Ionospheric modeling and data assimilation

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African School on Space Science: Related Applications and Awareness for Sustainable Development of the Region
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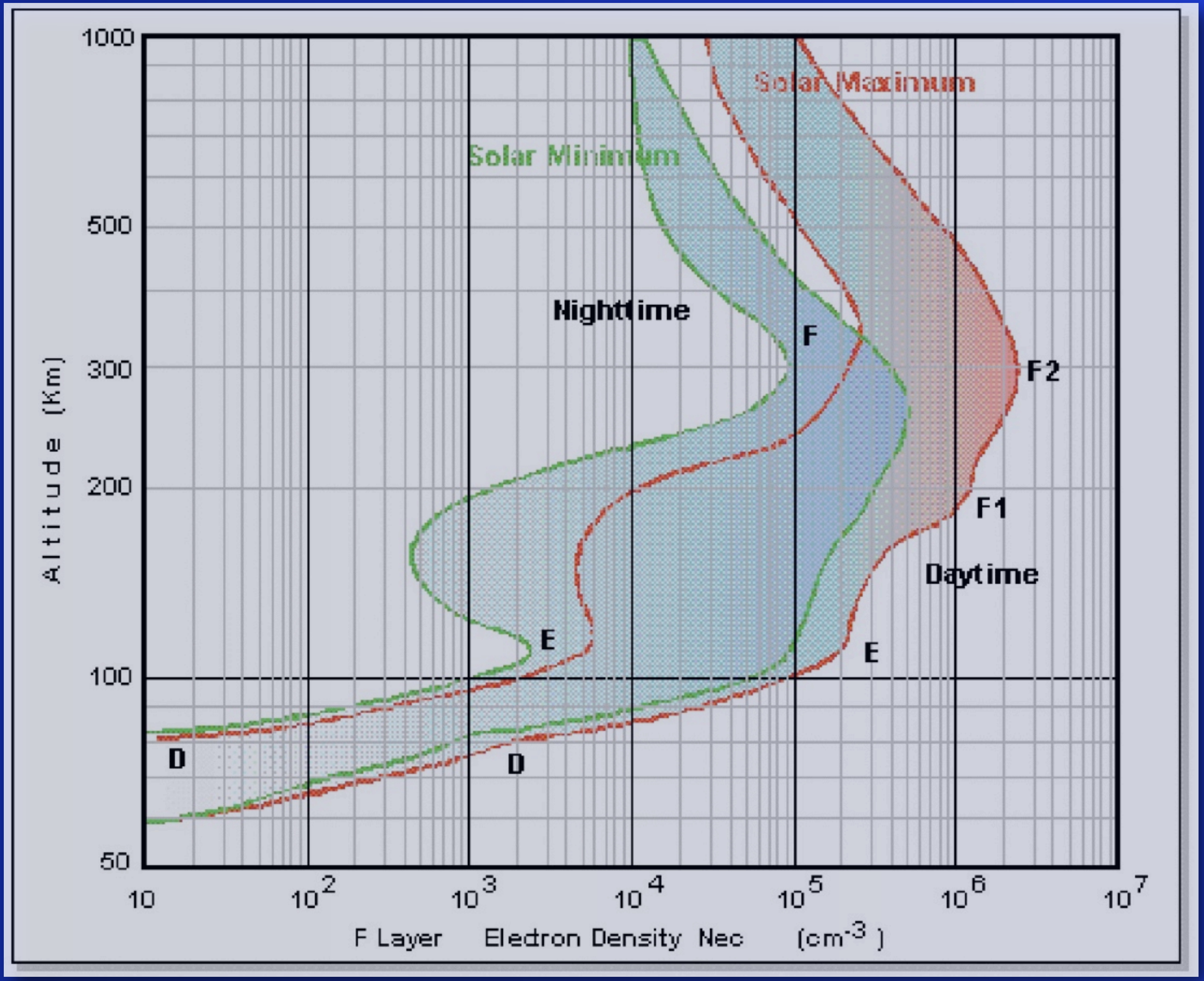
Outline

- Ionosphere structure
  - (Layers)
- NeQuick model
  - General description
- Data assimilation into NeQuick
  - Use of effective parameters (examples)
  - Least Square Estimation (test case)

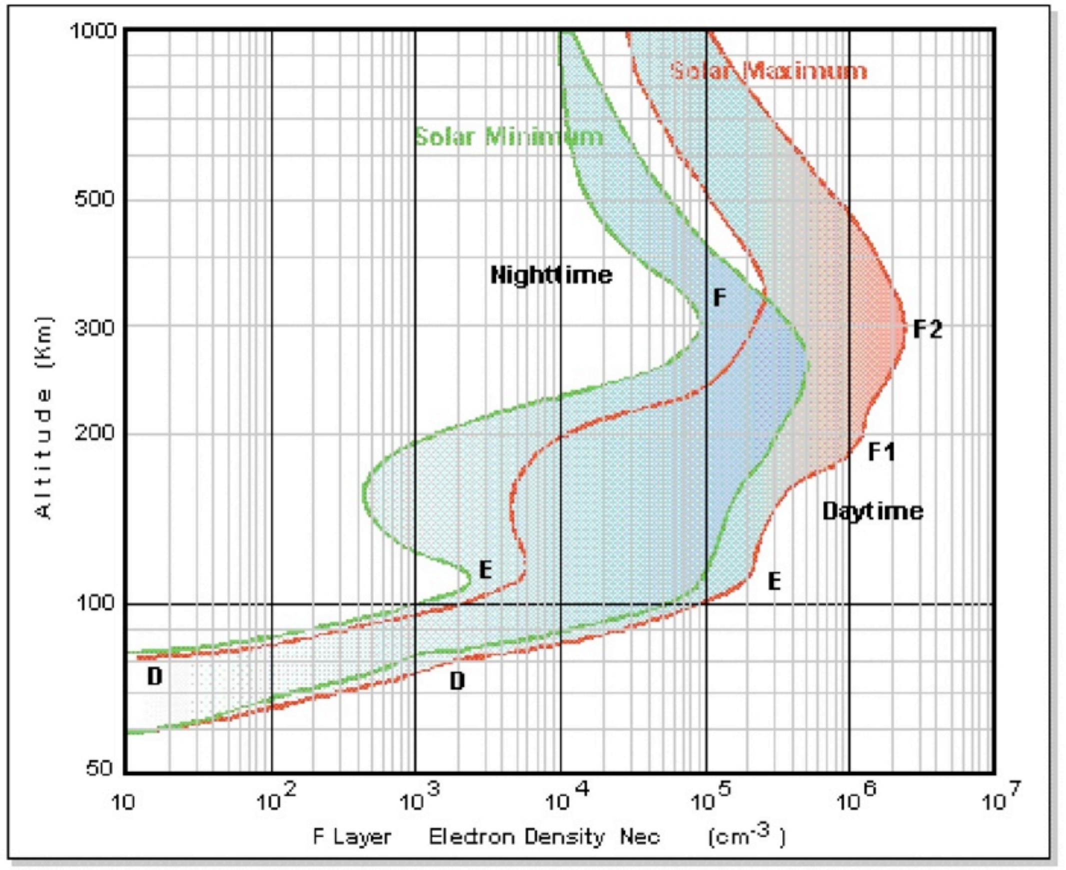
Layers of the ionosphere

- D region
- E region
  - sporadic E
- F region
  - F1 and F2 layers
- Topside



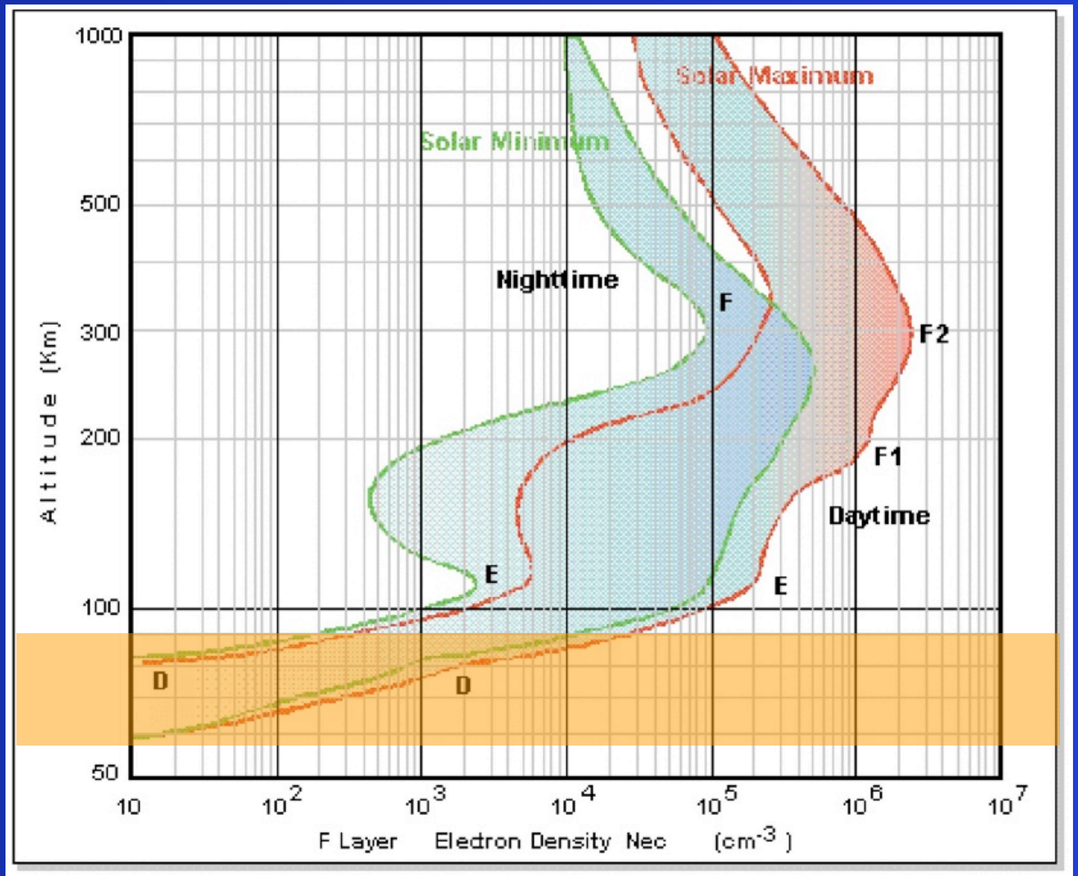
http://gbailey.staff.shef.ac.uk/researchoverview.html

D Region



- It extends from 70 to 90 km height
- Under special conditions it might be present from 50 km
- In this region the electron density:
  - increases quickly with height
  - is very low during night-time
  - its maximum is reached right after local noon during summer

D Region



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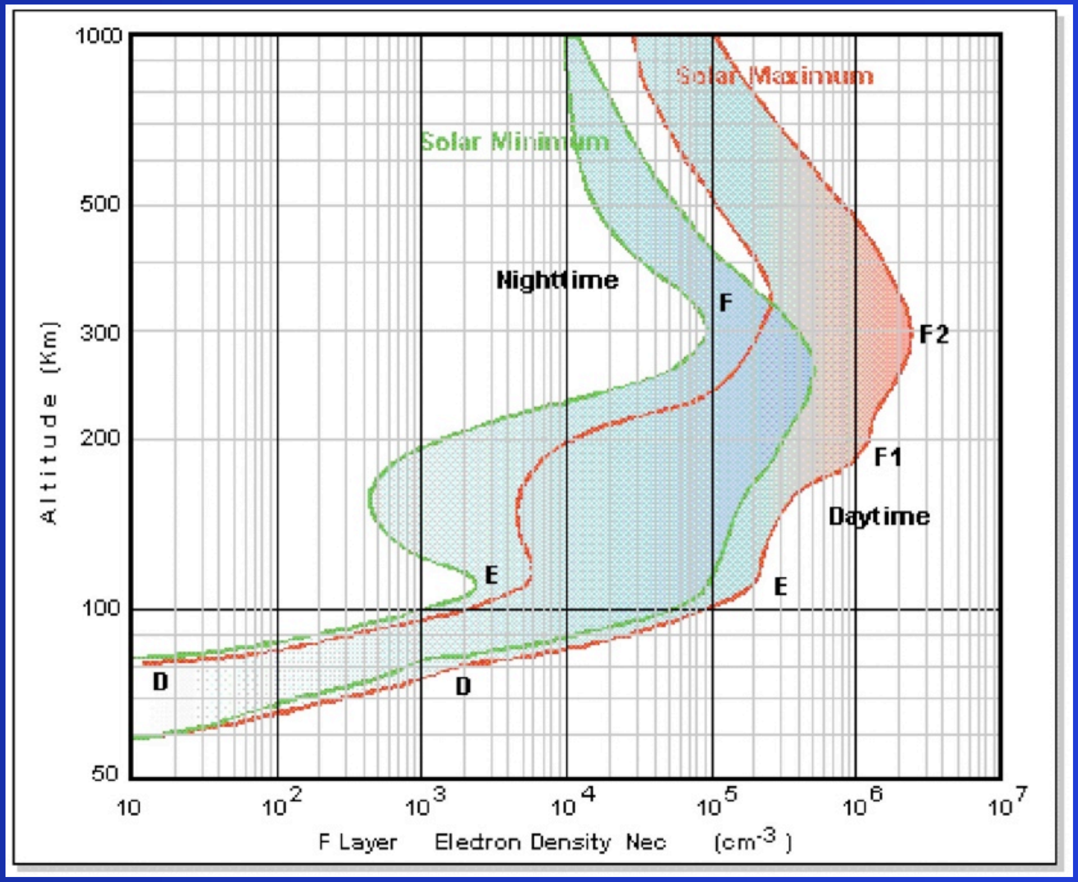
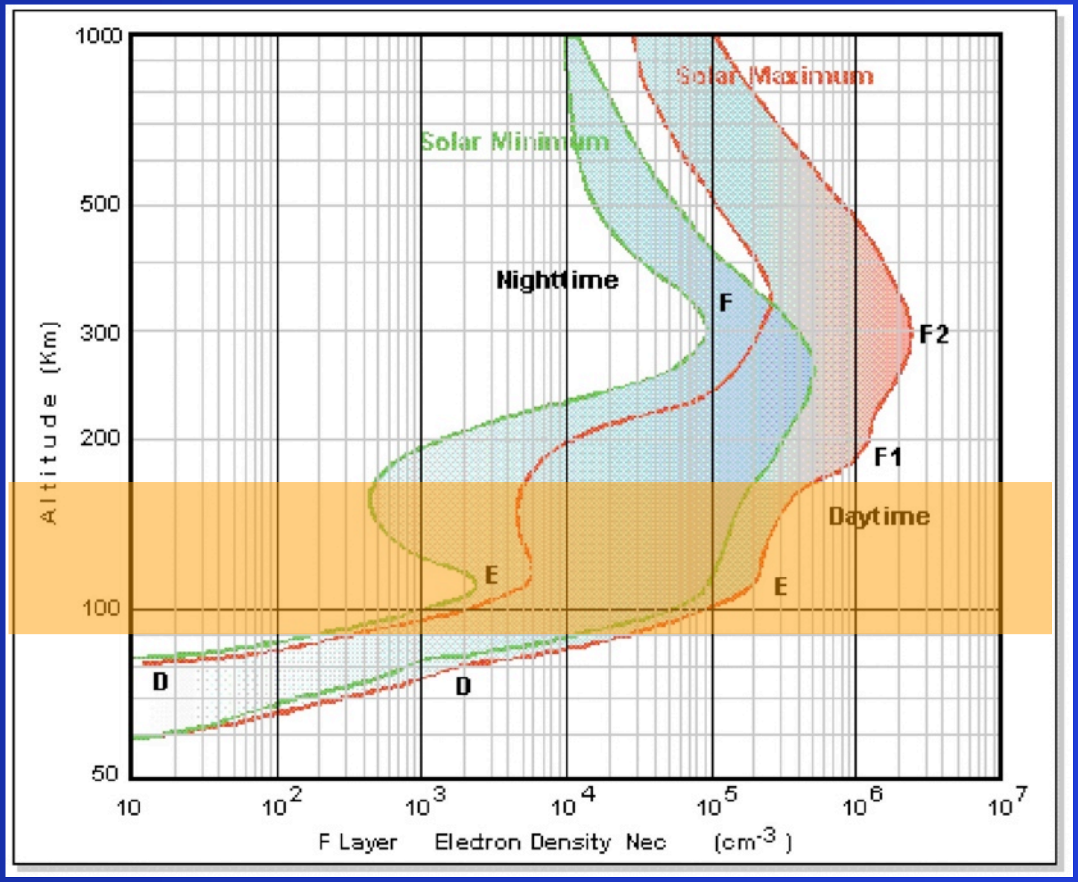
E Region



- It extends from 90 to about 140 km
- It develops clearly after sunrise
- In this region the electron density
  - reaches its maximum value:
    - near the local noon
    - in summer
    - at about 110 km height

E Region



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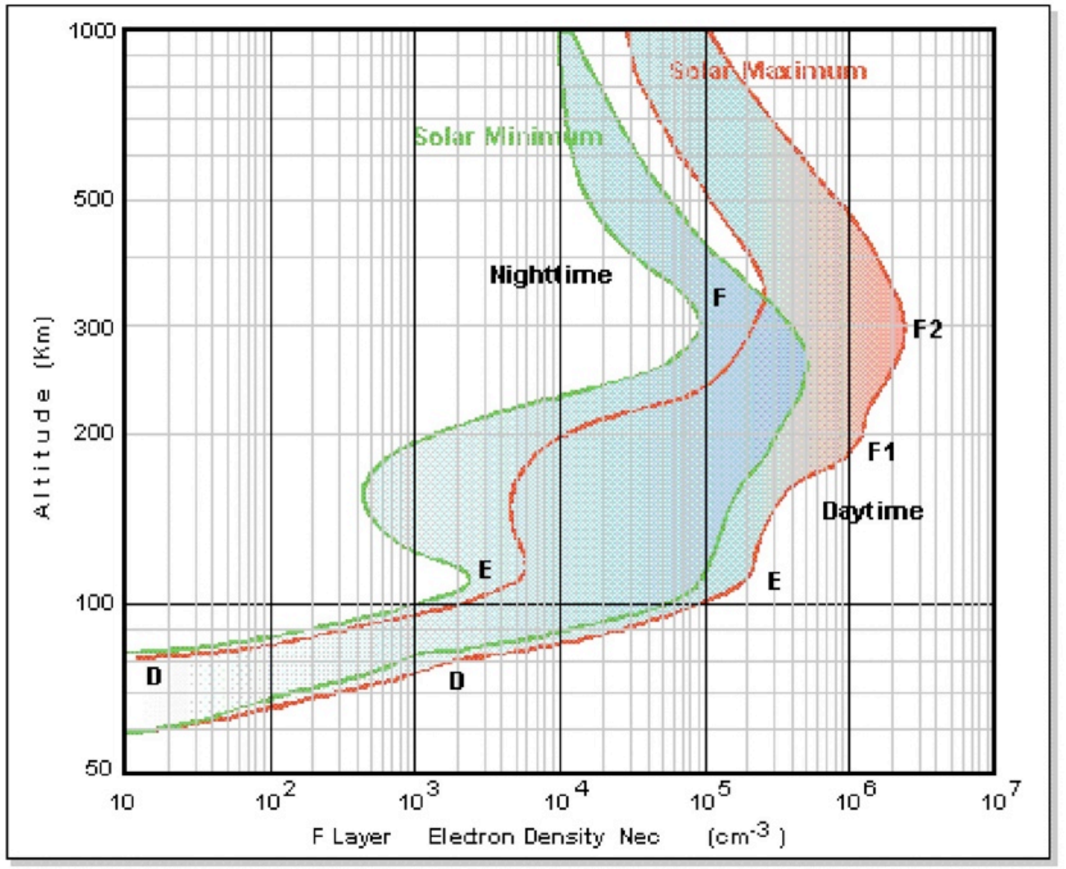
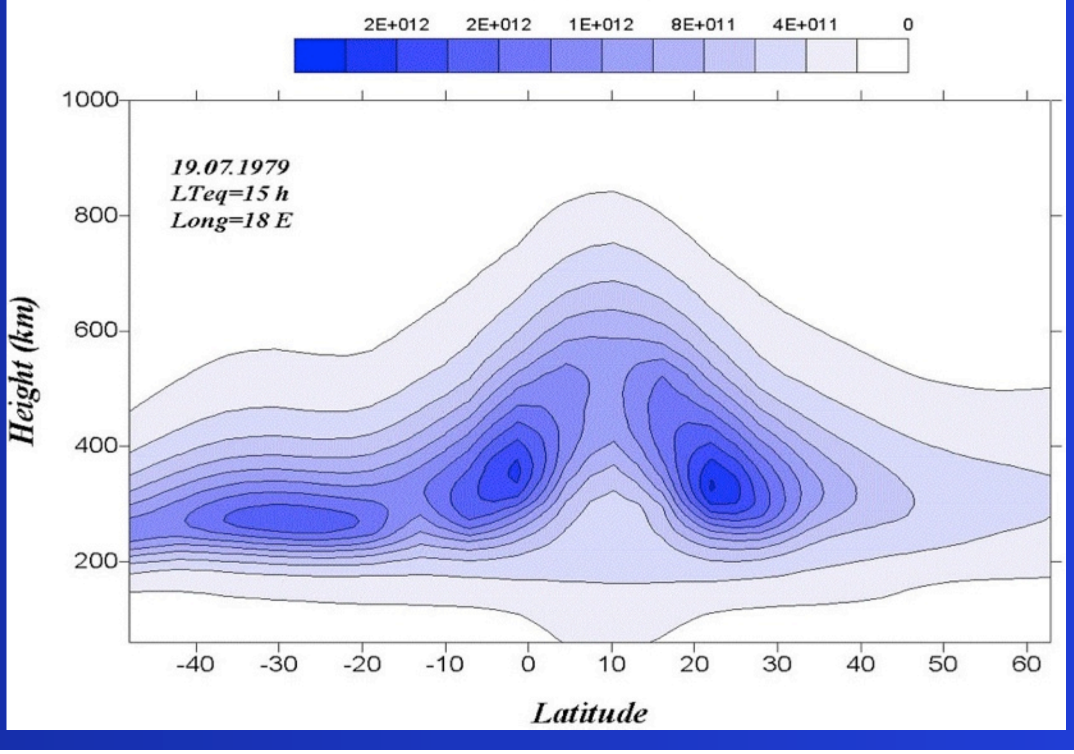
F Region

- It extends from 140 km upwards:
- During the day hours it is possible to distinguish two layers: F1 and F2, which are merging during the night.
- It shows a clear geographic variation with higher electron density values around 20° N and S of the dip equator. (Equatorial Anomaly)





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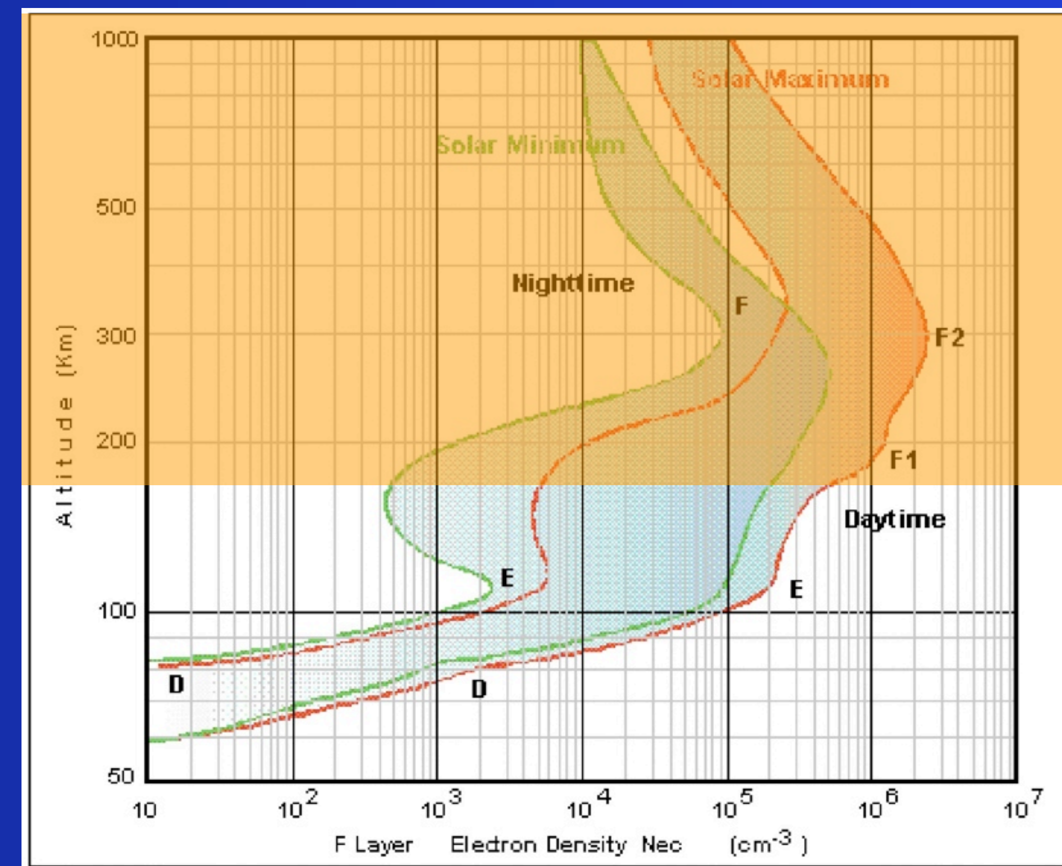

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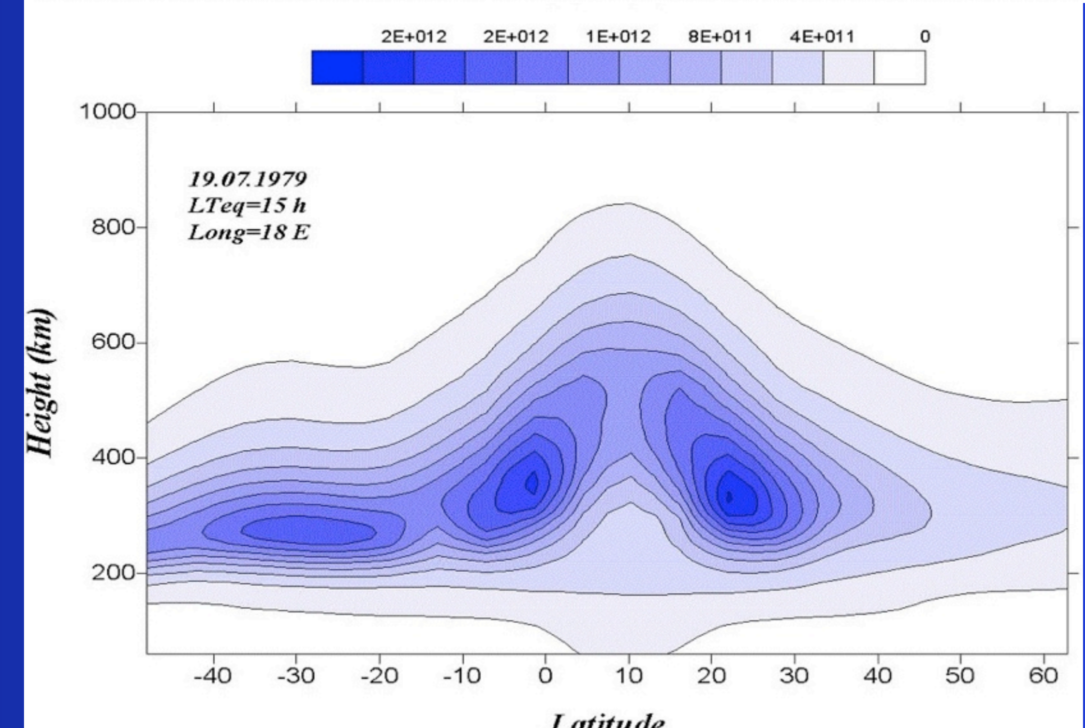
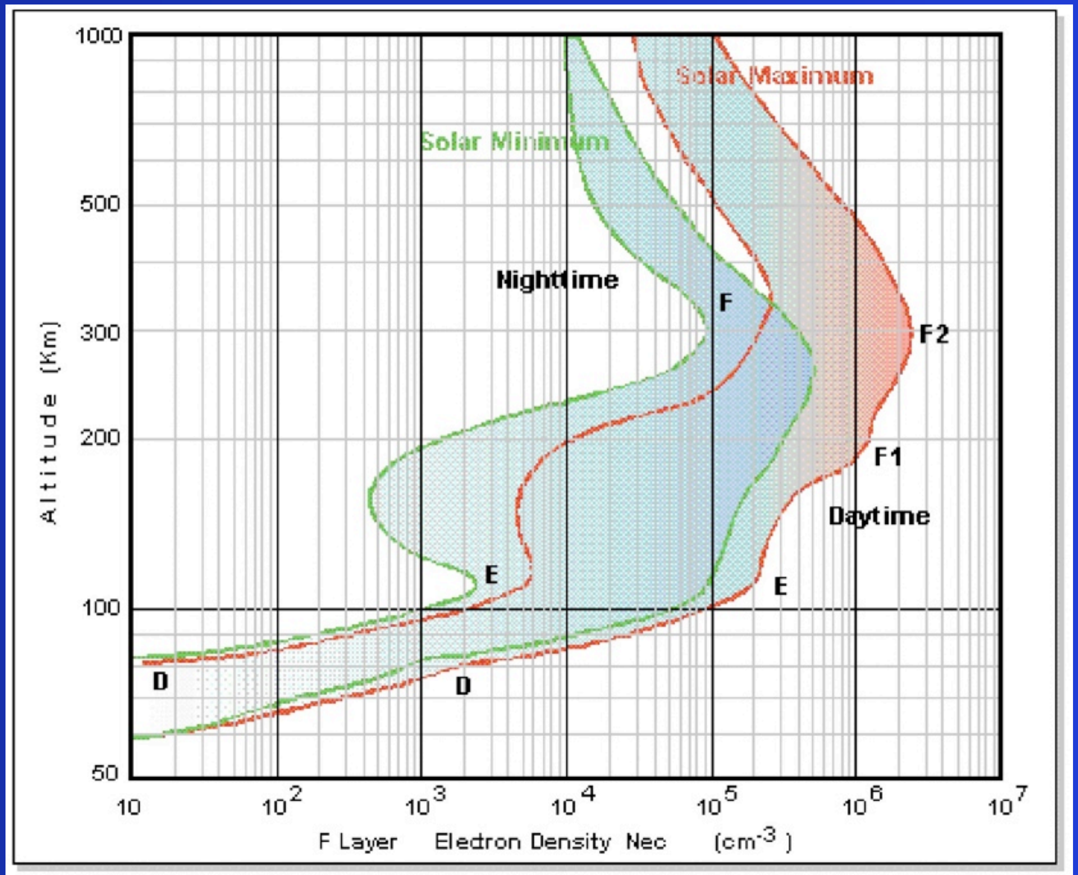


F1 Layer

- It extends form about 140 to 200 km
- It is well developed especially during summer
- The maximum of electron density is
  - between 170-190 km,
  - before noon
  - in the equatorial region



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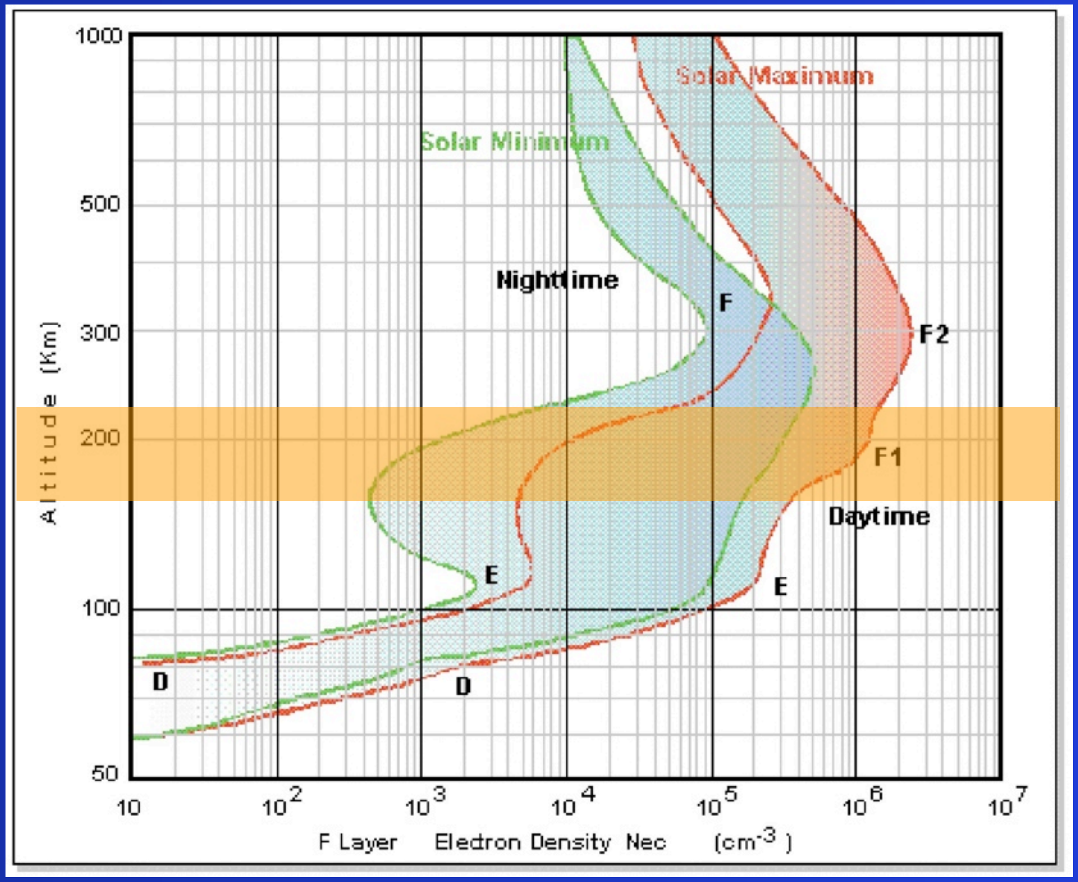
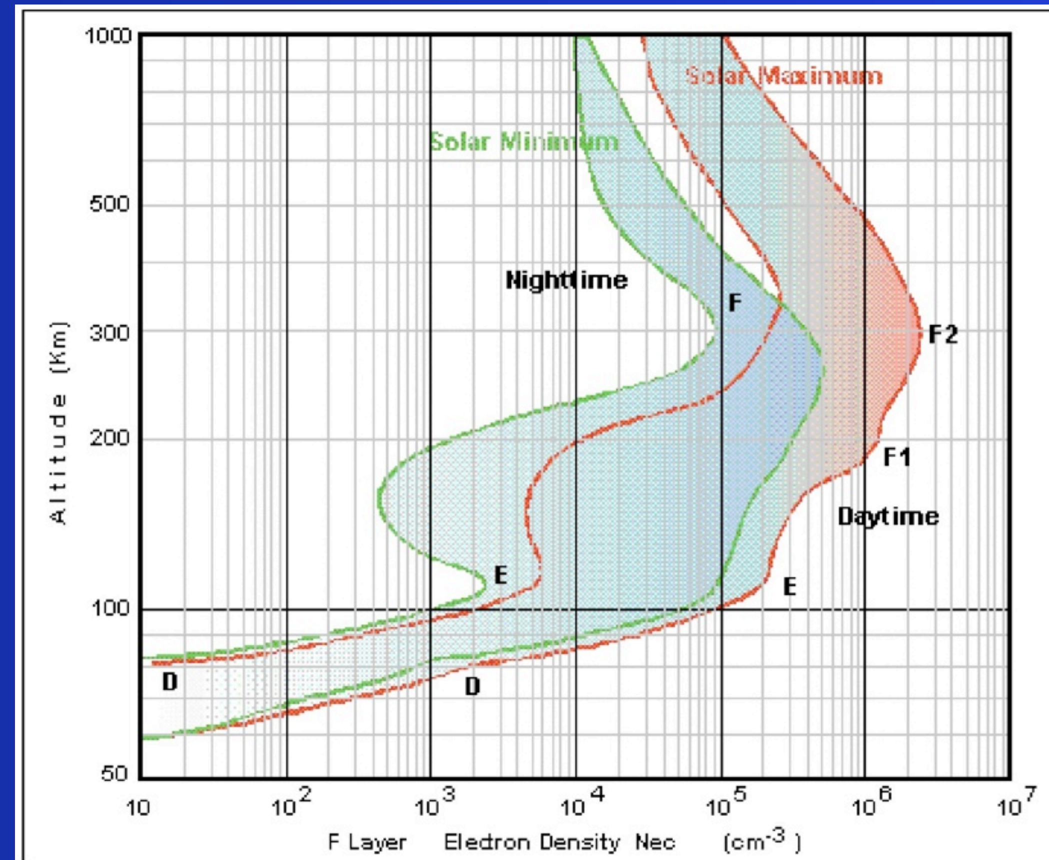
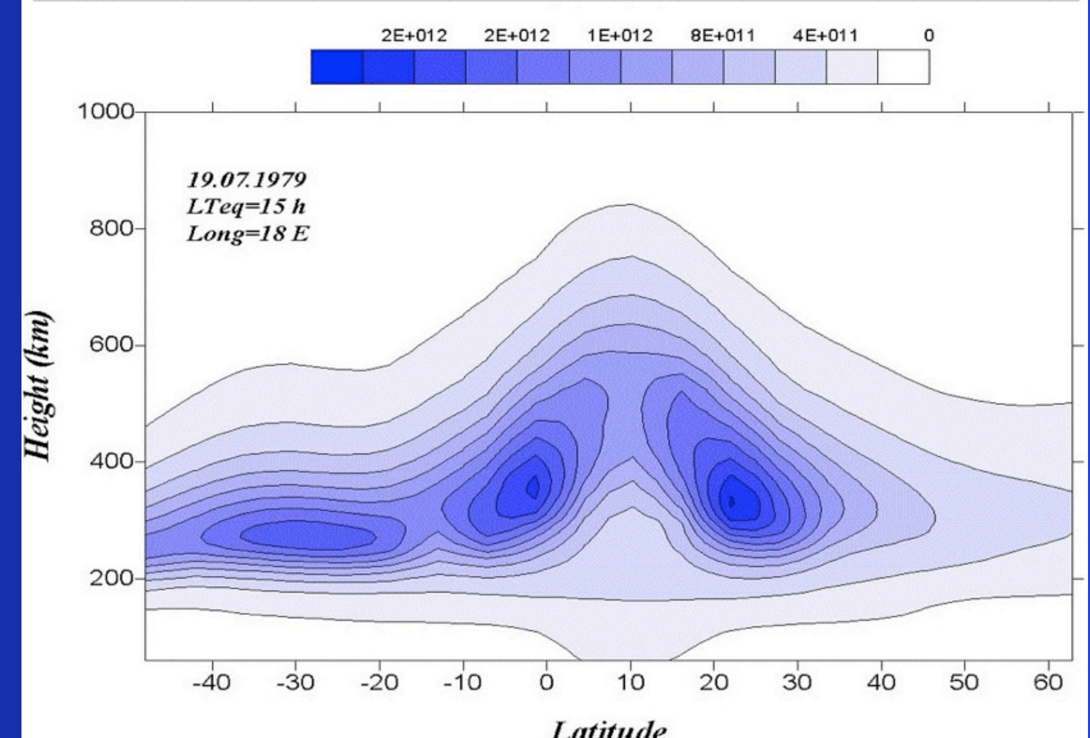


F2 Layer

- It extends above the F1 layer
- The electron density maximum in this layer (NmF2) is in average between 250 and 350 km of height
- NmF2:
  - reaches the minimum value between 4-6 LT
  - reaches its maximum around local noon but also in the late afternoon or early evening
  - depends on geomagnetic latitude
  - reaches the highest values around 20° N and S of the dip equator
  - is affected by geomagnetic activity





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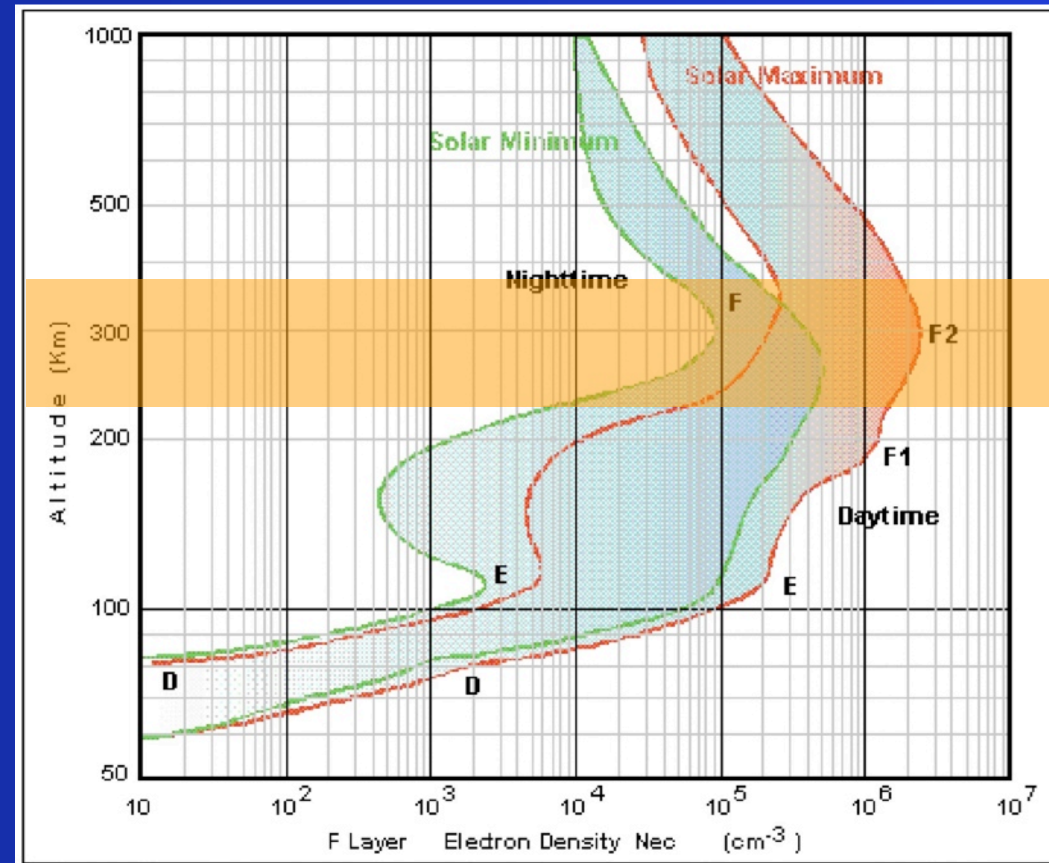
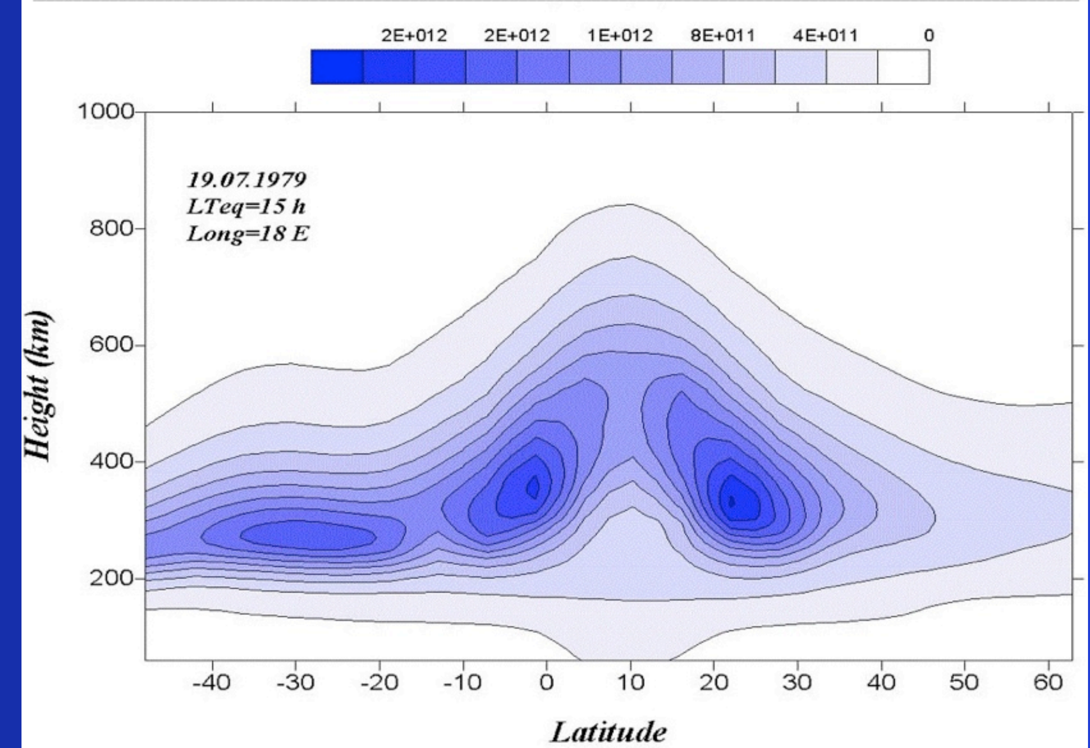
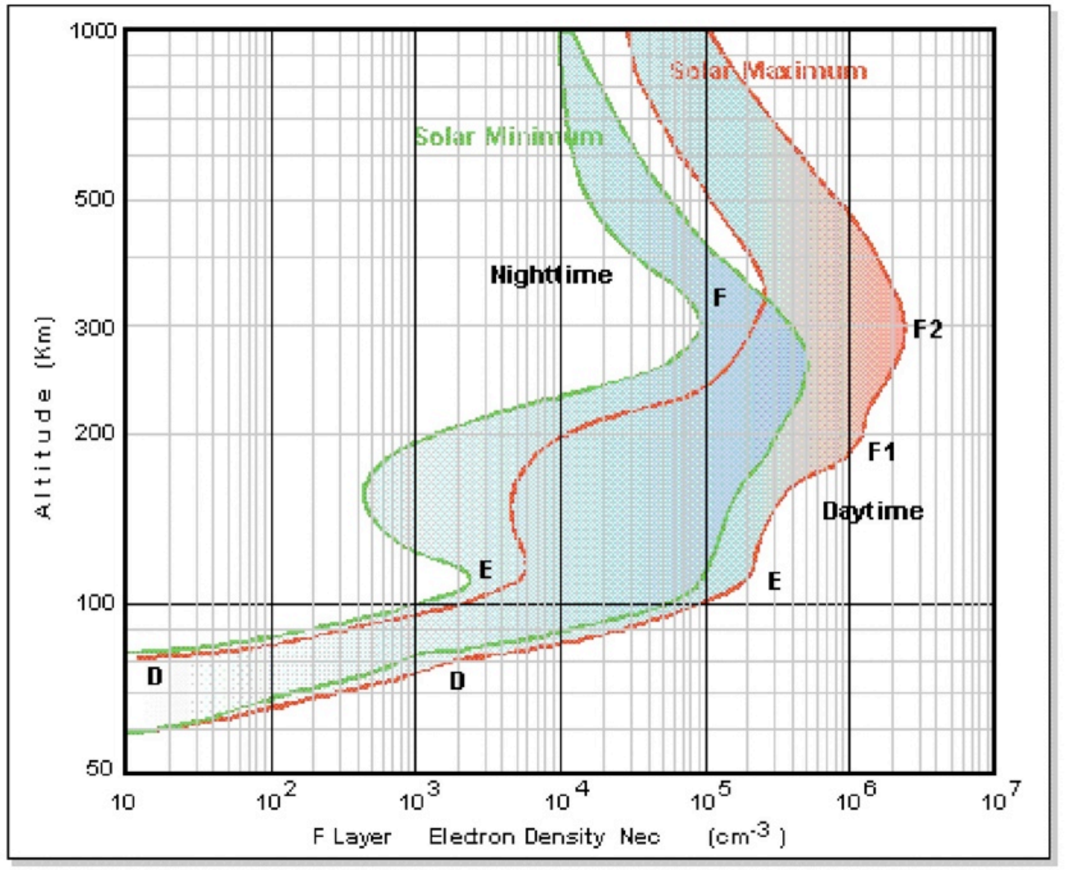




Topside

- Topside ionosphere is the region above the F2 maximum
- The electron density decreases with height reaching very low values at about 1500 - 2000 km(*plasmasphere*)



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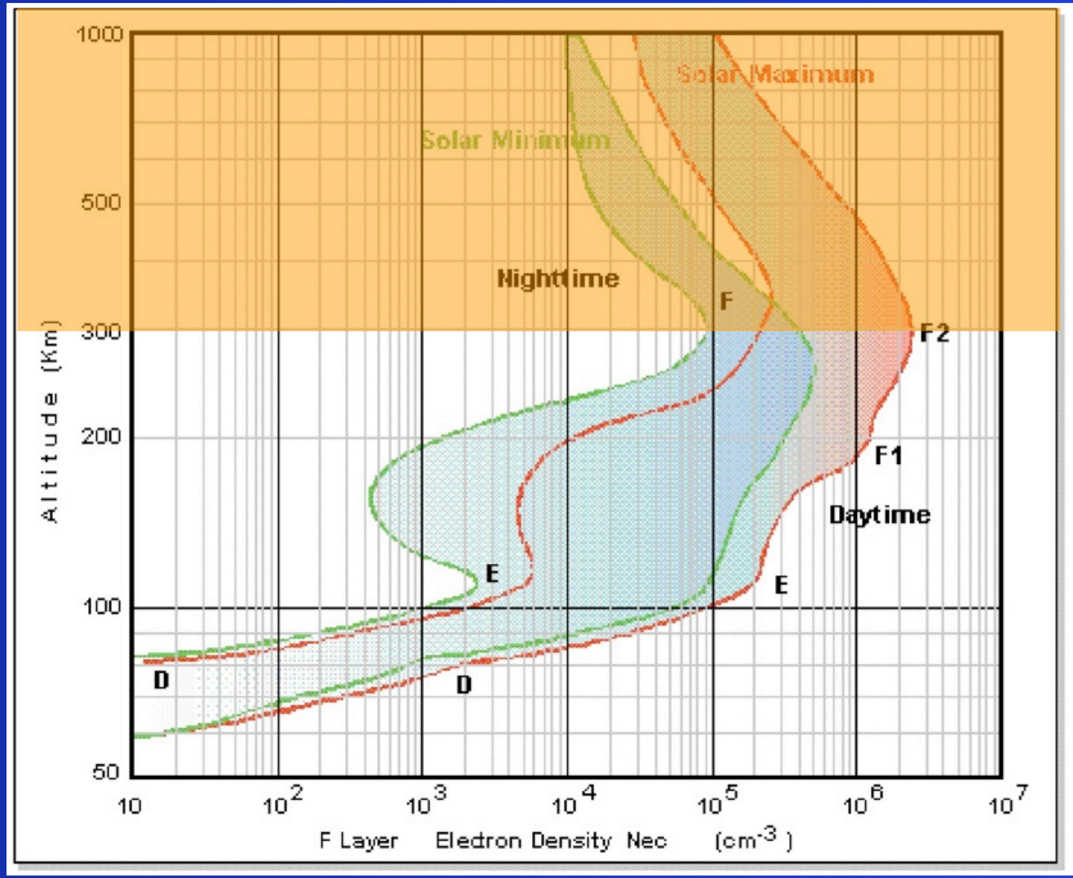

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NeQuick model

- The NeQuick is an ionospheric electron density model developed at the former Aeronomy and Radiopropagation Laboratory of The Abdus Salam International Centre for Theoretical Physics (ICTP), Trieste, Italy, and at the Institute for Geophysics, Astrophysics and Meteorology (IGAM) of the University of Graz, Austria.

- It is based on the DGR "profiler" proposed by Di Giovanni and Radicella [1990] and subsequently modified by Radicella and Zhang [1995] and is a quick run model particularly tailored for transionospheric propagation applications.

NeQuick 2

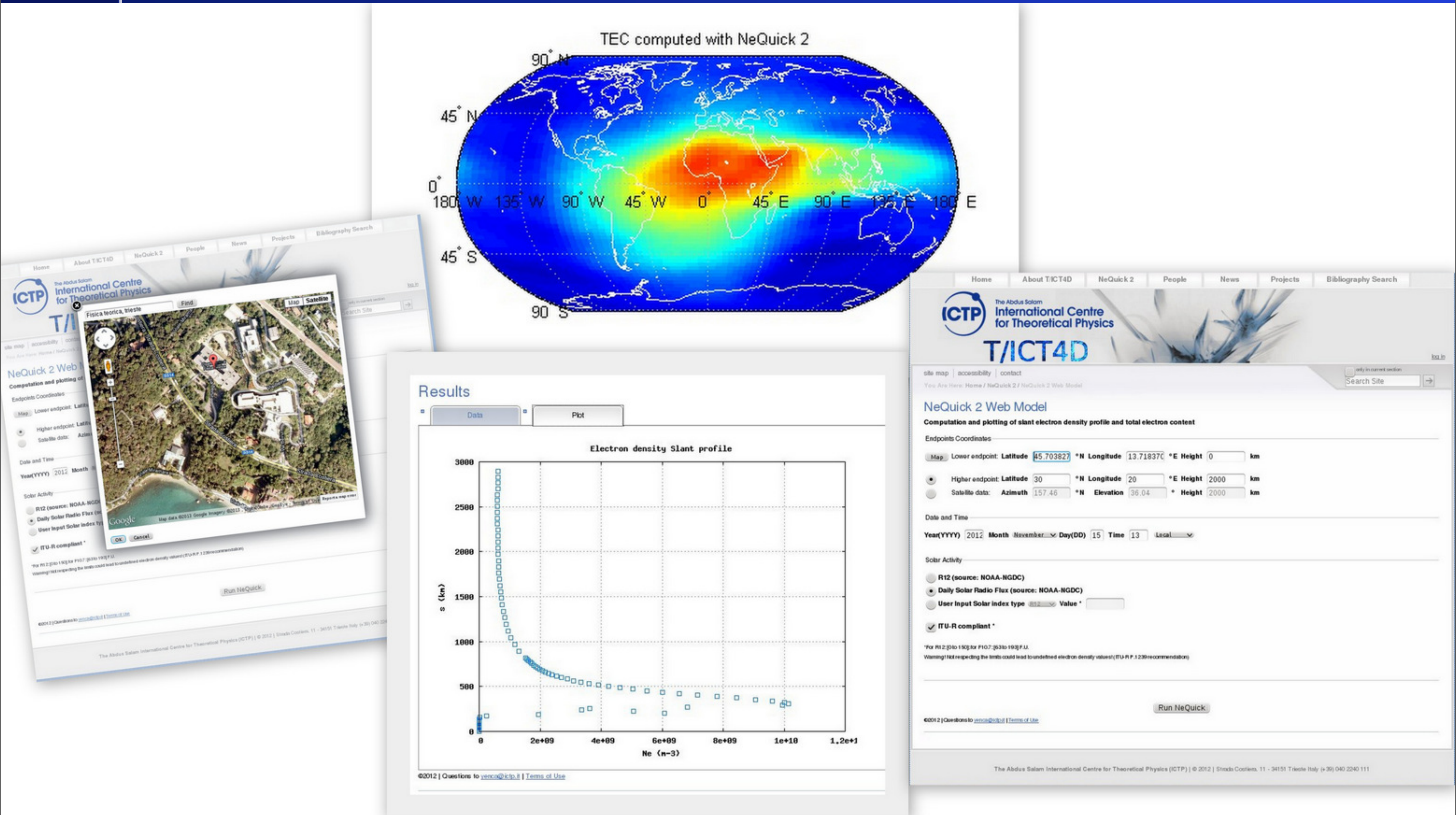
- Further improvements have been implemented by Radicella and Leitinger [2001].
- A modified bottomside has been introduced by Leitinger, Zhang, and Radicella [2005].
- A modified topside has been proposed by Coïsson, Radicella, Leitinger and Nava [2006].
- All these efforts, directed toward the developments of a new version of the model, have led to the implementation of the NeQuick2.

B. Nava, P. Coïsson, S. M. Radicella, "A new version of the NeQuick ionosphere electron density model", Journal of Atmospheric and Solar-Terrestrial Physics (2008), doi:10.1016/j.jastp.2008.01.015

NeQuick 2

- 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 (e.g. ITU-R coefficients for foF2, M(3000)F2) or experimentally derived.
- NeQuick inputs are: position, time and solar flux; the output is the electron concentration at the given location and time.
- NeQuick package includes routines to evaluate the electron density along any ray-path and the corresponding Total Electron Content (TEC) by numerical integration.

NeQuick 2 online
http://t-ict4d.ictp.it/nequick2



NeQuick 2 formulation

The model is represented by a sum of Epstein functions for the E, F1 and F2 layers:

$$N_{bot}(h) = N_E(h) + N_{F1}(h) + N_{F2}(h)$$

where

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

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

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

NeQuick 2 formulation

with

$$Nm^*E = NmE - N_{F1}(hmE) - N_{F2}(hmE)$$

$$Nm^*F1 = NmF1 - N_E(hmF1) - N_{F2}(hmF1)$$

and

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

is a function that ensures a “fade out” of the E and F1 layers layers in the vicinity of the F2 layer peak in order to avoid secondary maxima around hmF2.

NeQuick 2 formulation

The model topside is represented by a semi-Epstein layer with a height-dependent thickness parameter H:

$$N(h) = \frac{4NmF2}{(1+\exp(z))^2}\exp(z)$$

with

$$z = \frac{h - hmF2}{H}$$

$$H = H_0\left[1 + \frac{rg(h - hmF2)}{rH_0 + g(h - hmF2)}\right]$$

NeQuick 2 formulation

Peak heights

$$hmE = 120$$

$$hmF1 = \frac{hmE + hmF2}{2}$$

$$hmF2 = \frac{1490MF}{M + \Delta M} - 176$$

with

$$\Delta M = \begin{cases} 0.253/(foF2/foE \\ \quad -1.215) - 0.012, \\ -0.012 & \text{if } foE = 0, \end{cases}$$

$$MF = M\sqrt{\frac{0.0196M^2 + 1}{1.2967M^2 - 1}} \qquad M = M(3000)F2.$$

NeQuick 2 formulation

Thickness parameters

$$BE_{bot} = 5$$

$$BE_{top} = \max\left(0.5\left(hmF1 - hmE\right), 7\right)$$

$$B1_{bot} = 0.5\left(hmF1 - hmE\right)$$

$$B1_{top} = 0.3\left(hmF2 - hmF1\right)$$

$$B2_{bot} = \frac{0.385NmF2}{\left(dN/dh\right)_{max}}$$

$$H = kB2_{bot}\left[1 + \frac{rg\left(h - hmF2\right)}{rkB2_{bot} + g\left(h - hmF2\right)}\right]$$

NeQuick 2 formulation

where

$$\ln\left(\left(\frac{dN}{dh}\right)_{max}\right) = -3.467 + 1.714\ln\left(foF2\right) + 2.02\ln\left(M(3000)F2\right)$$

and

$$k = 3.22 - 0.0538 foF2 - 0.00664 hmF2 + 0.113\frac{hmF2}{B2_{bot}} + 0.00257 R12$$

NeQuick 2 formulation

Critical frequencies and propagation factor

$$(foE)^2 = \left(a_e\sqrt{F107}\right)^2 (\cos\chi_{eff})^{0.6}$$

$$foF1 = \begin{cases} 1.4\ foE & \text{if} \quad foE \geq 2 \\ 0 & \text{if} \quad foE < 2 \\ 0.85\ 1.4\ foE & \text{if } 1.4\ foE > 0.85\ foF2 \end{cases}$$

$foF2$ modeled in terms of ITU – R coefficients

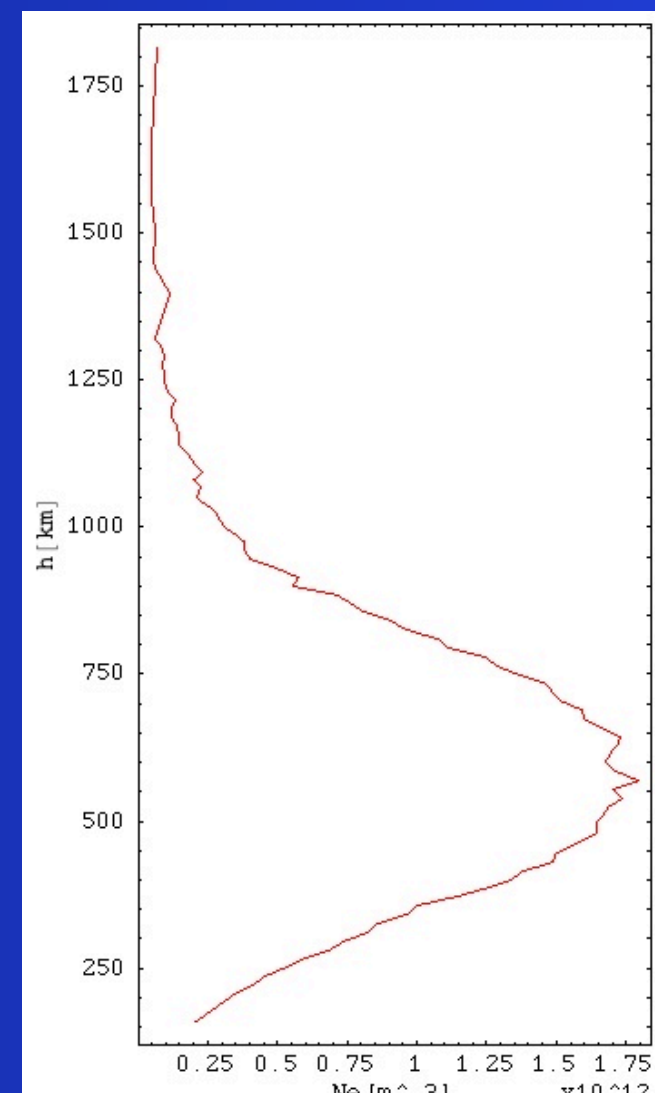
$M = M(3000)F2.$ modeled in terms of ITU – R coefficients

Ionospheric measurements

Remote sensing techniques

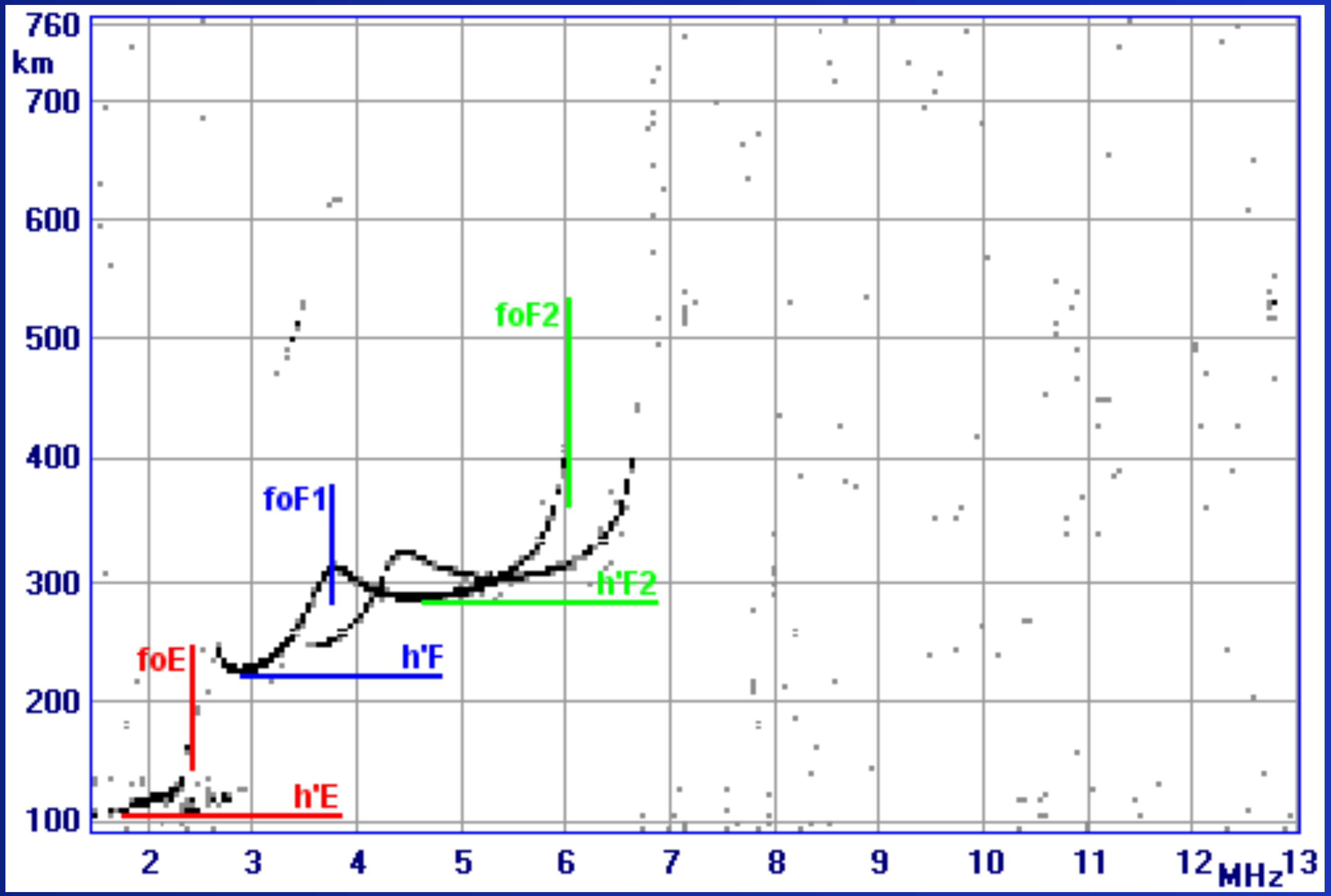
- Bottom-side soundings (ionosonde, from the ground, critical frequencies)
- Top-side soundings (ionosonde, satellite borne, critical frequency/ies)
- Ground based and space based Total Electron Content (TEC) measurements (GNSS)
- Incoherent scatter radar (from the ground, N profile)

The Jicamarca Radio Observatory
http://jicamarca.ece.cornell.edu/



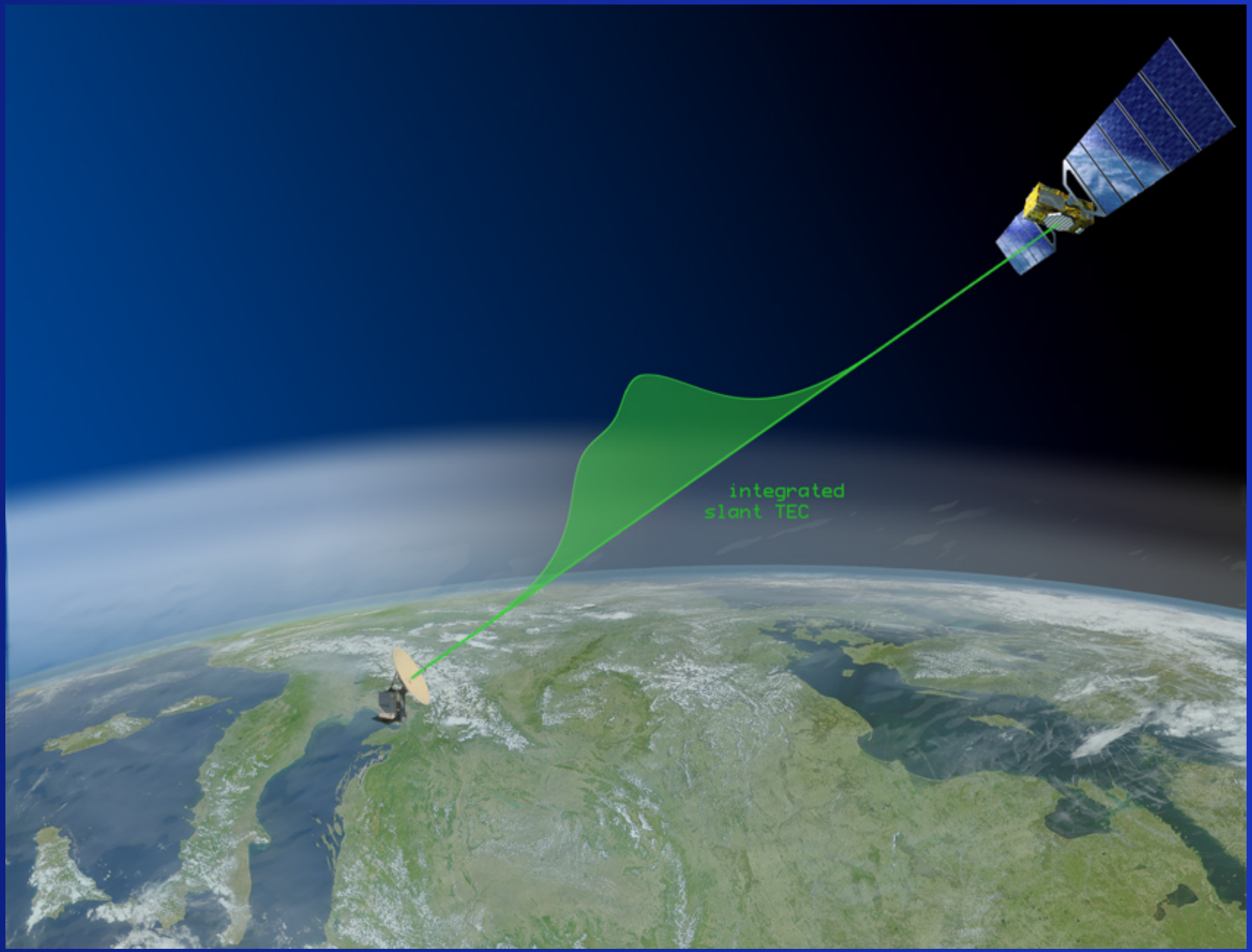
Ionospheric measurements

Ionogram



Critical frequency: the frequency at which an e.m. wave just penetrates an ionospheric layer is known as the critical frequency of that layer.
Frequency is related to the electron density by the simple relation: $f=9\sqrt{N}$
f in Hz; N in m^{-3}

Ionospheric measurements



TEC: The total electron content (TEC) is the number of free electrons in a column of one square-metre cross-section along a given ray-path.

$$TEC = \int N(s)ds$$

Model adaptation to experimental data

- Empirical models like IRI and NeQuick have been developed as climatological models, able to reproduce the typical median condition of the ionosphere.

- For research purposes and practical applications, in order to pass from “climate” to “weather”, there is a need to have models able to reproduce the current conditions of the ionosphere.

- Considering that there is an increasing availability of experimental data even in real time (ground and space-based GPS, ionosondes), several assimilation schemes have been developed. They are of different complexity and rely on different kinds of data.

Assimilation schemes (example)

- 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], for example, are based on assimilation of data originating from different sources and imply the use of first principle models.

- The Electron Density Assimilative Model (EDAM) [Angling and Khattatov, 2006] provides a means to assimilate ionospheric measurements into a background ionospheric model (that can be the IRI).

- Review paper: Bust, G. S., and C. N. Mitchell (2008), “History, current state, and future directions of ionospheric imaging, Rev. Geophys., 46,RG1003, doi:10.1029/2006RG000212.

Effective parameters

- In the case of NeQuick, the methods used to adapt the model to experimental data in order to retrieve the 3D electron density of the ionosphere are intended to be simple and quick.

- Therefore they rely on the use of “effective” parameters, that are defined on the bases of model (e.g. NeQuick) and the experimental data used (e.g. foF2 or TEC).

- One of the first effective parameter that has been proposed is the “effective sunspot number” (SSNe). This parameter valid for a set of foF2 observations has been defined as the SSN value that, when used as input to the URSI foF2 model, gives a weighted zero-mean difference between the observed and the modeled foF2 values.

Effective parameters

- IRI IG 12
  http://gge.unb.ca/gauss/htdocs/grads/attila/papers/52am/ion52am.pdf

- T-index
  http://www.ips.gov.au/HF_Systems/1/6
  (The T index is an indicator of the highest frequencies able to be refracted from regions in the ionosphere).

- Klobuchar-Style Ionospheric Coefficients
  http://aiuws.unibe.ch/ionosphere/#cgim
  (Klobuchar-style alpha and beta coefficients best fitting VTEC data)

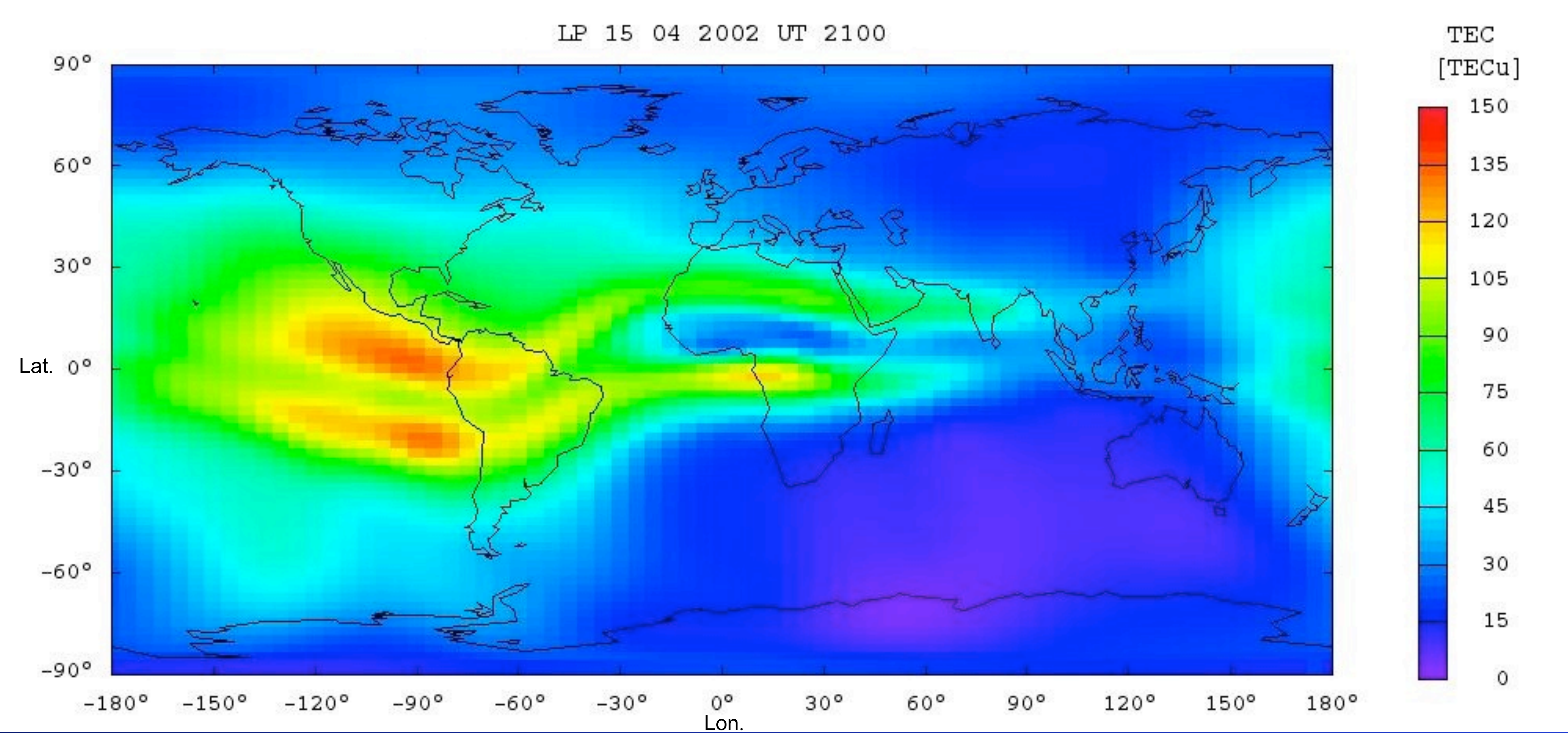
Basic concepts

Model(s) features relevant to implement adaptation techniques.

- The model can be considered as profiler.
  - The profile formulation is based on anchor points modeled in terms of ionosonde parameters (e.g. foE, foF1, foF2 and M(3000)F2).
- For a given epoch & ray-path the model TEC is a monotonic function of the solar activity index, that can be regarded as an "effective ionization level" parameter.

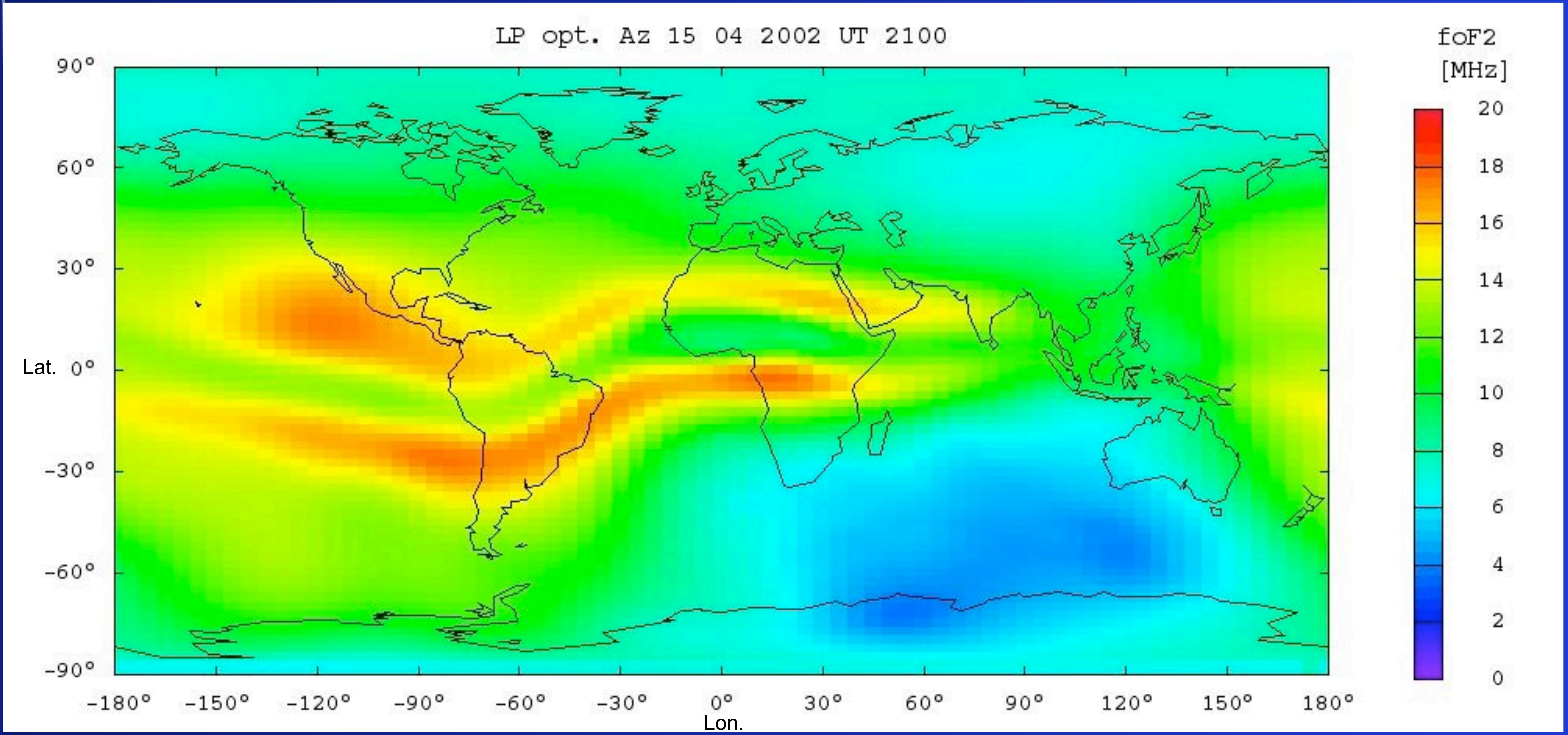
Adapting NeQuick model to vertical TEC maps

vTEC map La Plata



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

Reconstructed foF2 map



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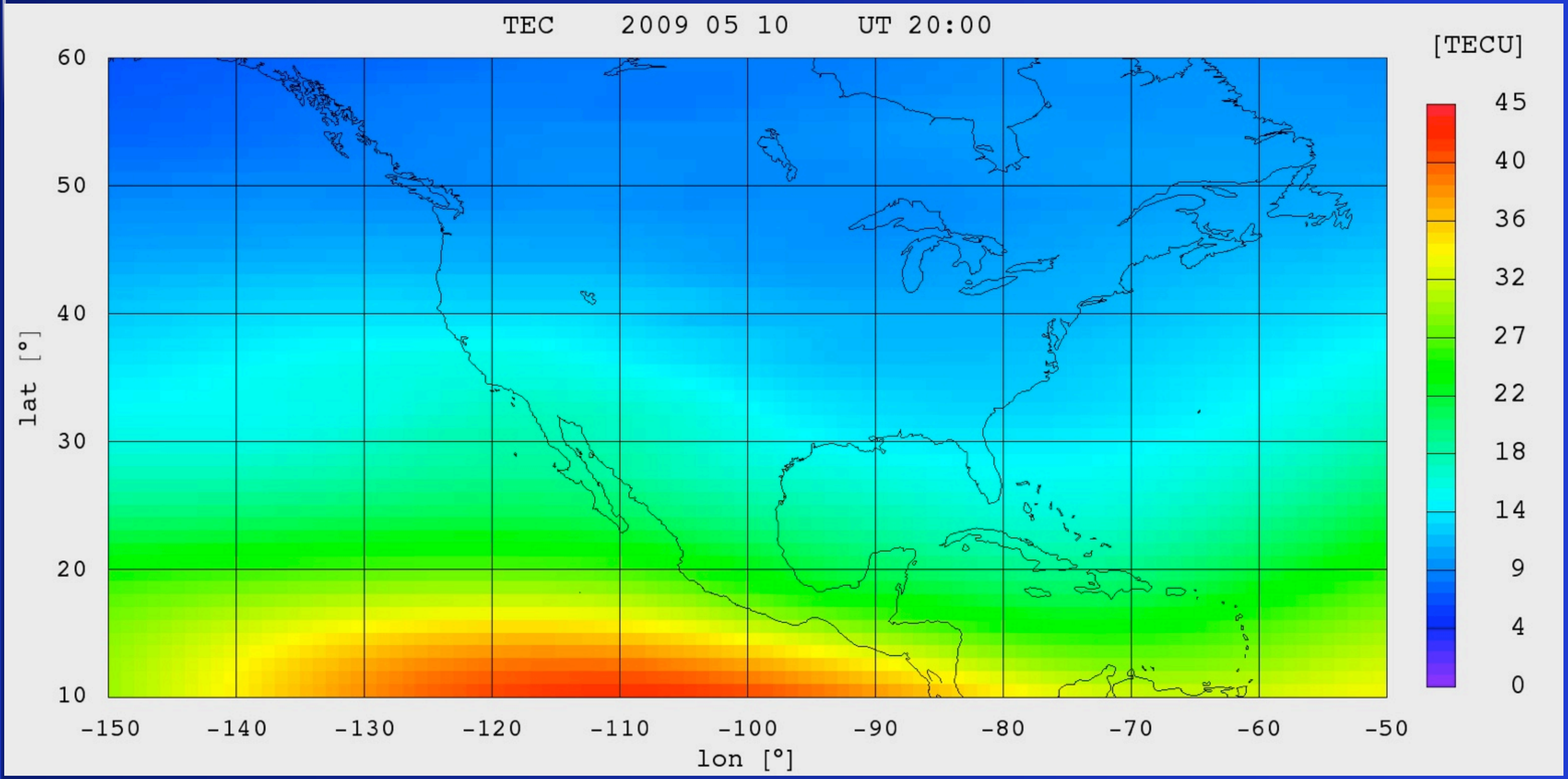
vTEC map USTEC



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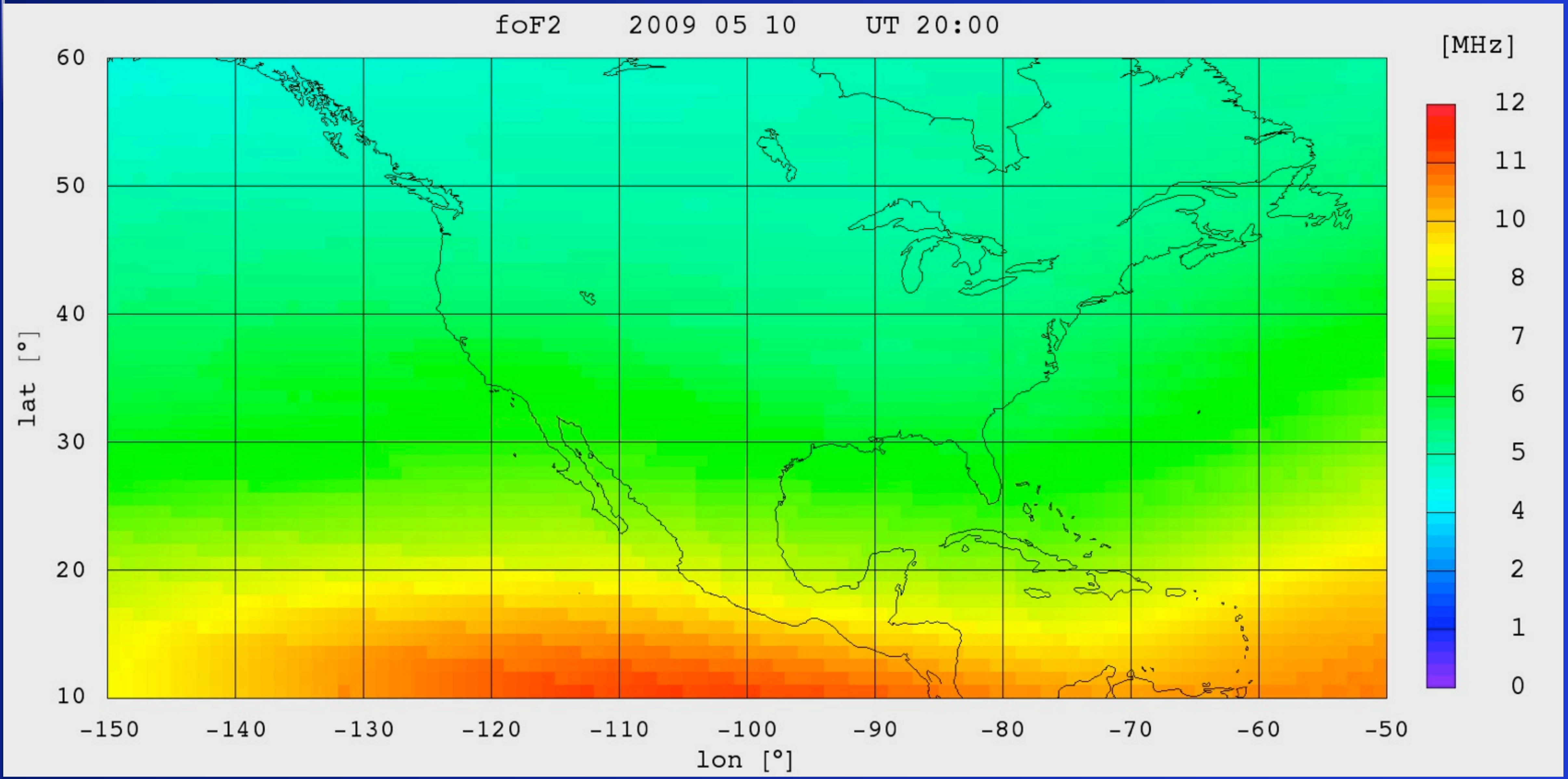
Reconstructed foF2 map



grid points:
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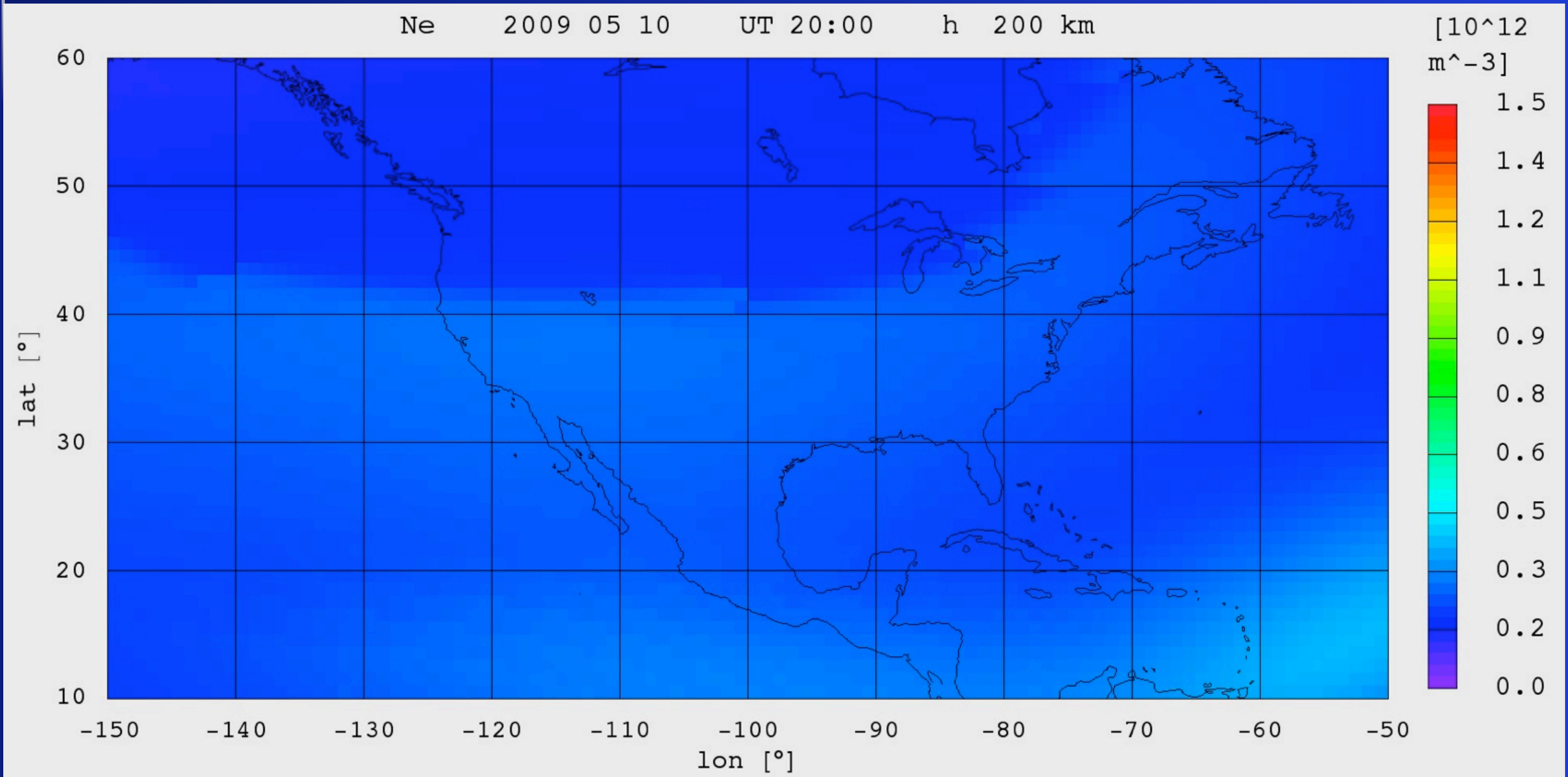
Reconstructed Ne map



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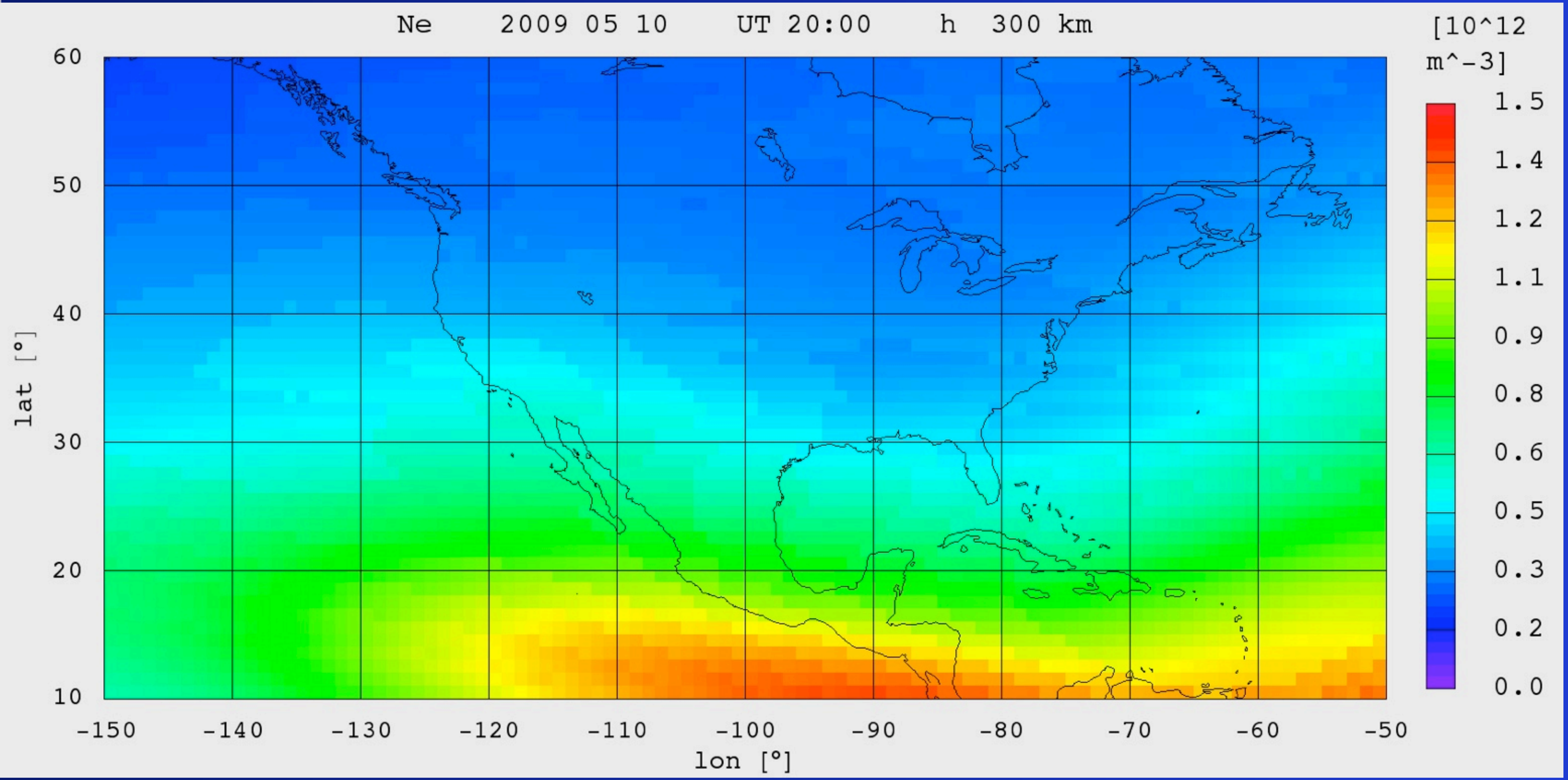
Reconstructed Ne map



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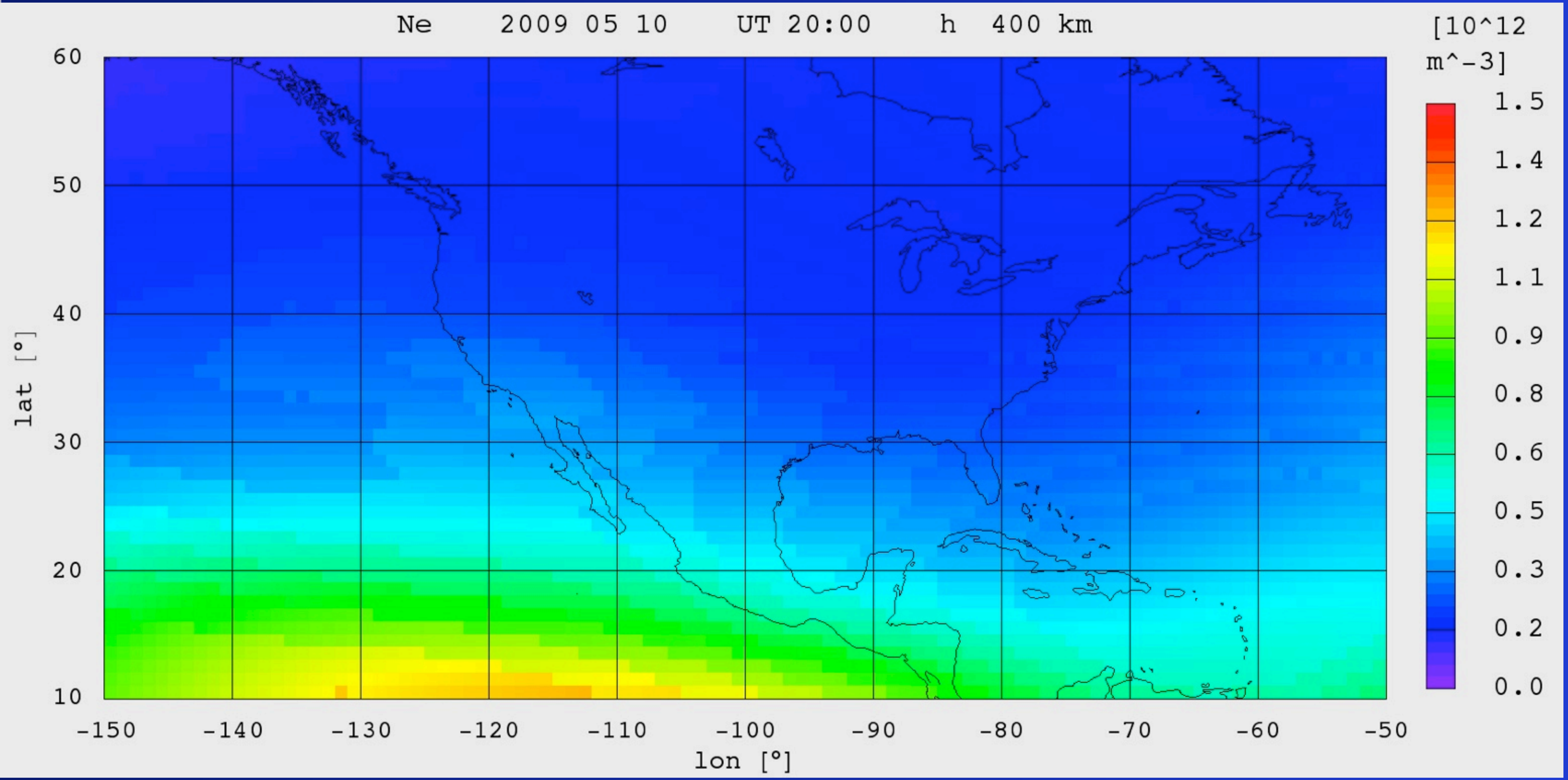

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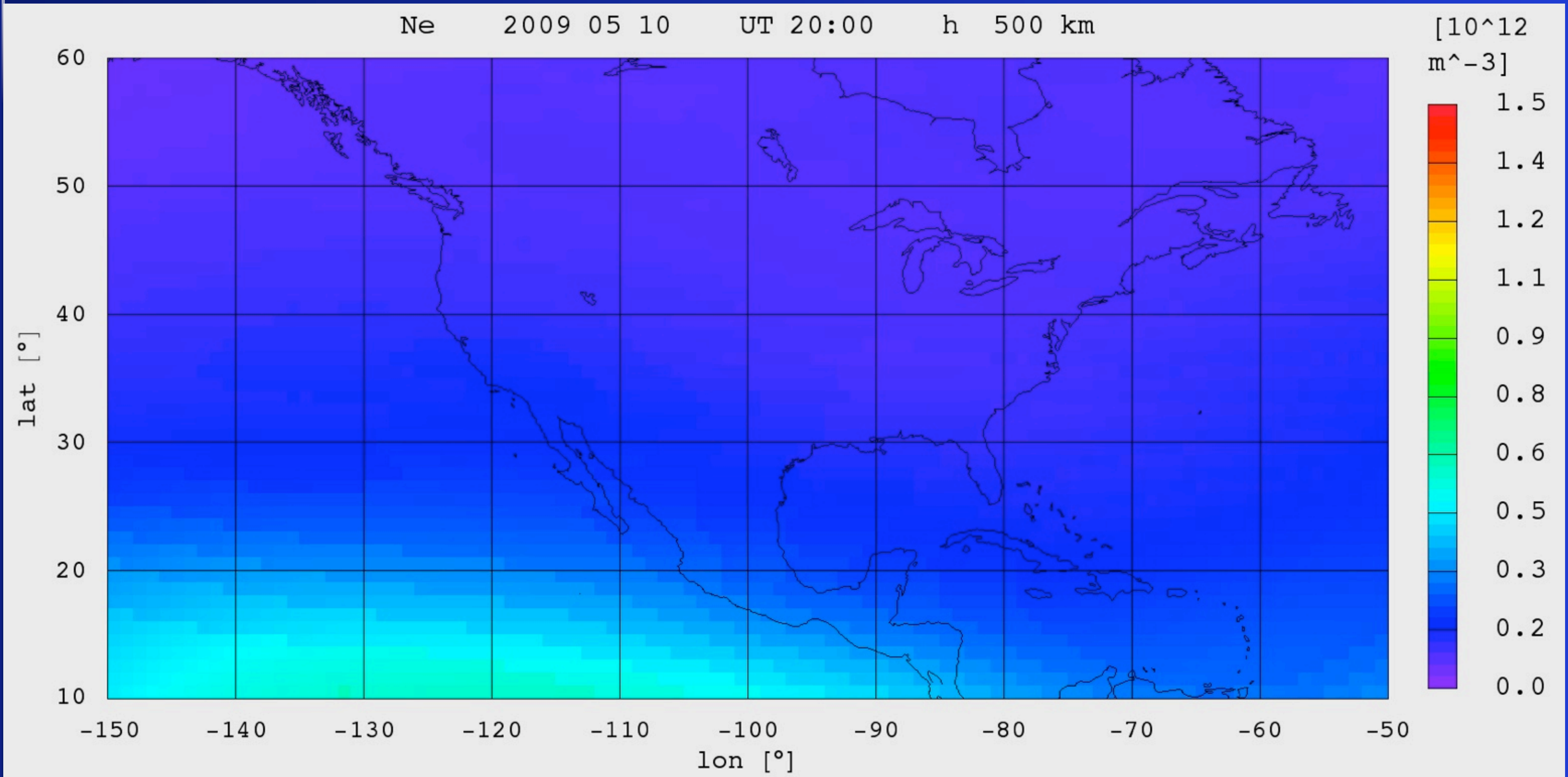

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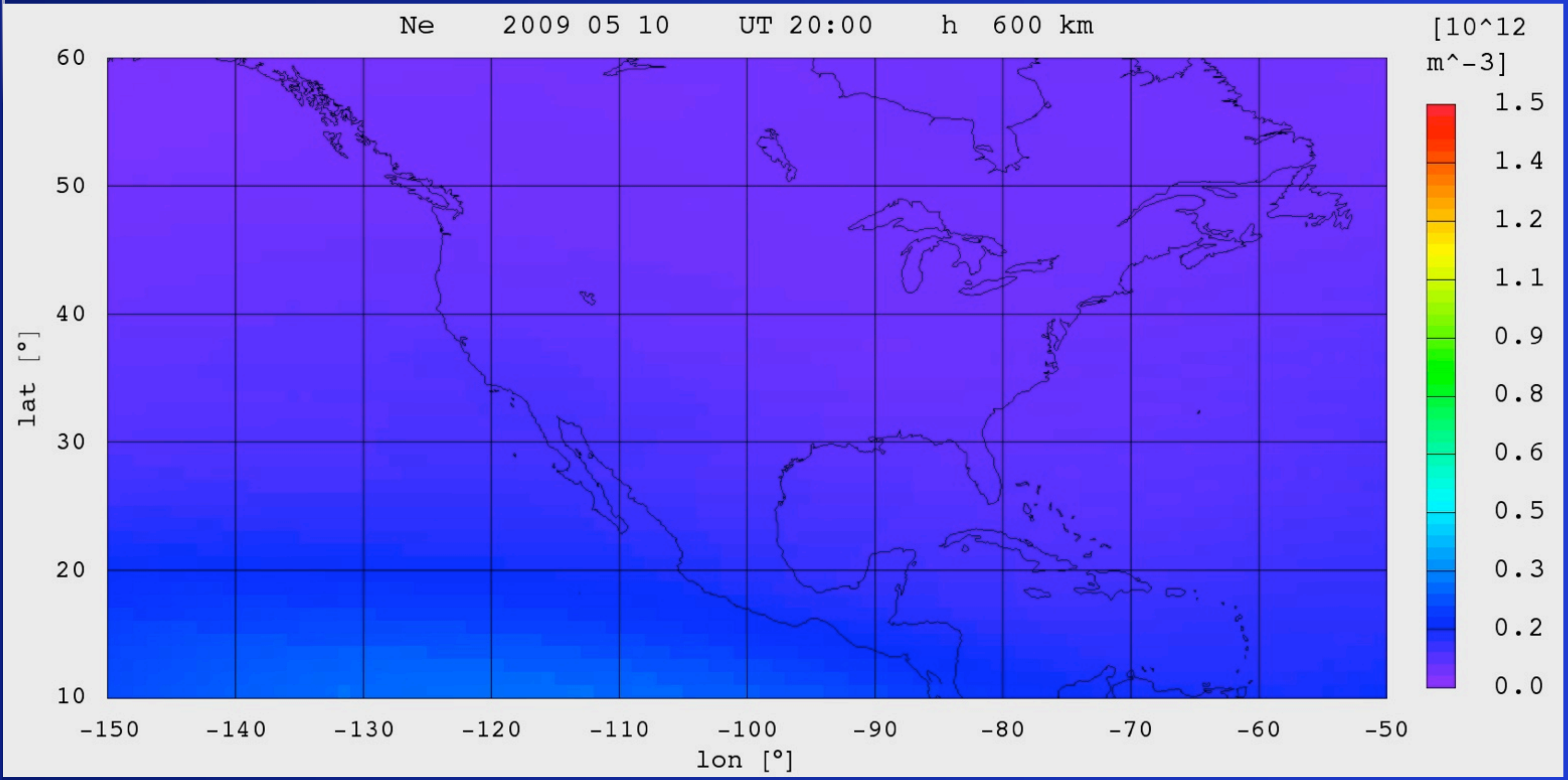

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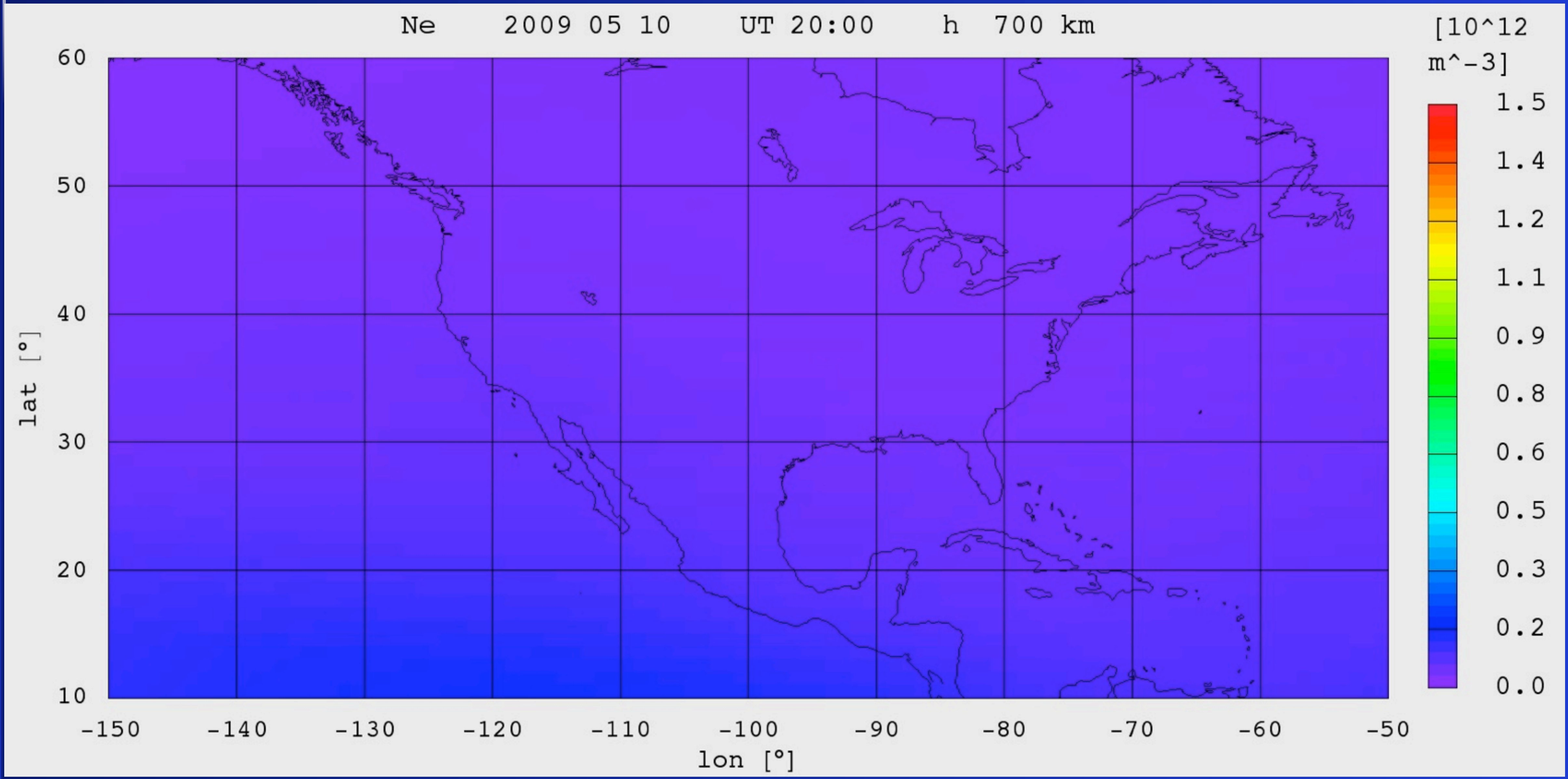

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vTEC map data ingestion

At a given epoch

One vTEC map

↓

Minimize the mismodelings

$|vTECexp_i - vTECmod(az)_i|$

↓

Az (effective F10.7) grid

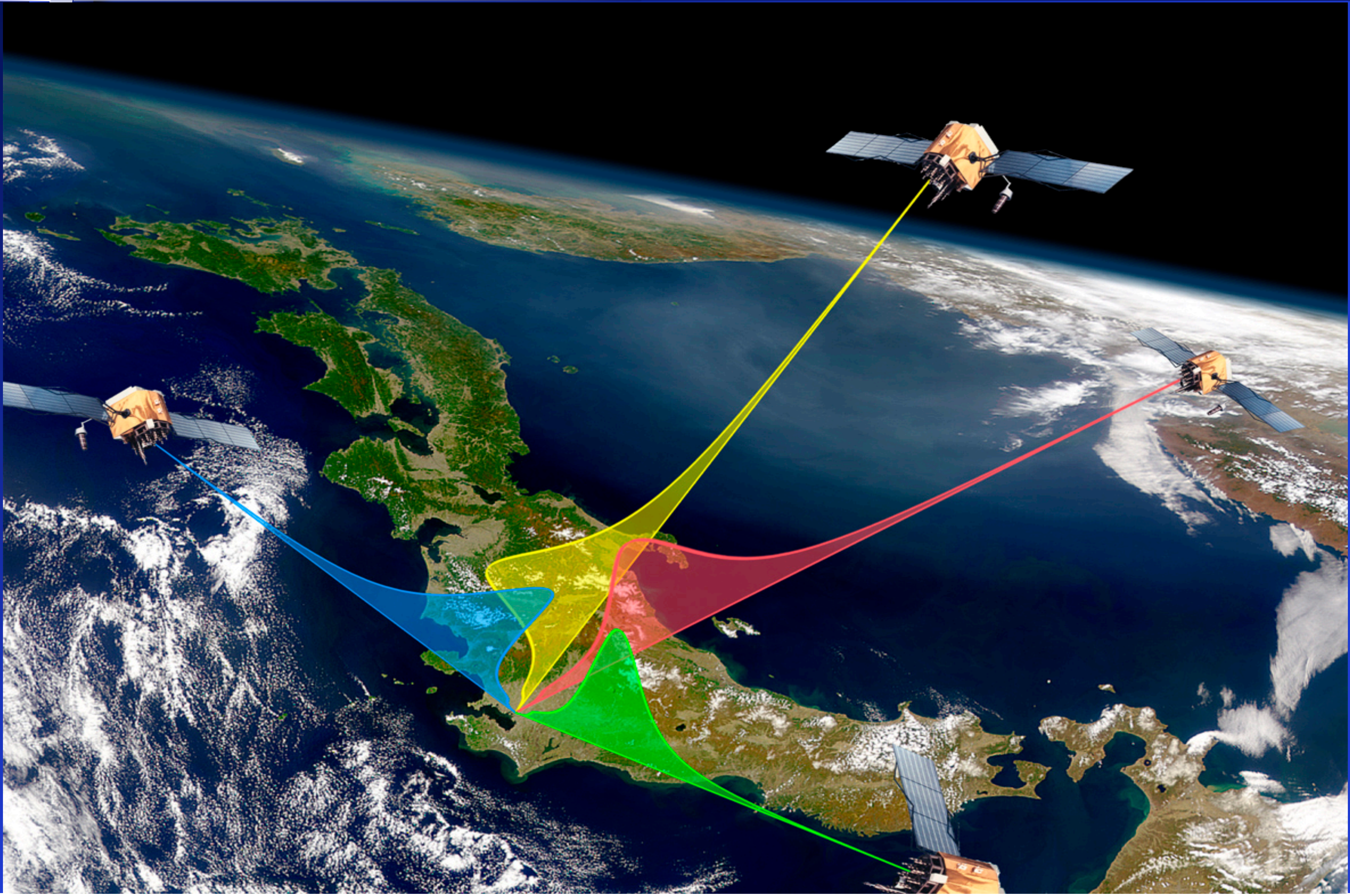
↓

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

An application



The test case

Position calculation mitigating
the ionospheric effect with:

↙ ↘

ICA, Klobuchar model
(driven by 8 coefficients)

NeQuick 2 model
(driven by f10.7)

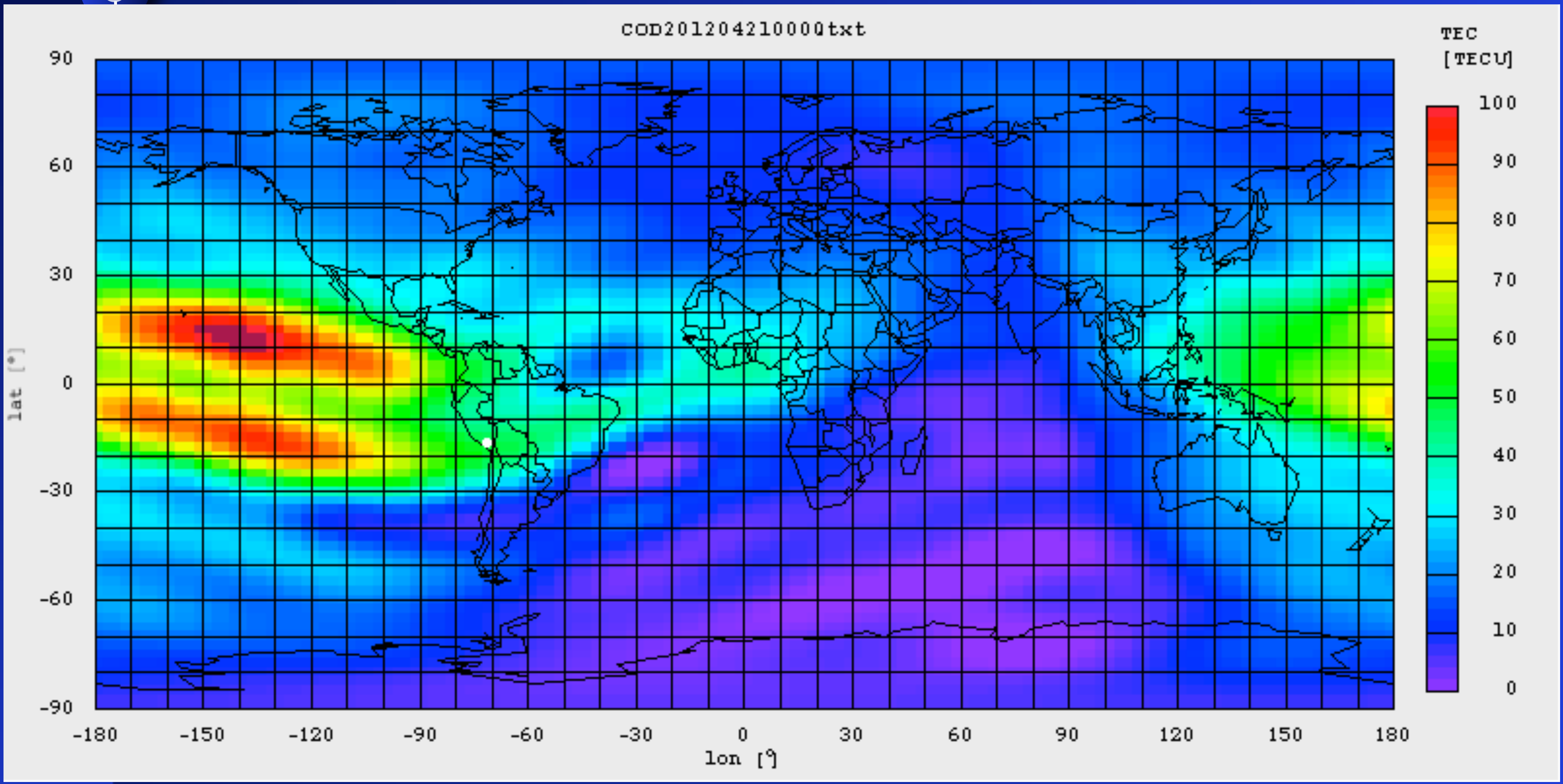
CODE VTEC maps
(SBAS type approach)

NeQuick 2 model
(driven by Az grids)

areq (-16.46°N; -71.48°E)

2012 Apr 21; (doy 112)

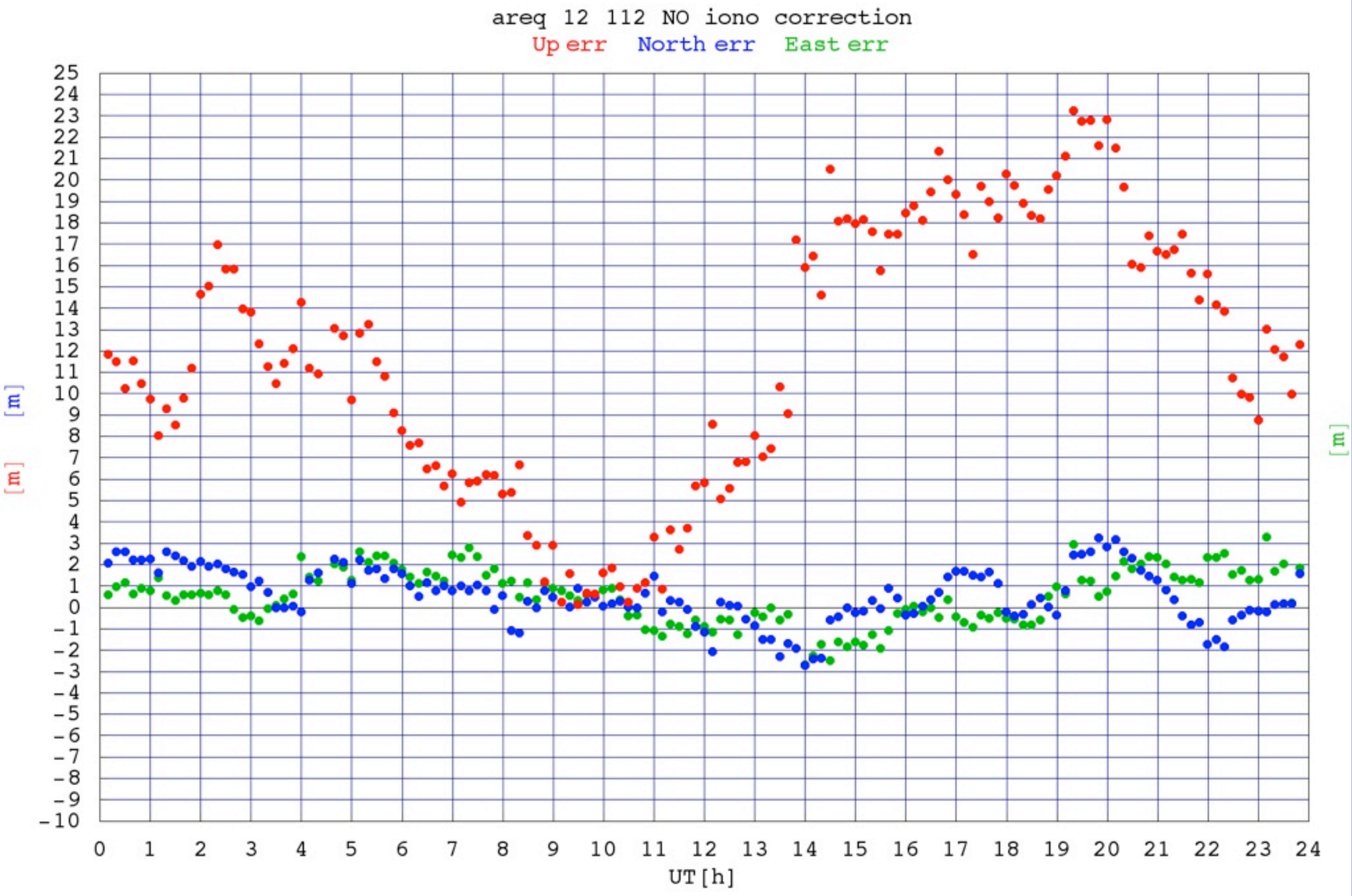
CODE VTEC map 2012 04 21



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

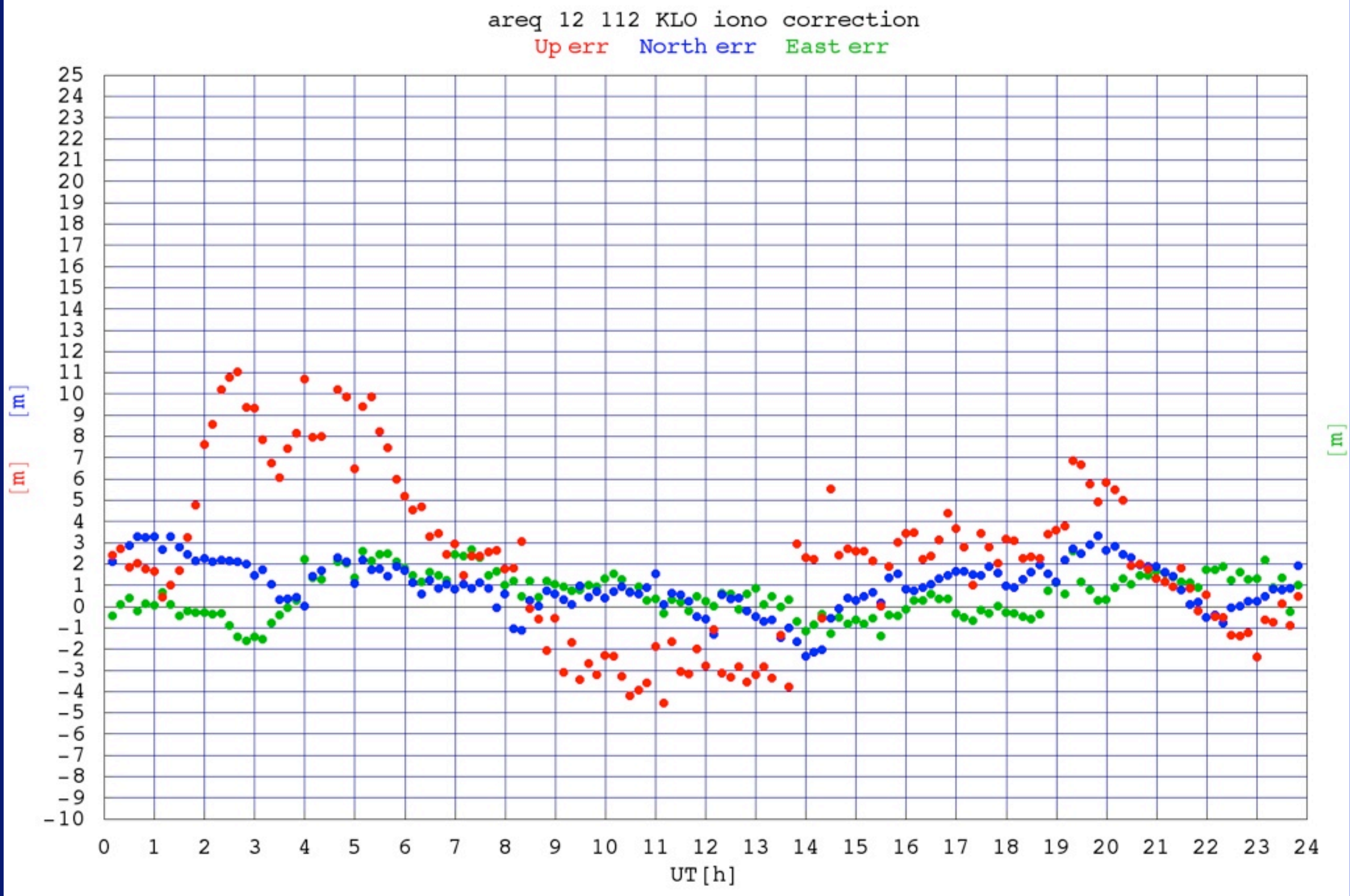
time interval:
10 min.
(interpolation)

Results



areq 12 112 NO iono correction
Up err North err East err
[m]
[m]
[m]
UT [h]
25 24 23 22 21 20 19 18 17 16 15 14 13 12 11 10 9 8 7 6 5 4 3 2 1 0 -1 -2 -3 -4 -5 -6 -7 -8 -9 -10
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24

Results



areq 12 112 KLO iono correction
Up err North err East err
[m]
[m]
[m]
25
24
23
22
21
20
19
18
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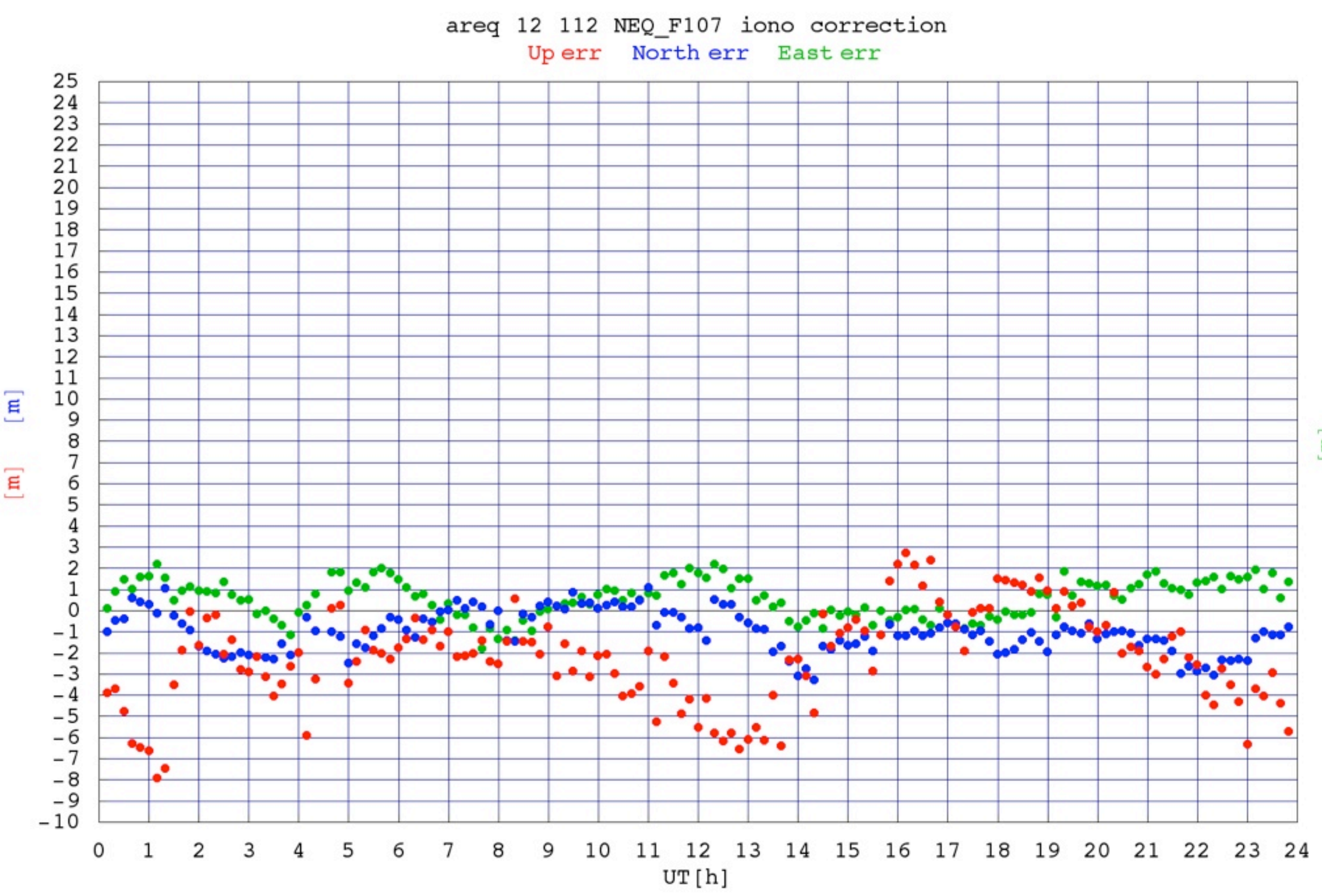
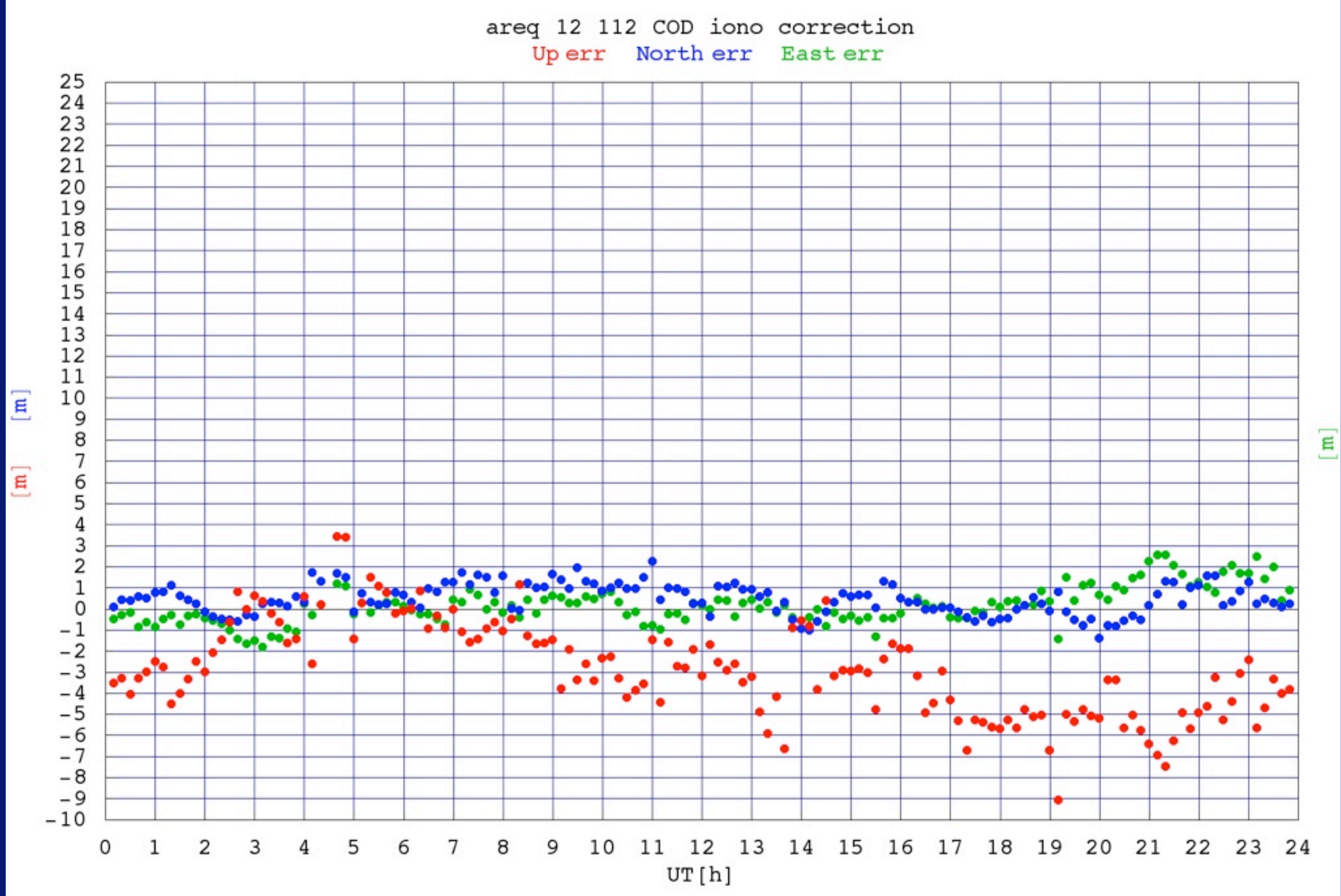
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
UT [h]

Results



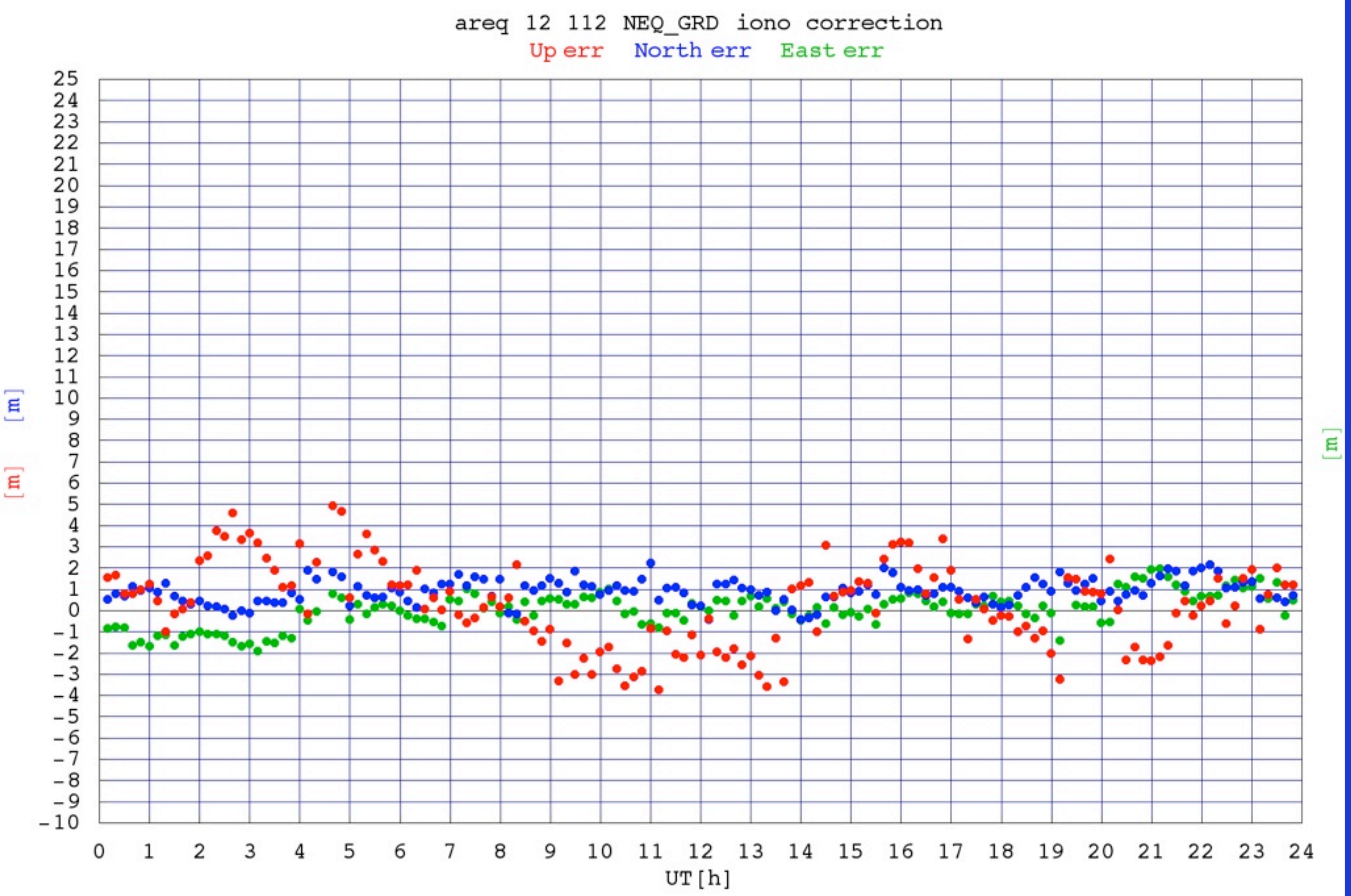
areq 12 112 NEQ_F107 iono correction
Up err
North err
East err
25 24 23 22 21 20 19 18 17 16 15 14 13 12 11 10 9 8 7 6 5 4 3 2 1 0 -1 -2 -3 -4 -5 -6 -7 -8 -9 -10
[m]
[m]
[m]
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
UT [h]

Results



areq 12 112 COD iono correction
Up err
North err
East err
[m]
[m]
[m]
UT [h]

Results


areq 12 112 NEQ_GRD iono correction
Up err
North err
East err
[m]
[m]
[m]
UT [h]
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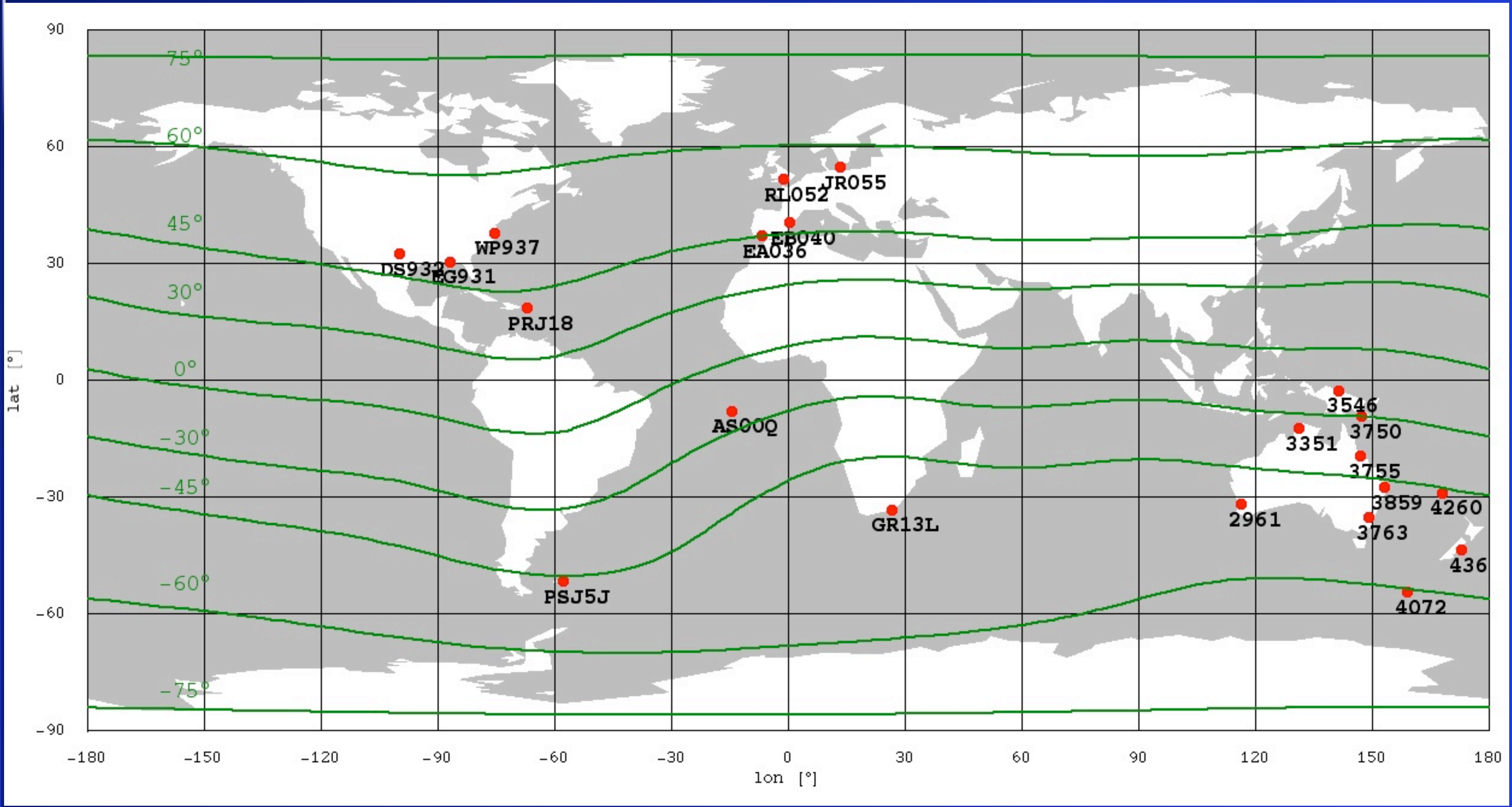
vTec map ingestion scheme validation

- using LaPlata global vTEC maps and manually scaled foF2 values
- hourly data for Apr. 2000 (HSA) and Sep. 2006 (LSA) have been used
- statistics on: $\Delta foF2 = foF2_{NeQ2} - foF2_{exp}$

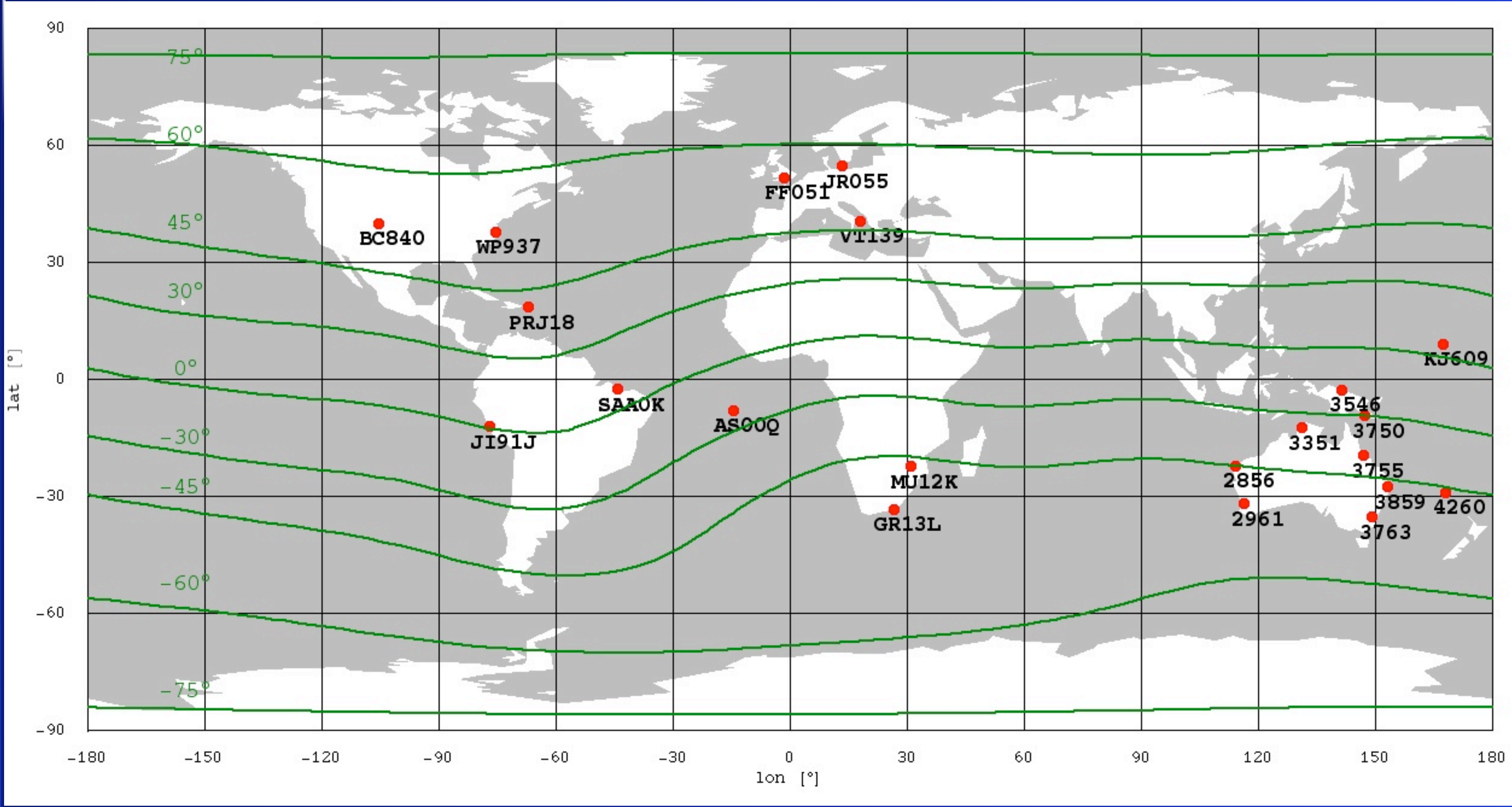
Notice: validation is on sTEC calibration + mapping function + spherical harmonics expansion + ITU-R coeff + model formulation + vTEC data ingestion technique.

Apr 2000



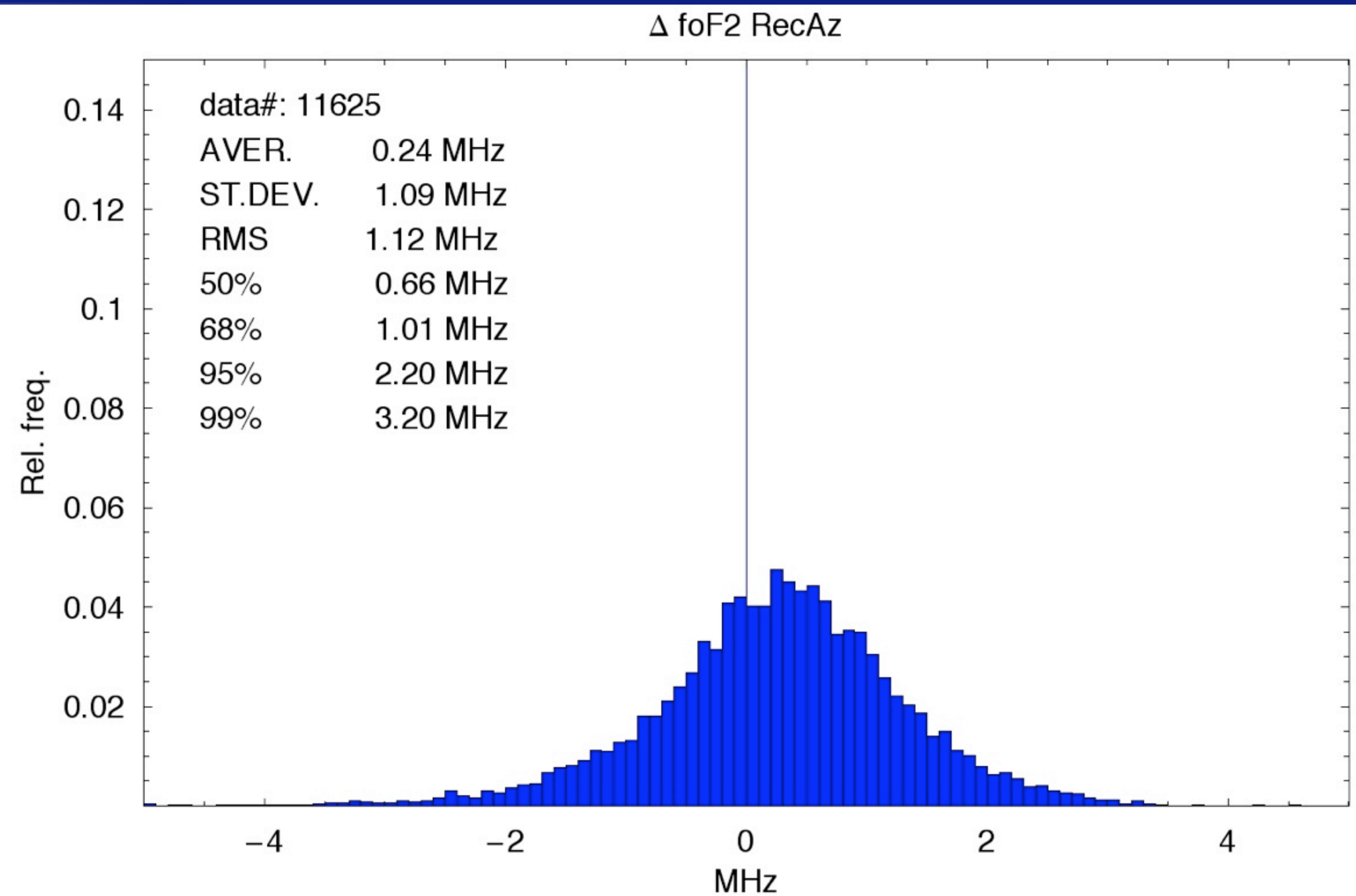
Location of the Ionosondes used for the validation

Sep 2006

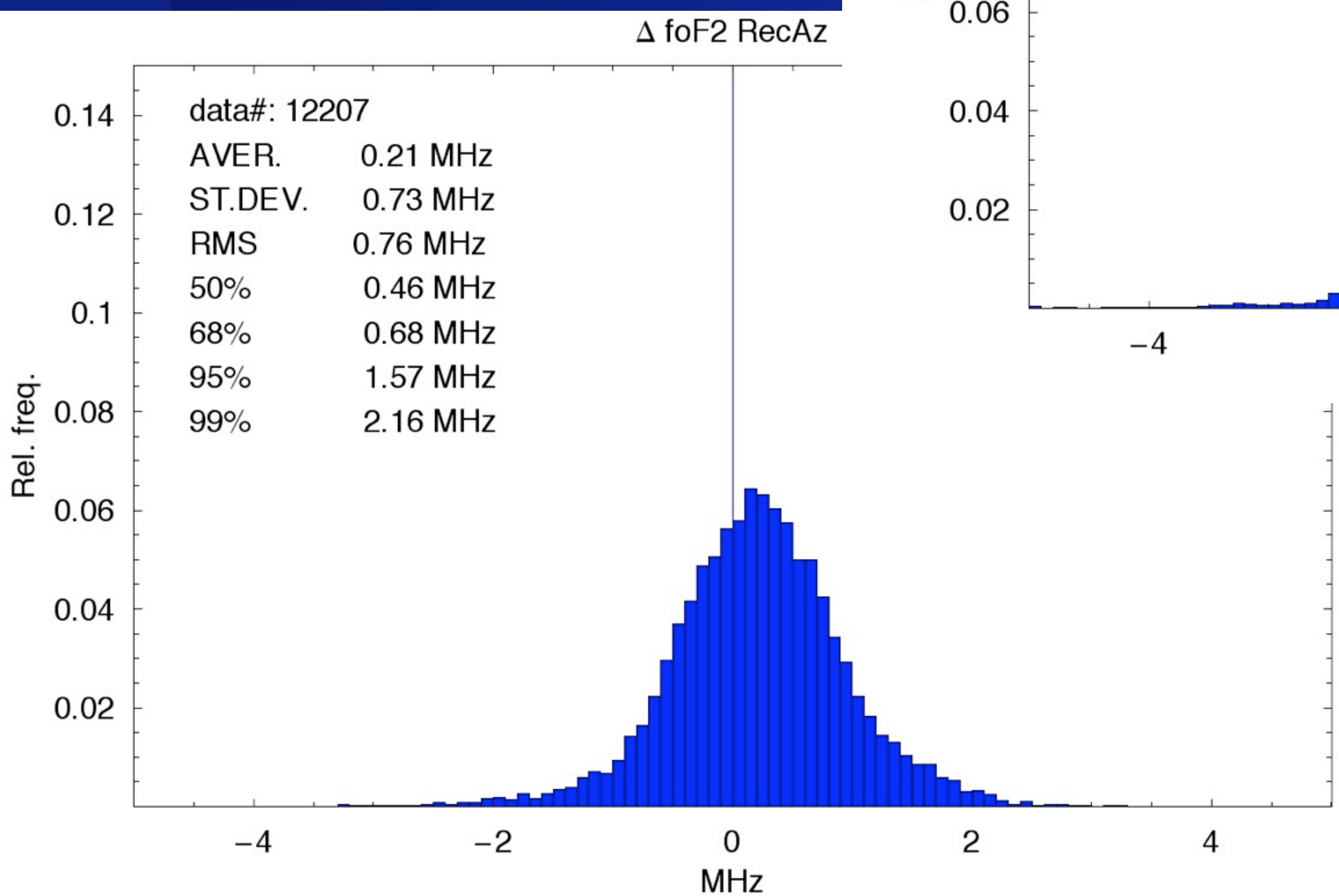


Location of the Ionosondes used for the validation

Global statistics (effective F10.7)

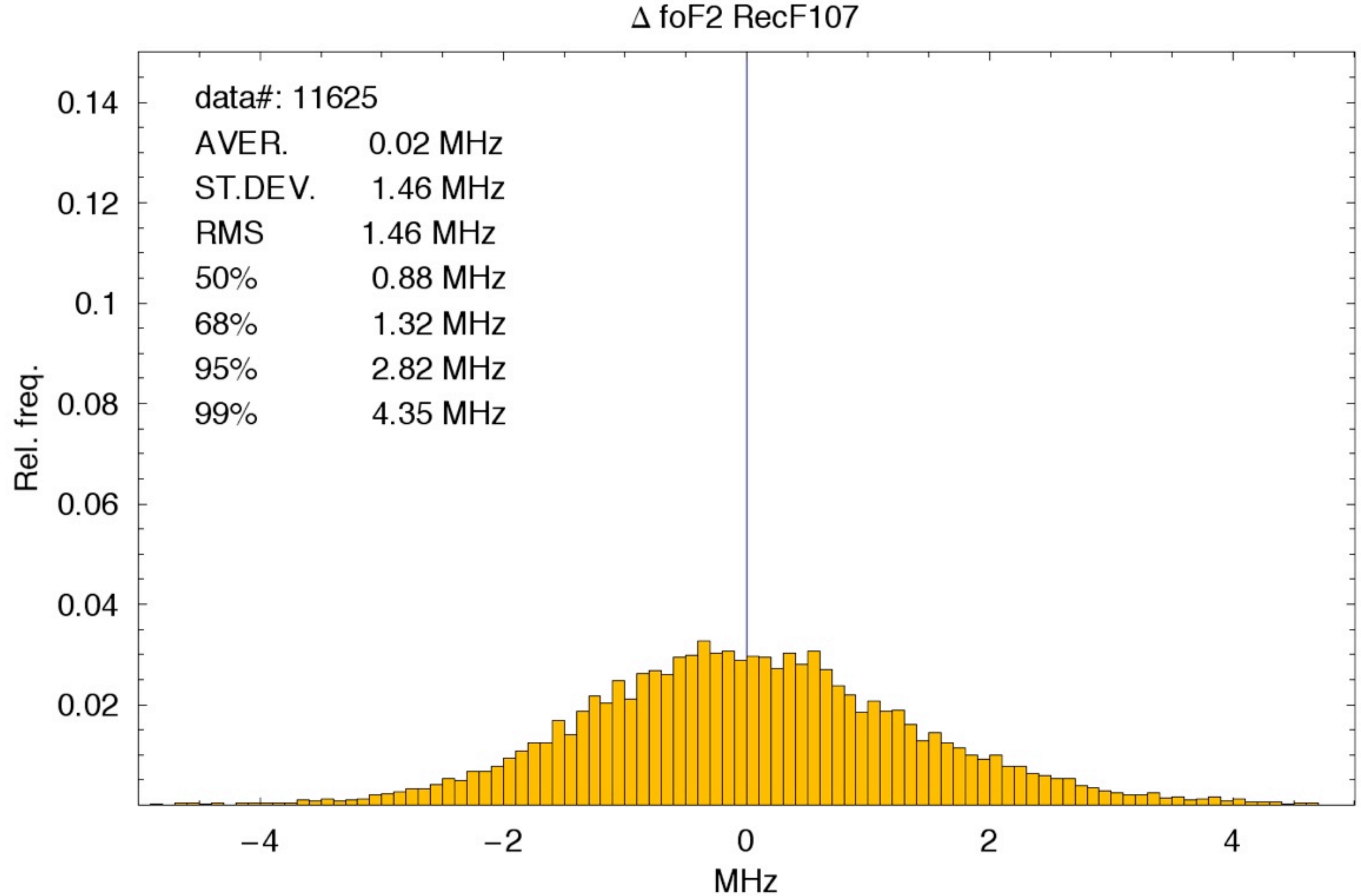


Apr. 2000

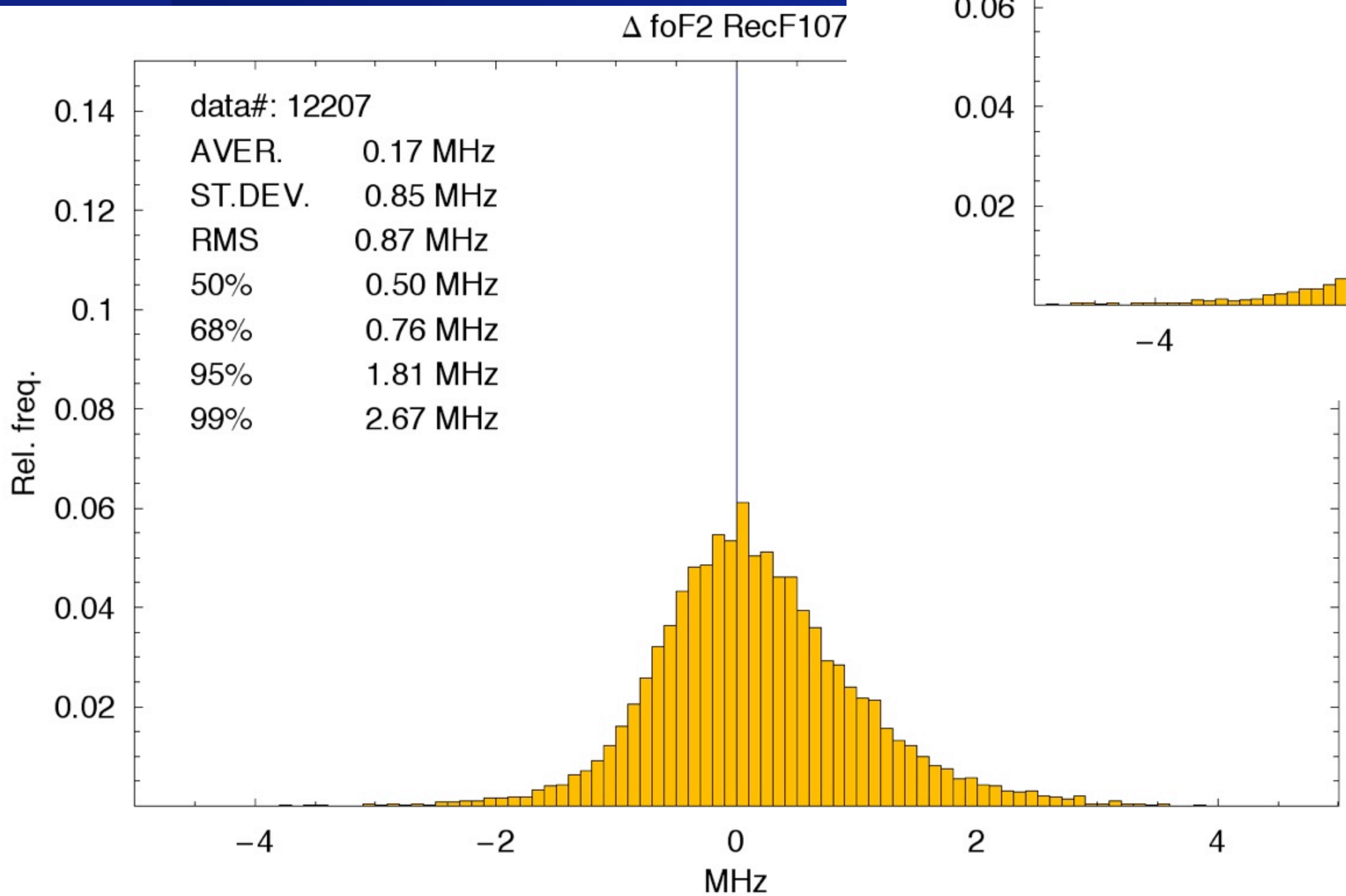


Sep. 2006

Global statistics (daily f10.7)

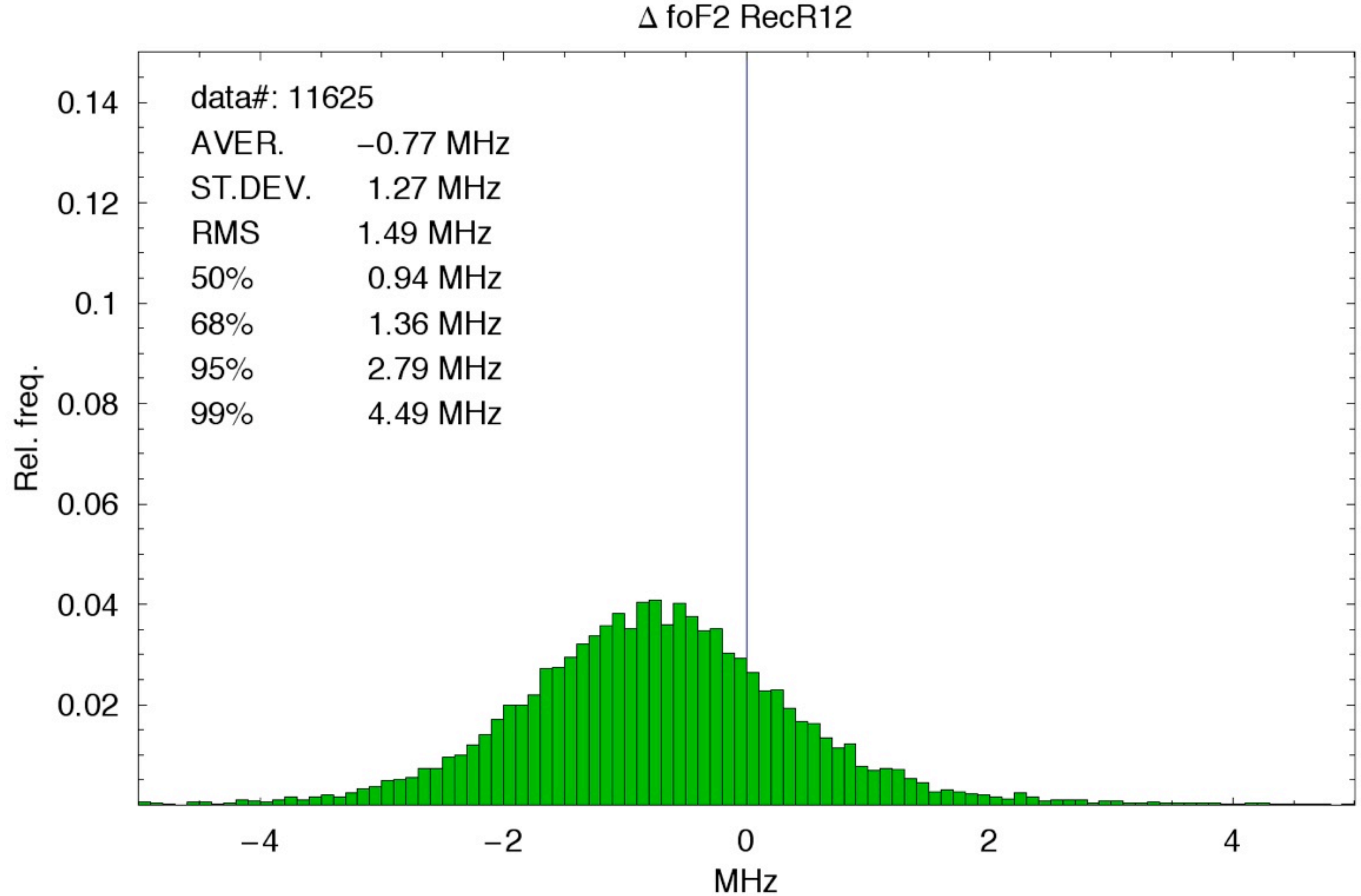


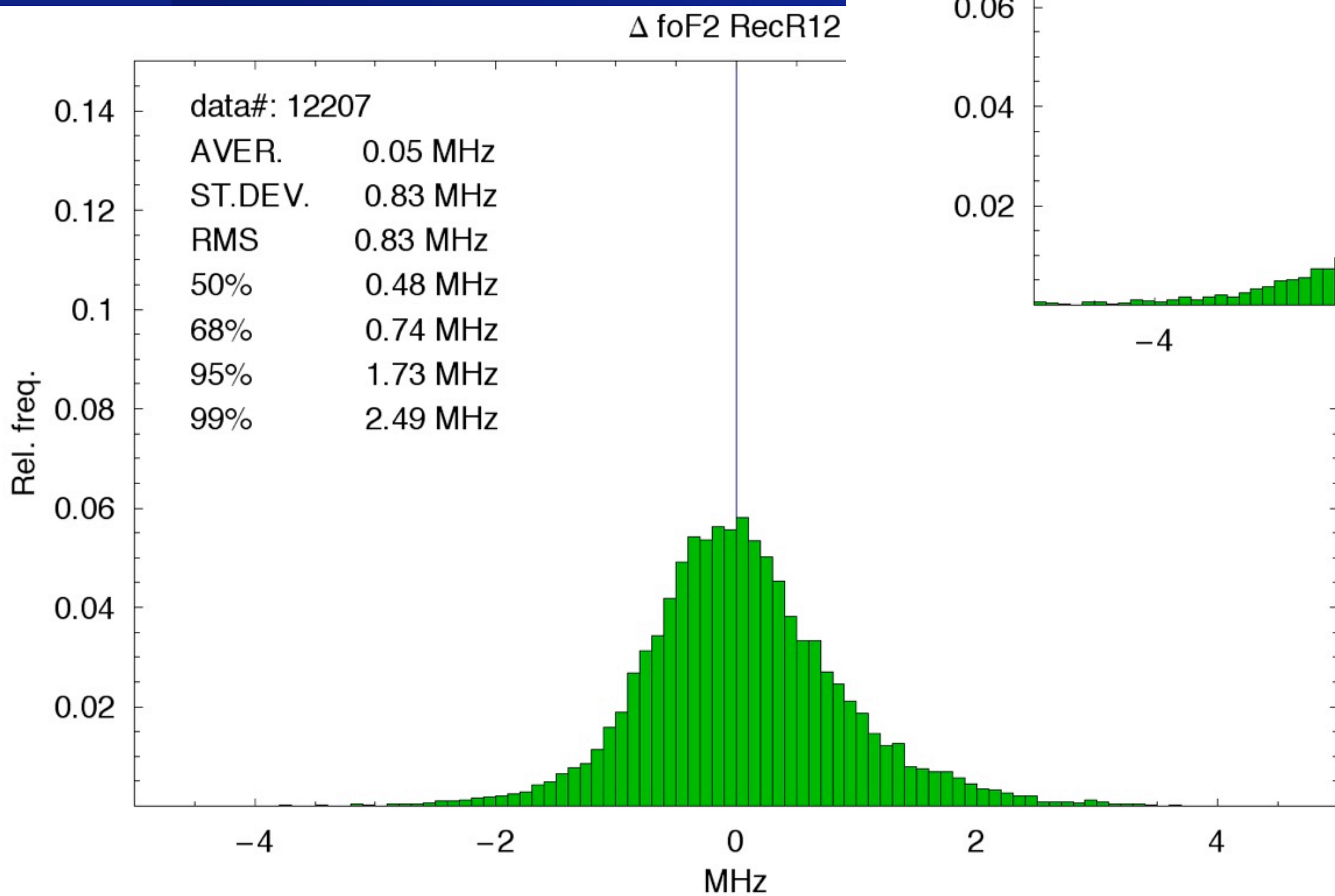
Apr. 2000



Sep. 2006

Global statistics (R12)





Apr. 2000

Sep. 2006

Validation statistics (HSA)

Table 1. April 2000: Statistics of the Differences Between Modeled and Experimental foF2 Data (in MHz) Considering All Ionosondes, Only the Mid-Latitude Ionosondes and Only the Low Latitude Ionosondes[a]

	All Lat, Data 11625			Mid Lat, Data 9556			Low Lat, Data 2069		
	Az	F107	R12	Az	F107	R12	Az	F107	R12
Aver	0.24	0.02	−0.77	0.23	0.04	−0.71	0.26	−0.05	−1.06
St dev	1.09	1.46	1.27	0.90	1.34	1.10	1.74	1.92	1.86
RMS	1.12	1.46	1.49	0.93	1.34	1.31	1.76	1.92	2.14
50%	0.66	0.88	0.94	0.60	0.84	0.89	1.20	1.18	1.17
68%	1.01	1.32	1.36	0.90	1.25	1.30	1.70	1.78	1.74
95%	2.20	2.82	2.79	1.82	2.61	2.53	3.19	3.77	4.49
99%	3.20	4.35	4.49	2.52	3.82	3.49	5.22	6.16	7.47

Table 3. April 2000: Statistics of the Differences Between Modeled and Experimental foF2 Median Data (in MHz) Considering All Ionosondes, Only the Mid-Latitude Ionosondes and Only the Low Latitude Ionosondes[a]

	All Lat, Data 488			Mid Lat, Data 395			Low Lat, Data 93		
	Az	F107	R12	Az	F107	R12	Az	F107	R12
Aver	0.17	−0.12	−0.83	0.16	−0.11	−0.78	0.22	−0.16	−1.07
St dev	0.89	0.76	0.82	0.68	0.55	0.55	1.48	1.32	1.48
RMS	0.91	0.77	1.17	0.70	0.56	0.95	1.49	1.32	1.81
50%	0.53	0.44	0.83	0.47	0.39	0.81	1.05	0.78	0.94
68%	0.81	0.61	1.05	0.72	0.54	1.01	1.45	1.00	1.44
95%	1.71	1.32	1.84	1.31	1.12	1.60	N/A	N/A	N/A
99%	2.44	2.84	4.26	1.87	1.65	2.18	N/A	N/A	N/A

Table 5. April 2000: Statistics of the Ratio [IDW of NeQuick 2 Errors]/[IDW of Experimental foF2] Considering All Ionosondes, Only the Mid-Latitude Ionosondes and Only the Low Latitude Ionosondes[a]

	All Lat, Data 488		Mid Lat, Data 395		Low Lat, Data 93	
	Az	F107	Az	F107	Az	F107
Aver	0.68	1.35	0.64	1.36	0.82	1.30
St dev	0.26	0.41	0.26	0.42	0.19	0.37
RMS	0.72	1.41	0.69	1.42	0.84	1.35
50%	0.64	1.28	0.59	1.29	0.81	1.24
68%	0.75	1.42	0.68	1.42	0.90	1.40
95%	1.05	2.03	1.03	2.05	N/A	N/A
99%	1.79	3.14	1.81	3.17	N/A	N/A

global performance

“climate” performance

“weather” performance

Validation statistics (LSA)

Table 2. September 2006: Statistics of the Differences Between Modeled and Experimental foF2 Data (in MHz) Considering All Ionosondes, Only the Mid-Latitude Ionosondes and Only the Low Latitude Ionosondes[a]

	All Lat, Data 12207			Mid Lat, Data 8814			Low Lat, Data 3393		
	Az	F107	R12	Az	F107	R12	Az	F107	R12
Aver	0.20	0.17	0.05	0.15	0.03	−0.08	0.35	0.52	0.38
St dev	0.73	0.85	0.83	0.57	0.69	0.67	1.03	1.1	1.08
RMS	0.76	0.87	0.83	0.59	0.69	0.68	1.09	1.22	1.15
50%	0.46	0.50	0.48	0.40	0.43	0.42	0.74	0.80	0.73
68%	0.68	0.76	0.74	0.58	0.63	0.63	1.11	1.19	1.11
95%	1.57	1.81	1.73	1.16	1.37	1.35	2.05	2.44	2.27
99%	2.16	2.67	2.49	1.57	1.98	1.93	2.78	3.12	3.05

Table 4. September 2006: Statistics of the Differences Between Modeled and Experimental foF2 Median Data (in MHz) Considering All Ionosondes, Only the Mid-Latitude Ionosondes and Only the Low Latitude Ionosondes[a]

	All Lat, Data 460			Mid Lat, Data 328			Low Lat, Data 132		
	Az	F107	R12	Az	F107	R12	Az	F107	R12
Aver	0.20	0.17	0.06	0.14	0.02	−0.07	0.35	0.53	0.39
St dev	0.54	0.58	0.57	0.41	0.42	0.41	0.75	0.73	0.76
RMS	0.57	0.60	0.58	0.43	0.42	0.42	0.82	0.90	0.85
50%	0.33	0.34	0.33	0.30	0.28	0.29	0.59	0.62	0.56
68%	0.49	0.51	0.49	0.40	0.39	0.41	0.86	0.87	0.86
95%	1.21	1.22	1.13	0.84	0.86	0.80	1.63	1.80	1.66
99%	1.66	1.96	1.79	1.17	1.17	1.07	1.77	2.35	2.22

Table 6. September 2006: Statistics of the Ratio [IDW of NeQuick 2 Errors]/[IDW of Experimental foF2] Considering All Ionosondes, Only the Mid-Latitude Ionosondes and Only the Low Latitude Ionosondes[a]

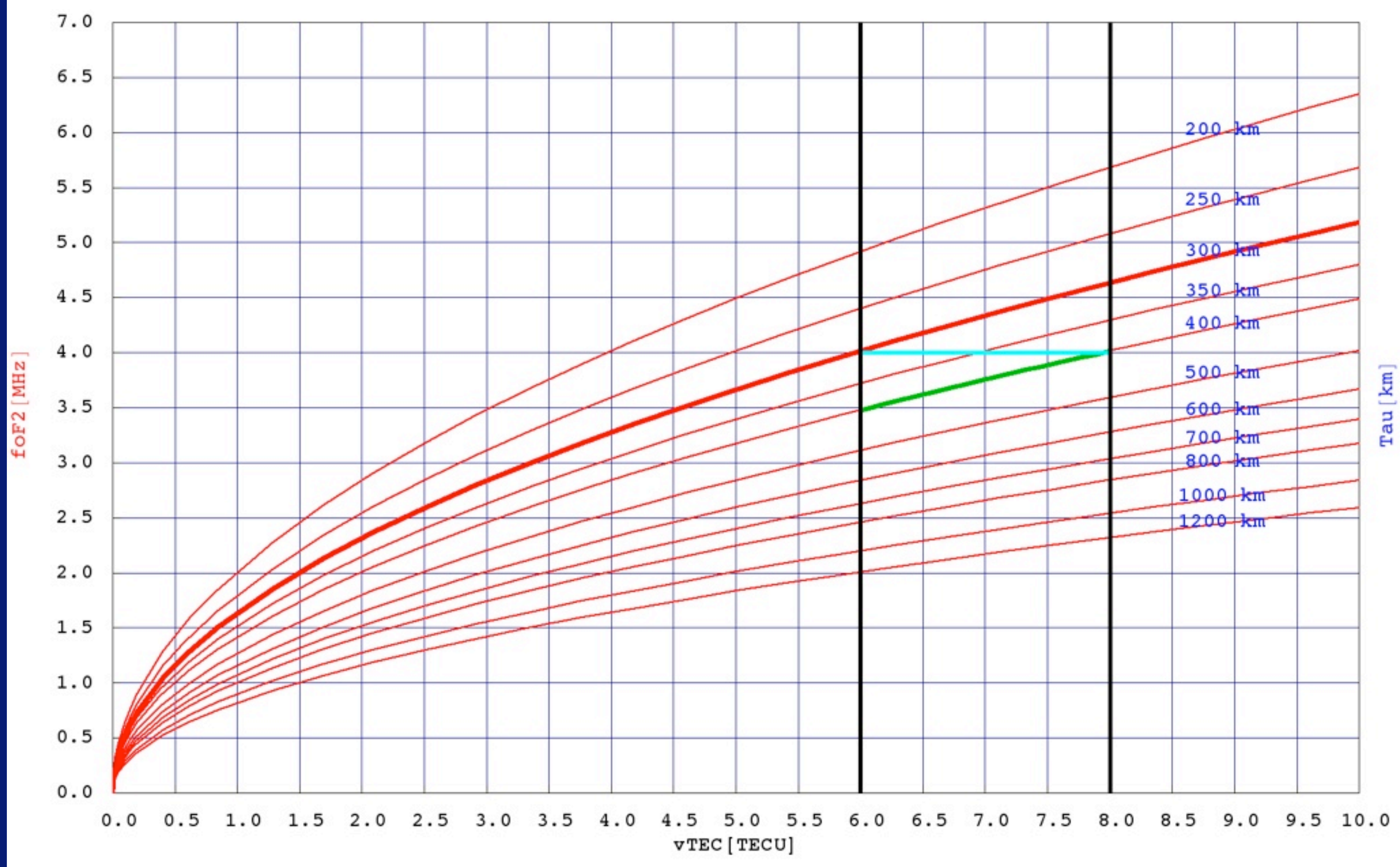
	All Lat, Data 460		Mid Lat, Data 328		Low Lat, Data 132	
	Az	F107	Az	F107	Az	F107
Aver	0.82	1.05	0.78	1.05	0.92	1.05
St dev	0.21	0.17	0.18	0.18	0.23	0.15
RMS	0.85	1.07	0.80	1.07	0.95	1.06
50%	0.80	1.03	0.77	1.02	0.89	1.04
68%	0.88	1.11	0.85	1.11	0.98	1.12
95%	1.22	1.38	1.13	1.39	1.36	1.35
99%	1.44	1.51	1.26	1.52	1.48	1.42

global performance

"climate" performance

"weather" performance

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]

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

↓ ↓

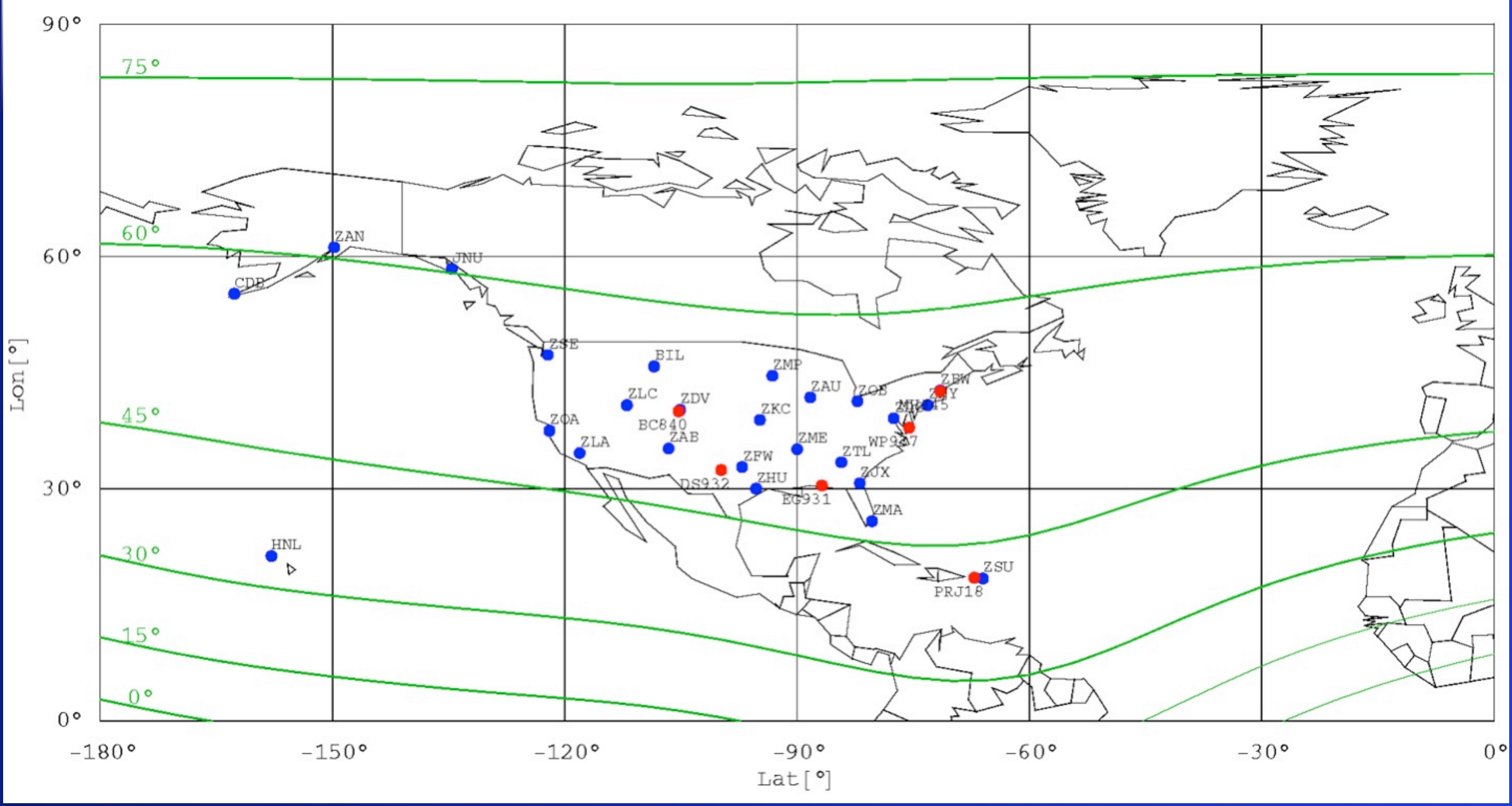
Reconstruct TEC along any
Station-to-satellite ray-path

Retrieve the foF2 values
at the Station

Adapting NeQuick model to experimental slant TEC data at 6 given locations

(Validation)

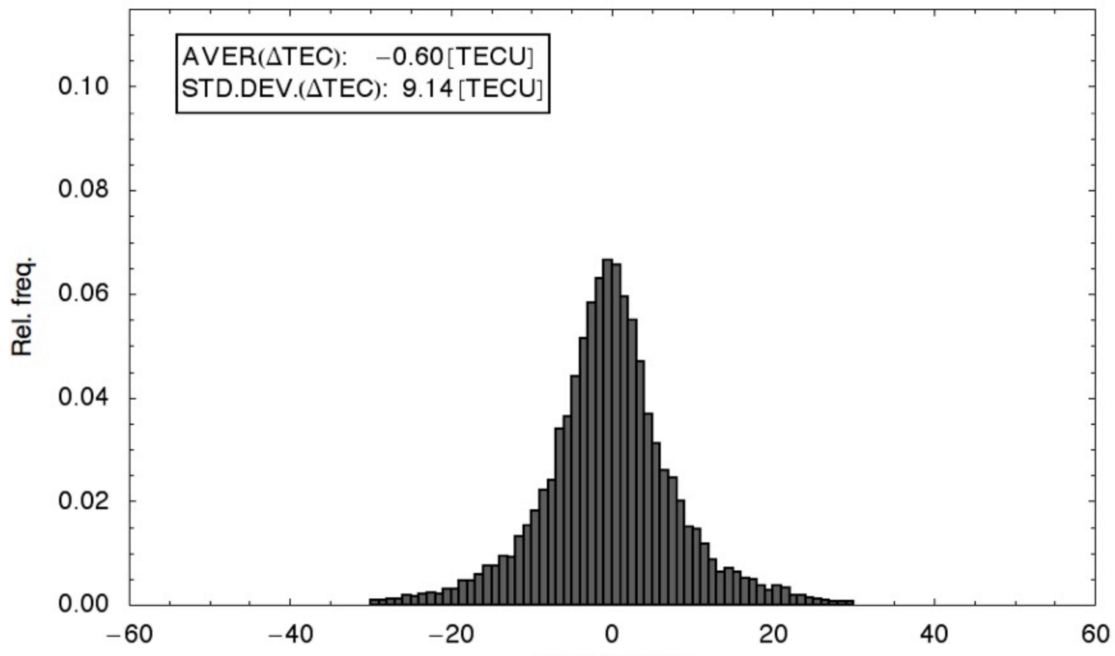
Stations & ionosondes locations

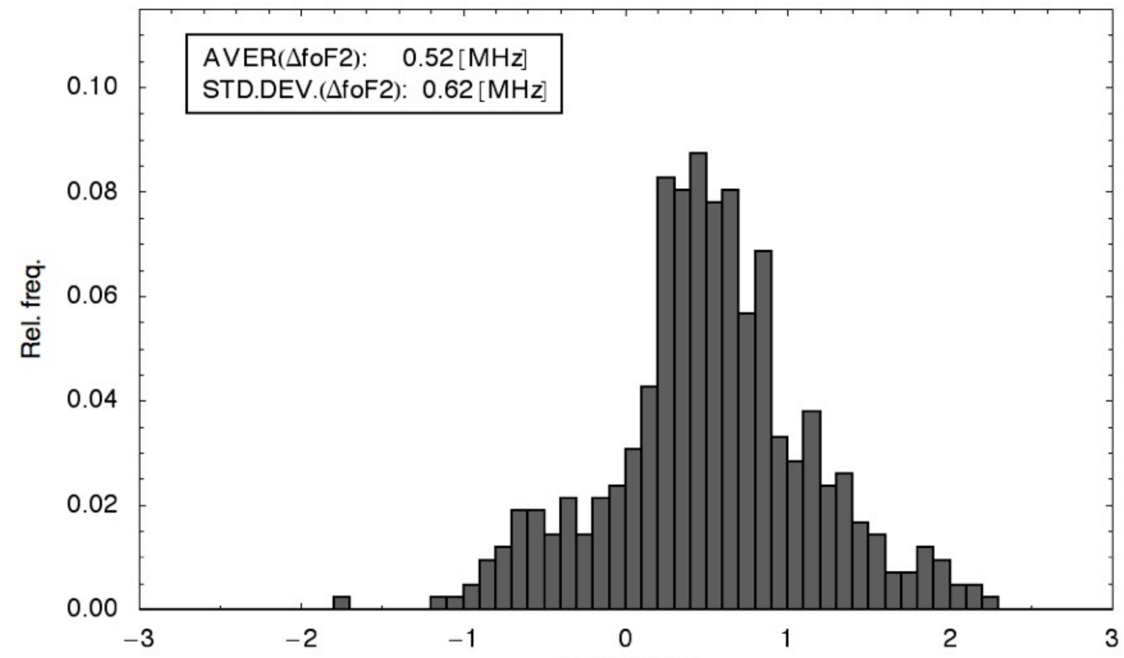


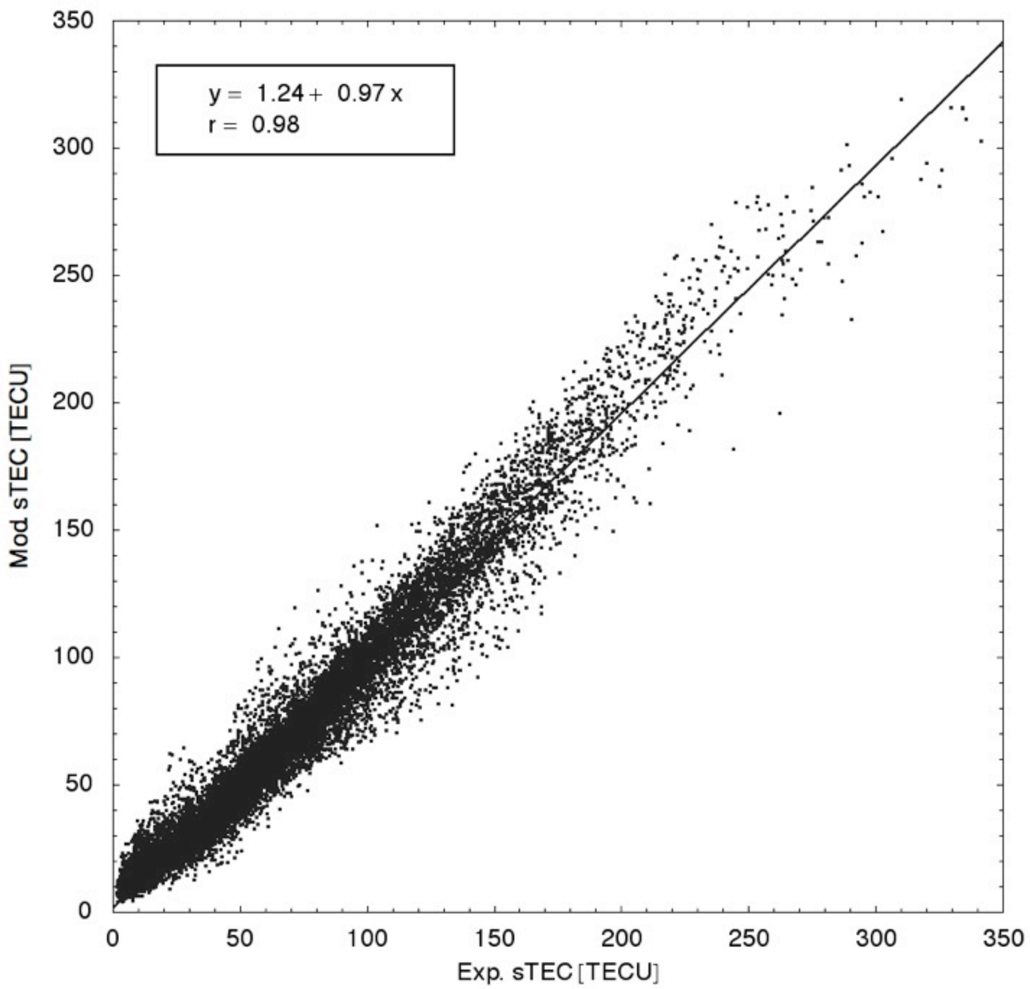
- GPS receivers
- Ionosondes

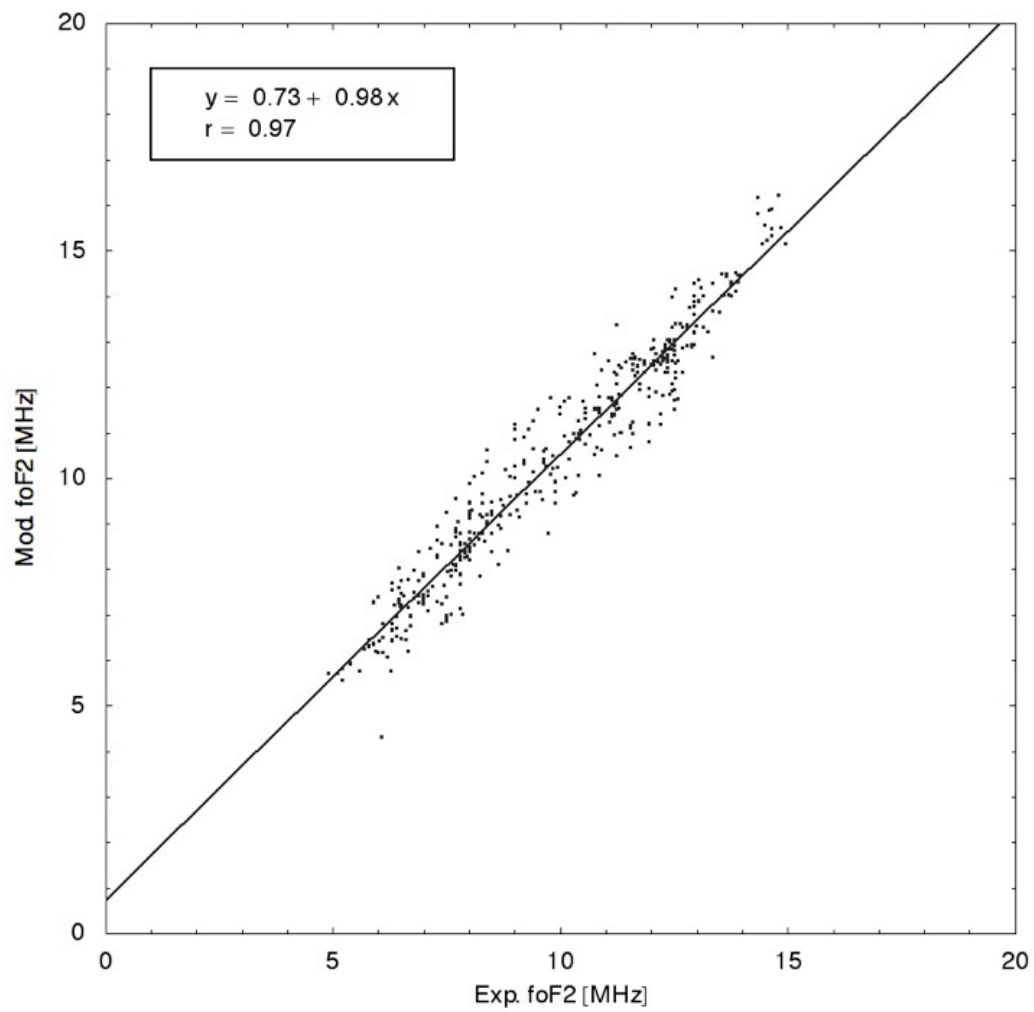
Modip isolines

(6) Single station statistics (000405)

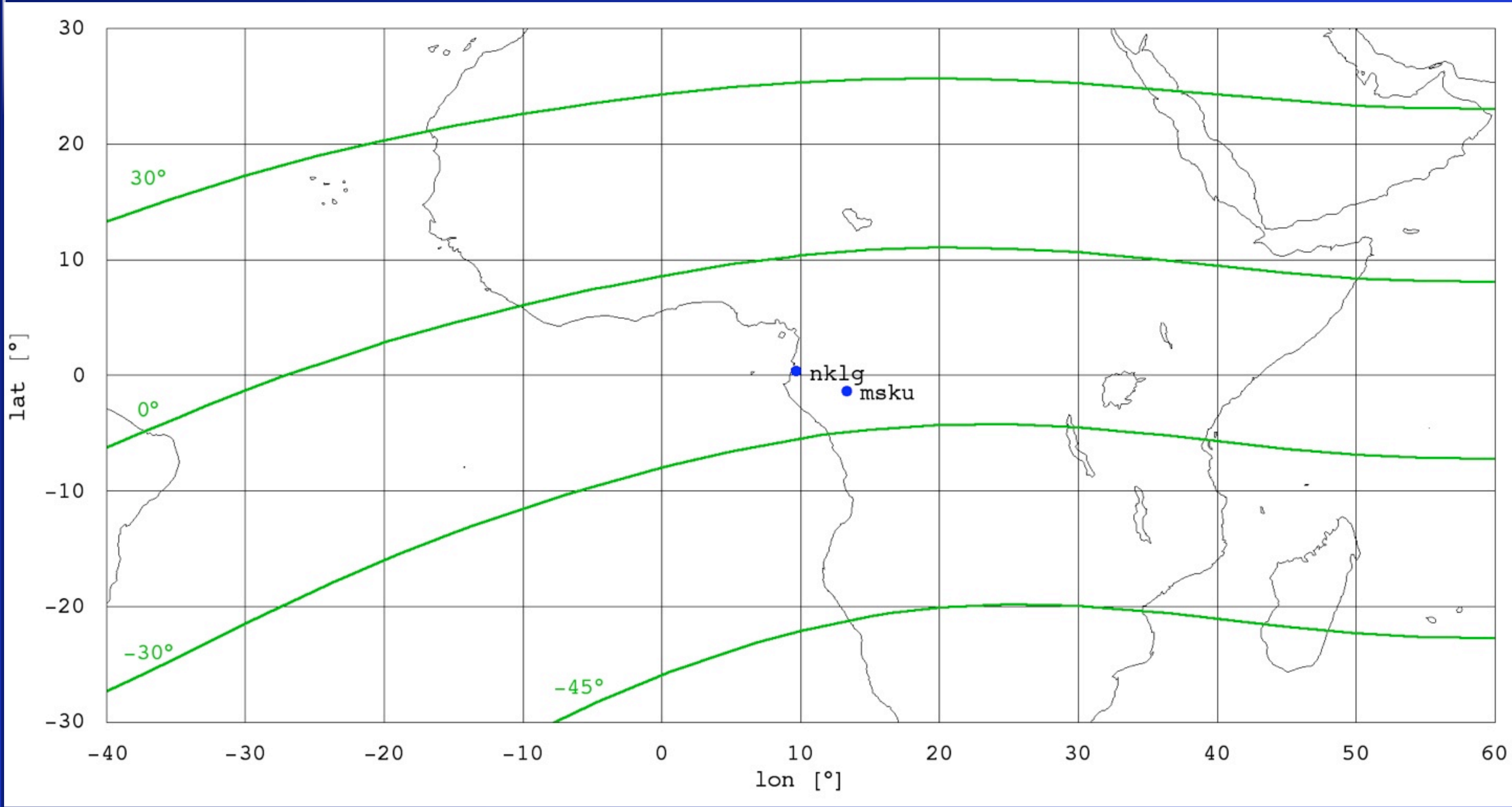








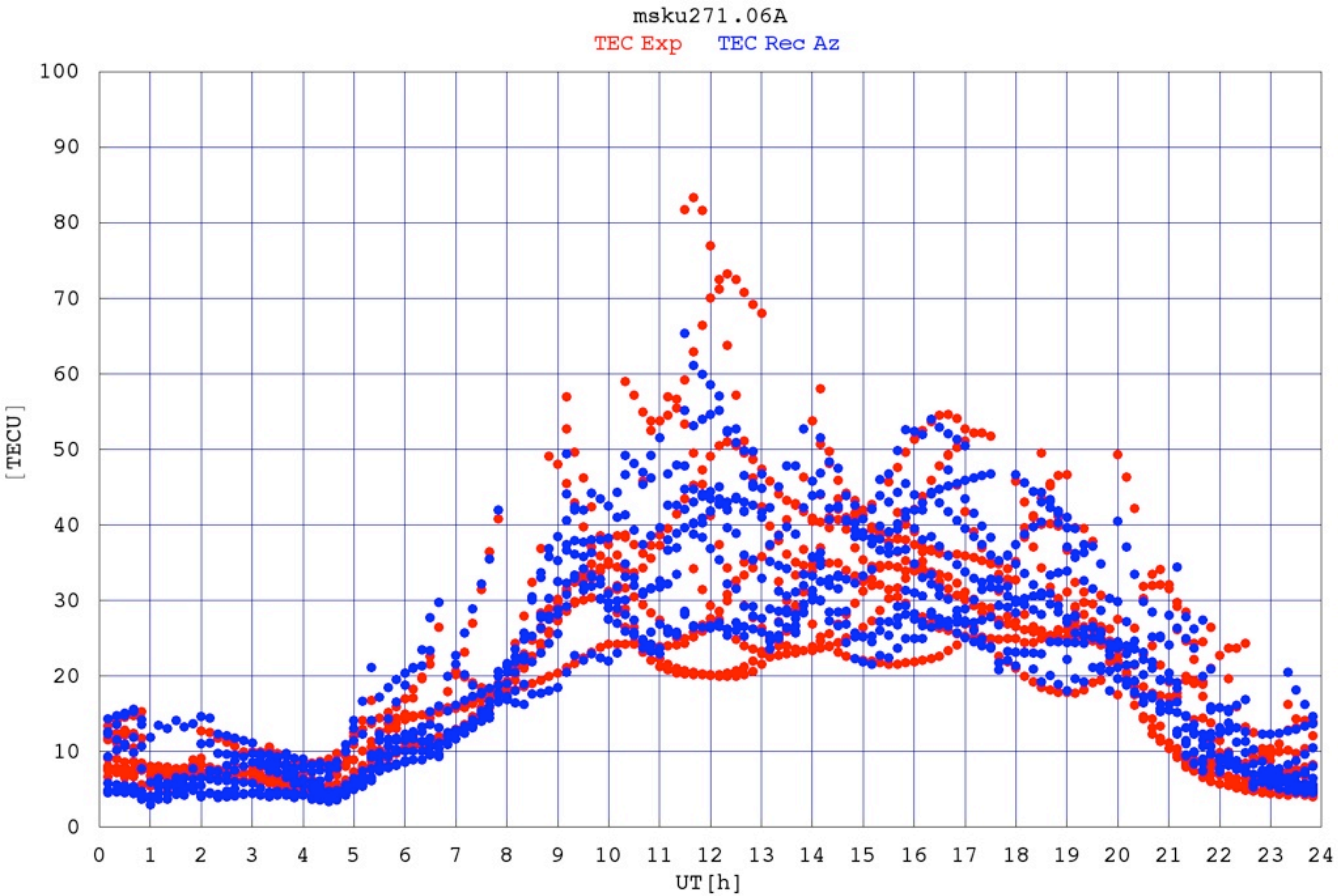
Stations locations



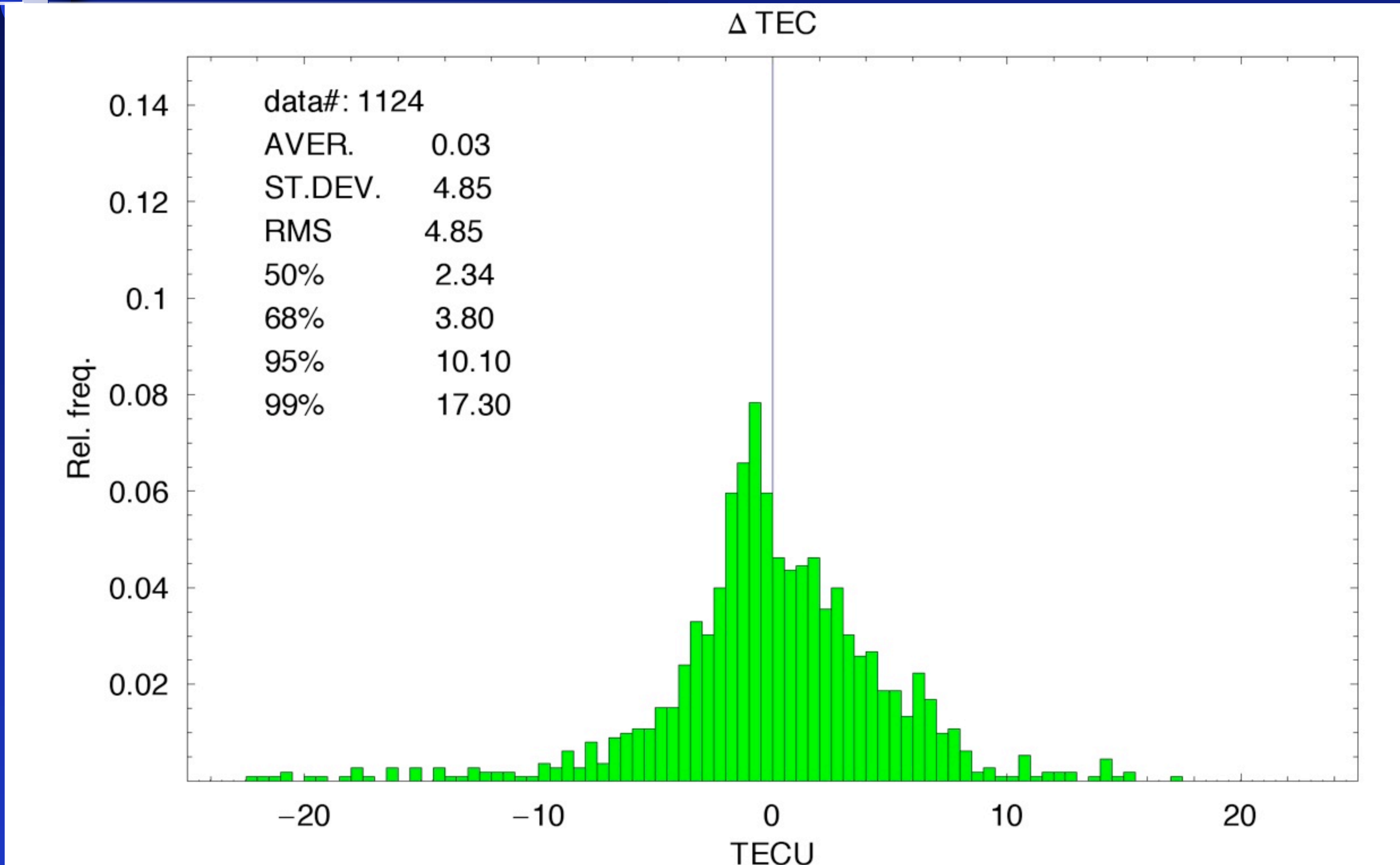
● GPS receivers

Modip isolines

msku TEC comparison; doy 271

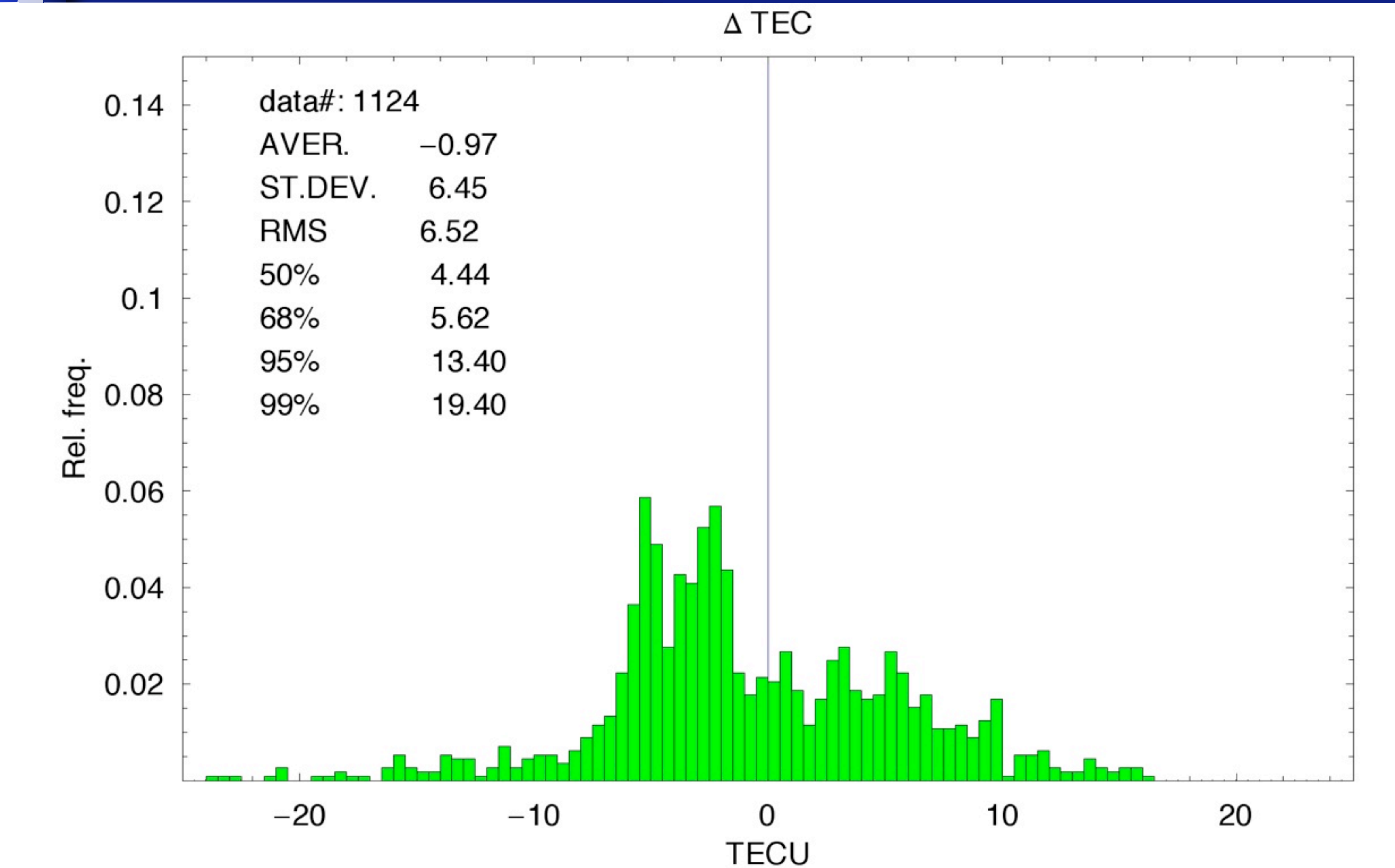


msku ΔTEC statistics; doy 271 2006



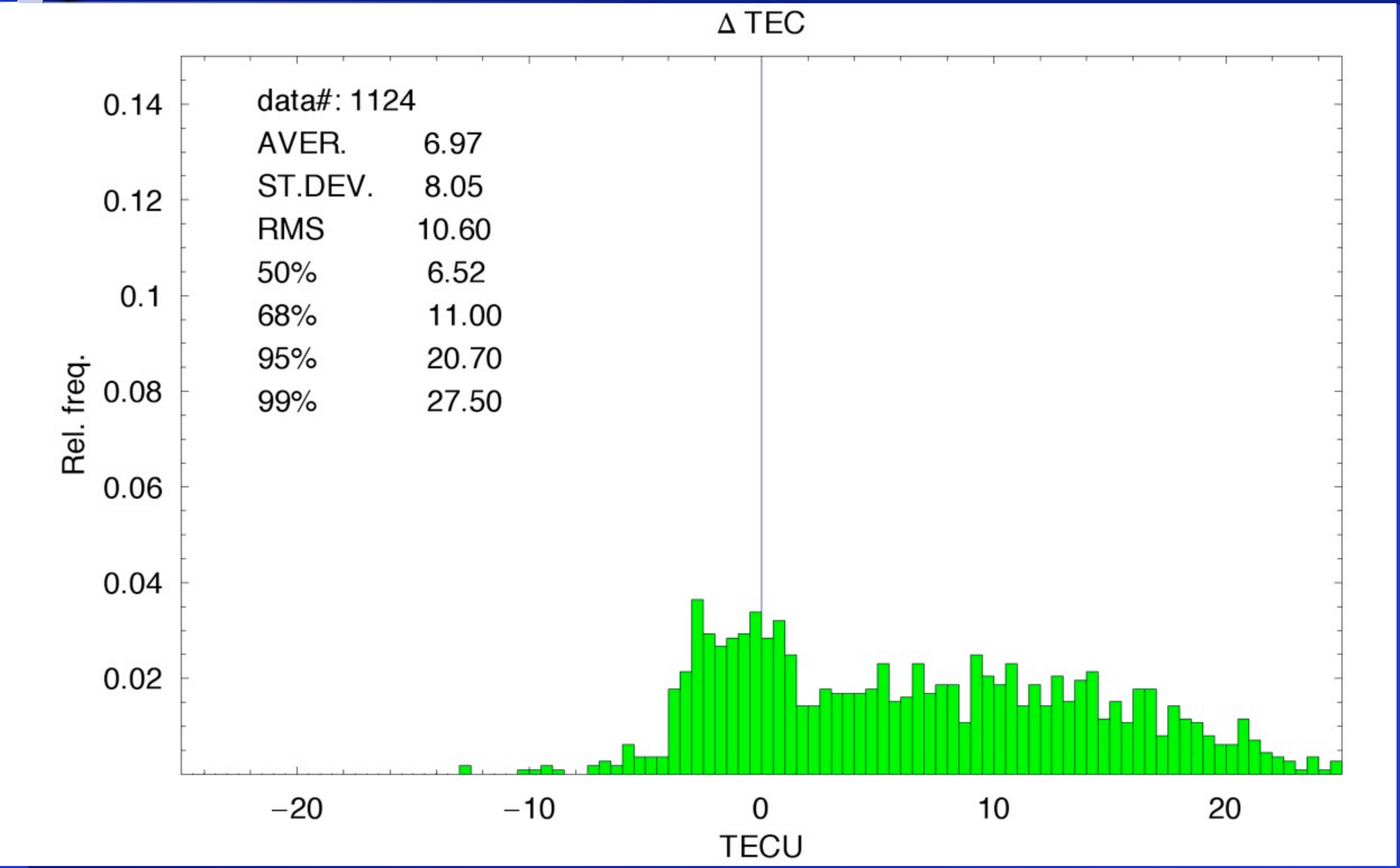
Reconstructed Tec computed using Az at 10 min. time interval

msku ΔTEC statistics; doy 271 2006



Reconstructed Tec computed using one Az for all the day

msku ΔTEC statistics; doy 271 2006



Reconstructed Tec computed using f10.7

Galileo Single Frequency Iono algorithm

SENSOR STATION

Observe slant TEC in Sensor Stations for 24 hours

↓

Optimise effective ionisation parameter for NeQuick to match observations

↓

SATELLITE

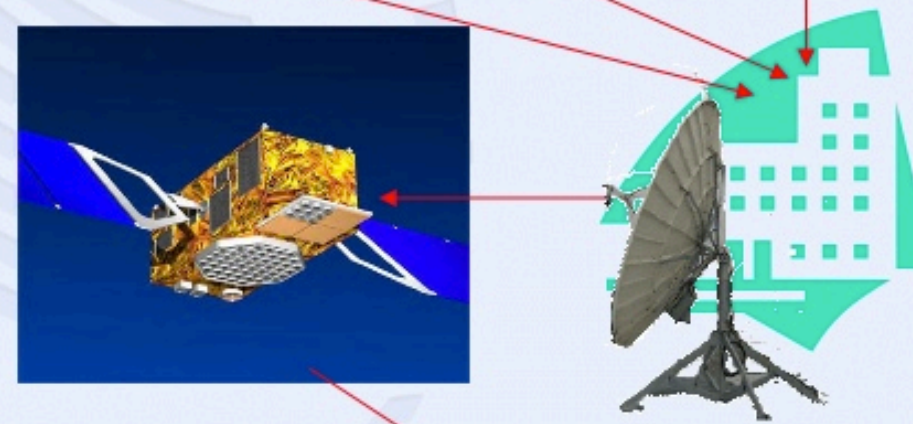
Transmit effective ionisation parameter in Navigation message

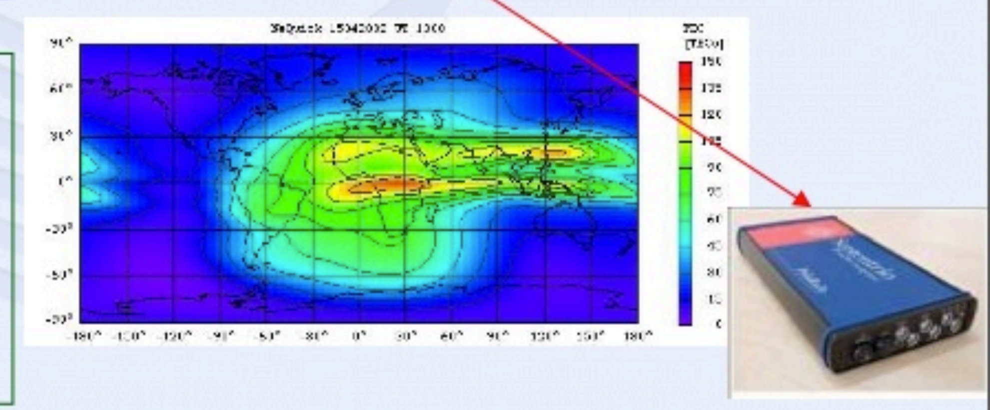
$$Az = a_0 + a_1 \cdot \mu + a_2 \cdot \mu^2$$

↓

USER RECEIVER

Calculate slant TEC using NeQuick with broadcast ionisation parameter. Correct for Ionospheric delay at frequency in question.





esa — ESWW3 Brussels — 2006-11-15 — 10

from: http://sidc.oma.be/esww3/presentations/Session4/Arbesser.pdf
(see e.g. http://www.navipedia.net/index.php/NeQuick_Ionospheric_Model)

Performance have been recently confirmed during In-Orbit Validation (Roberto Prieto-Cerdeira et al.; GPS World, June 2014)

Adapting NeQuick model to experimental slant TEC data at several locations

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

↓

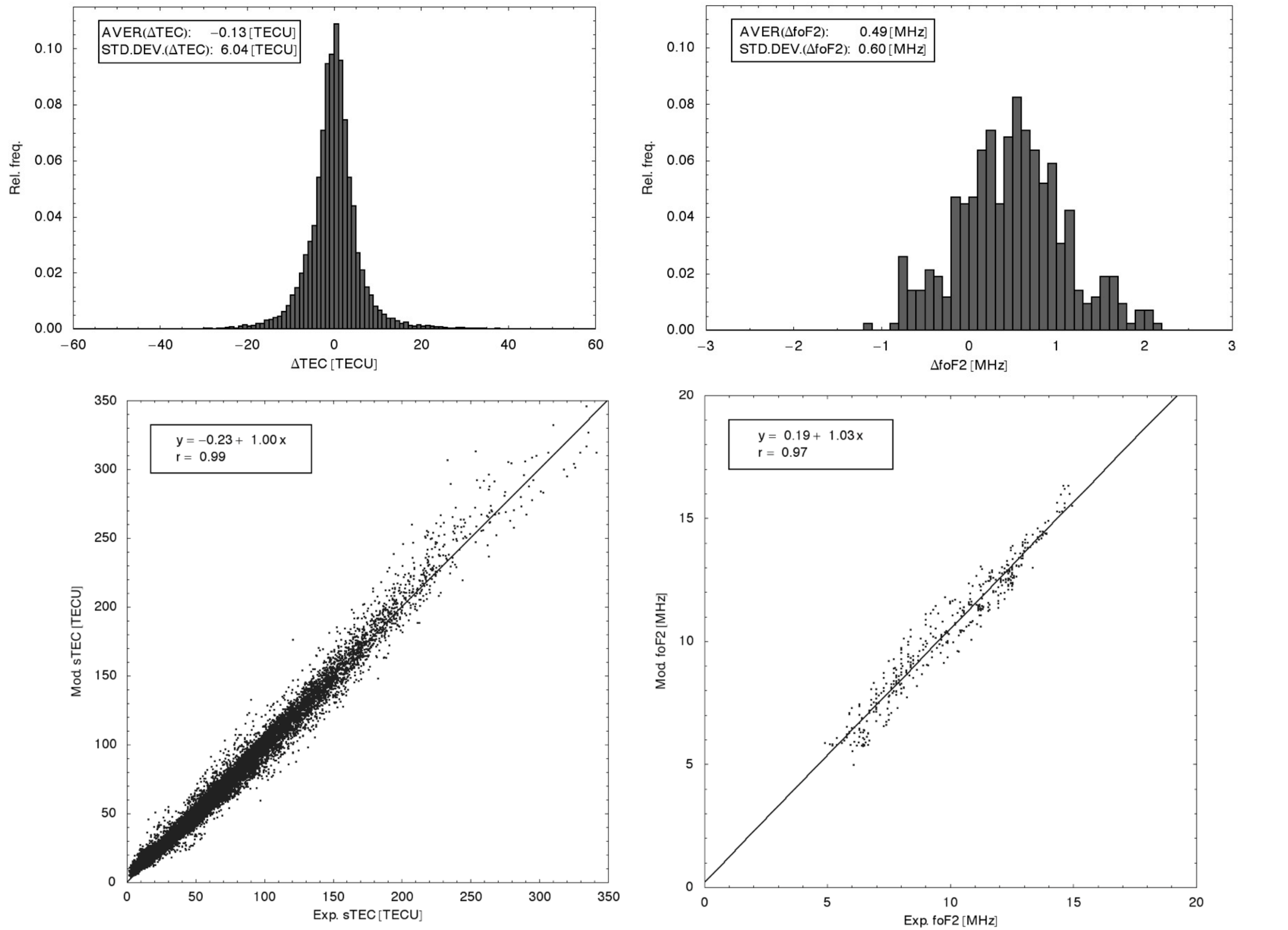
Use NeQuick to reconstruct the 3D electron density of the ionosphere

↓ ↓

Reconstruct TEC along any given ray-path

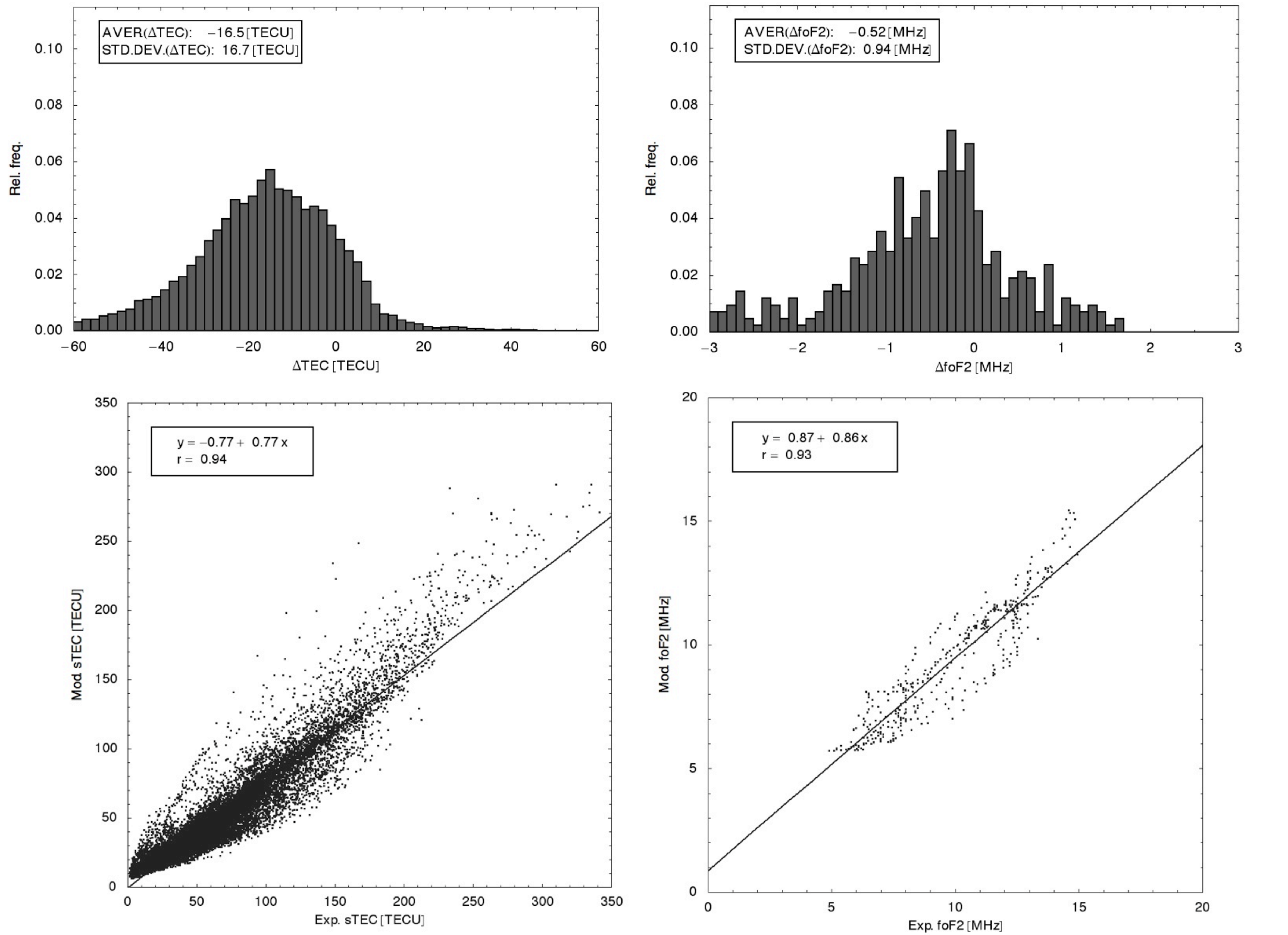
Reconstruct any foF2 value (foF2 map)

Multiple station statistics (000405)



Using NeQuick model in a standard way (F10.7 input -> no adaptation)

Flux of the day statistics (000405)



Remark

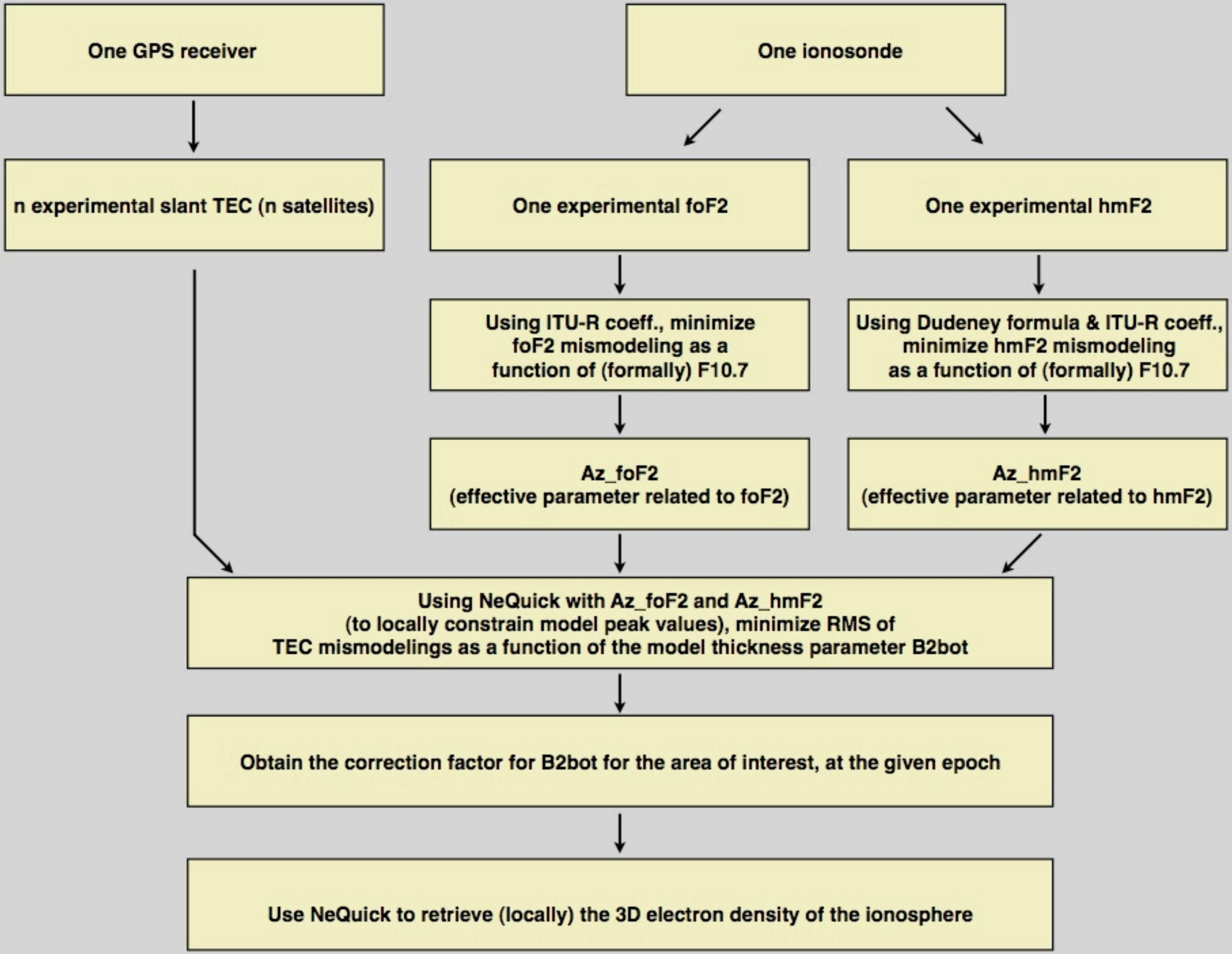
Model is adapted to TEC but foF2 is not always adequately retrieved.

The results of these studies have indicated that there is the need to further improve the model formulation in terms of slab thickness.

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)

At a given epoch:



Remarks

- The use of two effective parameters has been considered in order to use the ITUR coefficients to estimate foF2 and hmF2 in a region surrounding the ground station.
- In this way the peak parameter values can be estimated for a slant TEC computation.

Adaptation method validation

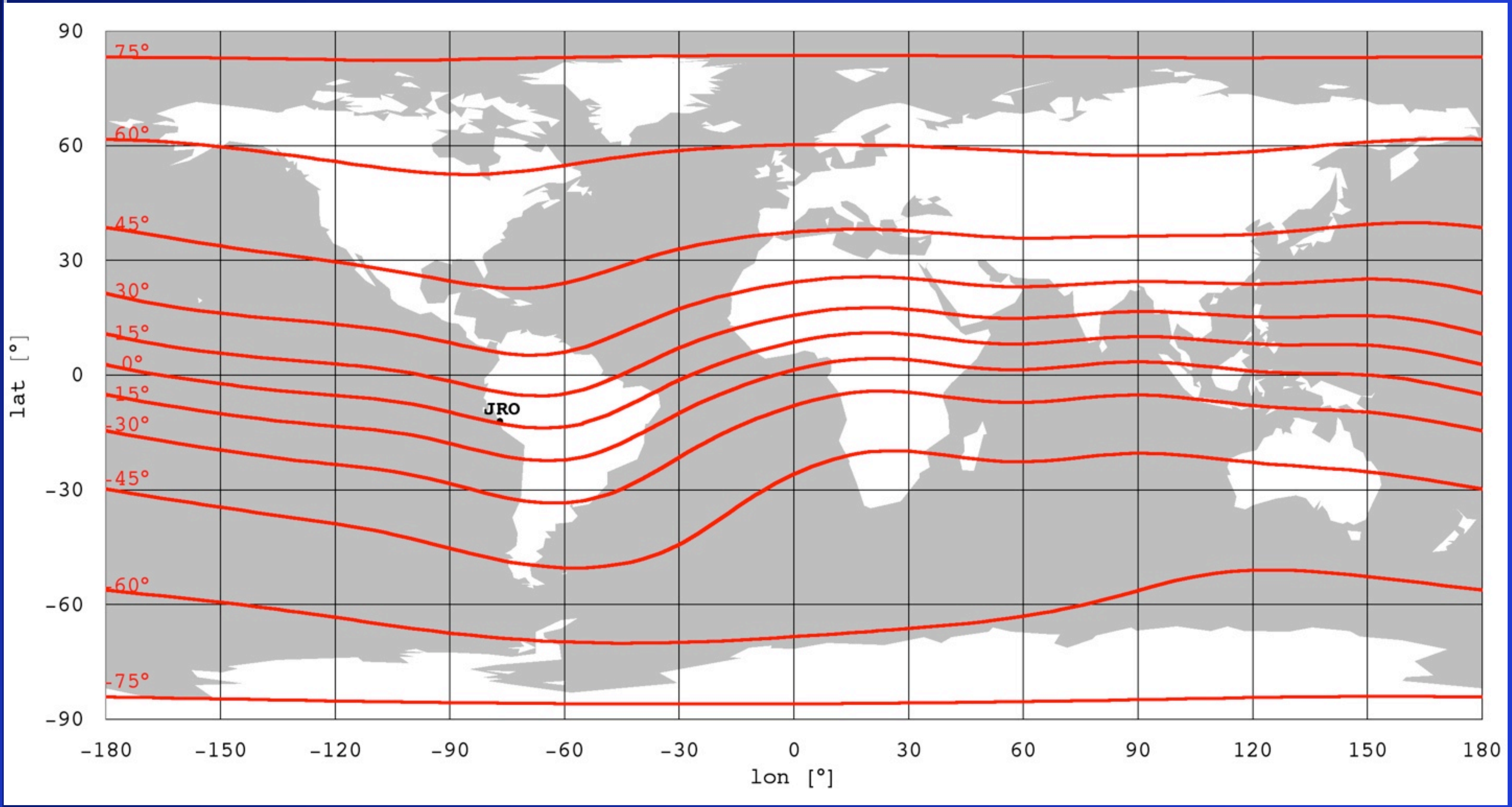
Use JRO profiles to simulate the process of adapting NeQuick to GPS derived TEC and ionosonde peak parameters data.

TEC and peak parameters are known from the profile.

↓

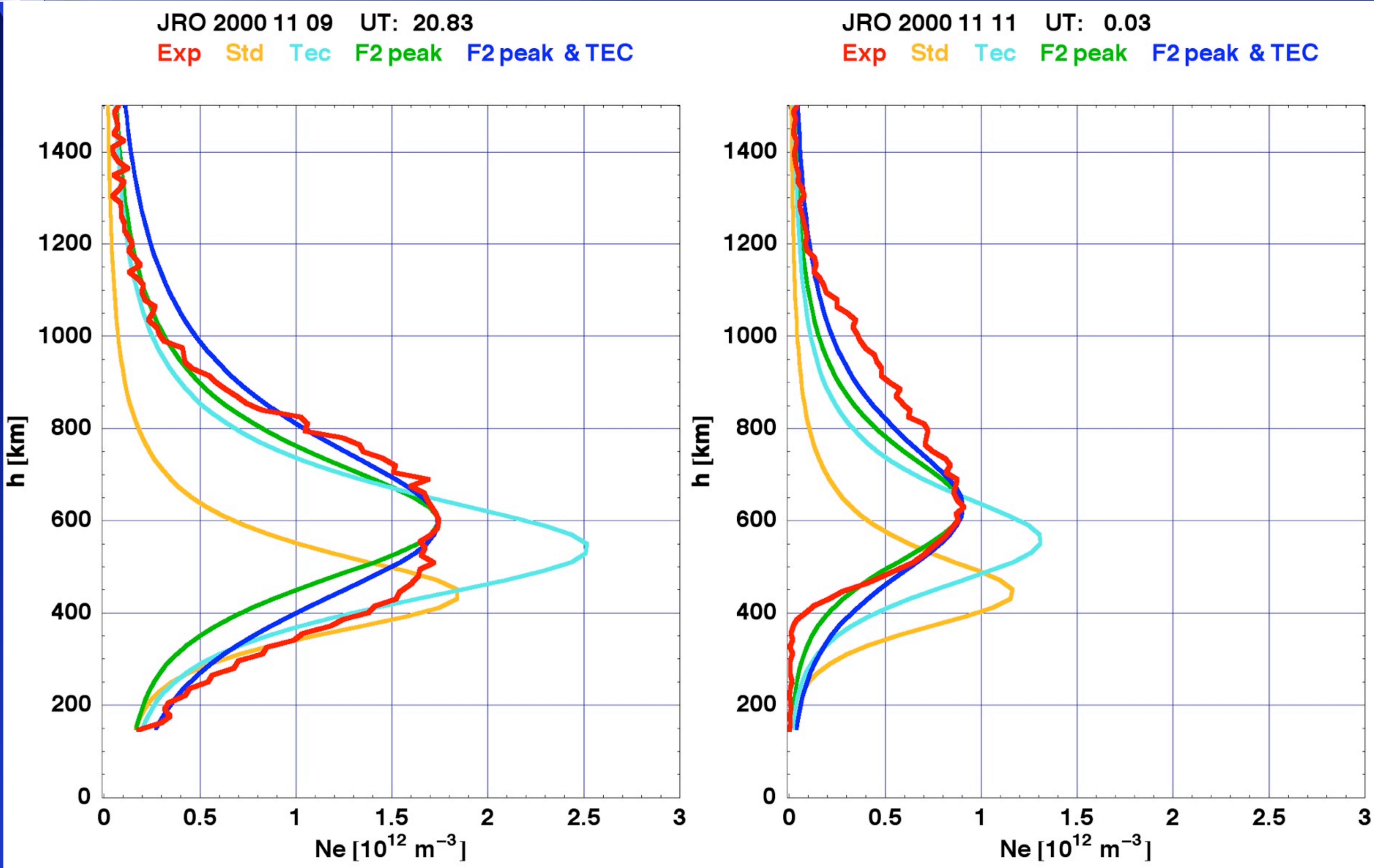
After model adaptation it is possible to compare profiles in order to evaluate the adaptation technique effectiveness.

Adaptation method validation



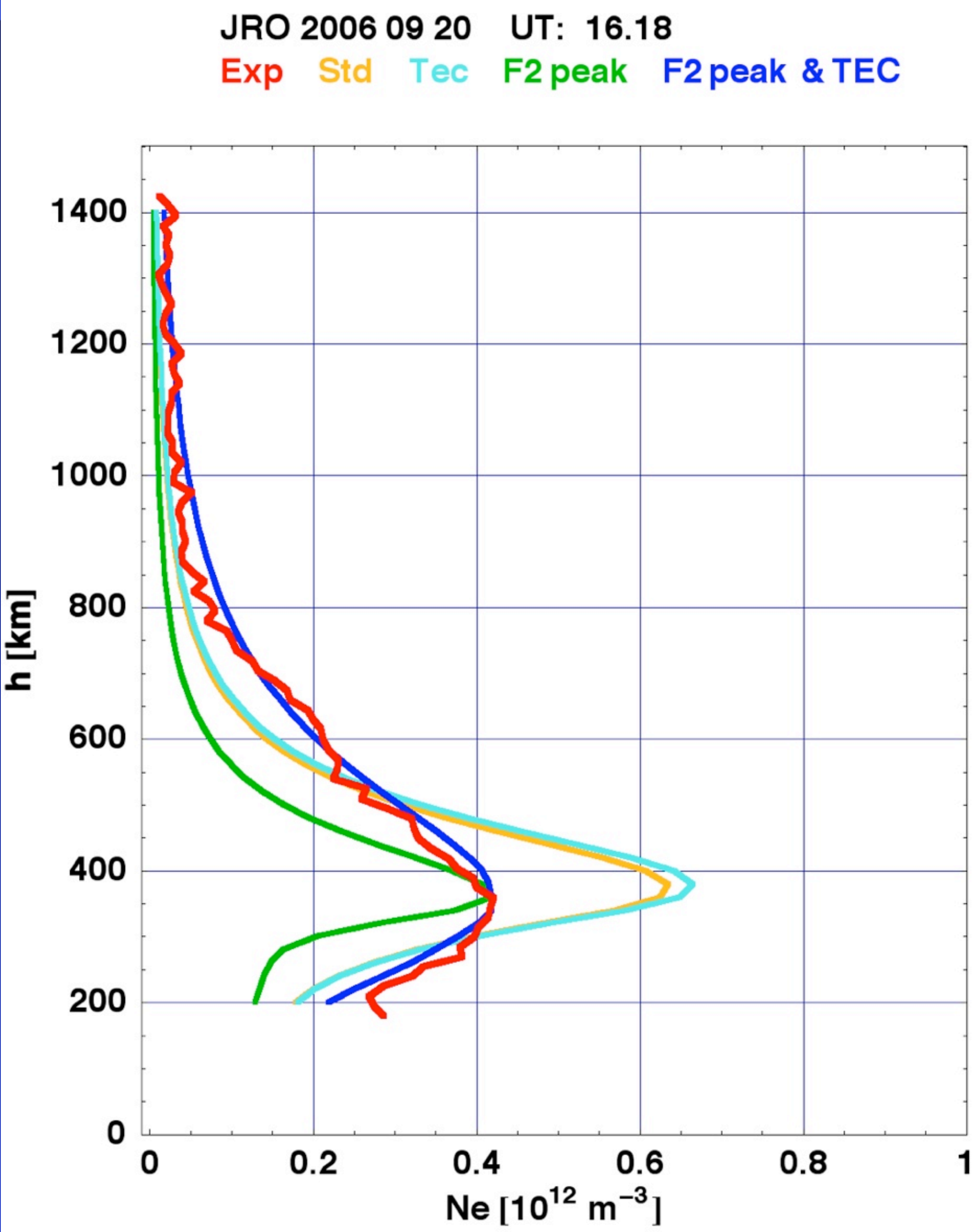
Jicamarca Radio Observatory (JRO) location

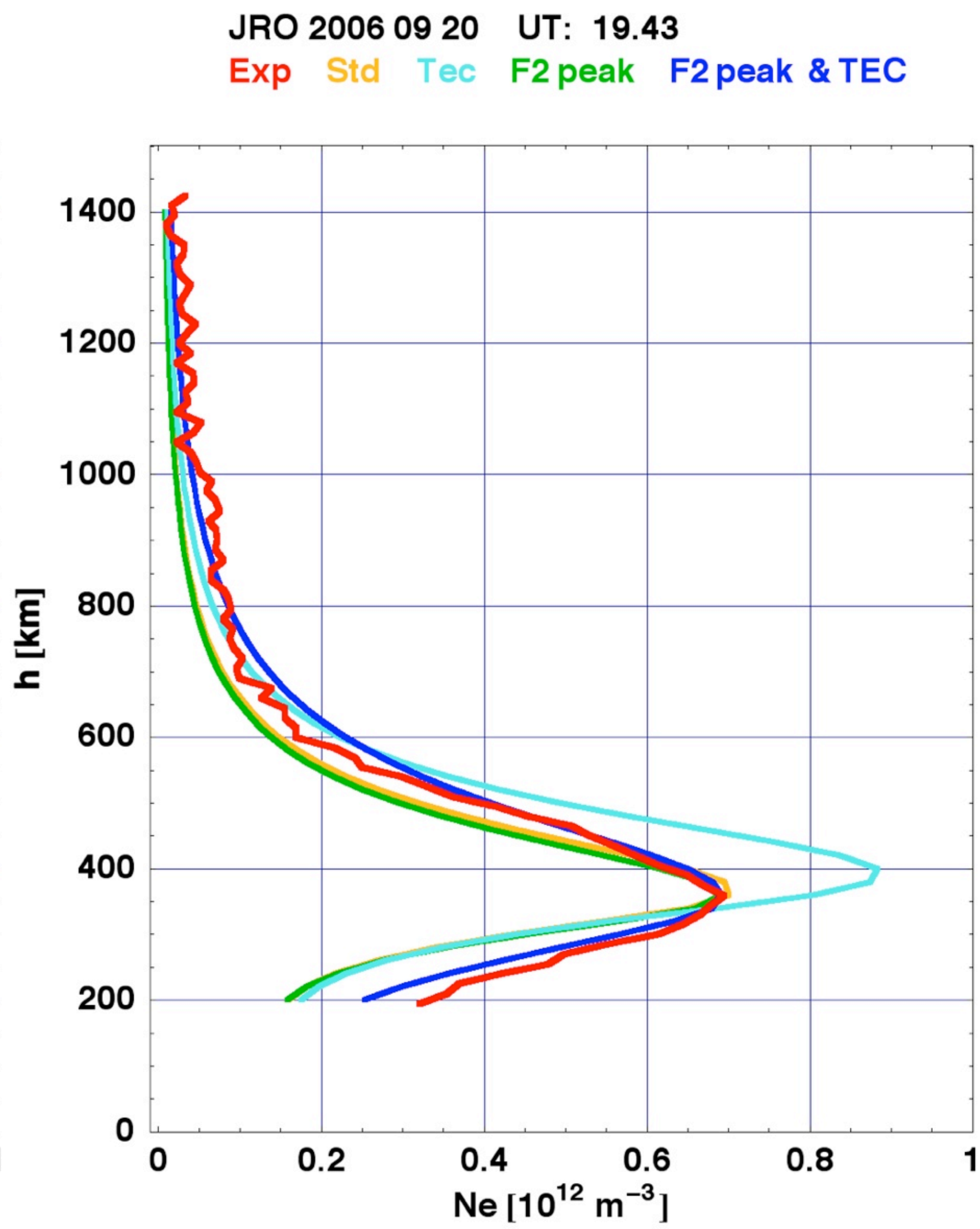
Adaptation method validation



Model: NeQuick

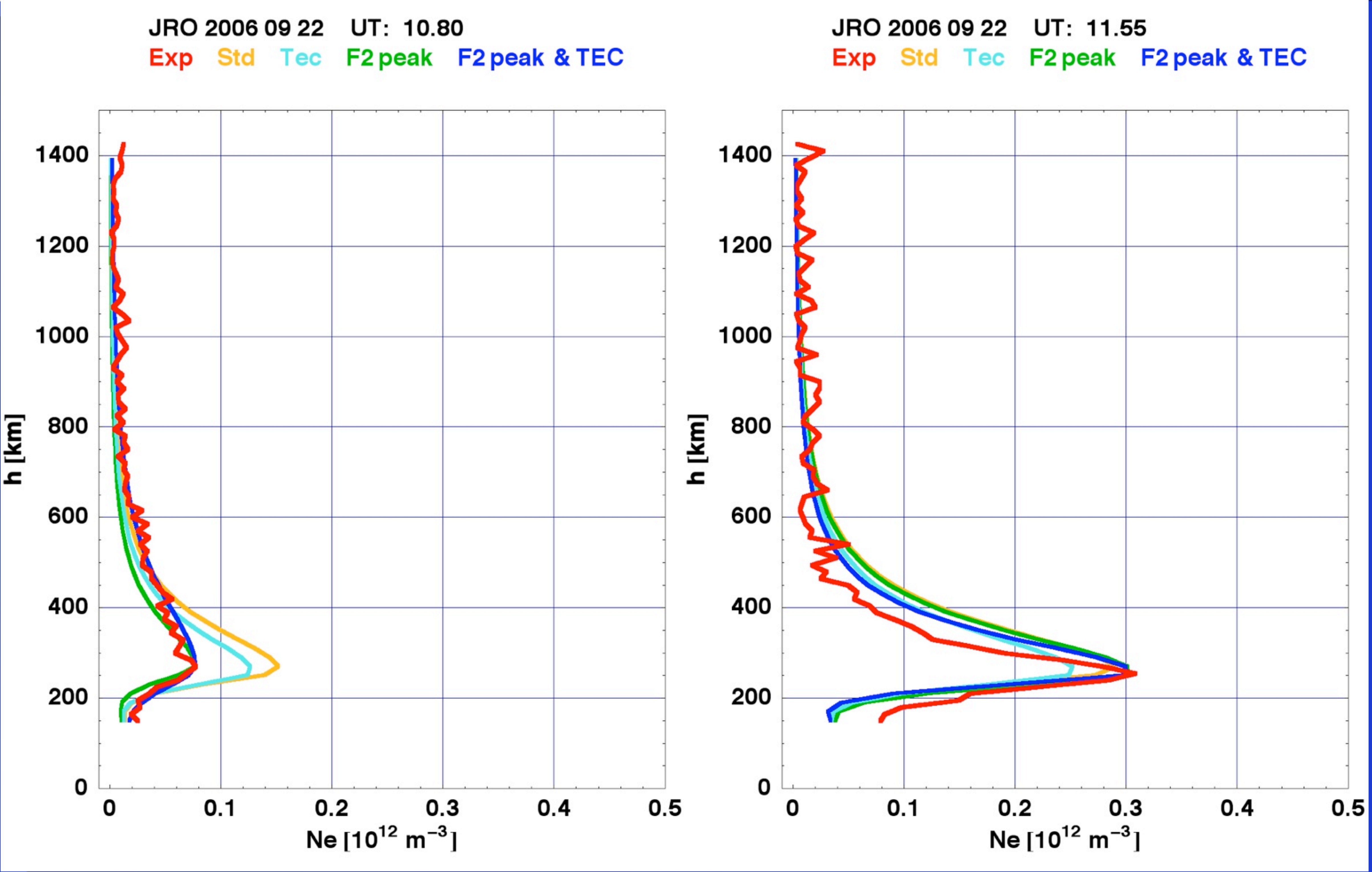
Adaptation method validation





Model: NeQuick

Adaptation method validation

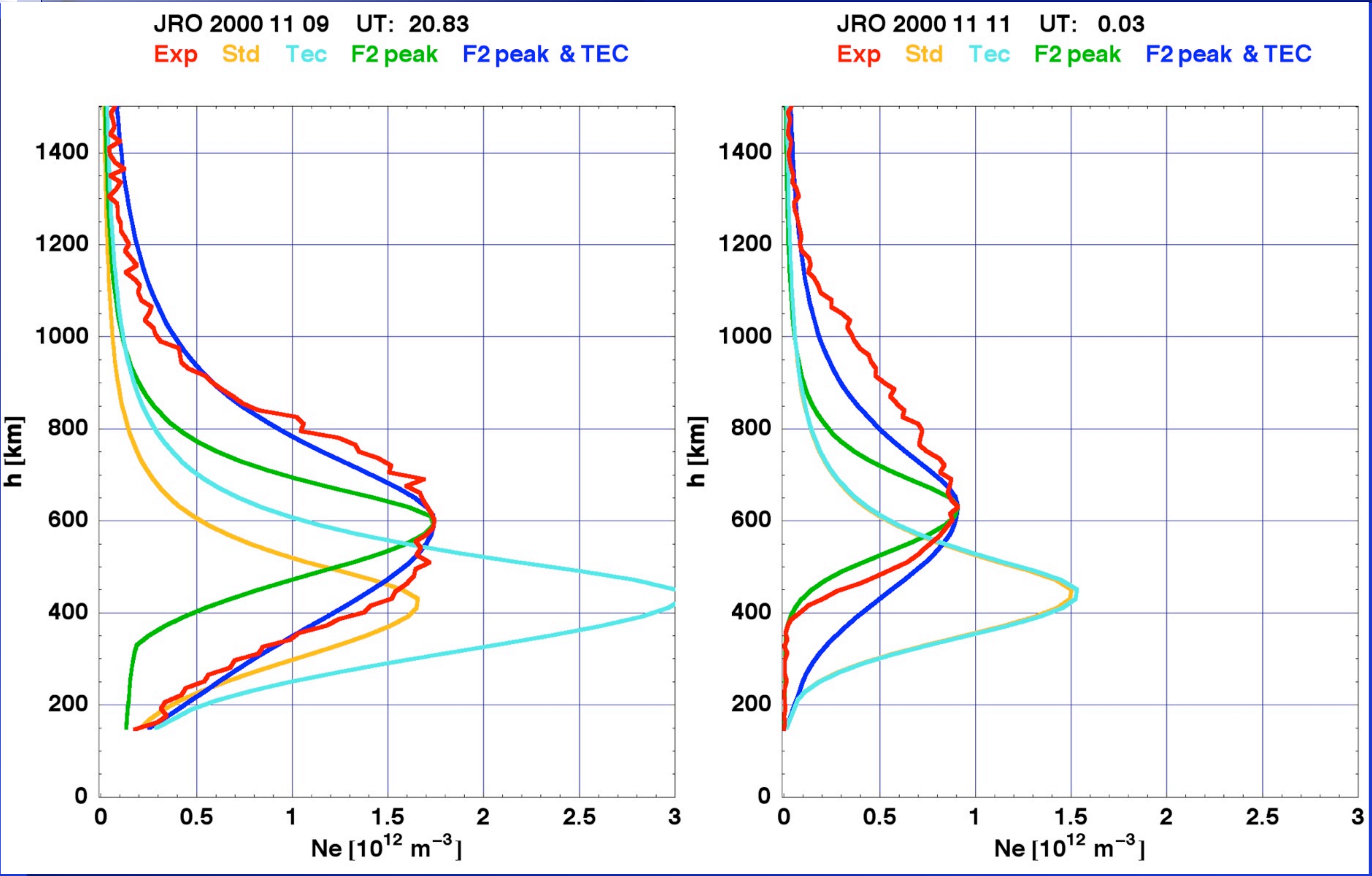


Model: NeQuick

Adaptation method effectiveness

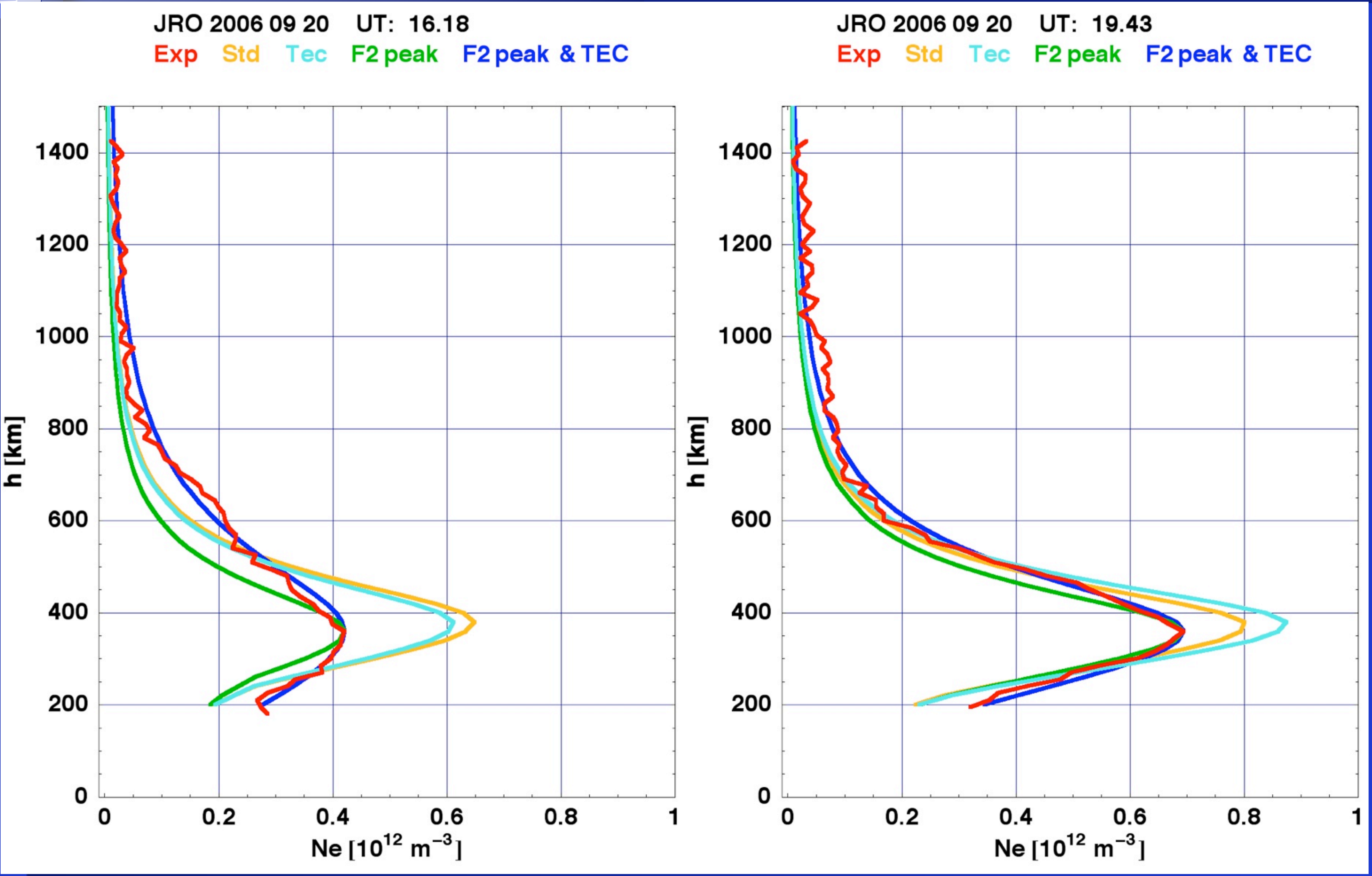
- In order to evaluate the adaptation technique effectiveness, the IRI model has been used instead of the NeQuick and the same data have been used for the adaptation.
- (Not so easy as in the case of NeQuick)

Adaptation method validation



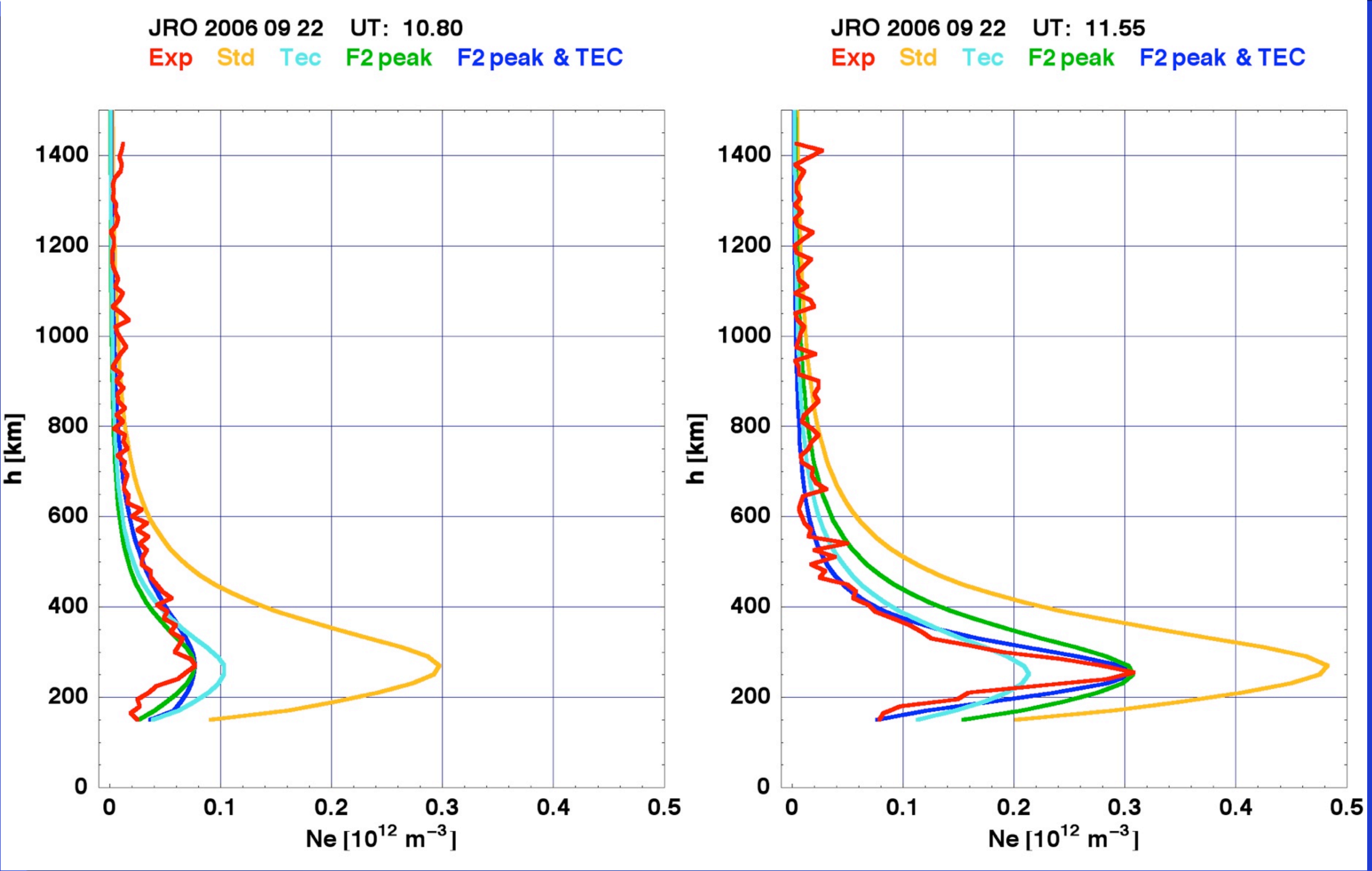
Model: IRI

Adaptation method validation



Model: IRI

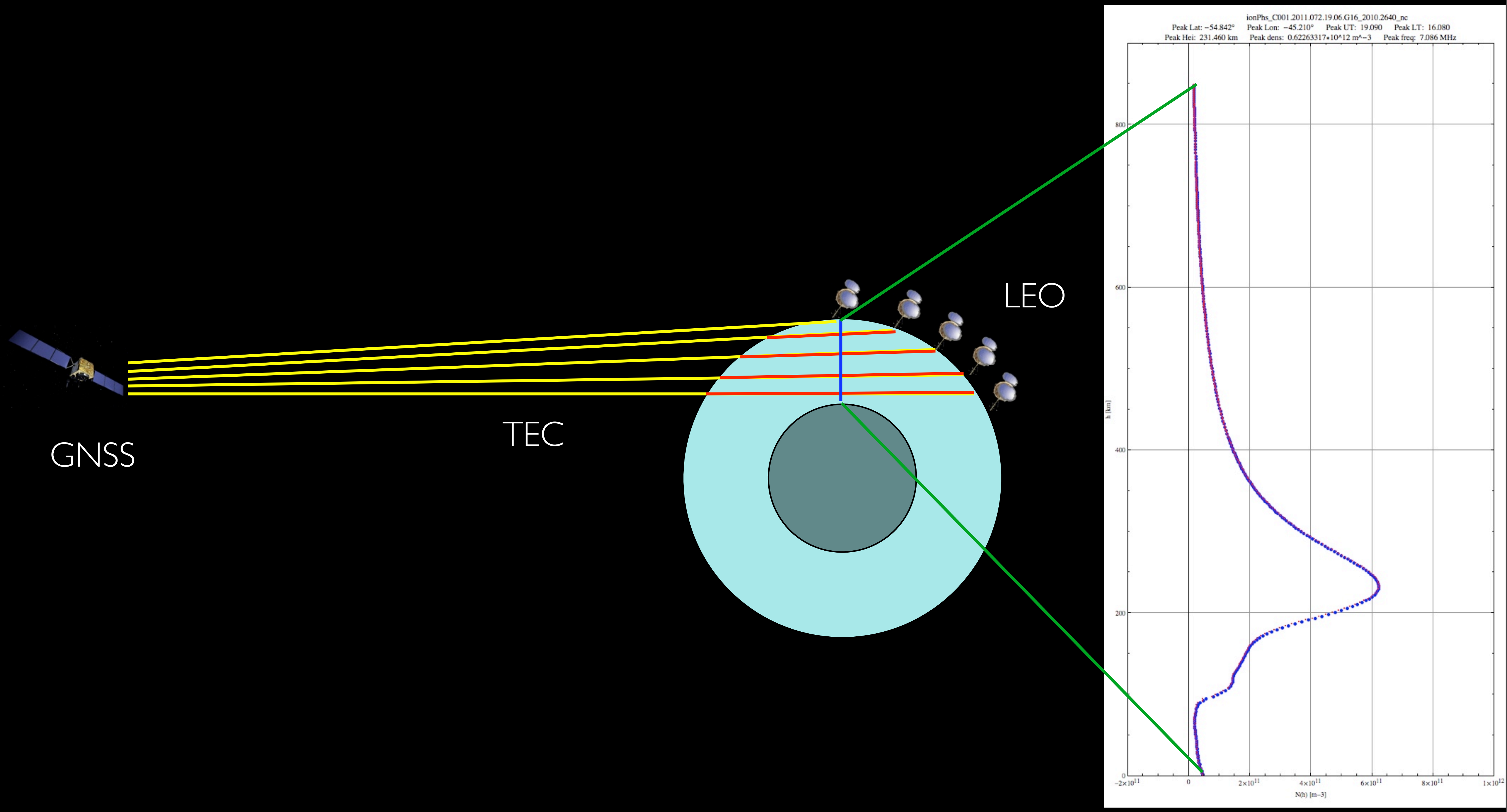
Adaptation method validation



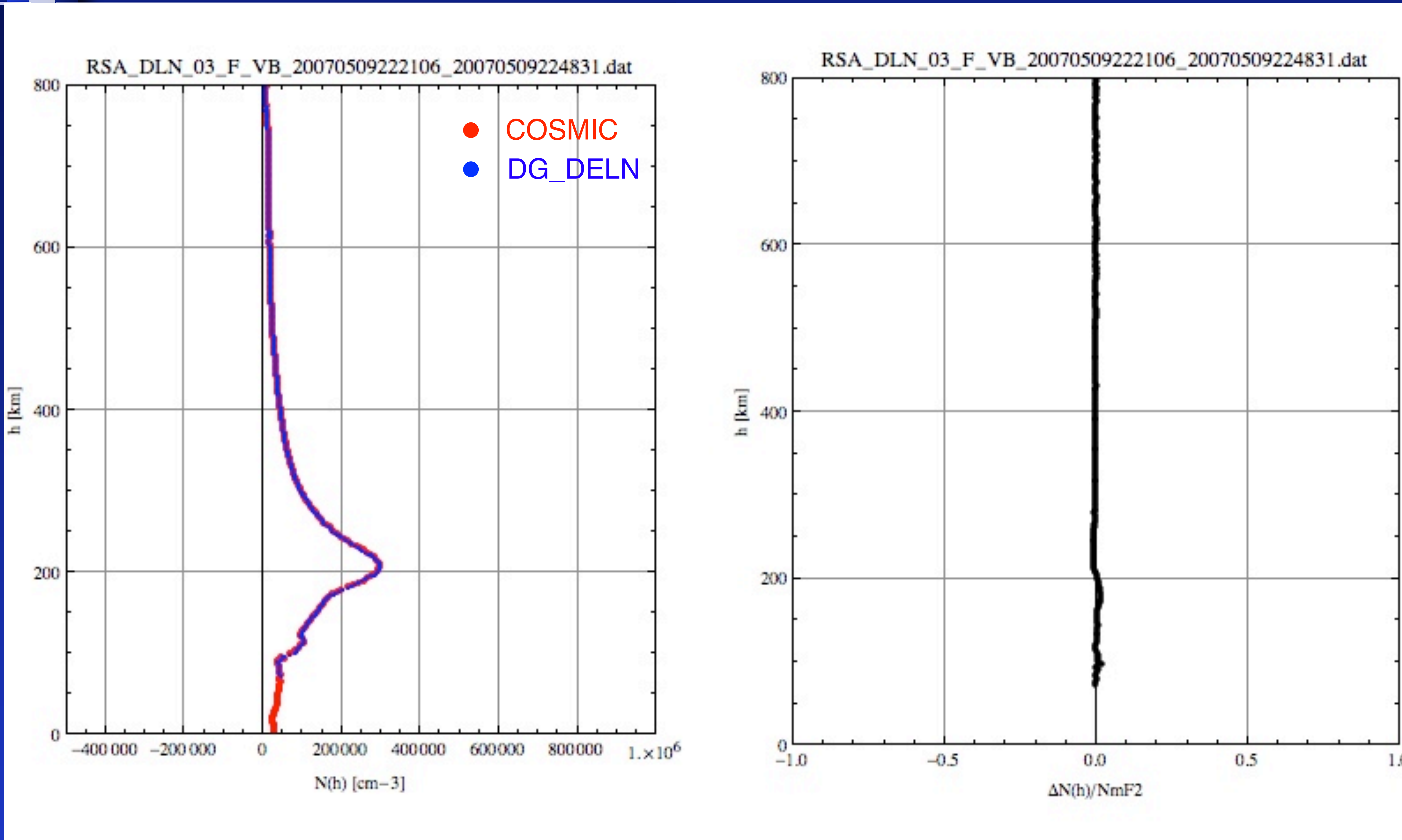
Model: IRI

Use of Radio Occultation data

GNSS RO data inversion

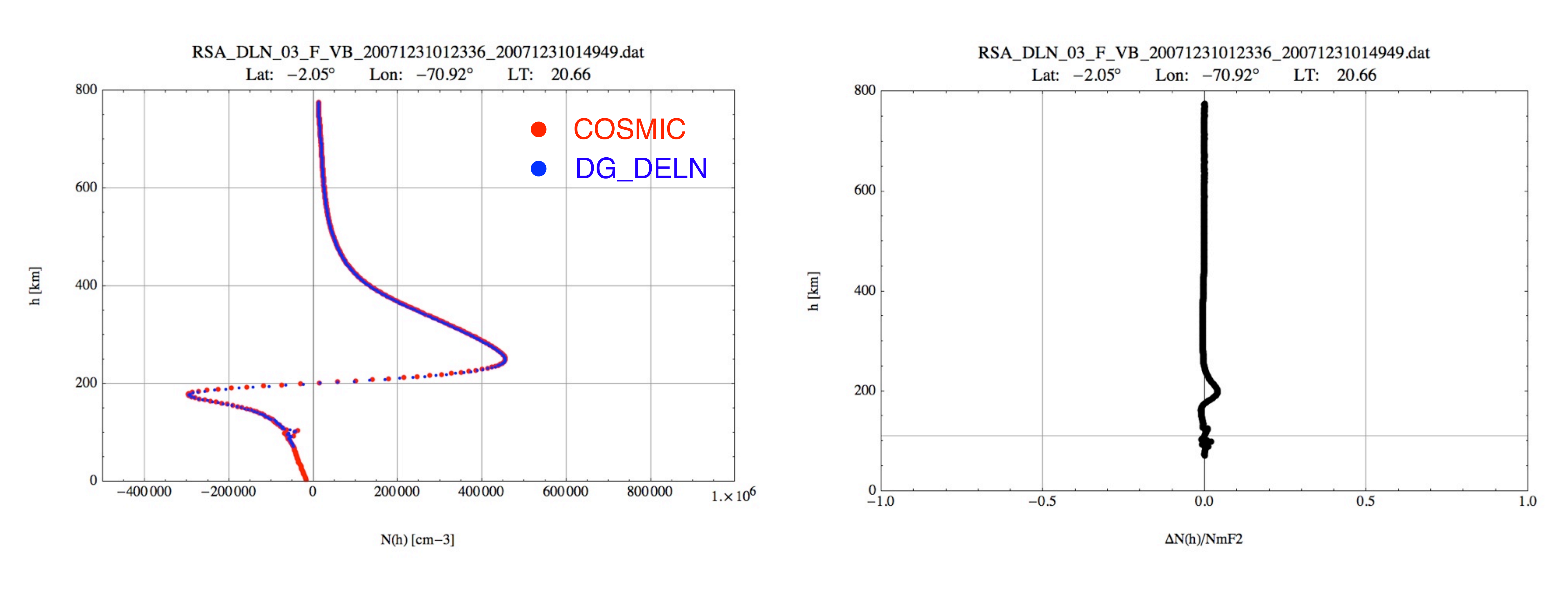


Onion peeling derived profile



COSMIC data are used

Profile example2



COSMIC data are used

Radio Occultation data ingestion

- RO data inversion through specific algorithms
  - Abel Inversion (bending angles).
  - A simple way to invert RO data (only) in the Ionosphere is to apply the "Onion Peeling" algorithm.
  - If additional data are available (e.g. TEC from ground GPS receivers), improved inversion techniques can be applied (e. g. variable separation).
    (Hernandez-Pajares M, Juan JM, Sanz J (2000); "Improving the Abel inversion by adding ground data to LEO radio occultations in the ionospheric sounding", Geoph Res Lett 27(16):2743–2746).

↓

- a) Adaptation to electron density profile
  - Using multiple effective parameters approach

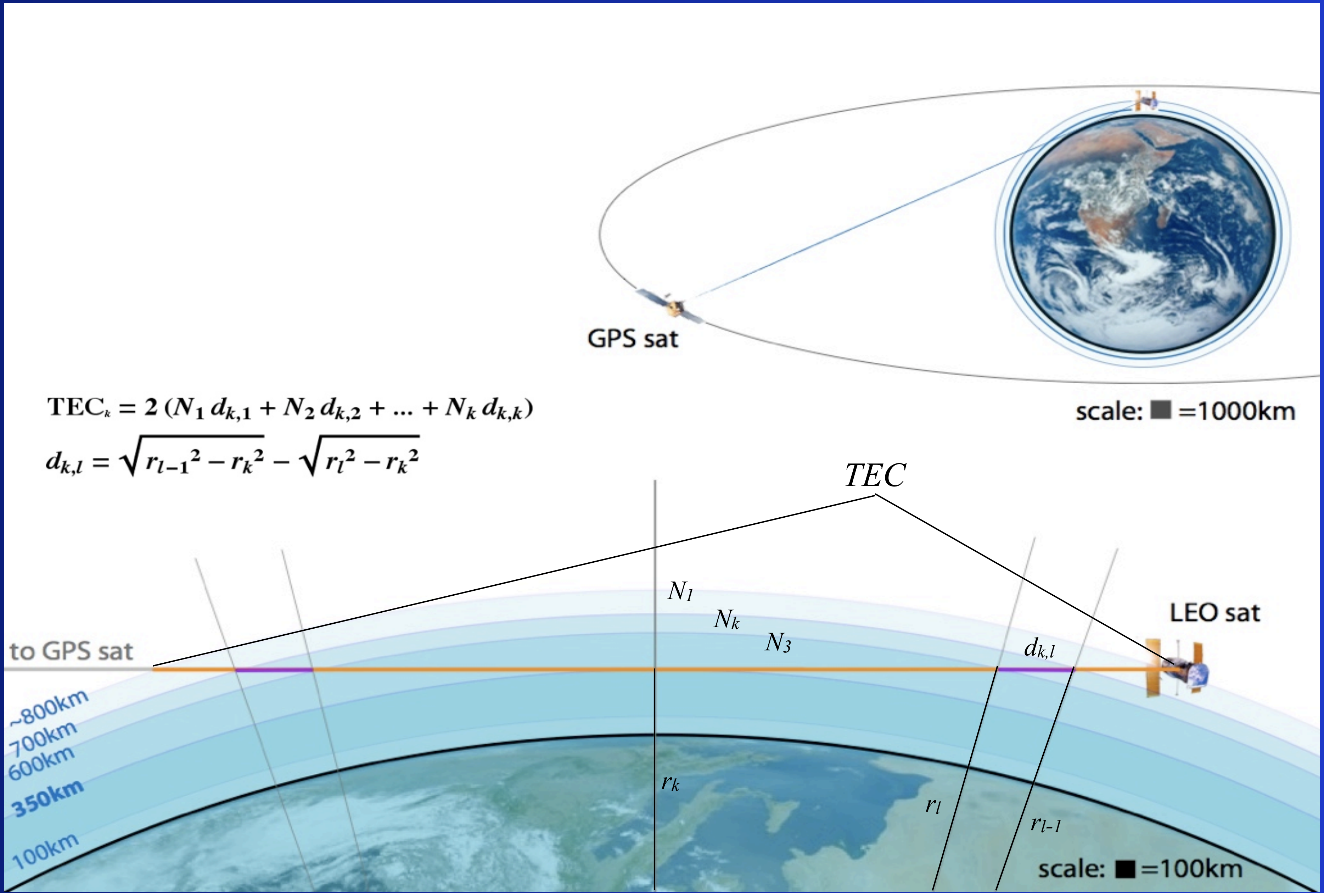
- b) Direct TEC assimilation into a background model.
  - EDAM, GAIM
  - NeQuick (multiple effective parameters)

Use of models for assessment studies

Use of an ionospheric 3D electron density model to evaluate the impact of specific algorithms/ assumptions in ionosphere-related parameters retrieval (e.g. in Satellite Navigation Systems).

NeQuick for assessment studies

Investigate the effects of spherical symmetry assumption for the ionosphere electron density in Radio Occultation data inversion (e.g. using the “Onion Peeling” algorithm);



A test case

Day: 31 Dec. 2007

True satellite orbits (GPS + COSMIC)

↙ Synthetic ionosphere (TEC from 3D electron density)

↓

Onion Peeling
vs
True profile
(NeQuick)

High & Low solar activity

↘ True ionosphere (excess phase @ L1,L2)

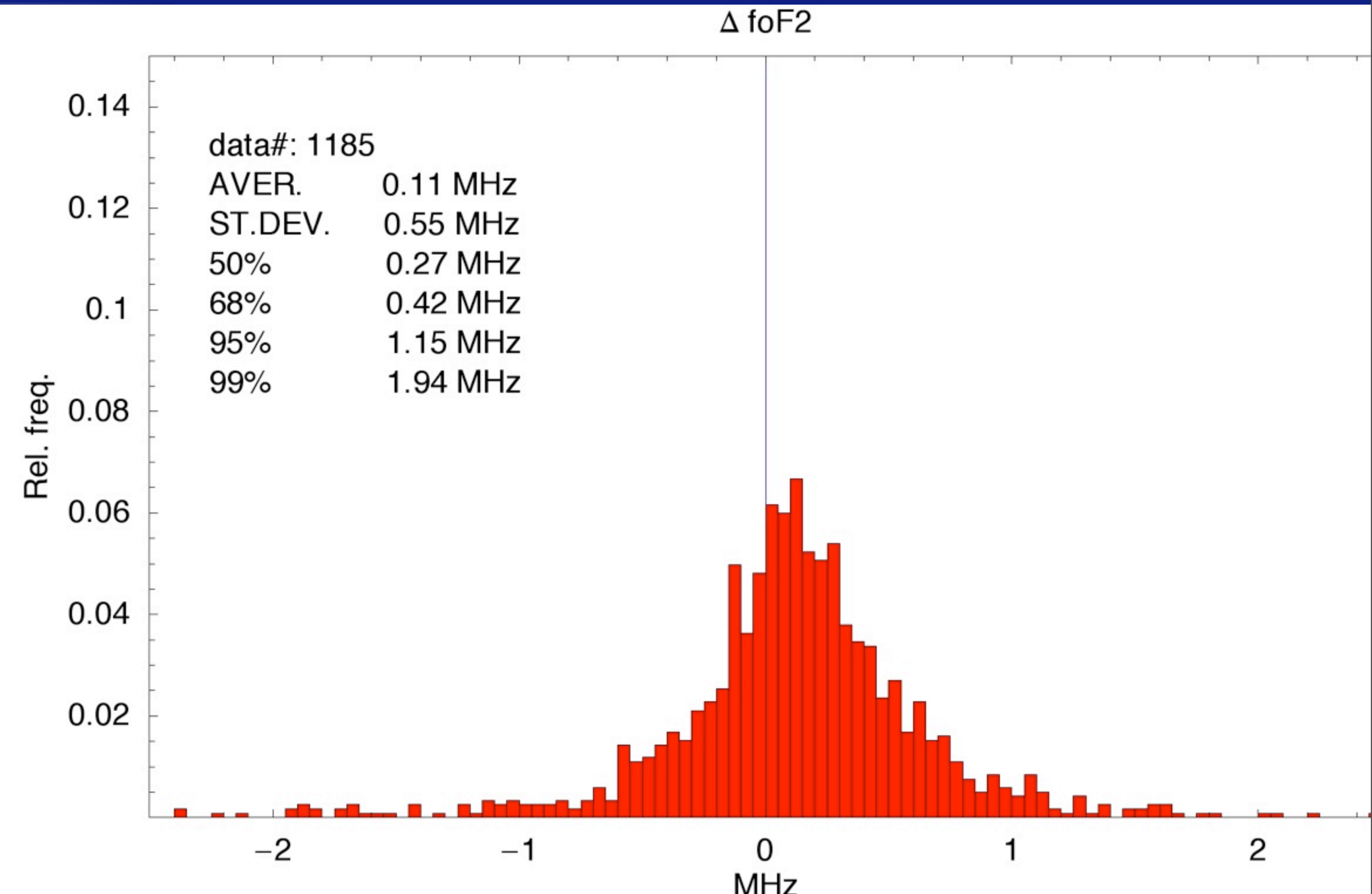
↓

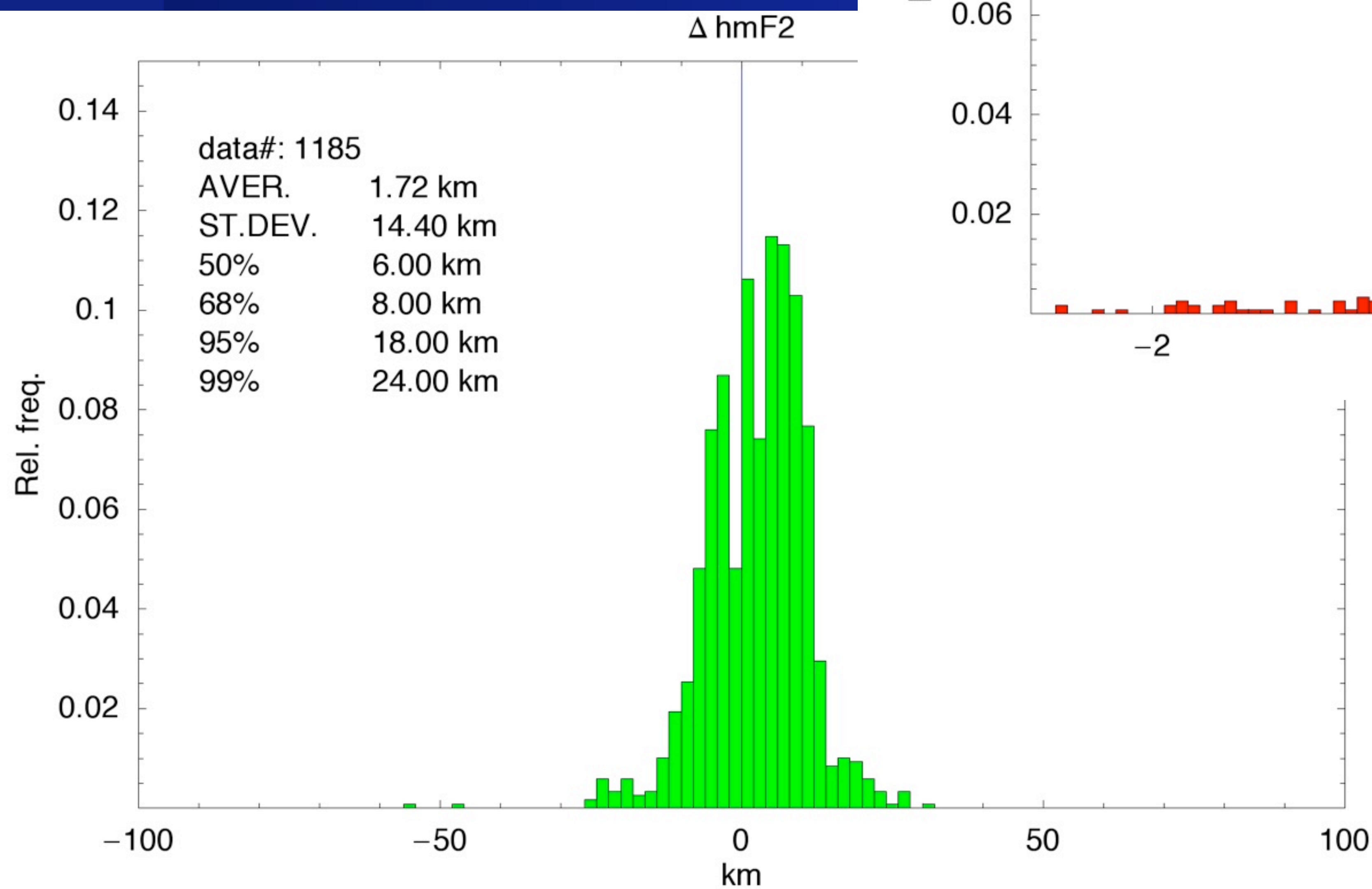
Onion Peeling
vs
True profile
(Ionosonde)

Onion Peeling performance analyzed in terms of foF2 & hmF2 error statistics

Simulation results (HSA)

foF2 and hmF2 errors statistics





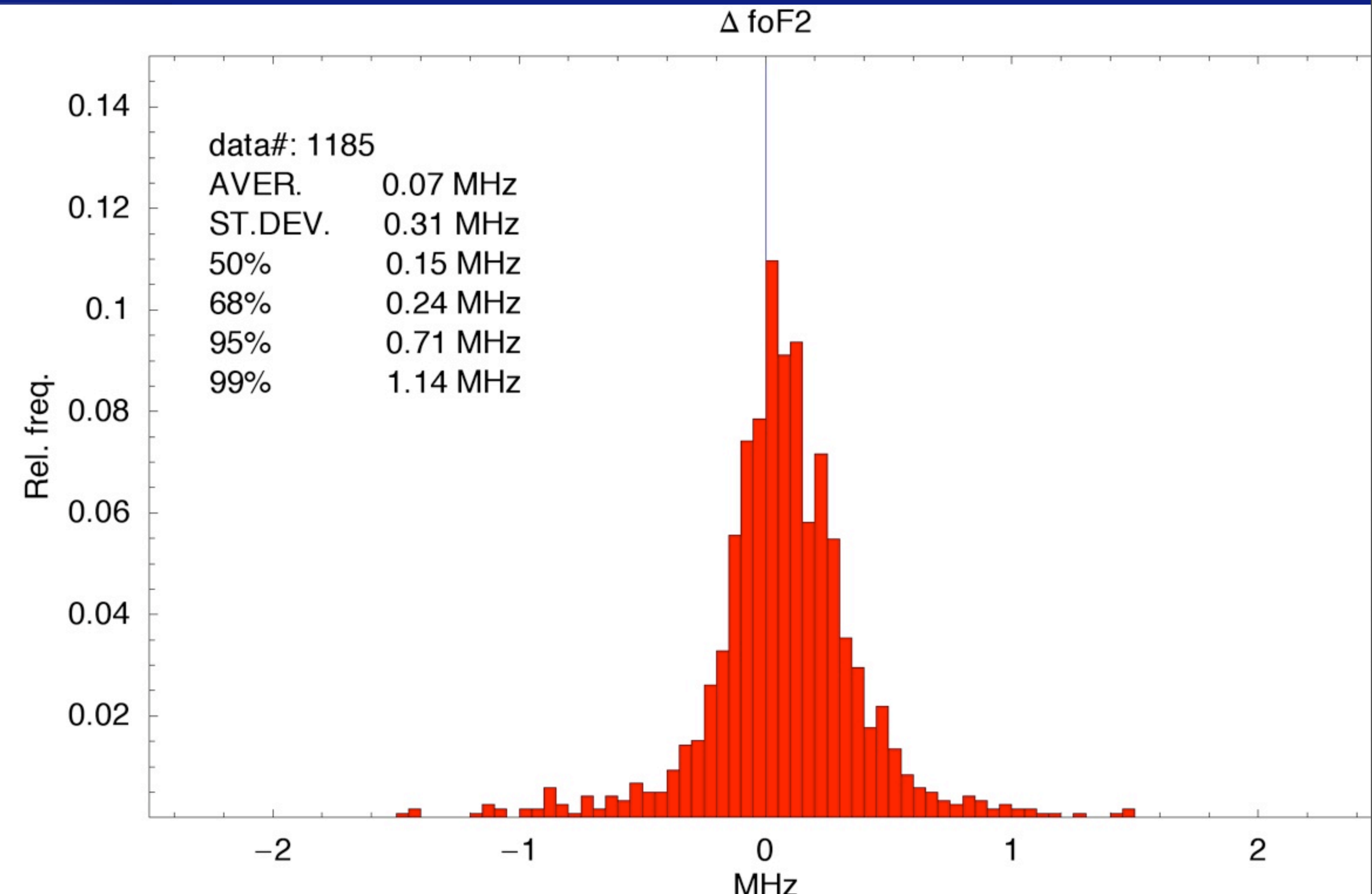
Co-location criteria for true profile and Onion Peeling derived profile

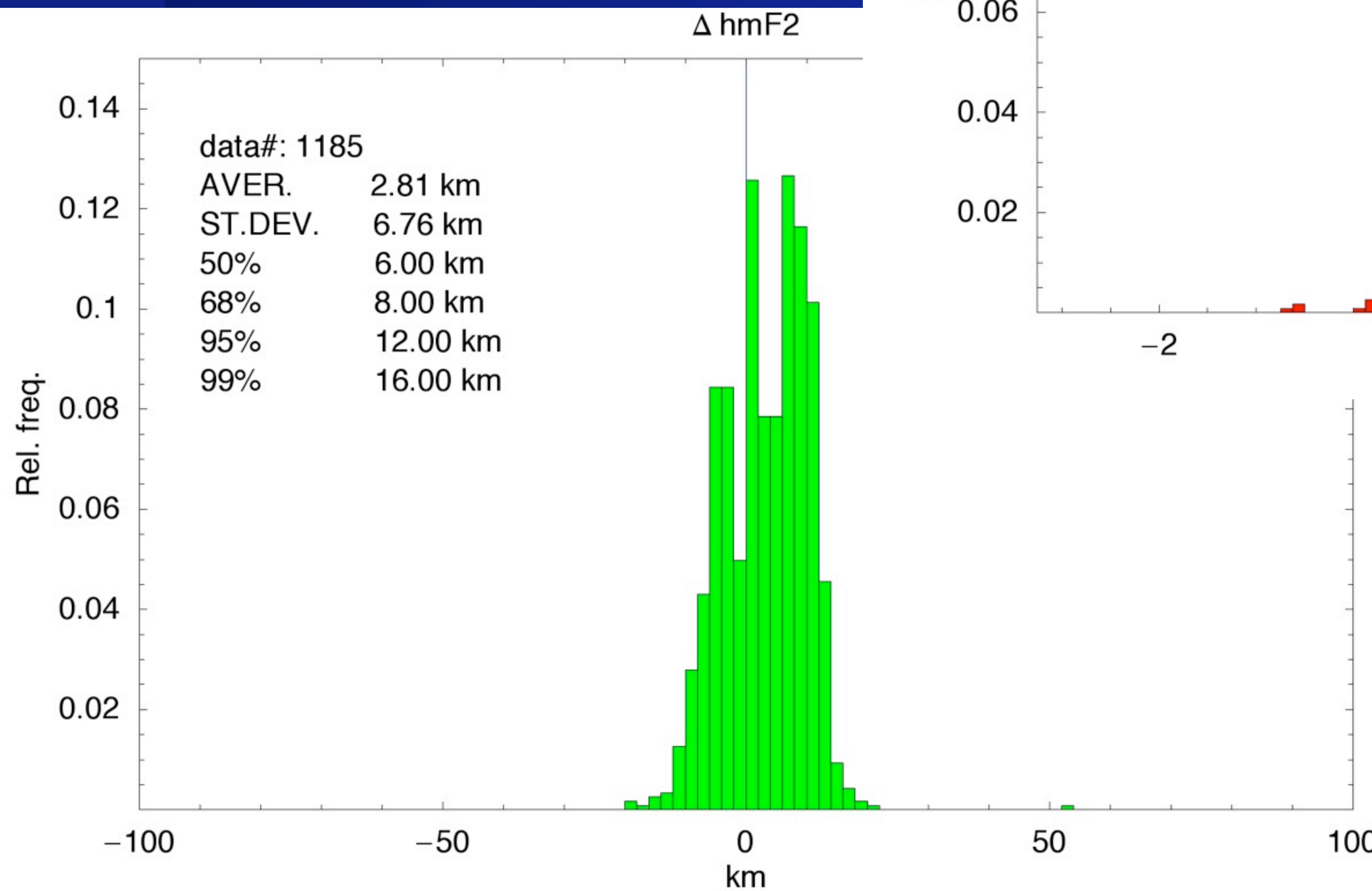
↓

exact matching

Simulation results (LSA)

foF2 and hmF2 errors statistics





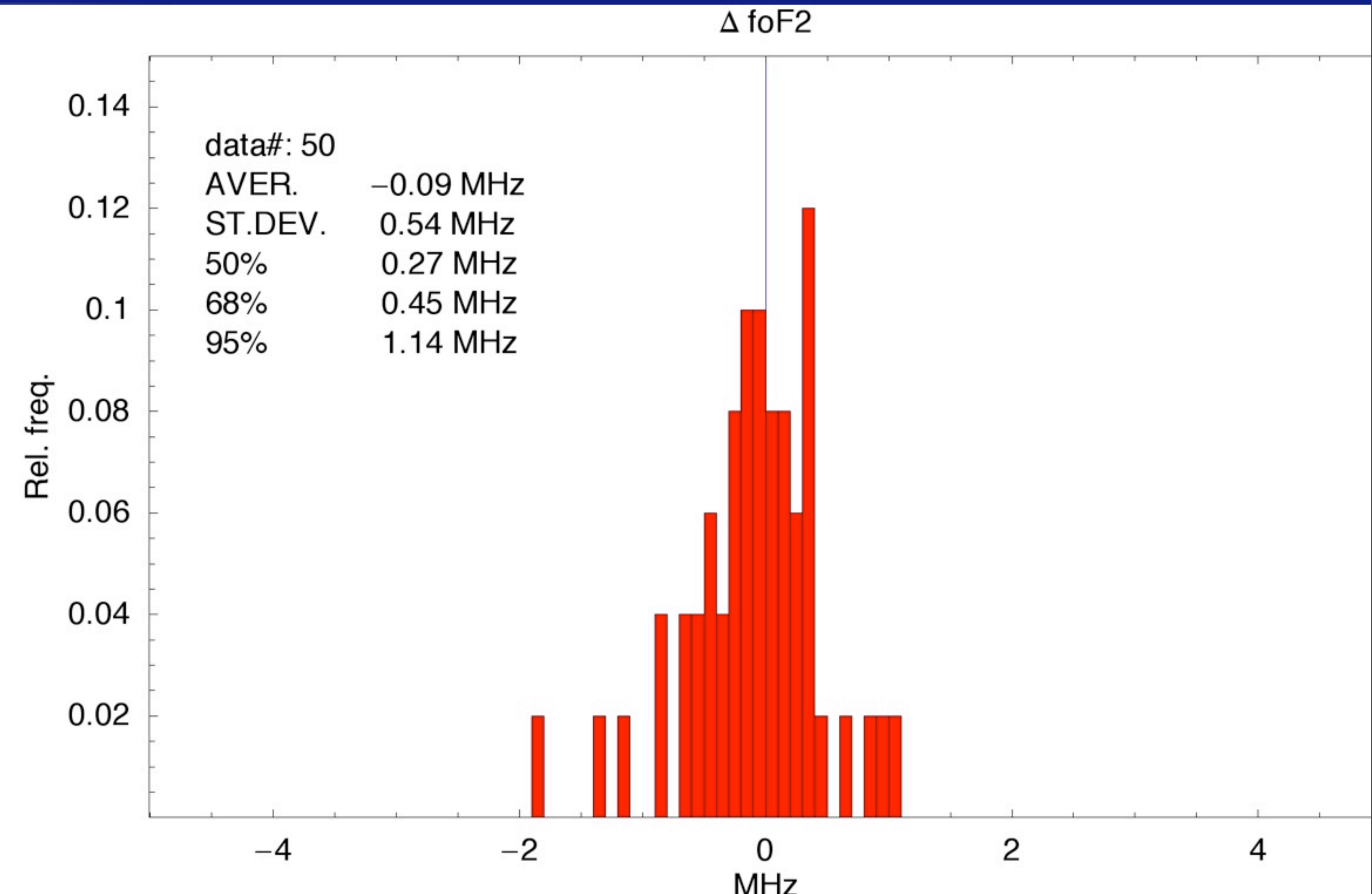
Co-location criteria for true profile and Onion Peeling derived profile

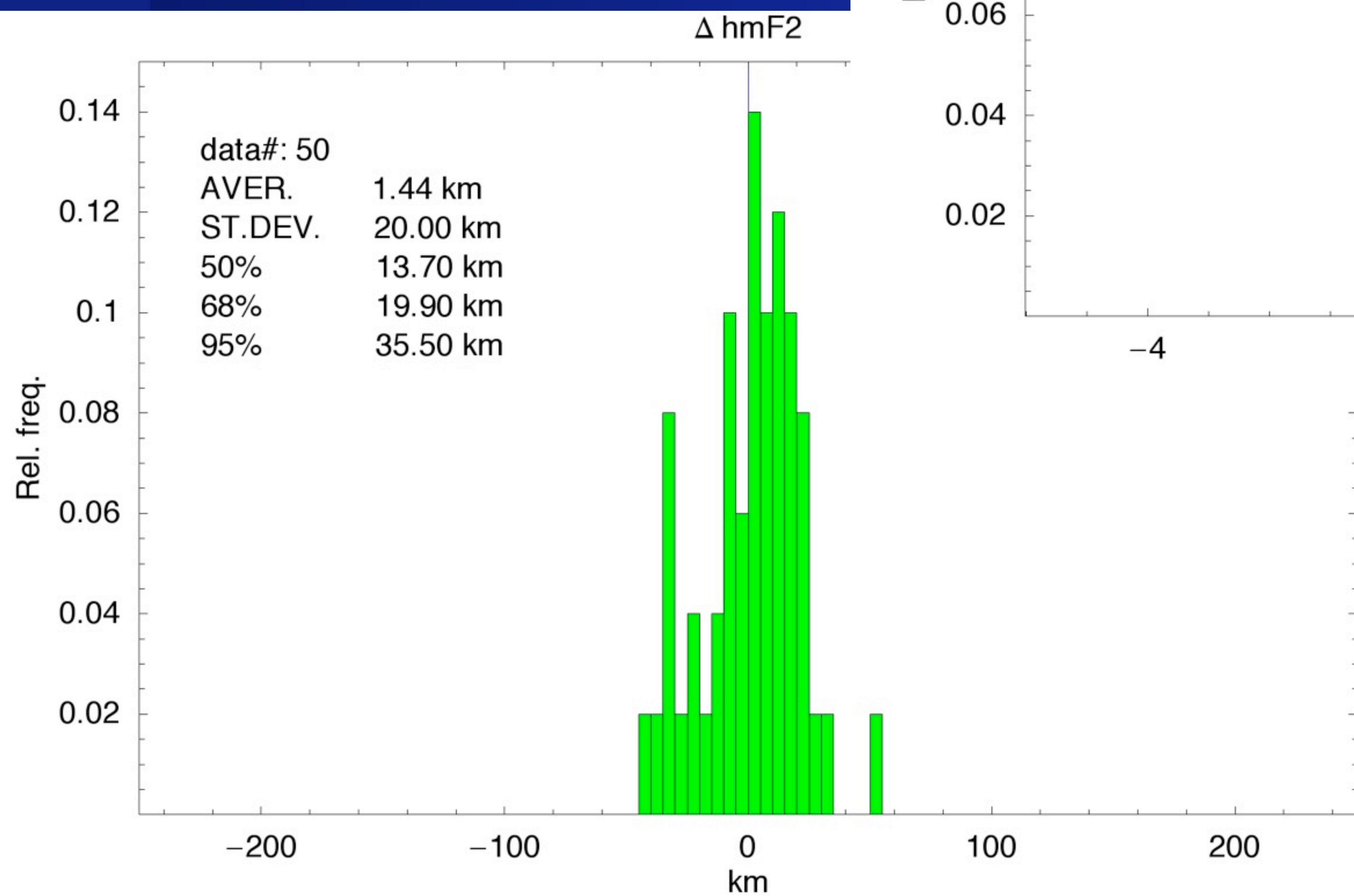
↓

exact matching

Experimental data (LSA)

foF2 and hmF2
errors statistics





Co-location criteria for true profile and Onion Peeling derived profile

↓

Delta Time < 15 min
Delta Lat < 5°
Delta Lon < 10°

Least Square Estimation

Least Square Estimation

Recently, to improve the NeQuick performance in retrieving the 3D electron density of the Ionosphere, a minimum variance least-squares estimation has also been utilized to assimilate ground and space-based TEC data into NeQuick 2.

Best Linear Unbiased Estimator (BLUE)*

y vector of observations

$\mathbf{x}_b$ background model state

$\mathbf{x}_a$ analysis model state

H observation operator

R covariance matrix of observation errors

B covariance matrix of background errors

A covariance matrix of analysis errors

*http://www.ecmwf.int/newsevents/training/rcourse_notes/DATA_ASSIMILATION/ASSIM_CONCEPTS/Assim_concepts2.html#962570

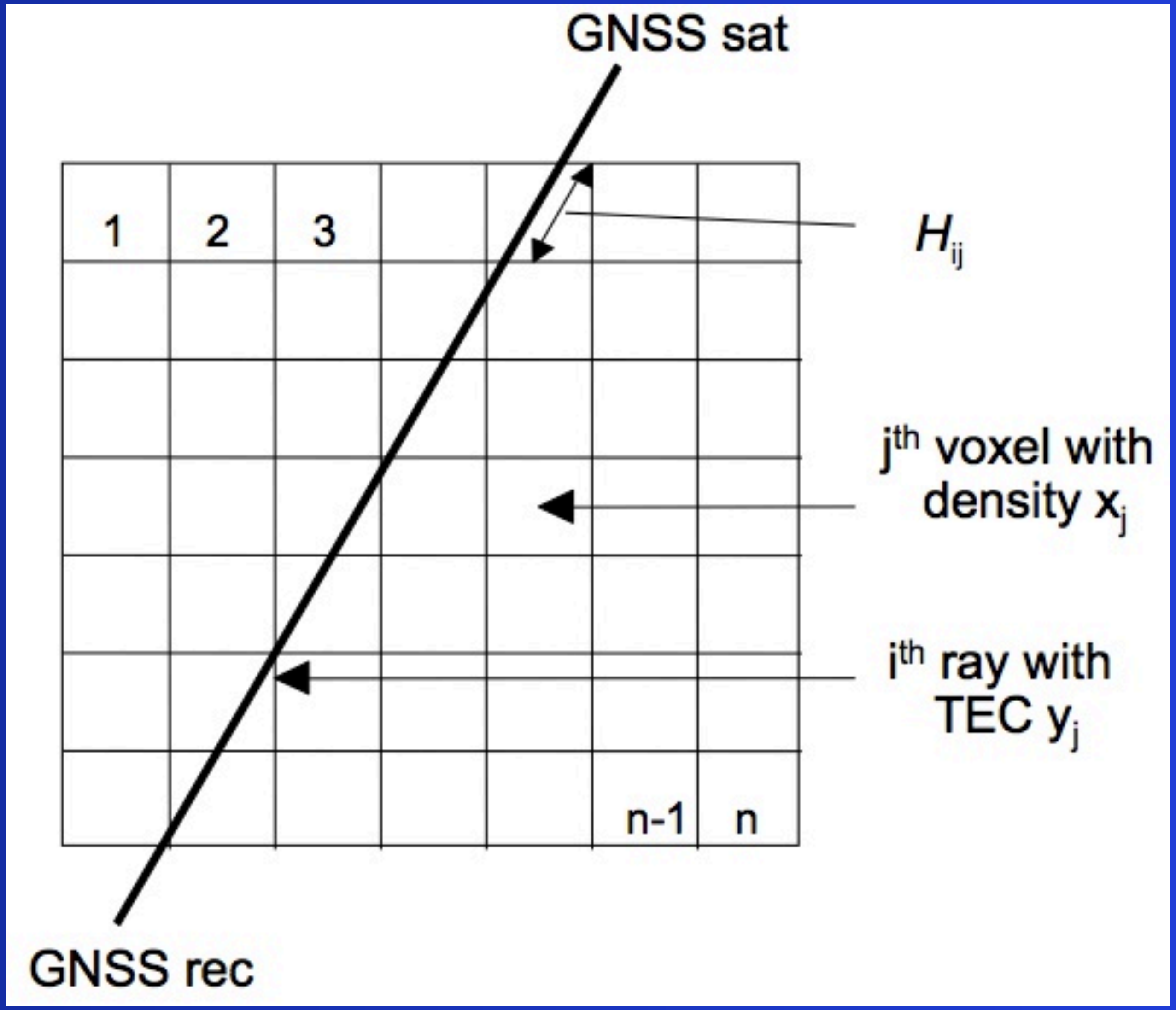
Least Square Estimation

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:

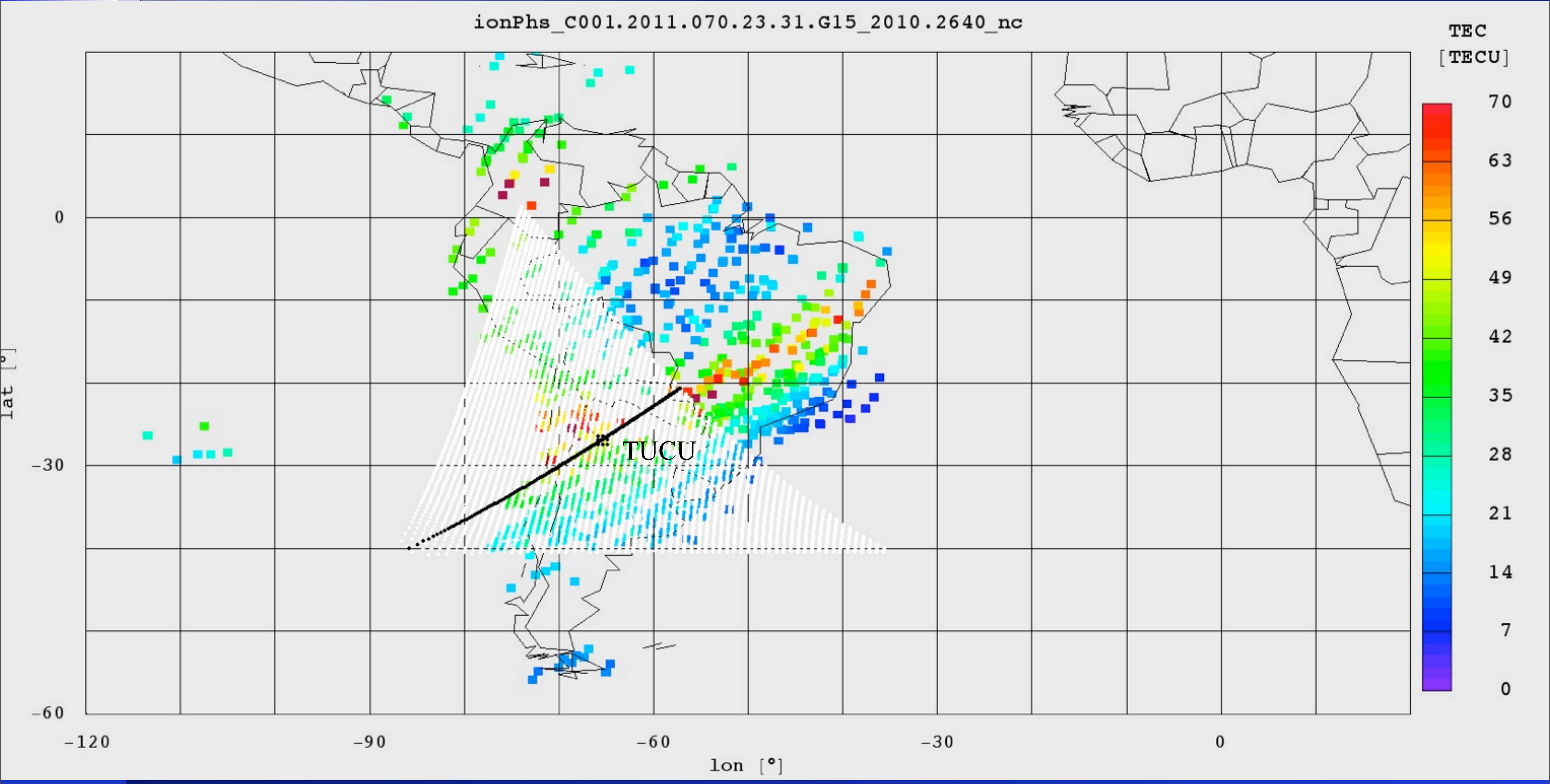
y = TEC
$\mathbf{x_a}$ = retrieved electron density
$\mathbf{x_b}$ = background electron density
H -> “crossing lengths” in “voxels”

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

Data used (test case)

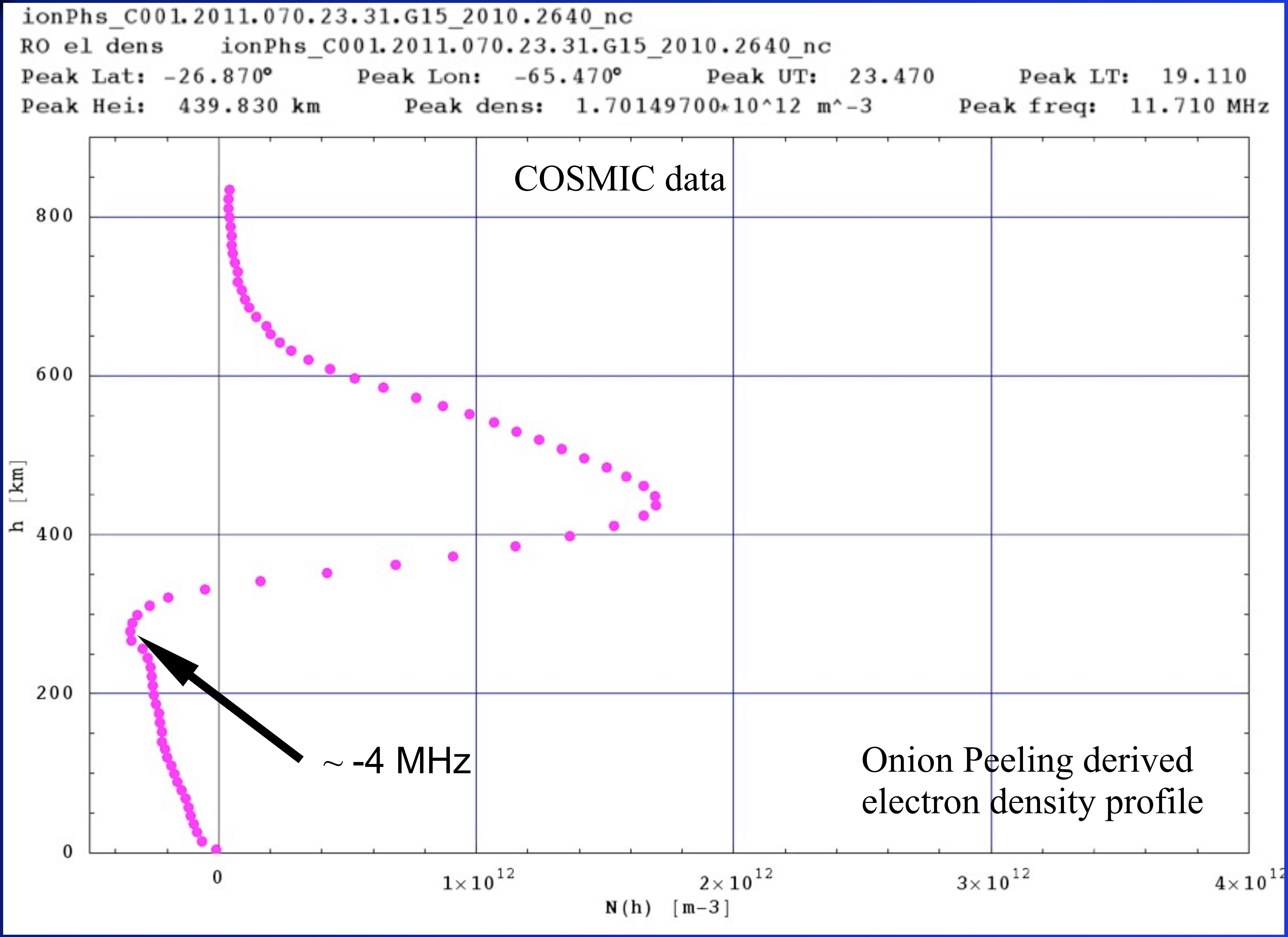
- For the assimilation
  - Ground-based GPS-derived slant TEC data provided by the Low Latitude Ionospheric Sensor Network (LISN)
  - Radio-Occultation-derived TEC data obtained by COSMIC (calibrated TEC values along the LEO-to-GPS link below the LEO orbit)
- For the validation
  - Manually scaled foF2 data obtained from the Tucuman Ionosonde
  - JRO electron density profiles

LS solution: a challenging case

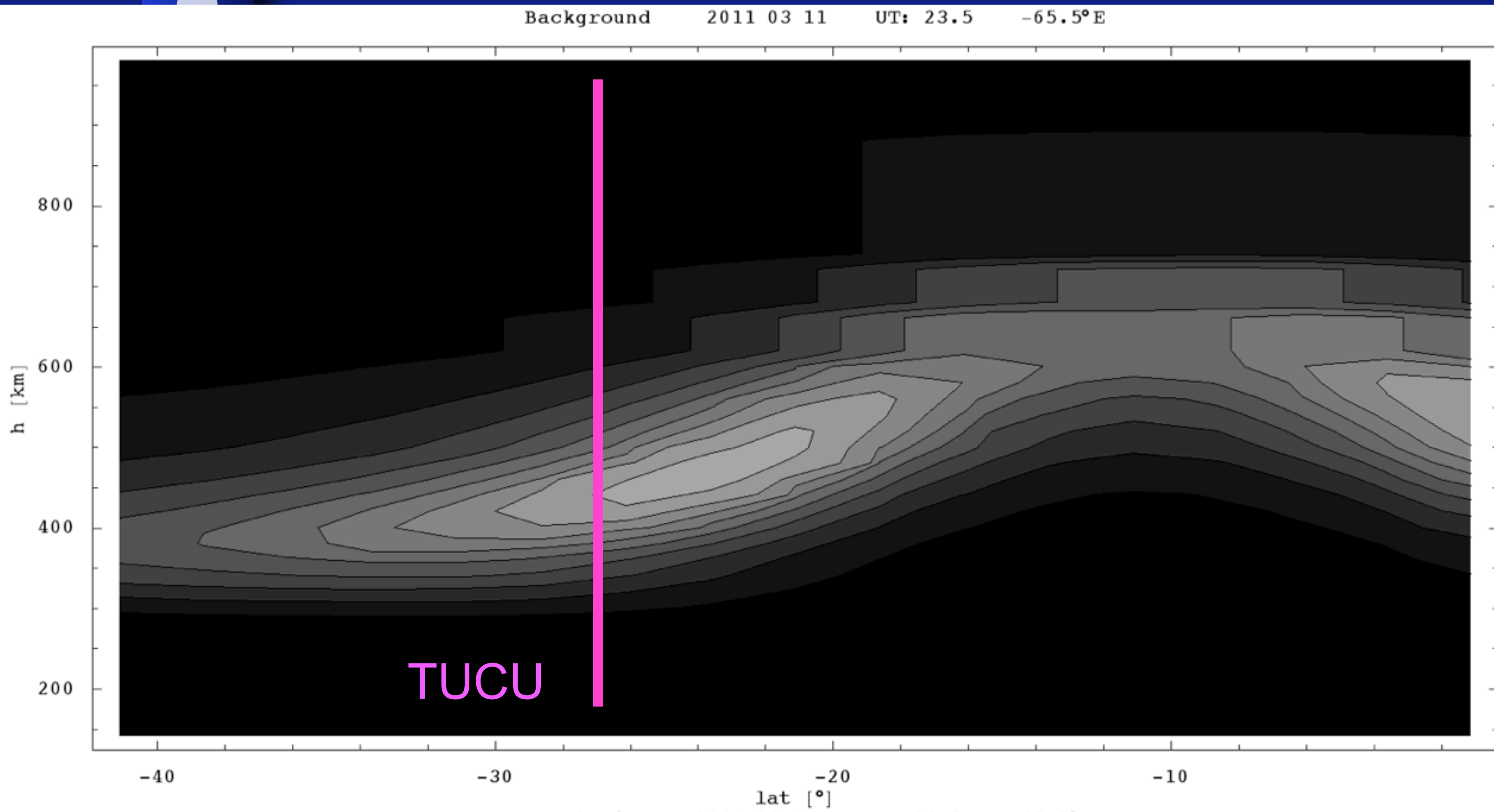


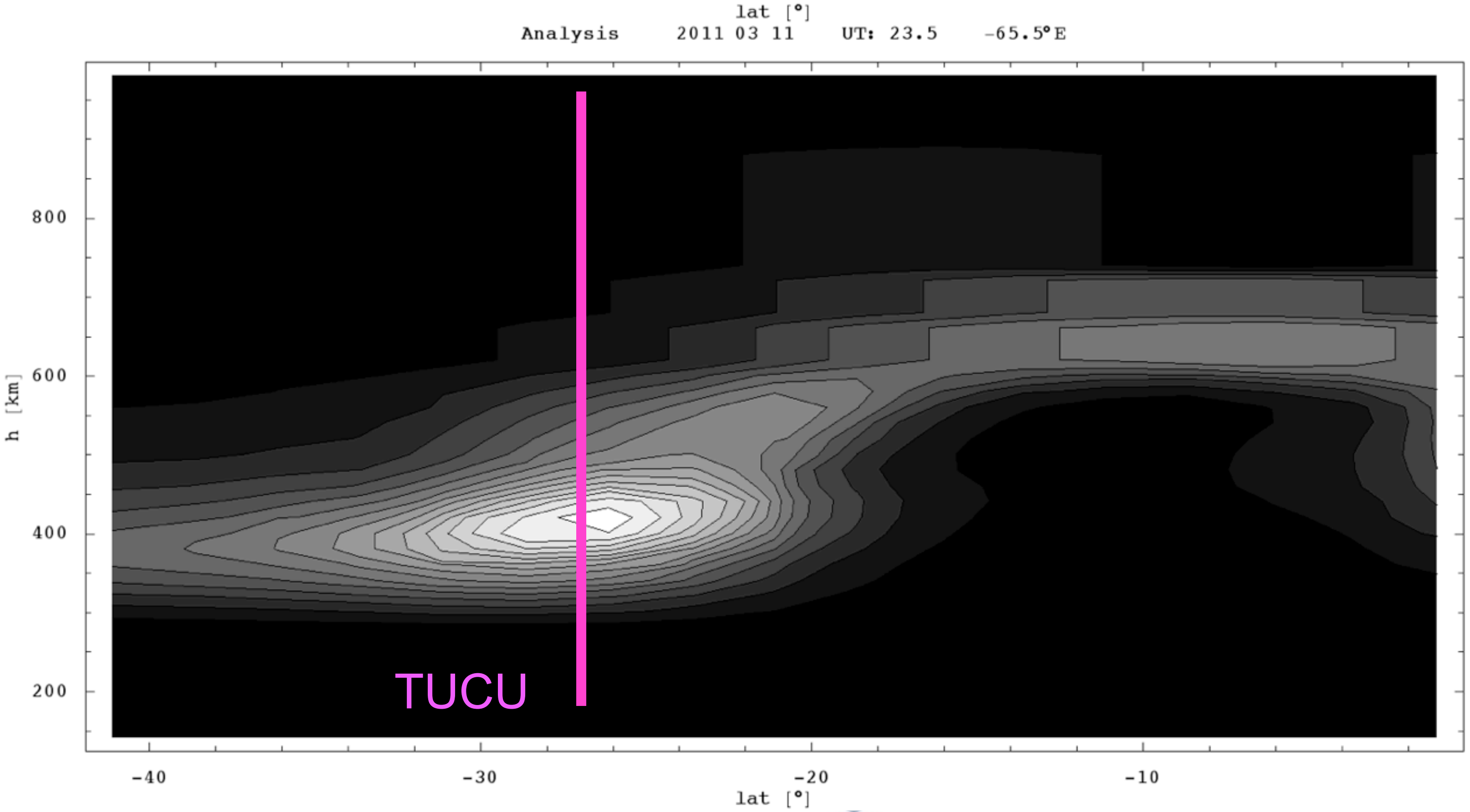
- projections of the LEO -> GPS links below the LEO orbit
- tangent points of the LEO -> GPS links

LS solution: a challenging case



Results: retrieved electron density





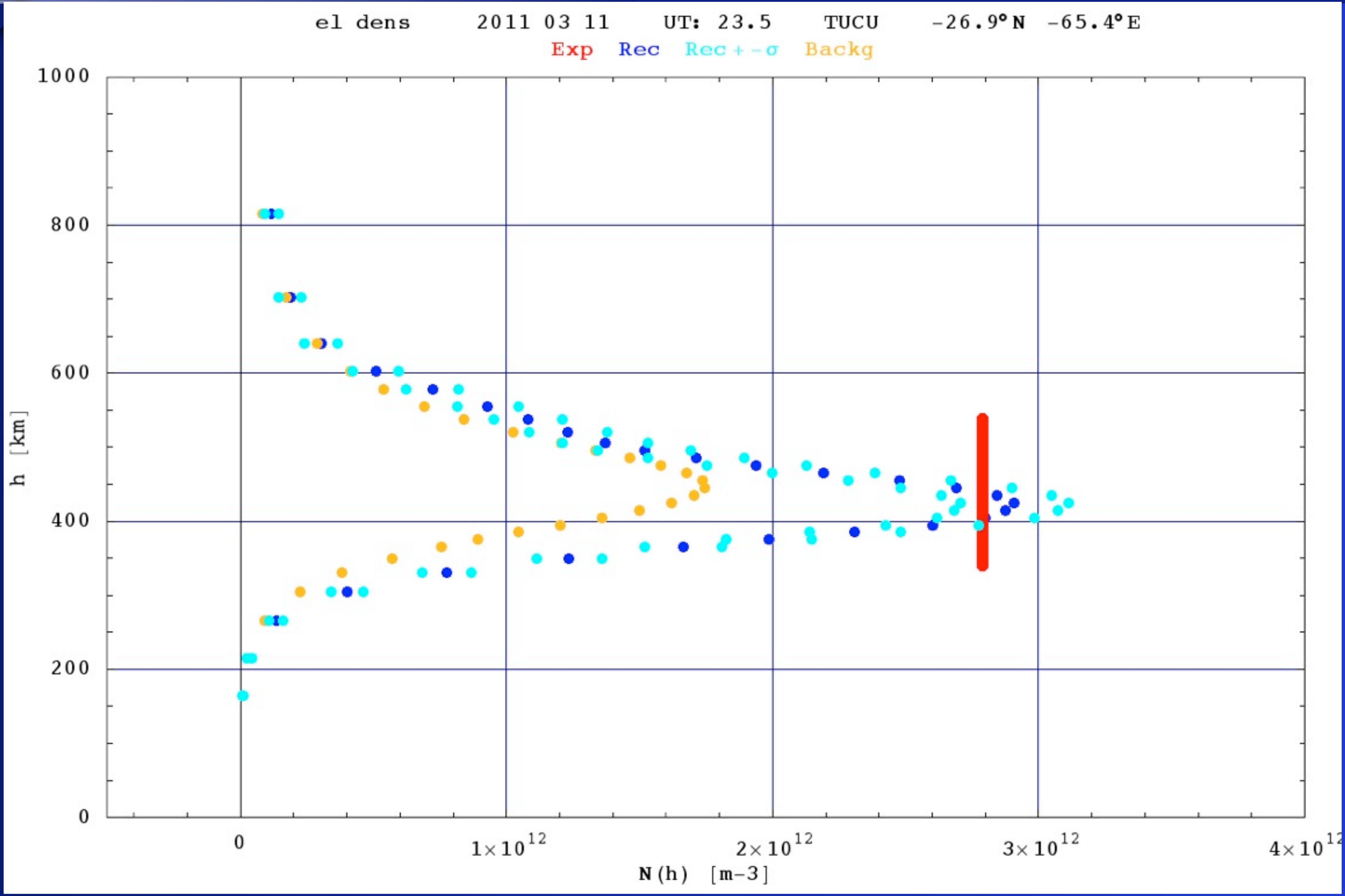
Cross section

23:30UT; -65.5ºE
from -40ºN to -2ºN

Background model
(before the assimilation)

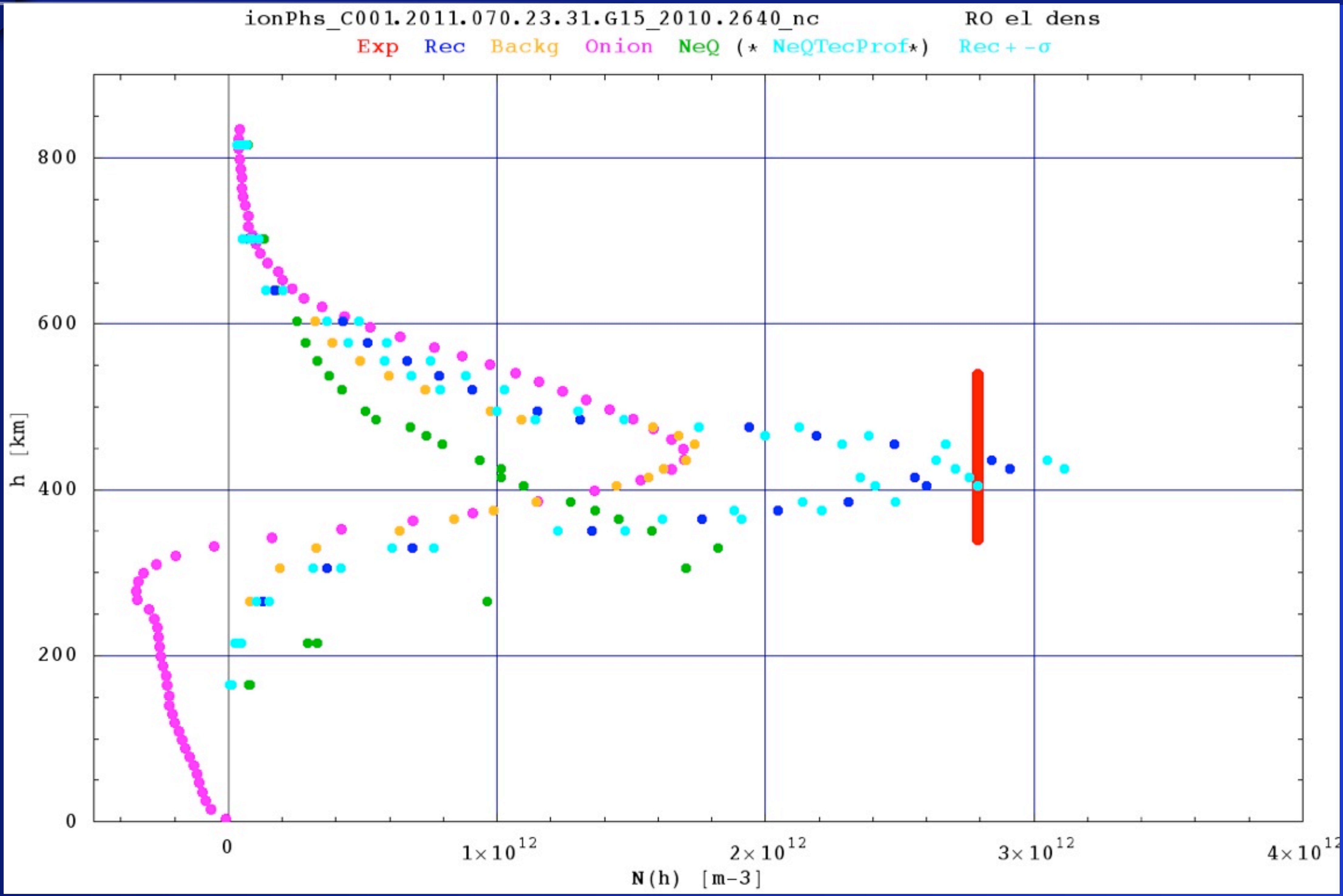
Analysis
(after the assimilation)

Method validation



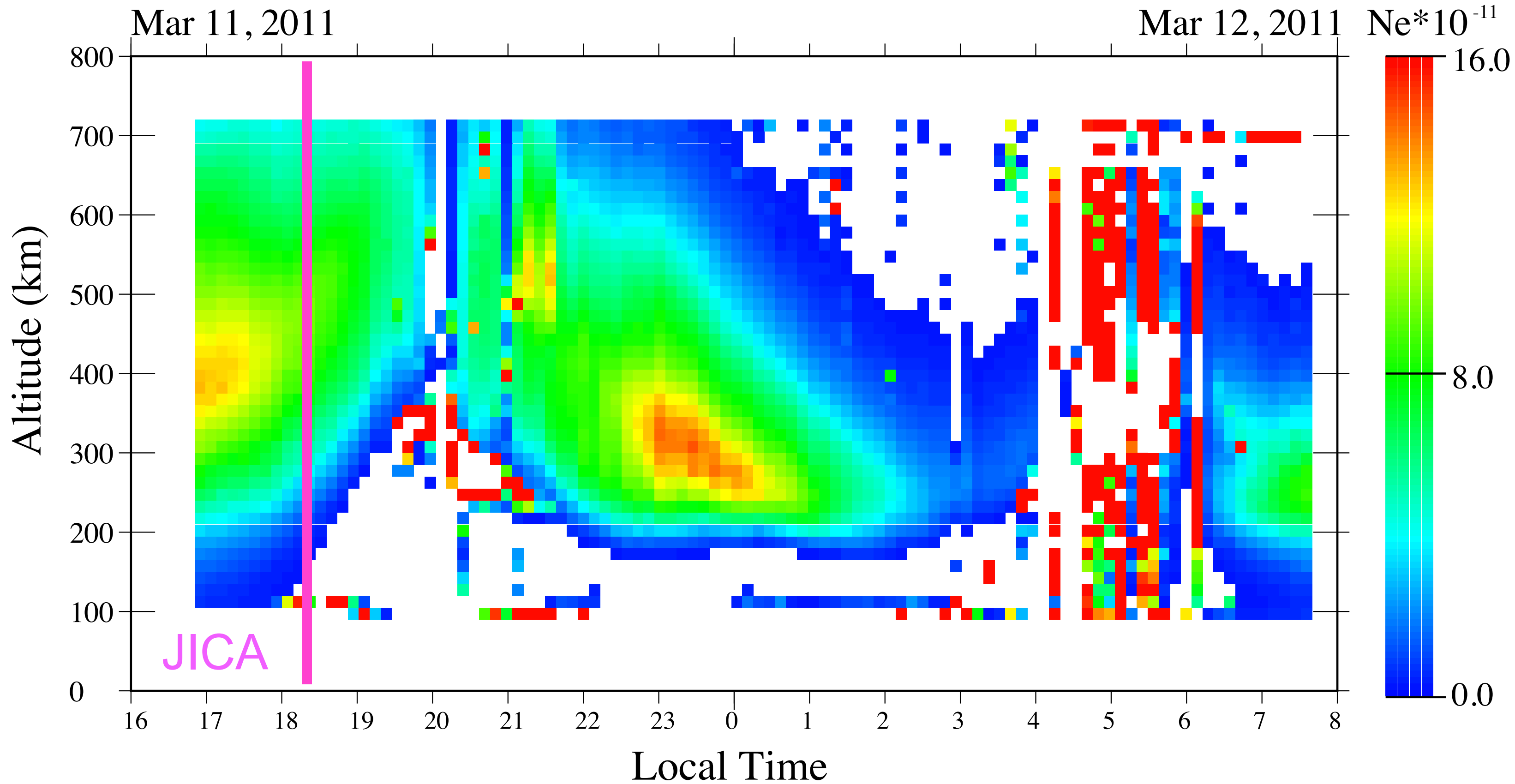
Electron density profiles at Ionosonde location

Method validation

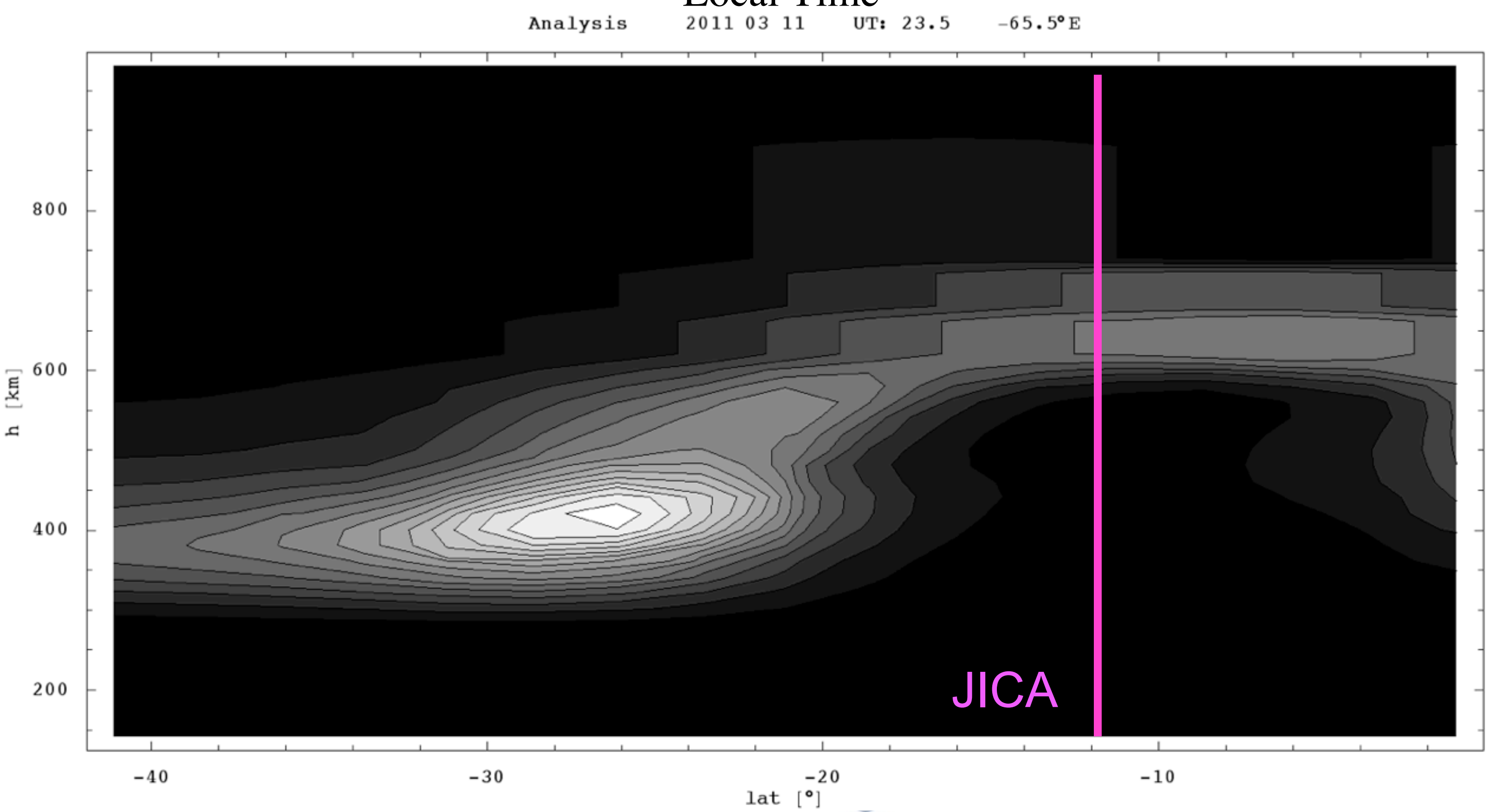


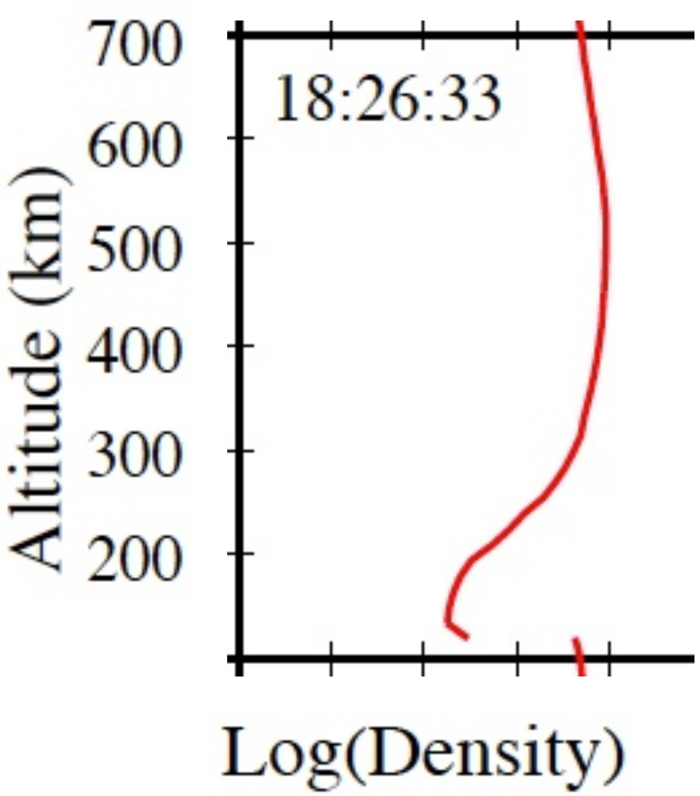
Electron density profiles “along” tangent points

Results: retrieved electron density

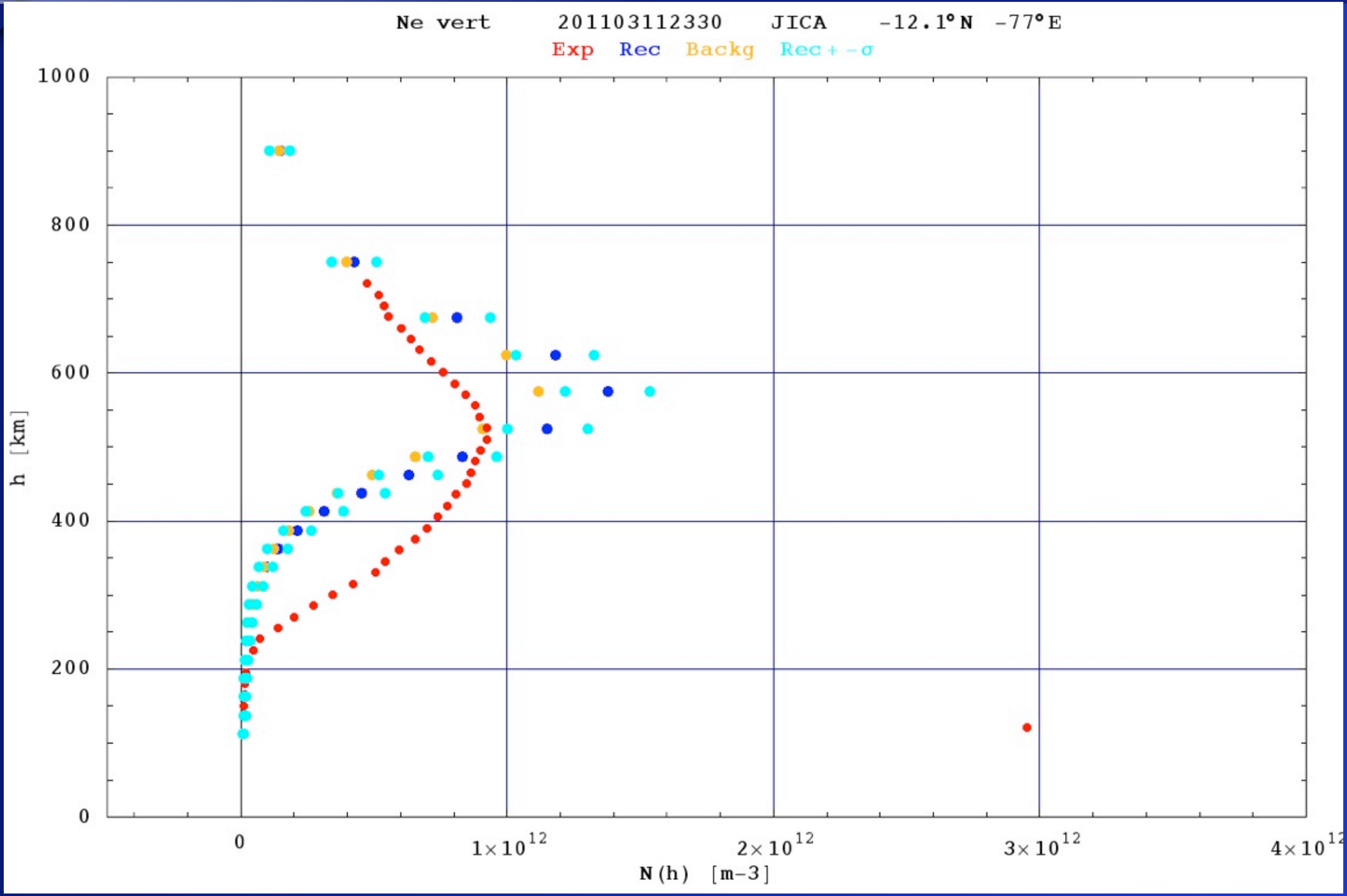


Jicamarca data
(C. Valladares)



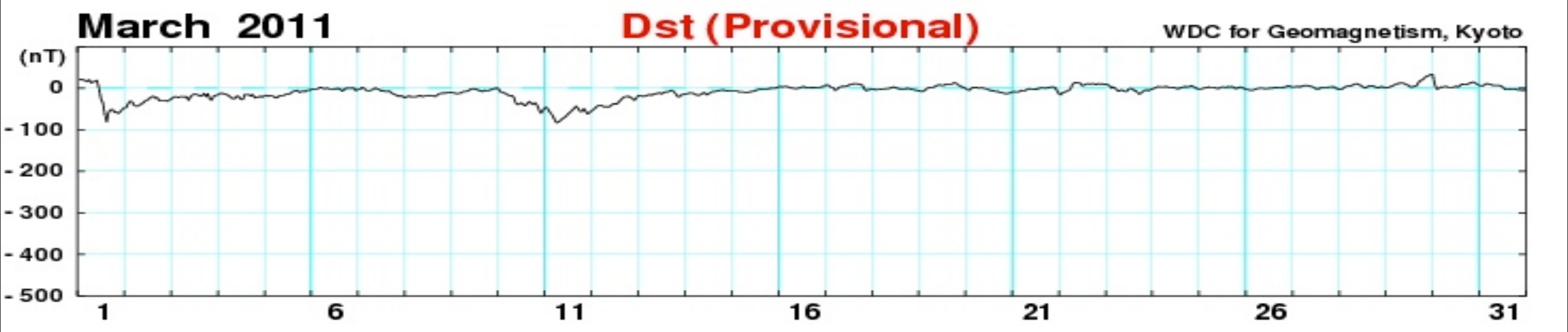


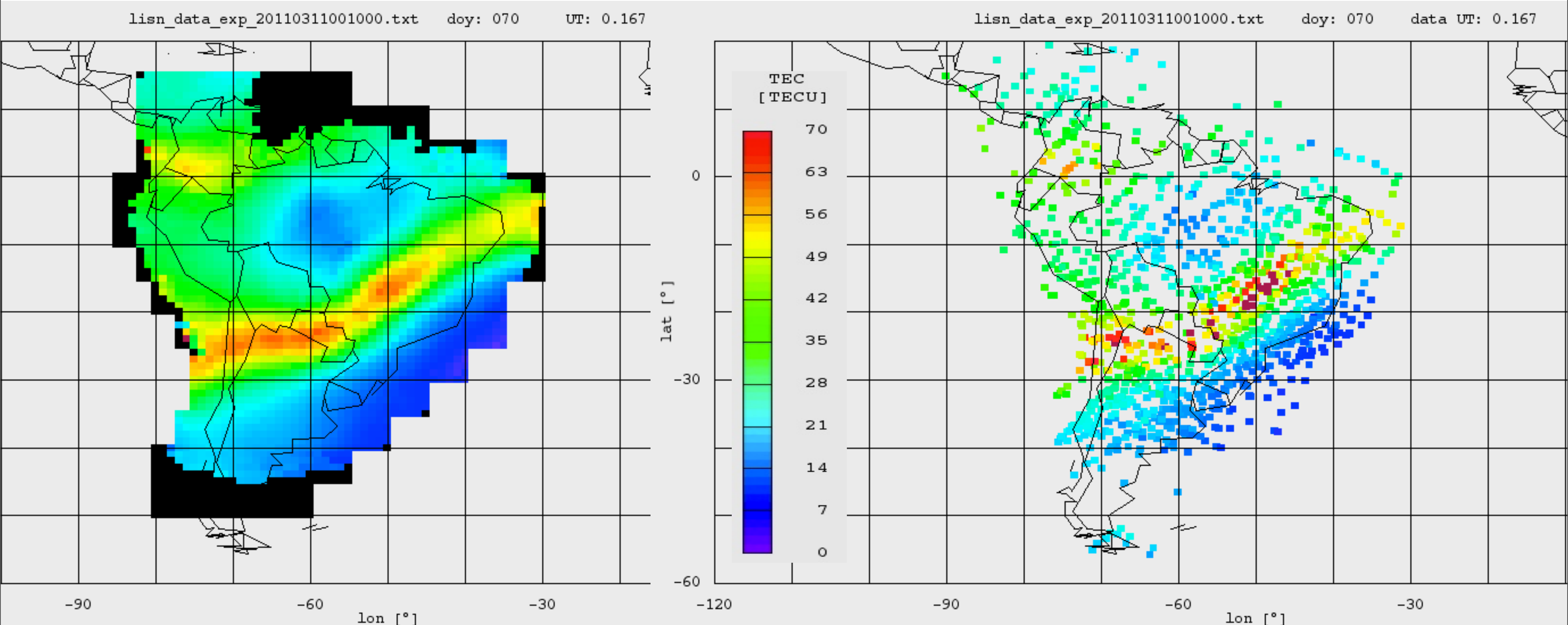
Results: method validation



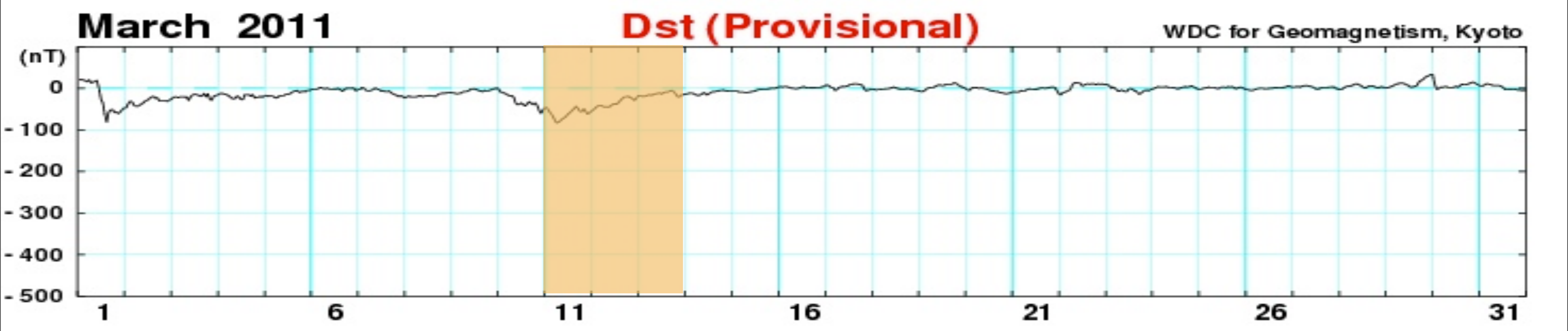
Electron density profiles at JRO location

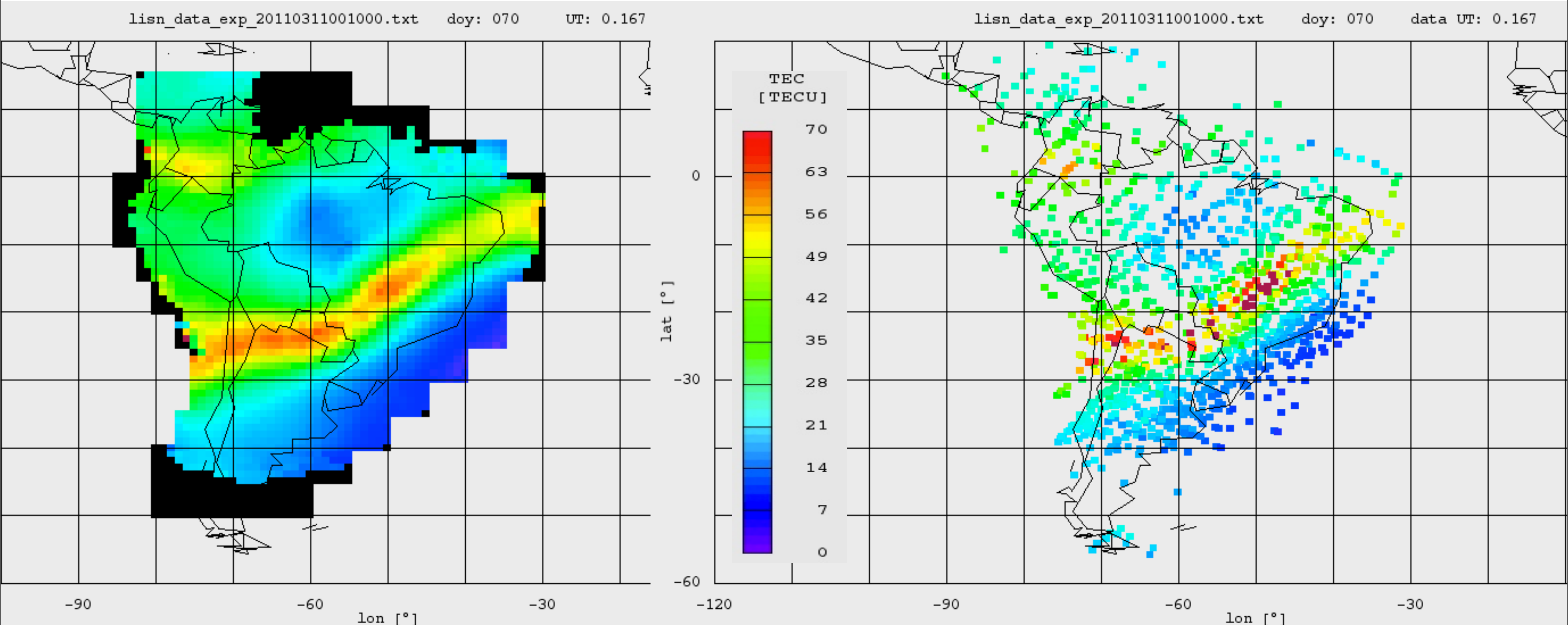
LISN: 3 days data (2011/03/11-12-13)





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





LS solution: Ne cross-section

Cross section
-64.75°E
from -38°N to 8°N
(low resolution; no RO data)

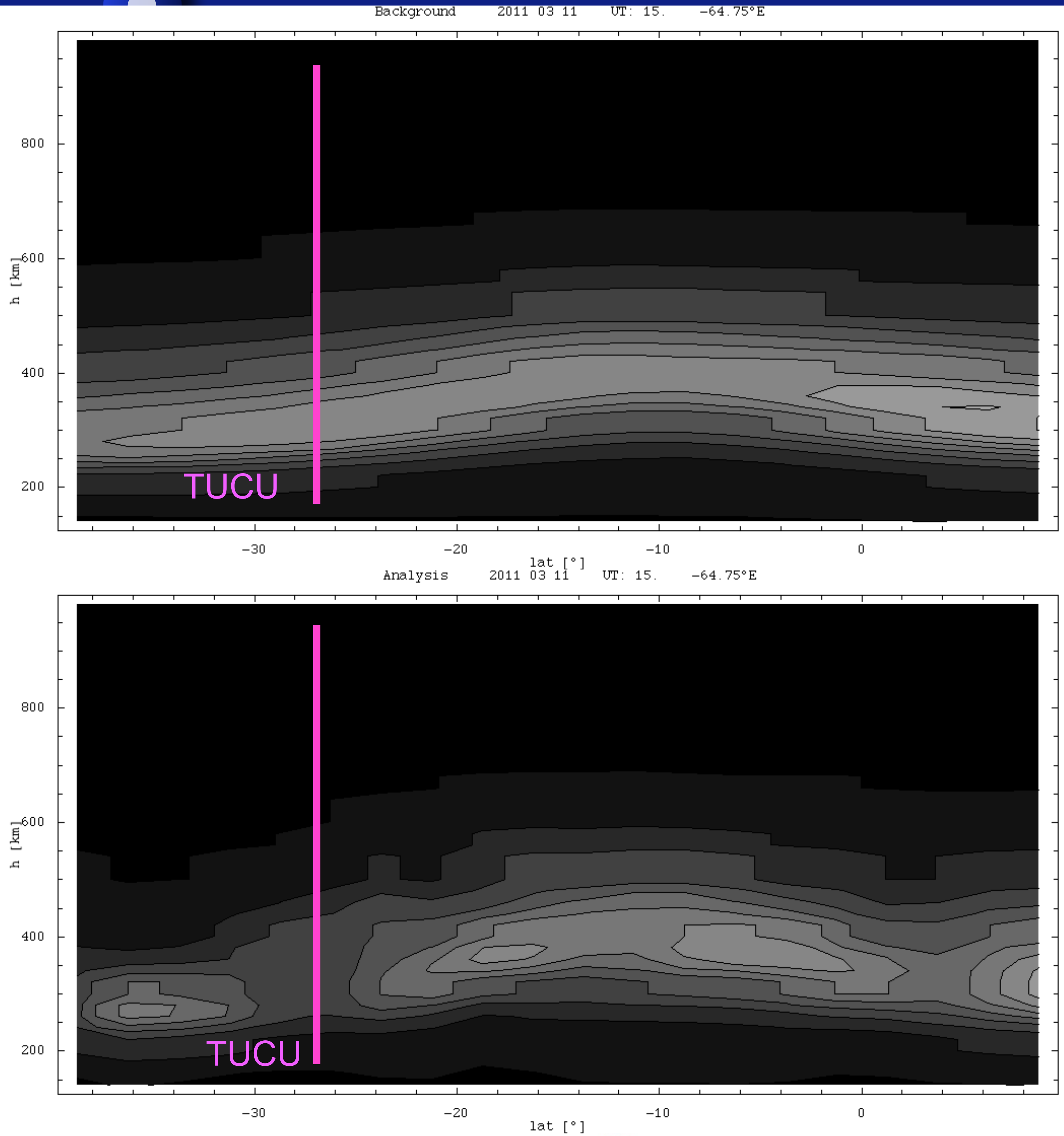
TUCU

Background model
(before the assimilation)

TUCU

Analysis
(after the assimilation)

LS solution: Ne cross-section



Cross section
-64.75°E
from -38°N to 8°N
(low resolution; no RO data)

Background model
(before the assimilation)

Analysis
(after the assimilation)

Conclusion

- Data ingestion into NeQuick improves the model performance when it is used to provide 3D specifications of the electron density of the ionosphere.
- The adaptation to vTEC maps improves the NeQuick capabilities to follow the day-to-day variability "weather" of the ionosphere (applications can be considered).
- The studies carried out with JRO profiles have indicated that the contemporary availability of TEC and foF2 (plus hmF2) data can be considered as a "minimum requirement" for the implementation of an effective electron density retrieval technique based on NeQuick adaptation to experimental data (RO-derived profiles included).
- The BLUE, with NeQuick used as a background model can improve the performance in terms of electron density retrieval (first results).

Acknowledgments

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Thank you for your attention