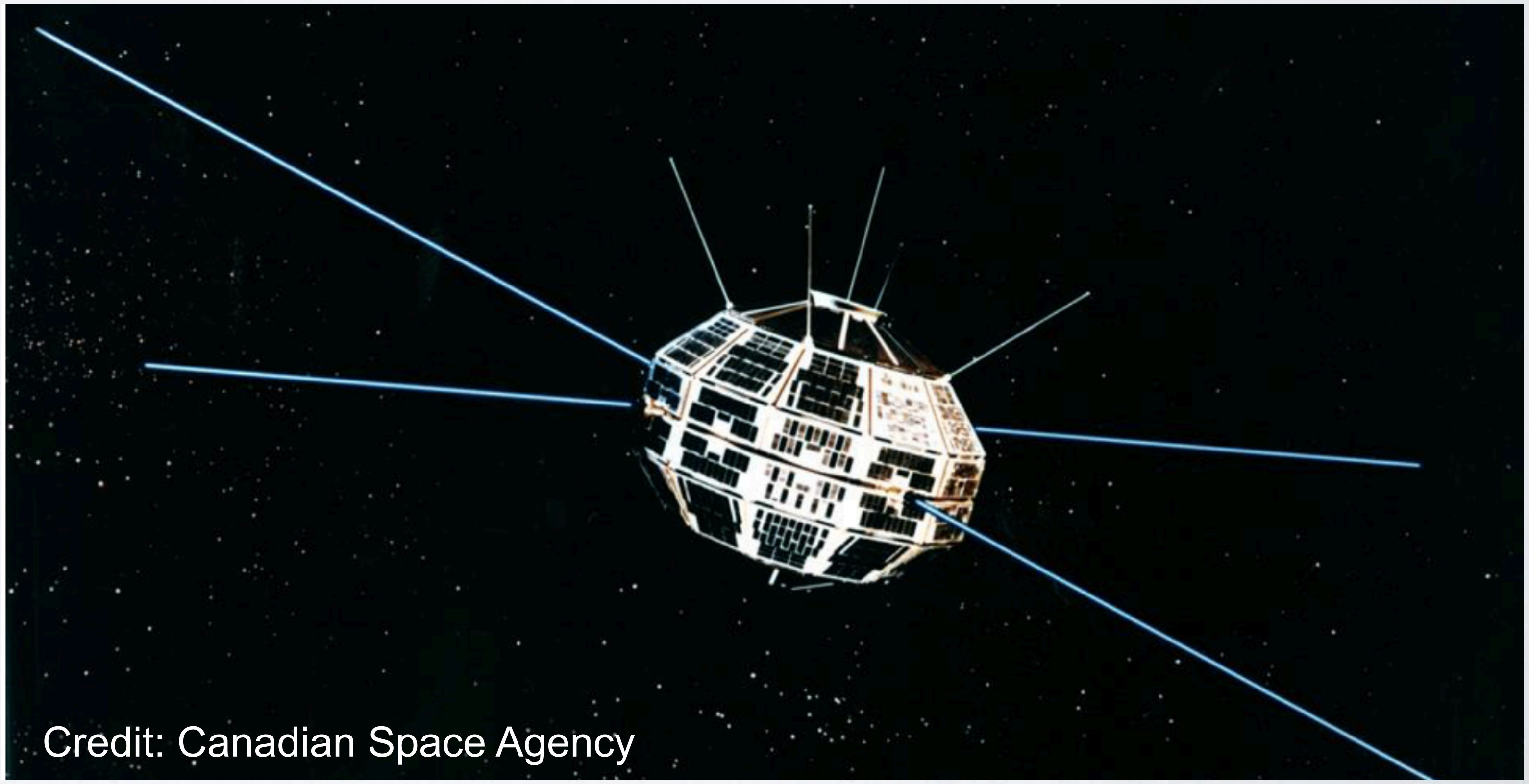
IRI

- The International Reference Ionosphere (IRI; Bilitza et al., 2001; Bilitza, 2015) is an empirical model of the ionosphere, obtained as the results of an international project sponsored by the Committee on Space Research and the International Union of Radio Science.
- For a given location and time, IRI provides the electron density, electron temperature, ion temperature and ion composition (O+, H+, He+, N+, NO+, O2+) in the altitude range 50-2000km and also the relevant TEC.
- The IRI electron density profile is divided in six sub-regions: the topside, the F2 bottomside, the F1 layer, the intermediate region, the E region valley, the bottomside E and D region.



IRI

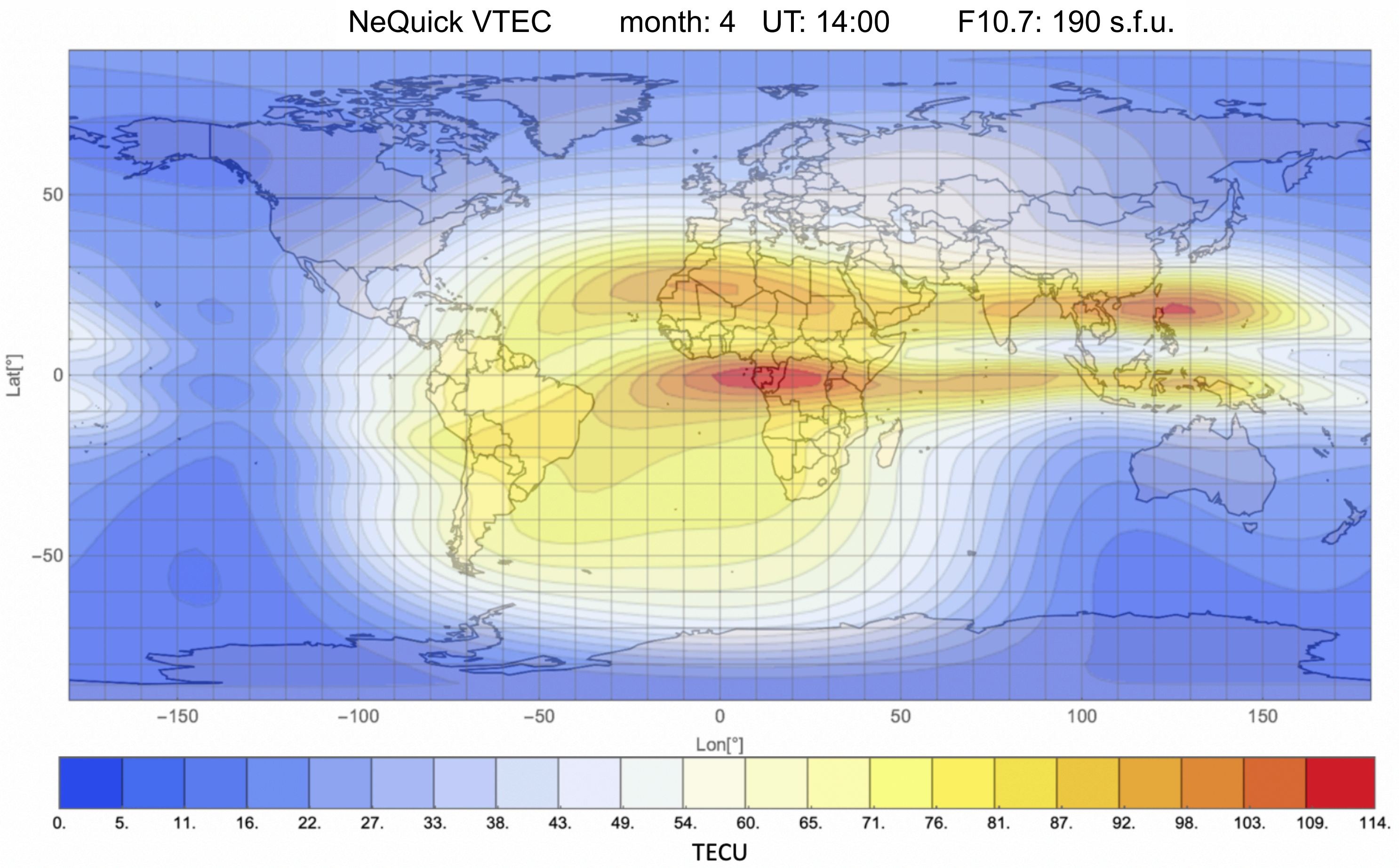
- The boundaries are defined by the presence of characteristic points that include the F2, F1 and E peaks.
- The shape of the IRI topside electron density profile was based on the descriptive compilation of Alouette topside sounder data and Epstein functions.
- Two parameters, B0 and B1, determine the bottomside thickness and shape, respectively.
- IRI includes a model to describe ionospheric storm-time conditions and has adopted, as an option, the NeQuick 2 model topside formulation.
- The latest version of IRI, IRTAM, has also the capability to describe real-time ionospheric weather conditions based on the ingestion of real-time measurements like ionosonde-derived peak parameter values.

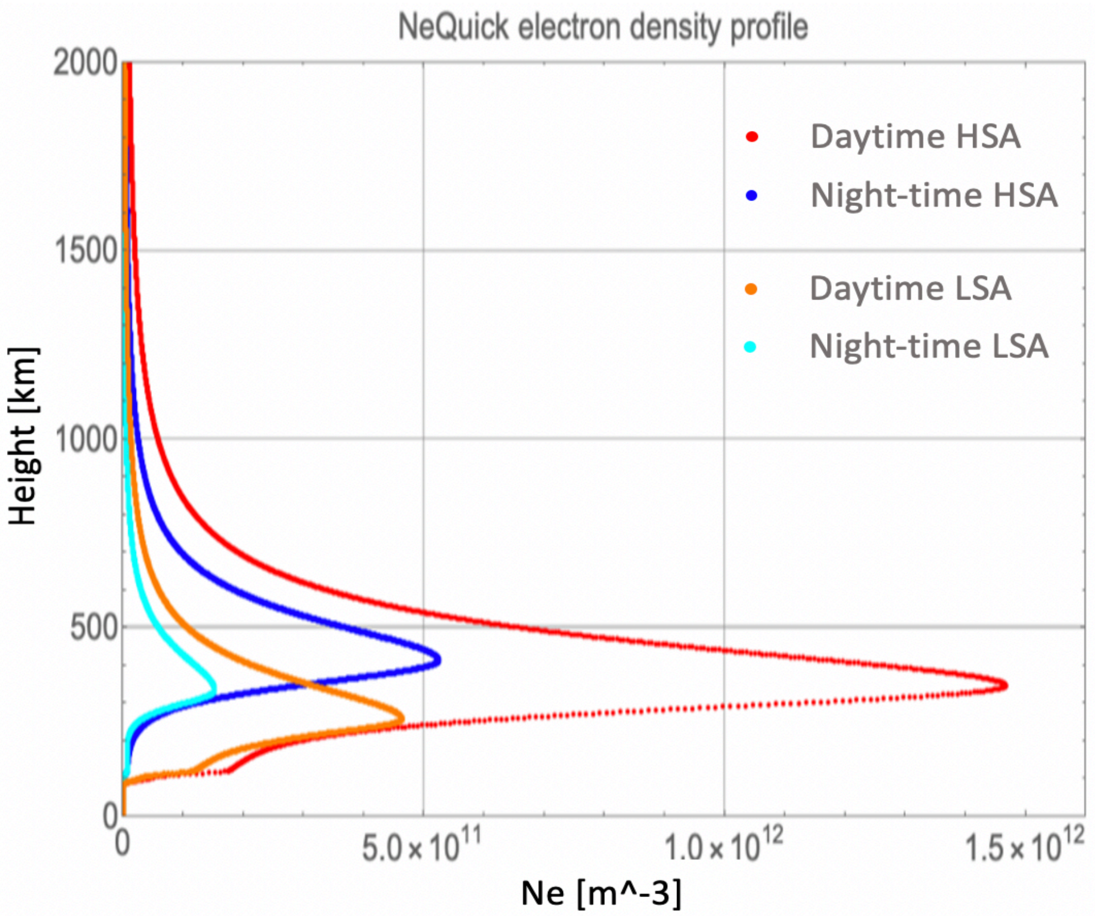


Credit: Canadian Space Agency

NeQuick

- The **NeQuick 2** is an ionospheric electron density model developed at the former ARPL of ICTP, Trieste, Italy, in collaboration with Institute for Geophysics, Astrophysics and Meteorology of 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

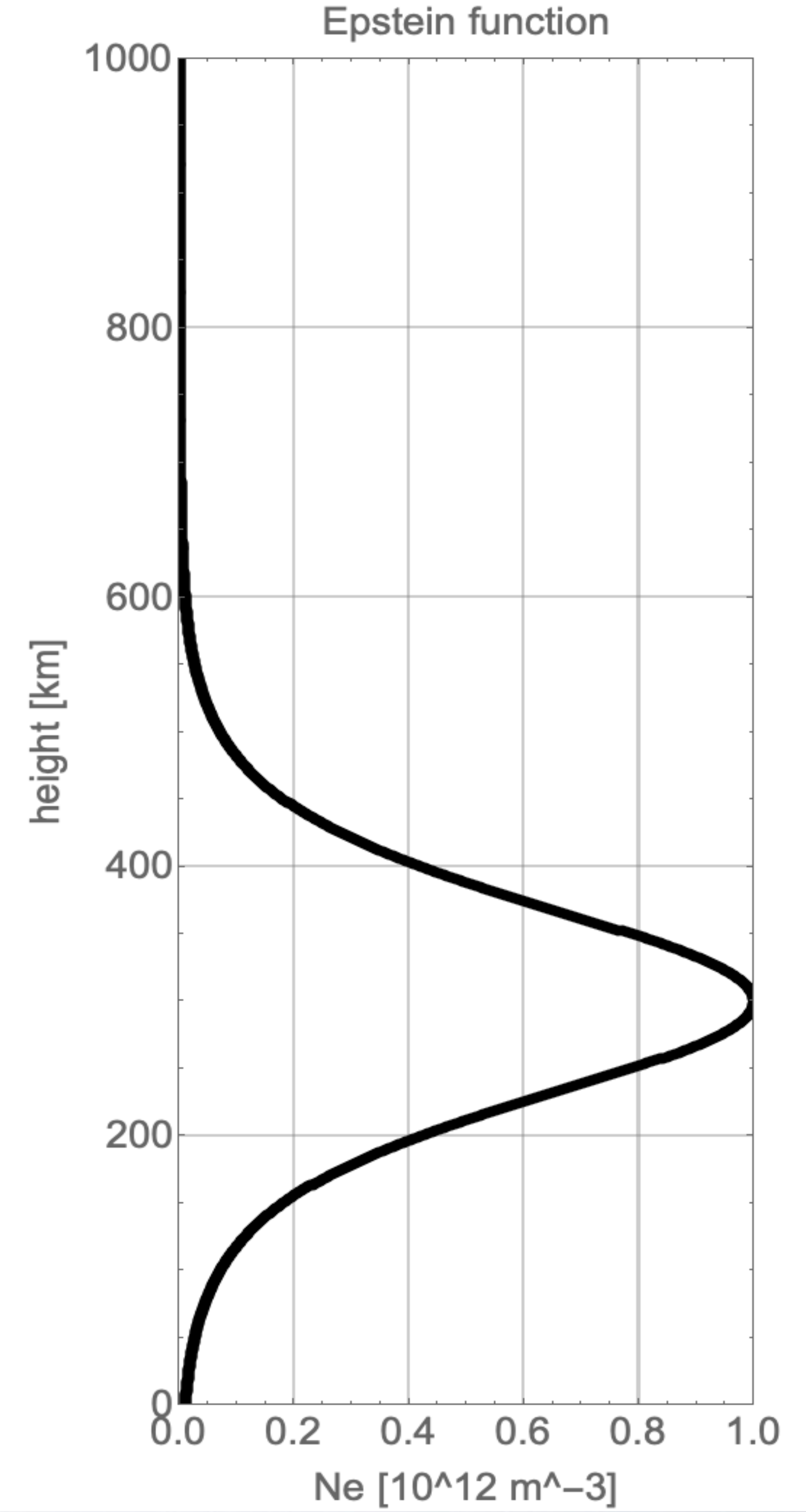
- The model profile formulation includes 6 semi-Epstein layers with modeled thickness parameters and is based on anchor points defined by foE, foF1, foF2 and M(3000)F2 values.
- These values can be modeled (ITU-R coefficients for foF2, M(3000)F2) or experimentally derived.

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

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

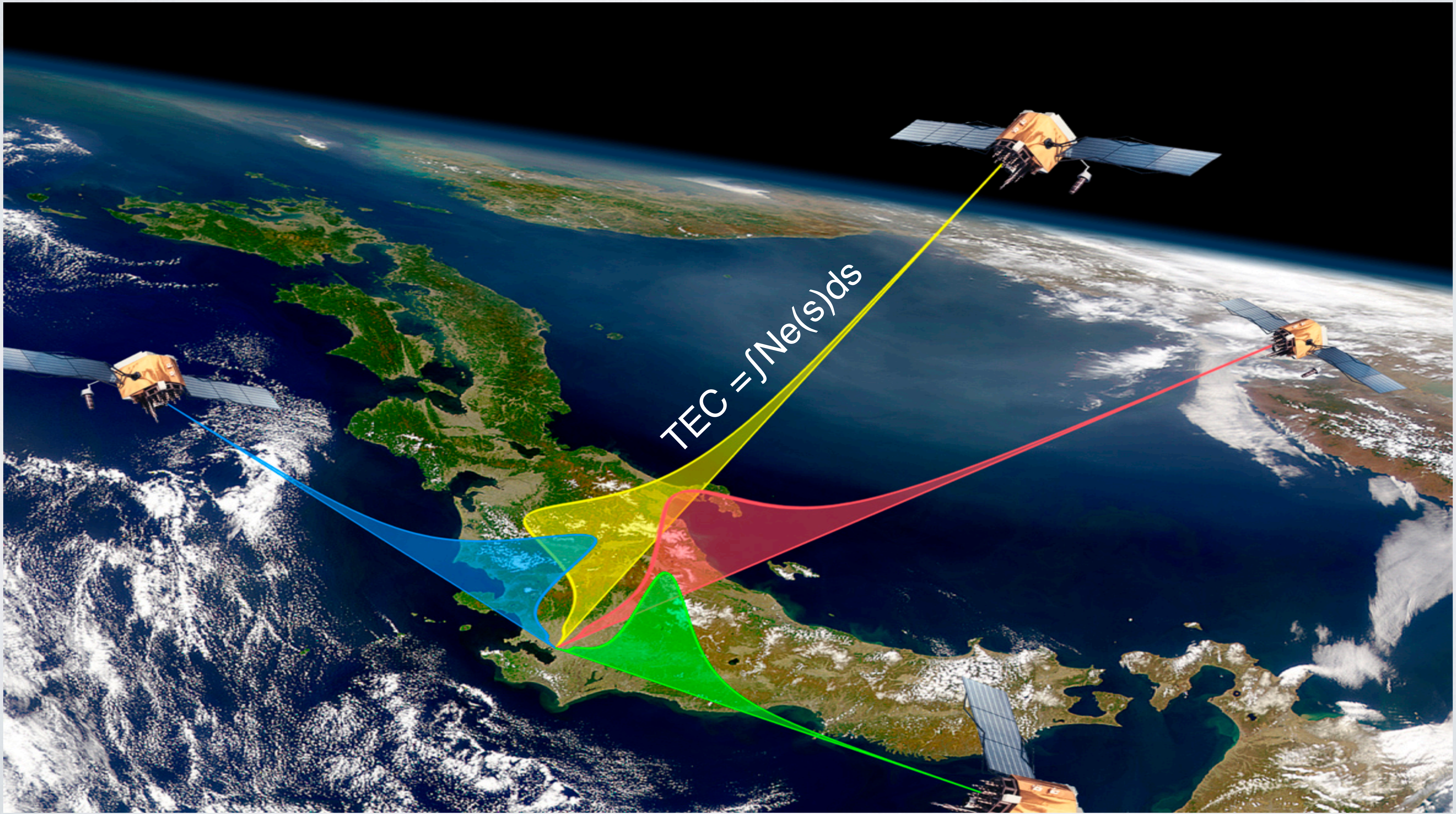
$$N_{F2}\left(h\right) = \frac{4NmF2}{\left(1+\exp\left(\frac{h-hmF2}{B2}\right)\right)^2}\exp\left(\frac{h-hmF2}{B2}\right)$$

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



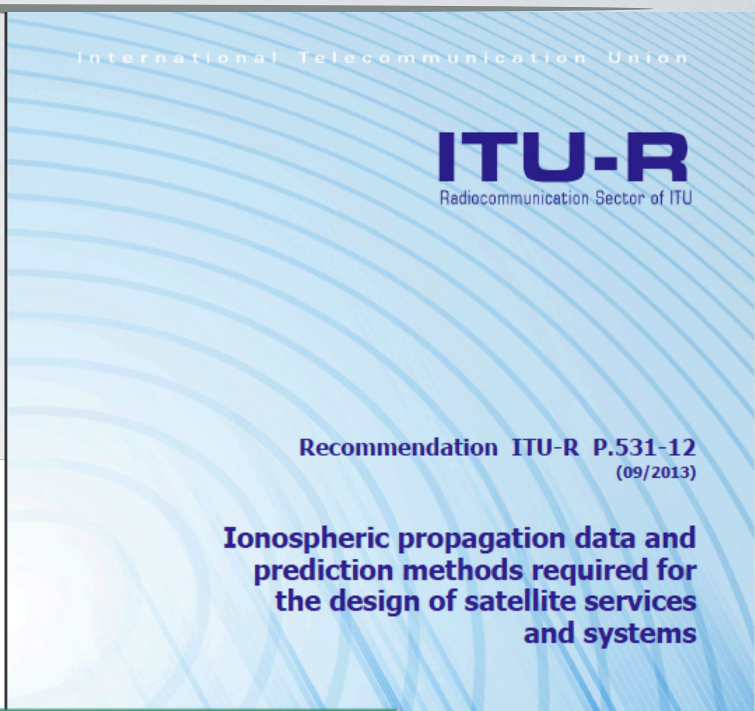
NeQuick

- 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.



NeQuick implementations

- The NeQuick (v1) has been adopted by Recommendation ITU-R P. 531 as a procedure for estimating TEC.
- Subsequently, the NeQuick 2 has substituted the NeQuick (v1) and it is the one currently recommended by ITU (ITU-R Recommendation P.531-12).
- A specific version of NeQuick (NeQuick G, implemented by ESA) has been adopted as Galileo Single-Frequency Ionospheric Correction Algorithm and its performance has been confirmed during In-Orbit Validation.
- ESA has also included NeQuick 2 in to Space Environment Information System.


International Telecommunication Union

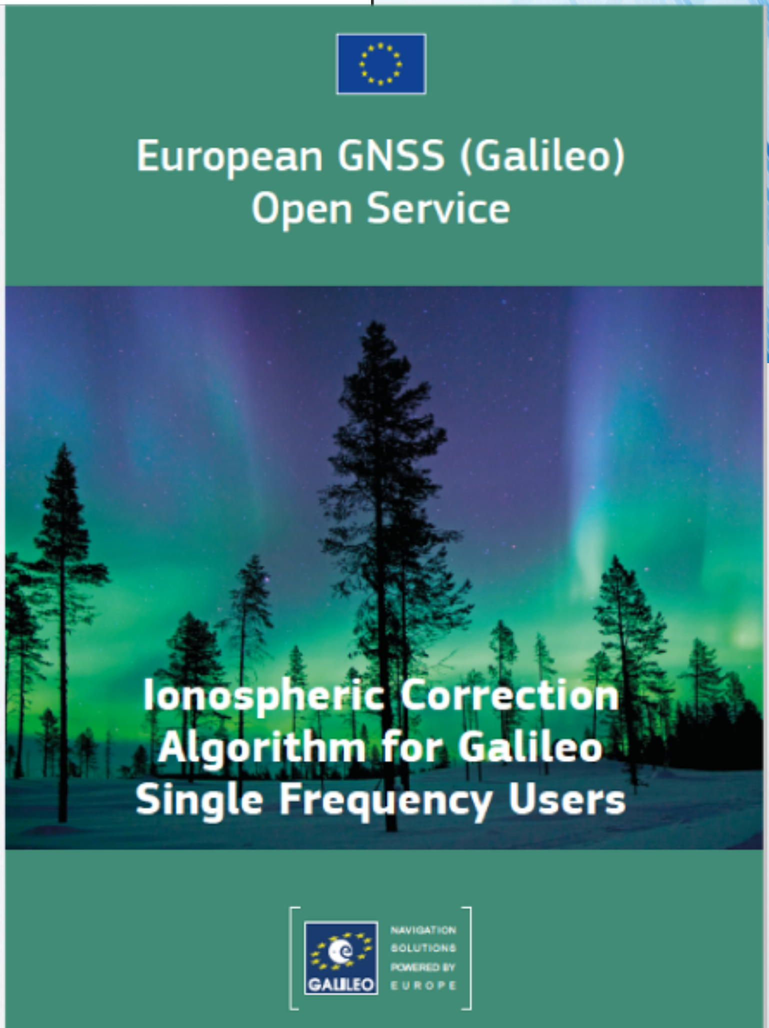
ITU-R
Radiocommunication Sector of ITU

Recommendation ITU-R P.531-12
(09/2013)

Ionospheric propagation data and prediction methods required for the design of satellite services and systems

P Series
Radiowave propagation

SPENVIS
The Space Environment Information System


European GNSS (Galileo) Open Service

Ionospheric Correction Algorithm for Galileo Single Frequency Users

ICA

- GPS uses a simple ionospheric model, the Ionospheric Correction Algorithm (ICA), which gives a representation of the mean vertical delay at L1, for given geomagnetic location and local time (Klobuchar, 1987).
- The diurnal variation of vertical delay is modeled by a cosine function, centered at 14 LT. During night-time the vertical ionospheric delay is approximated to a constant value: 5 ns.
- The amplitude and period of the cosine are represented in the model by 3rd order polynomials, which coefficients are broadcast in GPS navigation message. These coefficients were derived from numerical output of Bent model, determining a 370 sets of coefficients for the different conditions of the ionosphere.

ICA

$$T_{iono} = F\left(5\times10^{-9} + \sum_{n=0}^{3}\alpha_n\Phi_m^n\left(1-\frac{x^2}{2}+\frac{x^4}{24}\right)\right) \qquad \text{if } |x|\le 1.57$$

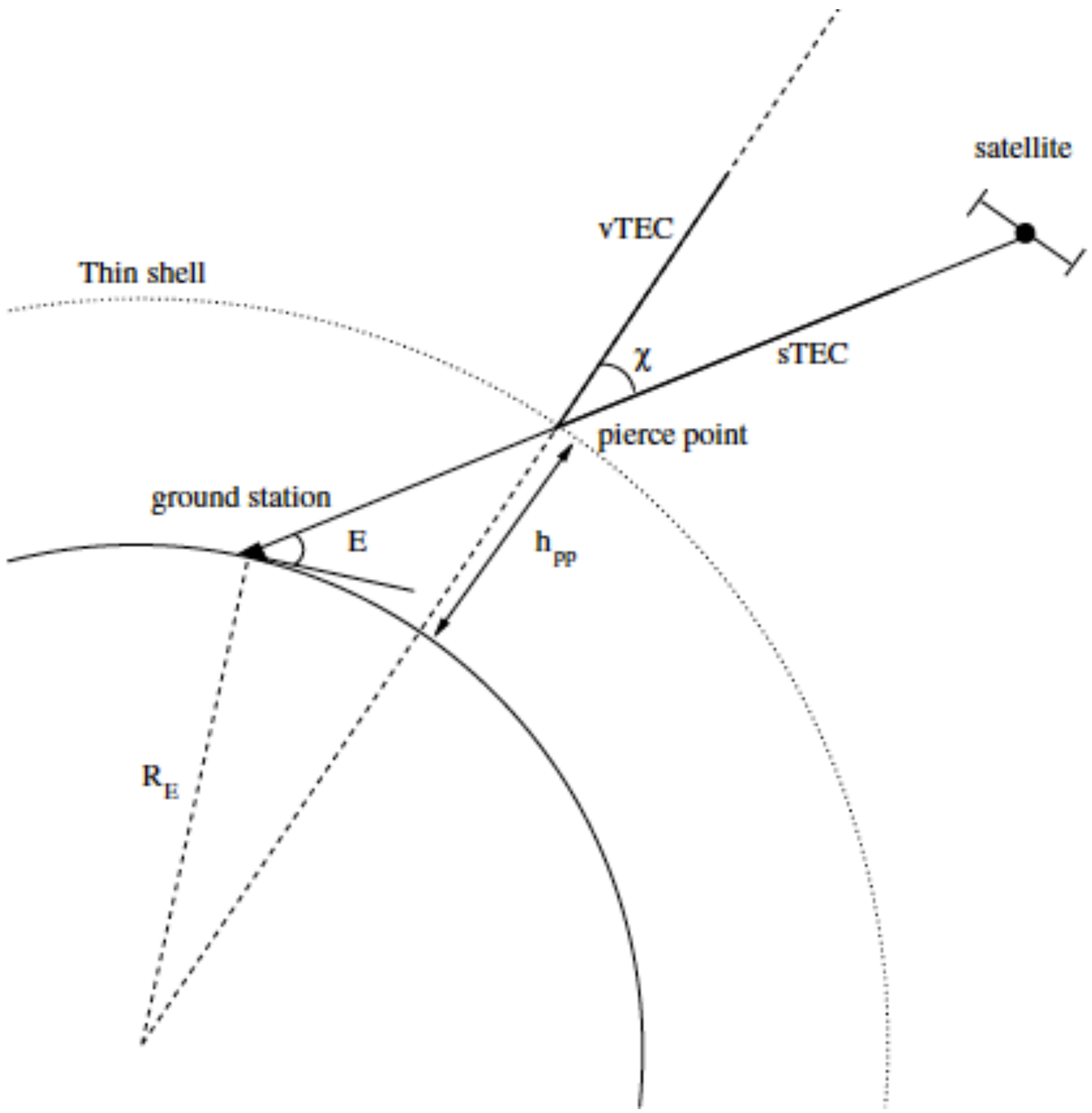
$$T_{iono} = 5\times10^{-9}F \qquad \text{if } |x|>1.57$$

with

$$x = \frac{2\pi(t-50400)}{\sum_{n=0}^{3}\beta_n\Phi_m^n}$$

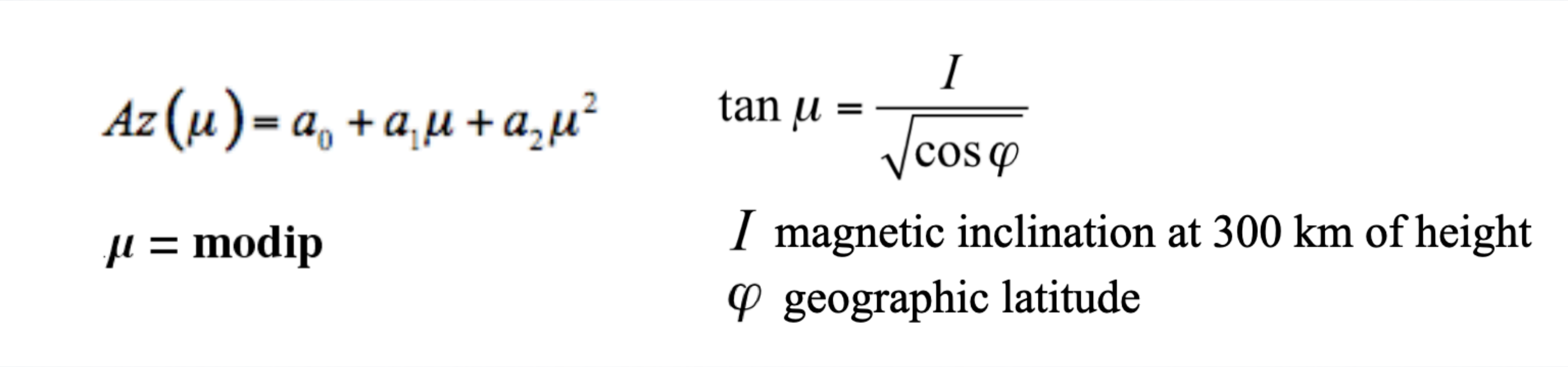
$$F = 1+16(0.53-\theta)^3$$

α_n β_n	broadcast coefficients
t	local time
Φ_m	geomagnetic latitude of the pierce point
F	obliquity factor
θ	satellite elevation



NeQuick G

- The model will be driven by an "effective ionisation level" Az, valid for the whole world and applicable for a period of typically 24 hours.



$$Az(\mu) = a_0 + a_1\mu + a_2\mu^2 \qquad \tan\mu = \frac{I}{\sqrt{\cos\varphi}}$$

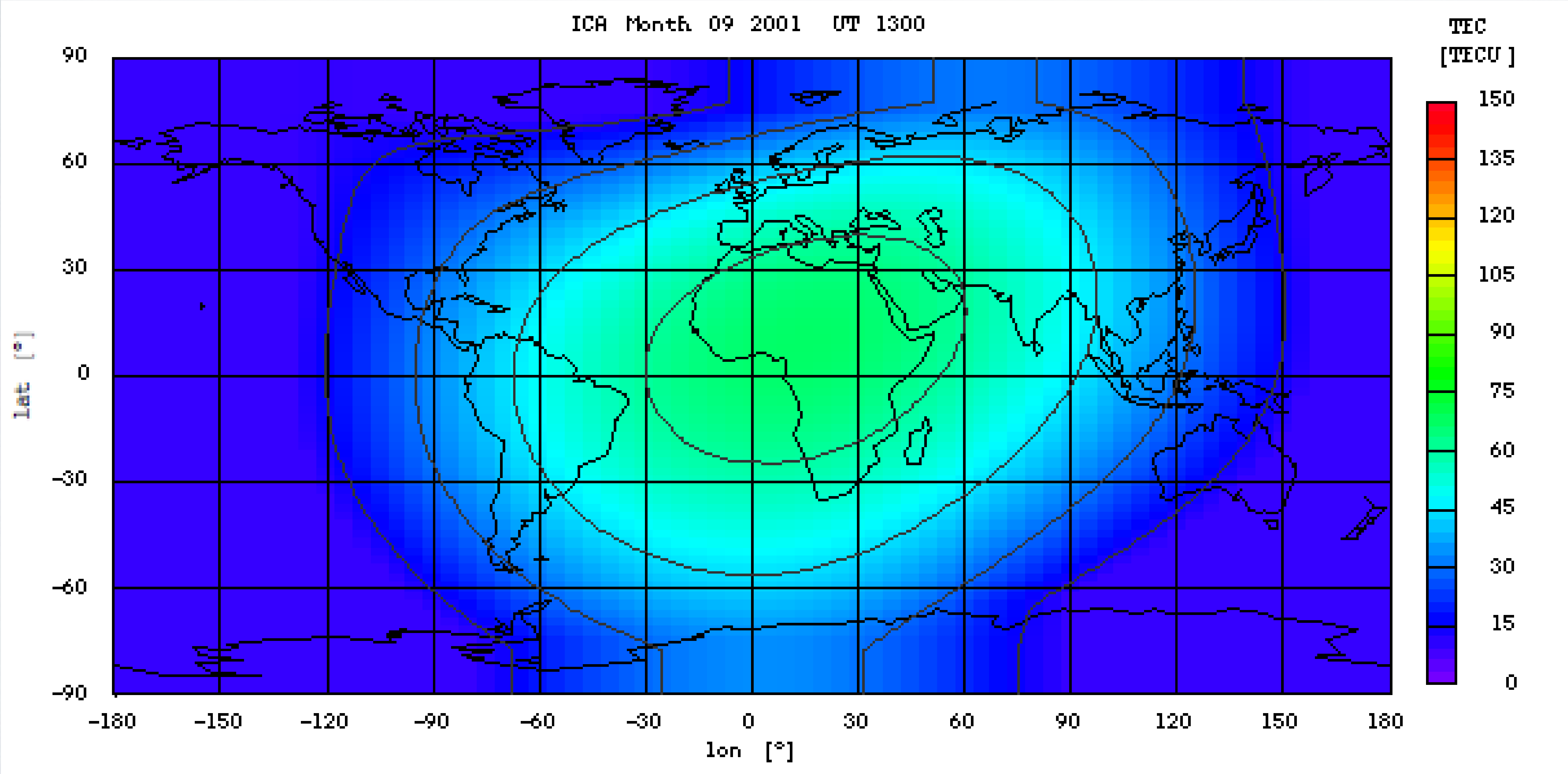
μ = **modip**

I magnetic inclination at 300 km of height

φ geographic latitude

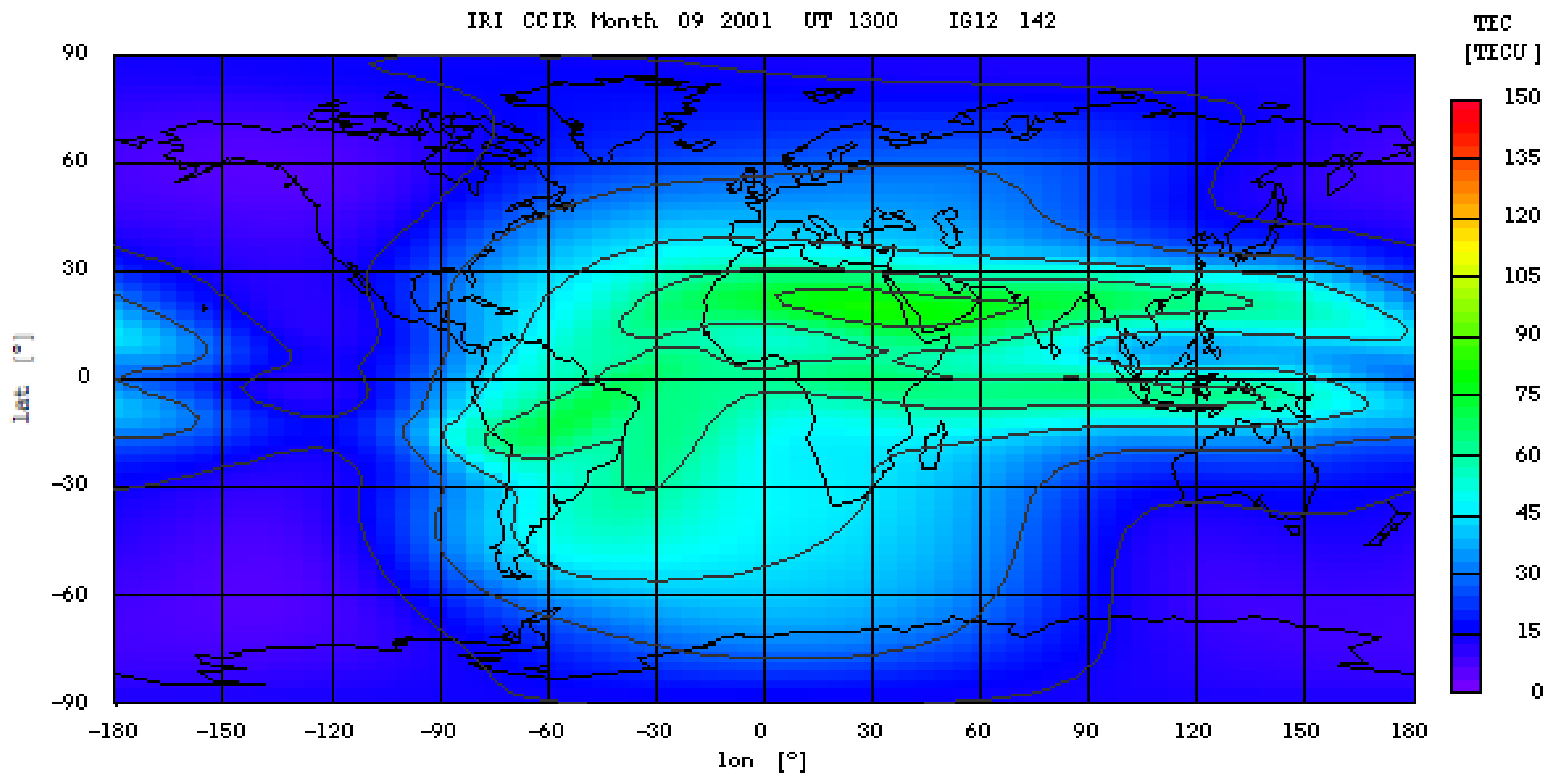
- The coefficients a0, a1, a2 are broadcast to the user to allow Az calculation at any wanted location.
- Az coefficients broadcasted and used for one day are computed at System level using TEC data of the previous day.

ICA vTEC



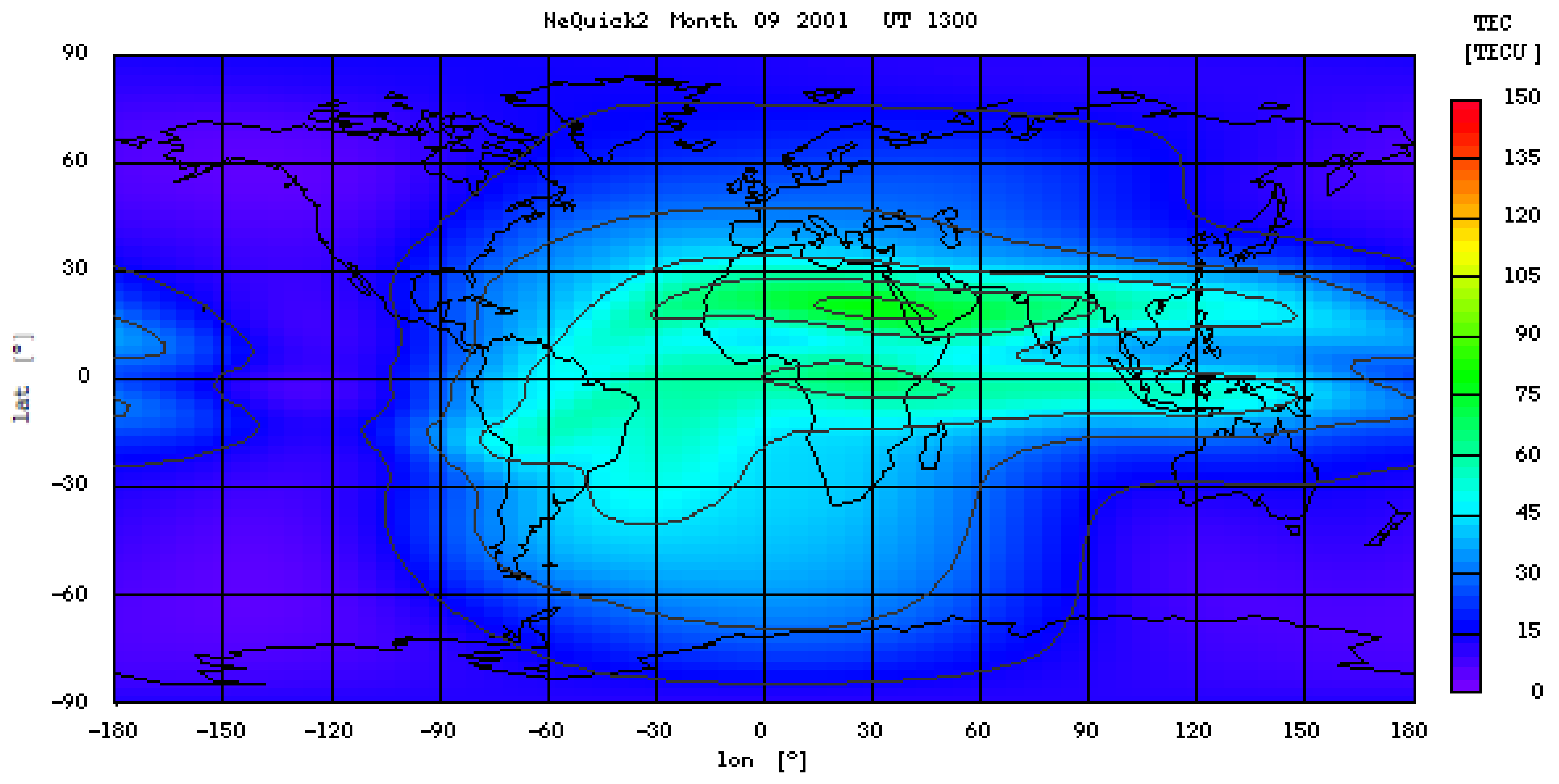
Global map of vertical TEC using ICA

IRI vTEC



Global map of vertical TEC using IRI

NeQuick 2 vTEC



Global map of vertical TEC using NeQuick 2

Other empirical models

- Semi-Empirical Low-Latitude Ionospheric Model (SLIM)
- Fully Analytical Ionospheric Model (FAIM)
- Parameterised Real-time Ionospheric Specification Model (PRISM)
- Bent Model
- NeQuick, COSTProf, NeUoG-plas (Trieste-Graz family)

- The more recently developed regional Empirical Canadian High Arctic Ionospheric Model (E-CHAIM) and the Neustrelitz Electron Density Model (NEDM2020).

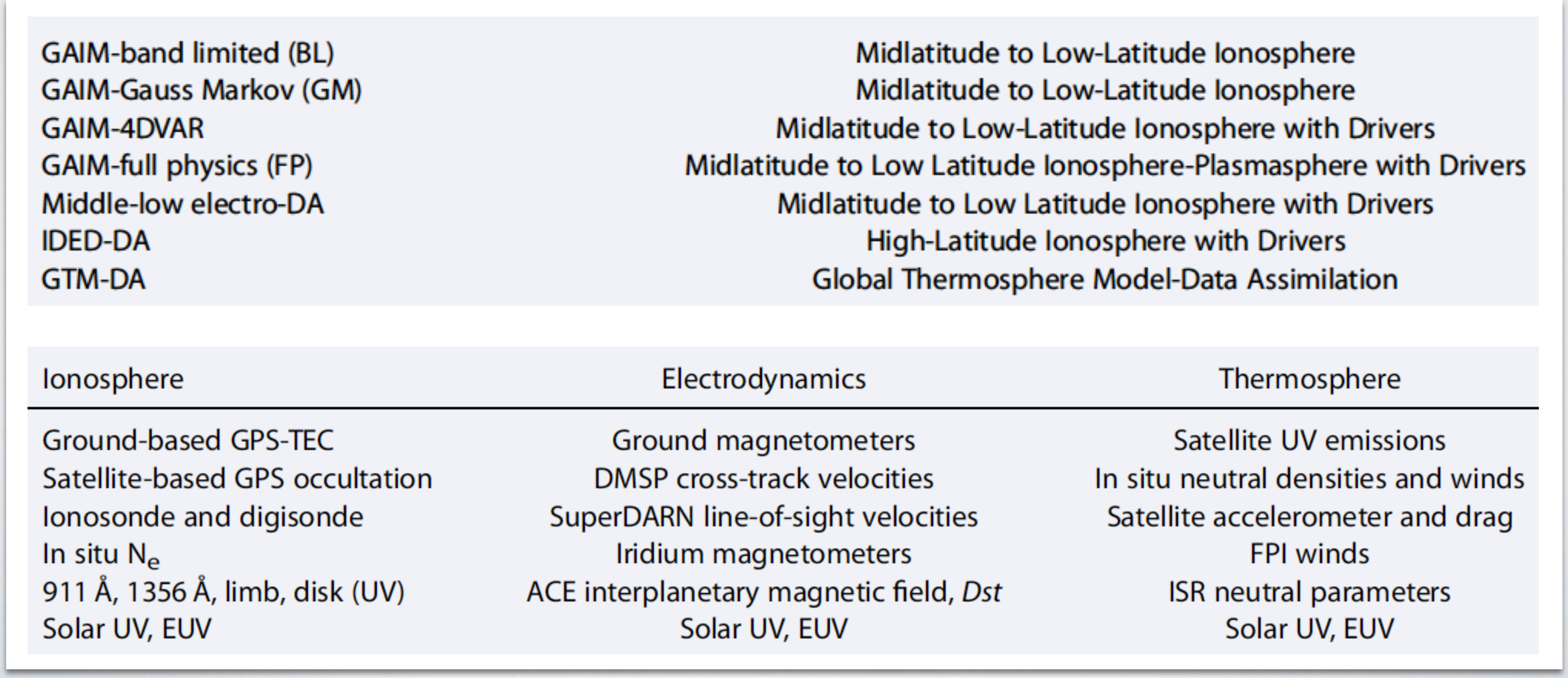
Data Assimilation (DA)

- "DA is an analysis technique in which the observed information is accumulated into the model state by taking advantage of consistency constraints with laws of time evolution and physical properties" (Bouttier and Courtier,1999).
- DA and Data Ingestion techniques are usually associated with each other and not clearly distinguished (Aa et al, 2018).
- Ionospheric DA schemes are based on different mathematical techniques:
  - Variational techniques
    - 3D-VAR
    - 4D-VAR
  - Kalman filters
    - extended Kalman filter (EKF)
    - ensemble Kalman filter (EnKF)
    - local ensemble transform Kalman filter (LETKF)

- Data are a critical element of a DA.

GAIM

- Utah State University (USU) Global Assimilation of Ionospheric Measurements (GAIM) [Schunk et al., 2004] or the Jet Propulsion Laboratory (JPL)/University of Southern California (USC) Global Assimilative Ionospheric Model (GAIM) [Wang et al., 2004], or [Schunk et al., 2014], for example, are based on assimilation of data originating from different sources and imply the use of first principle models.



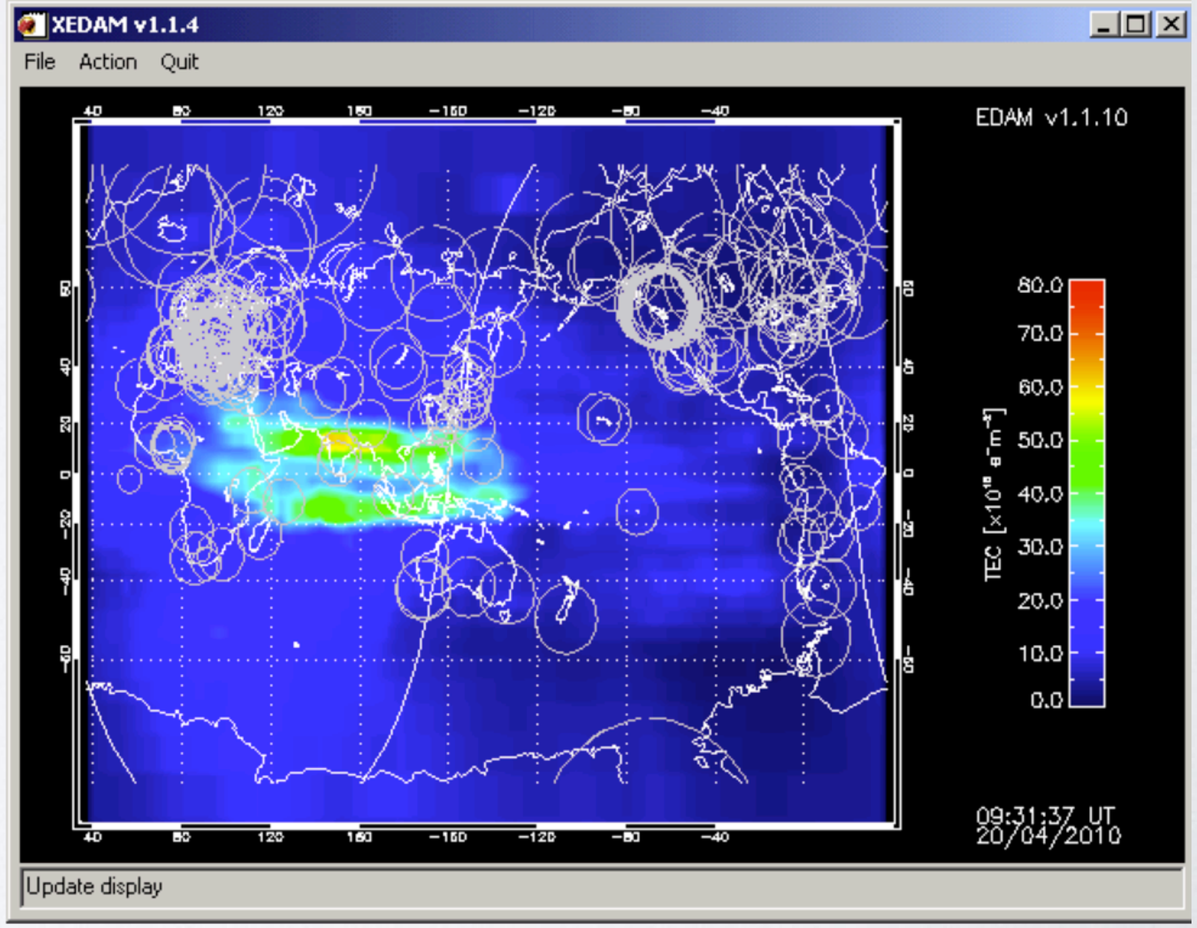
GAIM-band limited (BL)	Midlatitude to Low-Latitude Ionosphere
GAIM-Gauss Markov (GM)	Midlatitude to Low-Latitude Ionosphere
GAIM-4DVAR	Midlatitude to Low-Latitude Ionosphere with Drivers
GAIM-full physics (FP)	Midlatitude to Low Latitude Ionosphere-Plasmasphere with Drivers
Middle-low electro-DA	Midlatitude to Low Latitude Ionosphere with Drivers
IDED-DA	High-Latitude Ionosphere with Drivers
GTM-DA	Global Thermosphere Model-Data Assimilation

Ionosphere	Electrodynamics	Thermosphere
Ground-based GPS-TEC	Ground magnetometers	Satellite UV emissions
Satellite-based GPS occultation	DMSP cross-track velocities	In situ neutral densities and winds
Ionosonde and digisonde	SuperDARN line-of-sight velocities	Satellite accelerometer and drag
In situ N_e	Iridium magnetometers	FPI winds
911 Å, 1356 Å, limb, disk (UV)	ACE interplanetary magnetic field, *Dst*	ISR neutral parameters
Solar UV, EUV	Solar UV, EUV	Solar UV, EUV

EDAM

- The Electron Density Assimilative Model (EDAM) [Angling and Khattatov, 2006; Angling, M. J., and N. K. Jackson-Booth, 2011] provides a mean to assimilate ionospheric measurements into a background ionospheric model.
- Assimilated data are: ground-based and space-based GPS-derived TEC, ionosondes-derived parameters.
- Currently IRI is used as a background model (electron density only).

- Extended, localised Gauss Markov Kalman Filter
  - Time evolution of the differences between the measurements and the background ionosphere
  - Model variances are propagated
  - Covariances are estimated as required



MIDAS

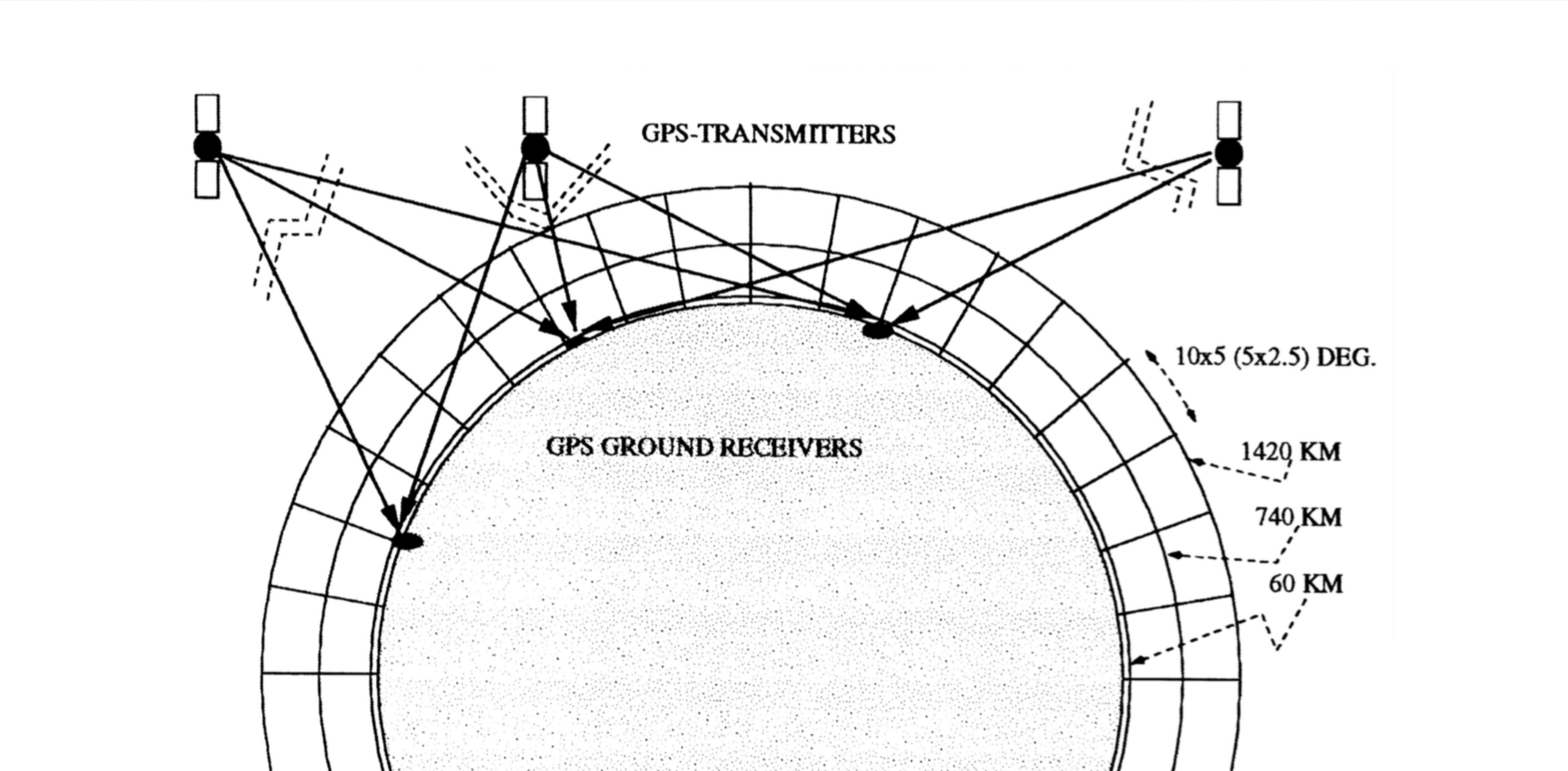
- The Multi Instrument Data Analysis System (MIDAS) (Mitchell C. N. and Spencer P. S., 2003) is a tomographic approach where TEC data are inverted to evaluate the distribution and time evolution of electron concentration. Orthonormal basis functions and Singular Value Decomposition (SVD) are used to solve the inverse problem. Additional information on MIDAS and other assimilation techniques can be found in the review paper by Bust, and Mitchell (2008).

IDA3D

- The Ionospheric Data Assimilation Three-Dimensional (IDA3D), (Bust et al., 2004) uses a 3D-VAR data assimilation technique. It is capable of incorporating ground based and space based GNSS-TEC measurements and electron density measurements from radars and satellites. The background 3D electron density is based upon empirical ionospheric models, but IDA3D is capable of using any global ionospheric specification as a background to produce a spatial analysis of the electron density distribution at a specified time.

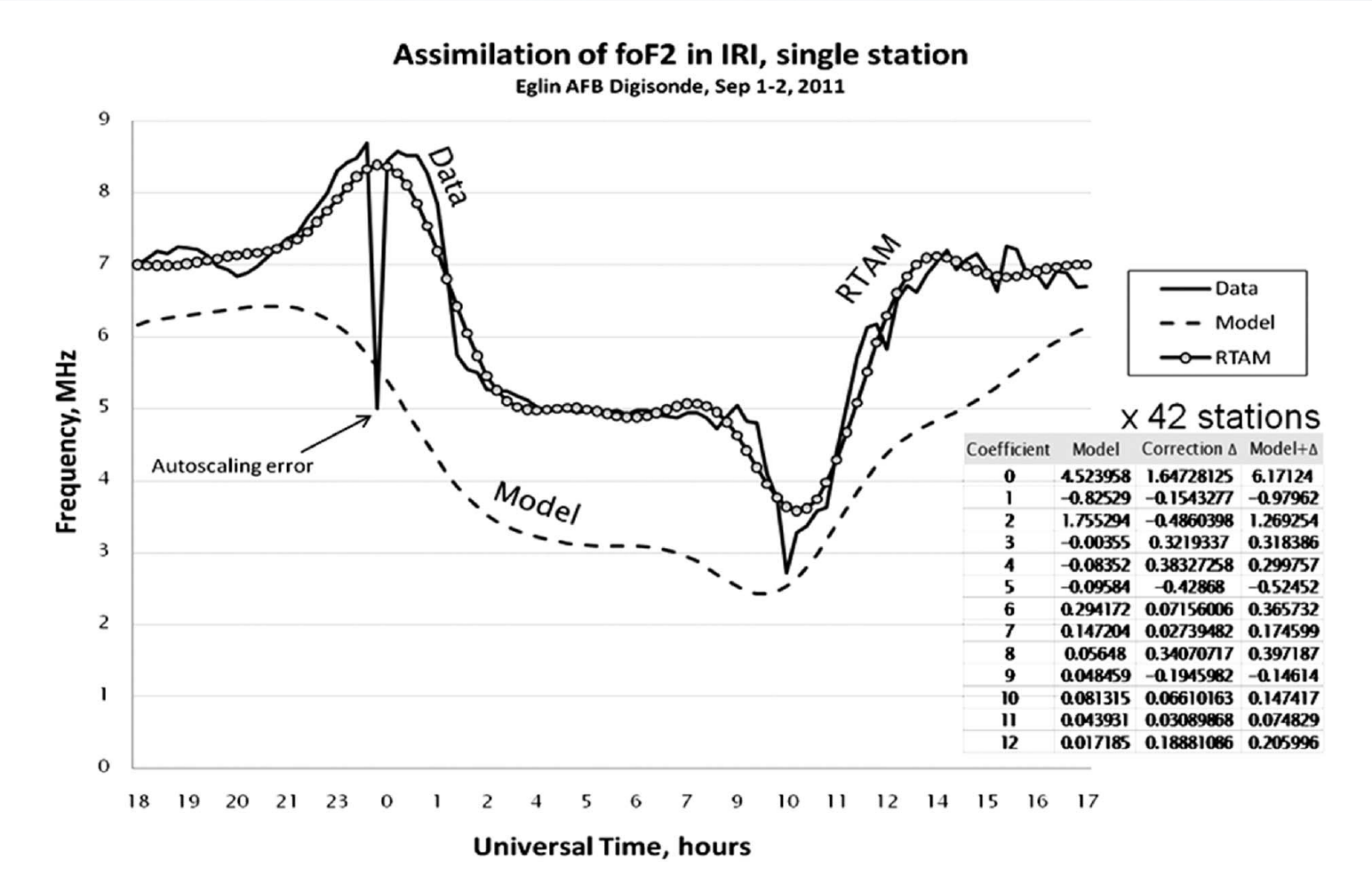
TOMION

- The TOMographic IONosphere model (TOMION), (Hernández-Pajares, M. et al., 1999) generates Global Ionospheric Maps (GIMs) of vertical TEC starting from ground based dual-frequency GNSS measurements. To overcome the assumption of a (single) thin shell approximation, in TOMION the ionosphere is represented by two or more layers of voxels, and in each voxel the electron density is assumed to be constant. It also includes an interpolation module relying on the Kriging technique to obtain the relevant vertical TEC at the grid-points (Orús et al., 2005). A remarkable feature of TOMION is that no background model is used.



IRTAM

- IRI Real Time Assimilative Model (IRTAM) [Galkin, I. A., et al. 2012], has been developed to assimilate Global Ionosphere Radio Observatory (GIRO) data (foF2, hmF2) in order to “update” the IRI electron density distribution, while preserving the IRI’s typical ionospheric feature representations.
- The technique calculates the corrected coefficients for the spherical/diurnal expansion used by the CCIR-67/URSI-88 model to specify the global foF2 maps, and similarly the maps for all other IRI profile parameters.

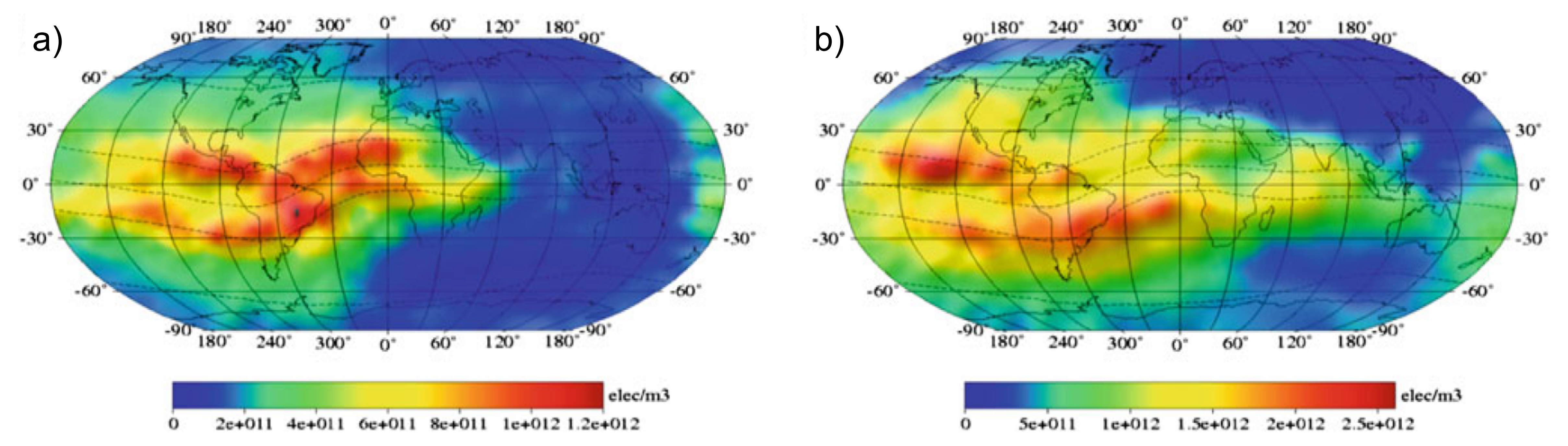


x 42 stations

Coefficient	Model	Correction Δ	Model+Δ
0	4.523958	1.64728125	6.17124
1	−0.82529	−0.1543277	−0.97962
2	1.755294	−0.4860398	1.269254
3	−0.00355	0.3219337	0.318386
4	−0.08352	0.38327258	0.299757
5	−0.09584	−0.42868	−0.52452
6	0.294172	0.07156006	0.365732
7	0.147204	0.02739482	0.174599
8	0.05648	0.34070717	0.397187
9	0.048459	−0.1945982	−0.14614
10	0.081315	0.06610163	0.147417
11	0.043931	0.03089868	0.074829
12	0.017185	0.18881086	0.205996

LPIM-AM

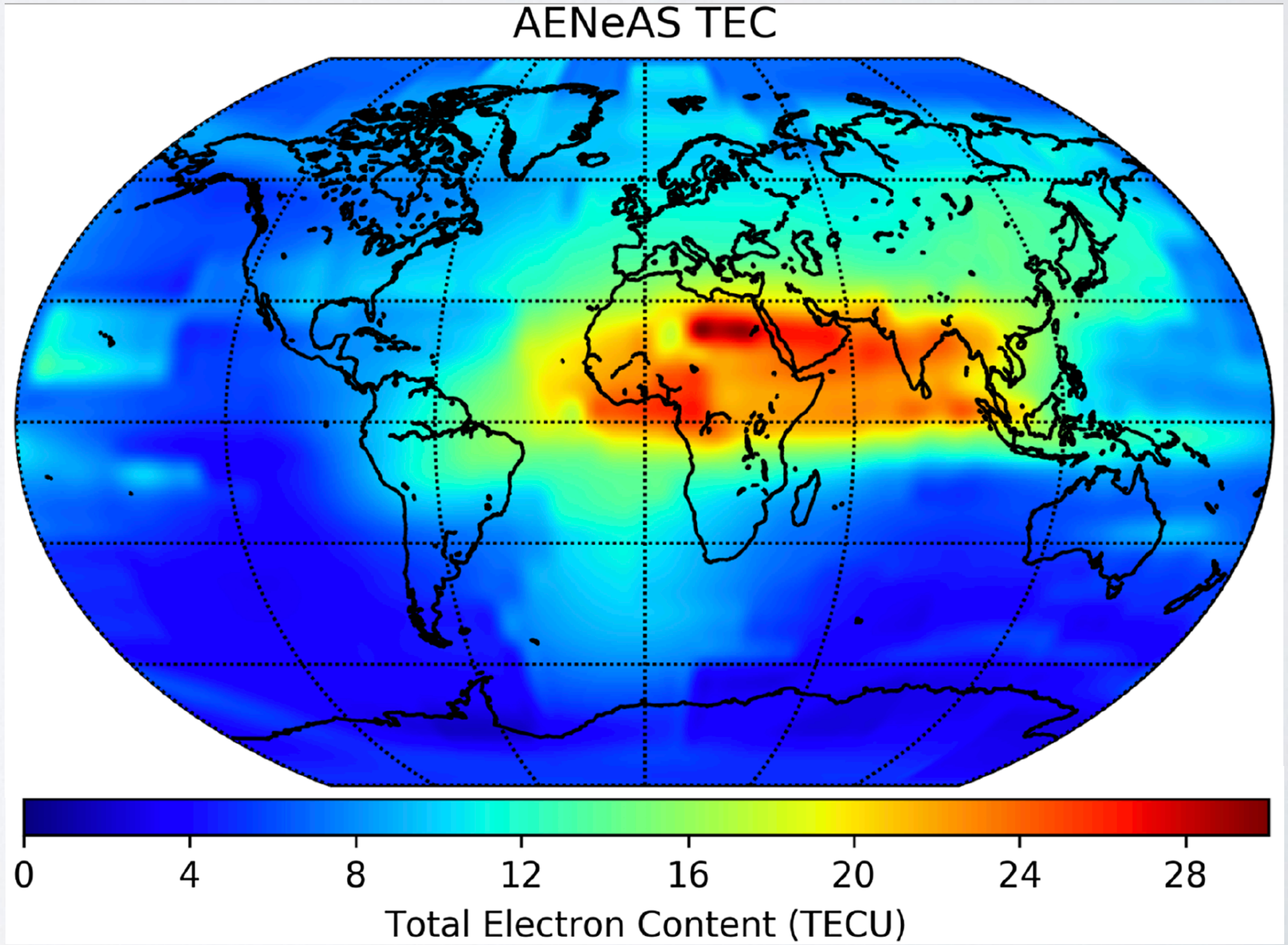
- A similar approach has been used by Brunini et al., [2013] in order to update the ITU-R database using radio occultation (COSMIC) electron density profiles.
- For this purpose the La Plata Ionospheric Model (LPIM) (after linearisation) is adjusted by Least Squares to every RO profile available for the time period of interest.



Global representation of the NmF2 estimated value within the 18–20 UT interval;
a) NmF2 for the 2007 September equinox b) NmF2 for the 2011 December solstice.

AENeAS

- The Advanced Ensemble electron density (Ne) Assimilation System (AENeAS; Elvidge and Angling, 2019) is a physics-based data assimilation model of the ionosphere/thermosphere.
- The background model is the TIE-GCM and the ionospheric data (mainly TEC) are assimilated by using the Local Ensemble Transform Kalman filter (LETKF).
- Since the TIE-GCM only reaches 600 km of height, in order to extend the electron density grids up to 25000 km, AENeAS currently adopts the NeQuick model topside.



AENeAS TEC map for June 5th at 1230 UT after slant TEC DA (from: Elvidge and Angling, 2019).

Use of effective parameters

- In order to incorporate experimental data into ionospheric models, methodologies relying on the use of effective parameters have also been implemented.
- During past years several solar indices have been developed to relate the response of the ionosphere to solar Extreme Ultraviolet (EUV) emissions.
- Indices like sunspot number (SSN), solar radio noise flux at 10.7 cm wavelength (F10.7) or smoothed sunspot numbers (R12) have become standard inputs for many ionosphere electron density models.
- Nevertheless, these solar indices are far from ideal proxies for the solar activity in the EUV part of the solar radiation spectrum.
- The difficulties found when applying these solar-based indices, led to the development of a number of "effective" indices, which are based on the use of models and experimental ionospheric data.
- One of the first effective parameter that has been proposed is the "effective sunspot number" (SSNe).
- More recently, other effective solar indices have been developed utilizing different kinds of models and observations.

Use of effective parameters

- The first works concerning the implementation of effective solar indices by means of electron density models adaptation to TEC data are described in the papers by
  - Komjathy et al. (1998), where IRI is used to infer an IG12 index by using GPS-derived vertical TEC maps;
  - Hernandez-Pajares et al. (2002), where IRI is fitted directly to slant TEC observations by tuning the SSN input.
- An example related to the use of TEC models is given by Center for Orbit Determination in Europe (CODE) of the University of Bern, where Klobuchar-style ionospheric coefficients ("effective" alphas and betas) are computed by fitting the CODE vertical TEC maps with the Klobuchar model.
- An exhaustive historical and critical review of the methodologies using effective solar indices to update climatological ionospheric models is given in Pignalberi et al. (2018).
- Some of these techniques will be considered in the following slides…..

vTEC map data ingestion

At a given epoch

One vTEC map

↓

Minimize the mismodelings

$|vTECexp_i - vTECmod(az)_i|$

↓

Az (effective F10.7) grid

↓

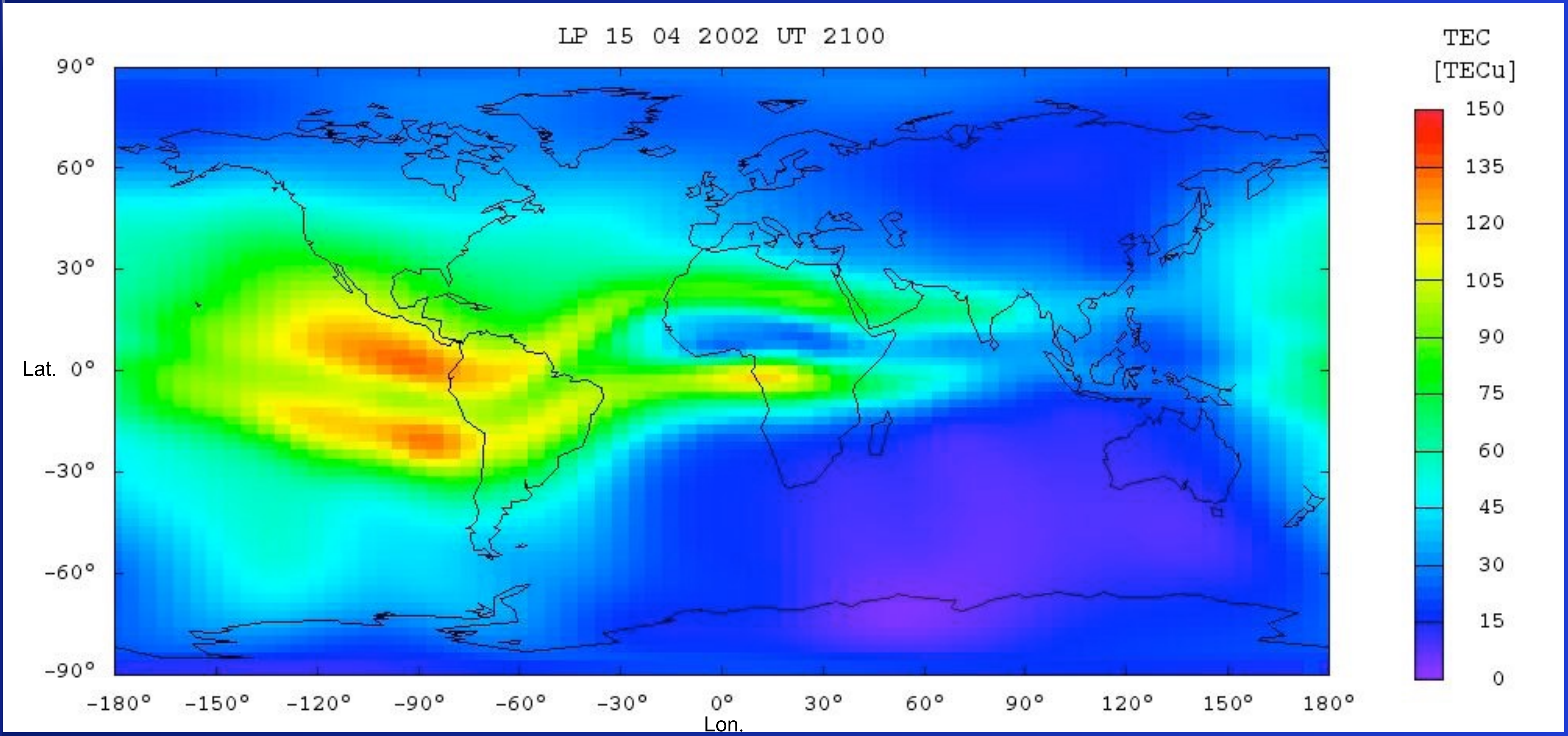
Use NeQuick to reconstruct the 3D electron density of the ionosphere that reproduces the starting vTEC map

↓ ↓

Reconstruct sTEC along any ray-path

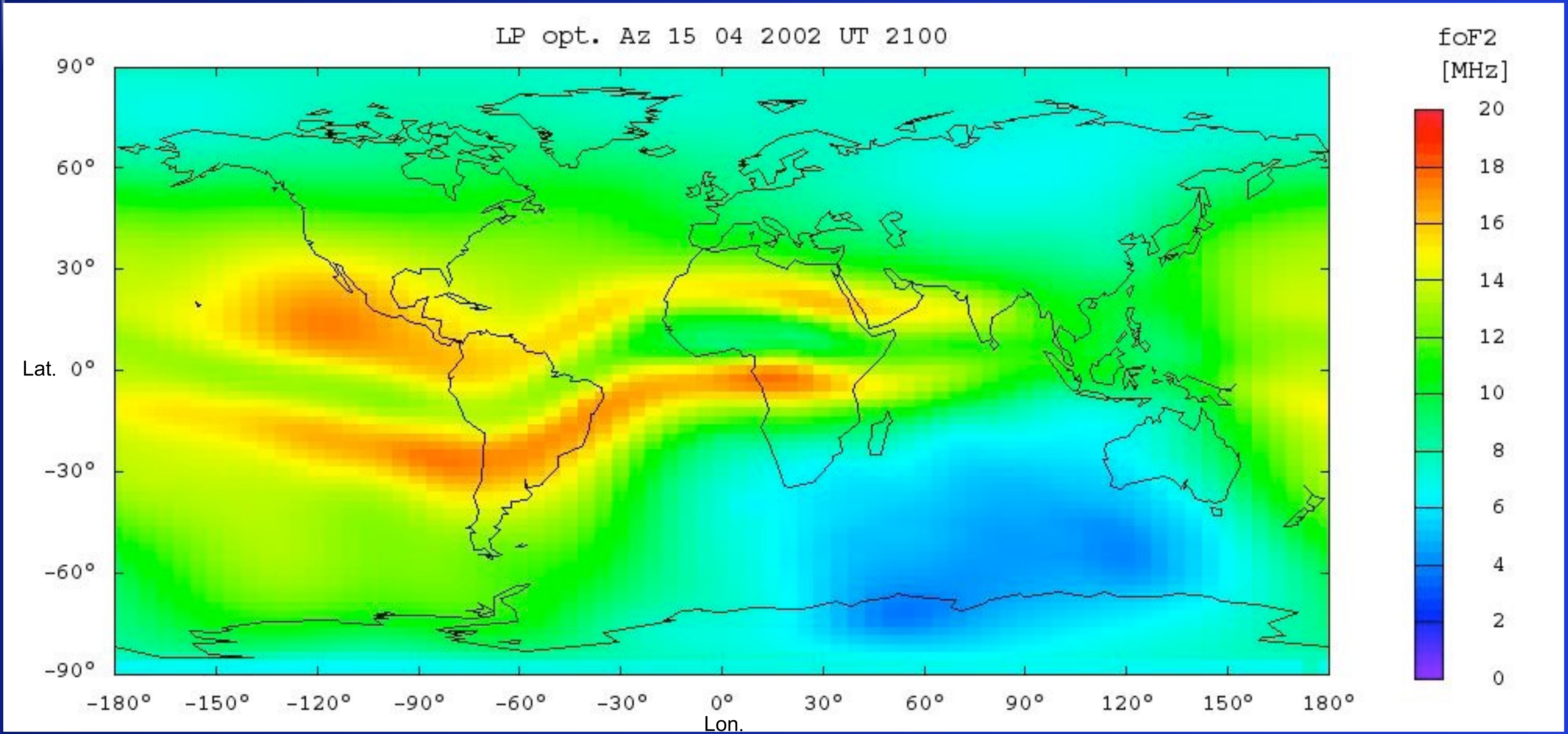
Reconstruct foF2 maps

vTEC map



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

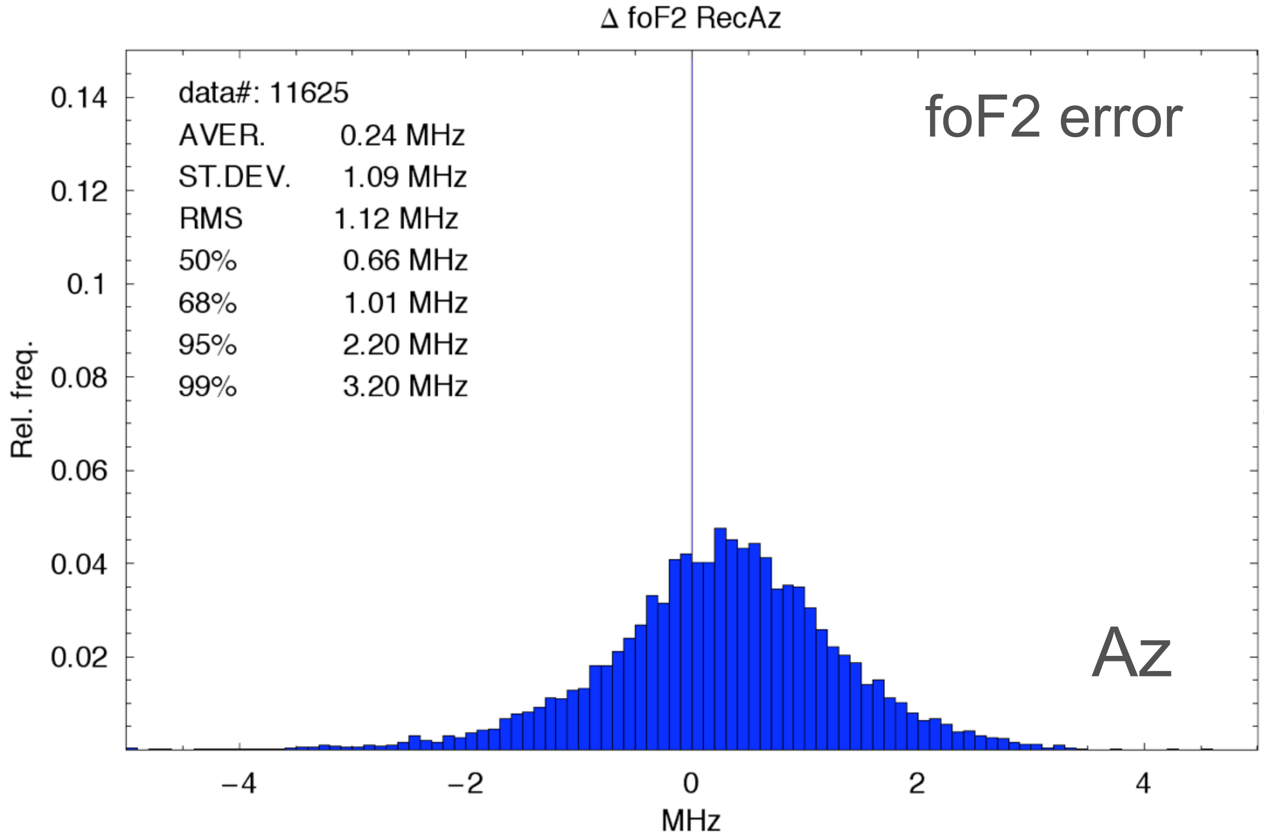
Reconstructed foF2 map



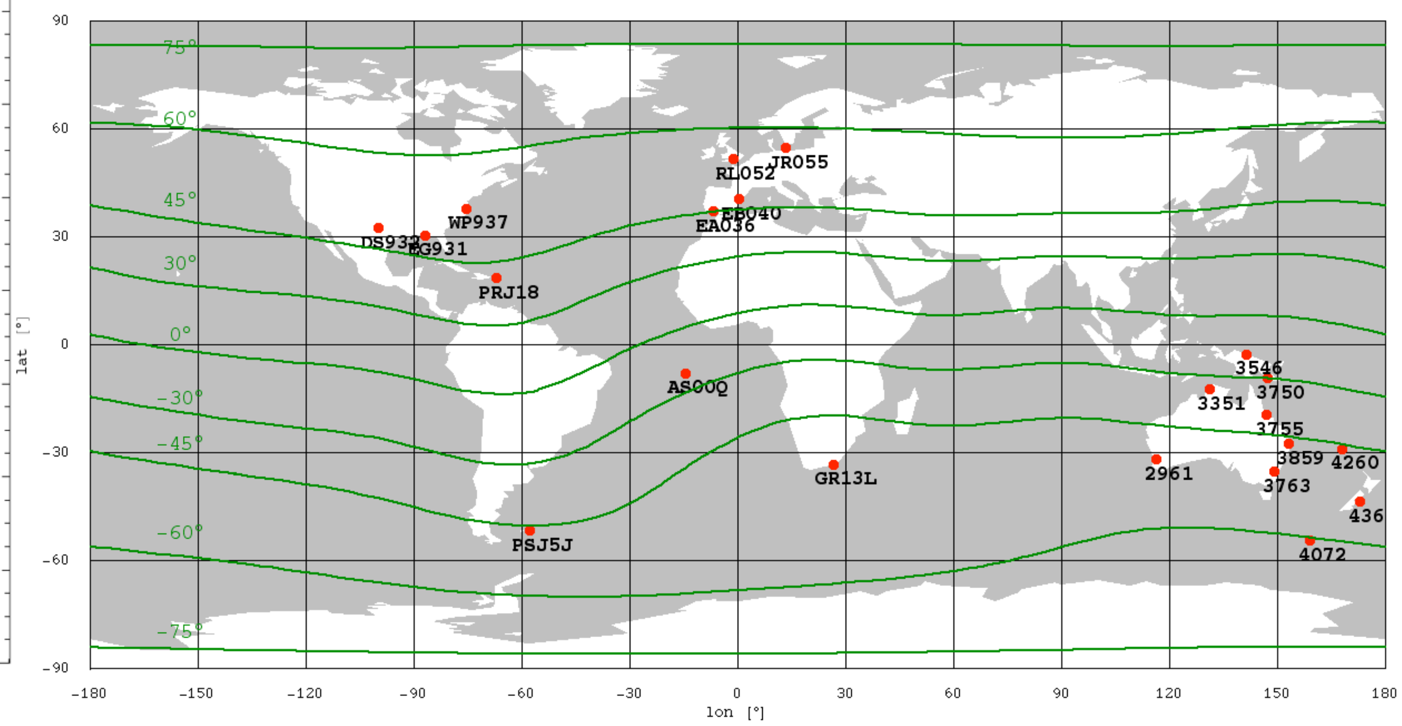
grid points:
lat.=-90°, 90° step 2.5°
lon.=-180°, 180° step 5°

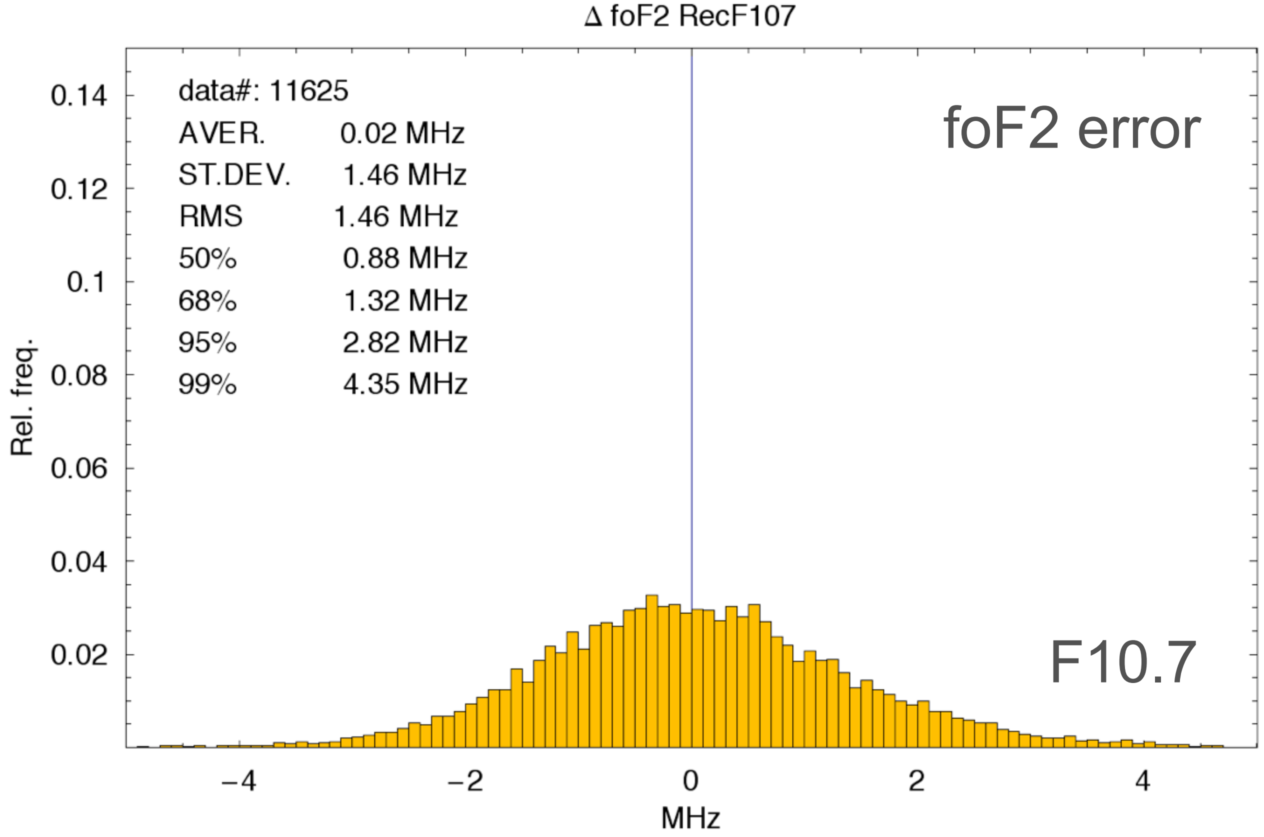
Vertical TEC map data ingestion

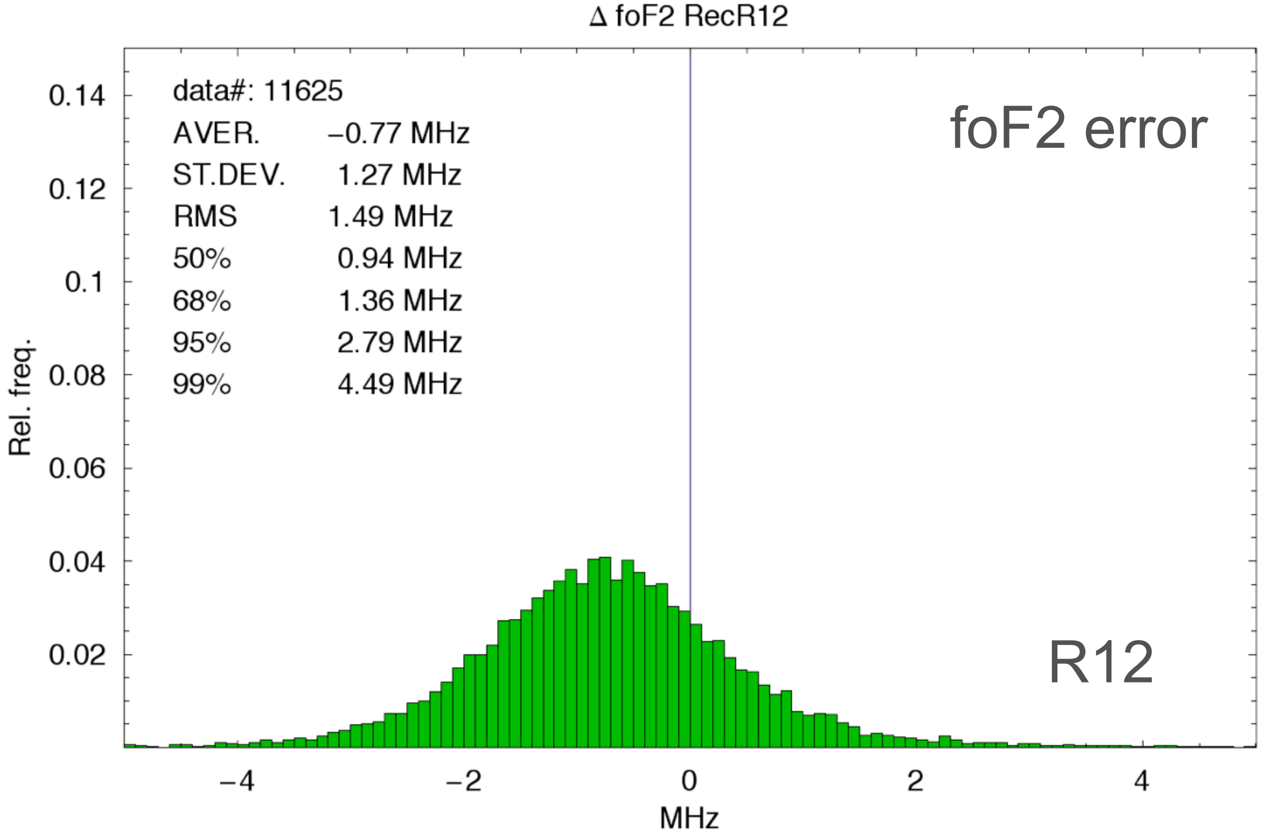
High Solar Activity



vTEC map data ingestion; Apr. 2000 (HSA)



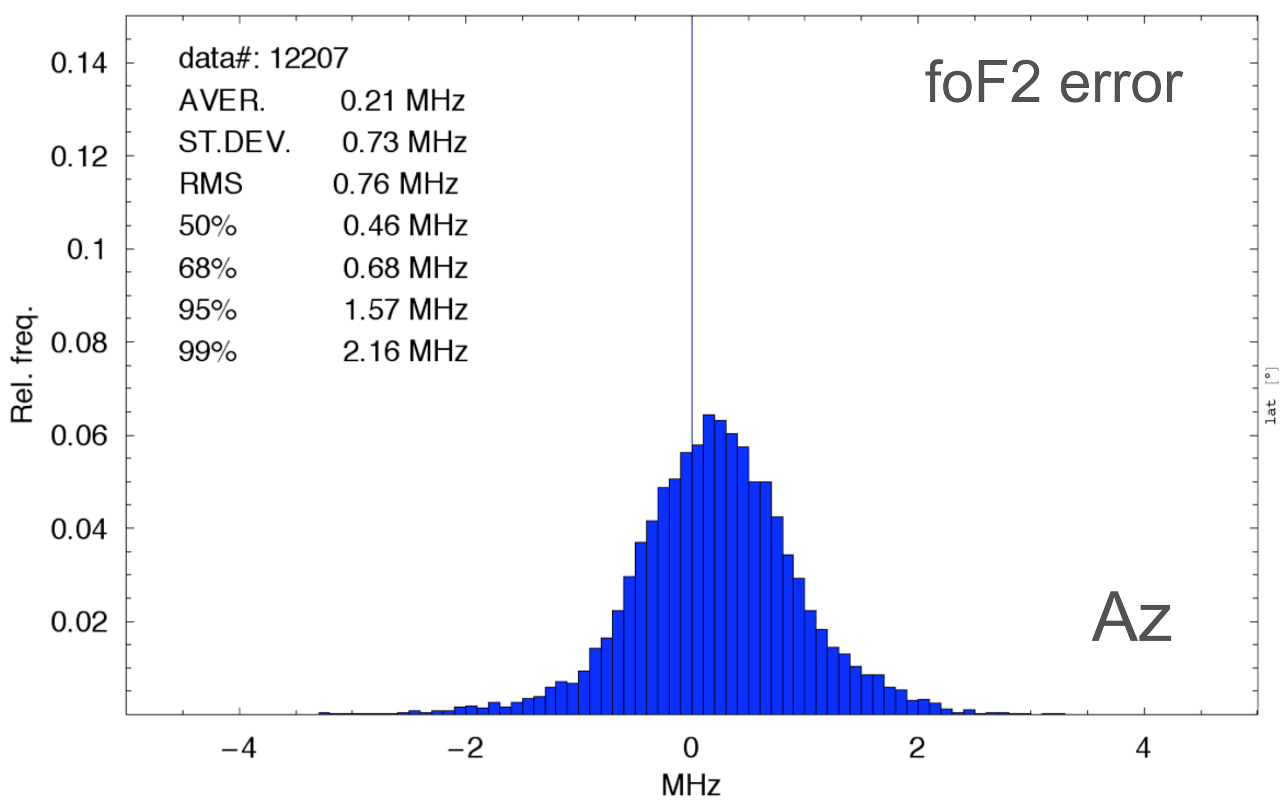




Vertical TEC map data ingestion

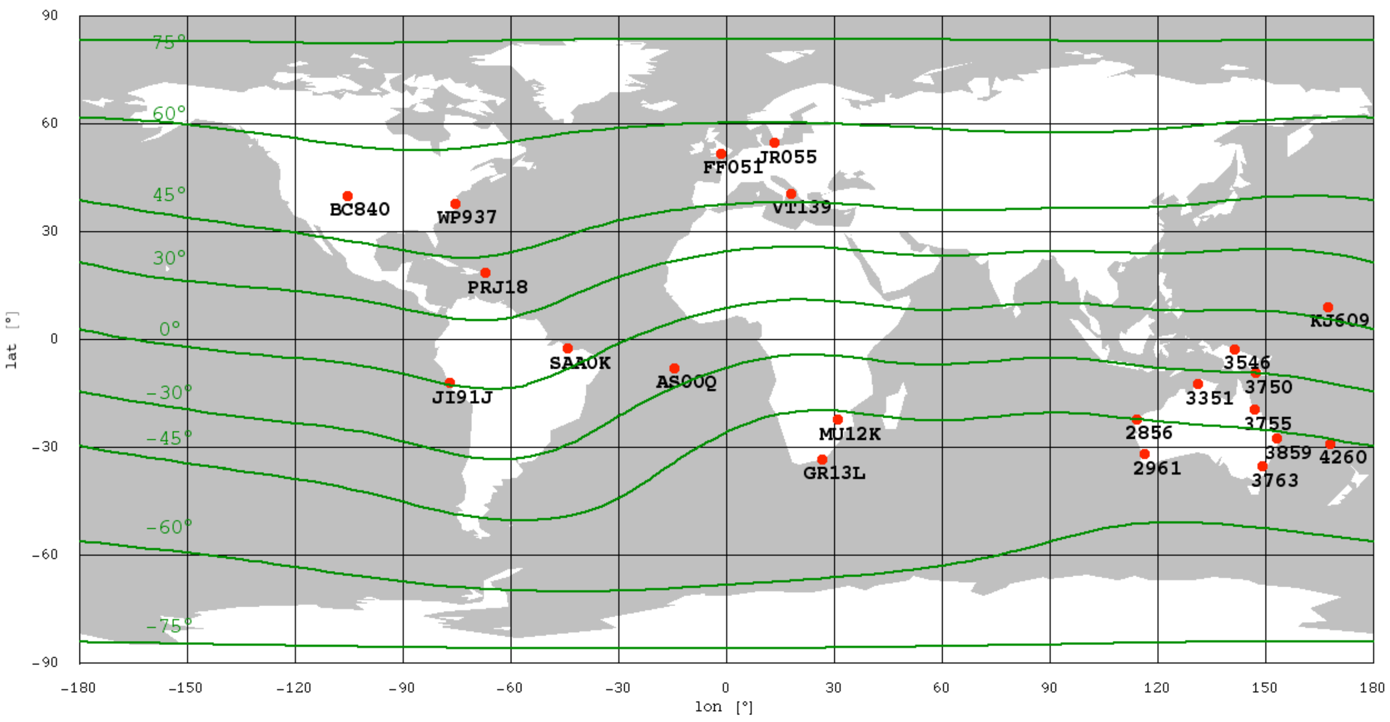
Low Solar Activity

Δ foF2 RecAz

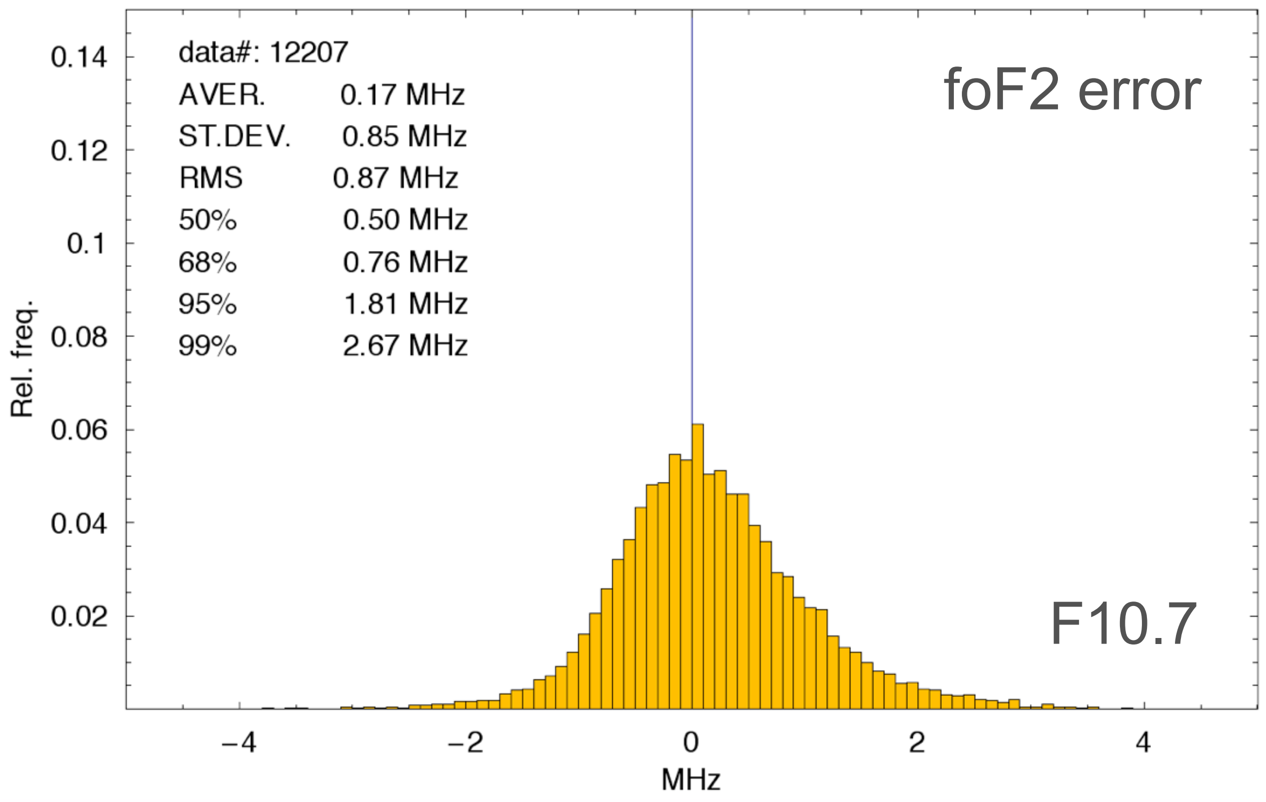


data#:	12207
AVER.	0.21 MHz
ST.DEV.	0.73 MHz
RMS	0.76 MHz
50%	0.46 MHz
68%	0.68 MHz
95%	1.57 MHz
99%	2.16 MHz

vTEC map data ingestion; Sep. 2006 (LSA)

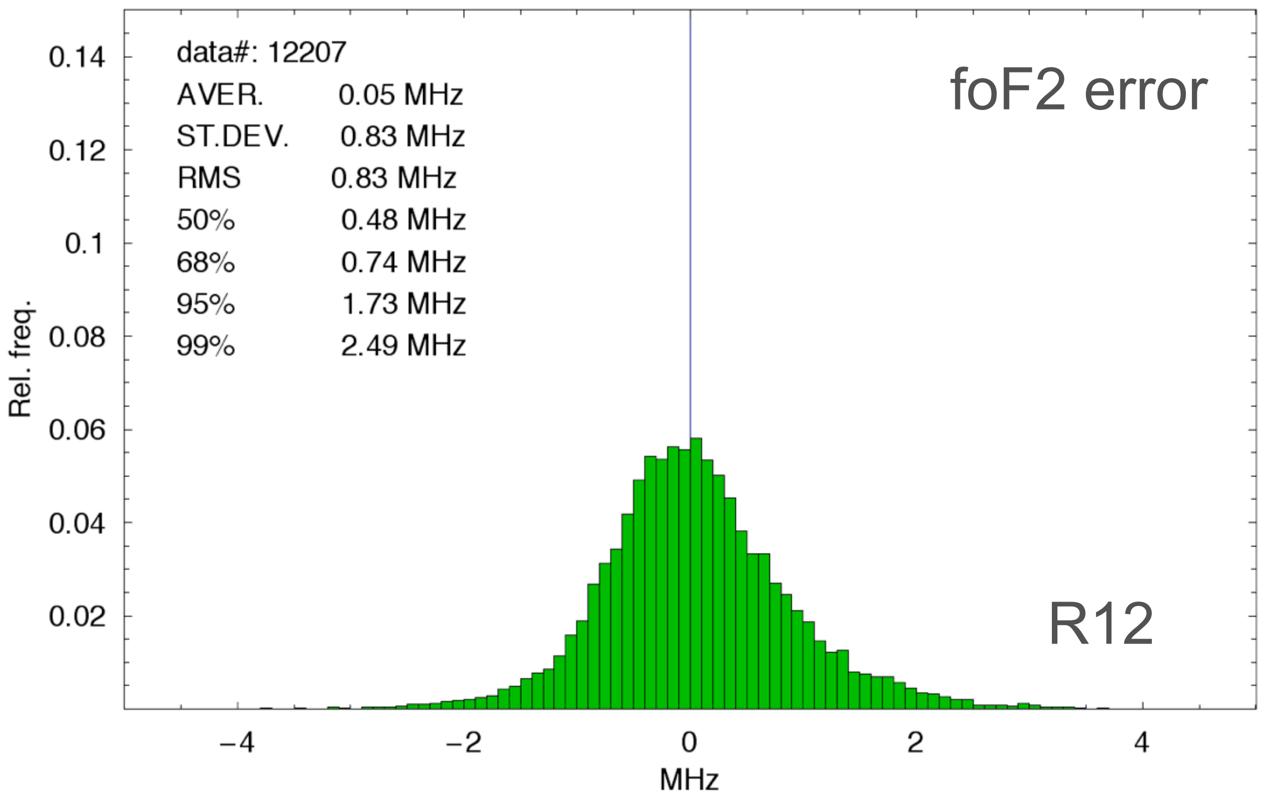


Δ foF2 RecF107



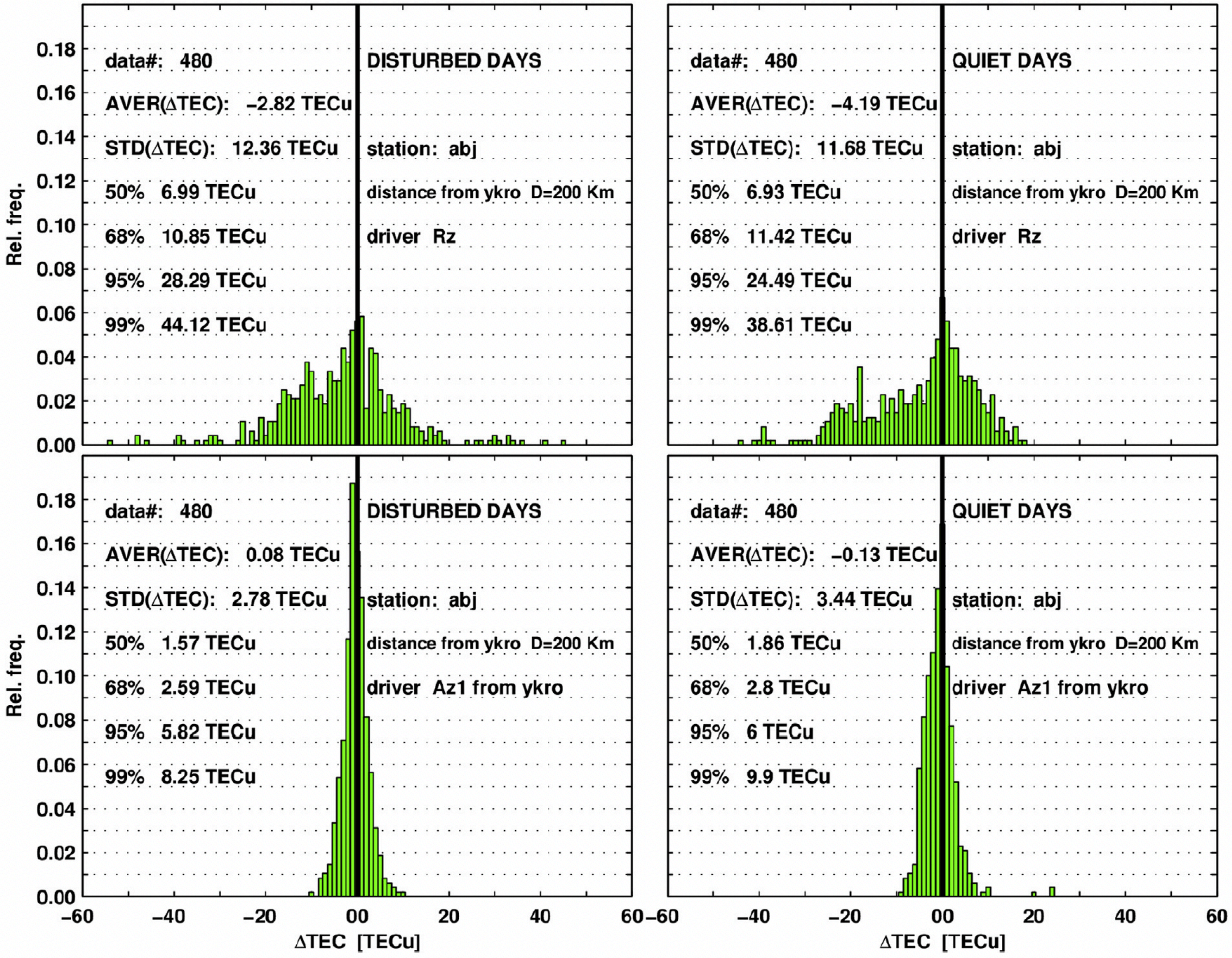
data#:	12207
AVER.	0.17 MHz
ST.DEV.	0.85 MHz
RMS	0.87 MHz
50%	0.50 MHz
68%	0.76 MHz
95%	1.81 MHz
99%	2.67 MHz

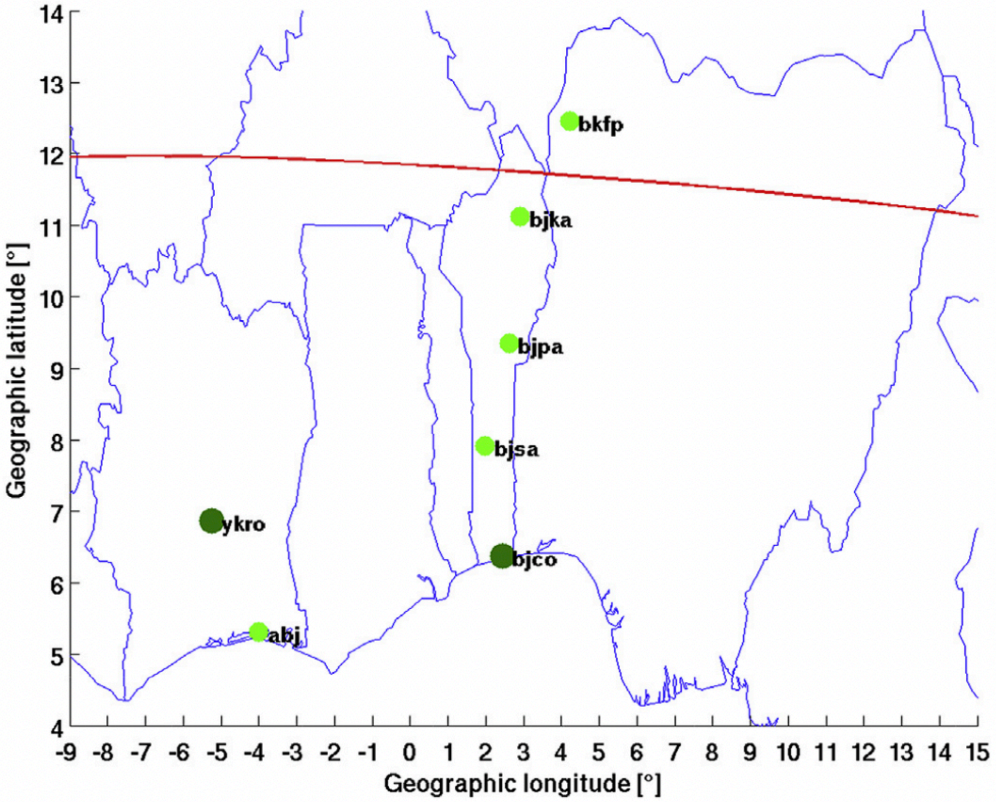
Δ foF2 RecR12



data#:	12207
AVER.	0.05 MHz
ST.DEV.	0.83 MHz
RMS	0.83 MHz
50%	0.48 MHz
68%	0.74 MHz
95%	1.73 MHz
99%	2.49 MHz

vTEC ingestion; geomagnetically disturbed period

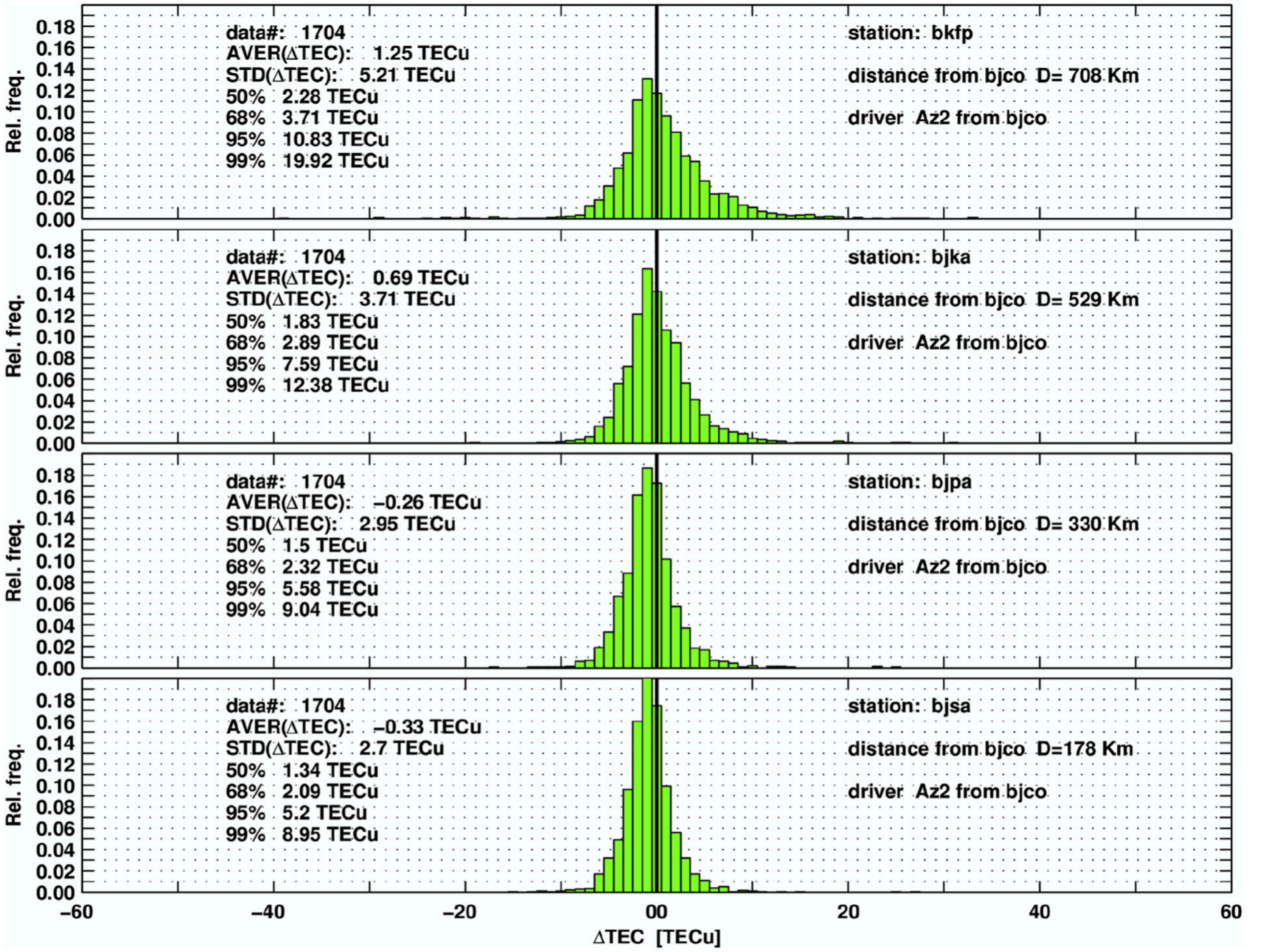


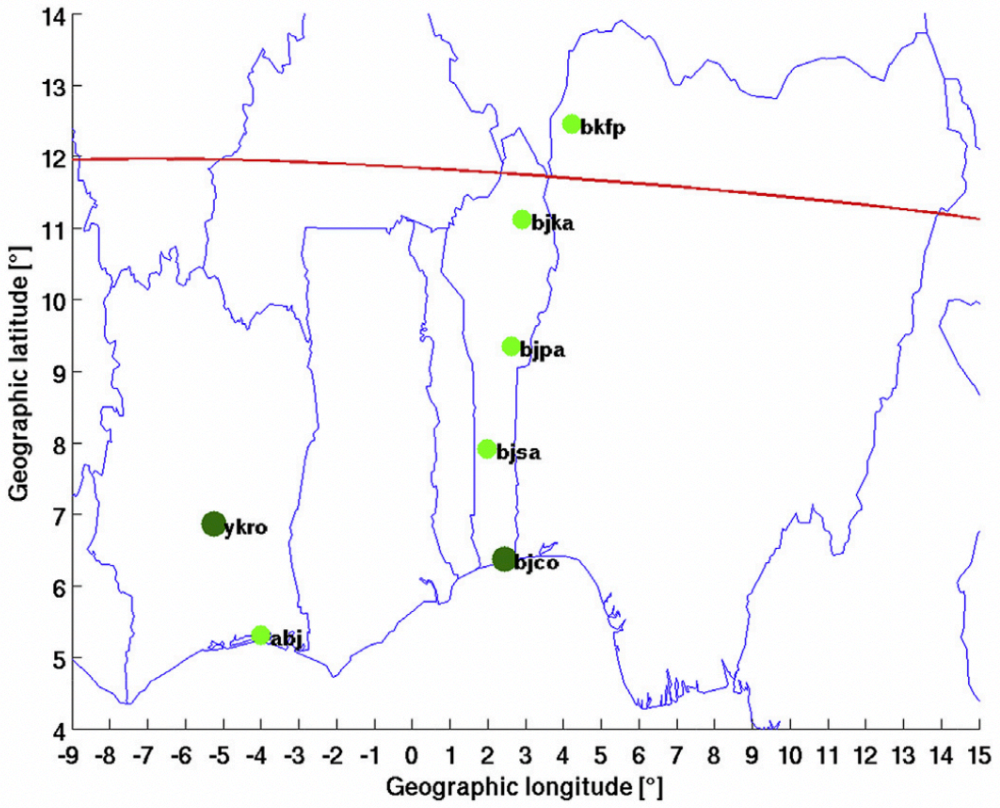


Yao et al., 2018

Distribution of the differences between modeled and experimental vertical TEC during geomagnetically disturbed days (left) and quiet days (right) in 2015 at abj station. NeQuick 2 is driven by the daily sunspot number Rz (top) and the effective solar flux Az1 as inferred from ykro data (bottom).

vTEC ingestion; correlation with distance

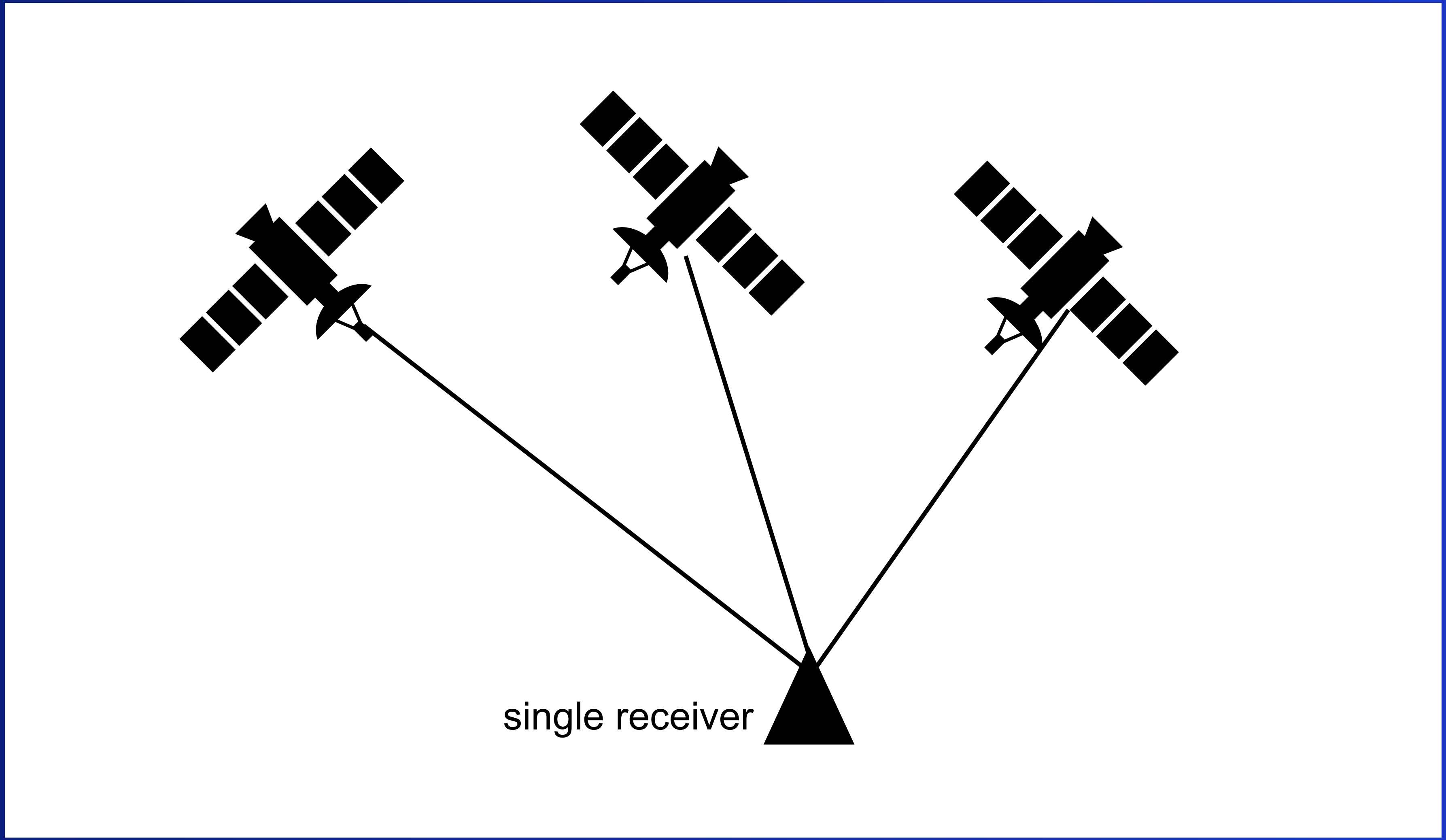




Yao et al., 2018

Distribution of the differences between modelled and corresponding experimental vertical TEC when NeQuick 2 is driven by the effective solar flux Az2 as inferred from *bjco* data during the years 2014-2015.

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



sTEC data ingestion, single stat.

At a given epoch

One station, n experimental sTEC (n satellites)

↓

Minimize RMS of the TEC mismodelings
as a function of (formally) F10.7

↓

Az (effective F10.7) at the station, for the given epoch

↓

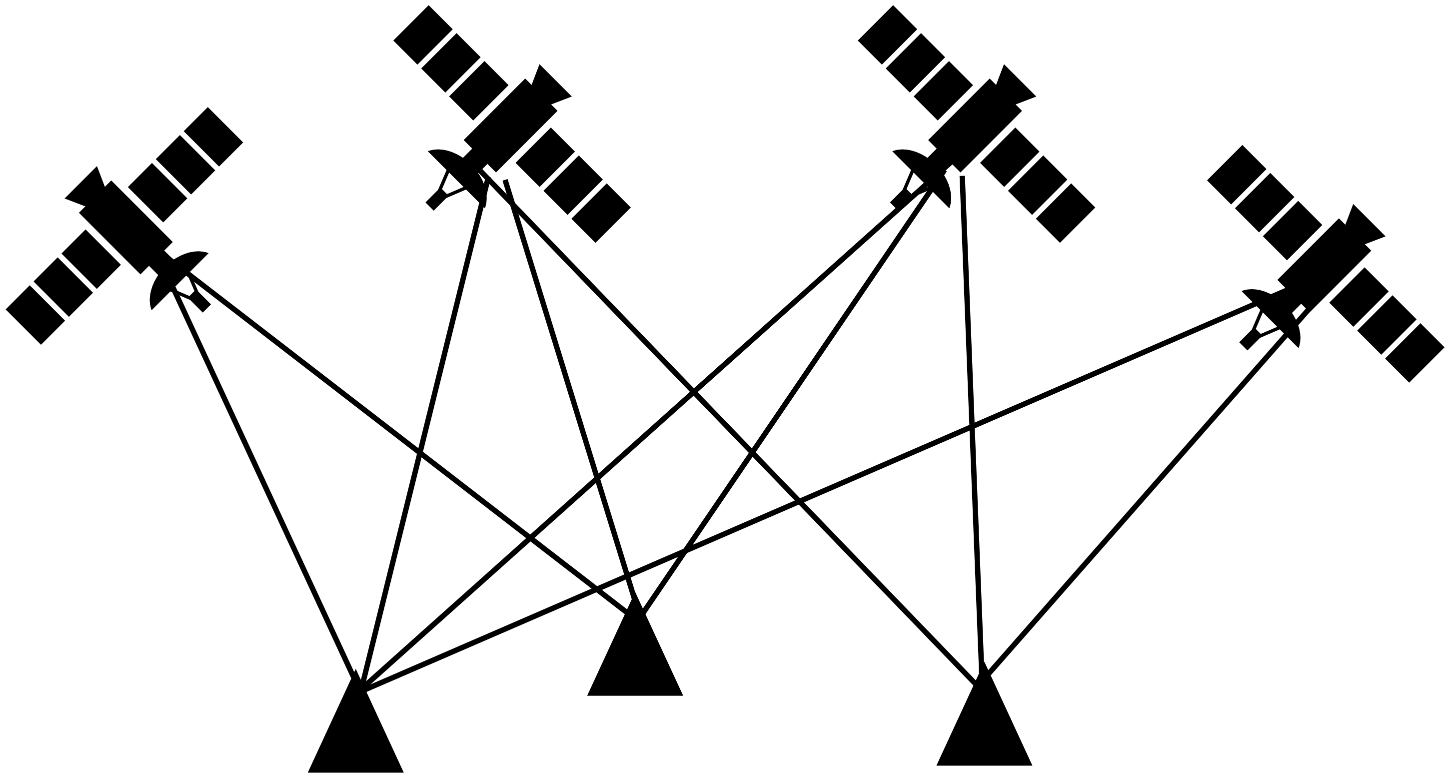
Use NeQuick to retrieve (locally) the 3D
electron density of the ionosphere

↓ ↓

Reconstruct TEC along any
Station-to-satellite ray-path

Retrieve the foF2 values
at the Station

Adapting NeQuick model to experimental slant TEC data at several locations



multiple receivers (Az grid)

sTEC data ingestion, multi stat.

At a given epoch

m sTECexp (several stations & satellites)

↓

Minimize each mismodeling

$|sTECexp_i - sTECmod(az)_i|$

↓

Scattered Az_i → Interpolate to get regularly spaced grid

↓

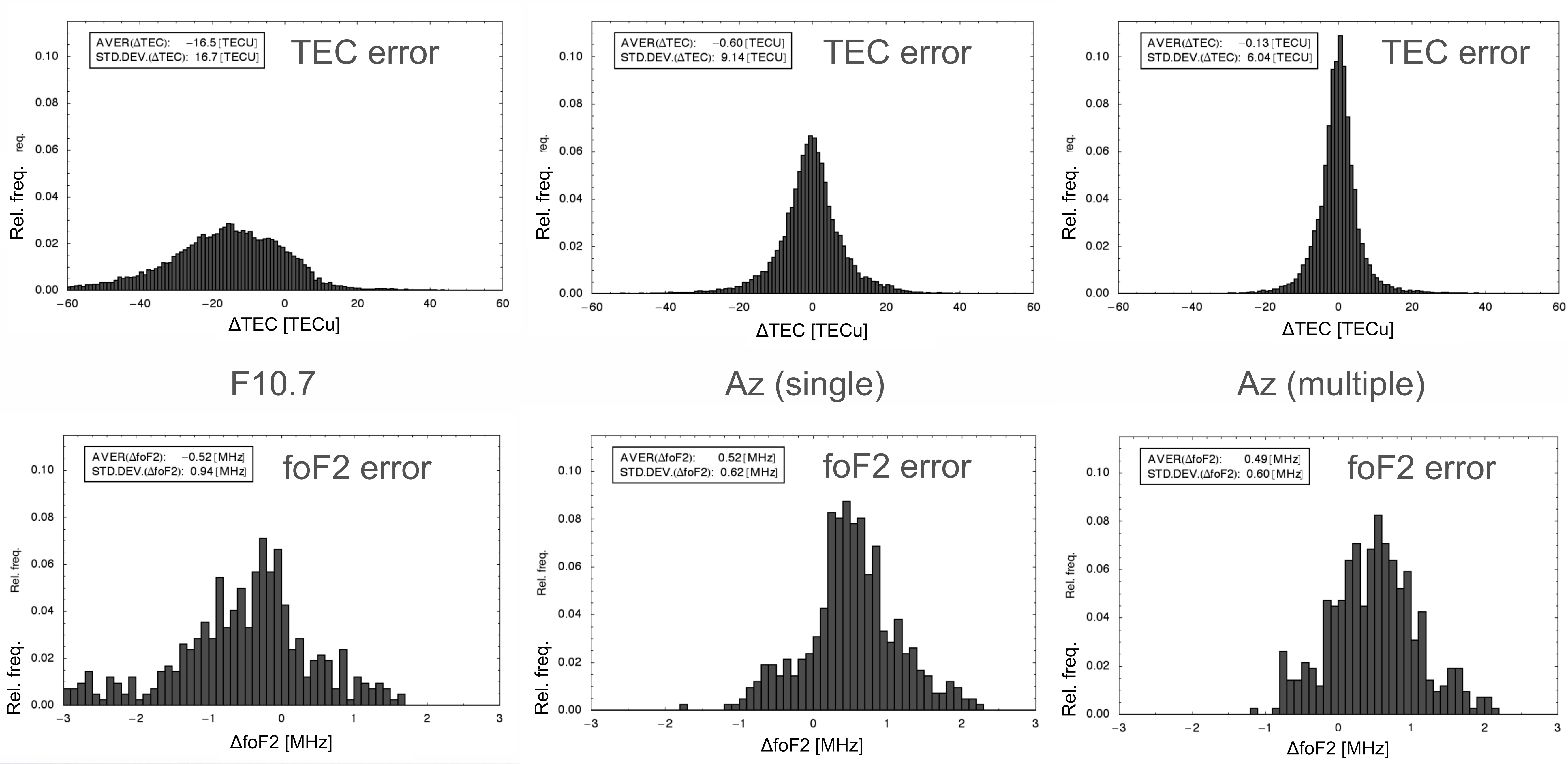
Use NeQuick to reconstruct the 3D electron density of the ionosphere

↓ ↓

Reconstruct TEC along any given ray-path

Reconstruct any foF2 value (foF2 map)

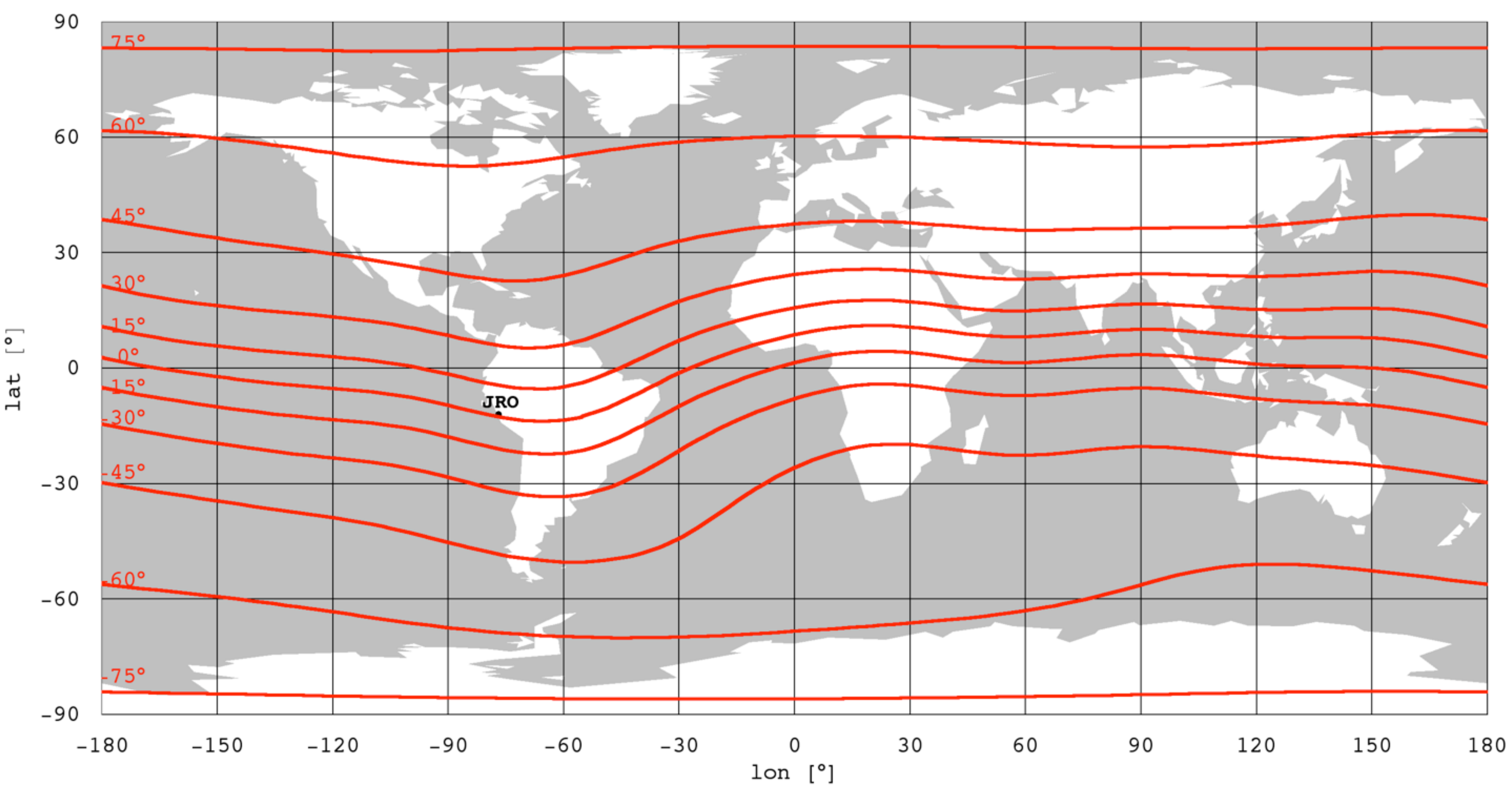
Slant TEC data ingestion



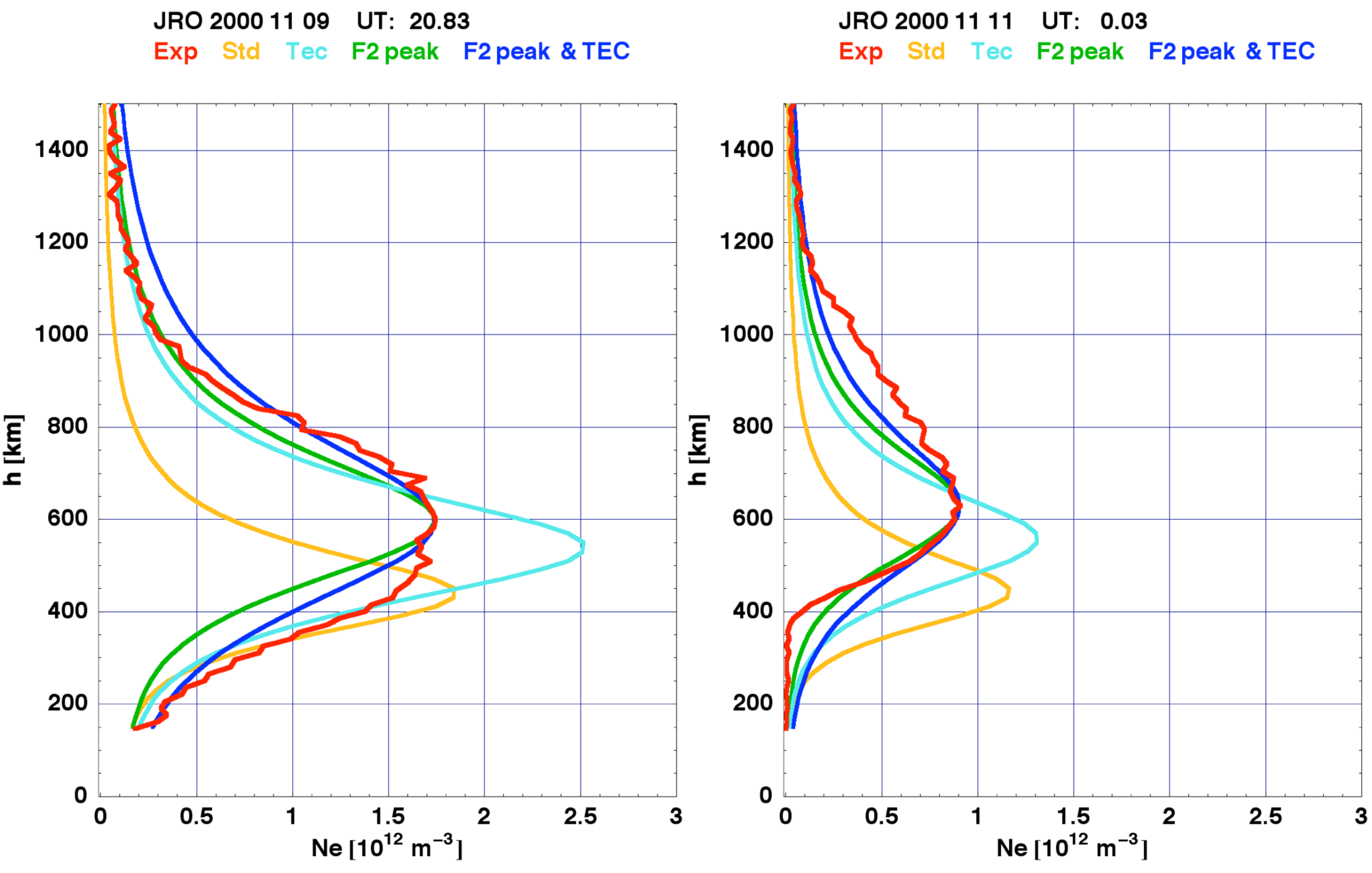
Distribution of the differences between modeled and experimental slant TEC data for 25 ground stations (top panels) and between modeled and experimental foF2 data for six ionosondes (bottom panels) when NeQuick is driven by F10.7 (first column), Az computed using the single (second column) and multiple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

Adapting NeQuick model to experimental slant TEC and foF2 data at a given location

(Use of slab thickness to constrain the NeQuick profile shape parameter)

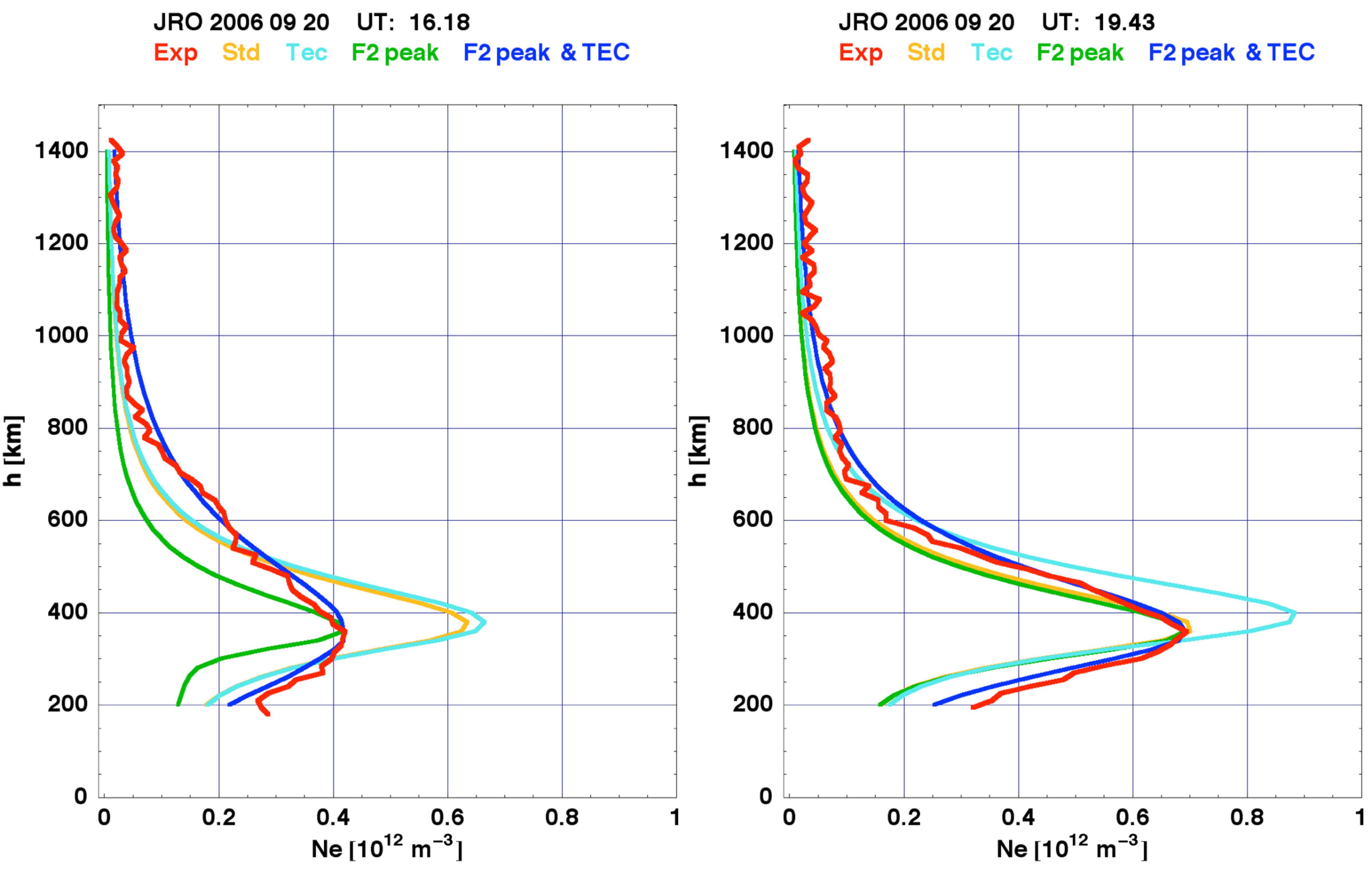


Adaptation method validation



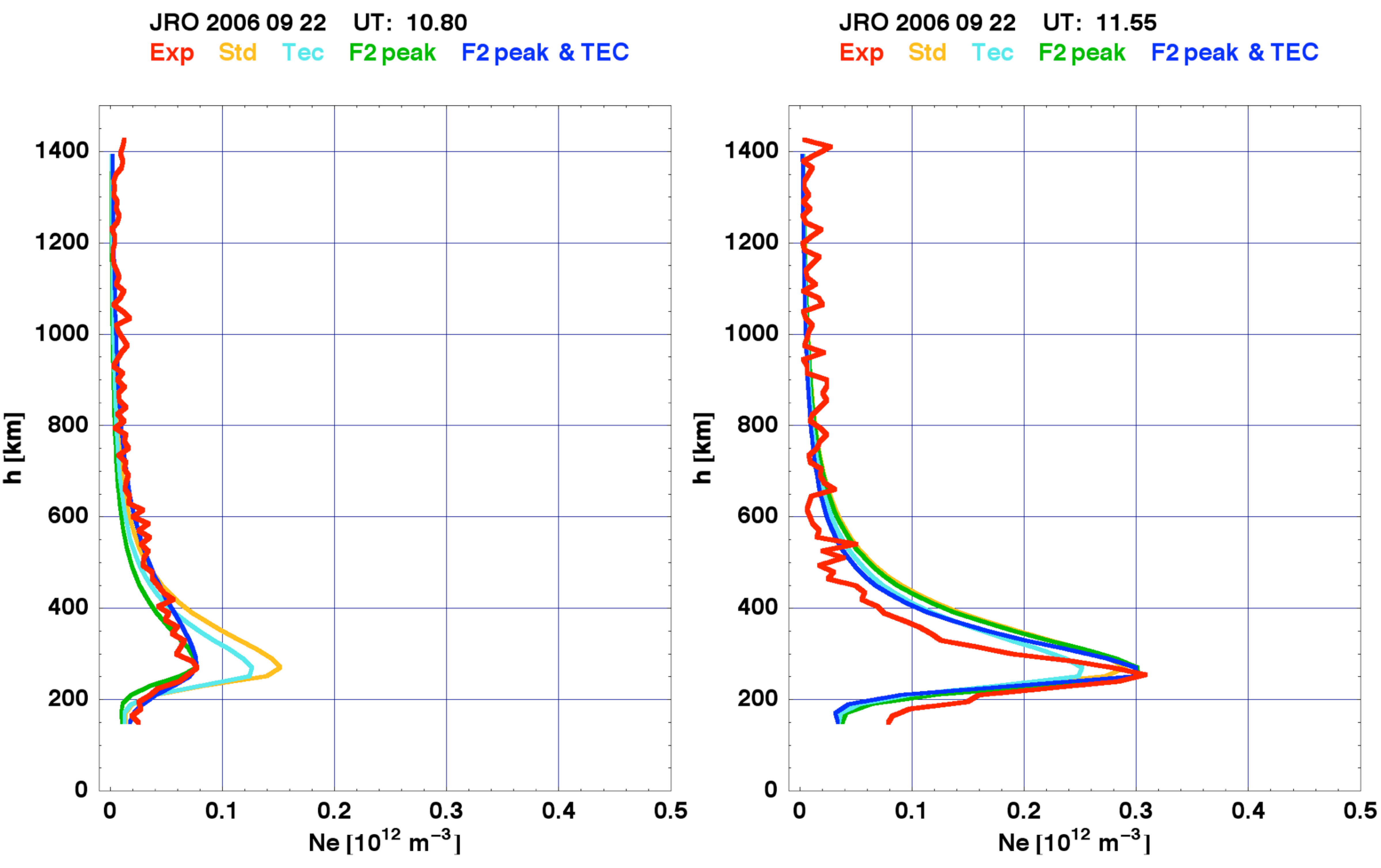
Model: NeQuick

Adaptation method validation



Model: NeQuick

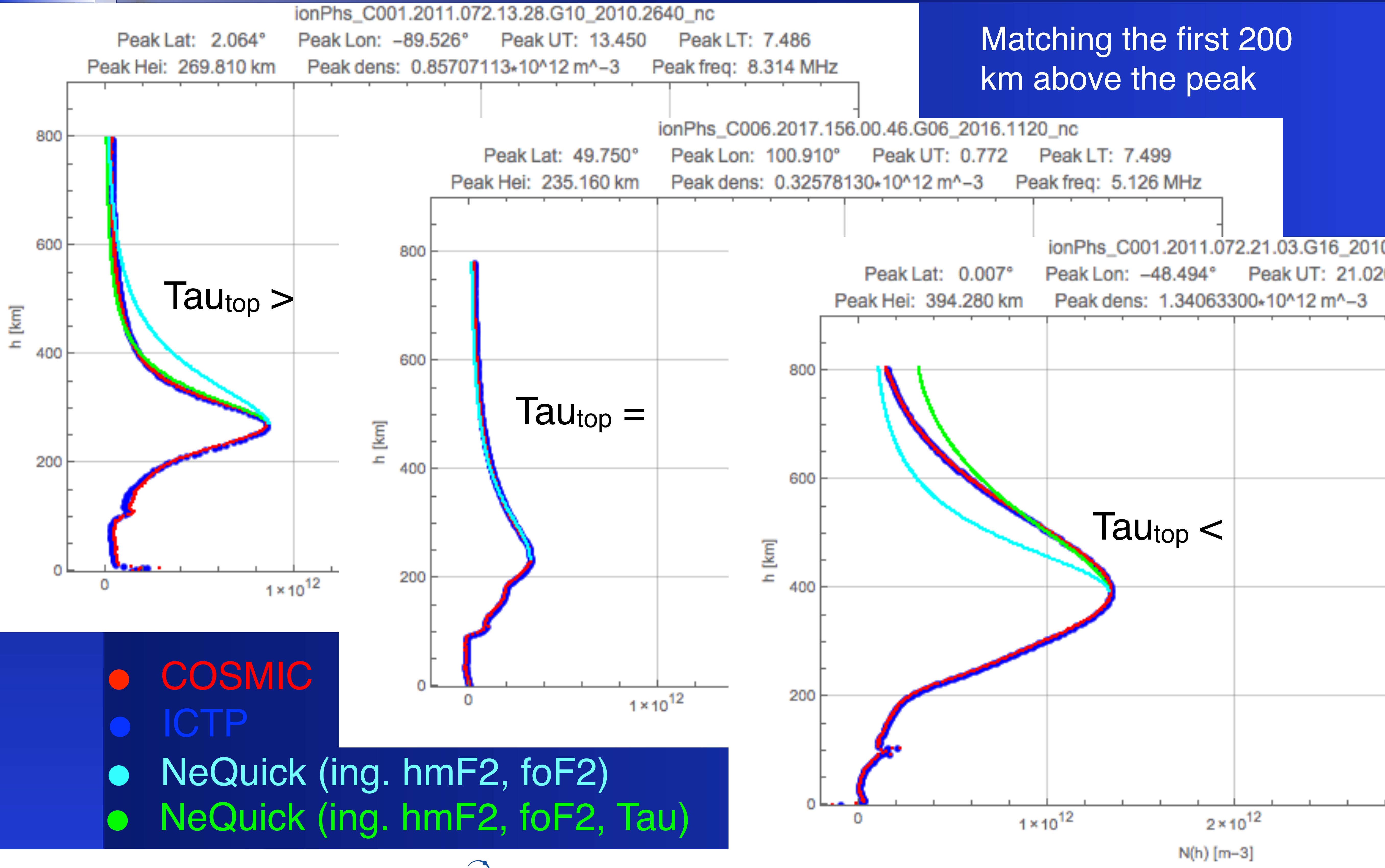
Adaptation method validation



Model: NeQuick

NeQuick adaptation to foF2, hmF2 (and Tau$_{top}$)

Matching the first 200 km above the peak



- 🟥 COSMIC
- 🟦 ICTP
- ● NeQuick (ing. hmF2, foF2)
- ● NeQuick (ing. hmF2, foF2, Tau)

Least Square Estimation

Least Square Estimation

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 $\boldsymbol{\varepsilon}_o=(\mathbf{y}-\boldsymbol{H}[\boldsymbol{x}_t])$ (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

Least Square Estimation

- The following hypotheses are assumed:
    - *Linearized observation operator*: the variations of the observation operator in the vicinity of the background state are linear.
    - *Non-trivial errors*: B and R are positive definite matrices.
    - *Unbiased errors*: the expectation of the background and observation errors is zero.
    - *Uncorrelated errors*: observation and background errors are mutually uncorrelated.
    - *Linear analysis*: we look for an analysis defined by corrections to the background which depend linearly on background observation departures.
    - *Optimal analysis*: we look for an analysis state which is as close as possible to the true state in an r.m.s. sense (i.e. it is a minimum variance estimate).

Least Square Estimation

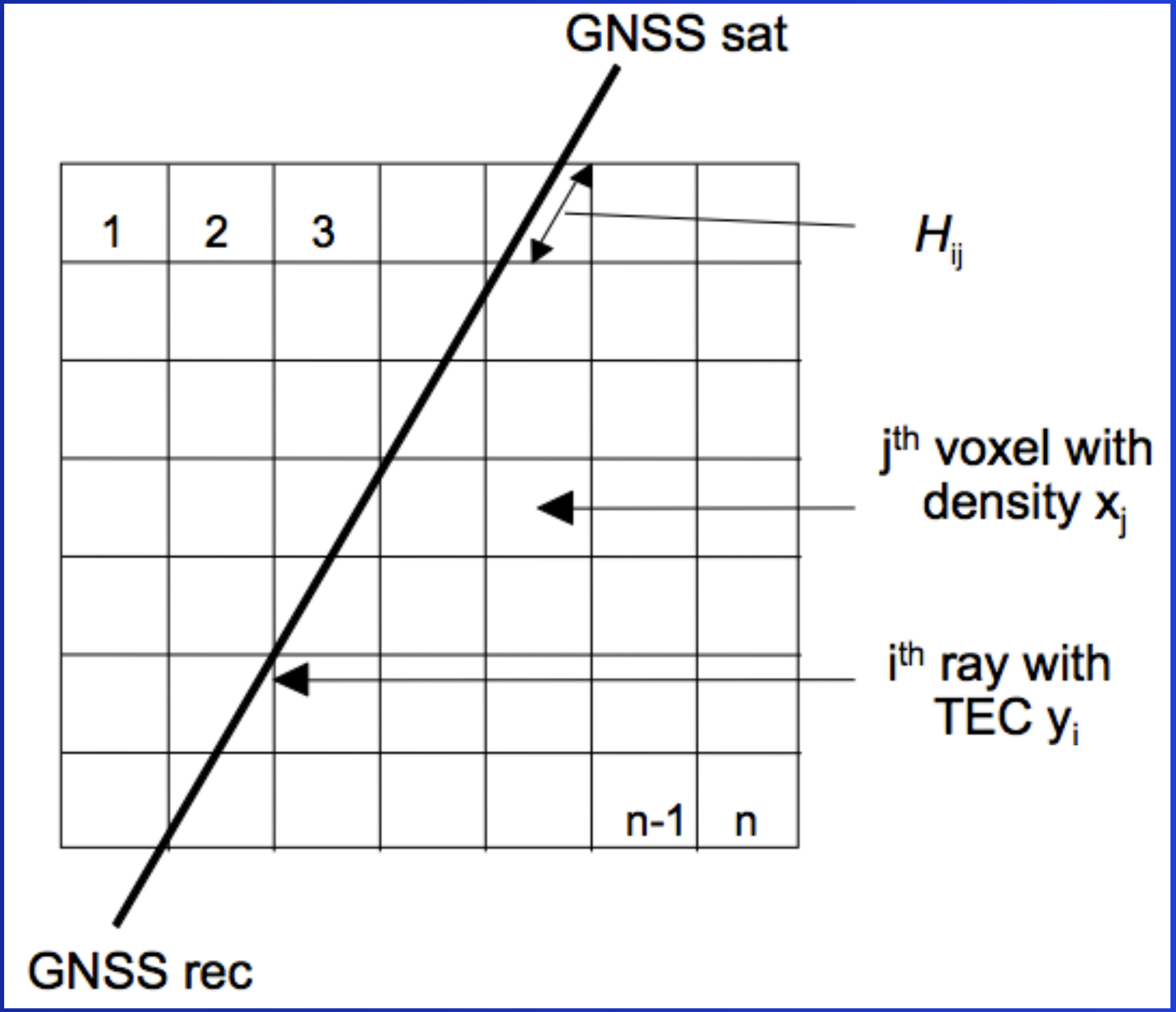
The optimal least-square estimator (BLUE analysis) is defined by

$$\mathbf{x_a} = \mathbf{x_b} + \mathbf{K}\,(\mathbf{y} - \mathbf{H}\mathbf{x_b})$$

$$\mathbf{K} = \mathbf{B}\mathbf{H}^T(\mathbf{H}\mathbf{B}\mathbf{H}^T + \mathbf{R})^{-1}$$

$$\mathbf{A} = (\mathbf{I}-\mathbf{K}\mathbf{H})\mathbf{B}$$

K is called *gain* of the analysis



In our case:

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

e.g. bckg_TEC = $\mathbf{H}\mathbf{x_b} = \sum_j H_{ij}\, x_{bj}$

Least Square Estimation

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

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

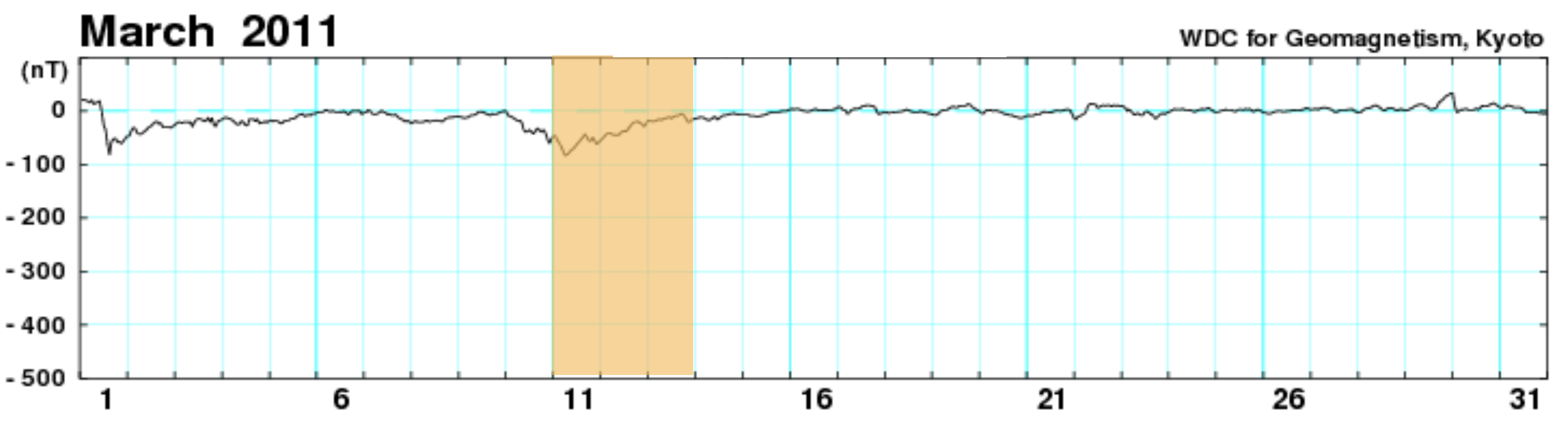
z_{ij} ~ height difference between voxels i and j
α_{ij} ~ angular (great circle) distance between voxels i and j

Lz ~ correl. distance in vert. direction (may depend on height)
$L\alpha$ ~ correl. (angular) distance in hor. direction (may depend location,…)

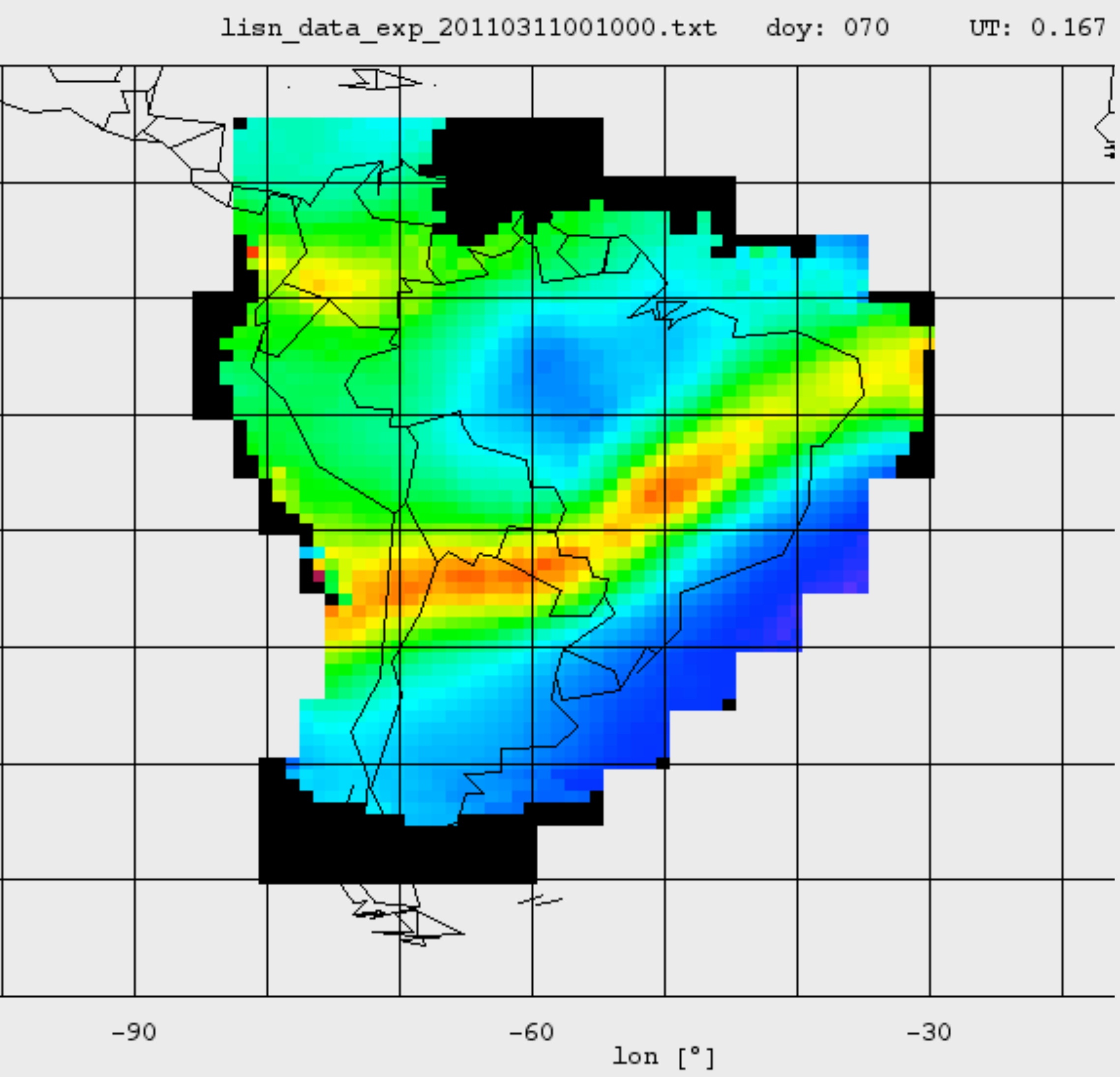
GNSS TEC DA - Example 1

- For the assimilation
  - Calibrated ground-based GNSS-derived slant TEC data from about 150 receivers of the LISN network (C. Valladares), located in the South American region.

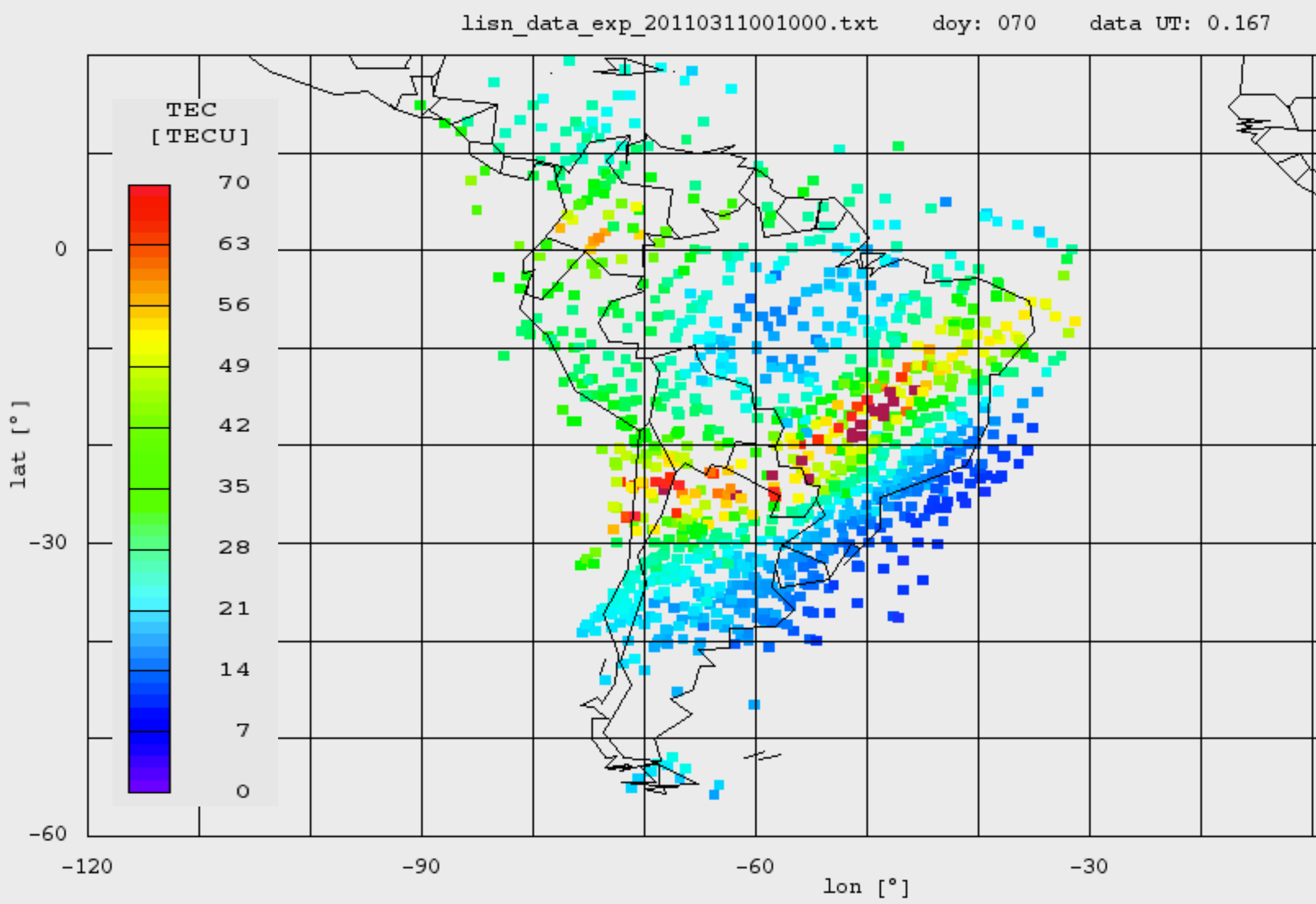
- The data correspond the period 11-13 March 2011



LISN: 3 days data (2011/03/11-12-13)

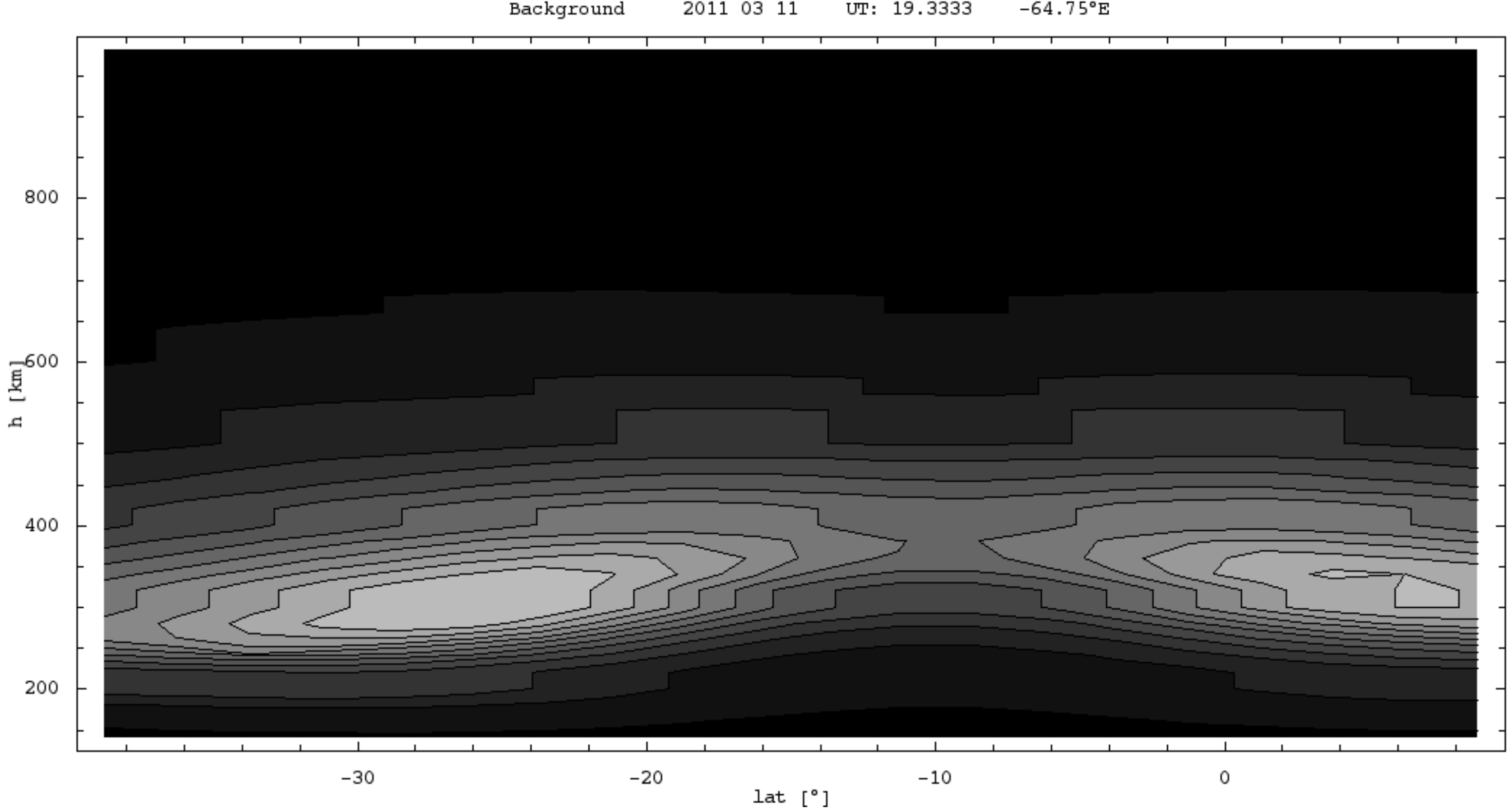


Equivalent vertical TEC
(LS adjustment)



Equivalent vertical TEC
at the pierce points

Assimilation effect

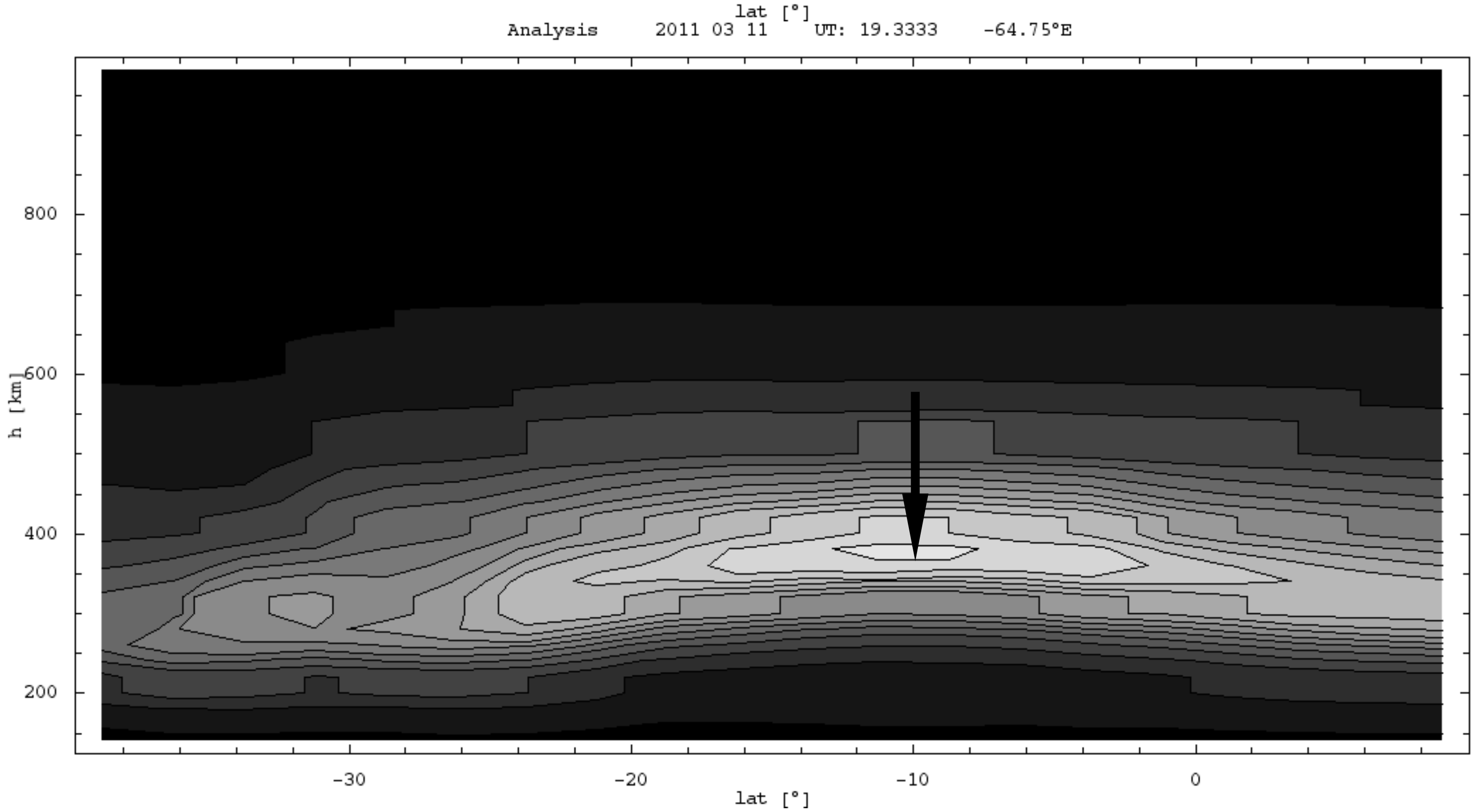


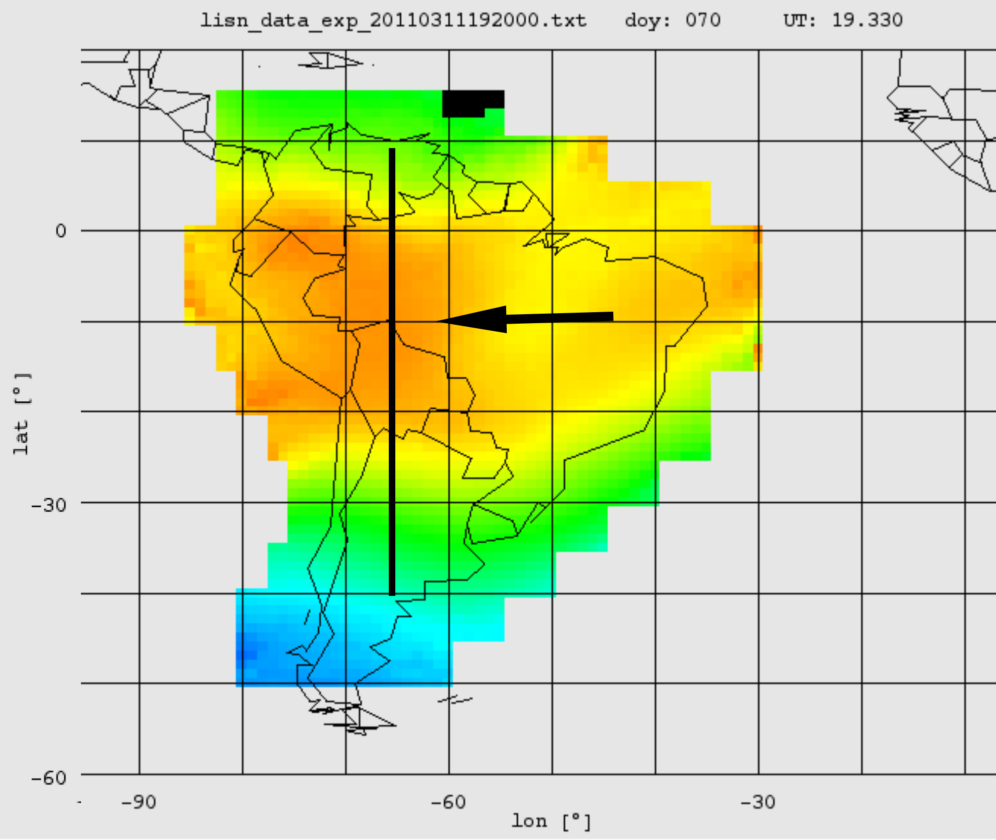
Background model

Cross section

19:33UT; -64.75°E
from -40°N to 10°N

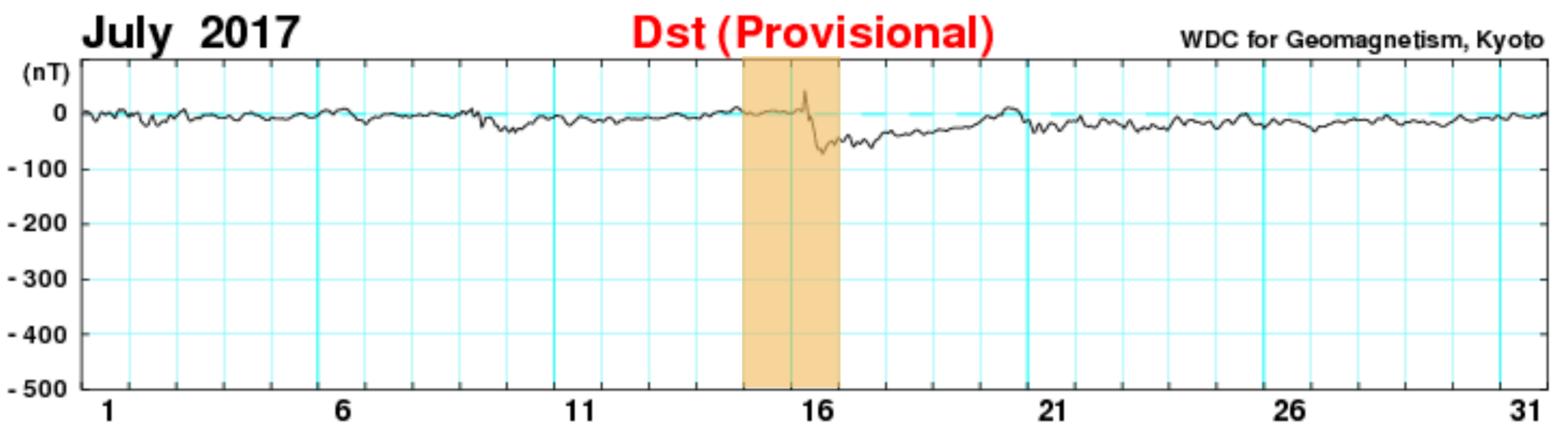
Analysis



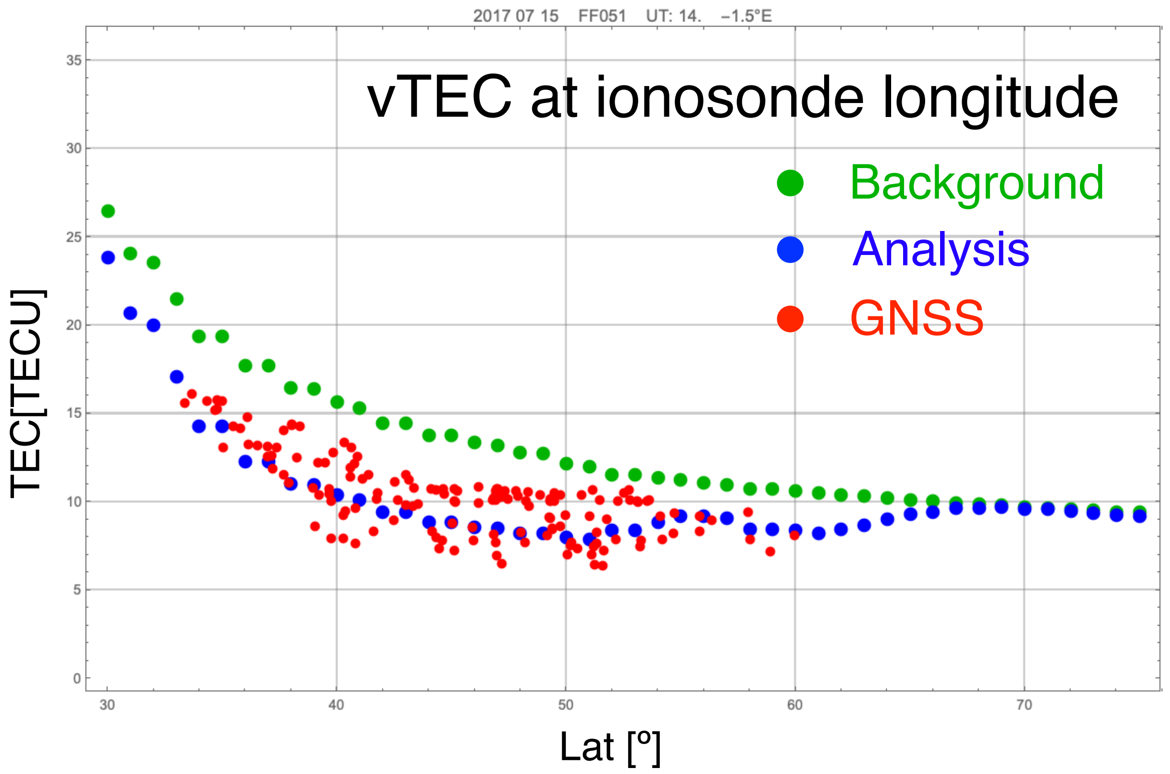


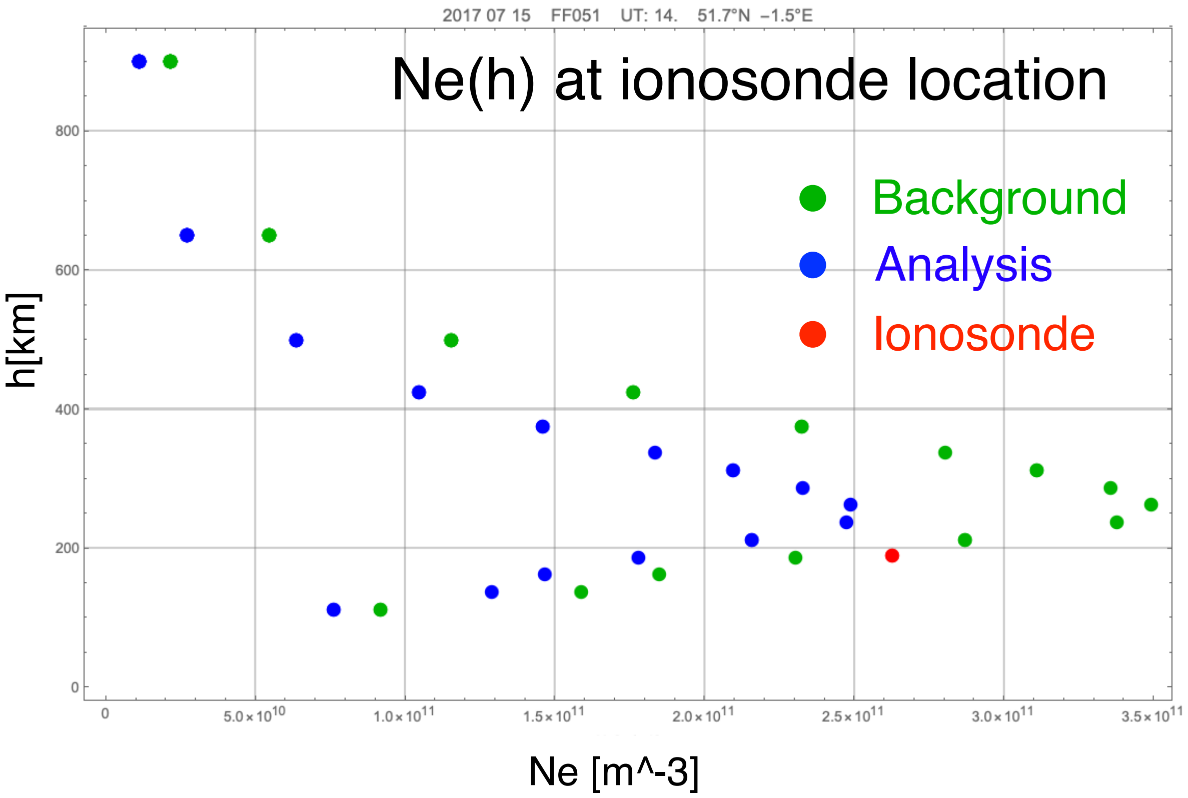
GNSS TEC DA - Example 2

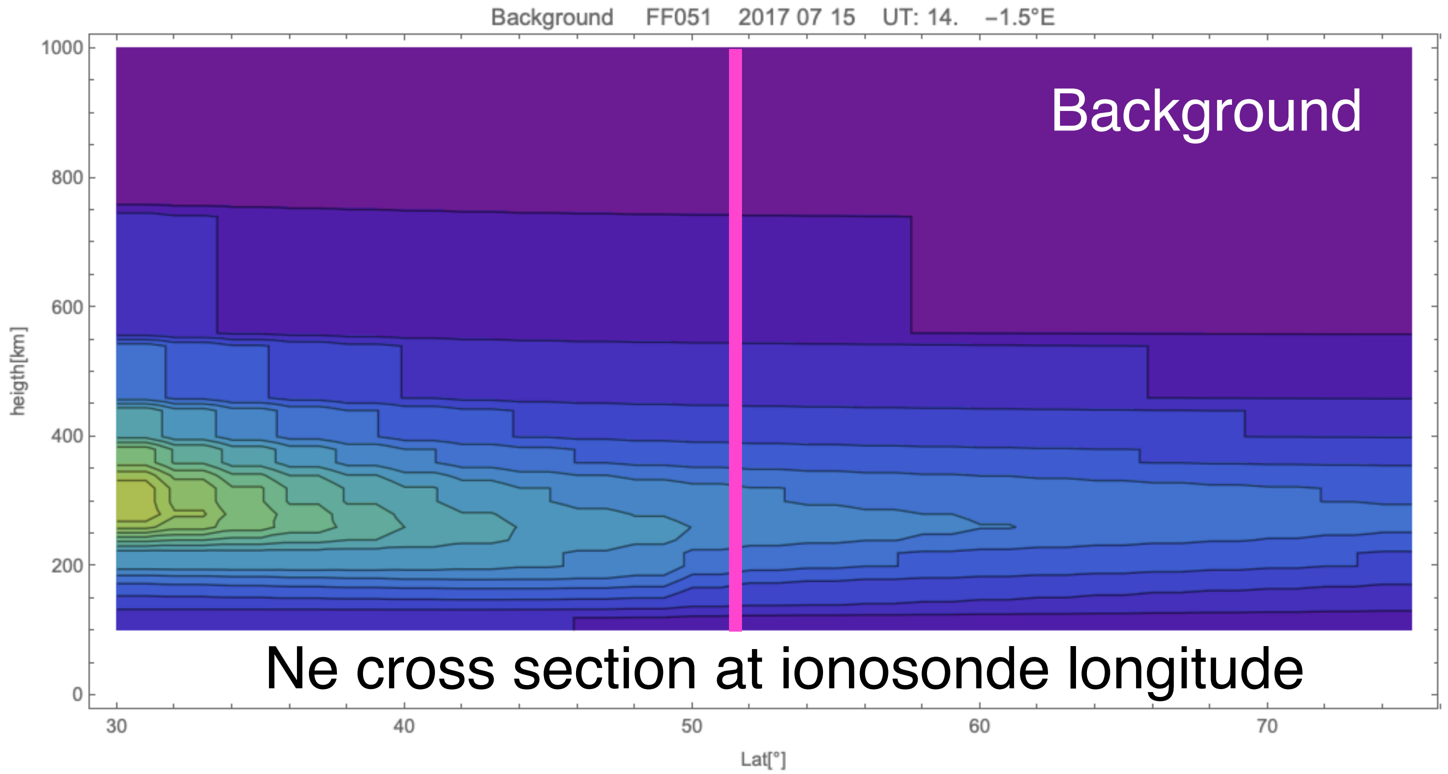
- For the assimilation
  - Calibrated (as in Themens et al. 2015) ground-based GNSS-derived slant TEC data from about 300 receivers located in the European region.
- For the validation
  - Manually scaled foF2 data obtained from Tromso (69.7ºN, 9.0ºE), Fairford (51.7ºN, 1.5ºW) and Juliusruh (54.6ºN, 13.4ºE) ionosondes at 1 hour time interval (only the result corresponding to Fairford will be illustrated).
- The data correspond the period 15-16 July 2017

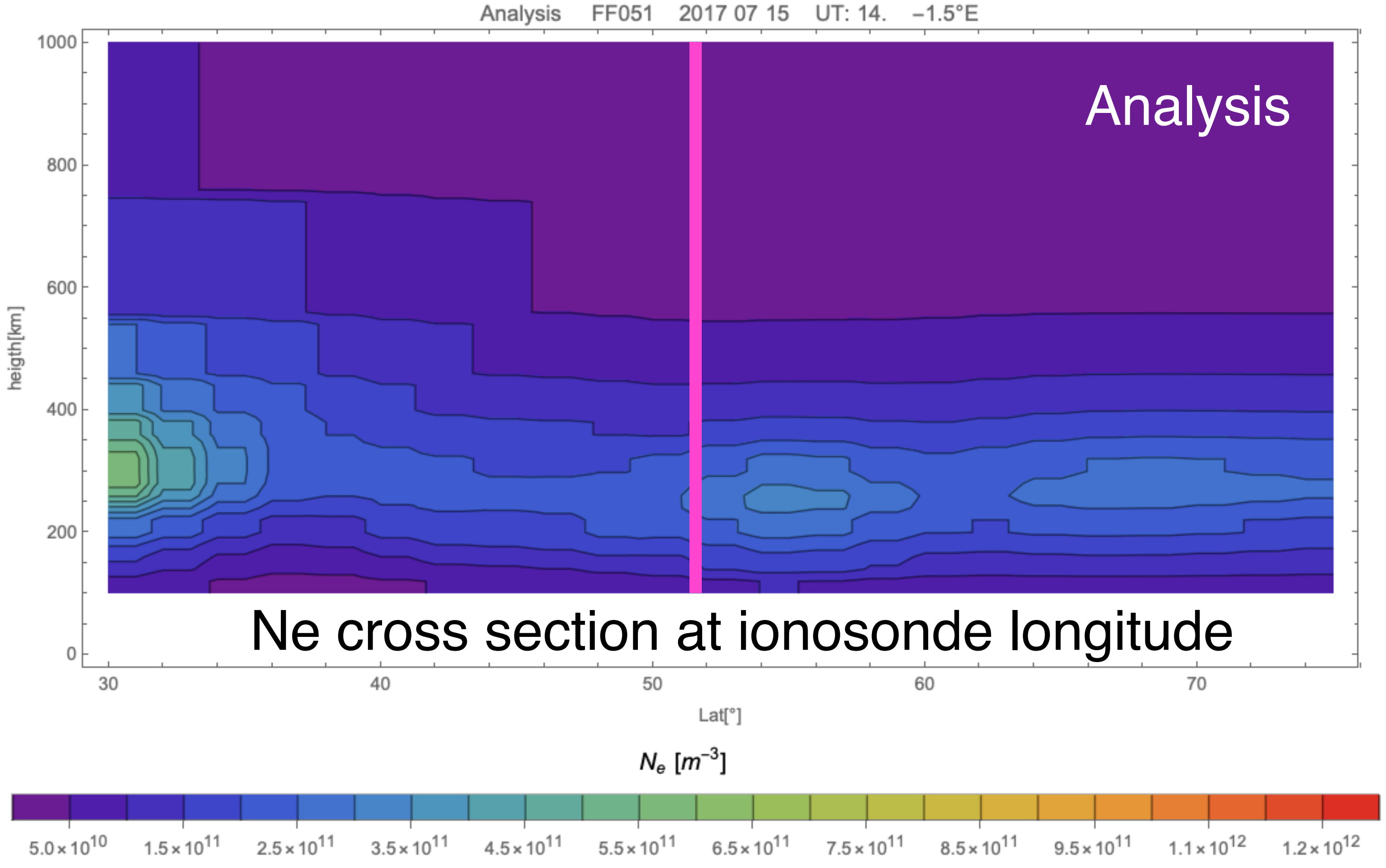


Results: 15 July 2017; 14:00UT; FF051

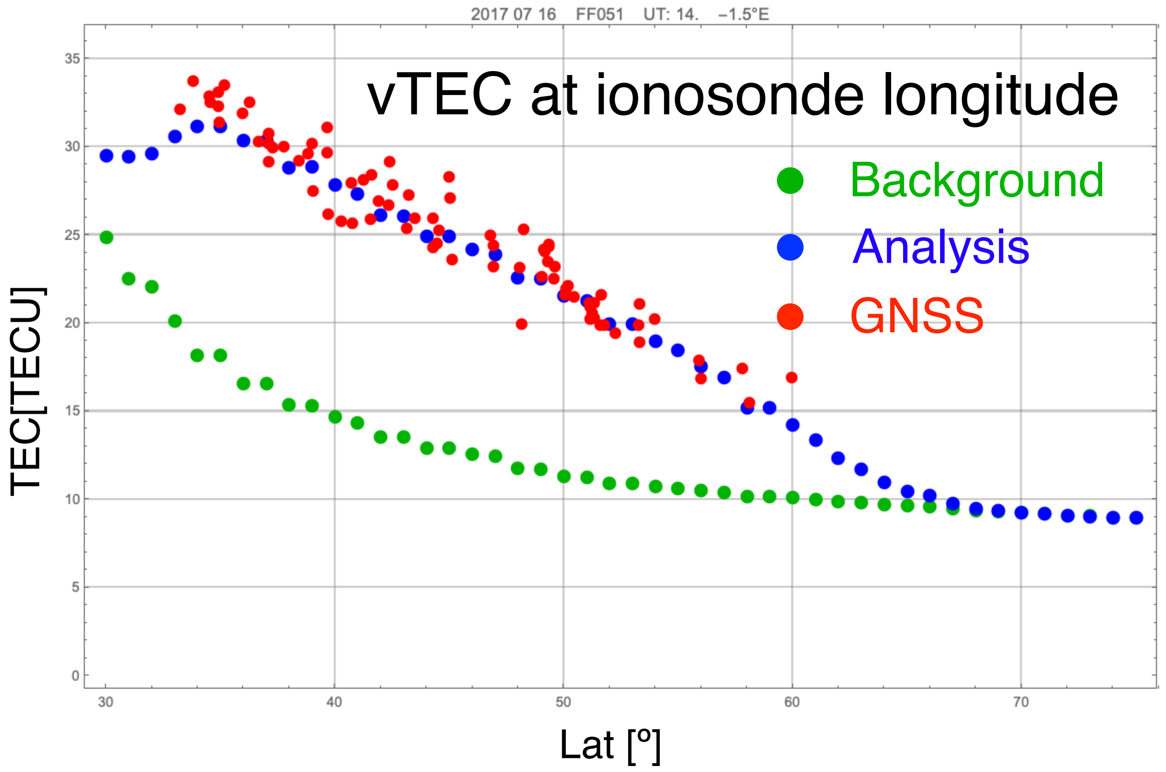


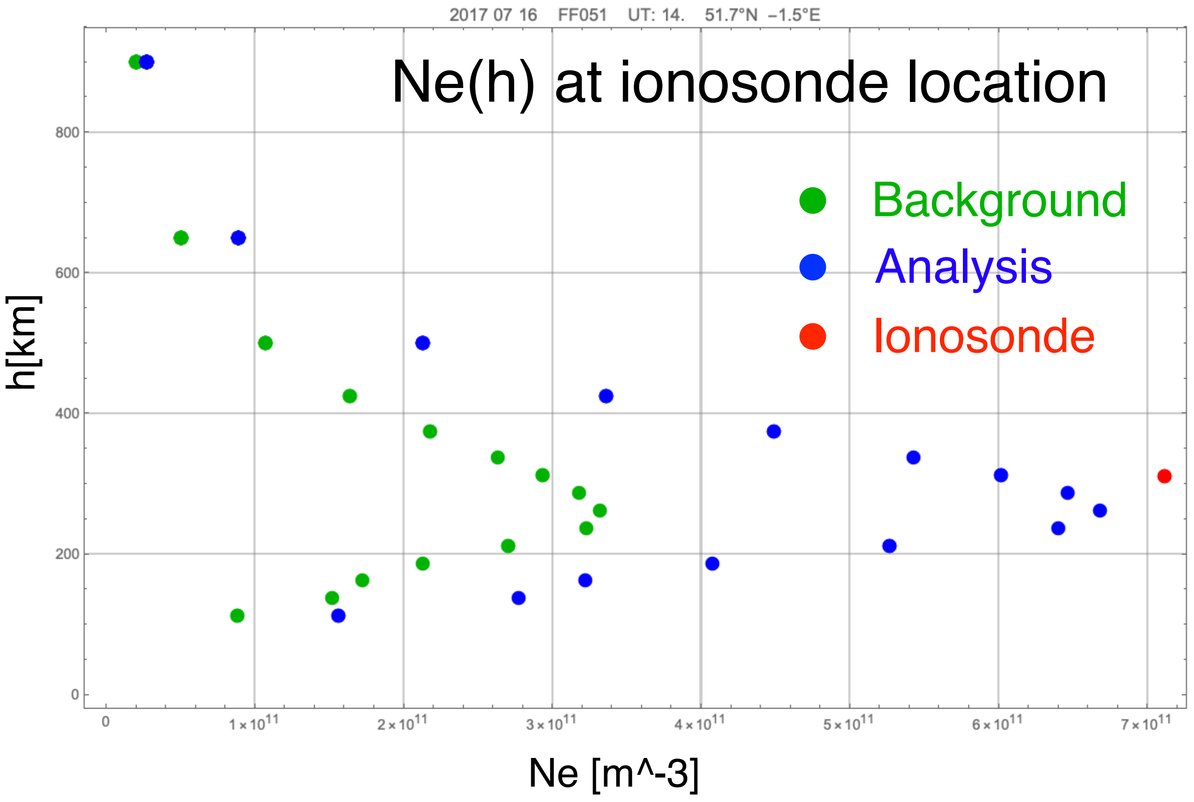


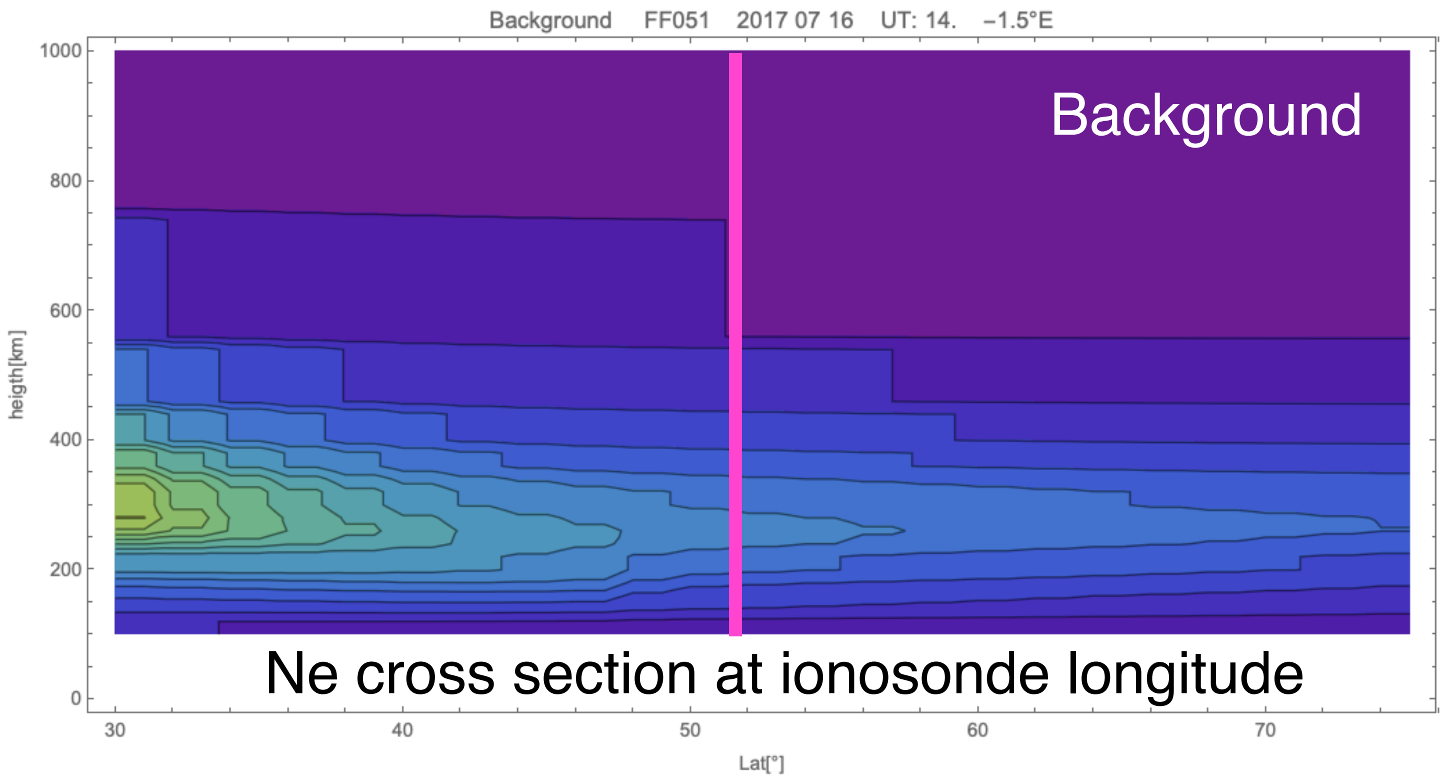


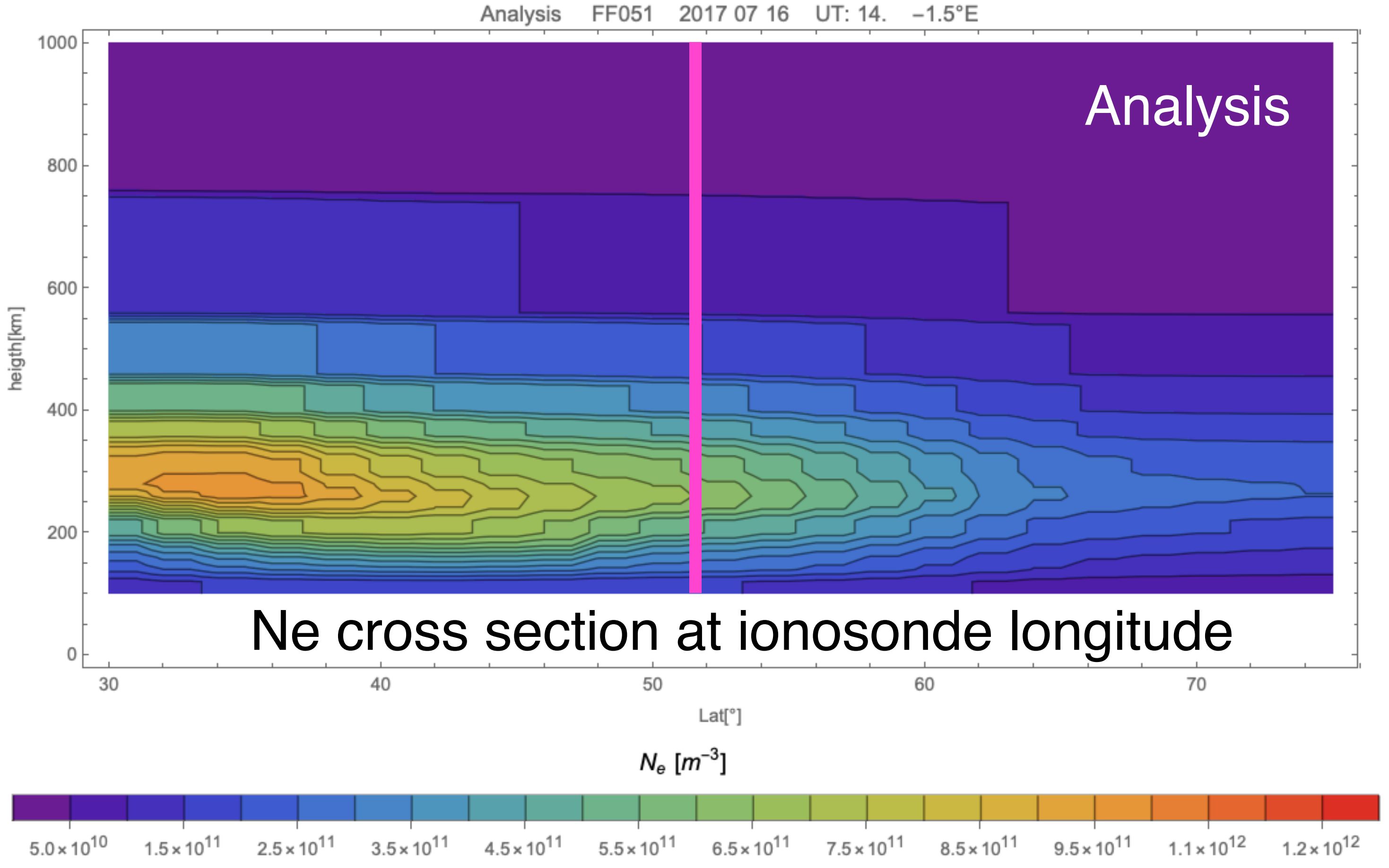


Results: 16 July 2017; 14:00UT; FF051

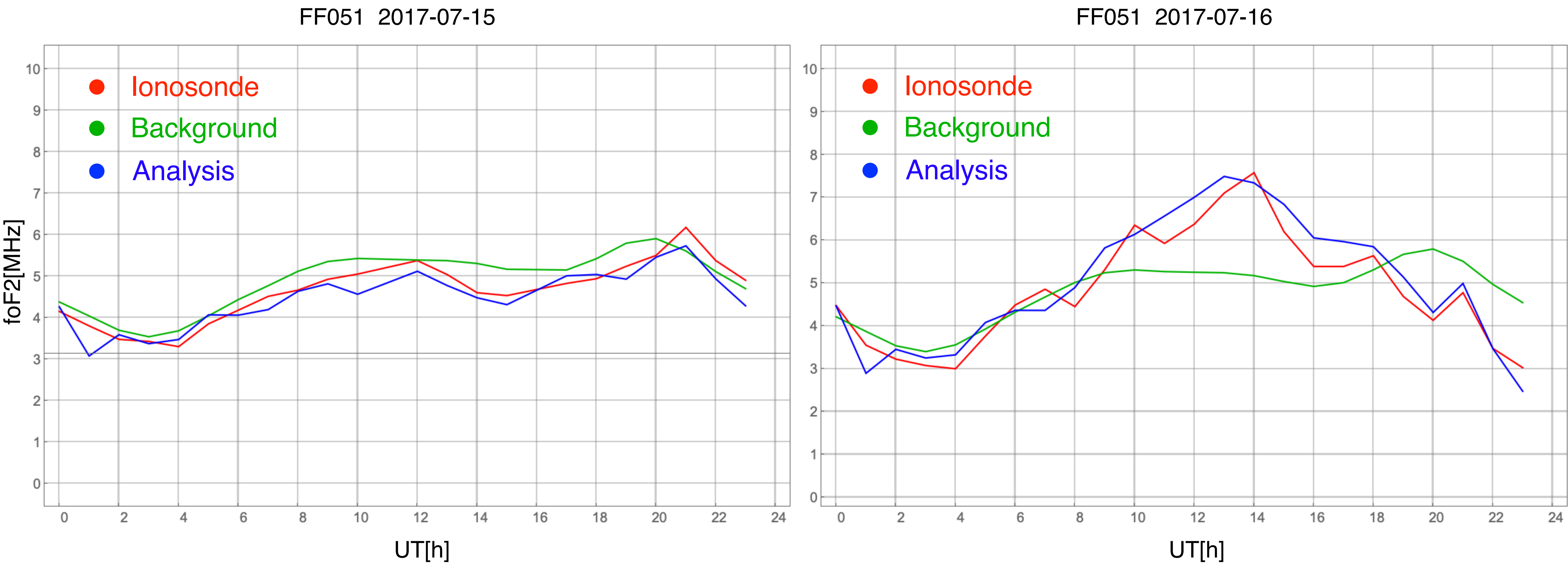






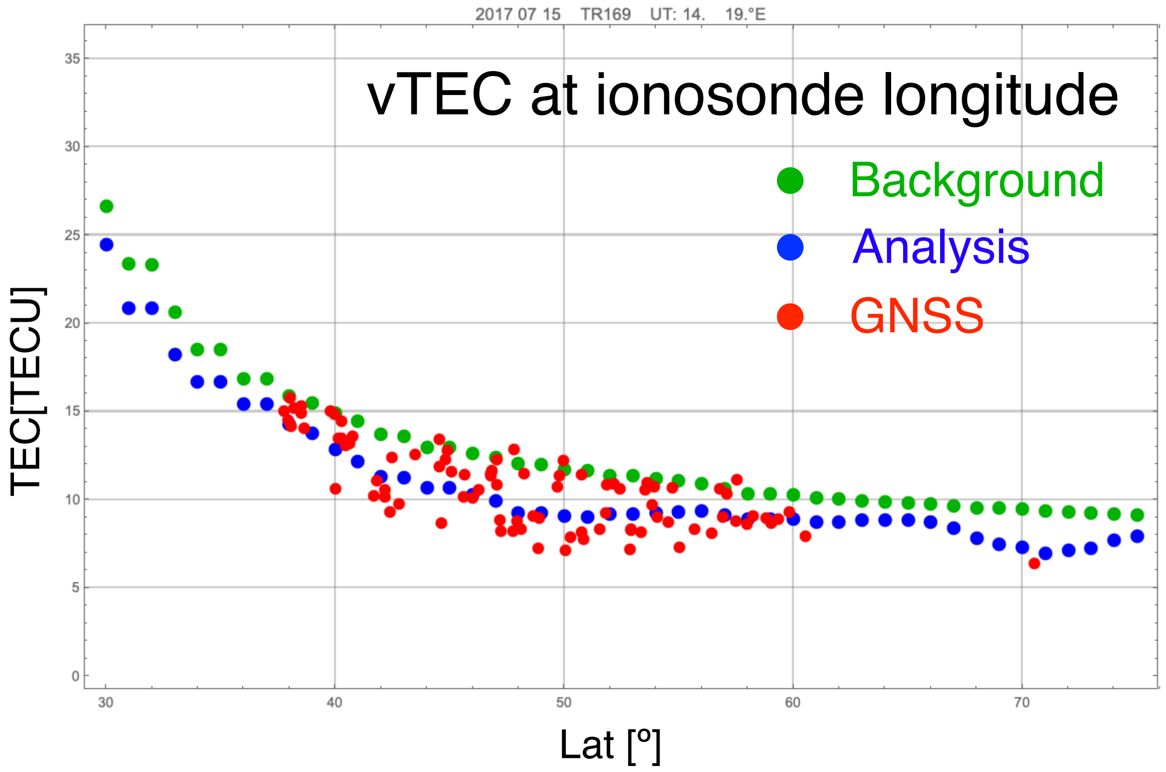


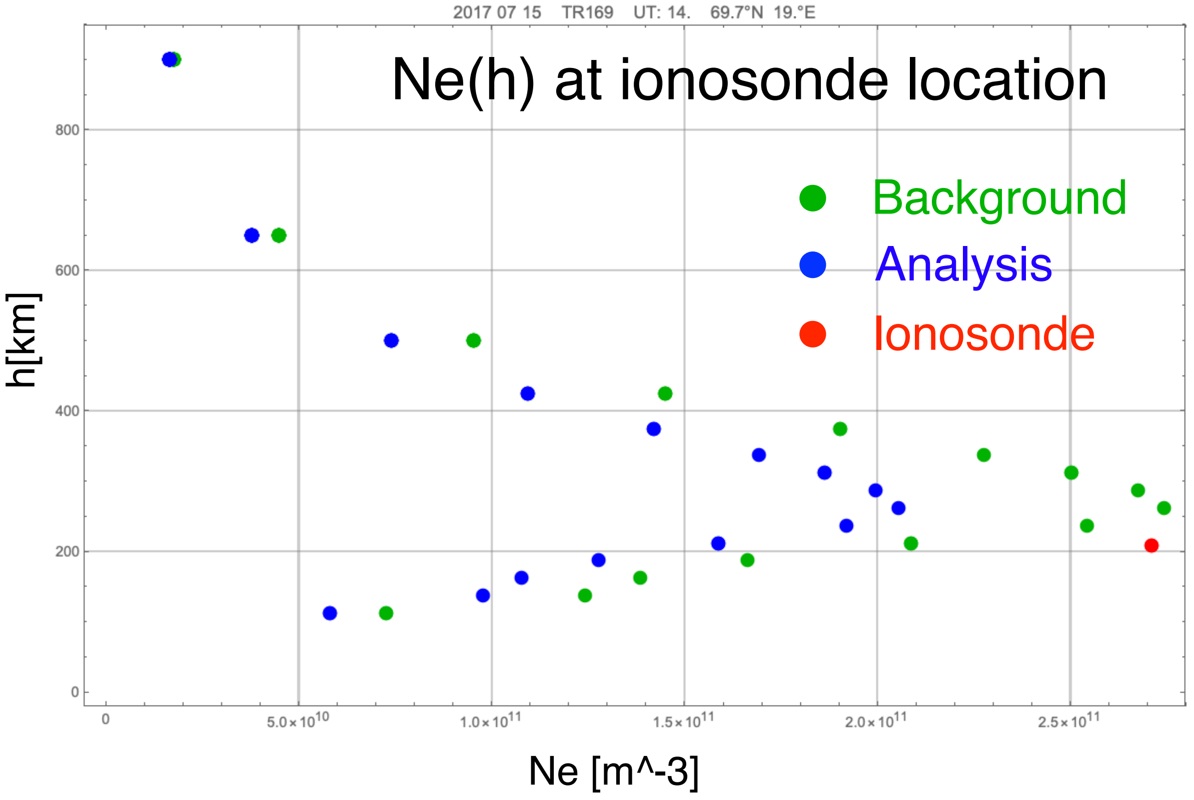
Results: 15-16 July 2017 (sTEC DA)

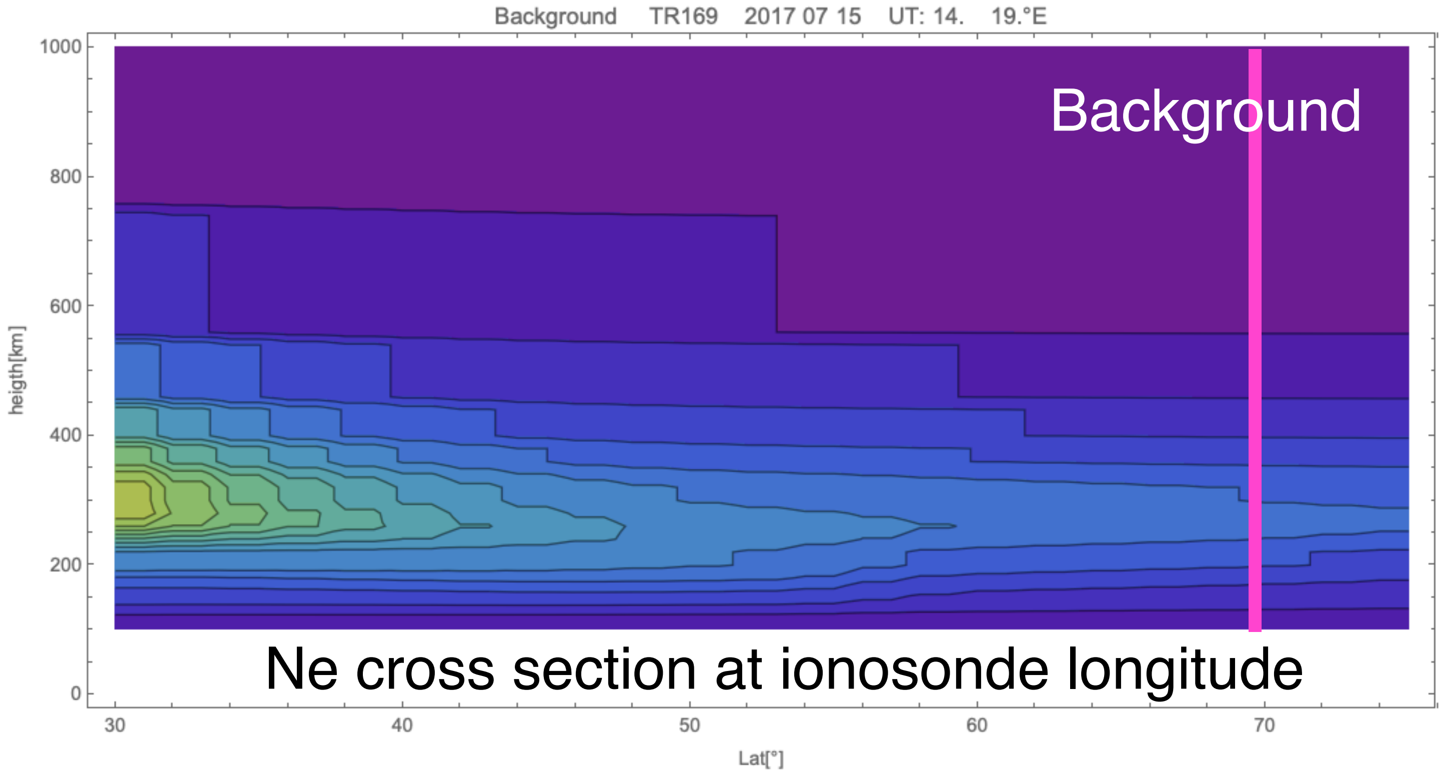


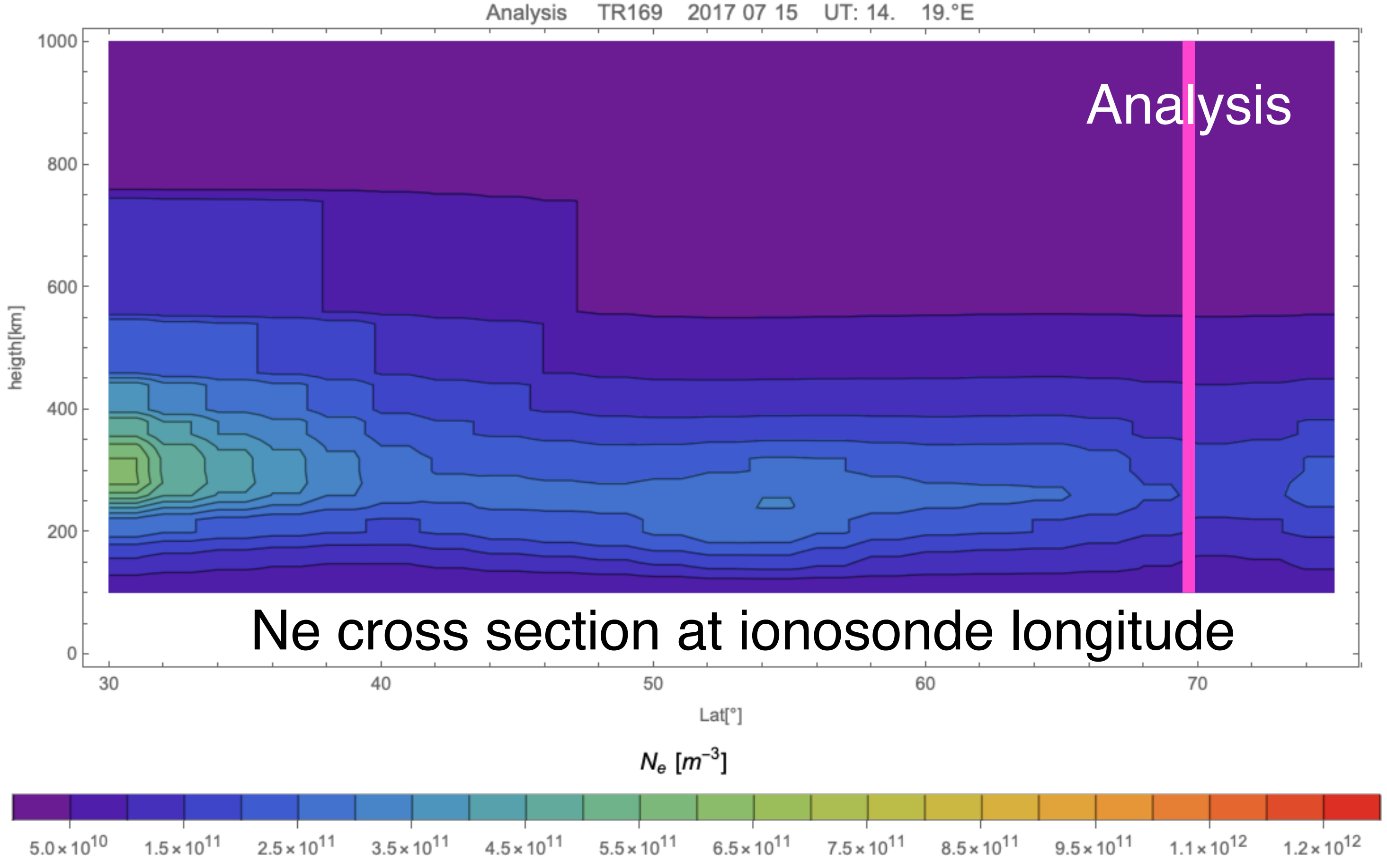
foF2 time evolution at ionosonde location

Results: 15 July 2017; 14:00UT; TR169

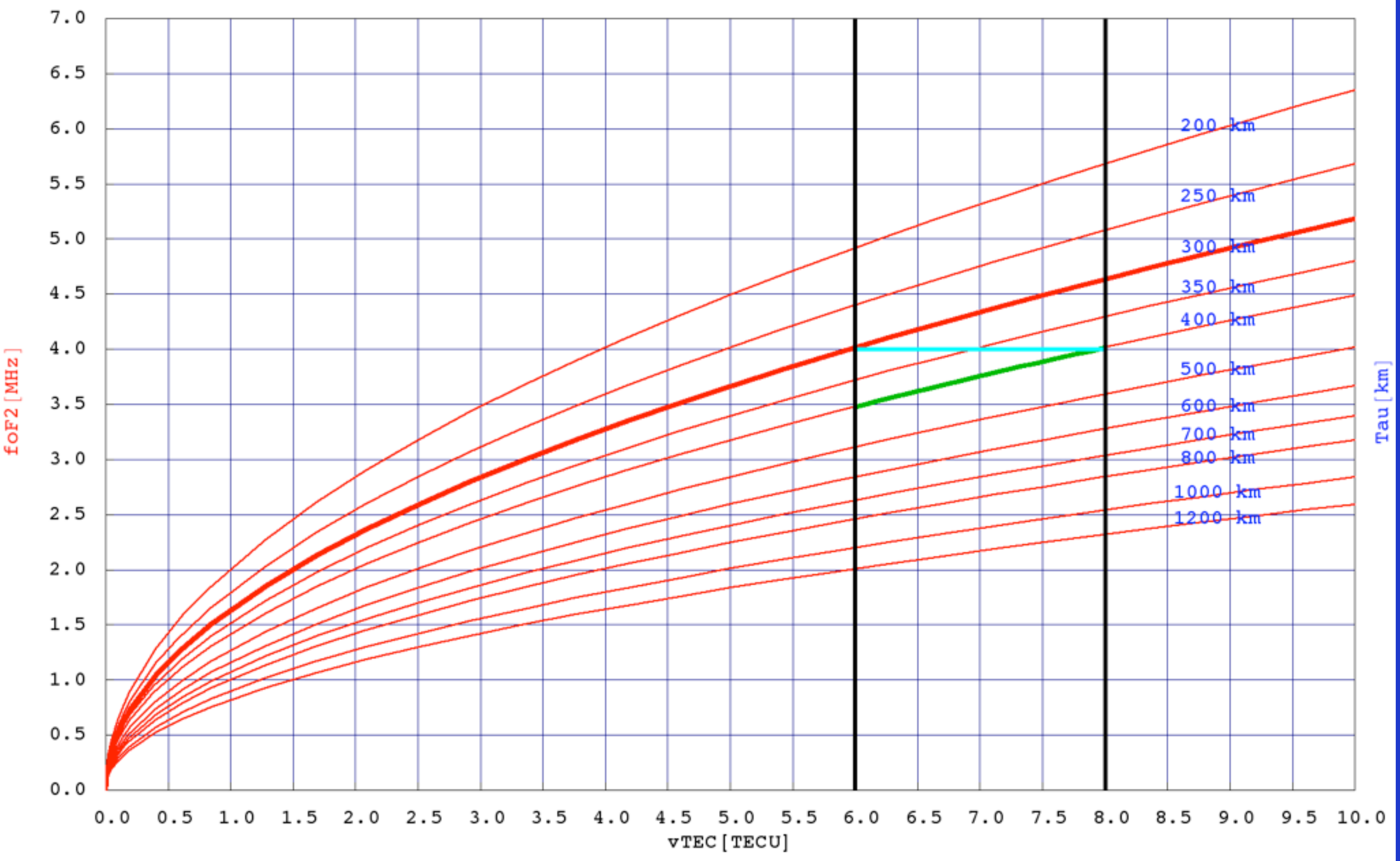








Remark



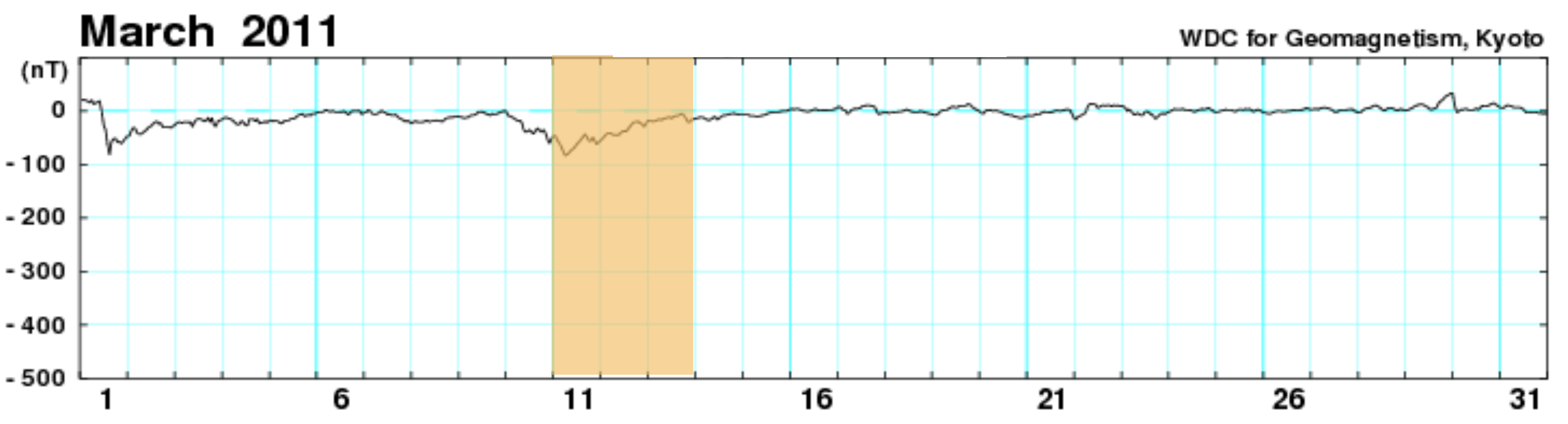
foF2 [MHz]
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0
6.5
7.0
7.5
8.0
8.5
9.0
9.5
10.0
vTEC [TECU]
200 km
250 km
300 km
350 km
400 km
500 km
600 km
700 km
800 km
1000 km
1200 km
Tau [km]

GNSS TEC DA - Example 3

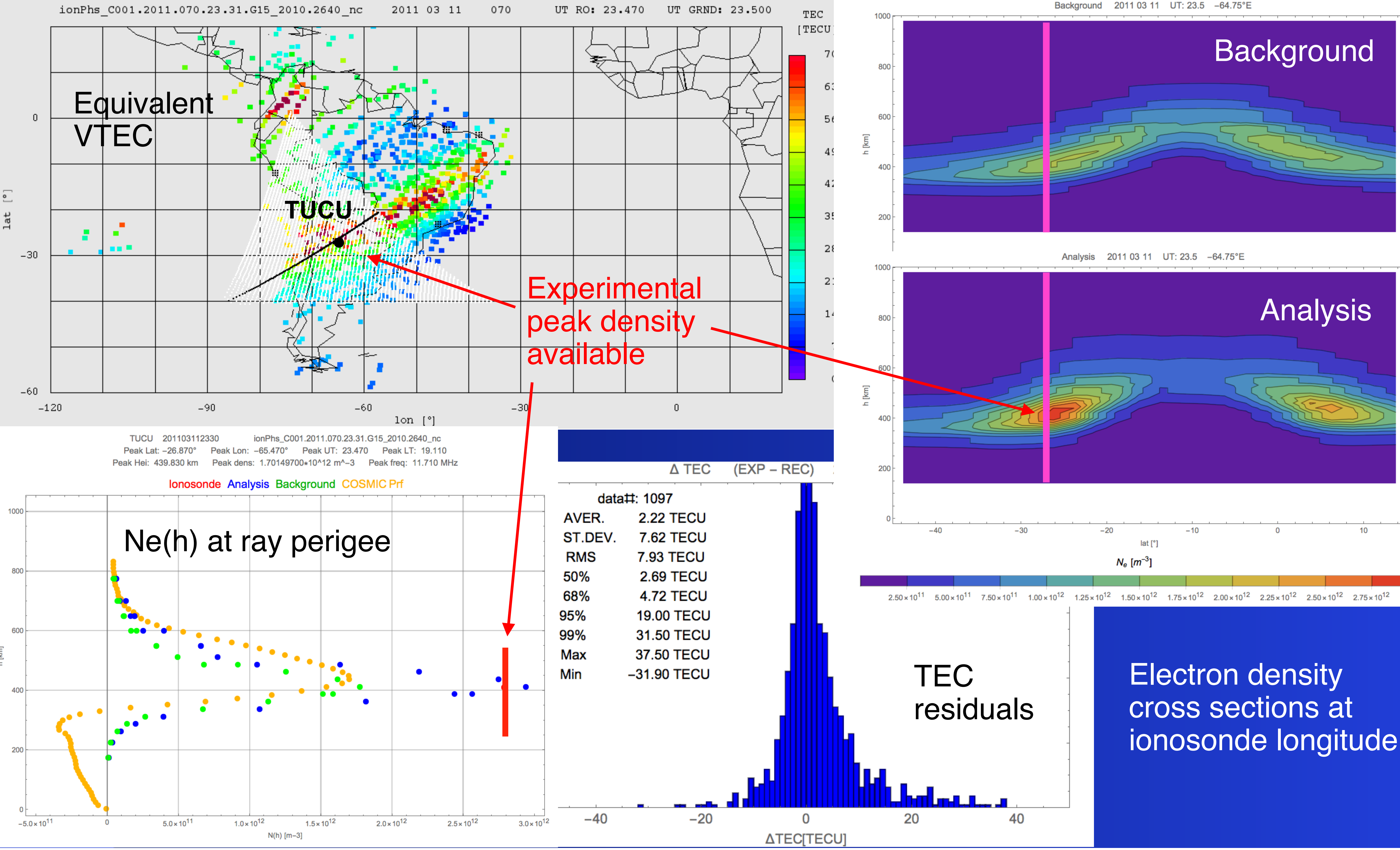
- For the assimilation
  - Ground-based GPS-derived slant TEC data provided by the Low Latitude Ionospheric Sensor Network (LISN)
  - Radio-Occultation-derived TEC data obtained by COSMIC (calibrated TEC values along the LEO-to-GPS link below the LEO orbit)

- For the validation
  - Manually scaled foF2 data obtained from the Tucuman Ionosonde
  - JRO electron density profiles

- The data correspond the period 11-13 March 2011



TEC DA into NeQuick



Equivalent VTEC

TUCU

Experimental peak density available

Ne(h) at ray perigee

data#: 1097

AVER.	2.22 TECU
ST.DEV.	7.62 TECU
RMS	7.93 TECU
50%	2.69 TECU
68%	4.72 TECU
95%	19.00 TECU
99%	31.50 TECU
Max	37.50 TECU
Min	-31.90 TECU

TEC residuals

Background

Analysis

Electron density cross sections at ionosonde longitude

Thank you for your attention