The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization
IAEA
International Atomic Energy Agency

SMR 2333-43

Workshop on Science Applications of GNSS in Developing Countries (11-27 April), followed by the: Seminar on Development and Use of the Ionospheric NeQuick Model (30 April-1 May)

11 April - 1 May, 2012

Data Ingestion in Ionospheric Electron Density Models

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Data Ingestion in Ionospheric Electron Density Models

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Workshop on Science Applications of GNSS in Developing Countries
Trieste, 11-27 April 2012

Outline

- Review of the techniques developed to update NeQuick with experimental data
  - Description
  - Examples
  - Validation

- 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)

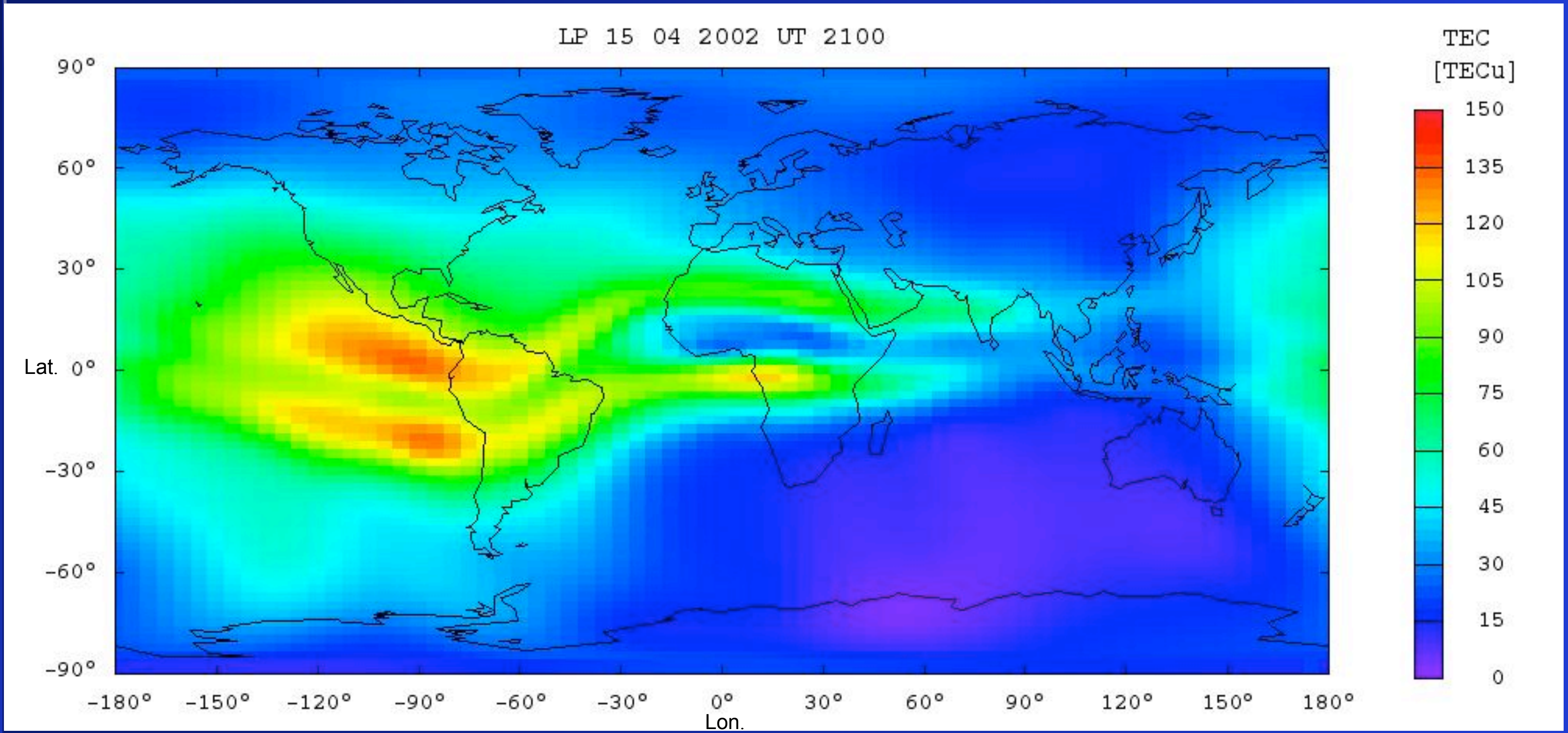
Basic concepts

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.

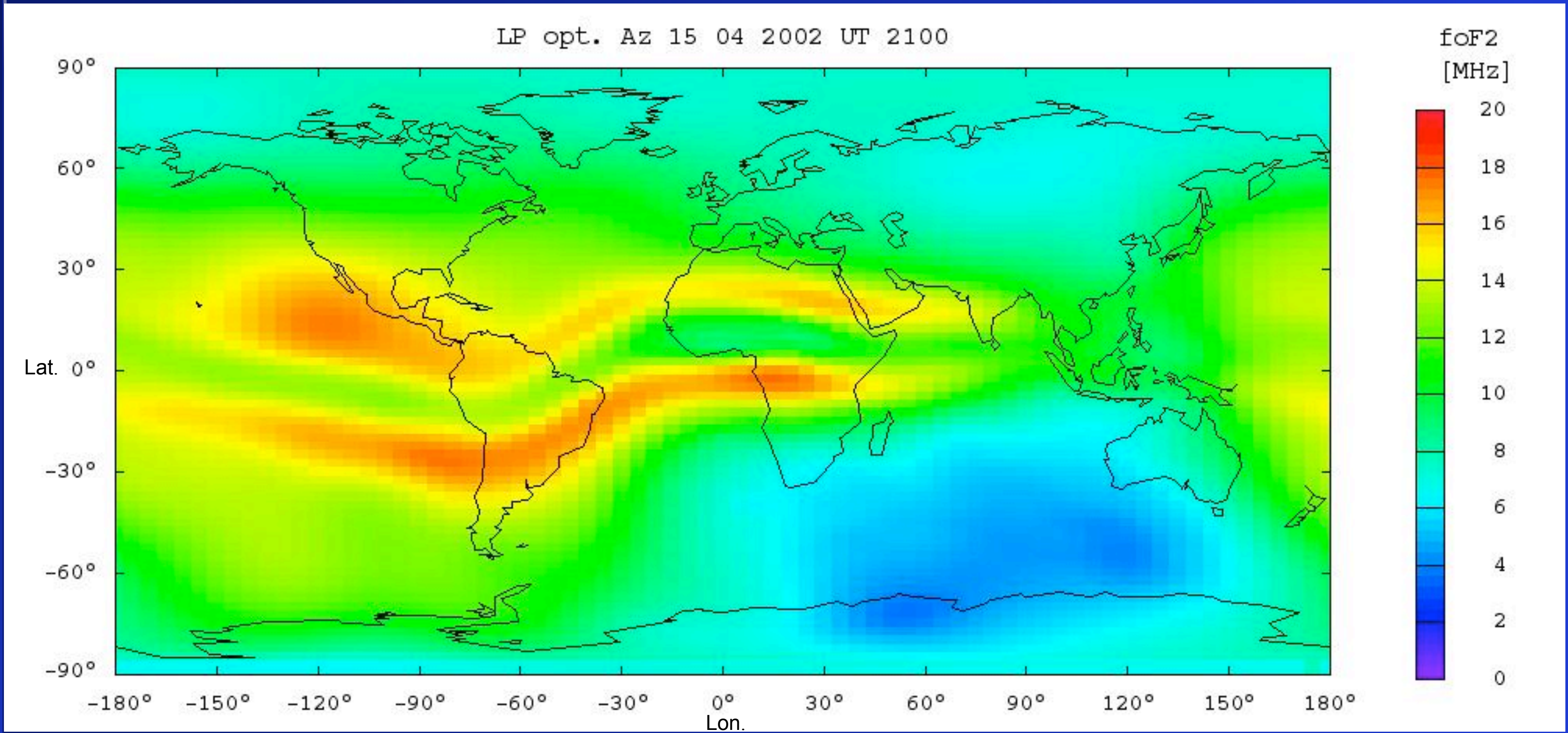
Adapting NeQuick model to vertical TEC maps

vTEC map La Plata



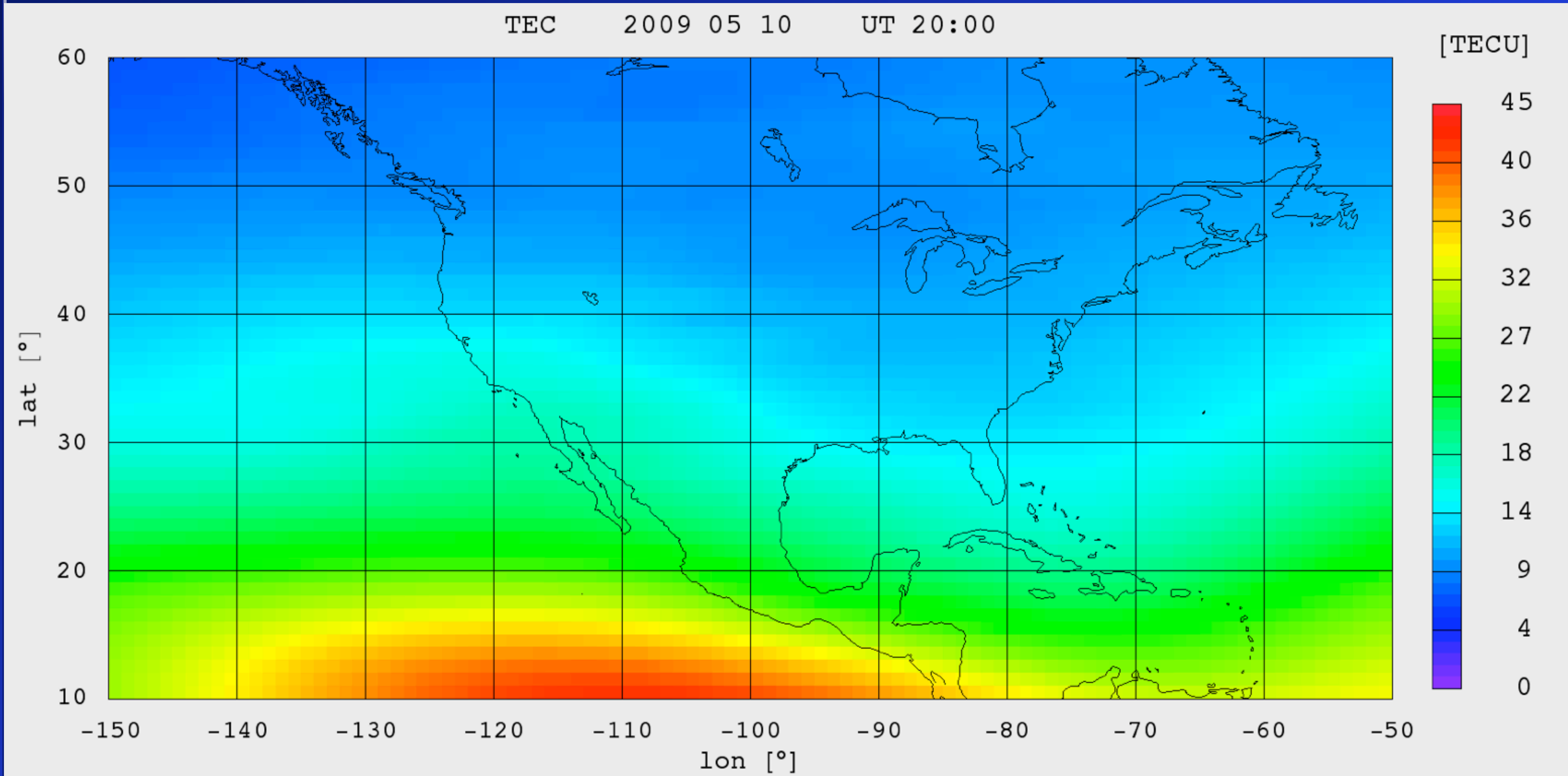
grid points:
lat.=-90°, 90° step 2.5°
lon.=-180°, 180° step 5°

Reconstructed foF2 map



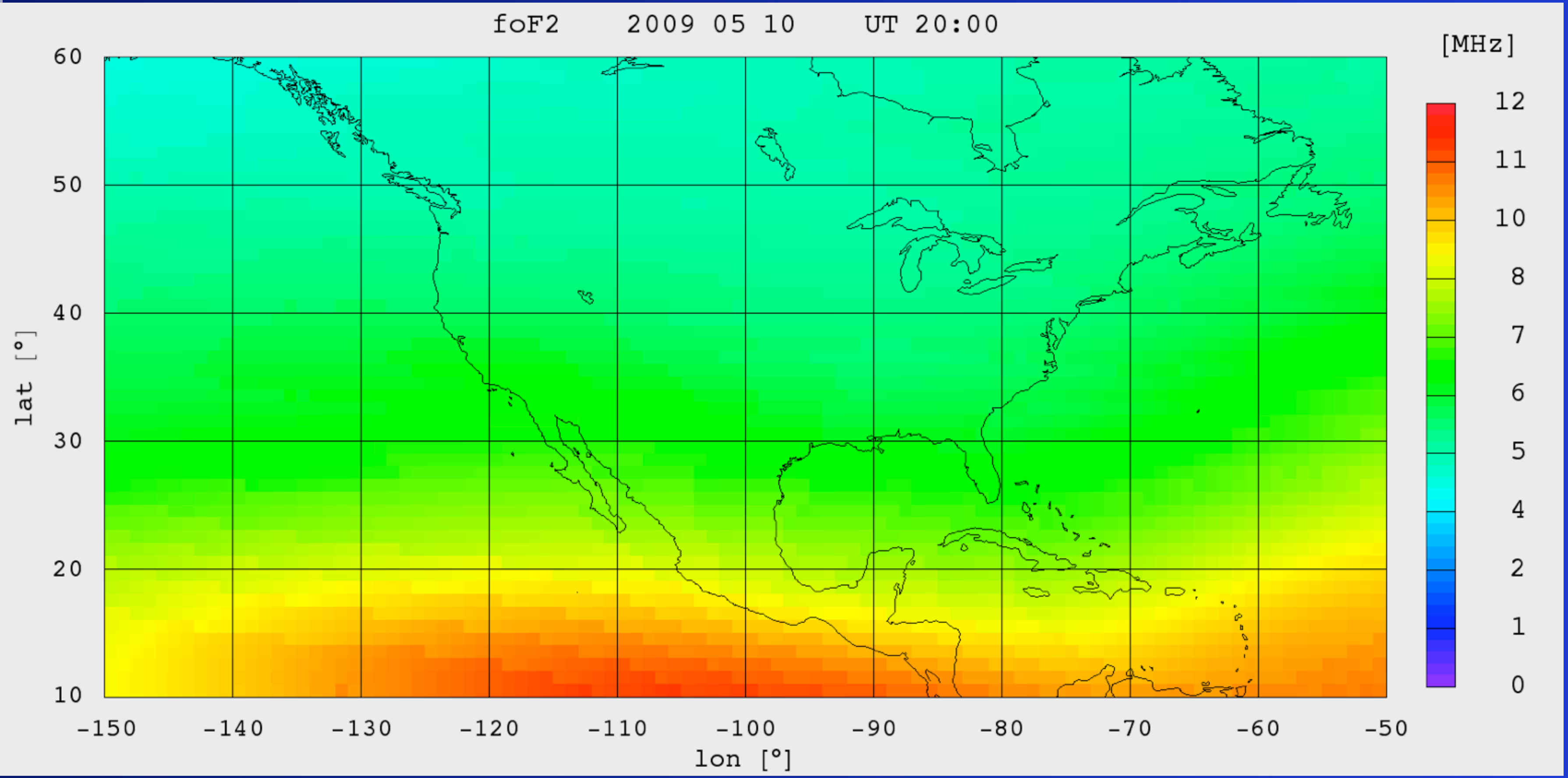
grid points:
lat.=-90°, 90° step 2.5°
lon.=-180°, 180° step 5°

vTEC map USTEC



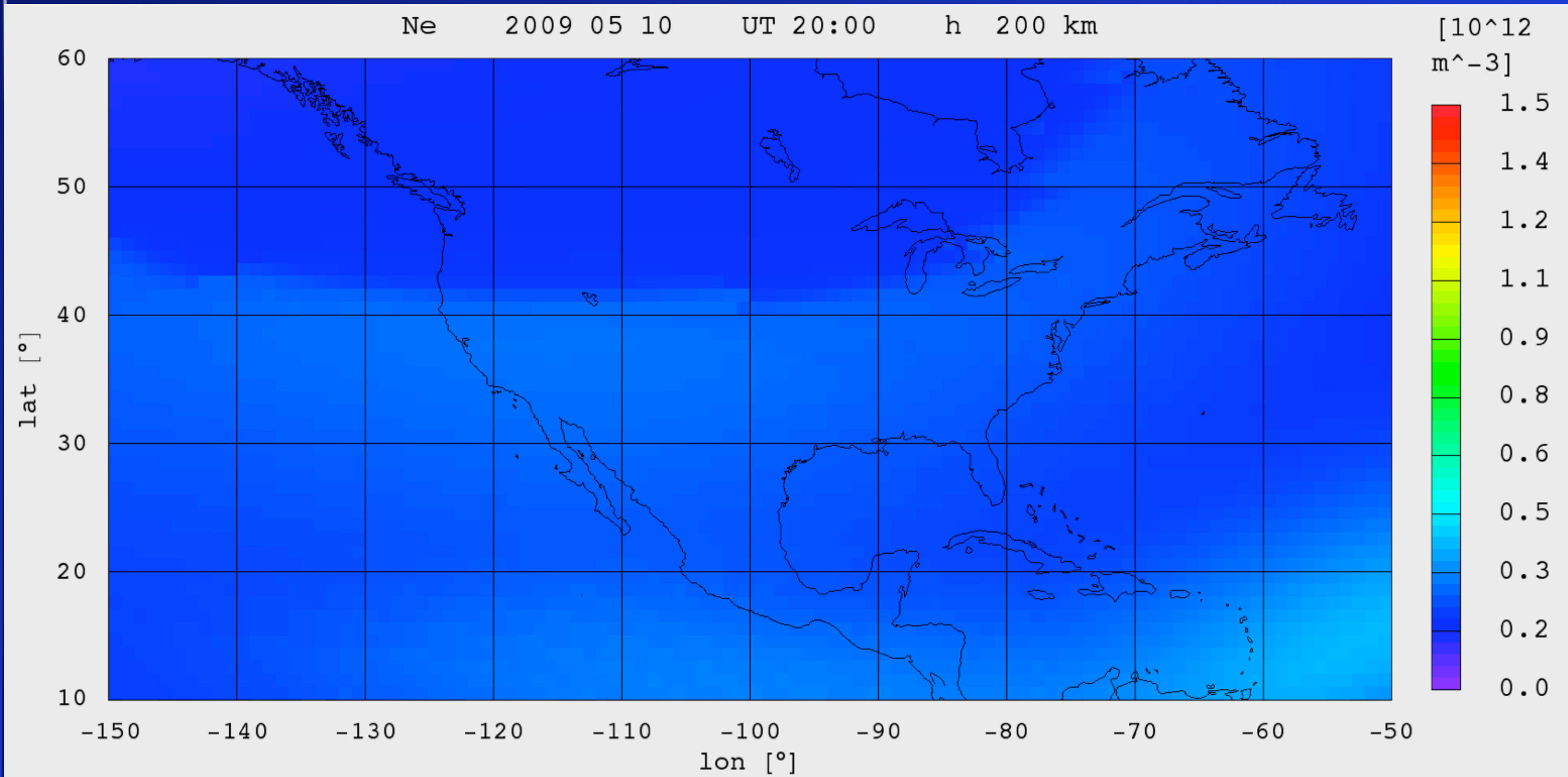
grid points:
lat.=10°, 60° step 1°
lon.= -150°, -50° step 1°

Reconstructed foF2 map



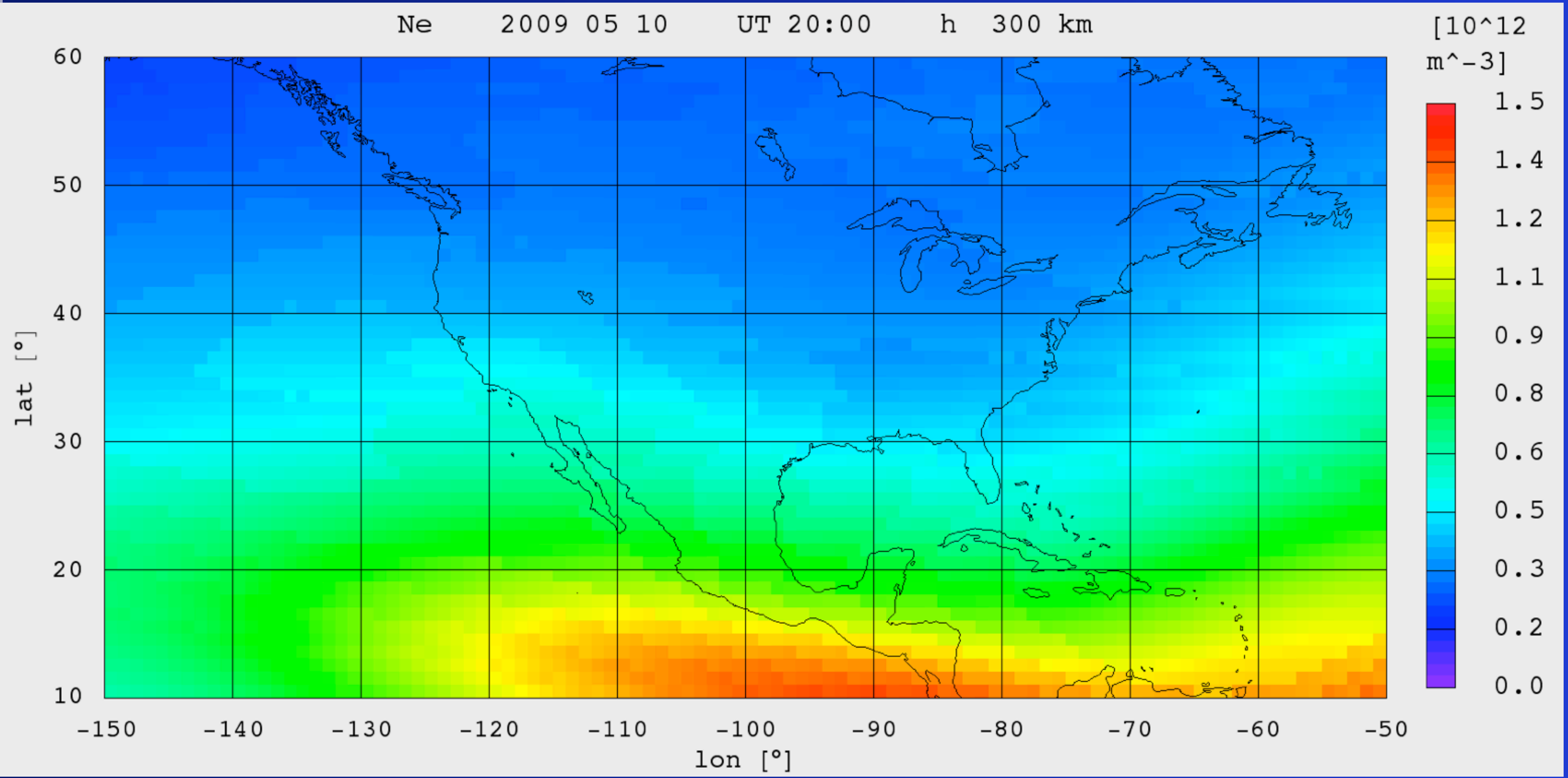
grid points:
lat.=10°, 60° step 1°
lon.= -150°, -50° step 1°

Reconstructed Ne map



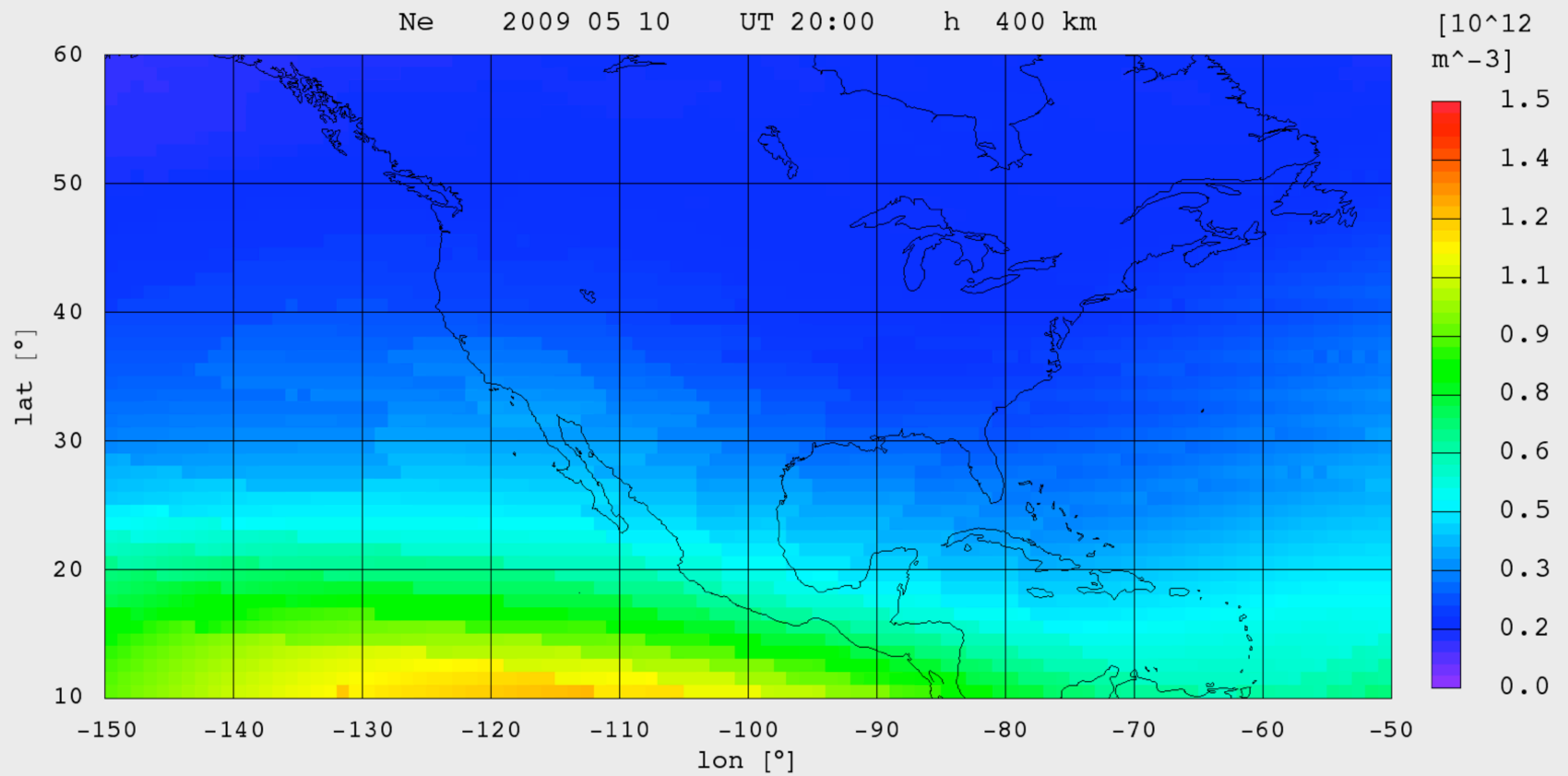
grid points:
lat.=10°, 60° step 1°
lon.= -150°, -50° step 1°

Reconstructed Ne map



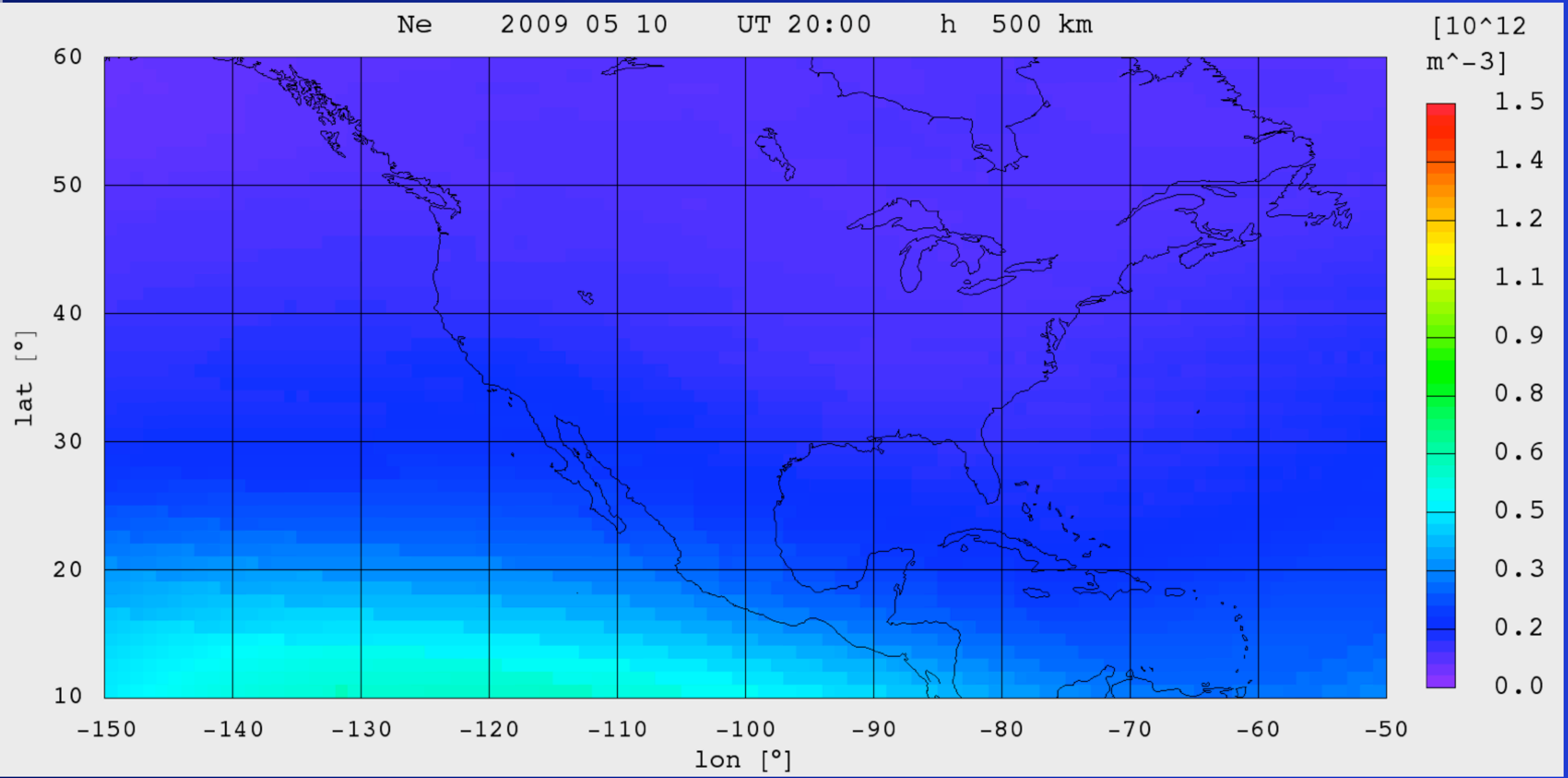
grid points:
lat.=10°, 60° step 1°
lon.= -150°, -50° step 1°

Reconstructed Ne map



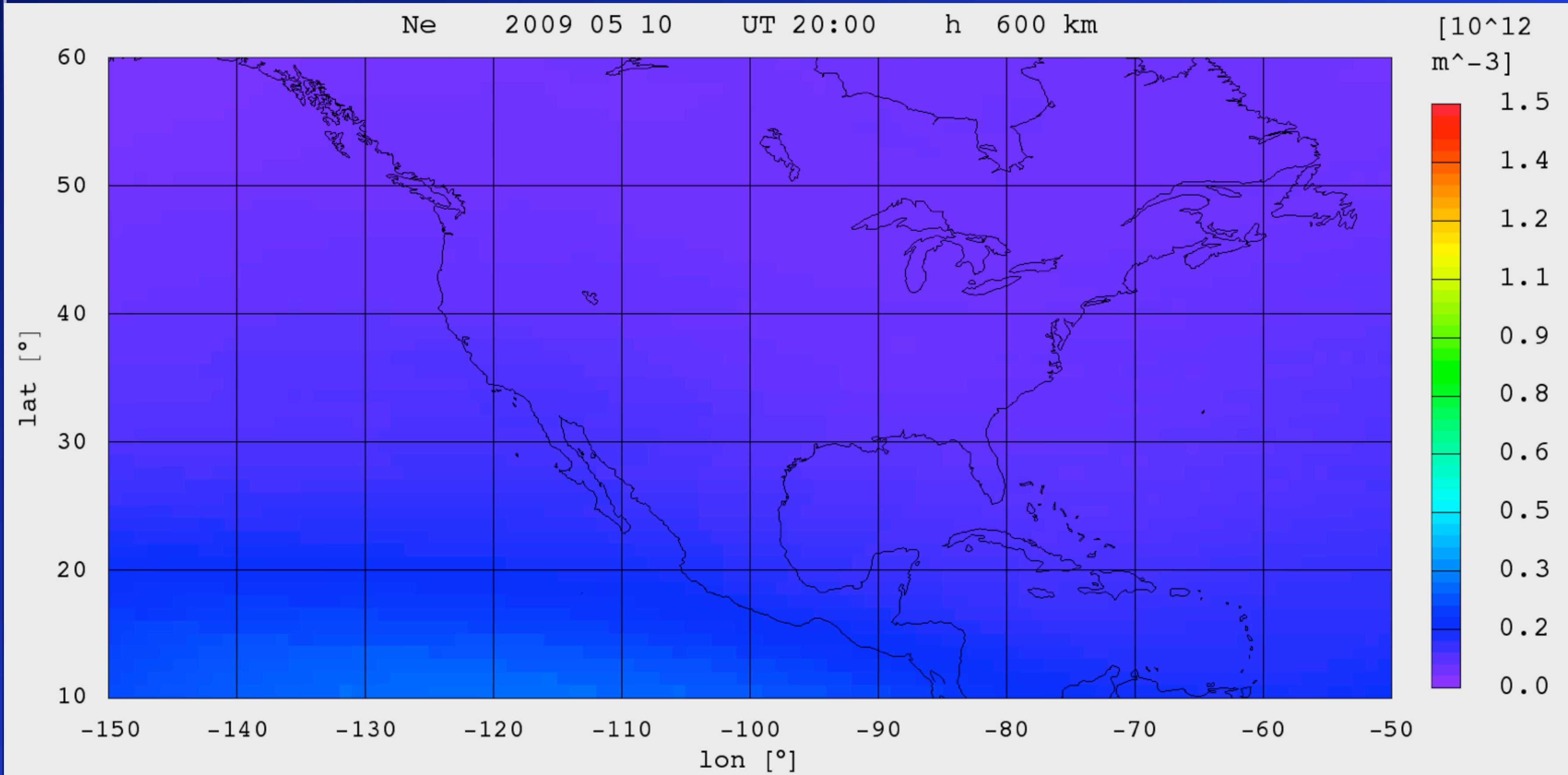
grid points:
lat.=10°, 60° step 1°
lon.= -150°, -50° step 1°

Reconstructed Ne map



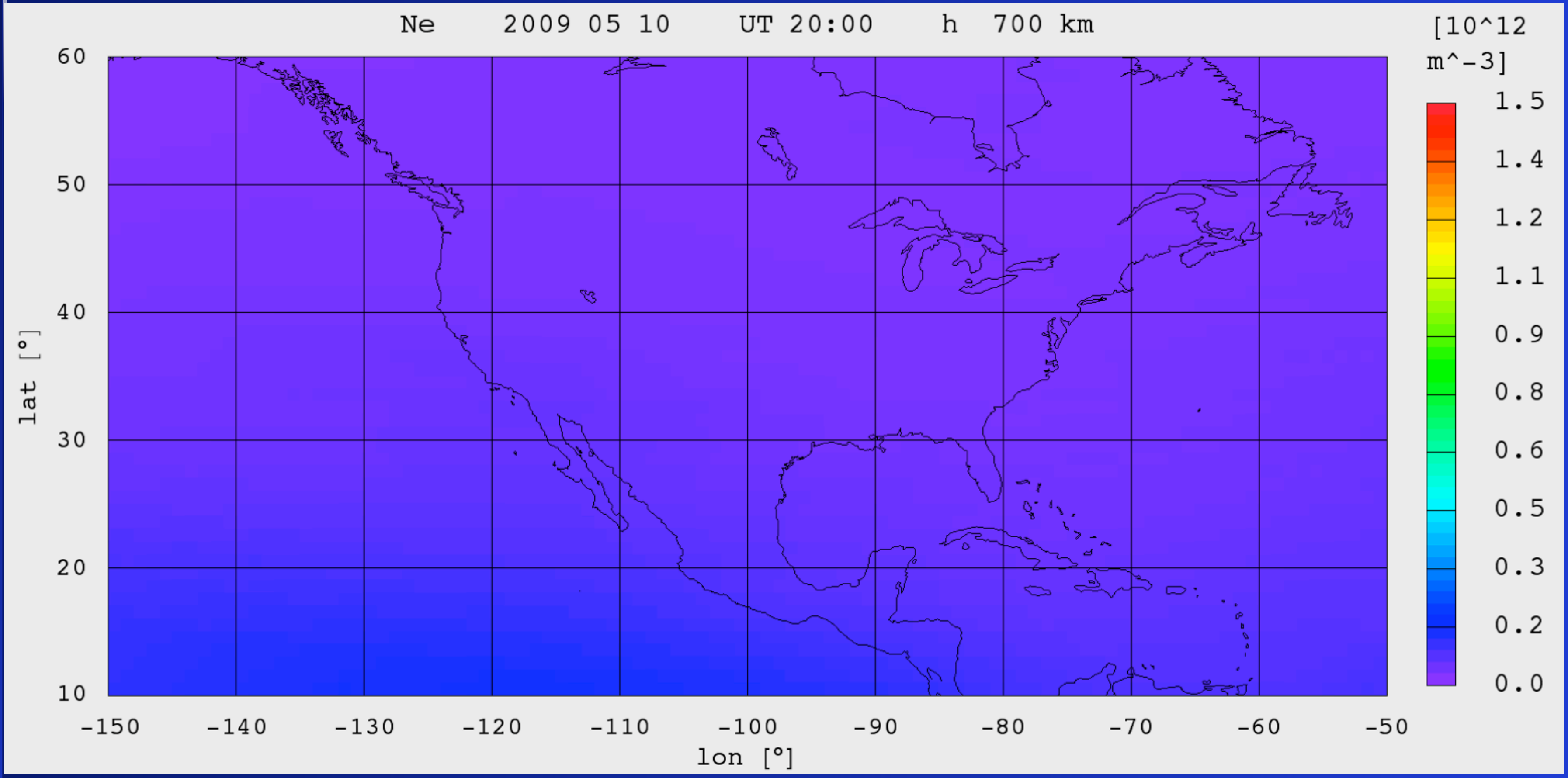
grid points:
lat.=10°, 60° step 1°
lon.= -150°, -50° step 1°

Reconstructed Ne map



grid points:
lat.=10°, 60° step 1°
lon.= -150°, -50° step 1°

Reconstructed Ne map



grid points:
lat.=10°, 60° step 1°
lon.= -150°, -50° step 1°

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

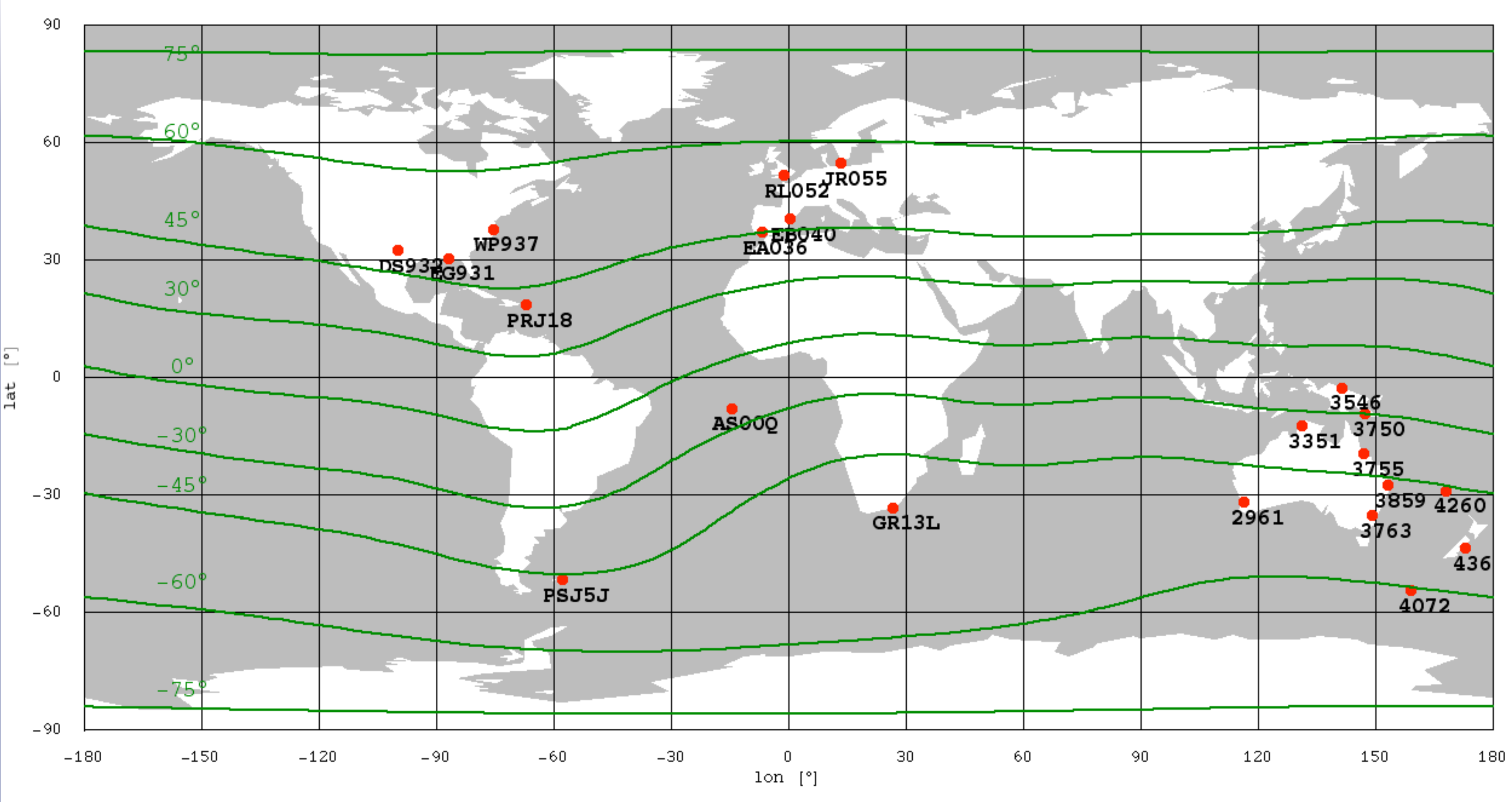
↓ Reconstruct sTEC along any ray-path

↓ Reconstruct foF2 maps

- vTec map ingestion scheme validation (1)
  - 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: $\Delta foF2 = foF2_{NeQ2} - foF2_{exp}$

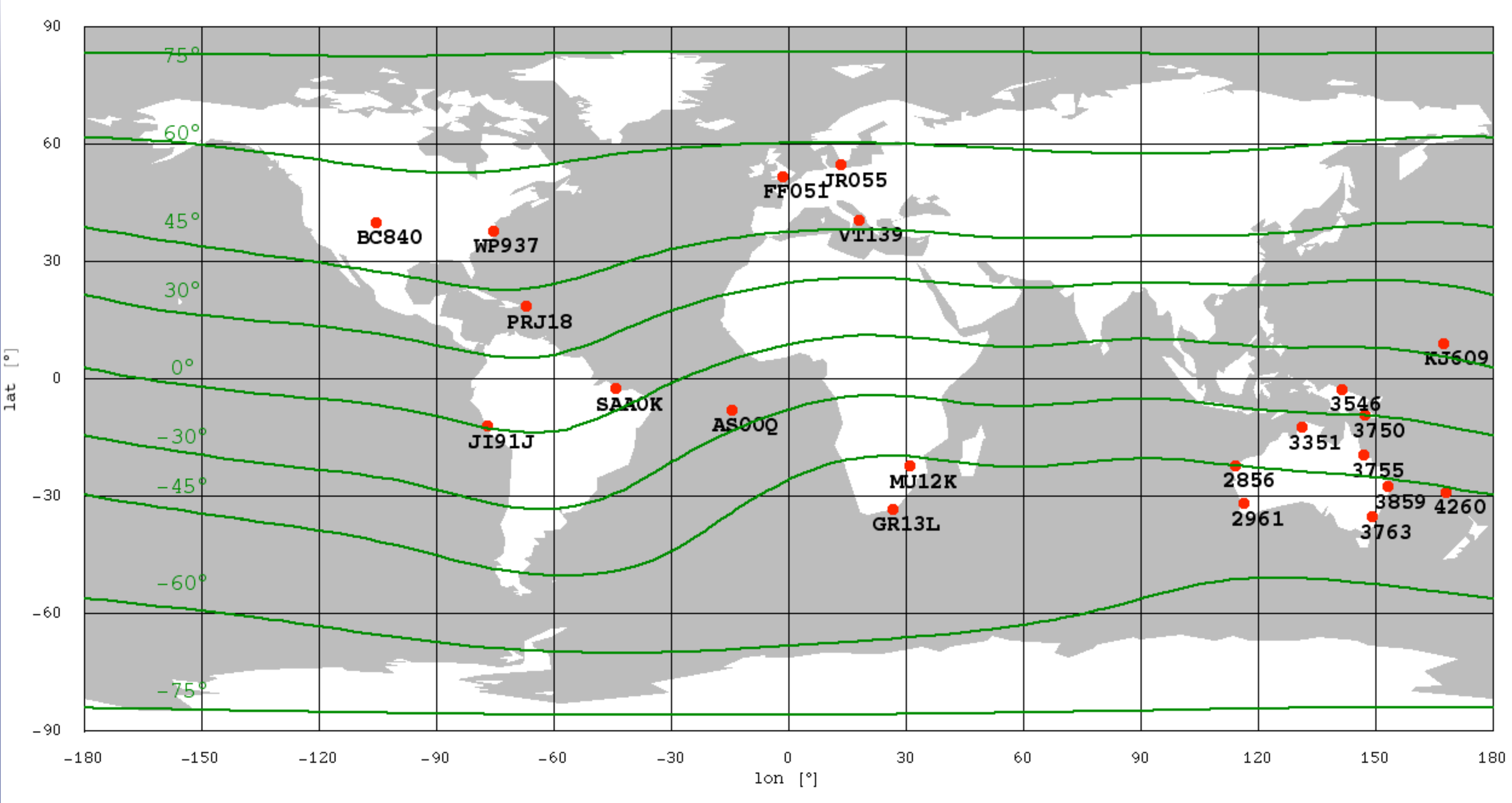
Notice: validation is on sTEC calibration + mapping function + spherical harmonics expansion + ITU-R coeff + model formulation + vTEC data ingestion technique.

Apr 2000



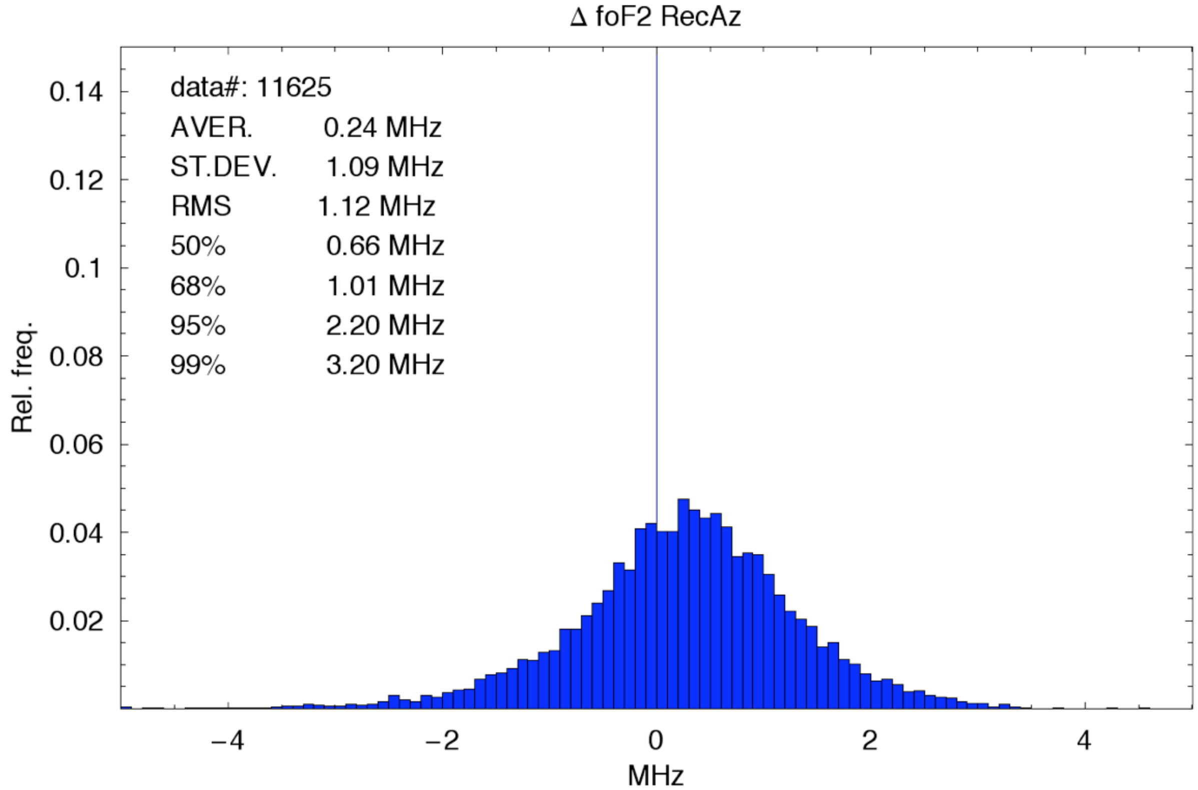
Location of the Ionosondes used for the validation

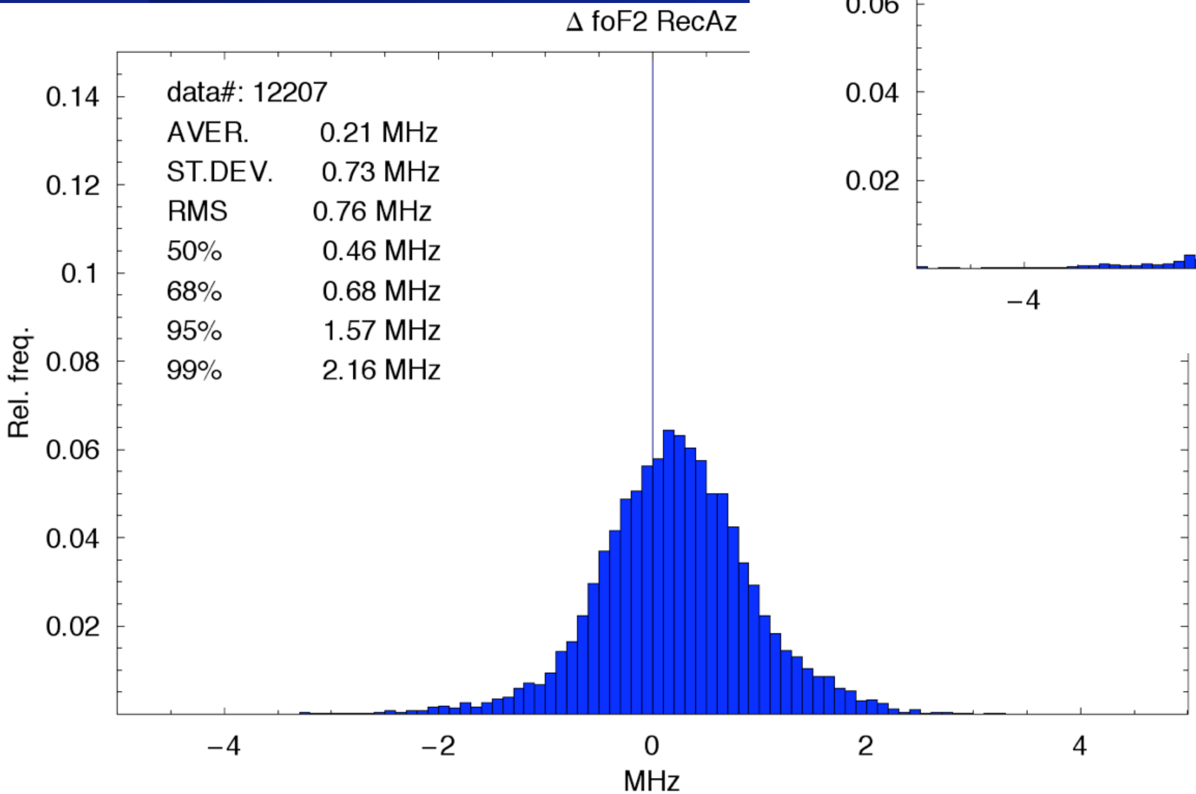
Sep 2006



Location of the Ionosondes used for the validation

Global statistics (effective F10.7)

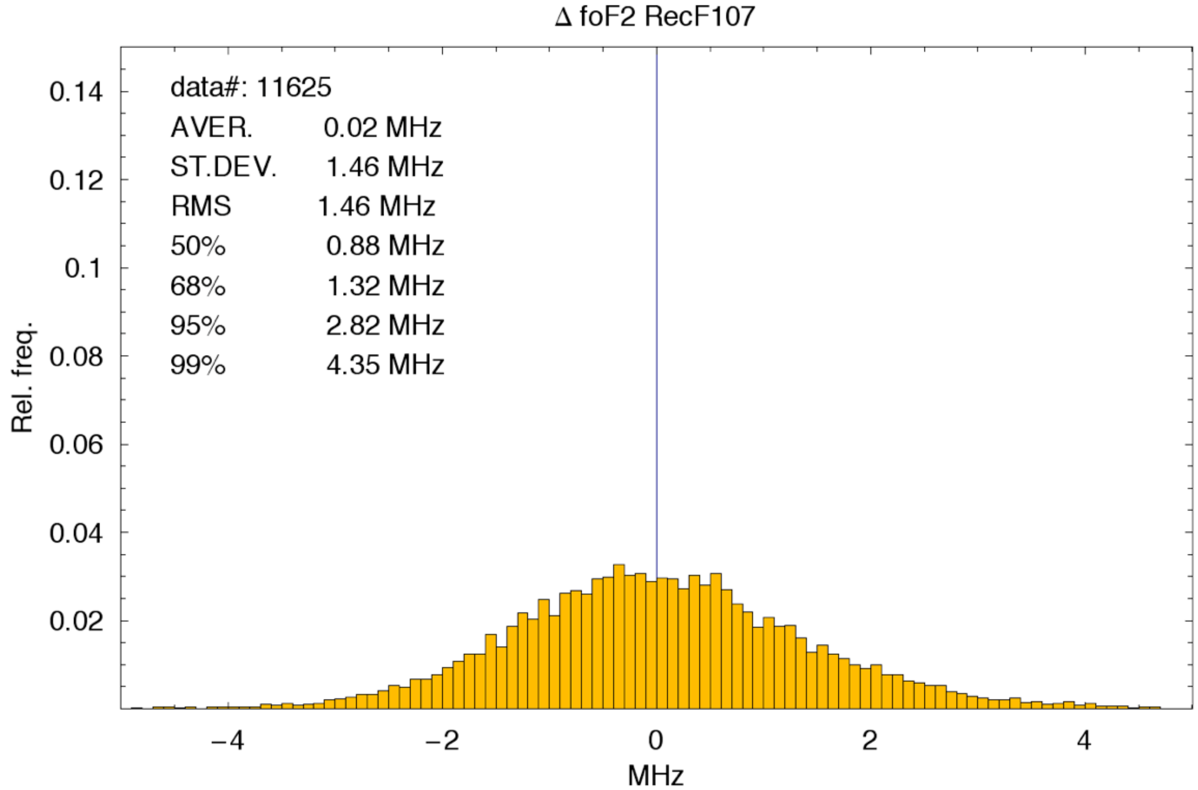


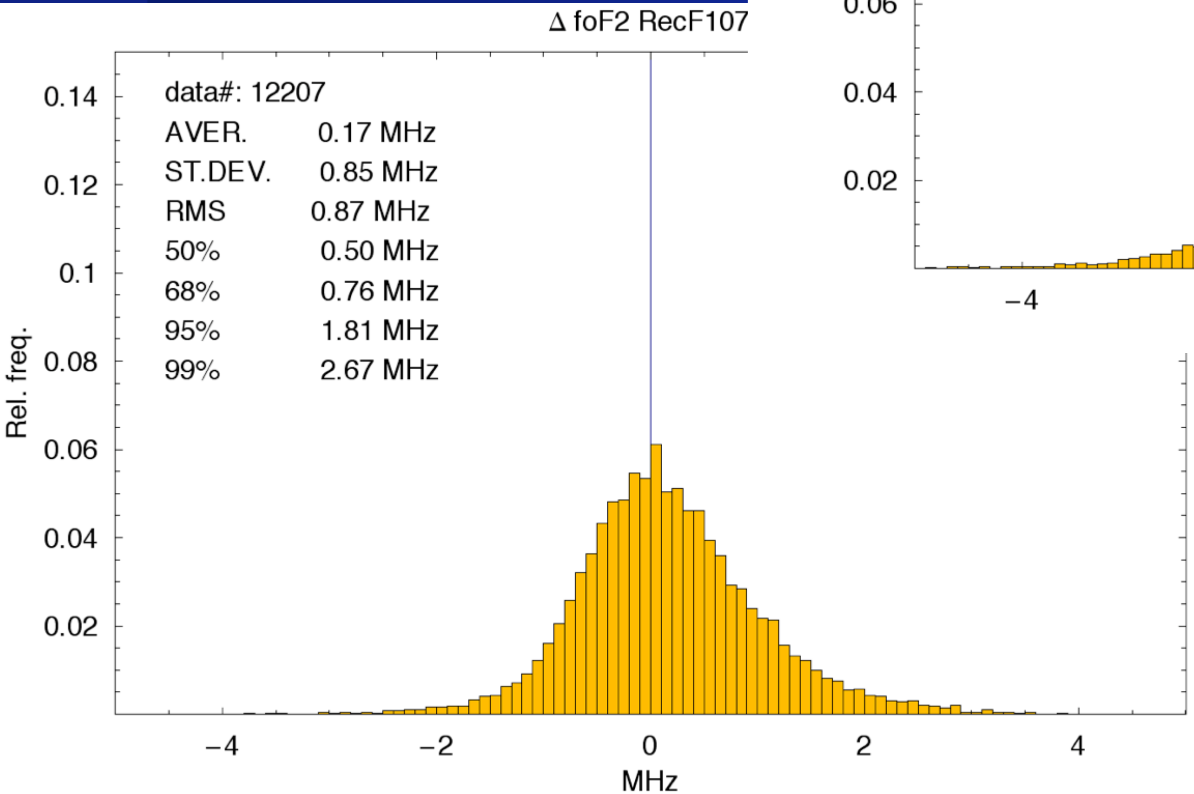


Apr. 2000

Sep. 2006

Global statistics (daily f10.7)

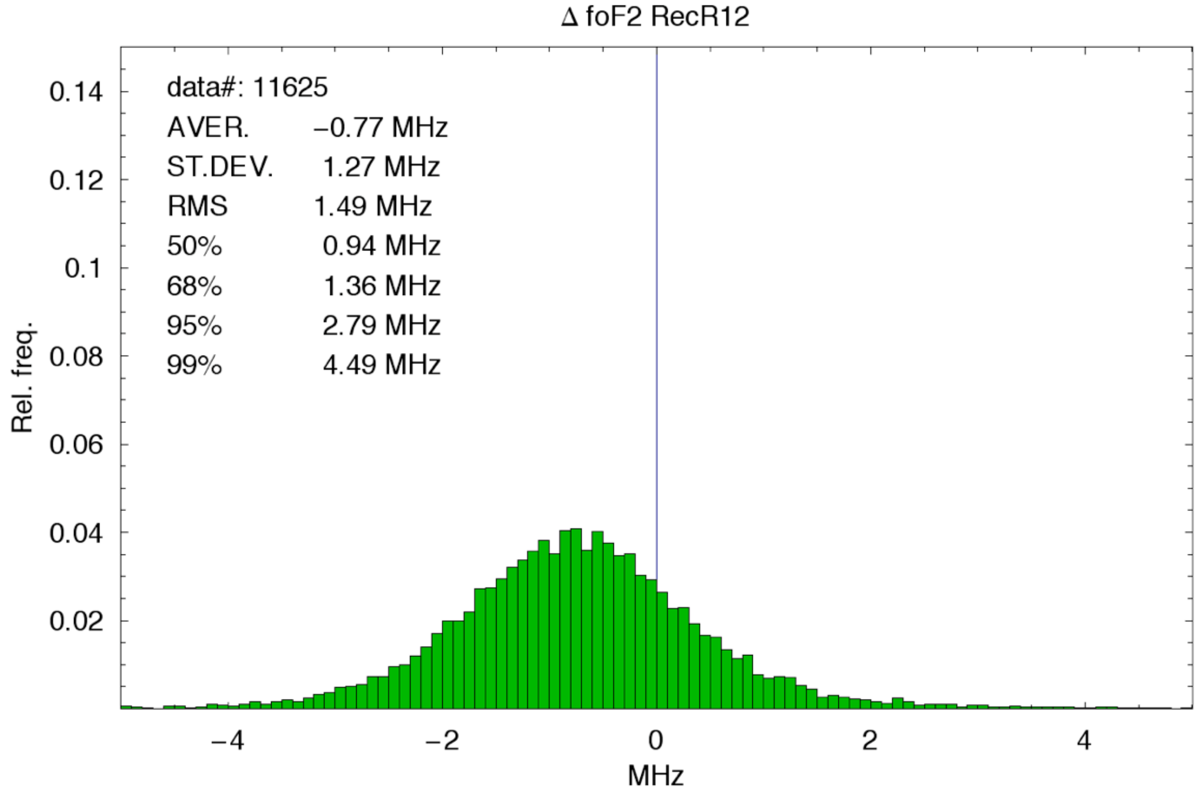


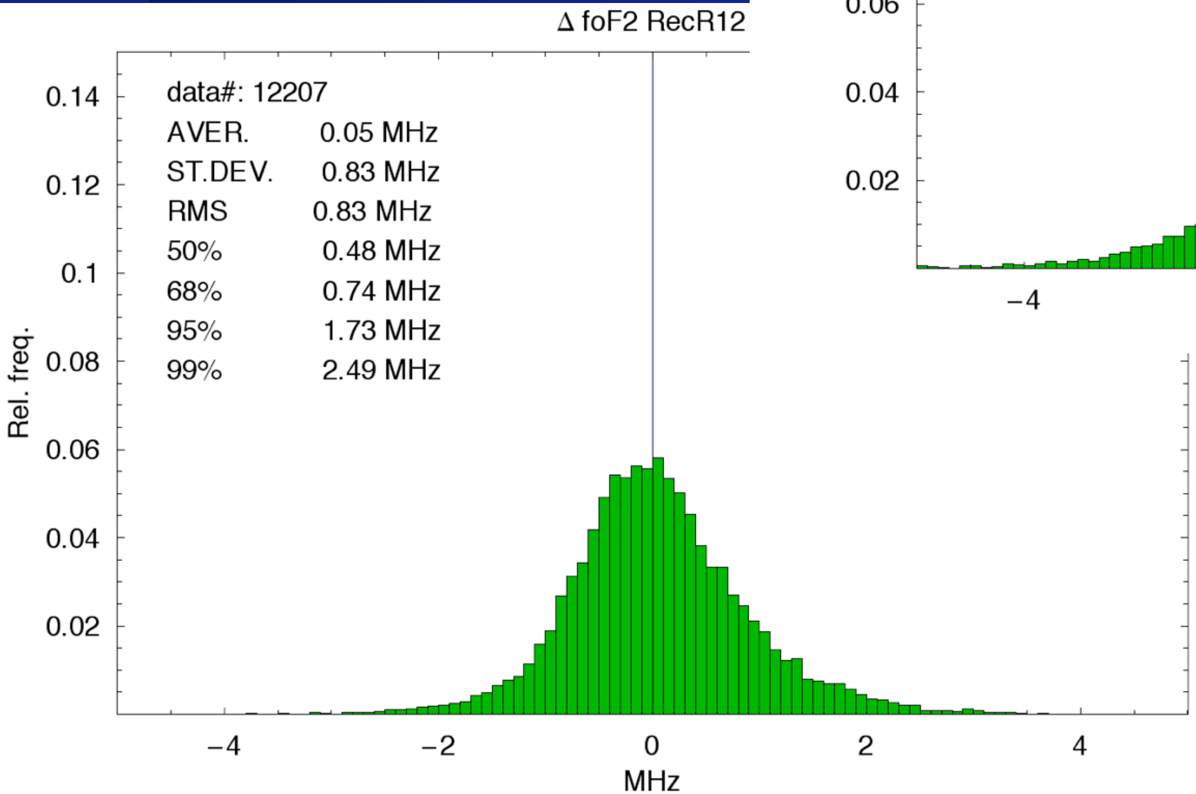


Apr. 2000

Sep. 2006

Global statistics (R12)





Apr. 2000

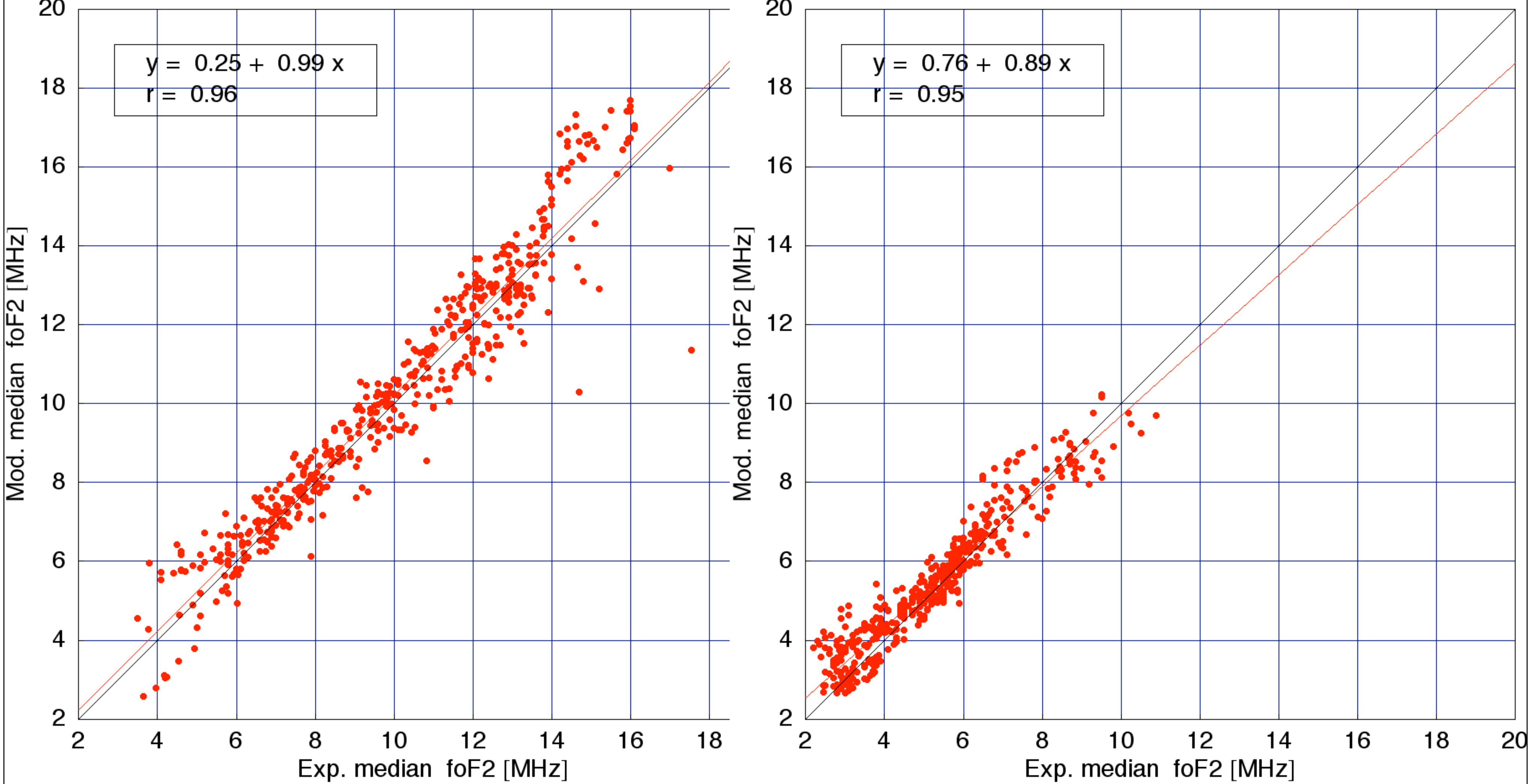
Sep. 2006

The ingestion technique requires that the model vertical TEC has to “match” the experimental vertical TEC at any given location and time. Therefore when the retrieved foF2 are different from the ground-truth values it can be said that NeQuick is not able to perfectly reproduce the experimental slab thickness.

↓

Weakness in the NeQuick slab thickness formulation

Global statistics (medians)

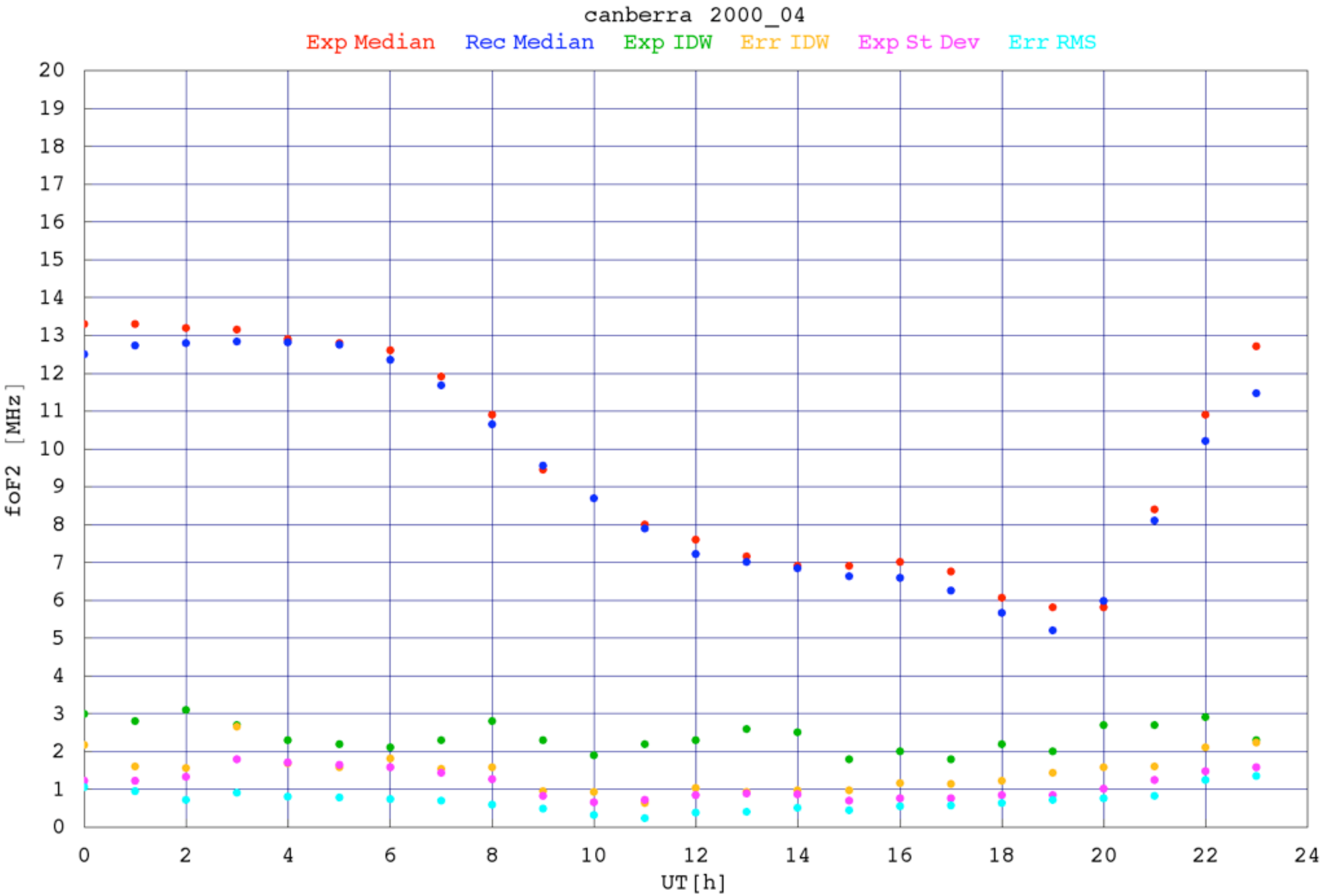


Apr. 2000

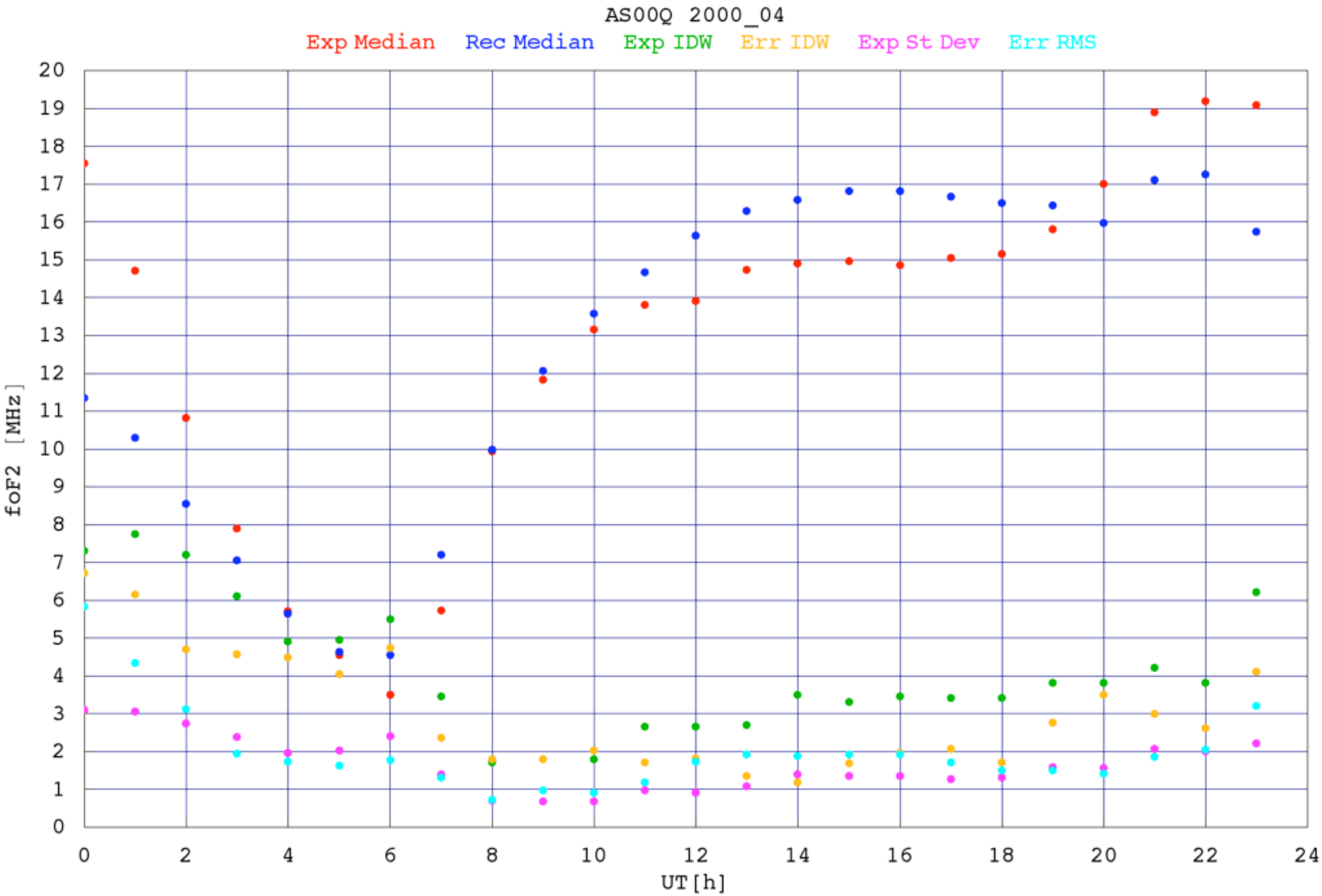
Sep. 2006

Effective F10.7

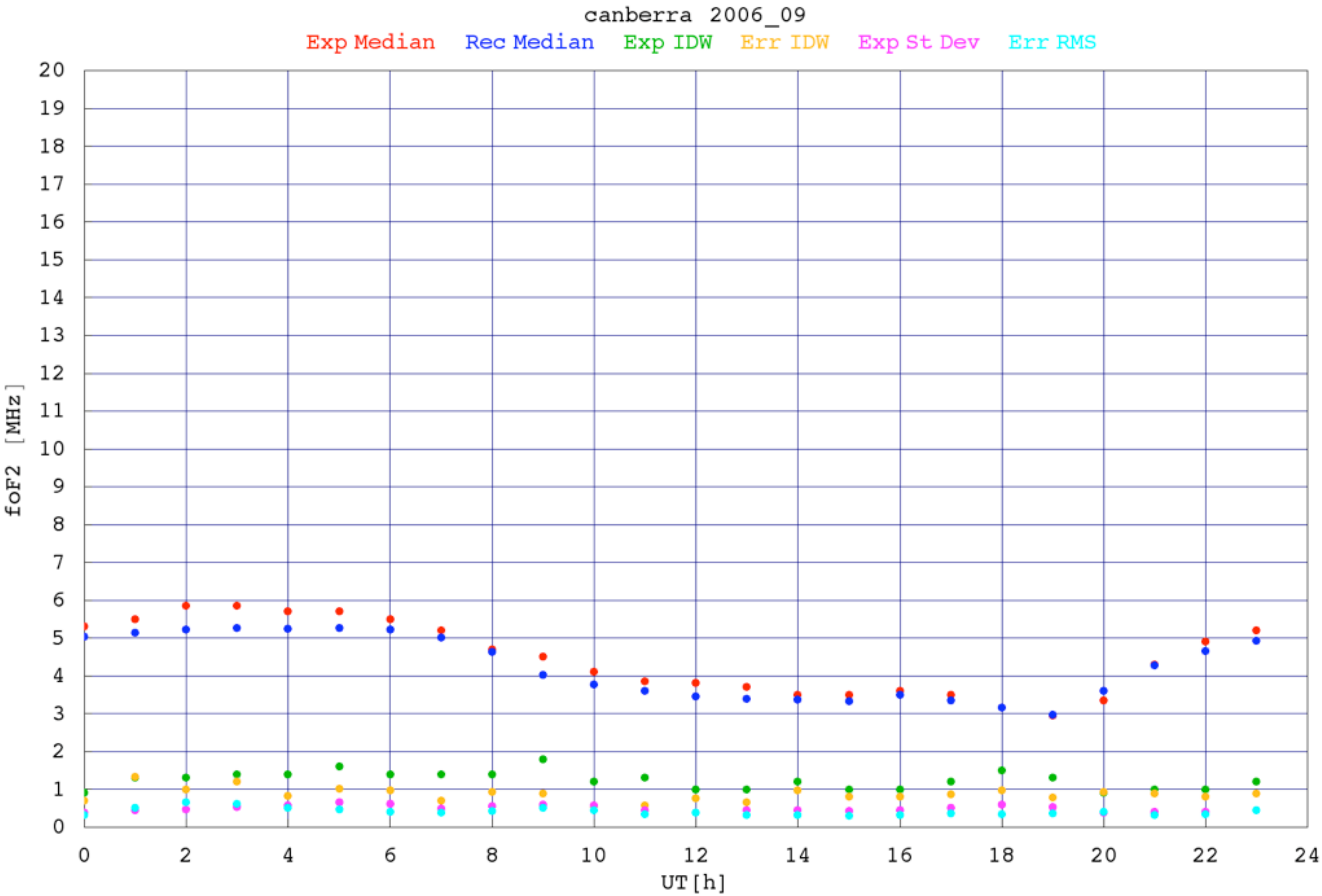
Statistics 3763 (Apr 2000)



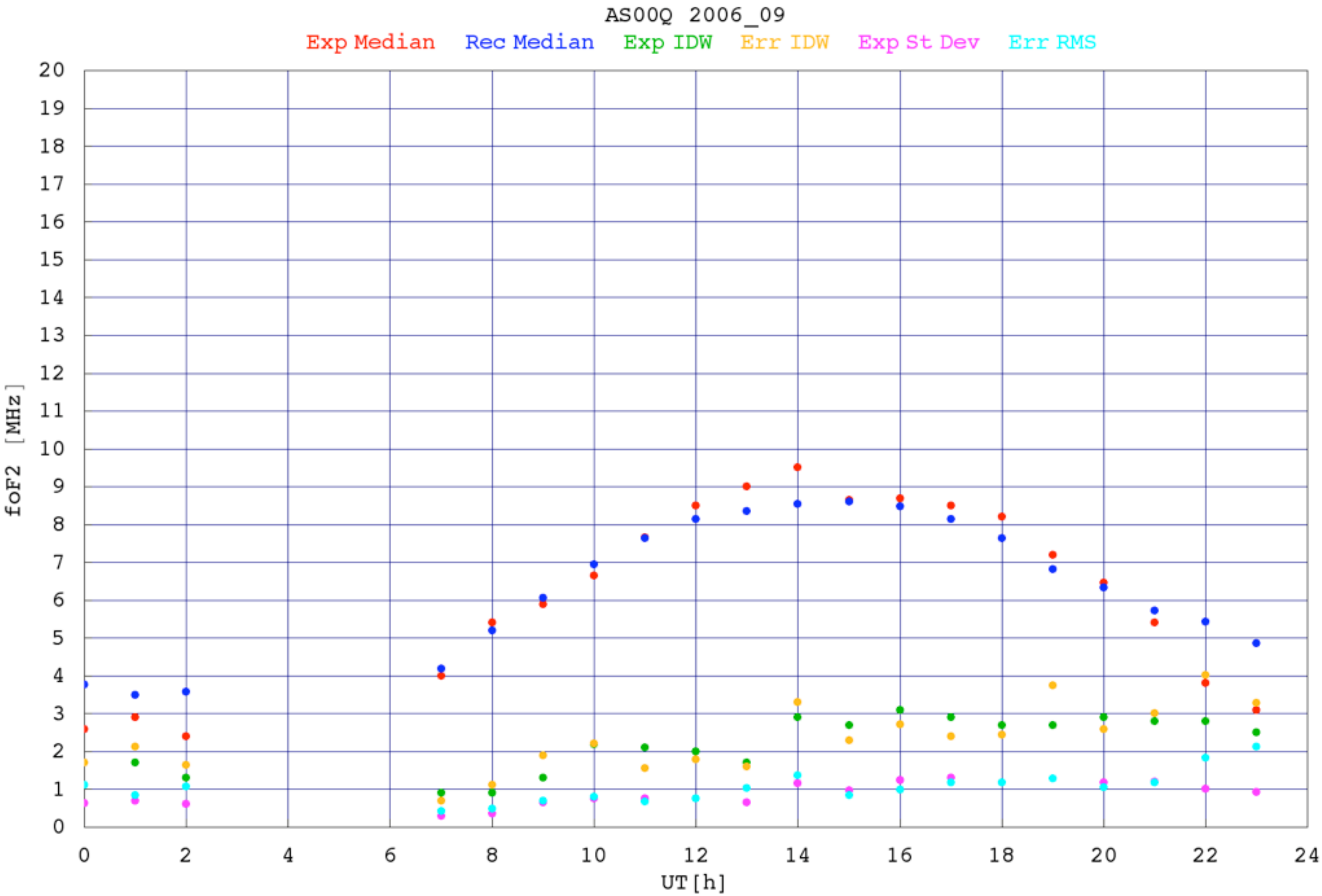
Statistics AS00Q (Apr 2000)



Statistics 3763 (Sep 2006)



Statistics AS00Q (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]

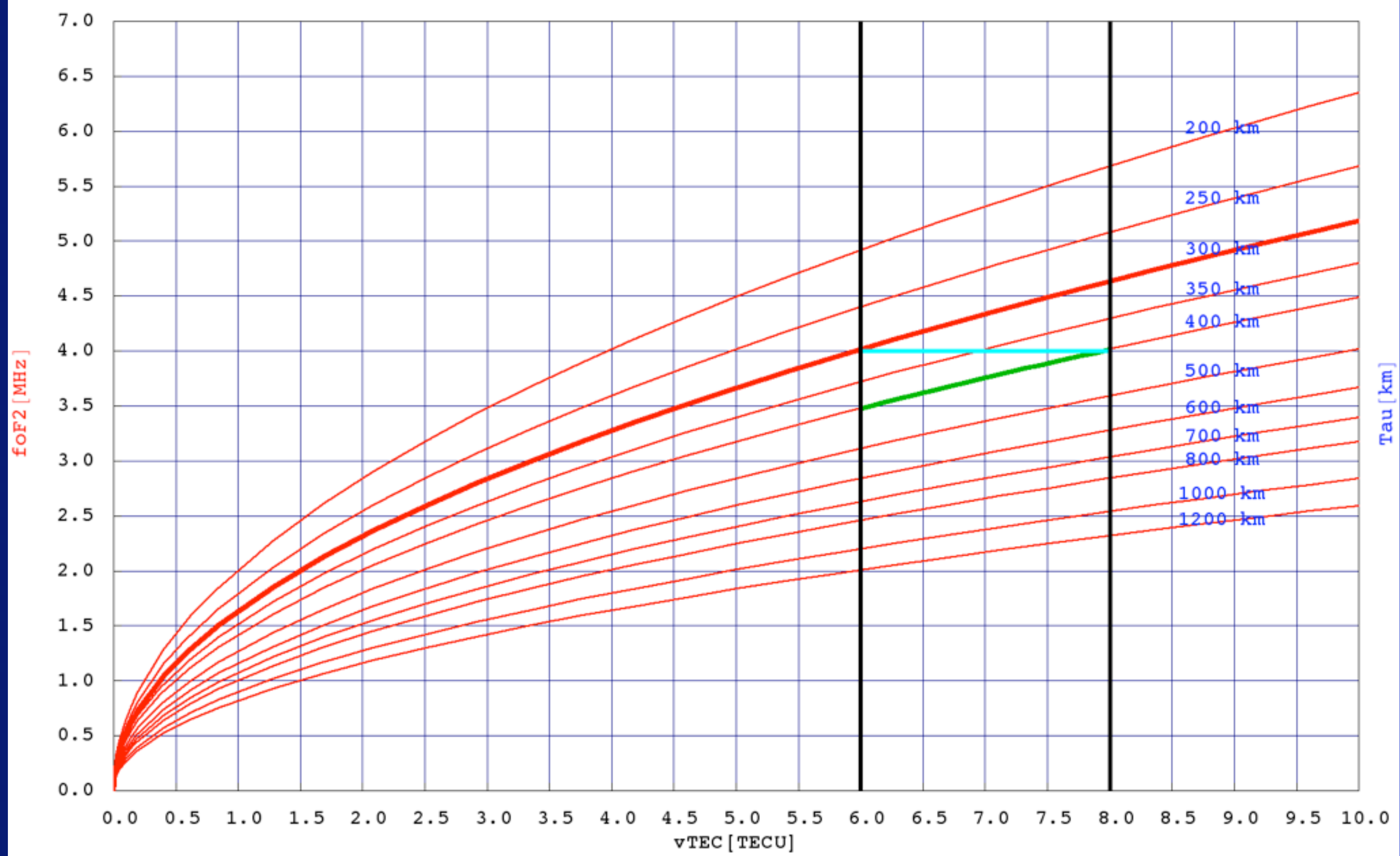
	All Lat, Data 460		Mid Lat, Data 328		Low Lat, Data 132	
	Az	F107	Az	F107	Az	F107
Aver	0.82	1.05	0.78	1.05	0.92	1.05
St dev	0.21	0.17	0.18	0.18	0.23	0.15
RMS	0.85	1.07	0.80	1.07	0.95	1.06
50%	0.80	1.03	0.77	1.02	0.89	1.04
68%	0.88	1.11	0.85	1.11	0.98	1.12
95%	1.22	1.38	1.13	1.39	1.36	1.35
99%	1.44	1.51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

global performance

“climate” performance

“weather” performance

Remark



foF2 [MHz]
vTEC [TECU]
Tau [km]
200 km
250 km
300 km
350 km
400 km
500 km
600 km
700 km
800 km
1000 km
1200 km

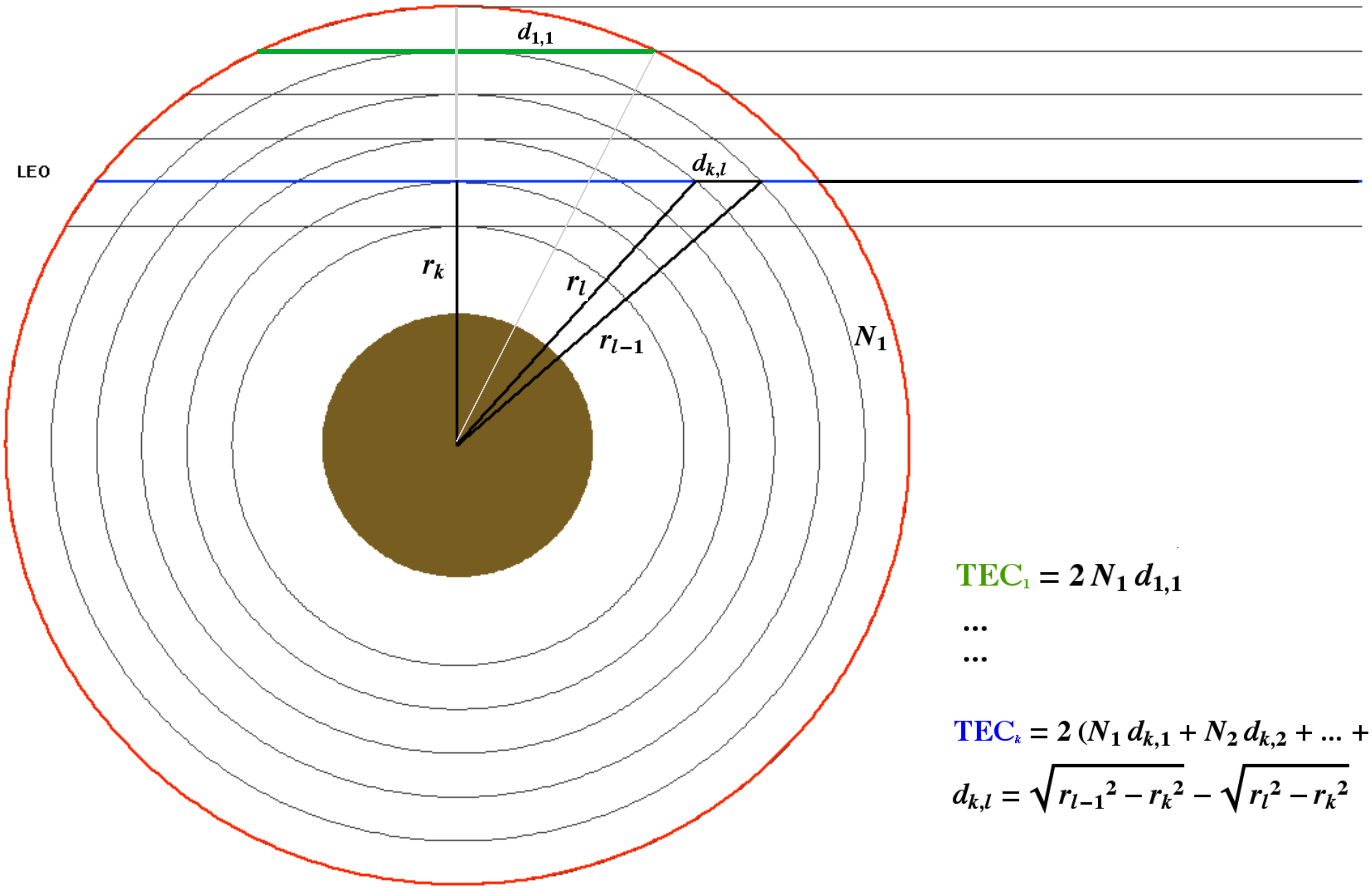
- vTec map ingestion scheme “internal” consistency check
  - using ground-based GPS-derived sTec from ~ 200 GPS receivers
  - hourly data for Sep. 21st, 2006
  - statistics on: $\Delta sTec = sTec_{NeQ2} - sTec_{exp}$

$sTec_{exp}$ are the same data used to produce the vTec maps

- vTec map ingestion scheme validation (2)
  - using space-based GPS-derived sTec from ~ 500 occultation (COSMIC)
  - hourly data for Sep. 21st, 2006
  - statistics on: $\Delta sTec = sTec_{NeQ2} - sTec_{exp}$

$sTec_{exp}$ and $sTec_{NeQ2}$ correspond to the part of the LEO -> GPS link below the LEO orbit

RO geometry



$$\mathrm{TEC}_1 = 2\,N_1\,d_{1,1}$$

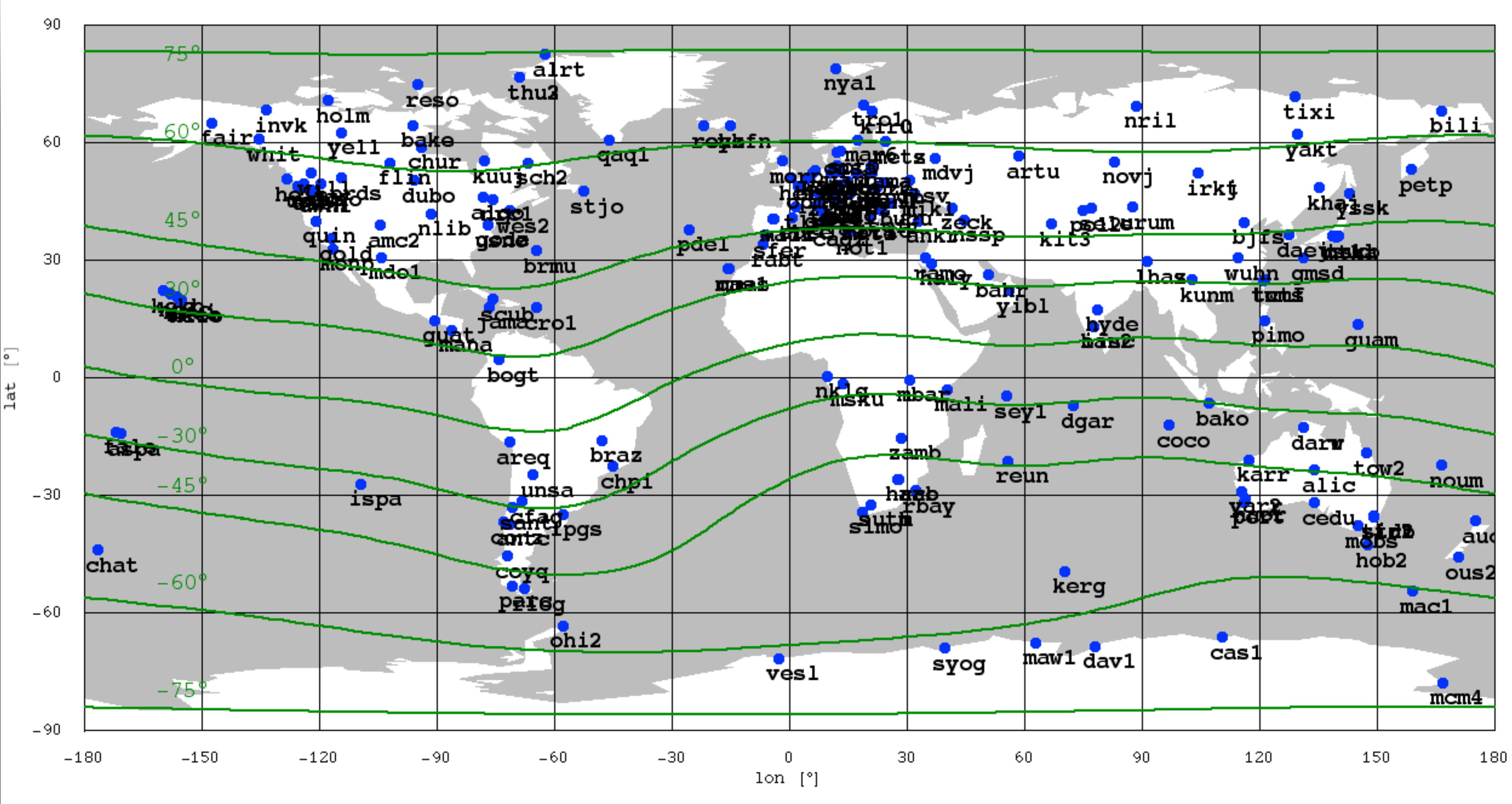
...

...

$$\mathrm{TEC}_k = 2\,(N_1\,d_{k,1} + N_2\,d_{k,2} + \ldots + N_k\,d_{k,k})$$

$$d_{k,l} = \sqrt{r_{l-1}^2 - r_k^2} - \sqrt{r_l^2 - r_k^2}$$

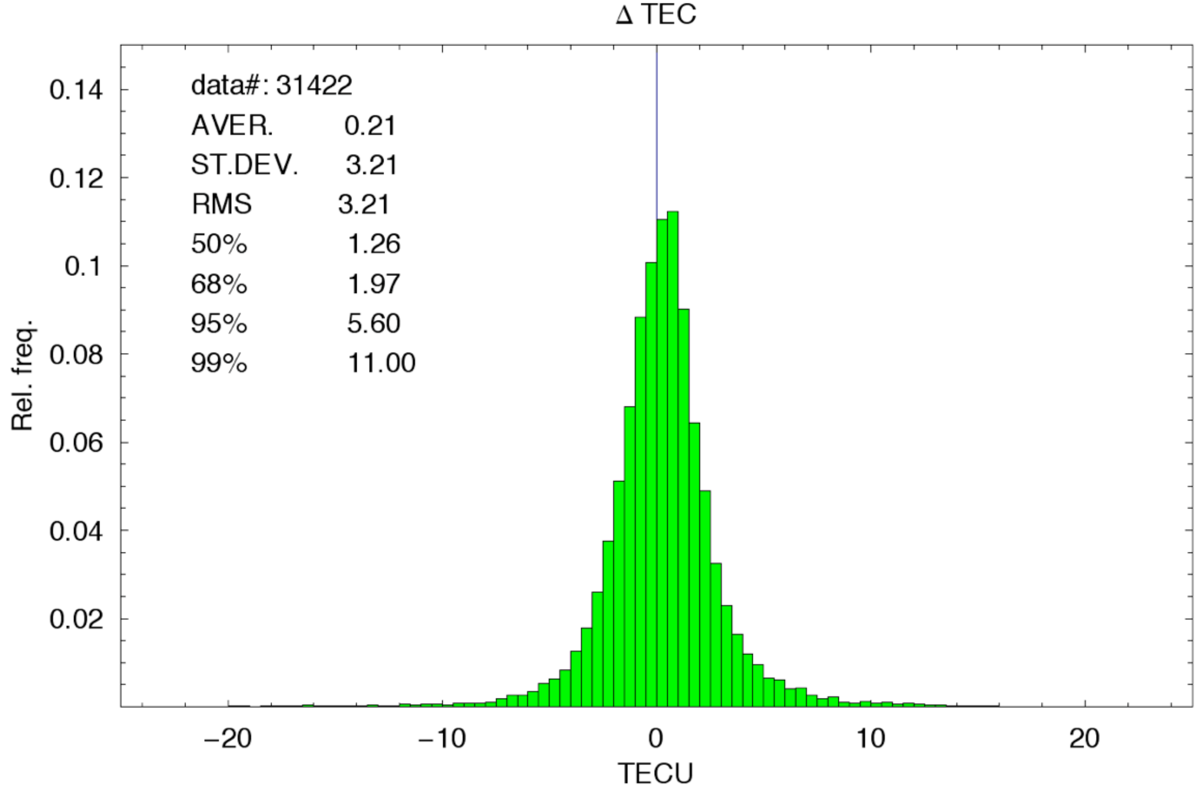
2006 09 21

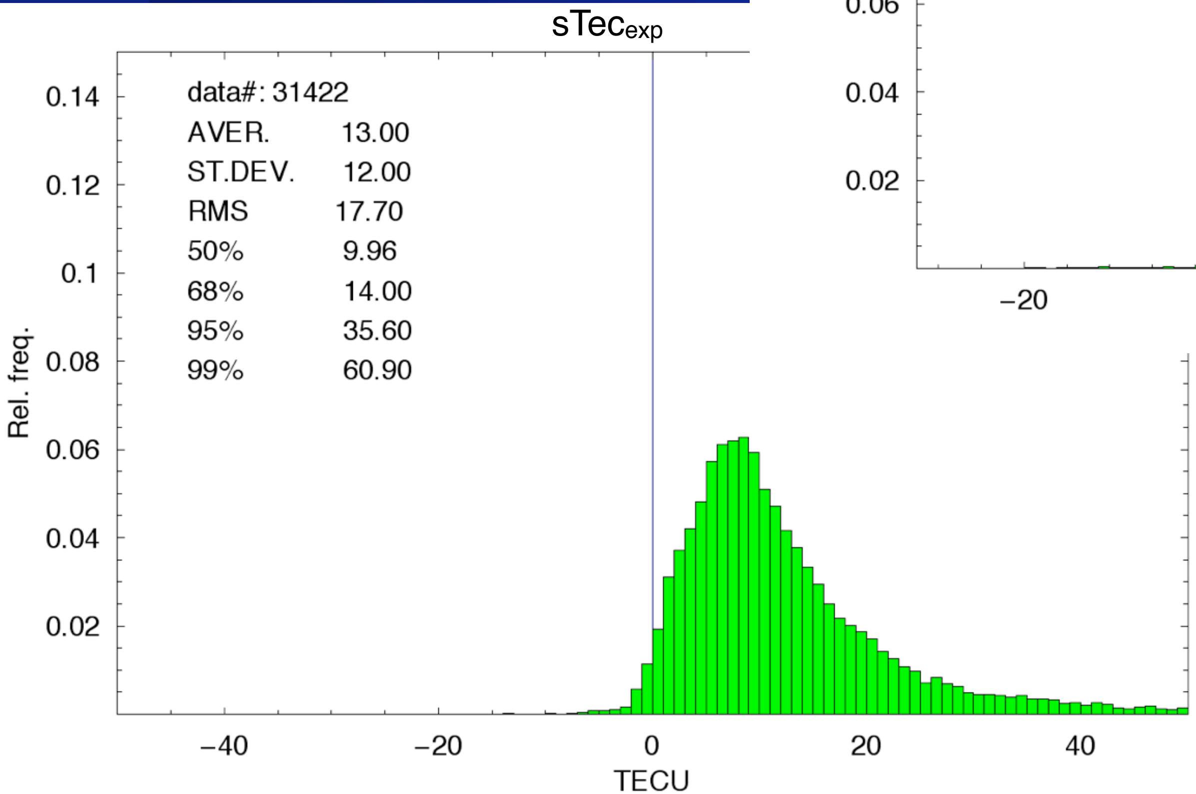


Location of the GPS receivers used for the consistency check

TEC & ΔTEC Statistics: 2006 09 21

Ground-based TEC data

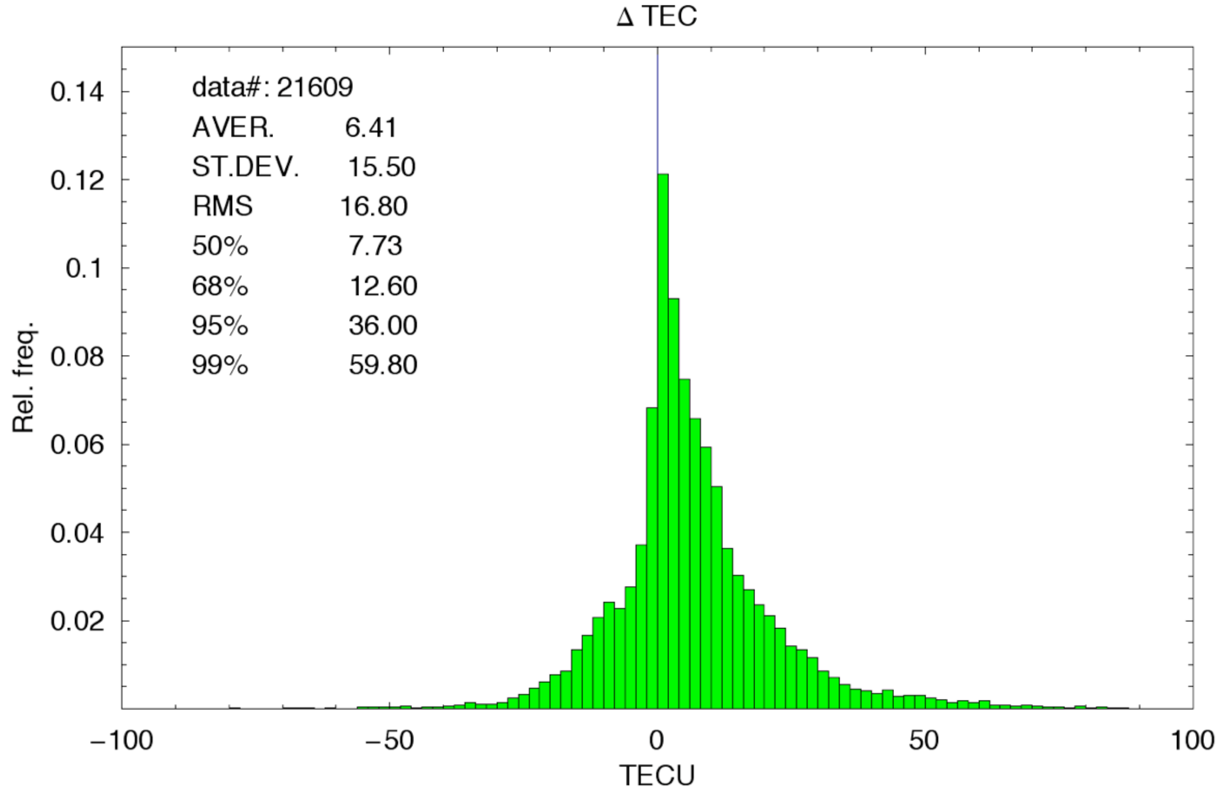


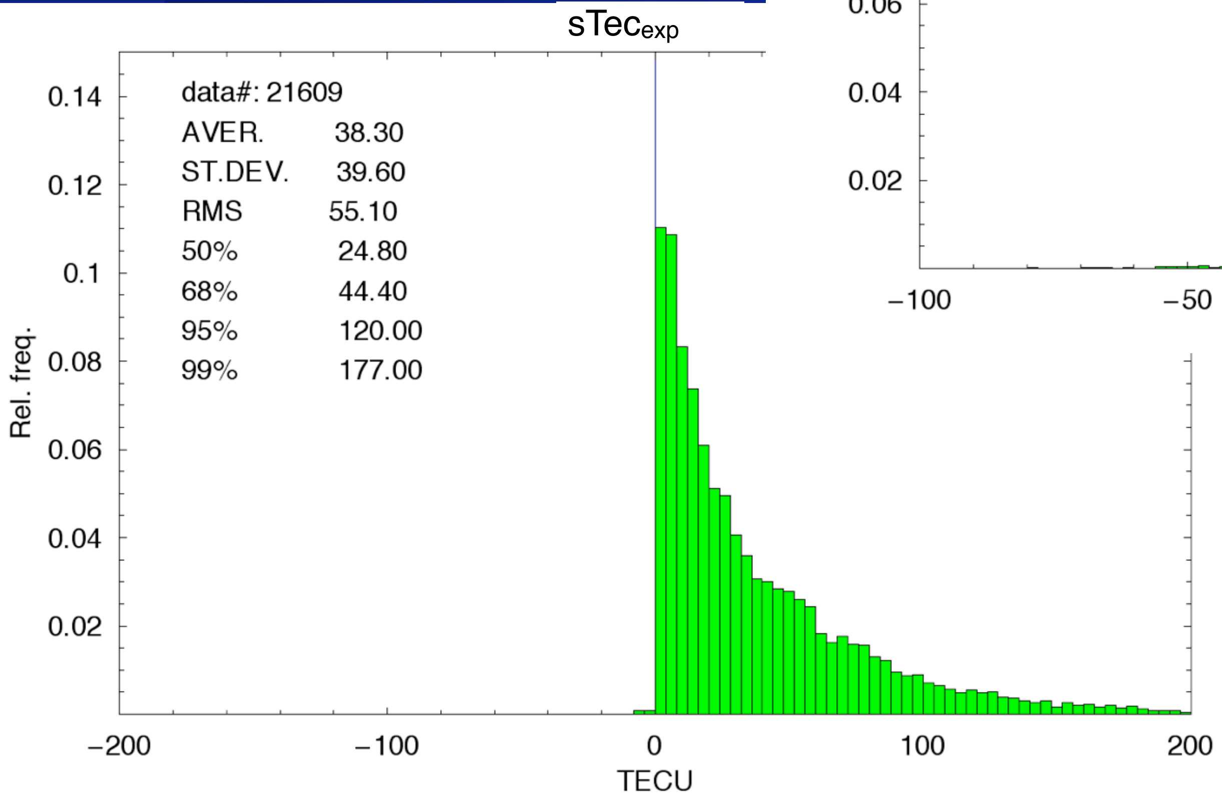


$\Delta Tec = sTec_{NeQ2} - sTec_{exp}$

TEC & ΔTEC Statistics: 2006 09 21

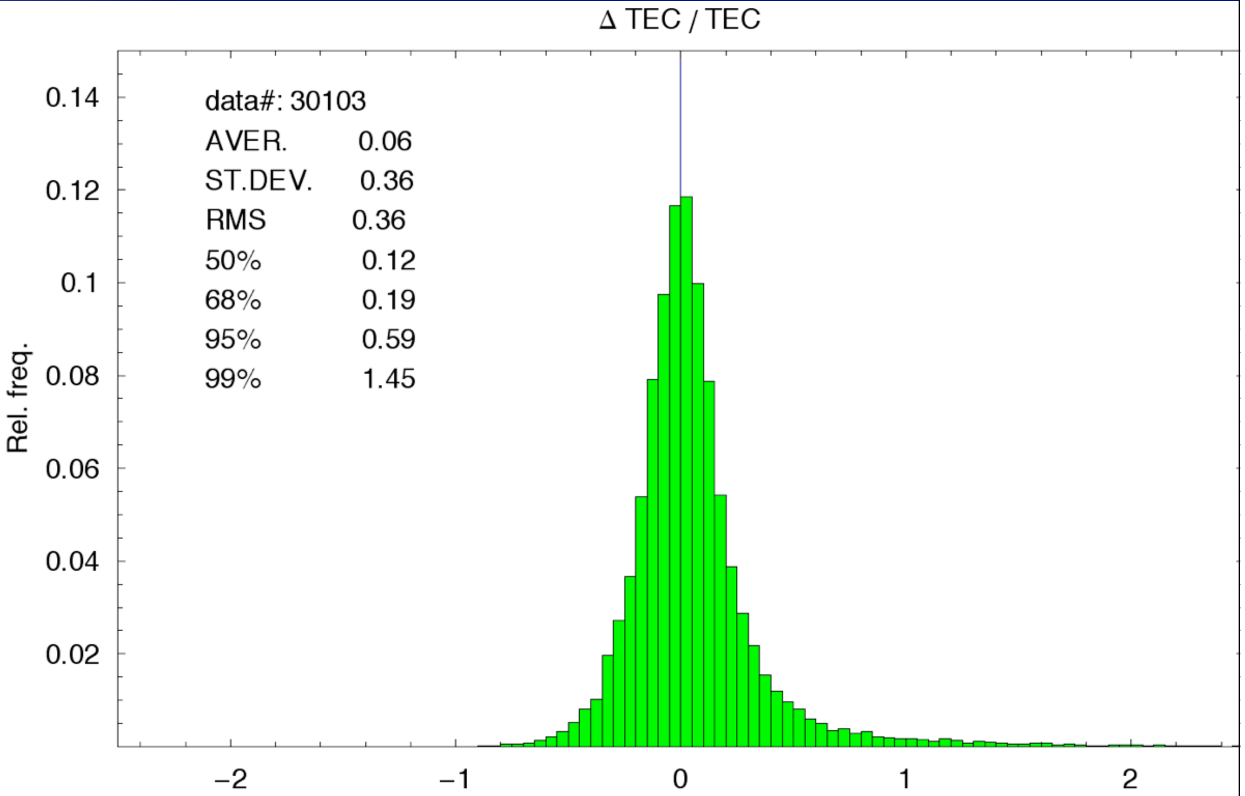
Space-based (RO)TEC data





$\Delta Tec = sTec_{NeQ2} - sTec_{exp}$

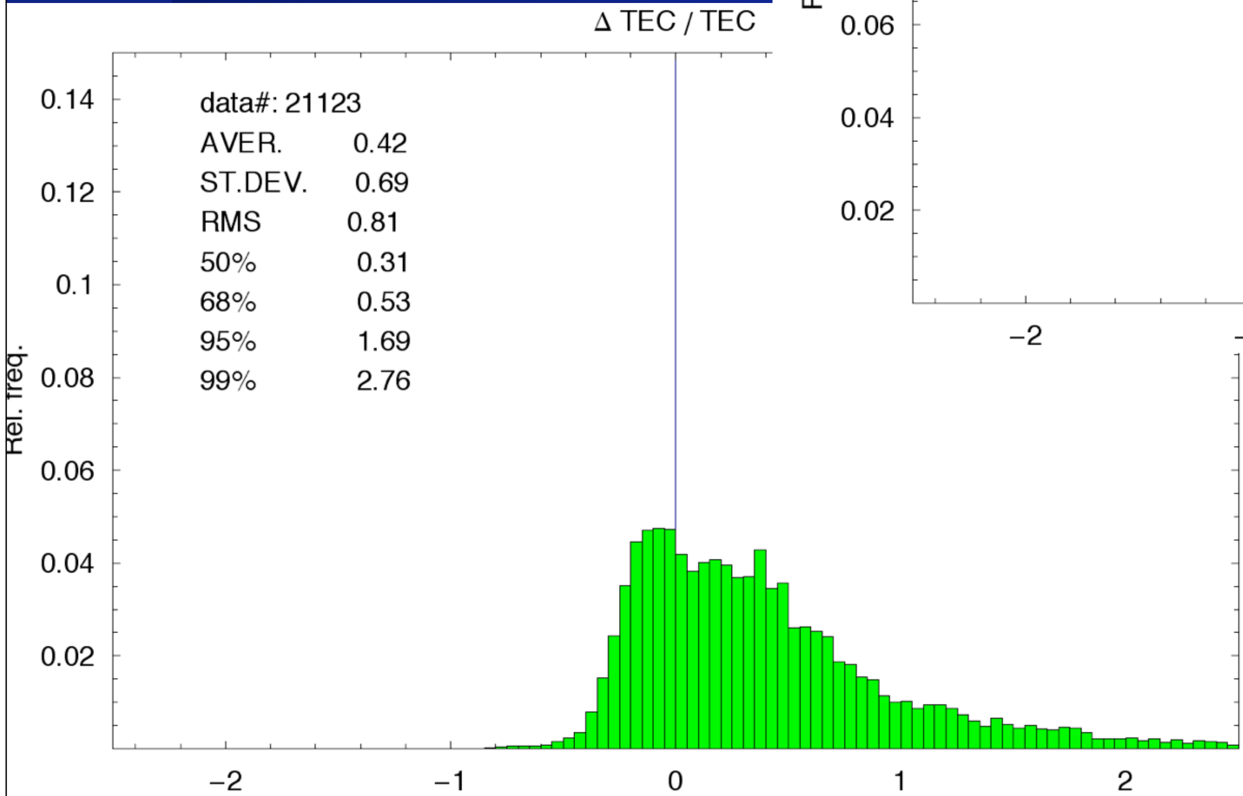
TEC/ΔTEC Statistics: 2006 09 21



Ground-based ΔTEC/TEC

(TEC < 1TECU removed)

Space-based (RO) ΔTEC/TEC



Comparing ground-based and space-based TEC statistics it is possible recognize that:

TEC/ΔTEC is remarkably bigger for RO than for ground-based TEC

↓

Possible NeQuick slab thickness weak formulation and/or incorrectly retrieved hmF2

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

(For possible near real time applications)

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

↓ ↓

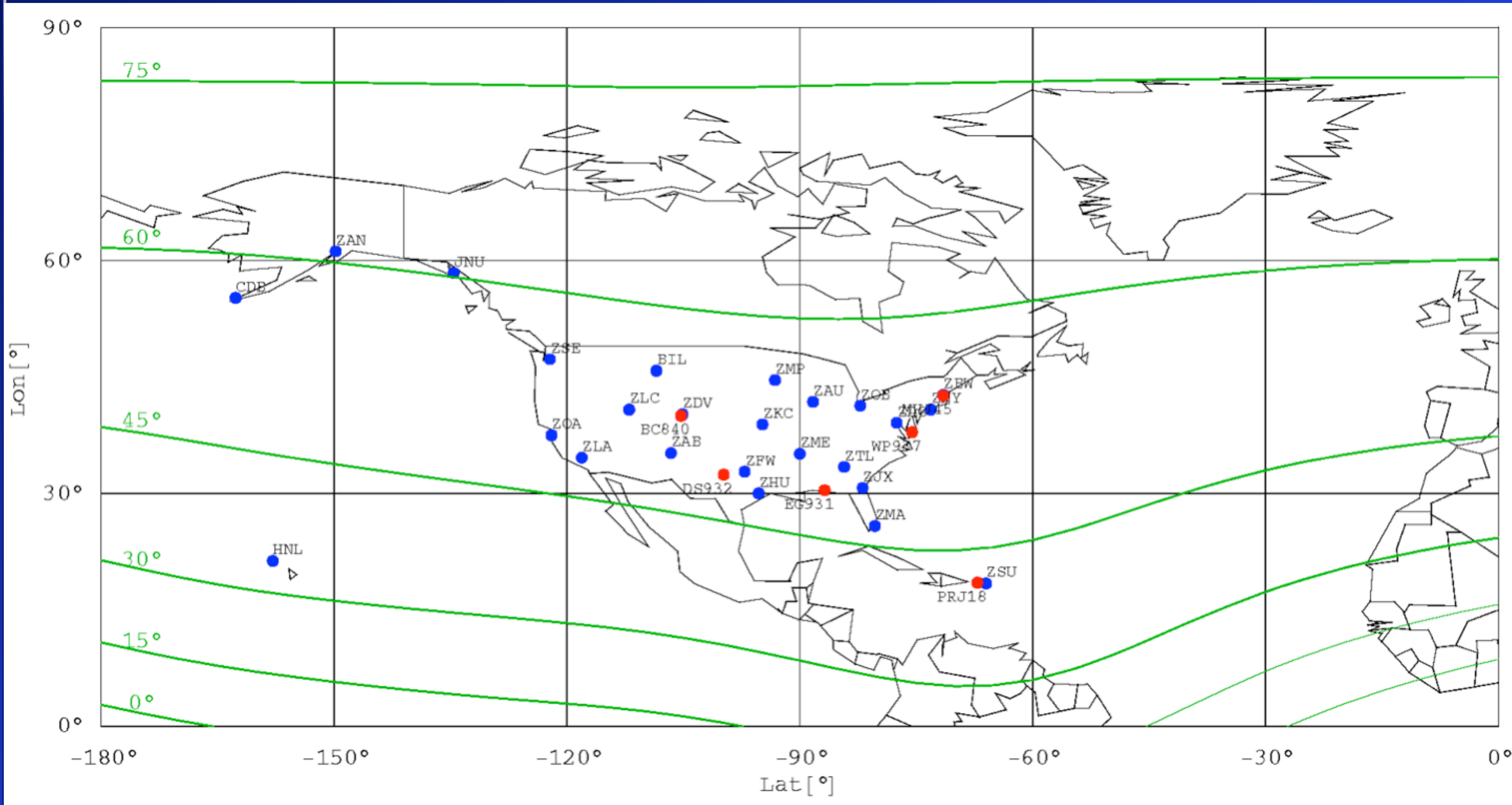
Reconstruct TEC along any
Station-to-satellite ray-path

Retrieve the foF2 values
at the Station

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

(Validation)

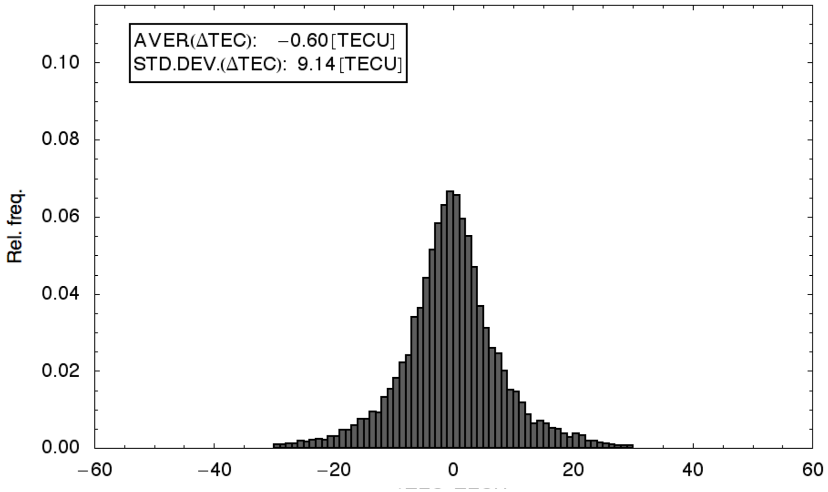
Stations & ionosondes locations

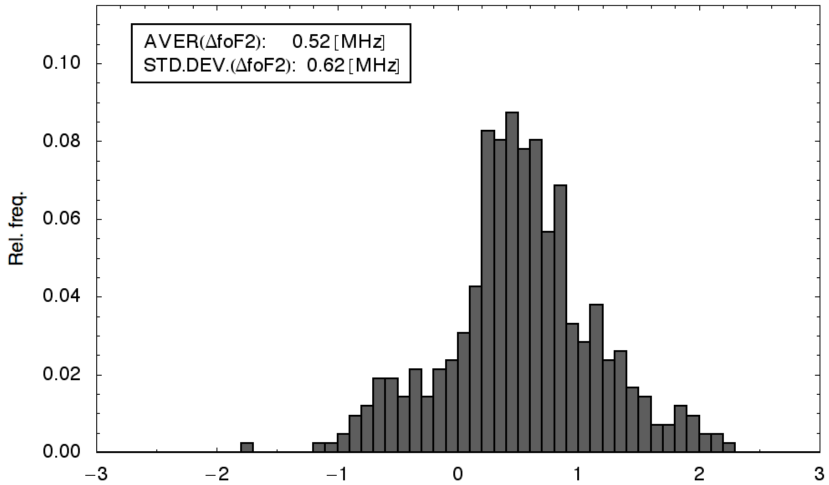


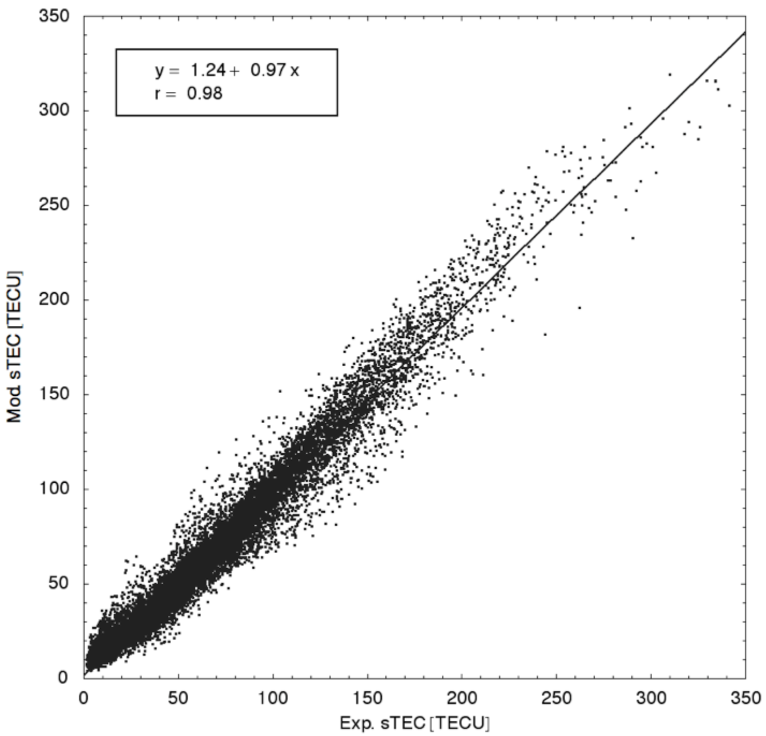
- GPS receivers
- Ionosondes

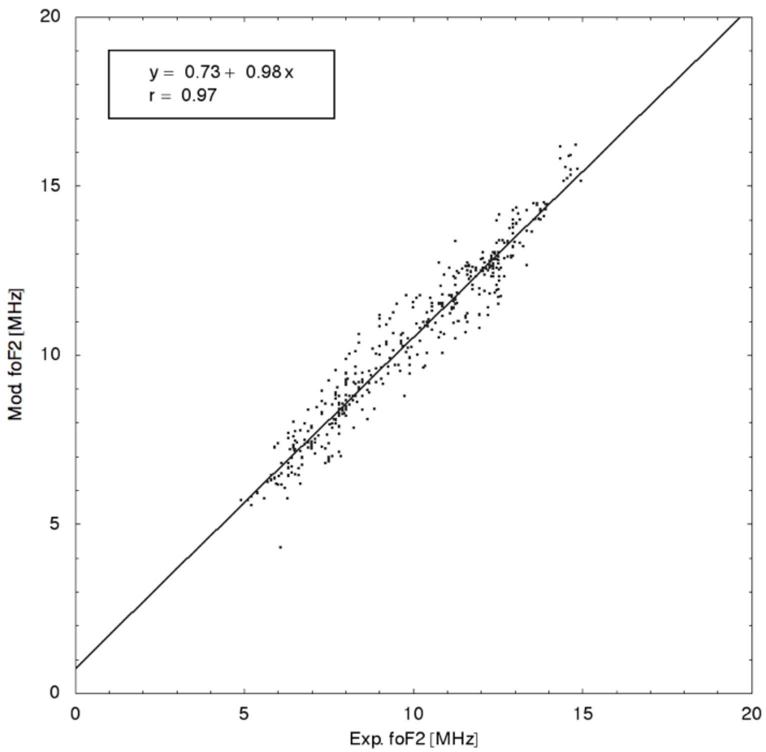
Modip isolines

(6) Single station statistics (000405)









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

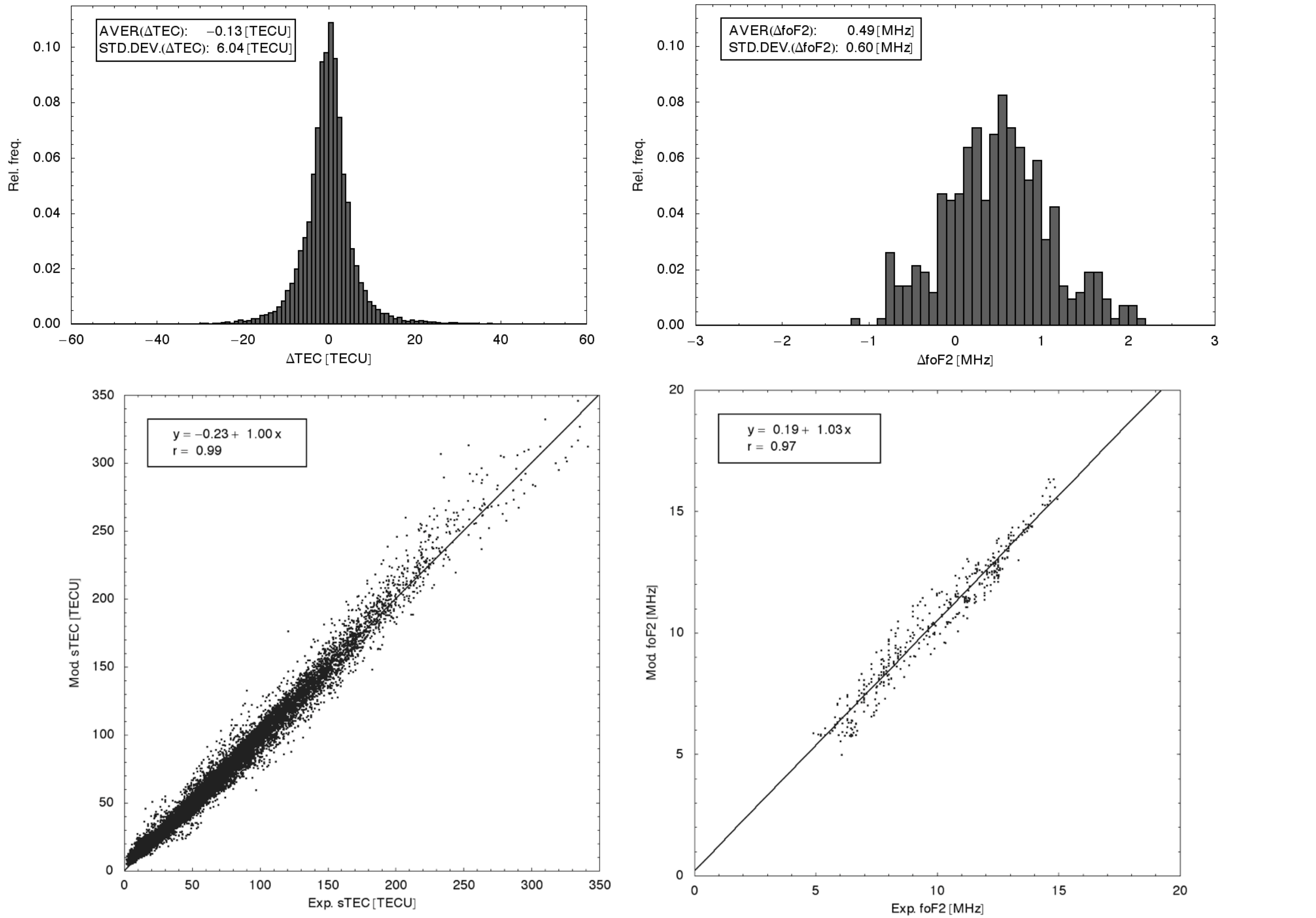
↓

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

↓ Reconstruct TEC along any given ray-path

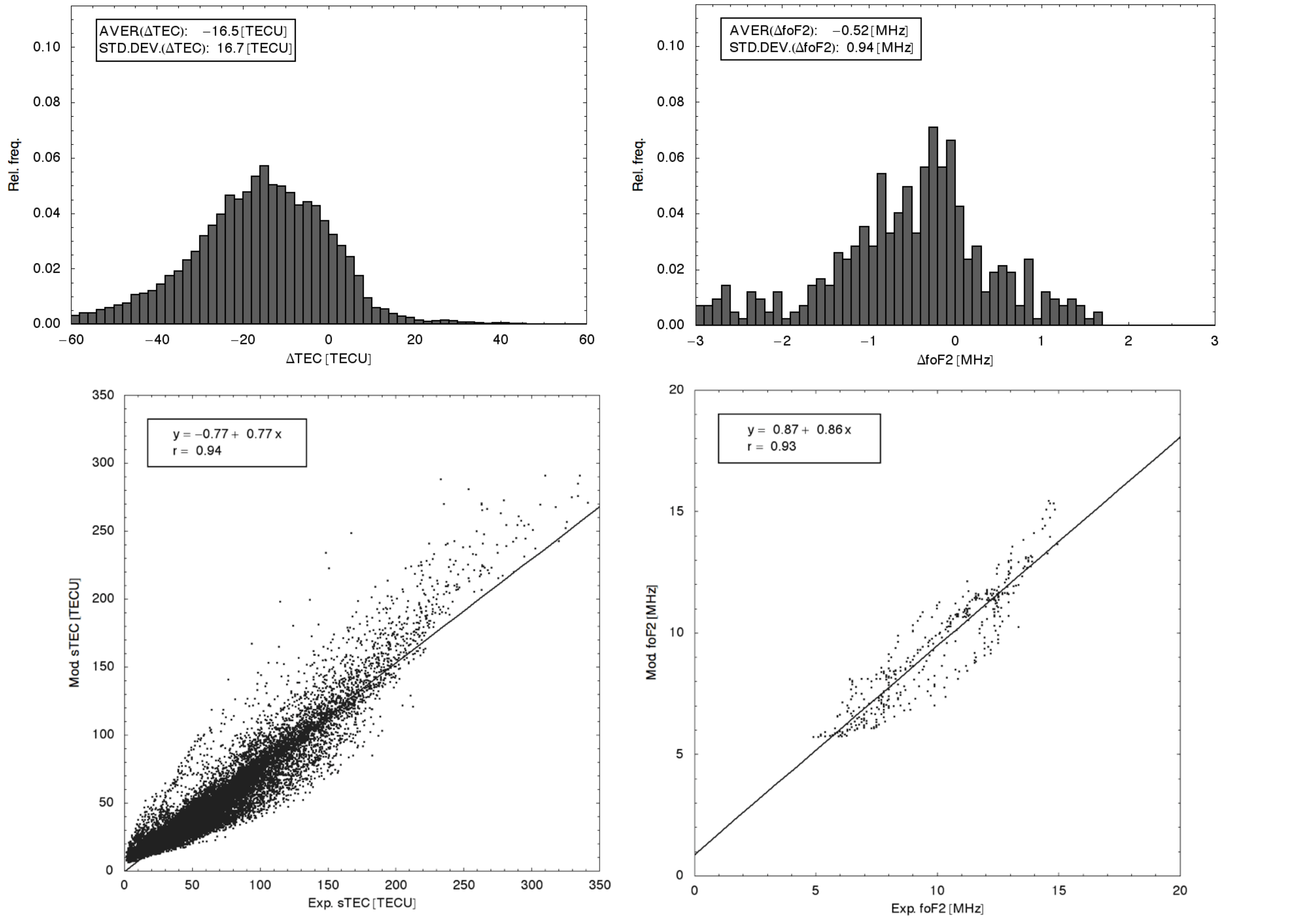
↓ Reconstruct any foF2 value (foF2 map)

Multiple station statistics (000405)



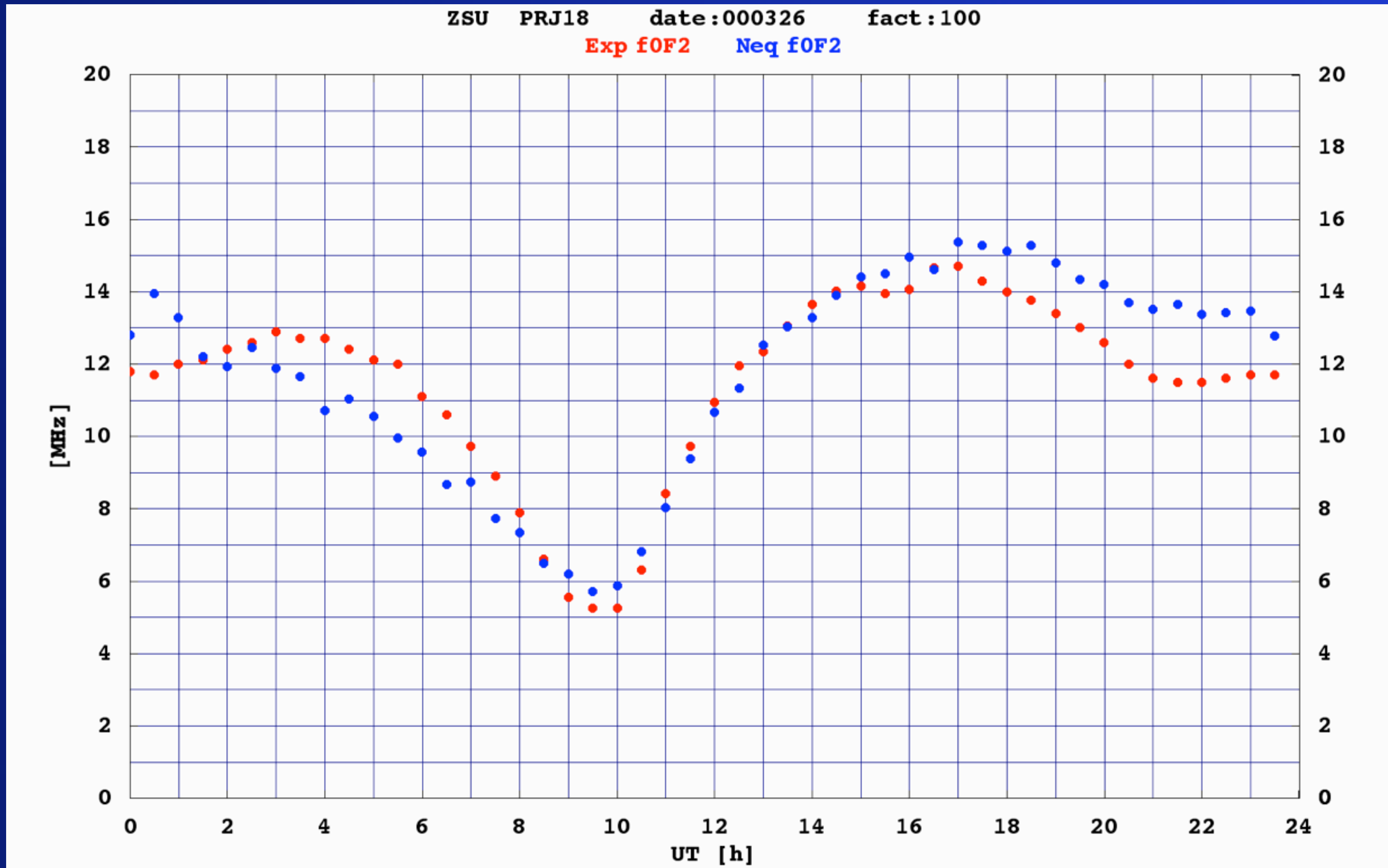
Using NeQuick model in a standard way
(F10.7 input -> no adaptation)

Flux of the day statistics (000405)



Remark

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

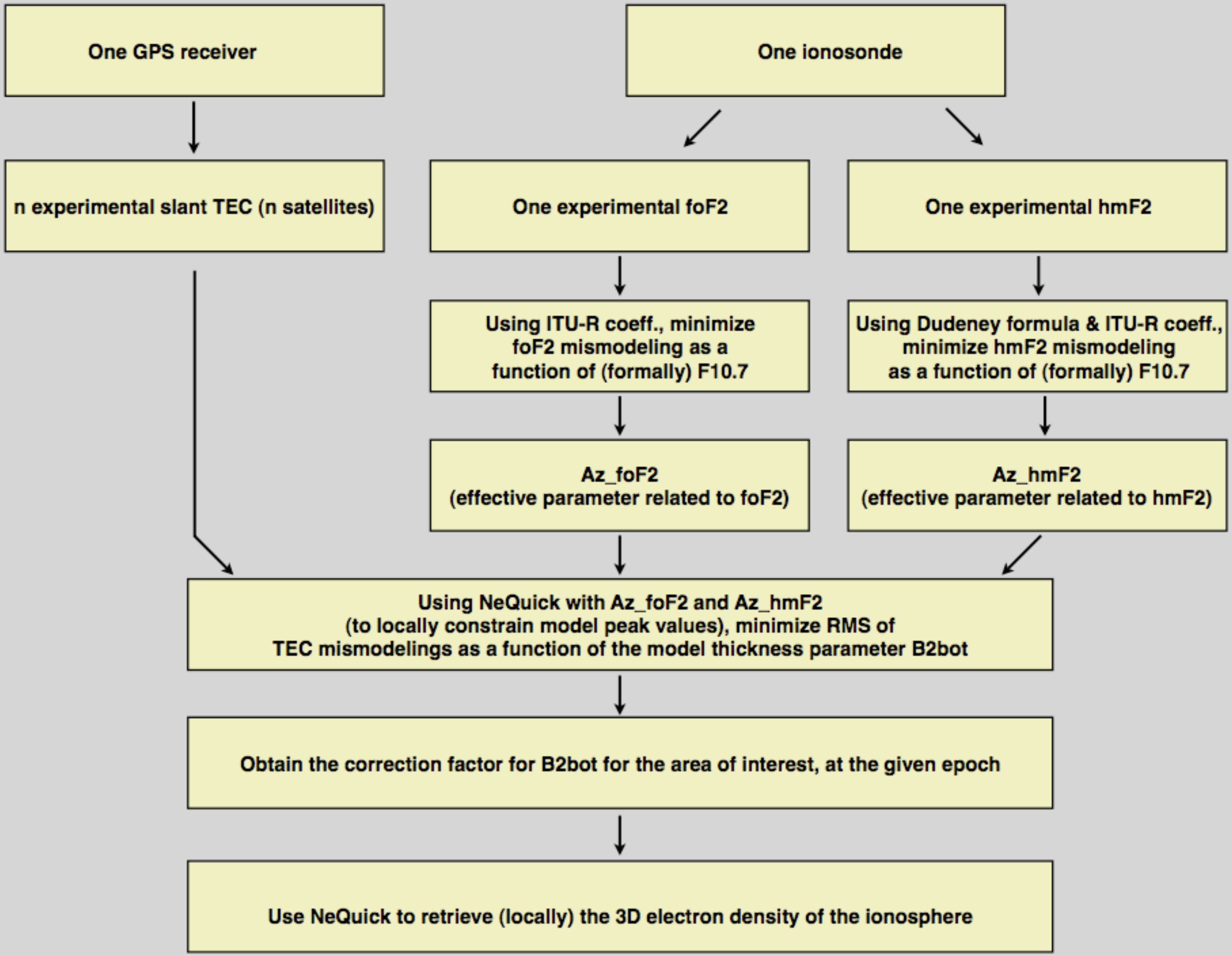


The results of these studies have indicated that there is the need to further improve the model formulation in terms of slab thickness.

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

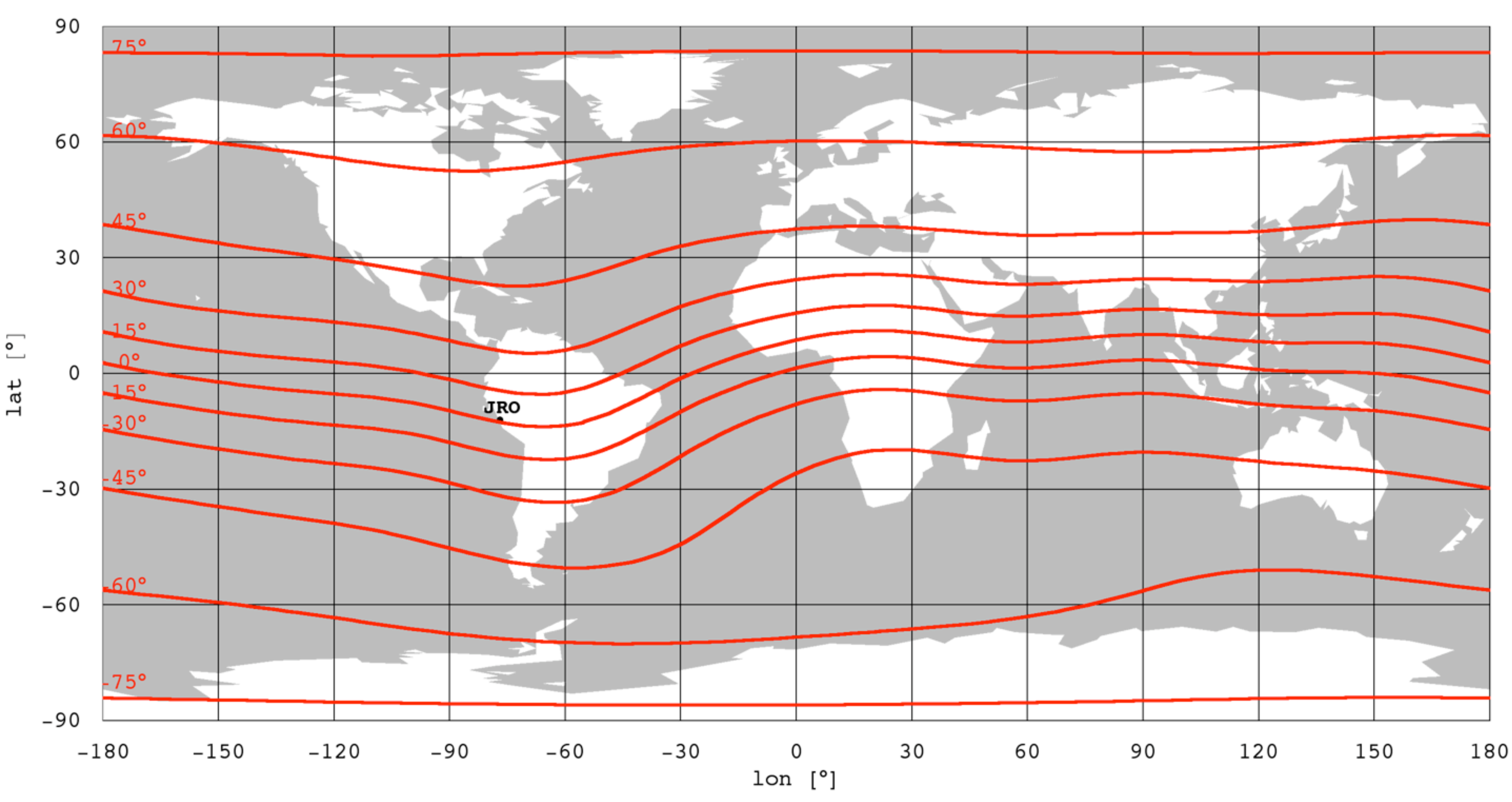
Use JRO profiles to simulate the process of adapting NeQuick to GPS derived TEC and ionosonde peak parameters data.

TEC and peak parameters are known from the profile.

↓

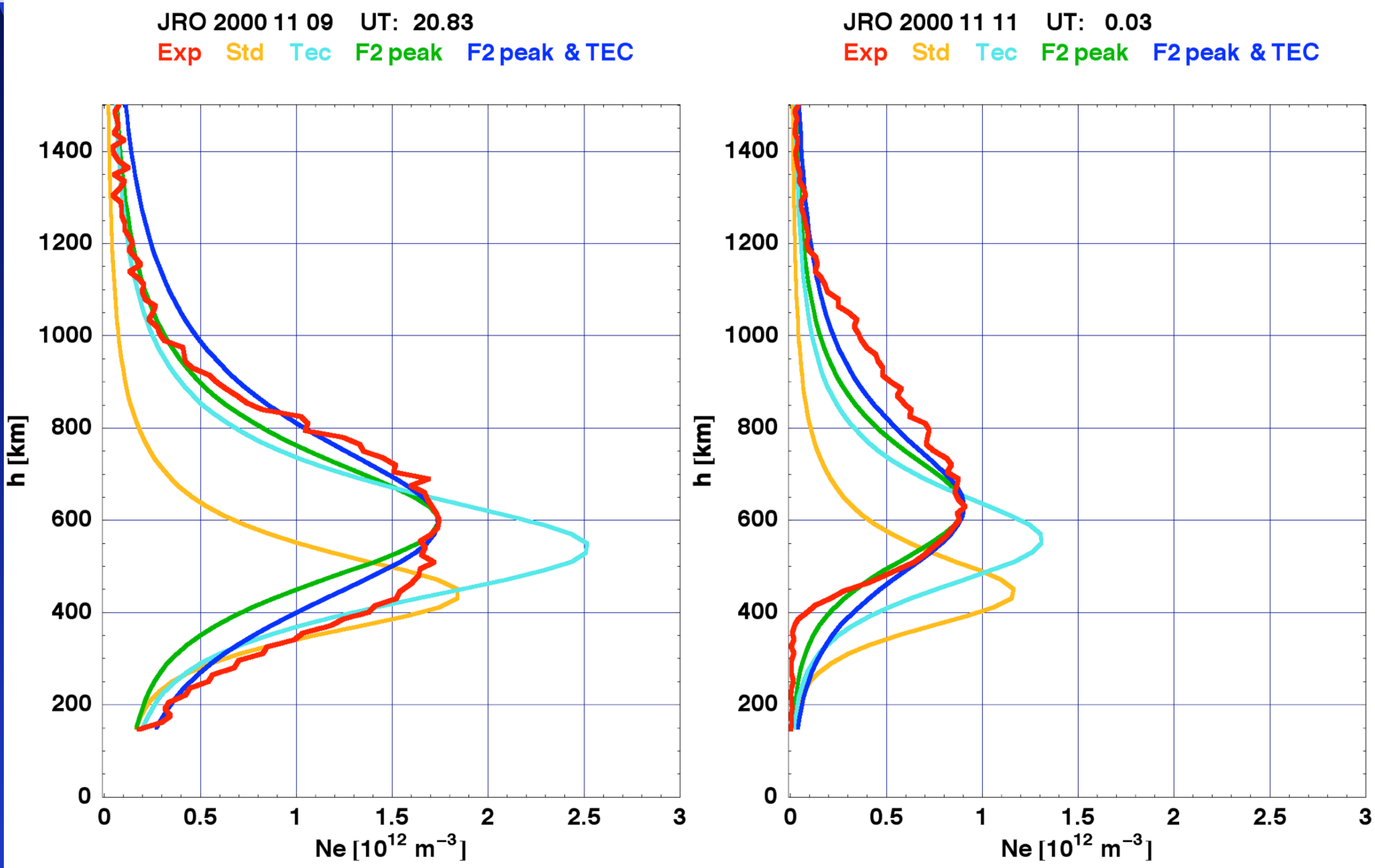
After model adaptation it is possible to compare profiles in order to evaluate the adaptation technique effectiveness.

Adaptation method validation



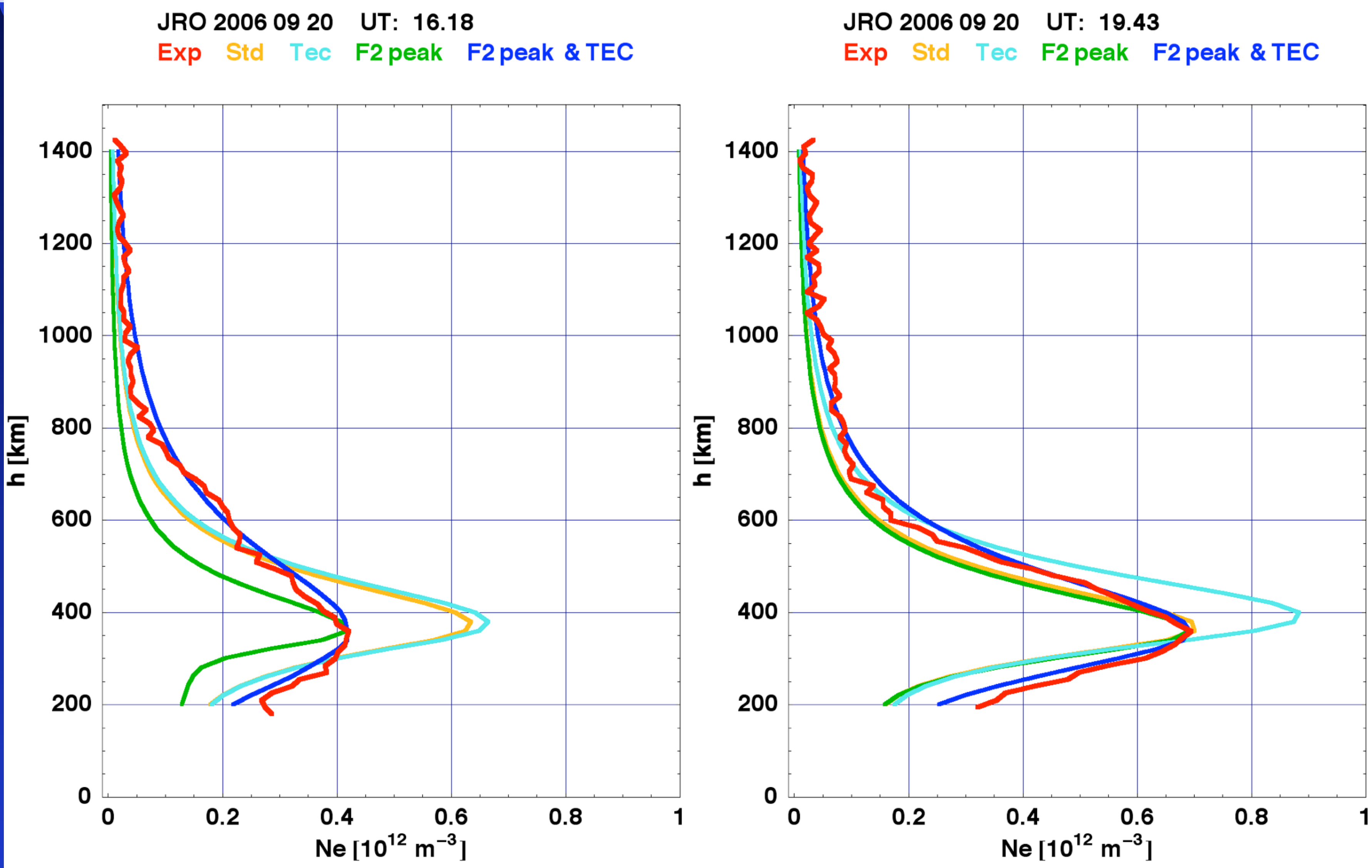
Jicamarca Radio Observatory (JRO) location

Adaptation method validation



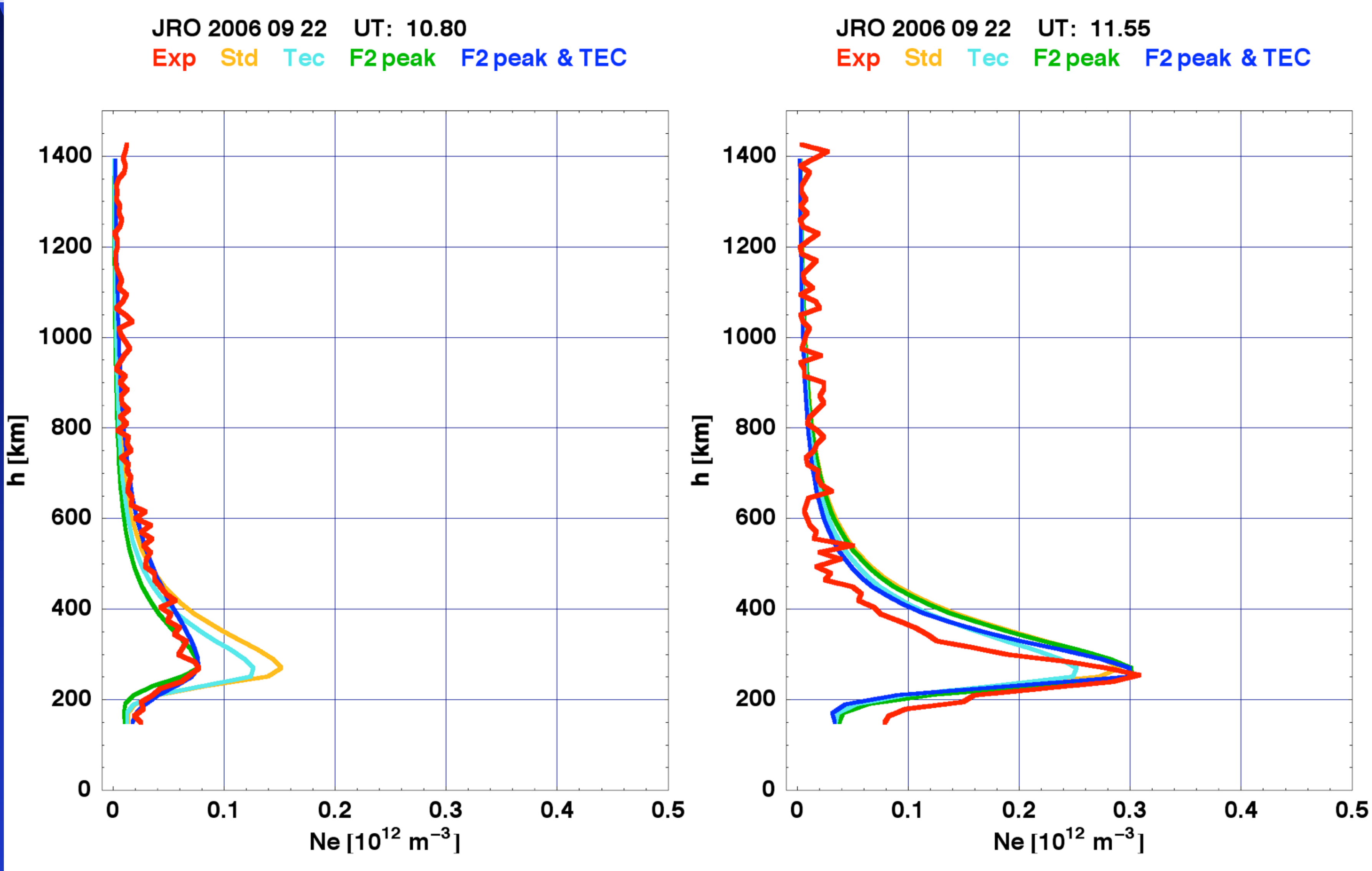
Model: NeQuick

Adaptation method validation



Model: NeQuick

Adaptation method validation

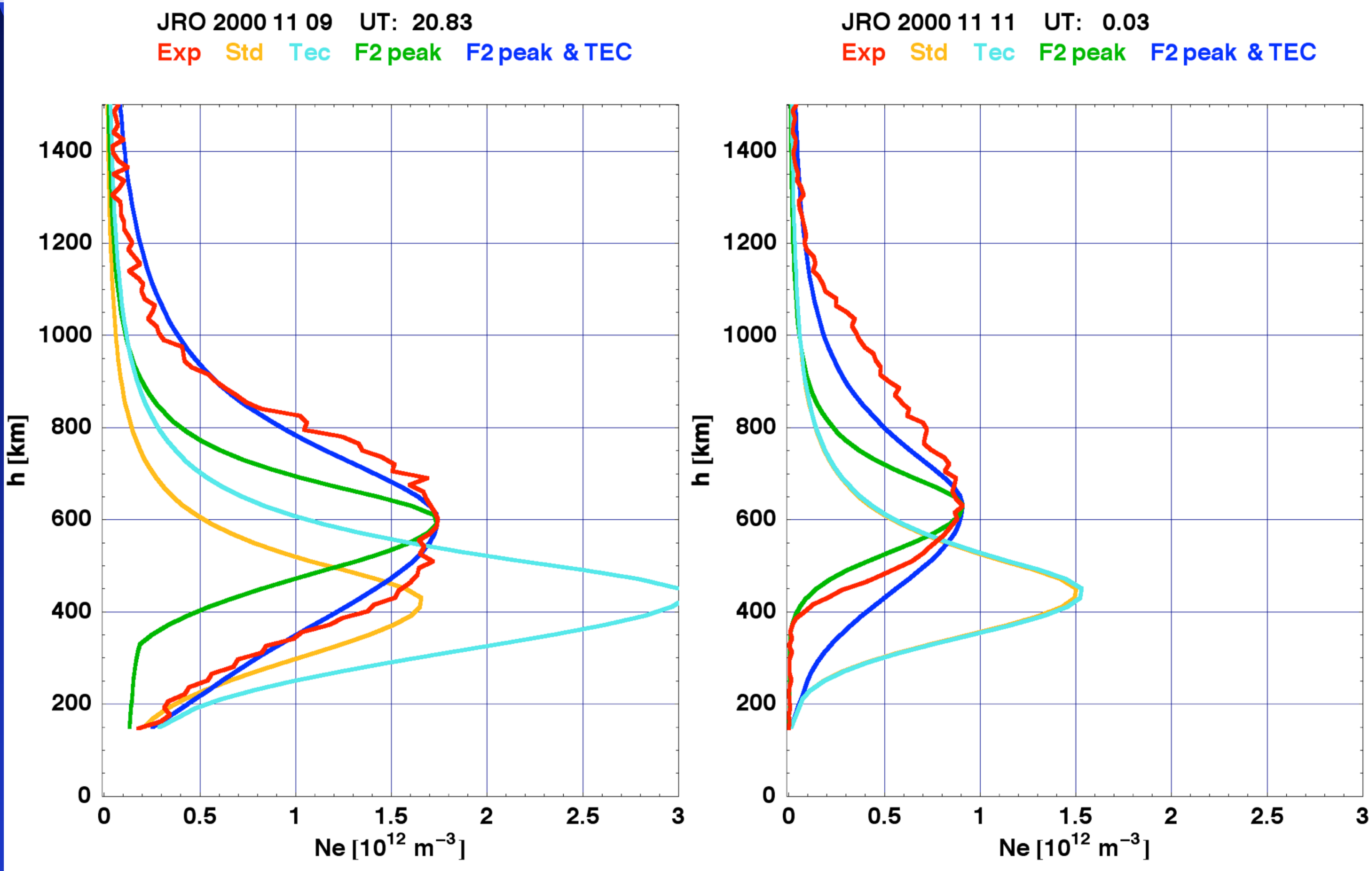


Model: NeQuick

Adaptation method effectiveness

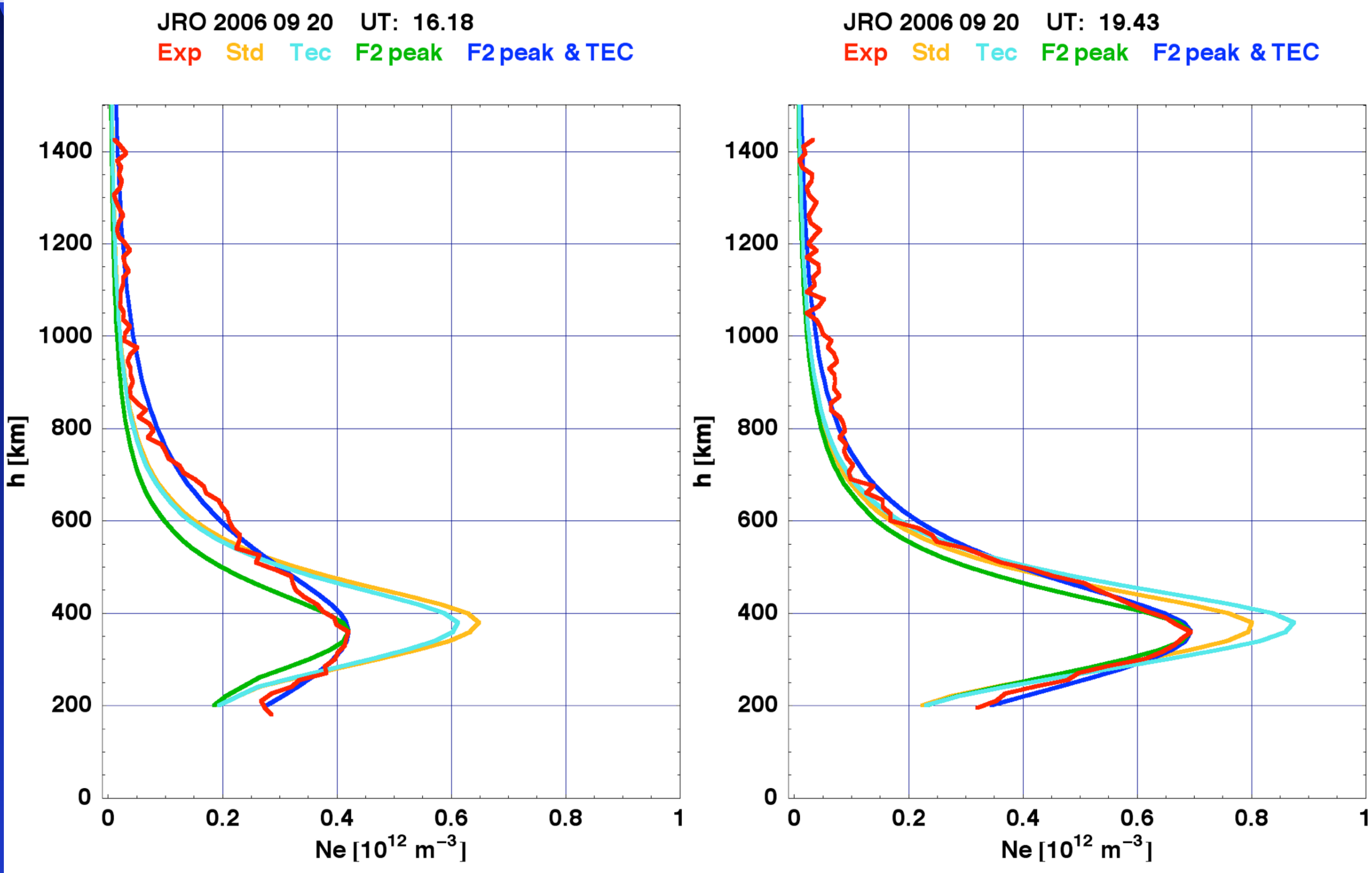
- In order to evaluate the adaptation technique effectiveness, the IRI model has been used instead of the NeQuick and the same data have been used for the adaptation.
- (Not so easy as in the case of NeQuick)

Adaptation method validation



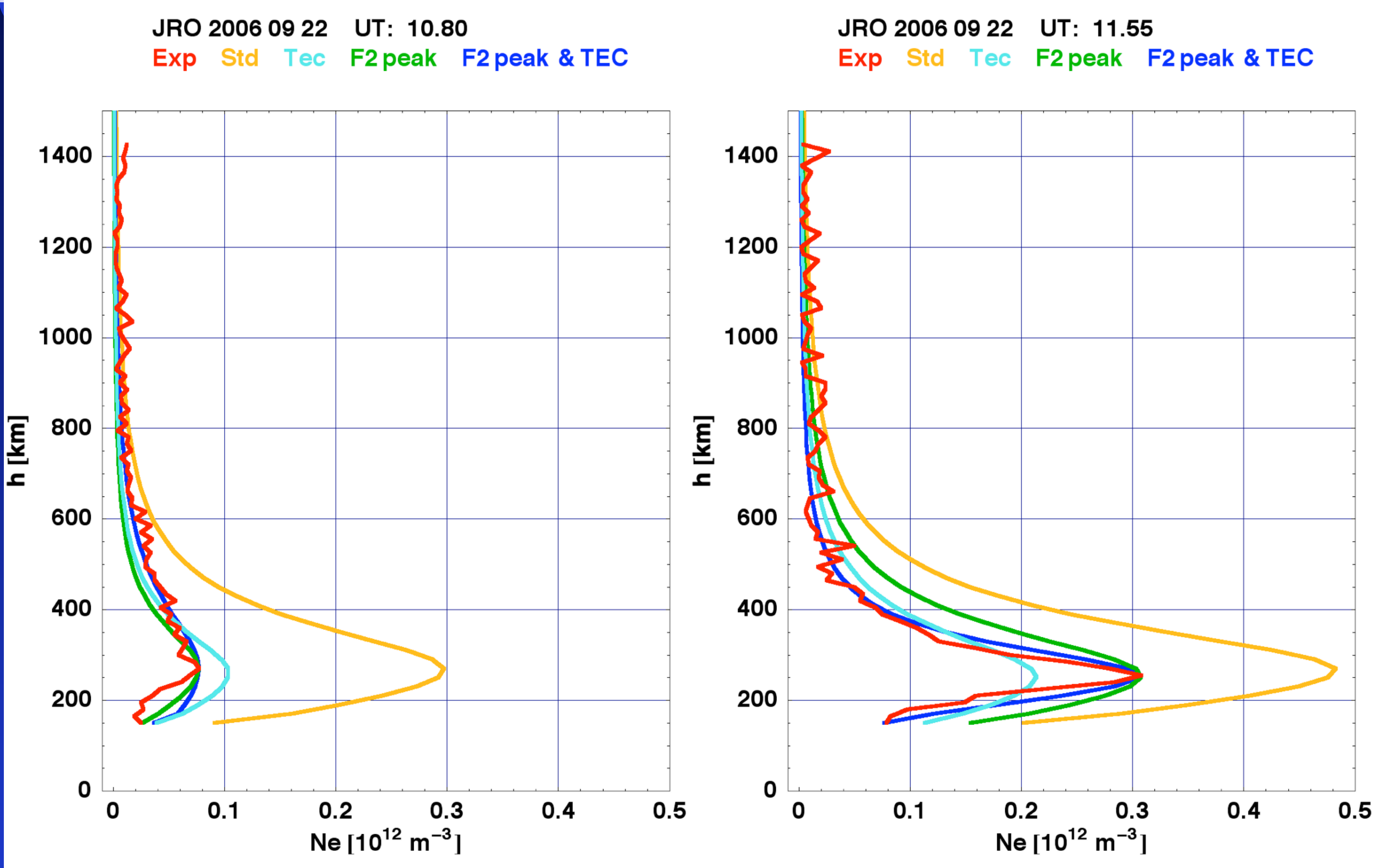
Model: IRI

Adaptation method validation



Model: IRI

Adaptation method validation



Model: IRI

Use of Radio Occultation data

Radio Occultation data ingestion

- a) 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).

↓

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

- Direct TEC assimilation into a background model.
  - EDAM
  - NeQuick (first results)

Adapting NeQuick model to RO-derived slant TEC

(corresponding to the LEO -> GPS link below the LEO orbit)

First results

RO-derived TEC data ingestion

At a given epoch

One occultation event

↓

Use "Onion Peeling" algorithm to invert the RO data and obtain an electron density profile

↓

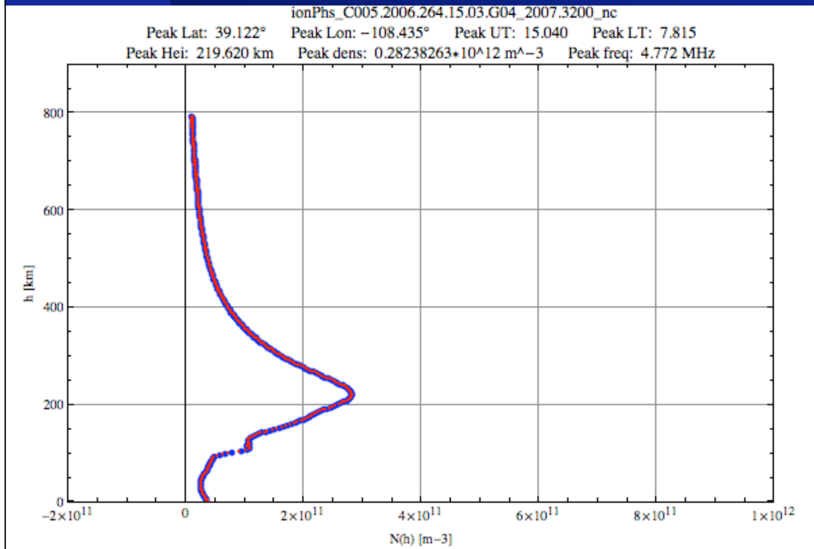
Use RO-derived hmF2

↓

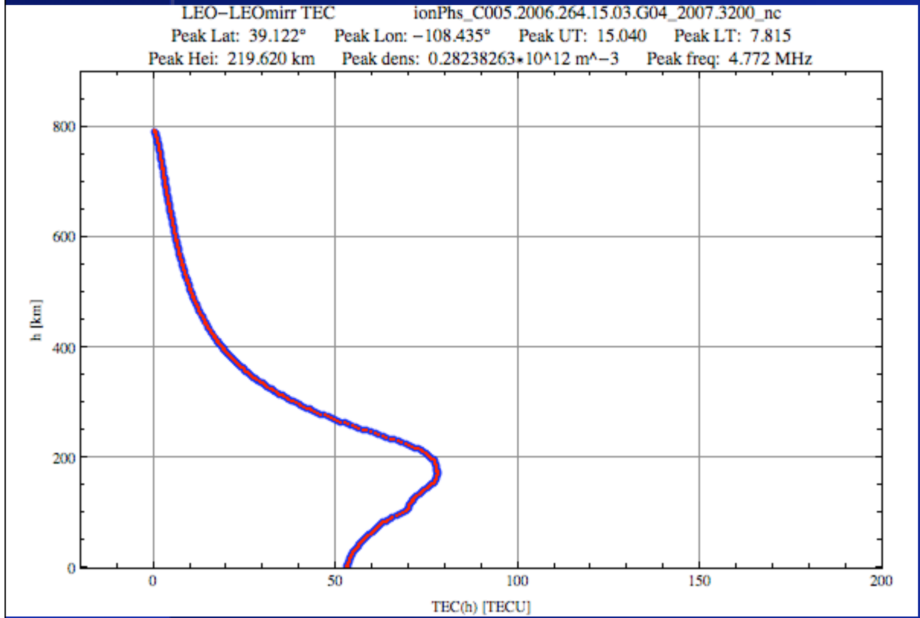
Using Dudeney formula & ITU-R coeff., minimize hmF2 mismodeling as a function of (formally) F10.7

↓

Az_hmF2
(effective parameter related to hmF2)



RO-derived TEC data ingestion



* LEO -> GPS link below the LEO orbit

↓

Using NeQuick with Az_hmF2

↓

Minimize the RMS of the RO-derived TEC* mismodelings as a function of b2bot modulating factor and F10.7

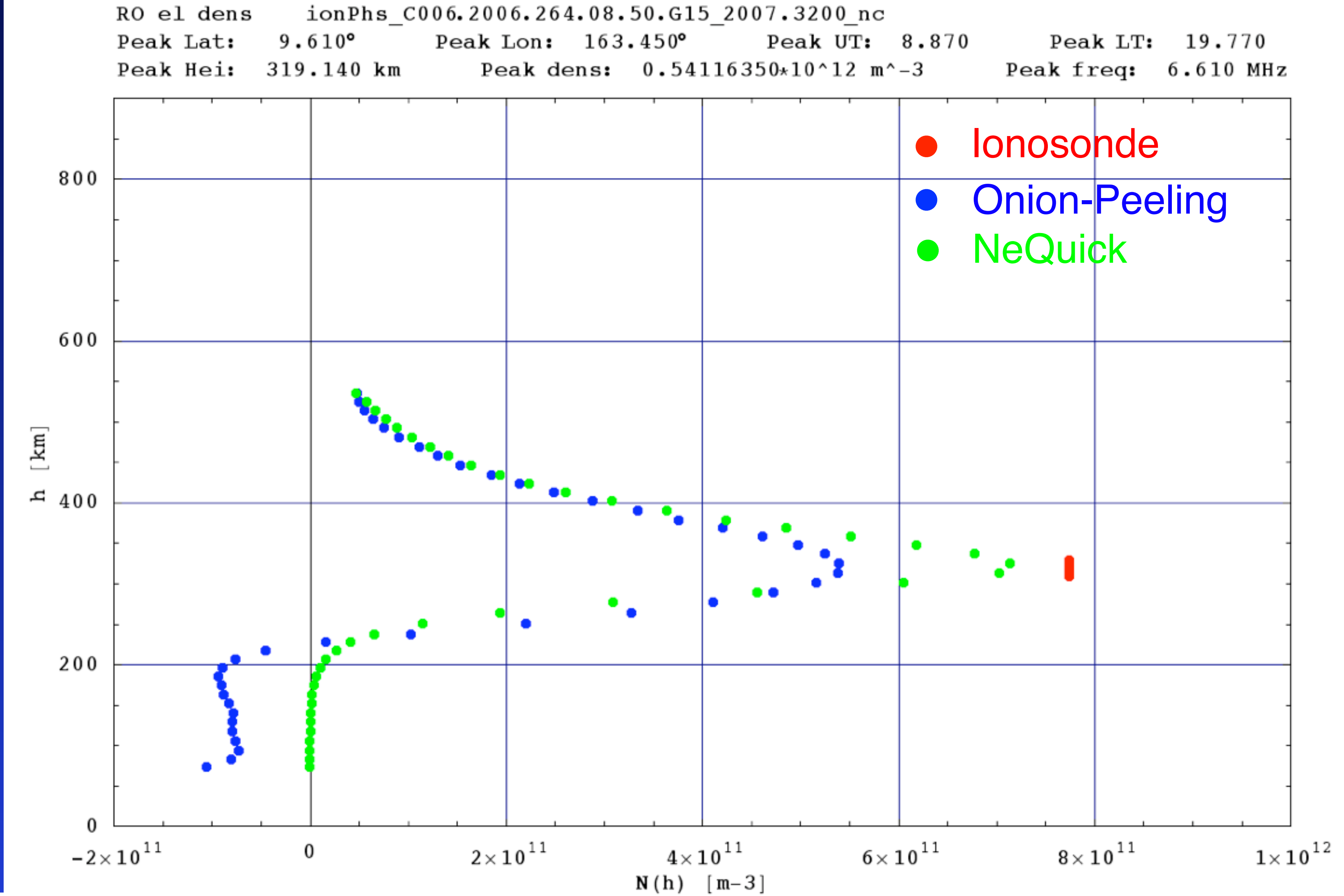
↓

Az_foF2
(effective parameter related to foF2)
b2bot_mod

↓

Drive NeQuick with Az_hmF2, Az_foF2, b2bot_mod to retrieve the 3D electron density

NeQuick adaptation to RO TEC



A case study

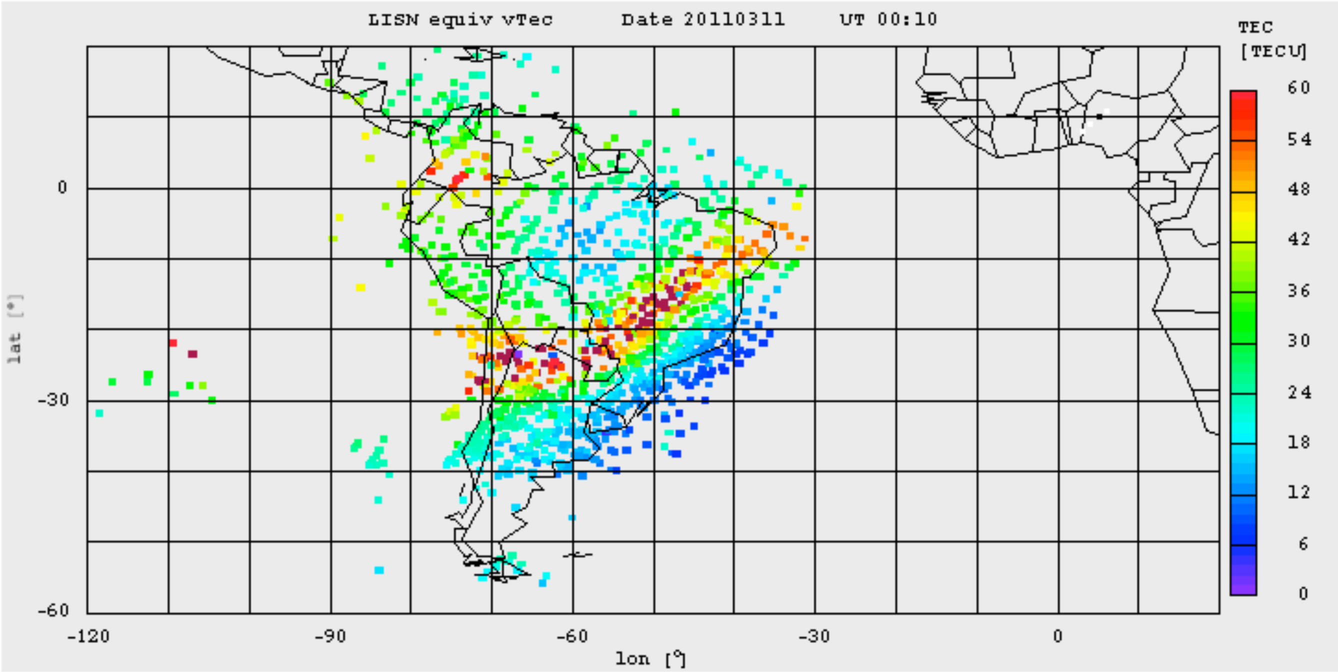
Adapt NeQuick model to LISN TEC data
(days 11-12-13 Mar 2011)

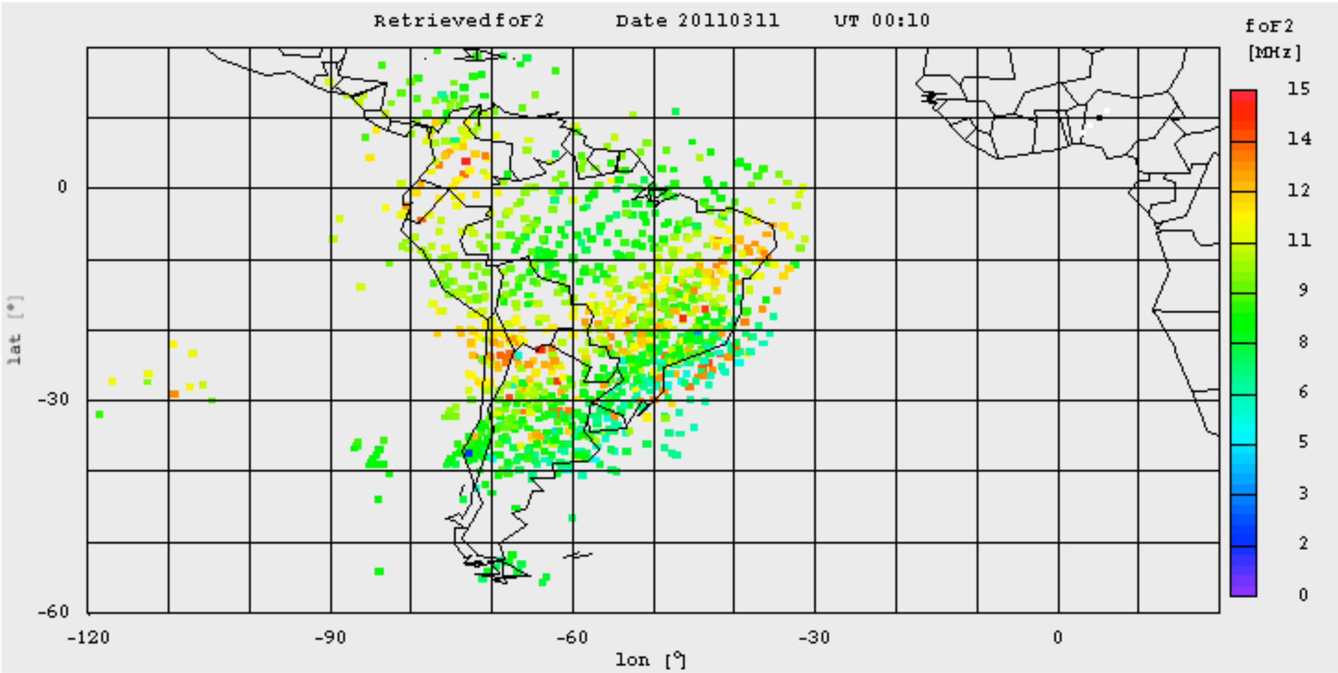
↓

Reconstruct foF2 values

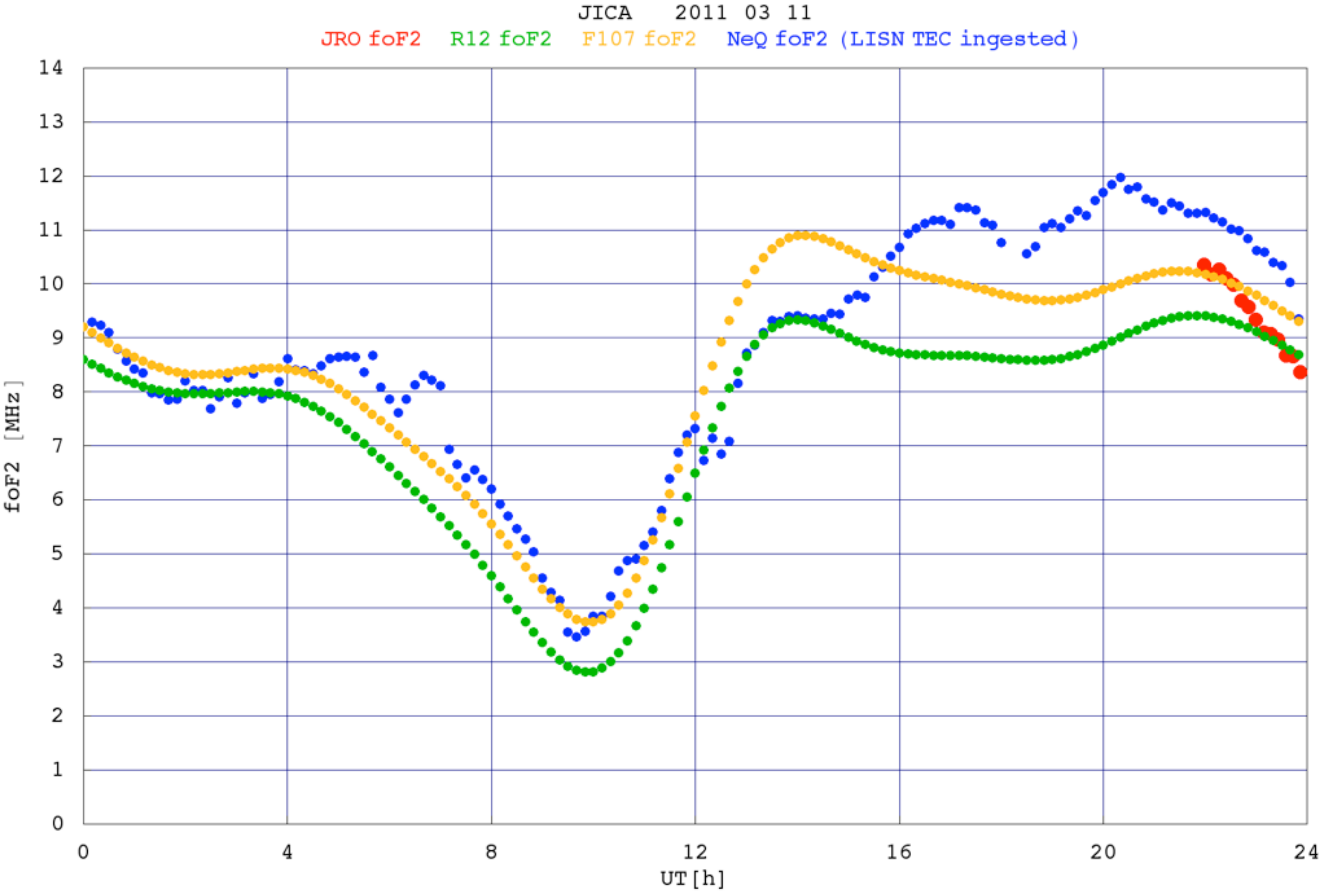
Validate the results (where possible) with:

- JRO data and
- manually scaled foF2 data from Tucumán ionosonde

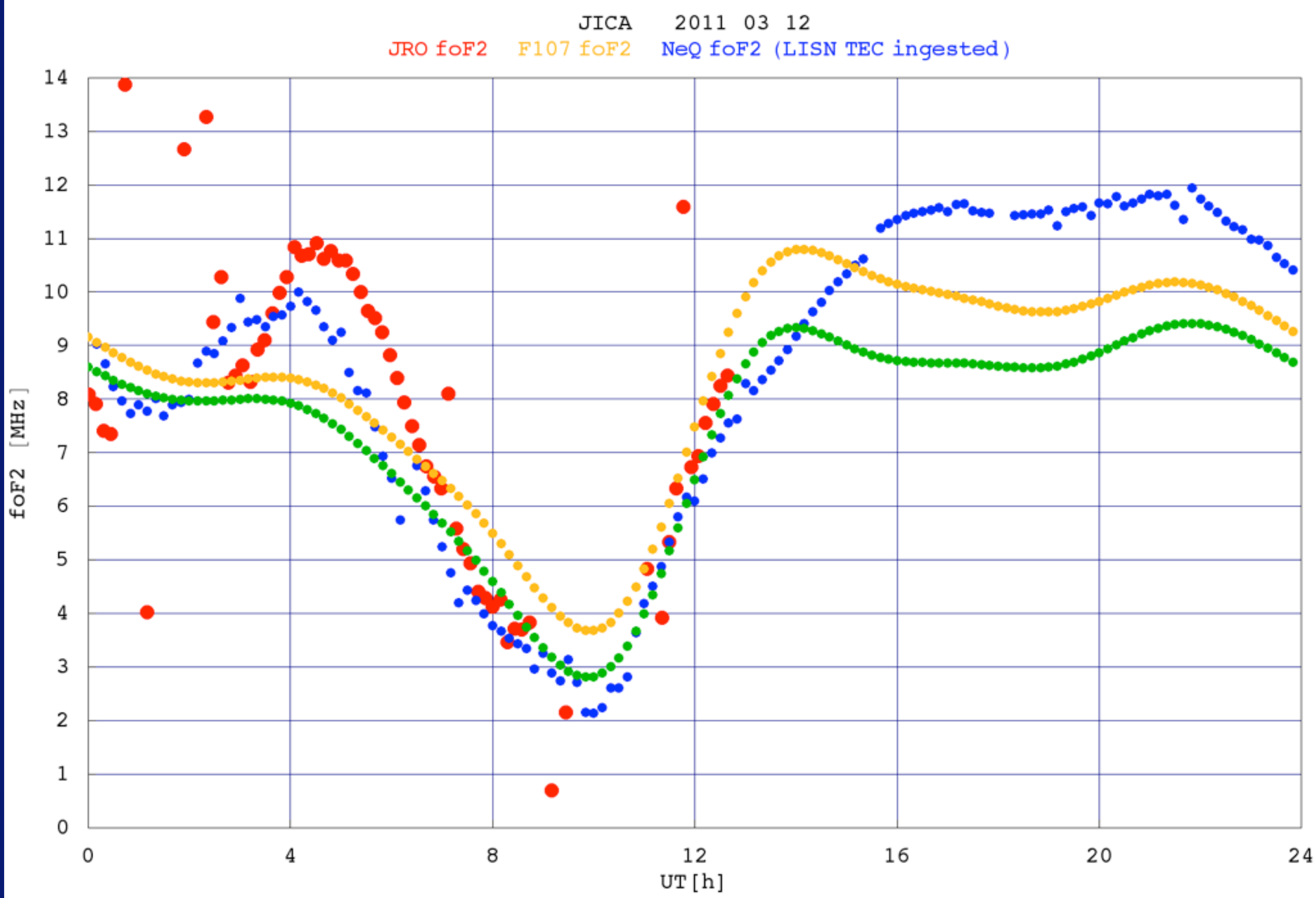

LISN equiv vTec
Date 20110311
UT 00:10
TEC
[TECU]
60
54
48
42
36
30
24
18
12
6
0
lat [°]
lon [°]
-120
-90
-60
-30
0


RetrievedfoF2
Date 20110311
UT 00:10
foF2
[MHz]
15
14
12
11
9
8
6
5
3
2
0
lat [°]
lon [°]
-120
-90
-60
-30
0

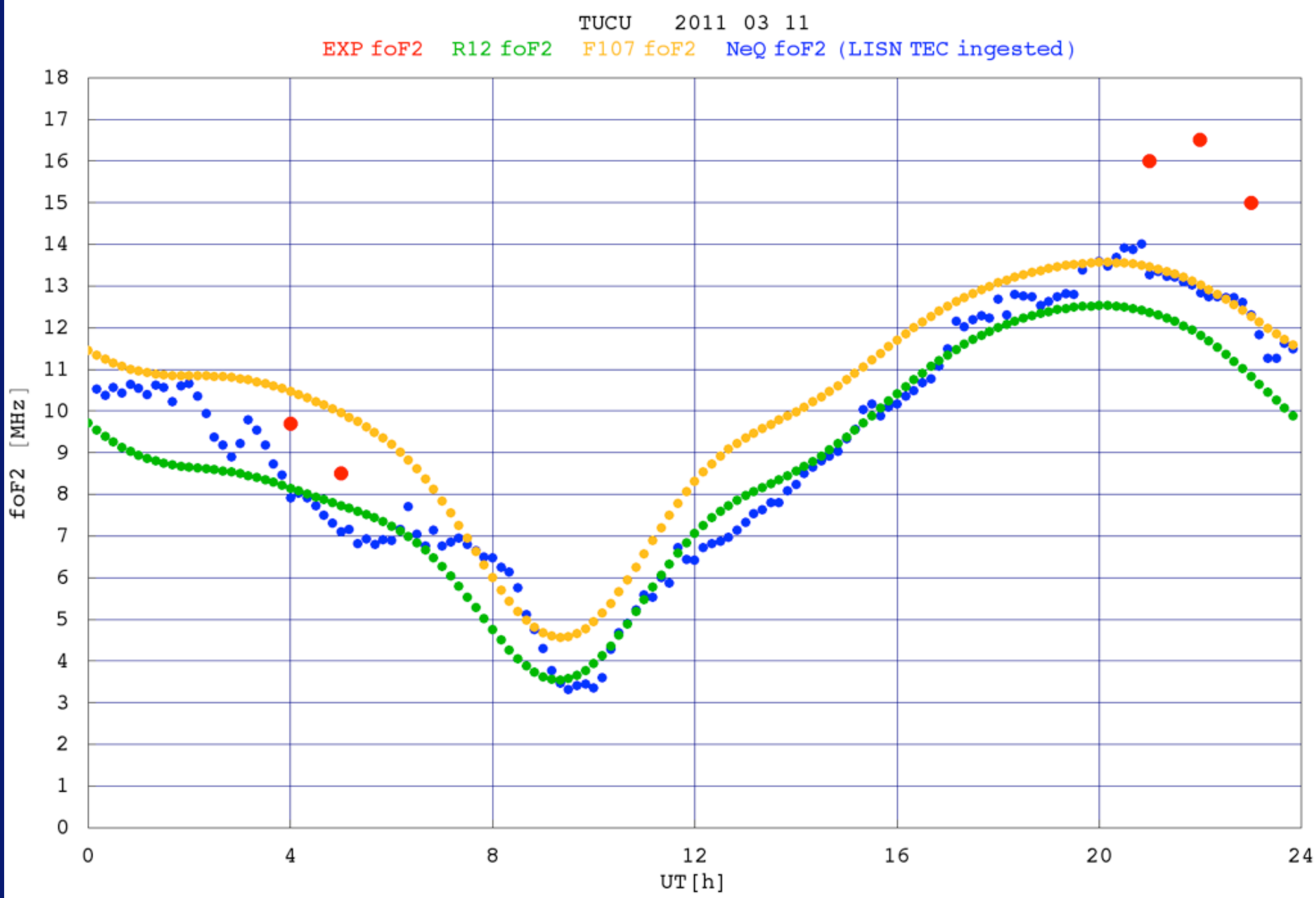
Validation example 1



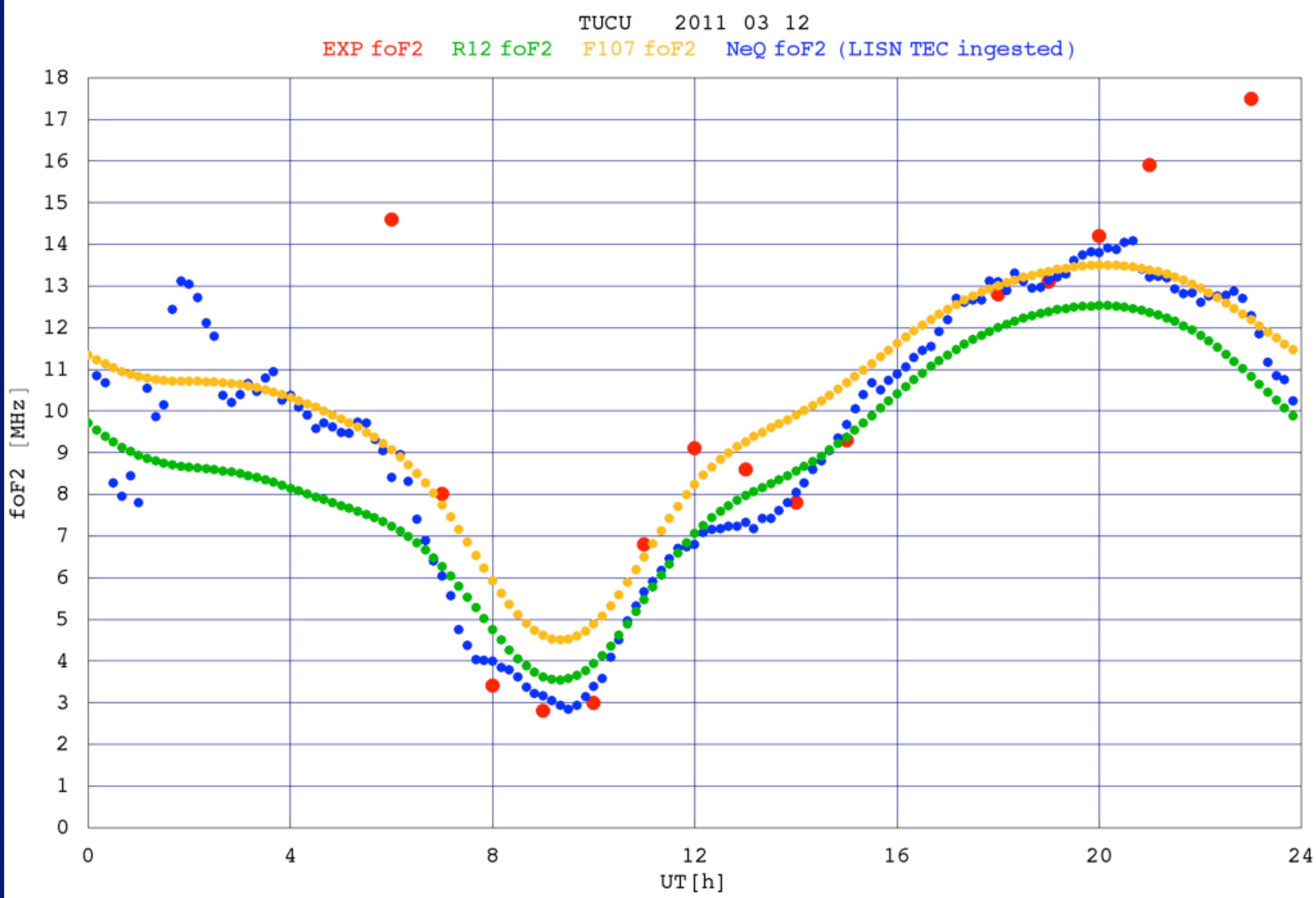
Validation example 2



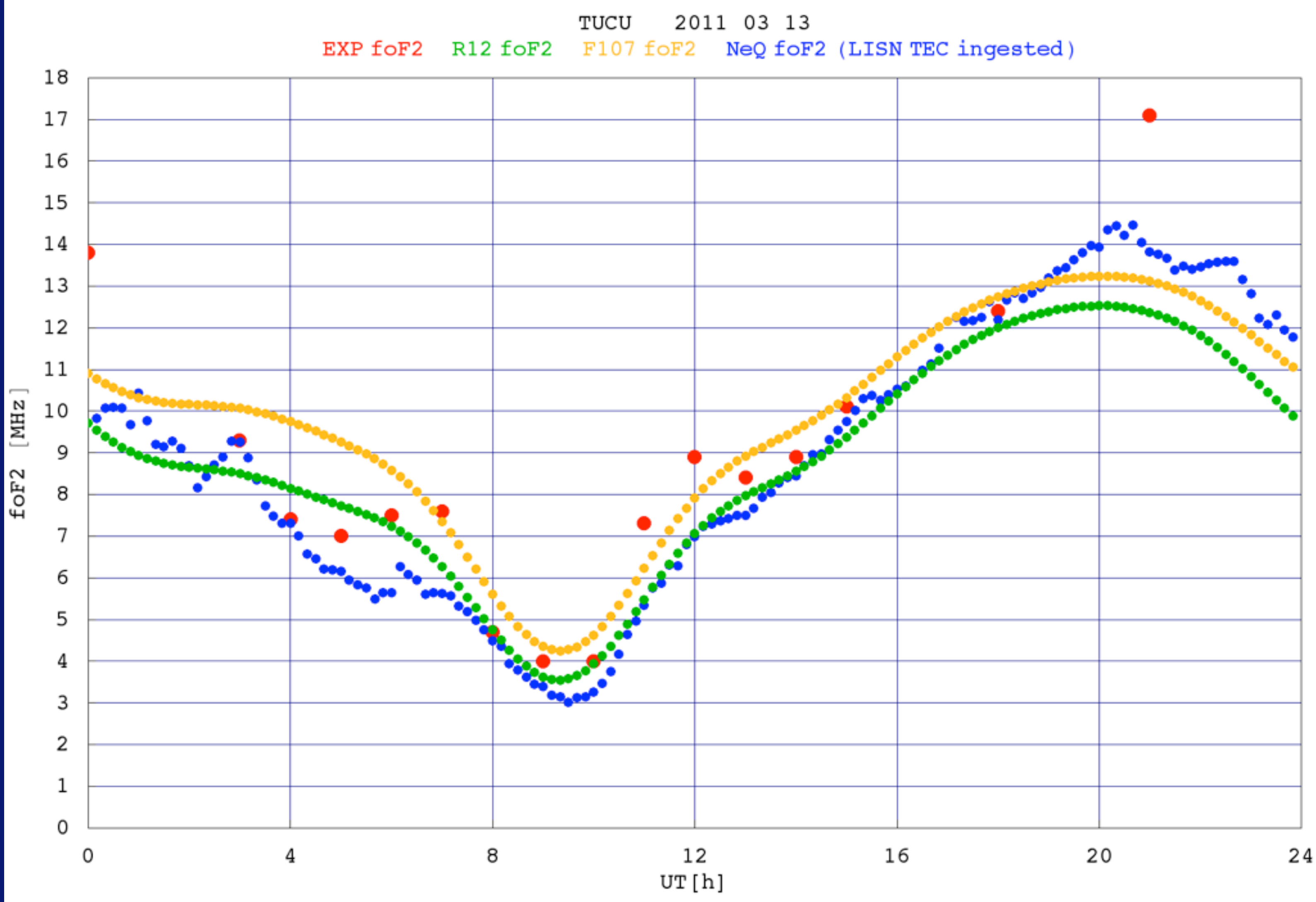
Validation example 3



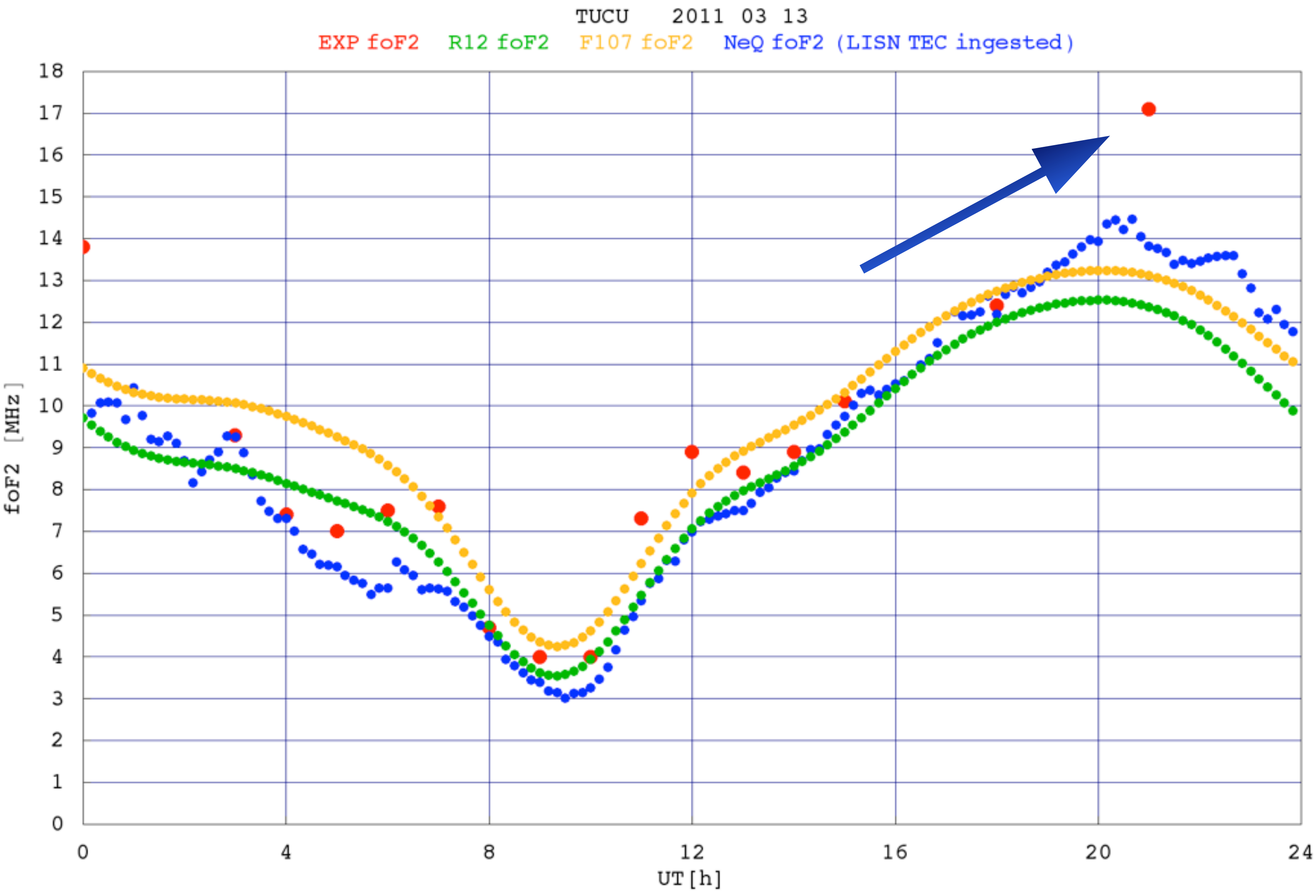
Validation example 4



Validation example 5



Validation example 5



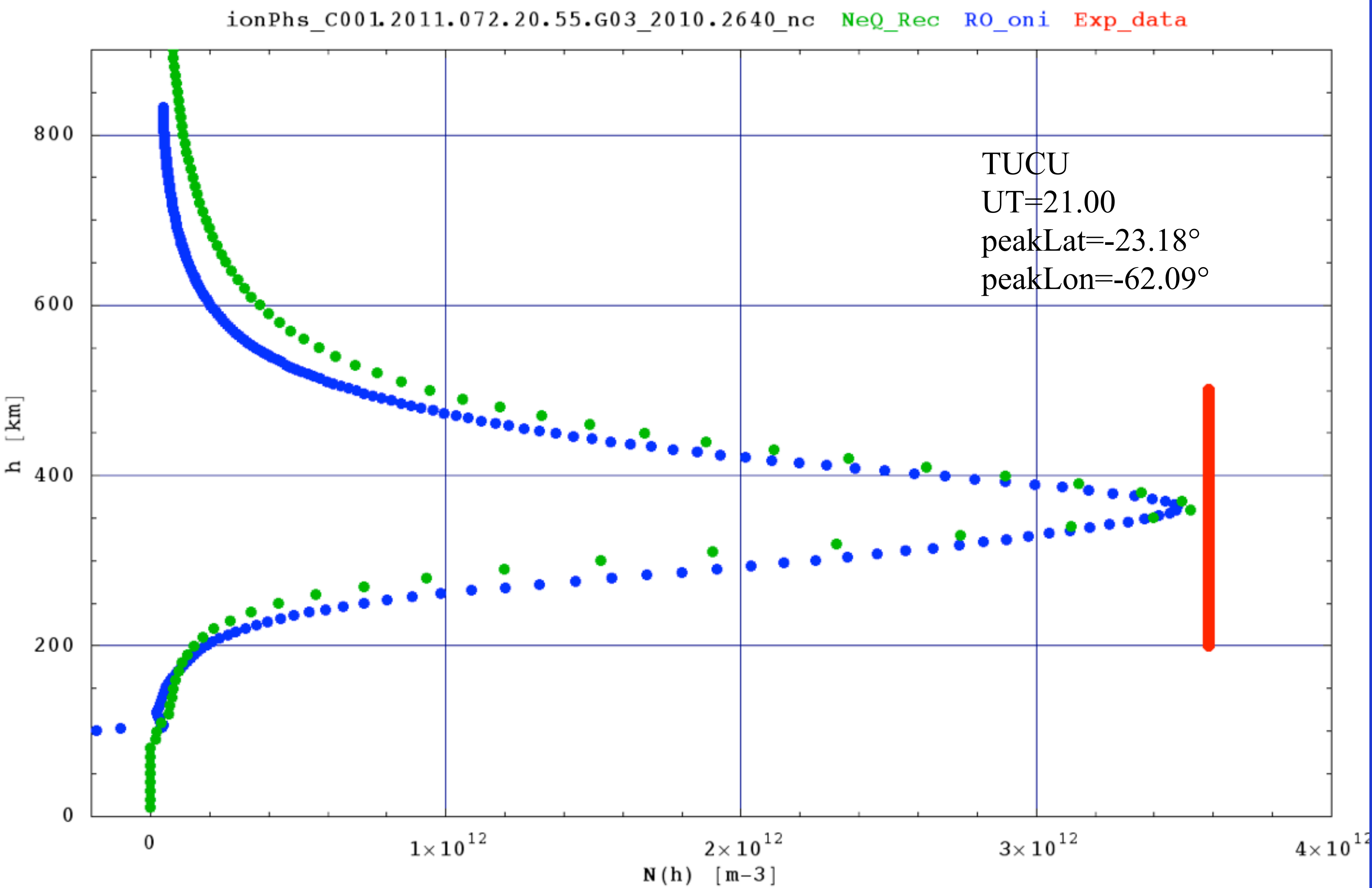
Use RO data

Adapting NeQuick model to RO-derived TEC

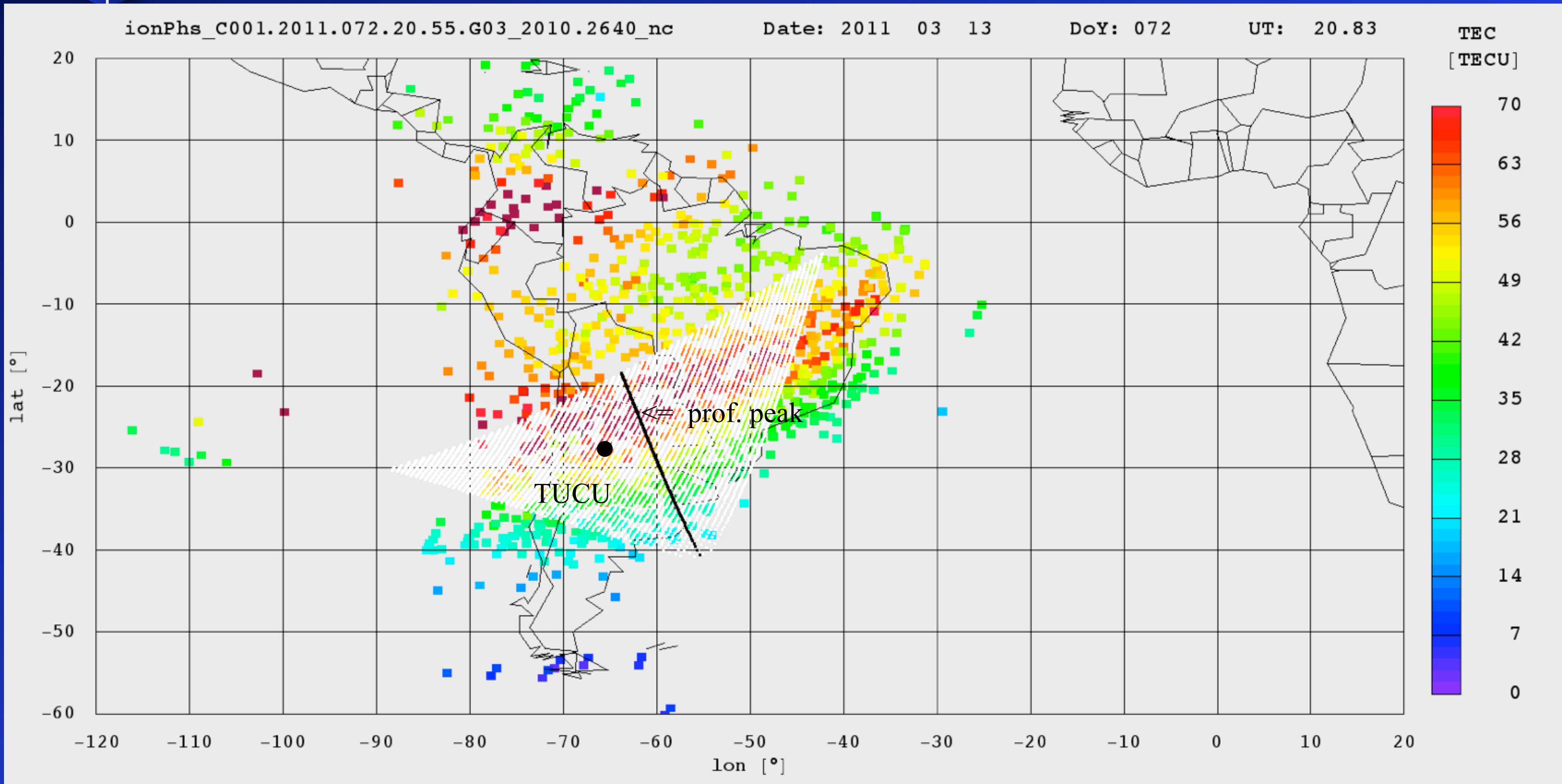
↓

Retrieve foF2

Validation example 5 (RO profile)



Validation example 5 (RO geom.)



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

Least Square Estimation

Best Linear Unbiased Estimator (BLUE)*

y vector of observations

x_b background model state

x_a analysis model state

H observation operator

R covariance matrix of observation errors

B covariance matrix of background 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

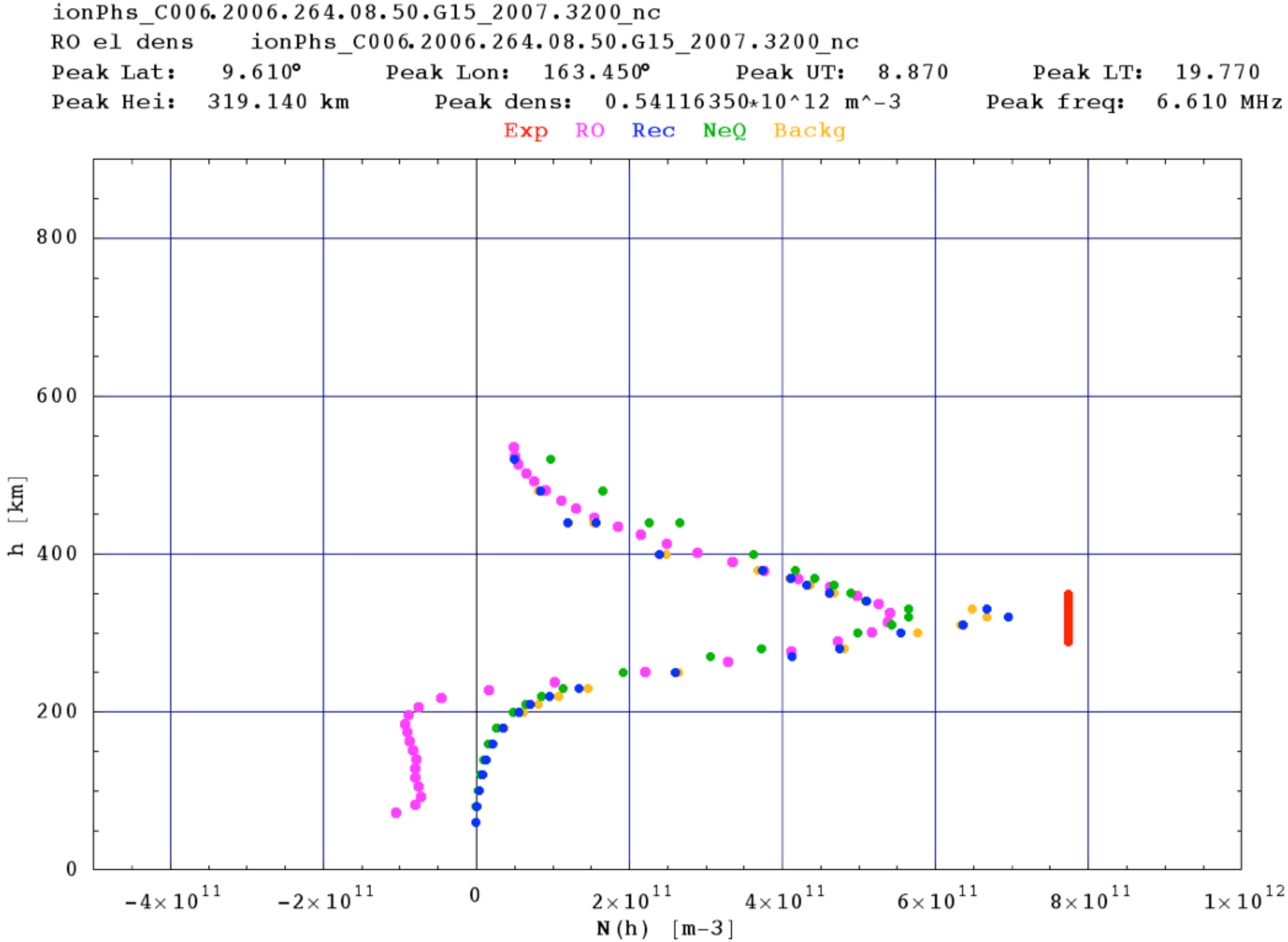
$$x_a = x_b + K\,(y - Hx_b)$$

$$K = BH_T(HBH^T + R)^{-1}$$

K is called *gain* of the analysis

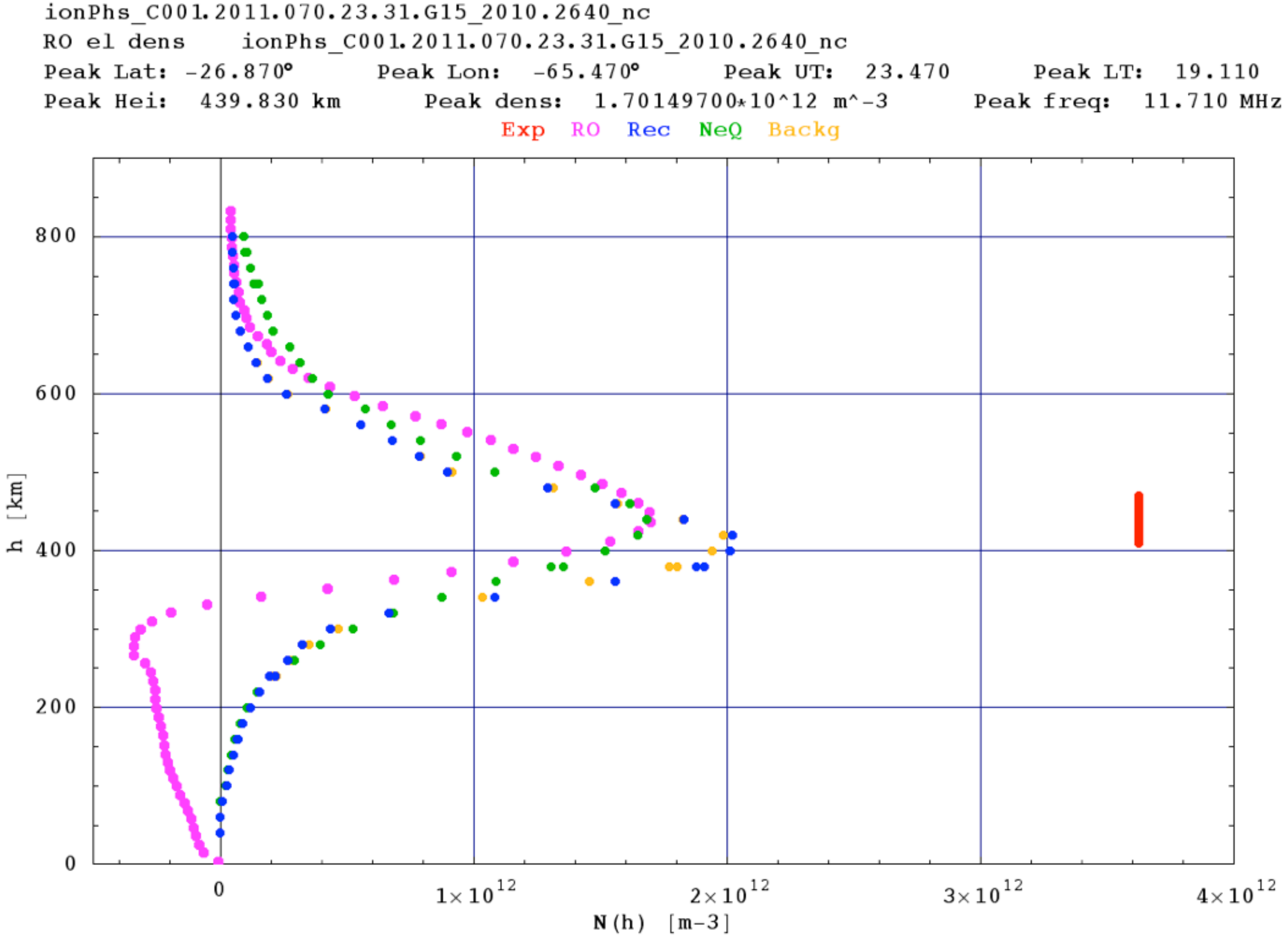
e.g. $bckg\_TEC = Hx_b$

LS solution



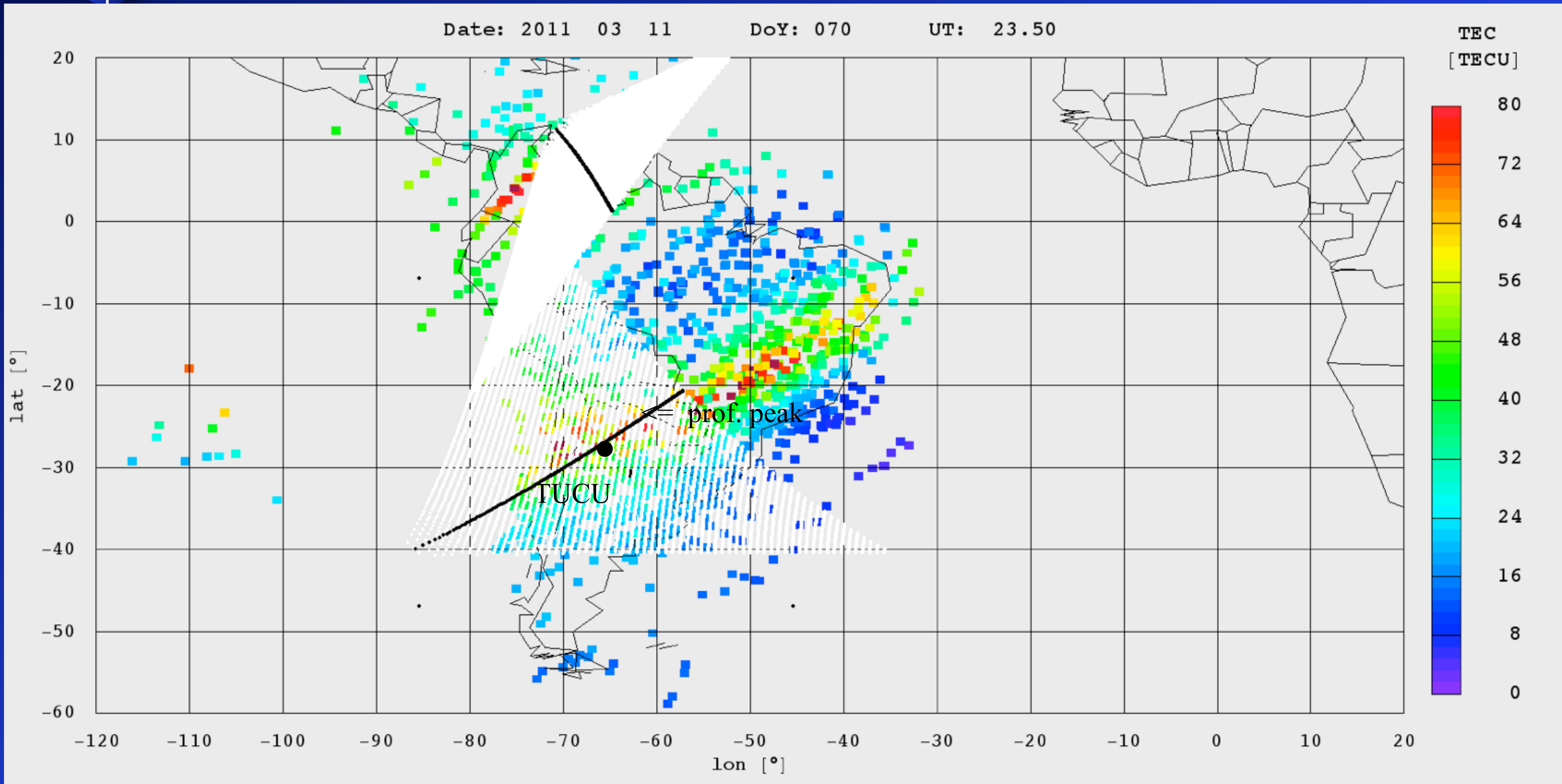
ionPhs_C006.2006.264.08.50.G15_2007.3200_nc
RO el dens ionPhs_C006.2006.264.08.50.G15_2007.3200_nc
Peak Lat: 9.610° Peak Lon: 163.450° Peak UT: 8.870 Peak LT: 19.770
Peak Hei: 319.140 km Peak dens: 0.54116350*10^12 m^-3 Peak freq: 6.610 MHz
Exp RO Rec NeQ Backg
800
600
400
200
0
h [km]
-4×10^11
-2×10^11
0
2×10^11
4×10^11
6×10^11
8×10^11
1×10^12
N(h) [m-3]

LS solution



ionPhs_C001.2011.070.23.31.G15_2010.2640_nc
RO el dens ionPhs_C001.2011.070.23.31.G15_2010.2640_nc
Peak Lat: -26.870° Peak Lon: -65.470° Peak UT: 23.470 Peak LT: 19.110
Peak Hei: 439.830 km Peak dens: 1.70149700*10^12 m^-3 Peak freq: 11.710 MHz
Exp RO Rec NeQ Backg
800
600
400
200
0
h [km]
0
1×10^12
2×10^12
3×10^12
4×10^12
N(h) [m-3]

RO geometry



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

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 of the ionosphere.

- 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 approach based on multiple parameters also allows to use RO-derived TEC data to obtain realistic electron density values for the area of interest.

Acknowledgments

The authors are grateful to FAA's WAAS Community; Cesar Valladares, Boston College; Leo McNamara of the AFRL; Francisco Azpilicueta Facultad de Ciencias Astronómicas y Geofísicas, Universidad Nacional de La Plata; K. Alazo of the Institute of Geophysics and Astronomy (IGA), Cuba; Marta Mosert, ICATE - CONICET; Rodolfo G. Ezquer, Universidad Tecnológica Nacional de Tucumán; the Center for Atmospheric Research of University of Massachusetts at Lowell for providing access to the digital ionogram database (DIDBase), and the Jicamarca Radio Observatory (JRO) group for providing the data used for the present work.

Thank you for your attention