NeQuick model: features and applications

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United Nations/ICTP Workshop on Global Navigation Satellite Systems for Scientific Applications
Trieste, 2 December 2014

Outline

- NeQuick model overview
- NeQuick for assessment studies
- Data assimilation into NeQuick
  - Use of effective parameters
    - Some applications
  - Least Square Estimation

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

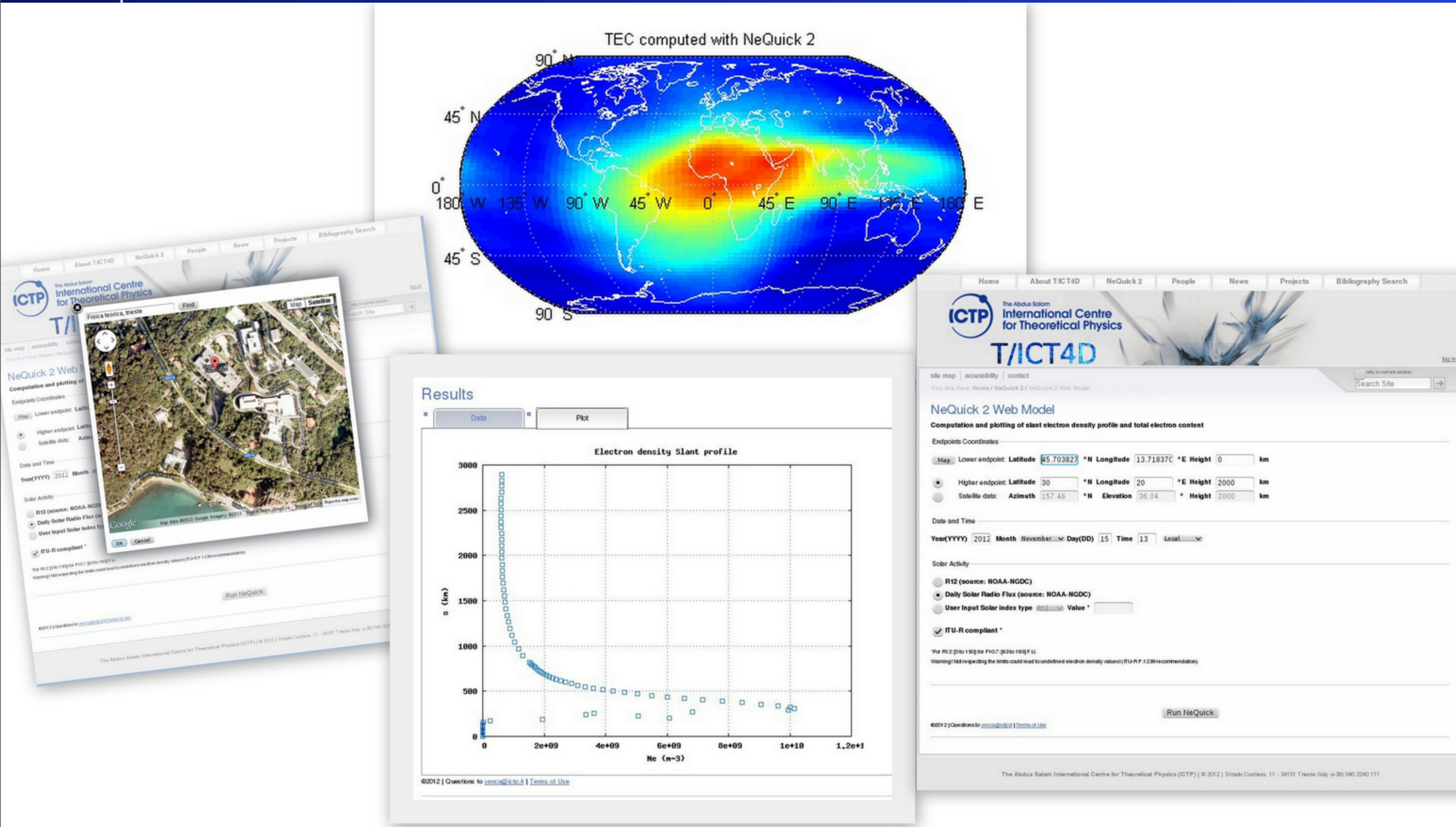
- Further improvements have been implemented by Radicella and Leitinger [2001].
- A modified bottomside has been introduced by Leitinger, Zhang, and Radicella [2005].
- A modified topside has been proposed by Coïsson, Radicella, Leitinger and Nava [2006].
- All these efforts, directed toward the developments of a new version of the model, have led to the implementation of the NeQuick 2.

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 “ground-to-satellite” ray-path and the corresponding Total Electron Content (TEC) by numerical integration.

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



NeQuick developments

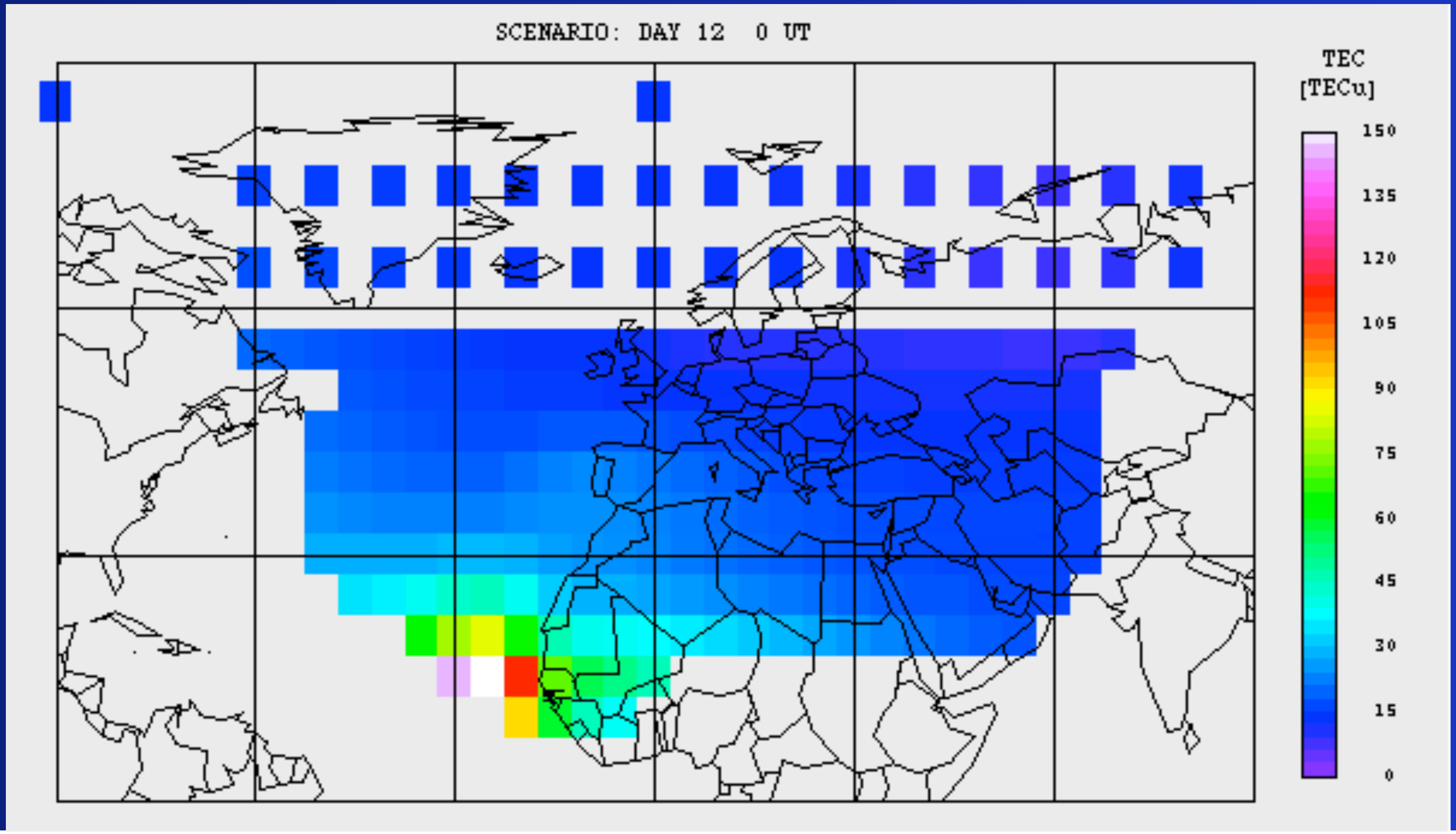
- The NeQuick (v1) has been adopted by Recommendation ITU-R P. 531 as a procedure for estimating TEC.
- Recently, the NeQuick 2 has substituted the NeQuick (v1) and it is the one currently recommended by ITU (ITU-R Recommendation P.531-12).
- IRI model has adopted, as default option, NeQuick 2 model topside considered as: “the most mature of the different proposals for the IRI topside” (Bilitza and Reinisch (2008)).
- A specific version of NeQuick has been adopted as Galileo Single-Frequency Ionospheric Correction algorithm and its performance has been recently confirmed during In-Orbit Validation (Roberto Prieto-Cerdeira et al.; GPS World, June 2014).

NeQuick 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).

In particular NeQuick was (and will be) used to:

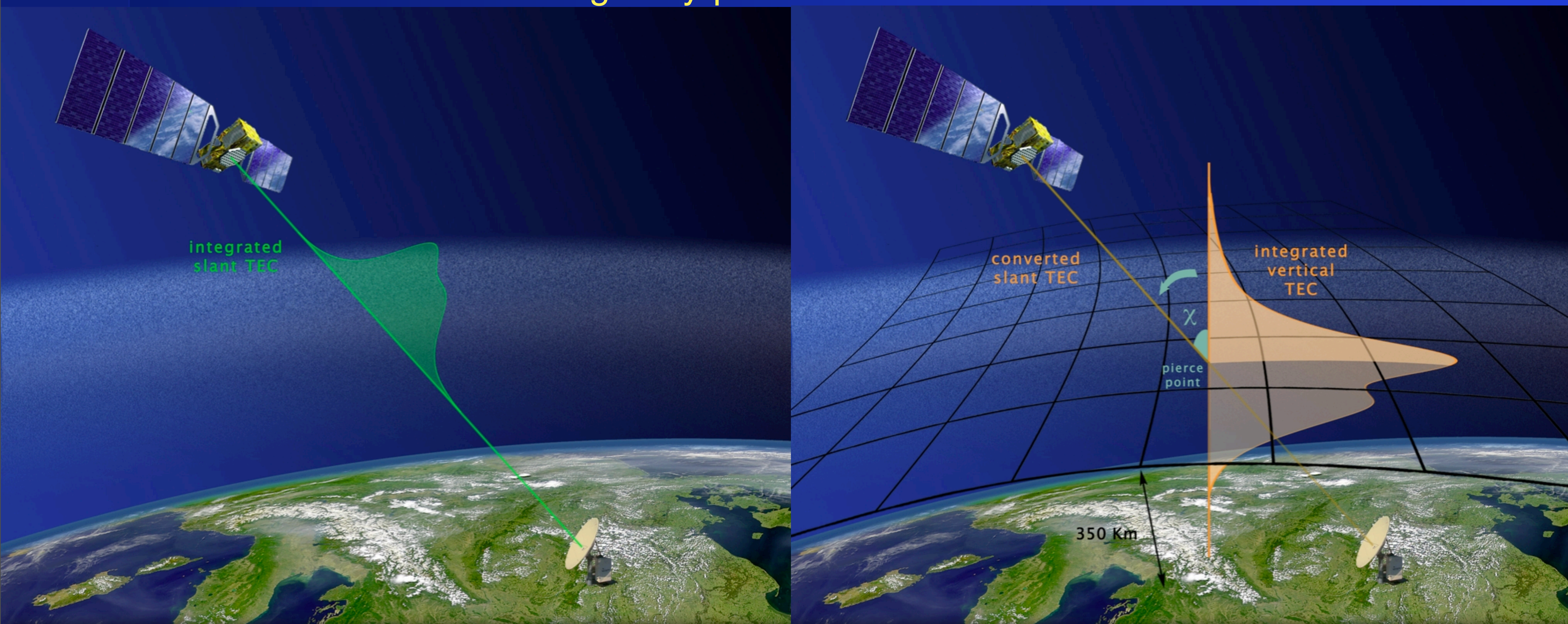
- generate “worst case” ionospheric scenarios for assessment and tuning of the operational ionospheric algorithms of EGNOS.



NeQuick for assessment studies

- investigate and characterize the "mapping function errors" in slant-to-vertical TEC conversion and vice-versa:
  - at range delay domain & at position domain

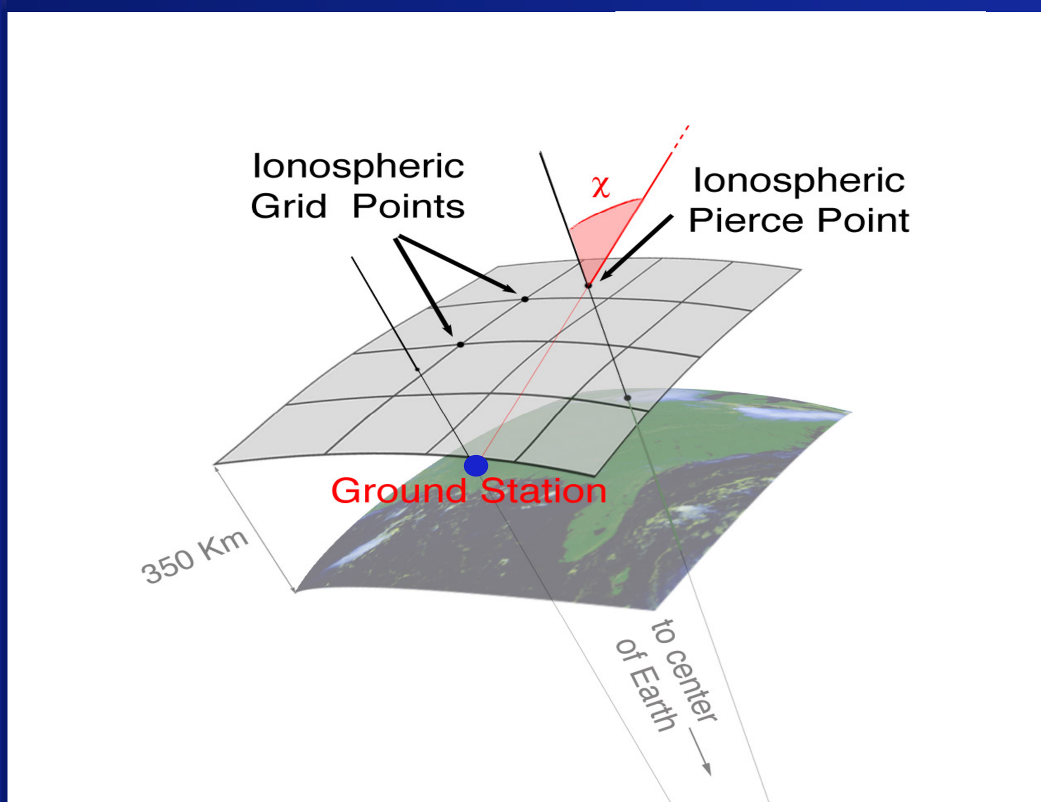
Single ray-path error definition

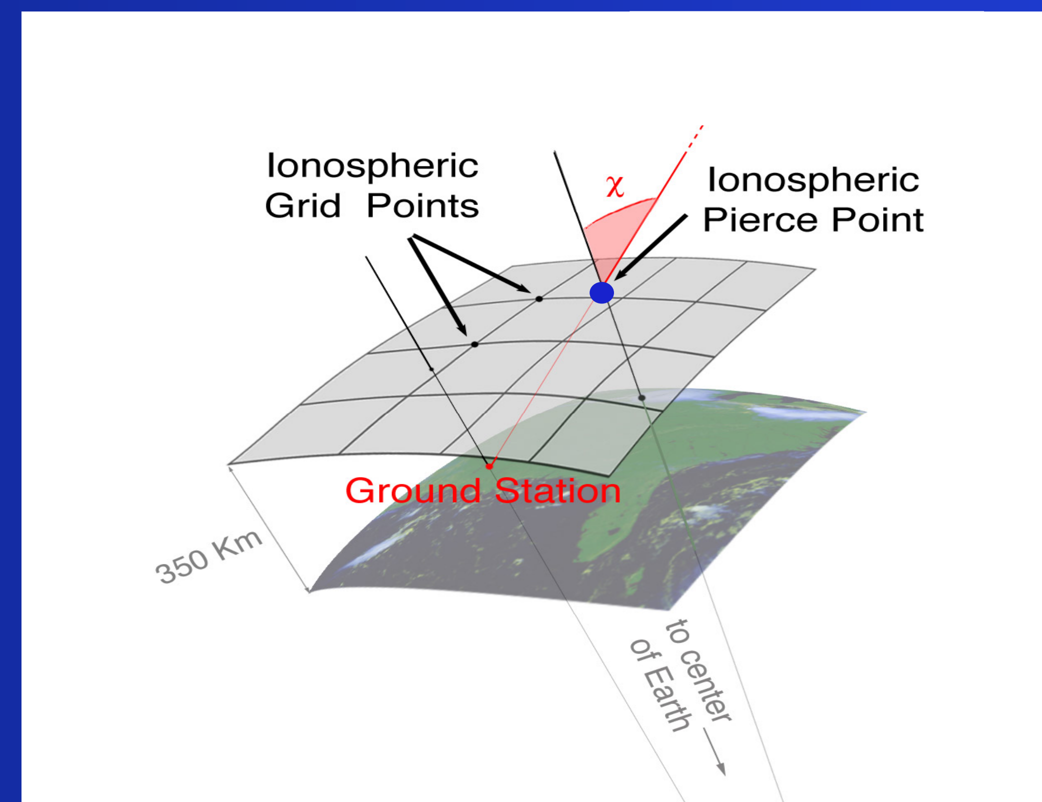


$$sTEC = \int_{ground}^{satellite} N_e(s)\,ds \qquad vTEC_{pp} = \int_0^{20000} N_e(h)\,dh \qquad err = sTEC - vTEC_{pp}/\cos\chi$$

Mapping function error

Single ray-path error evaluation





Ground Station point of view

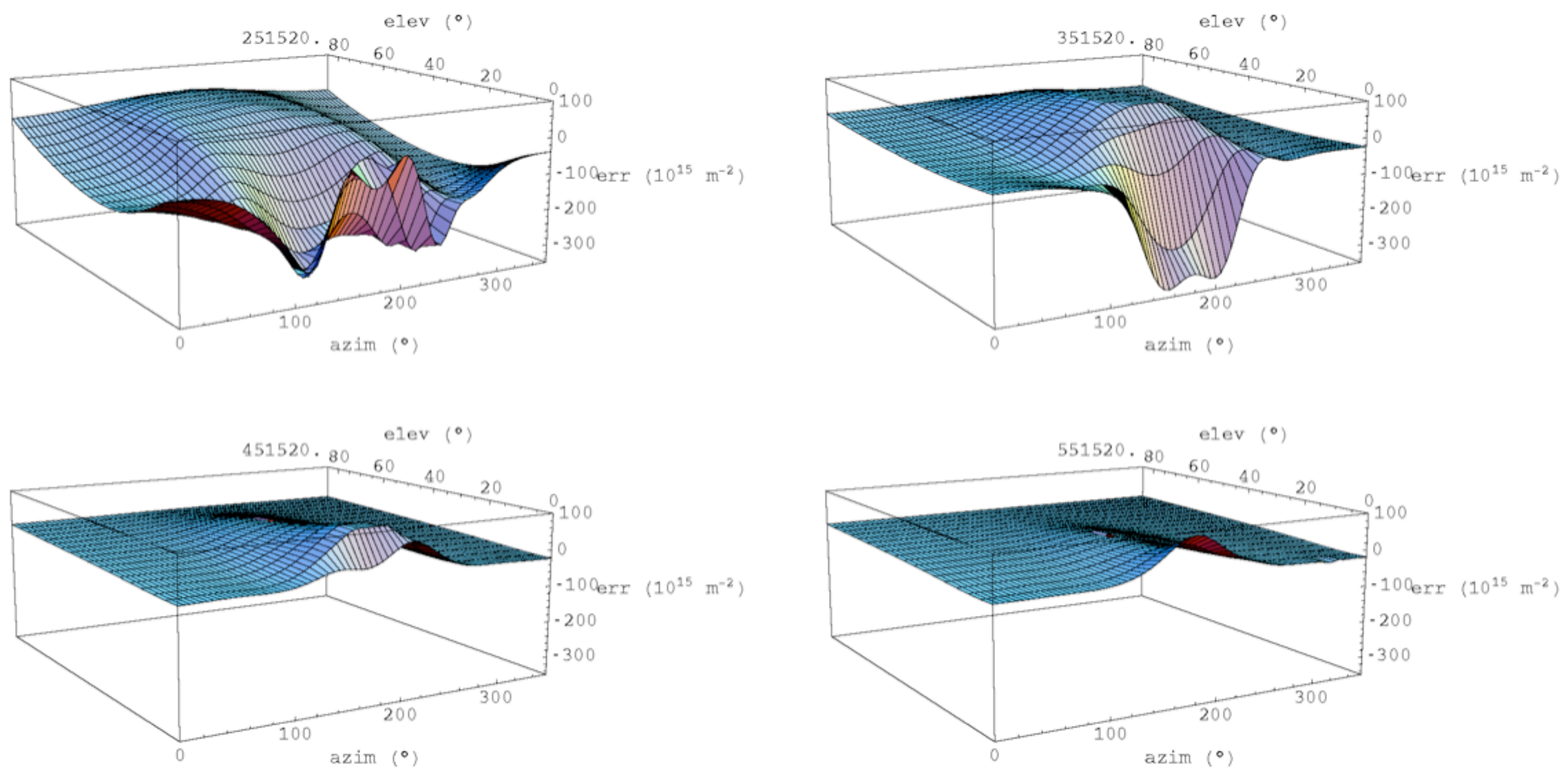
el $\in$ [0˚, 85˚] step 5˚
az $\in$ [0˚,355˚] step 5˚
measured with respect to Ground Station

Pierce Point point of view

el $\in$ [20˚, 85˚] step 5˚
az $\in$ [0˚,355˚] step 5˚
measured with respect to Pierce Point

Mapping function error analysis

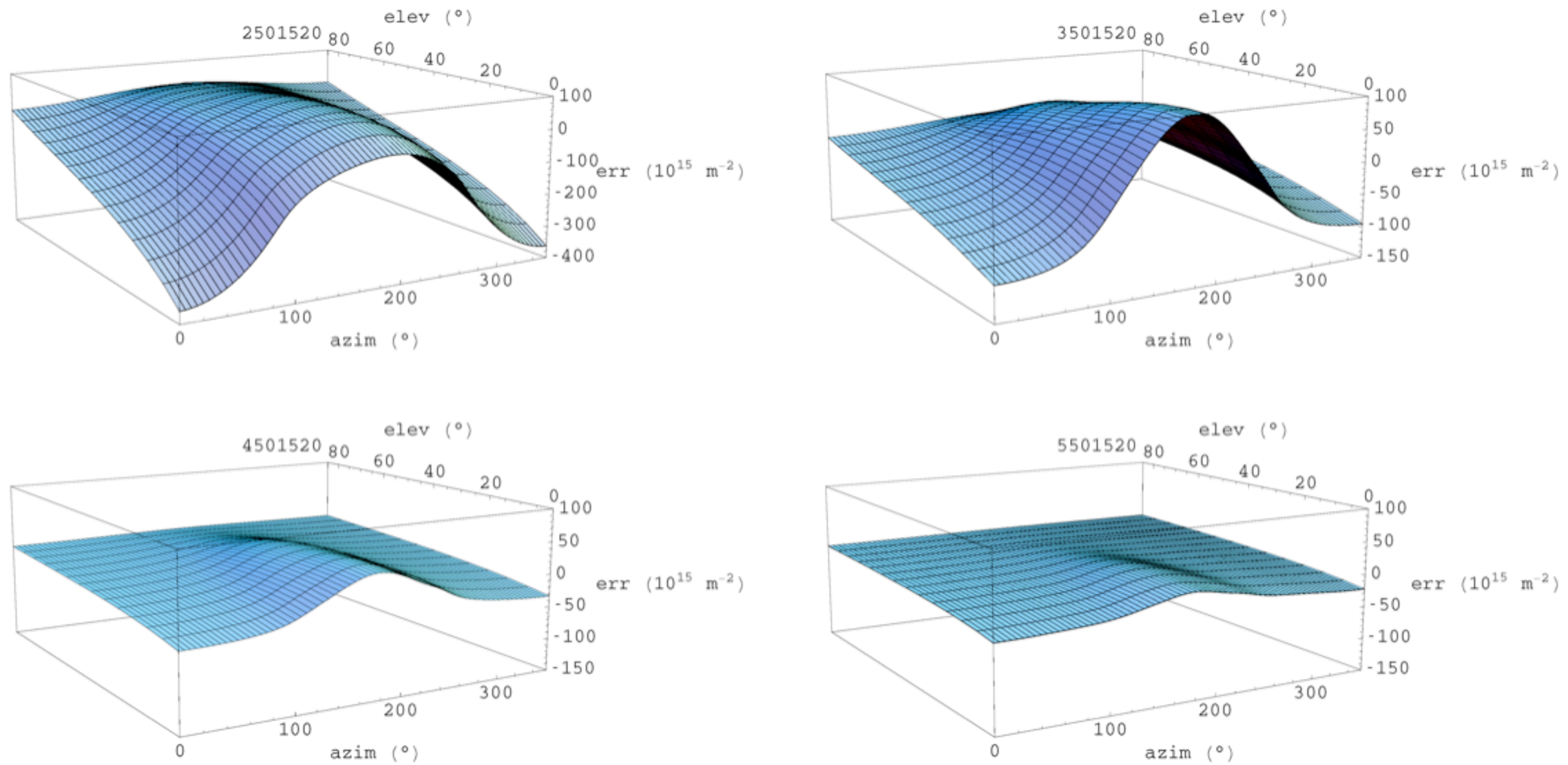
Ground Station point of view



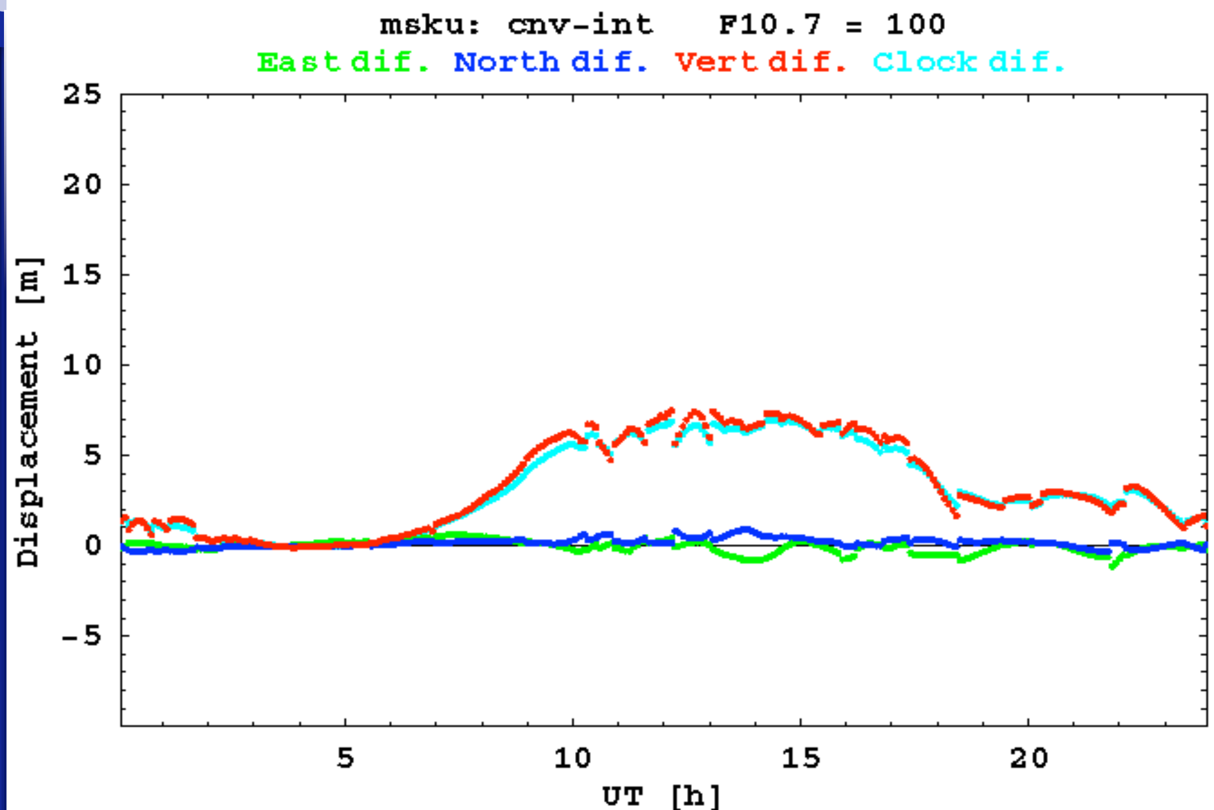
Mapping function error analysis

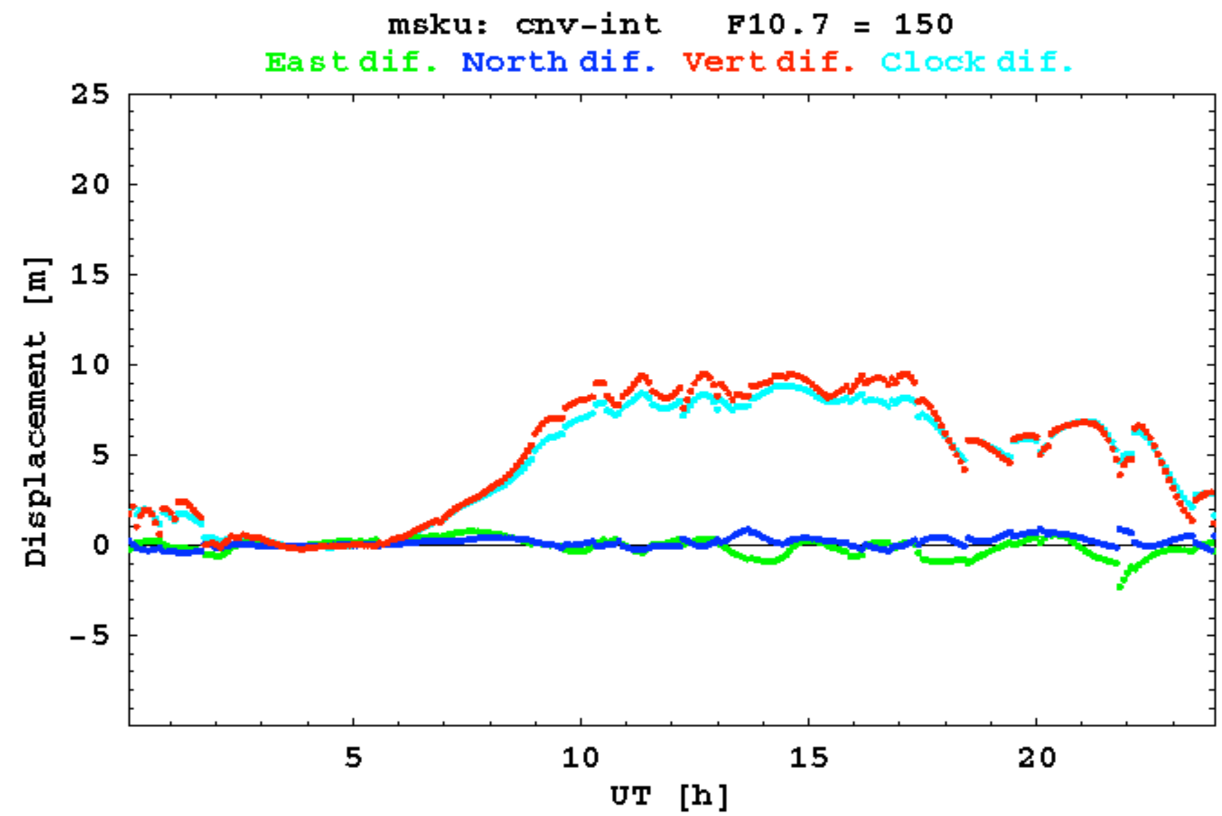
Pierce Point point of view

Different scale!

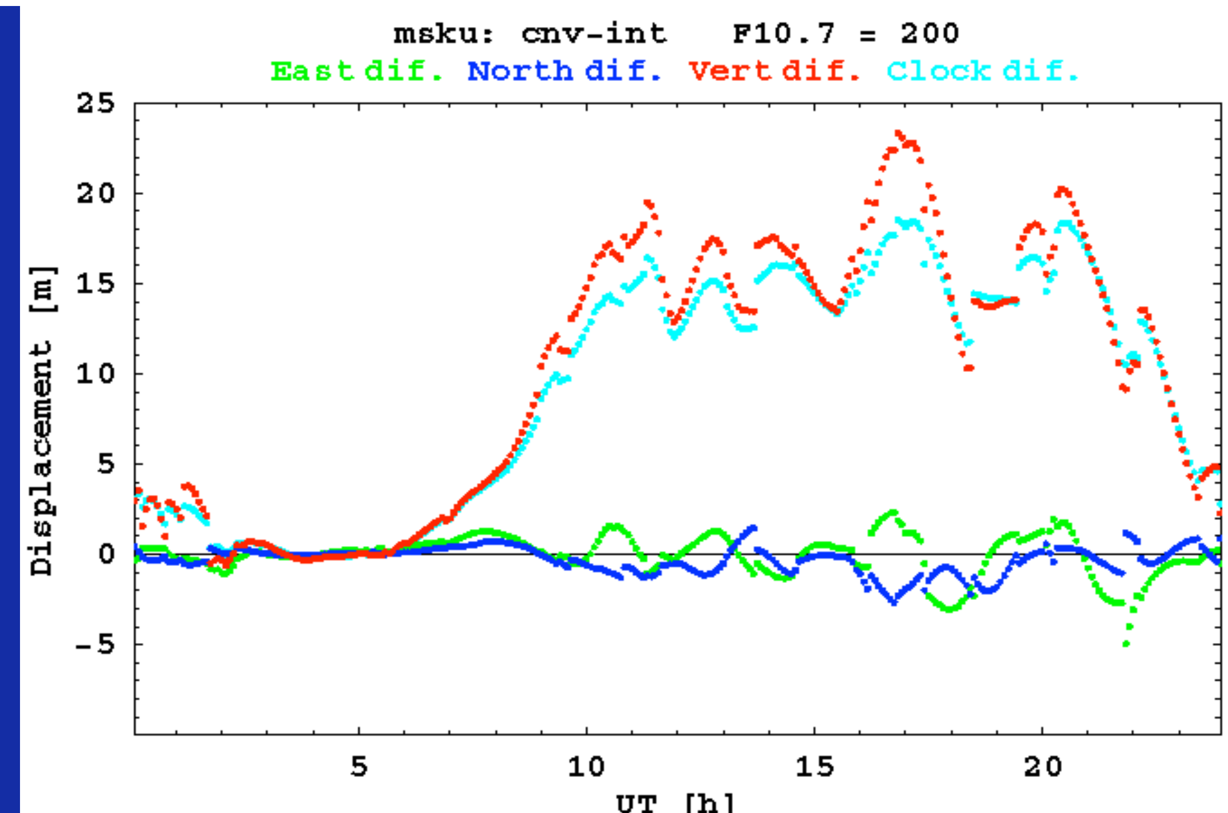


NeQuick for assessment studies



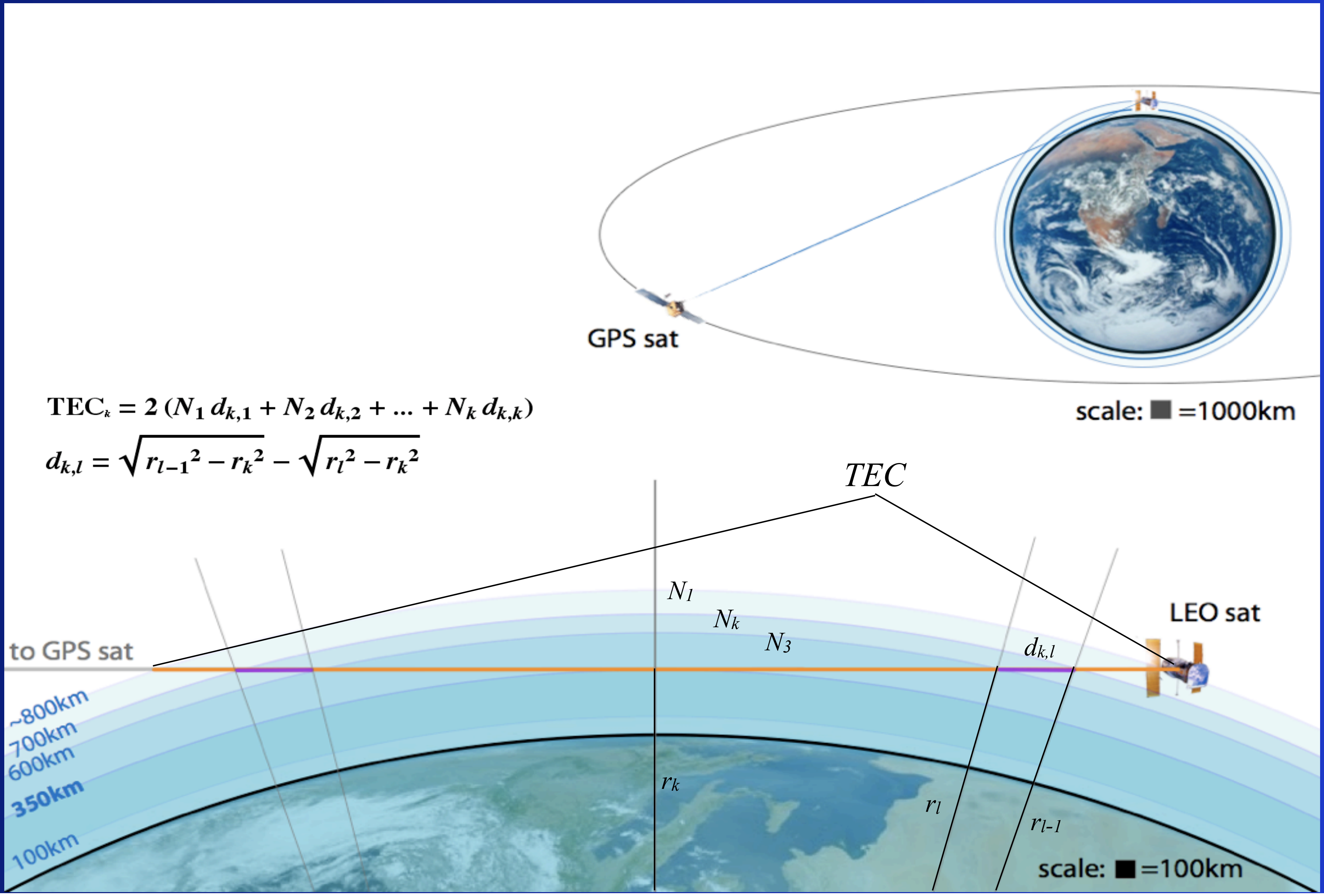


Mapping function errors effects at position domain for different levels of solar activity in a low latitude station: Franceville (-2° N, 14° E).

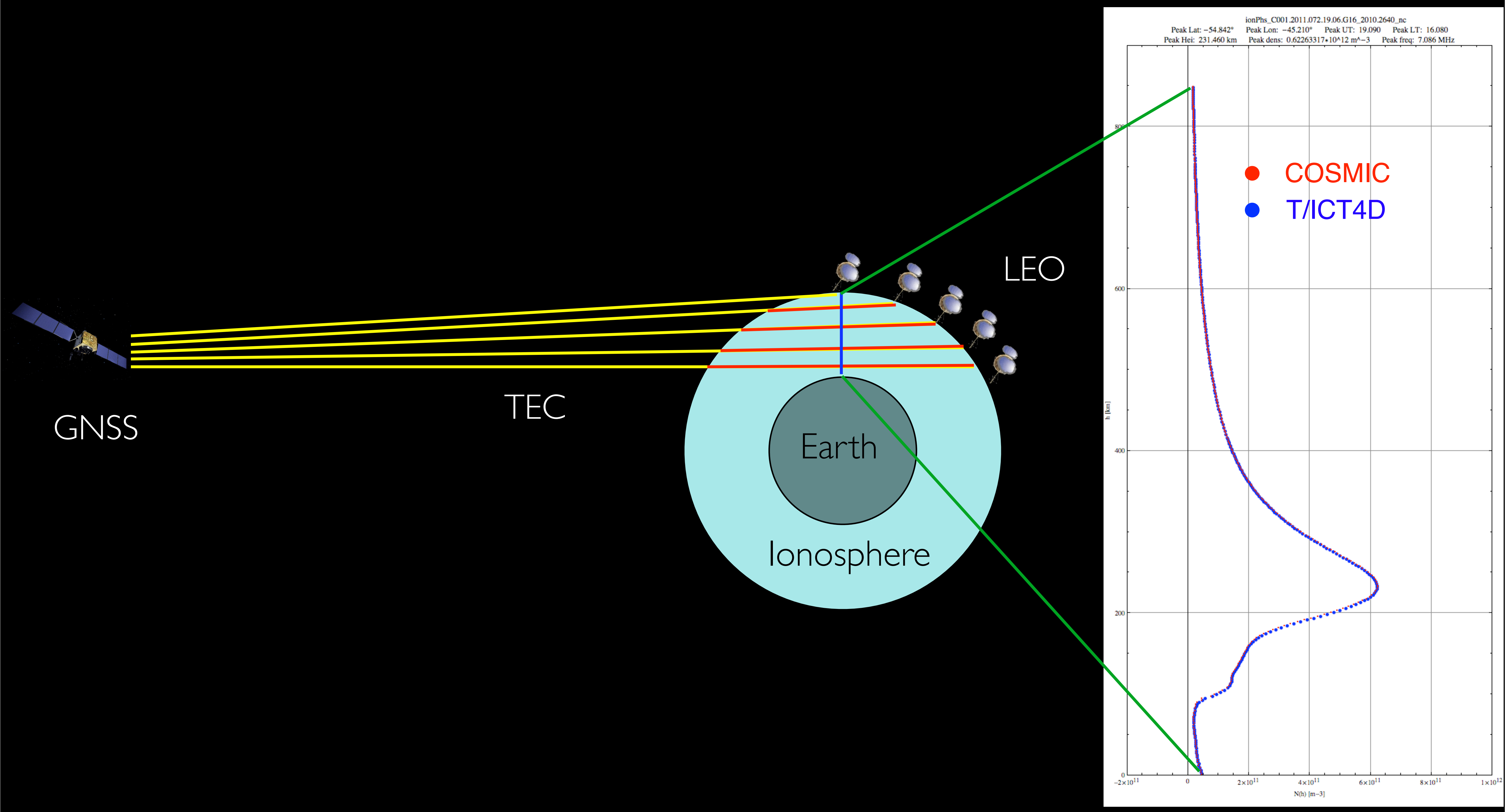


NeQuick for assessment studies

- to investigate the effects of spherical symmetry assumption for the ionosphere electron density in Radio Occultation data inversion (e.g. using the "Onion Peeling" algorithm);

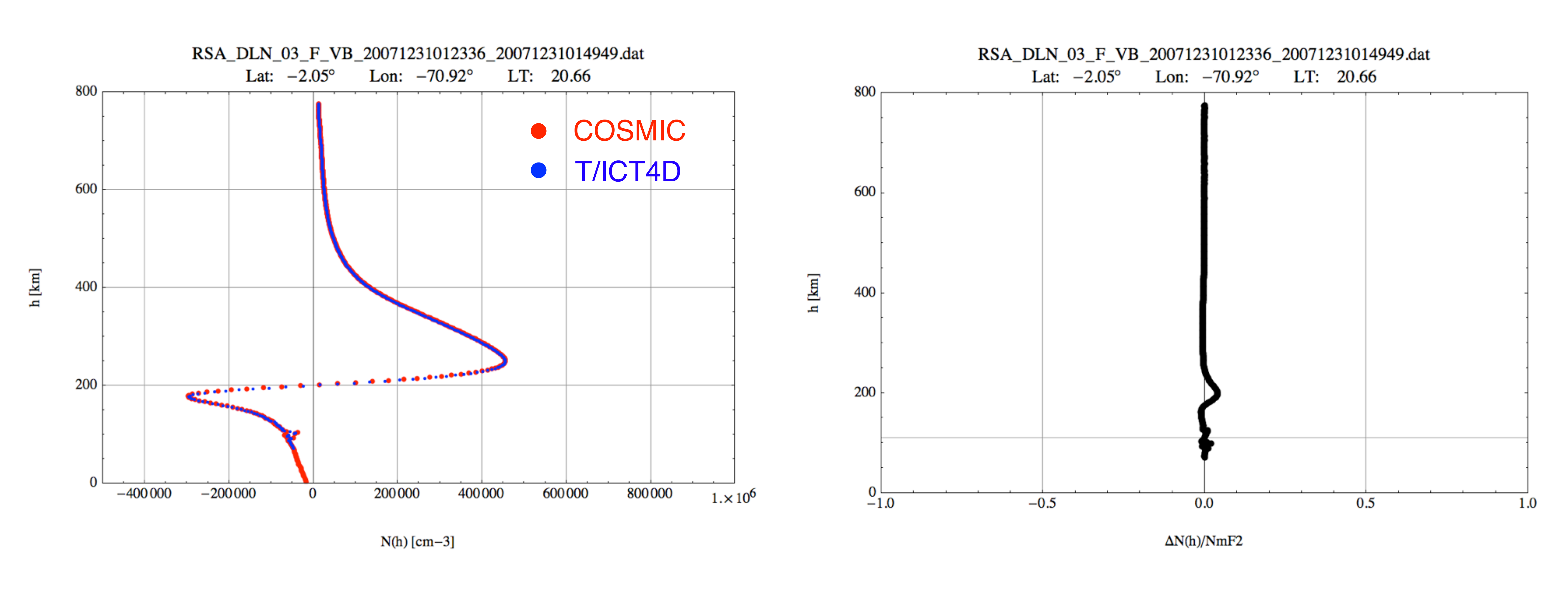


RO data inversion

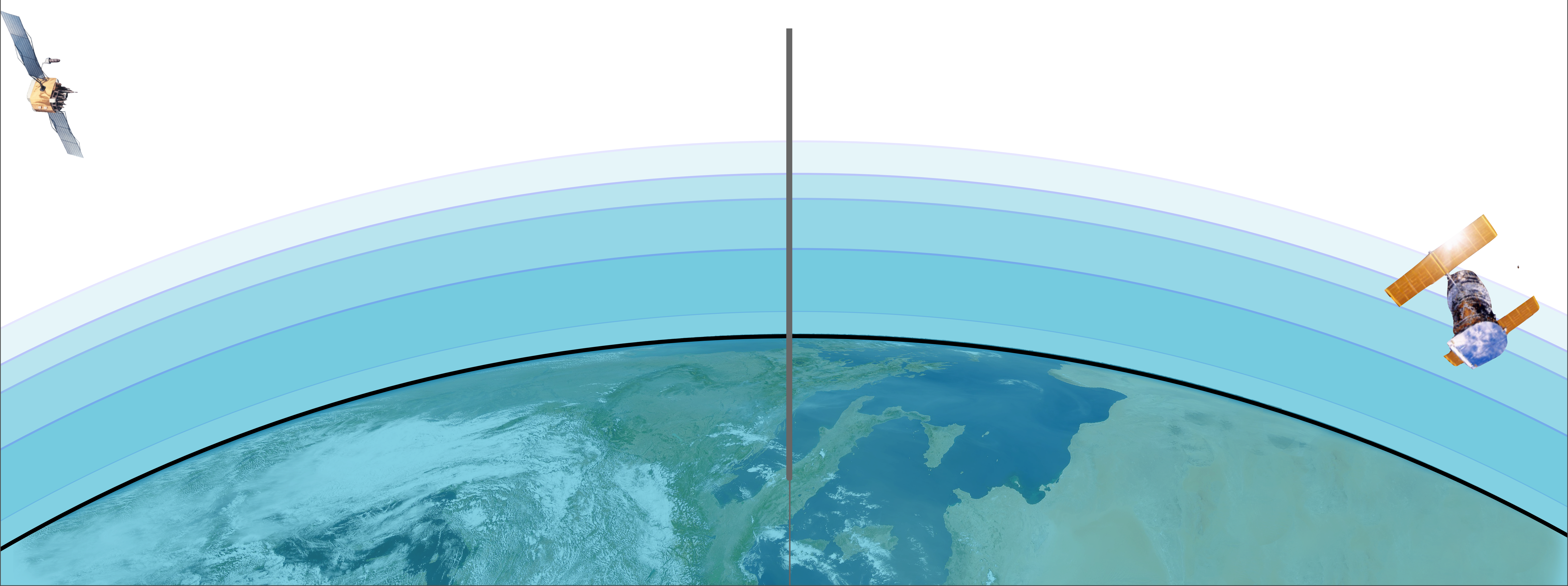


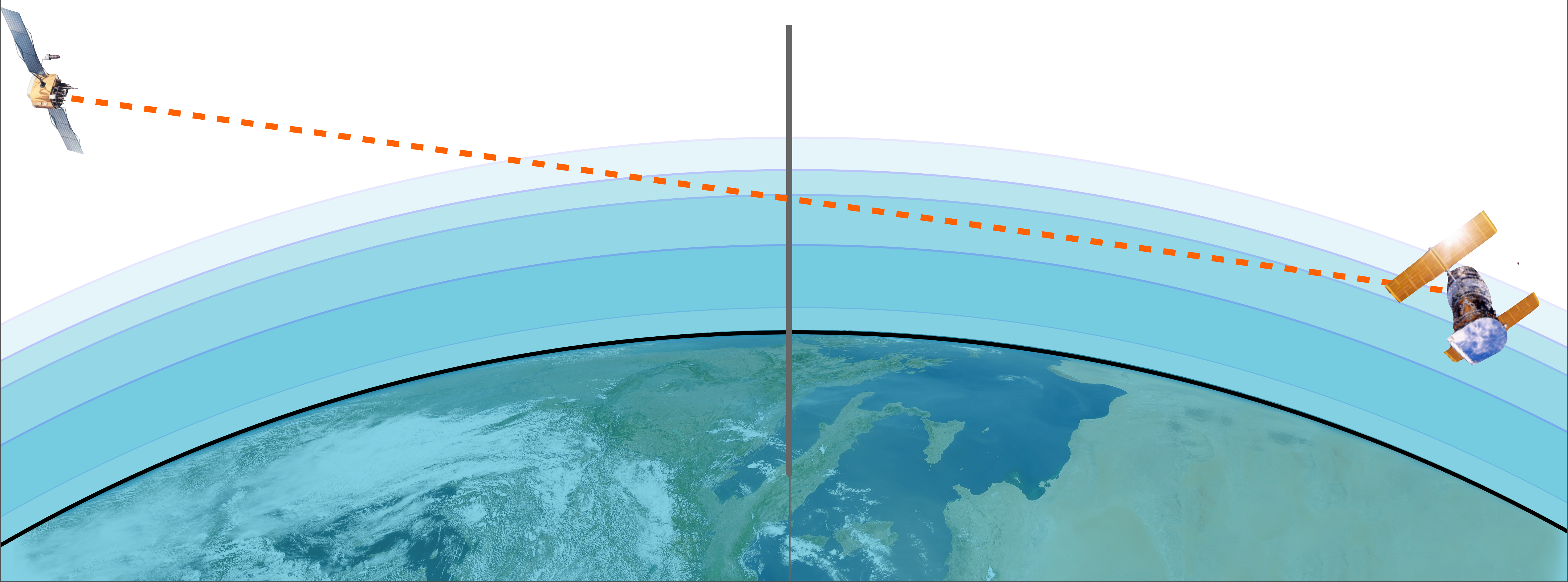
Profile example

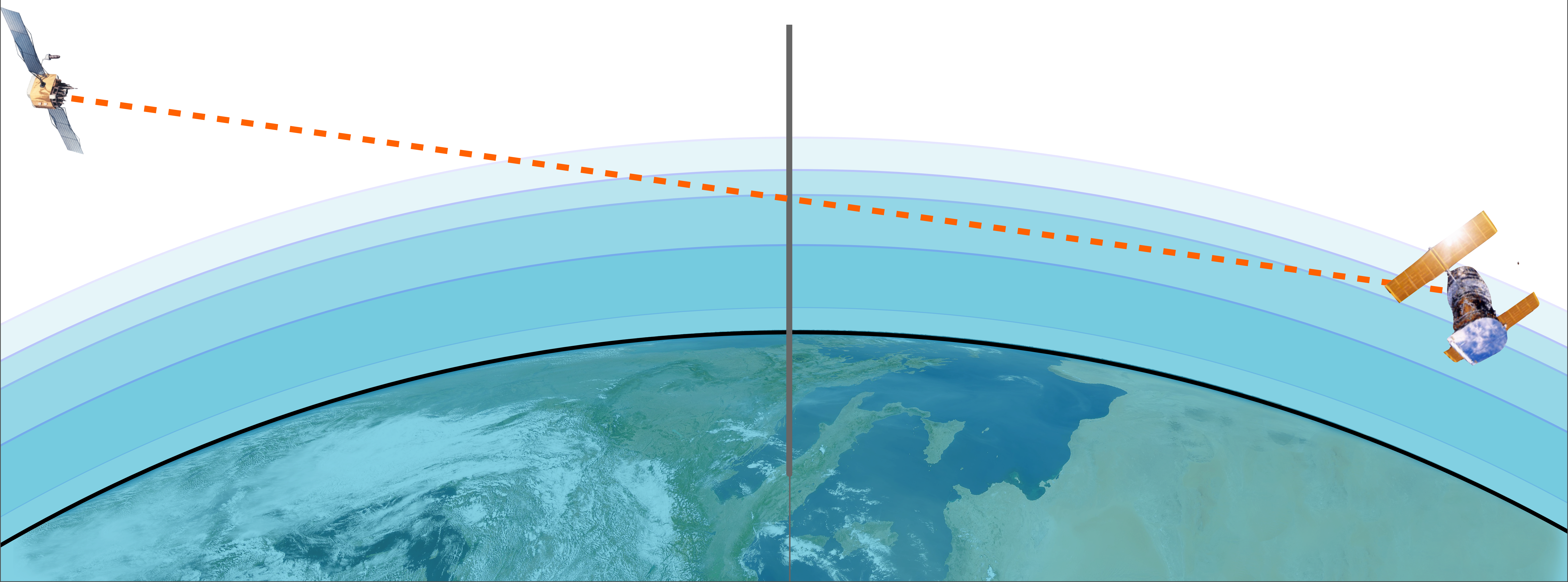
COSMIC data are used



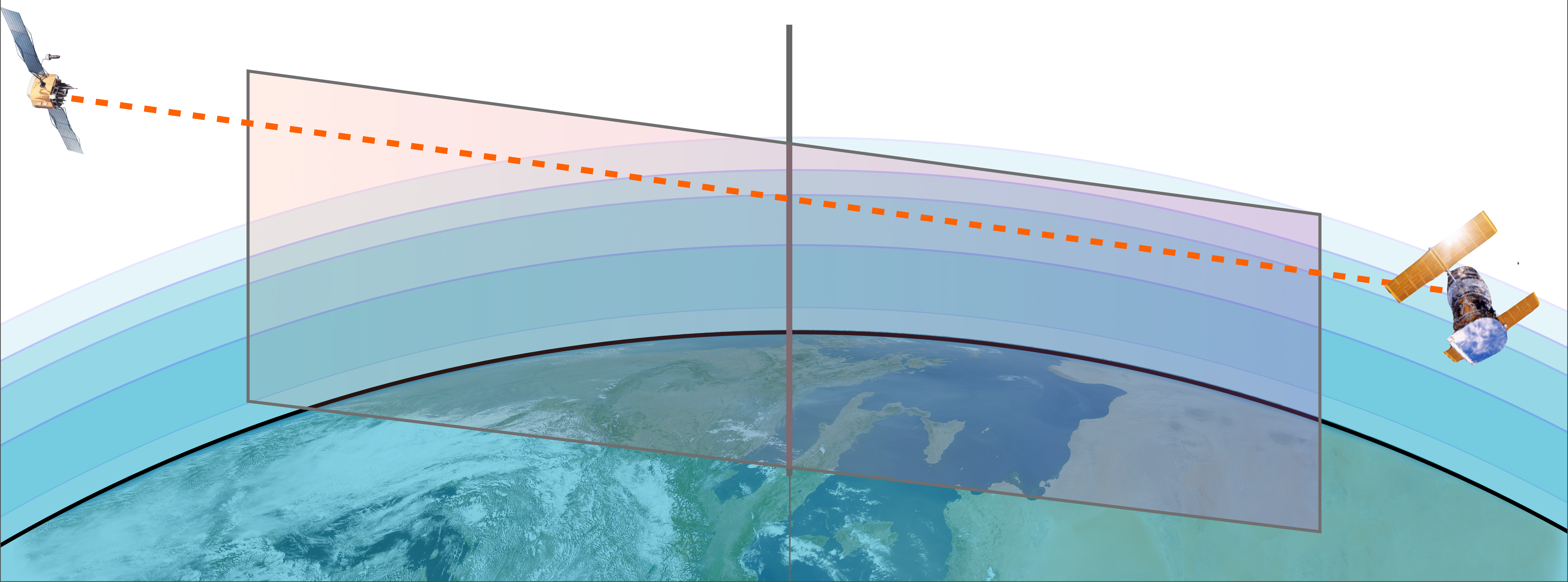
In some cases, negative electron densities can be retrieved

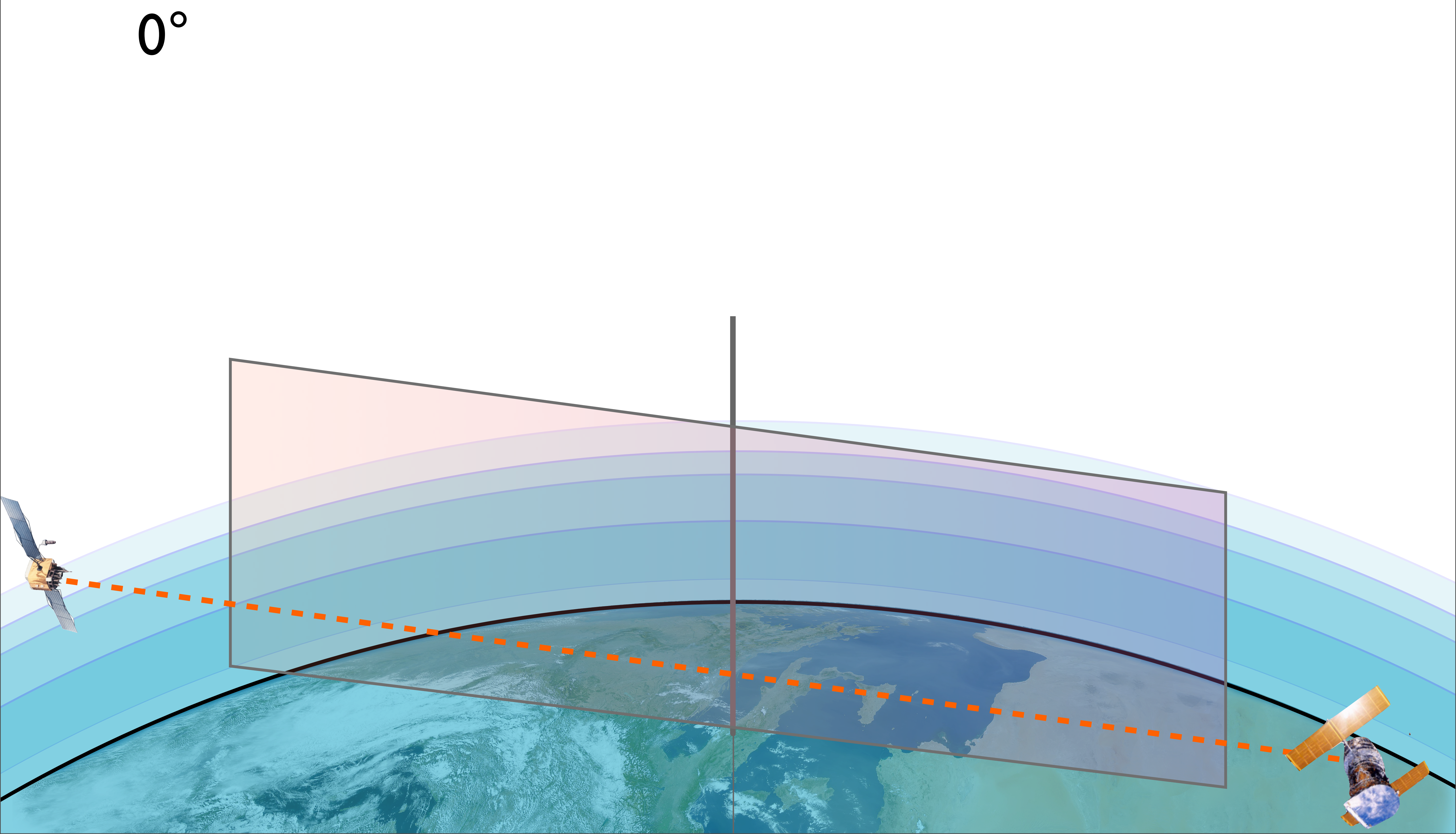






0°

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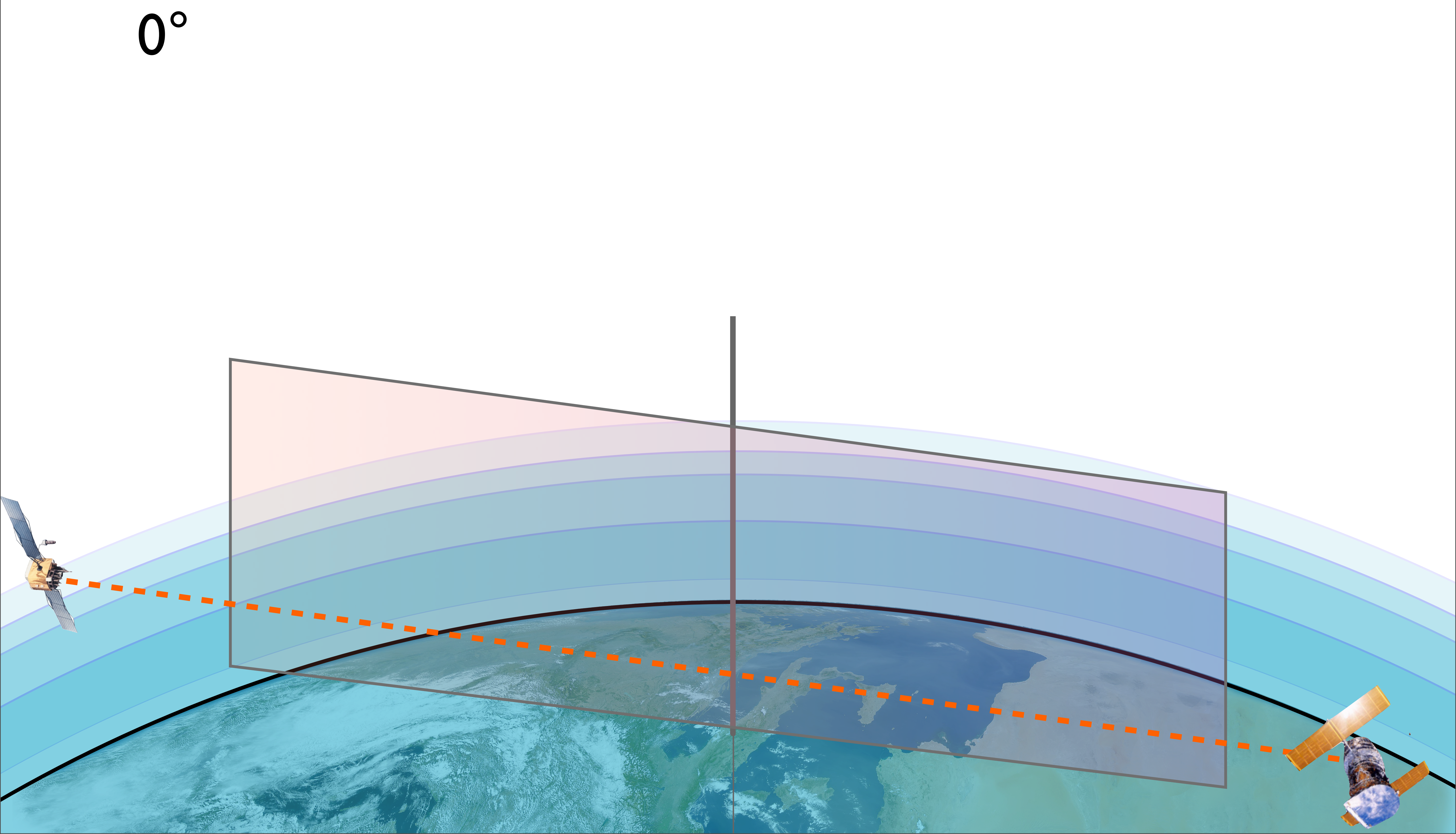

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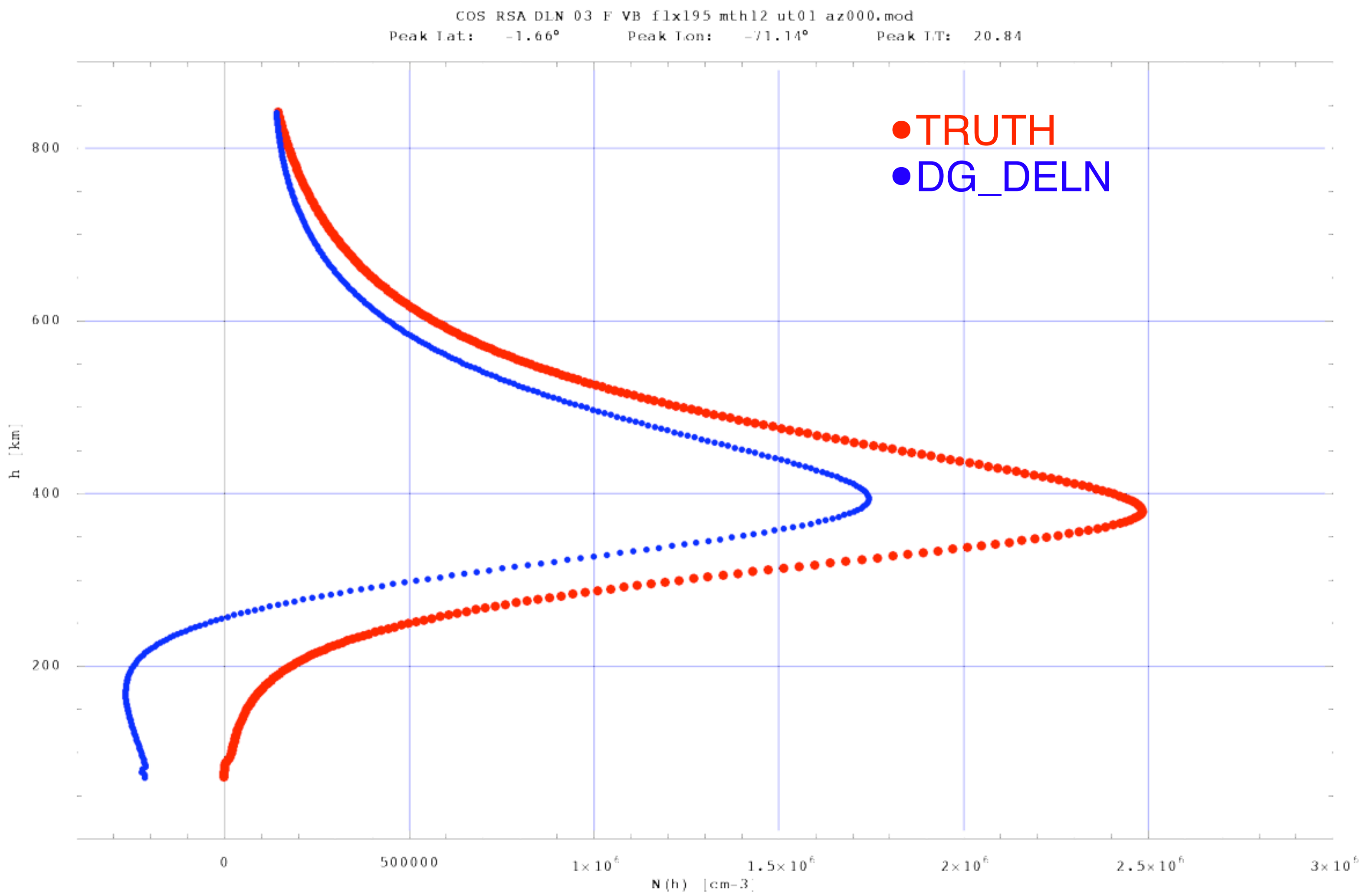

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Peak Lat: -1.66° Peak Lon: -71.14° Peak LT: 20.84
●TRUTH
●DG_DELN
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h [km]
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500000
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1.5×10^6
2×10^6
2.5×10^6
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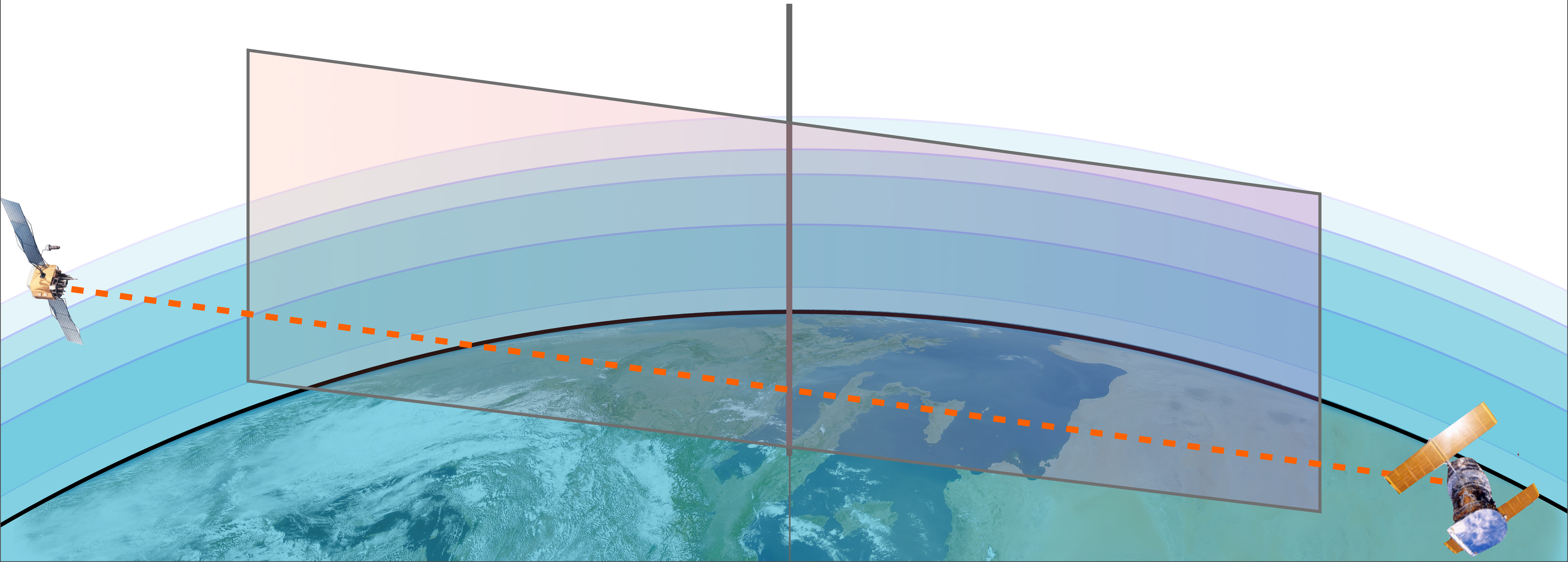
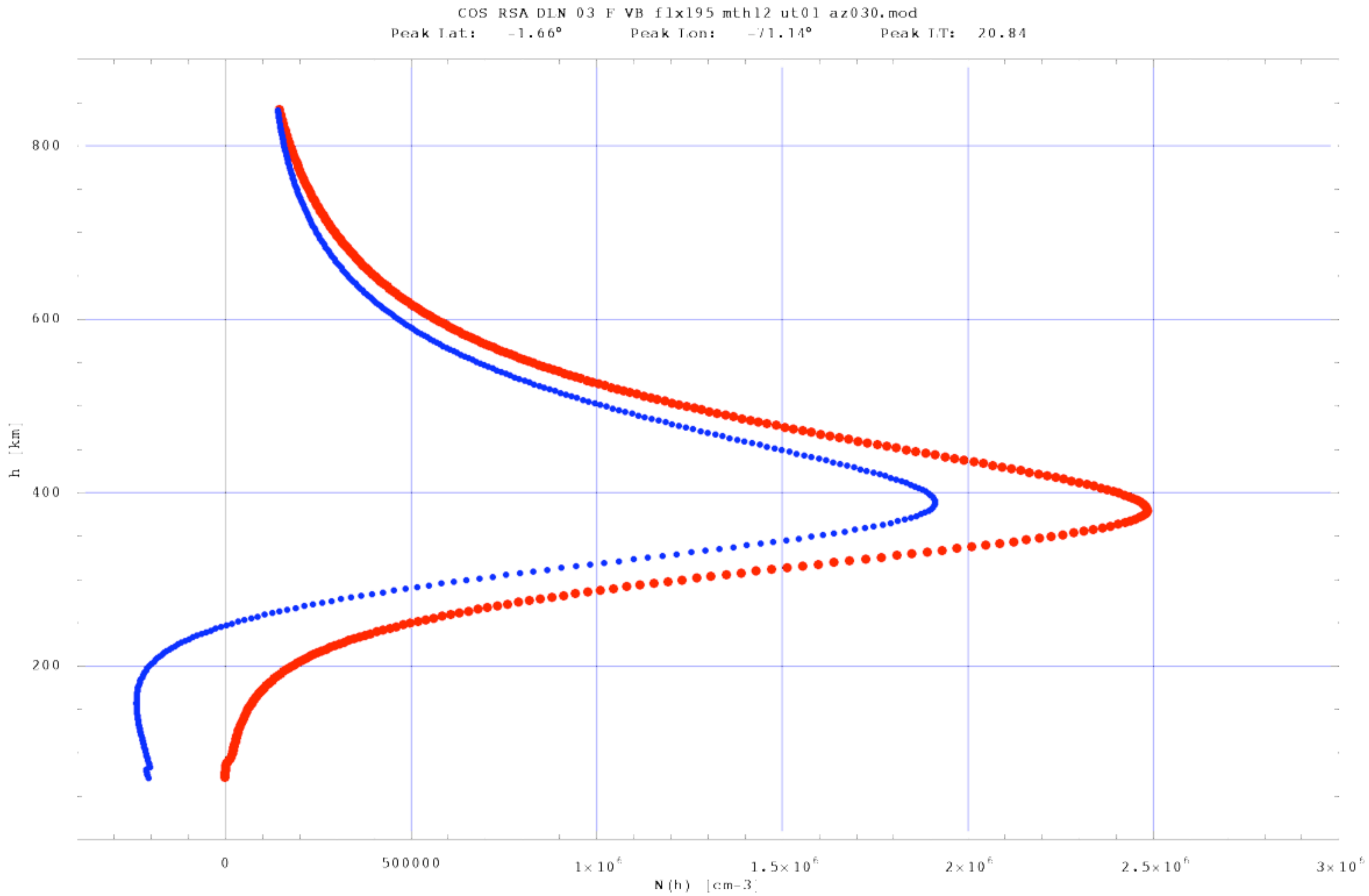
N(h) [cm-3]



30°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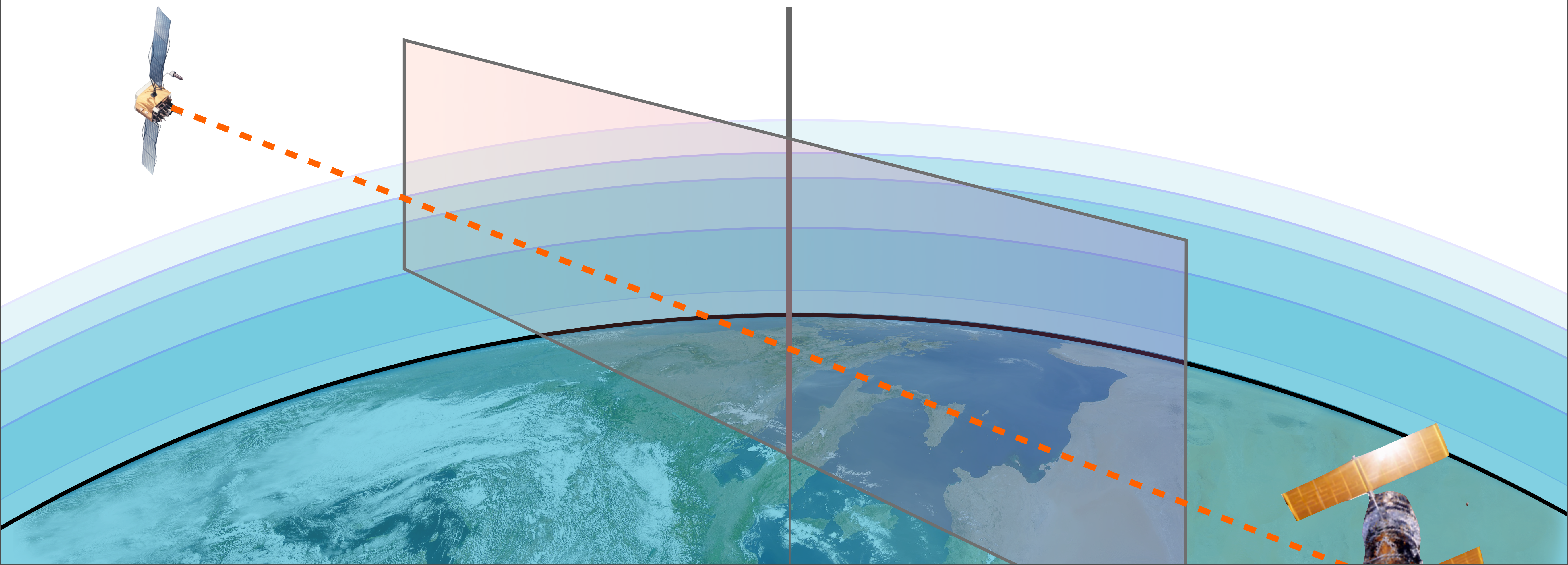
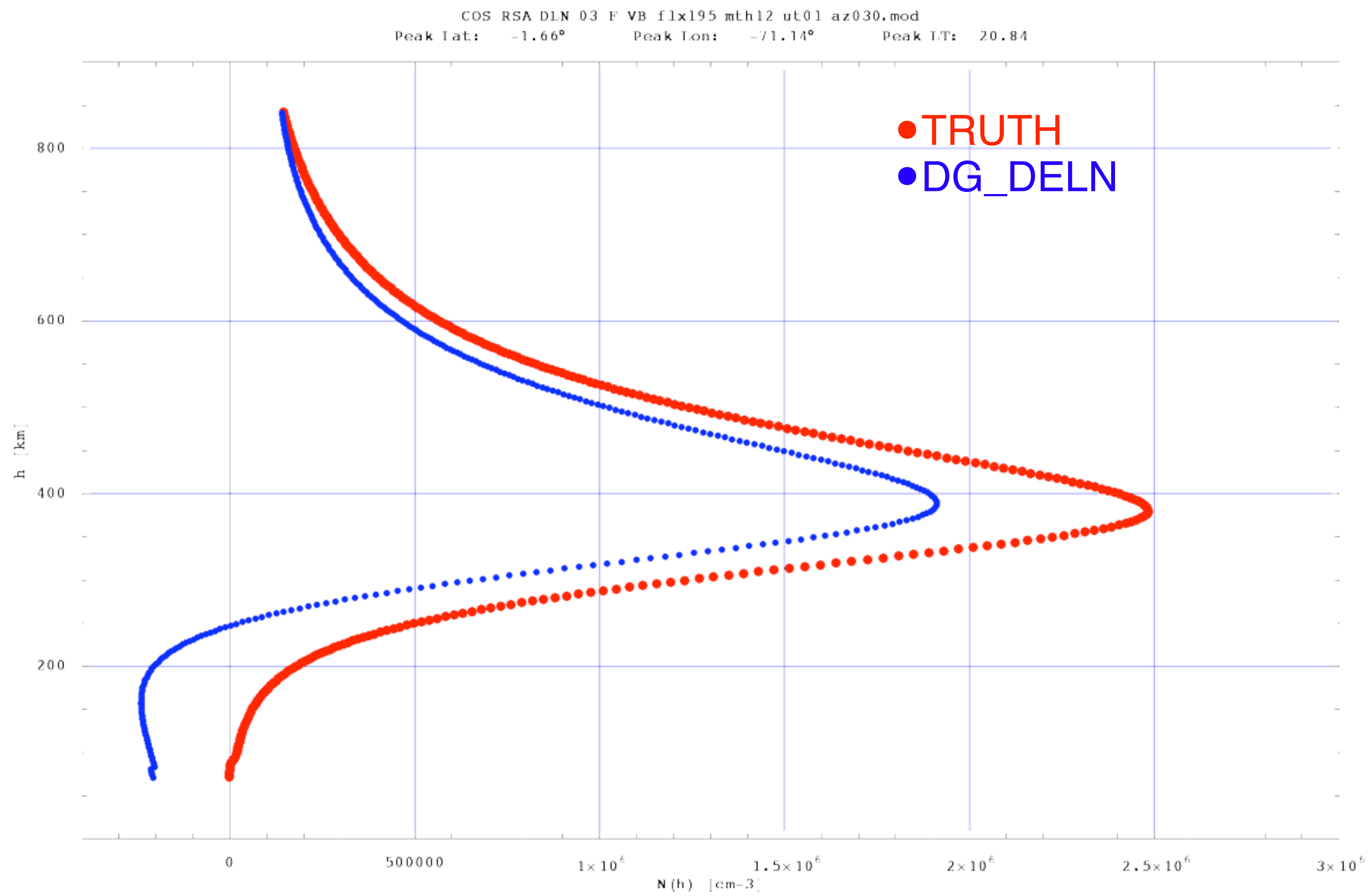
3× 10^6
N(h) [cm-3]



30°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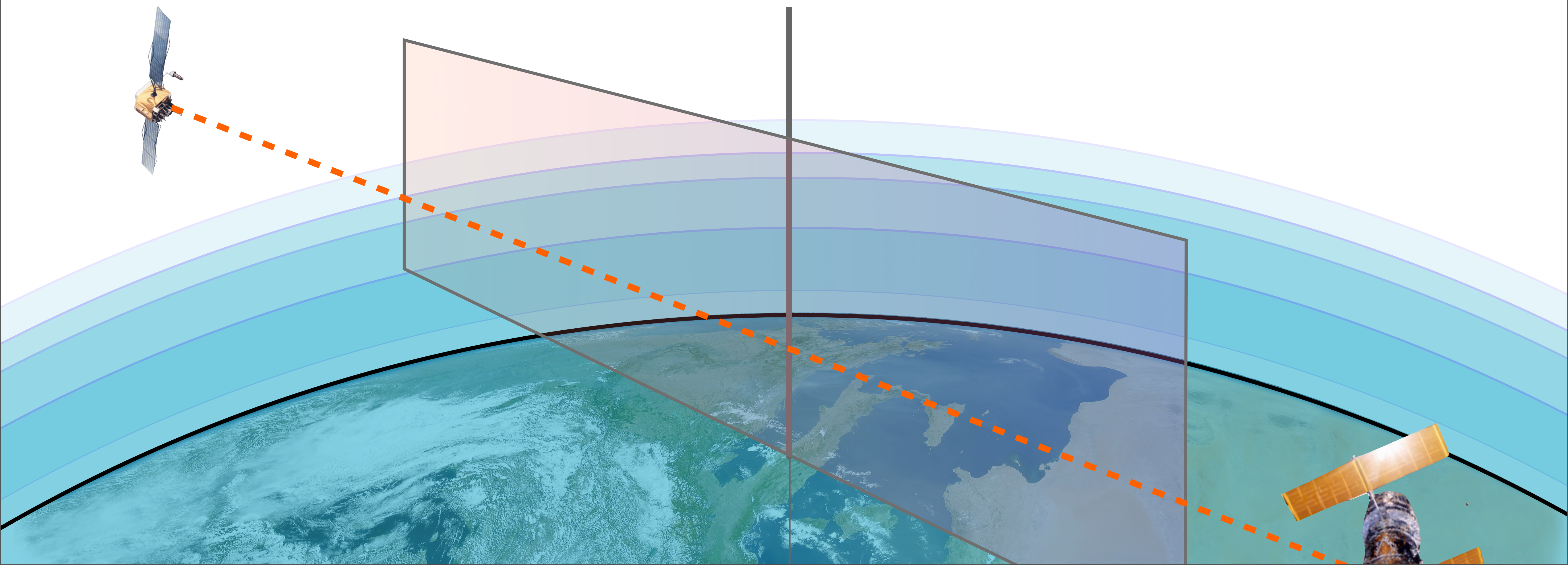
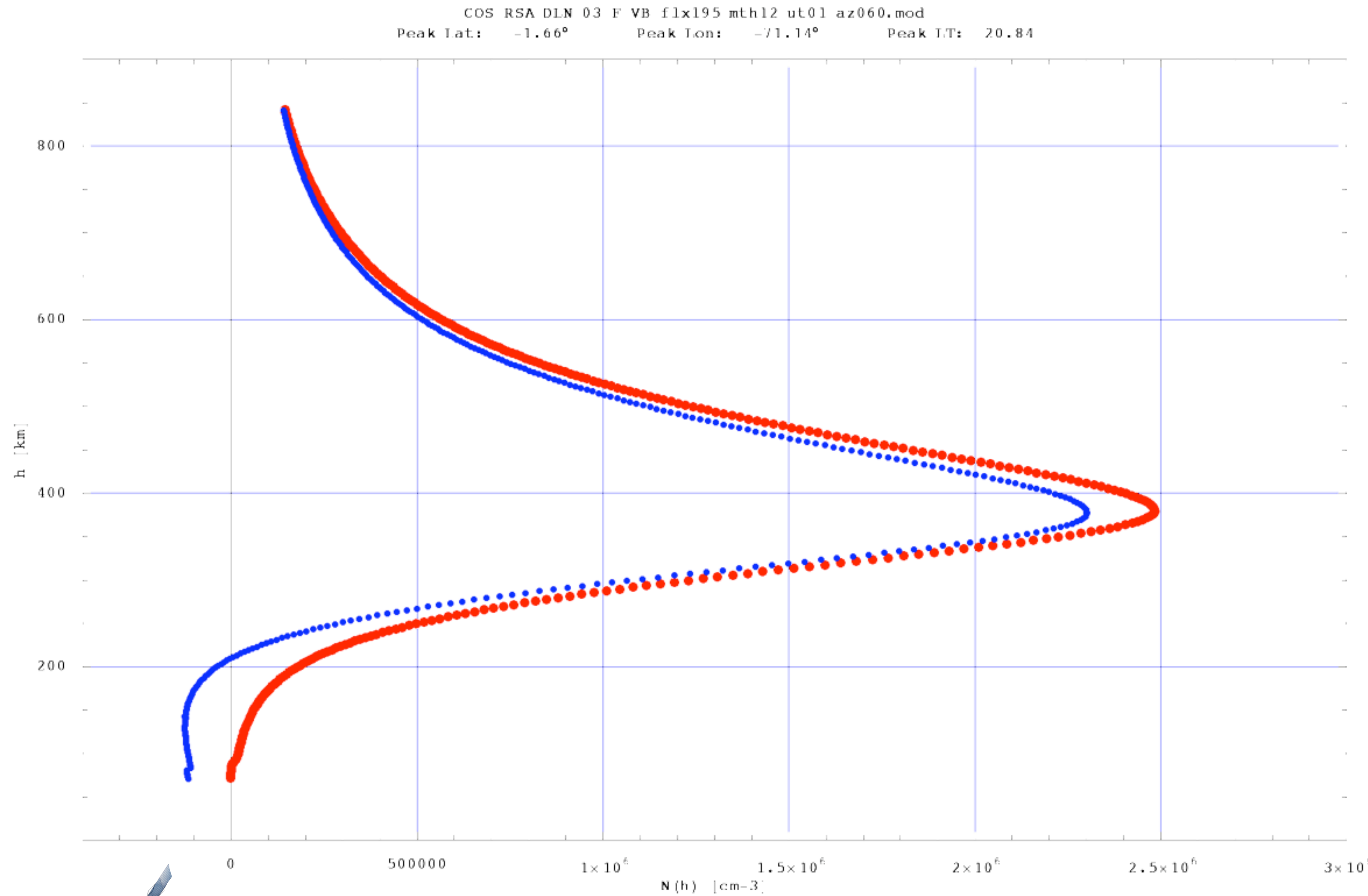
N(h) [cm-3]



60°



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h [km]
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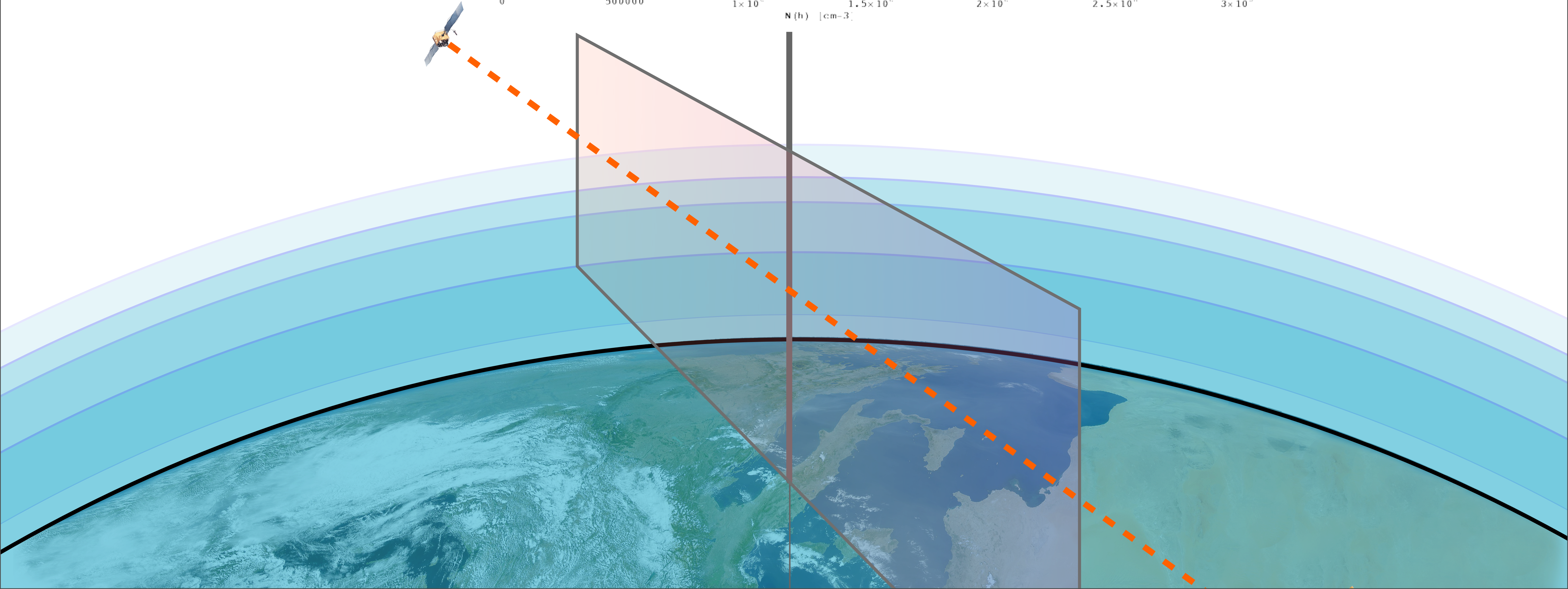
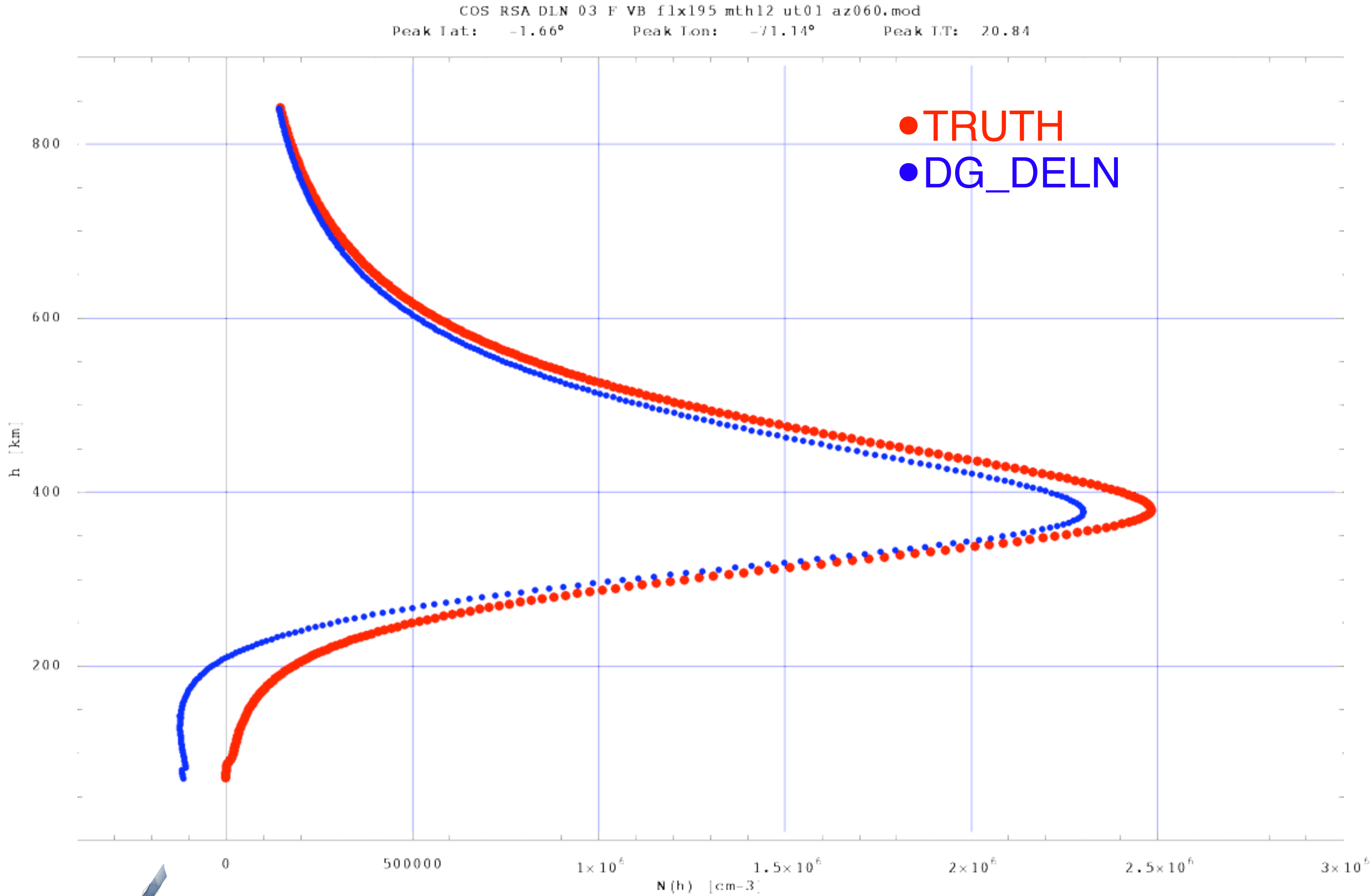
2×10^6
2.5×10^6
3×10^6
N(h) [cm-3]



60°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Peak Lat: -1.66° Peak Lon: -71.14° Peak LT: 20.84
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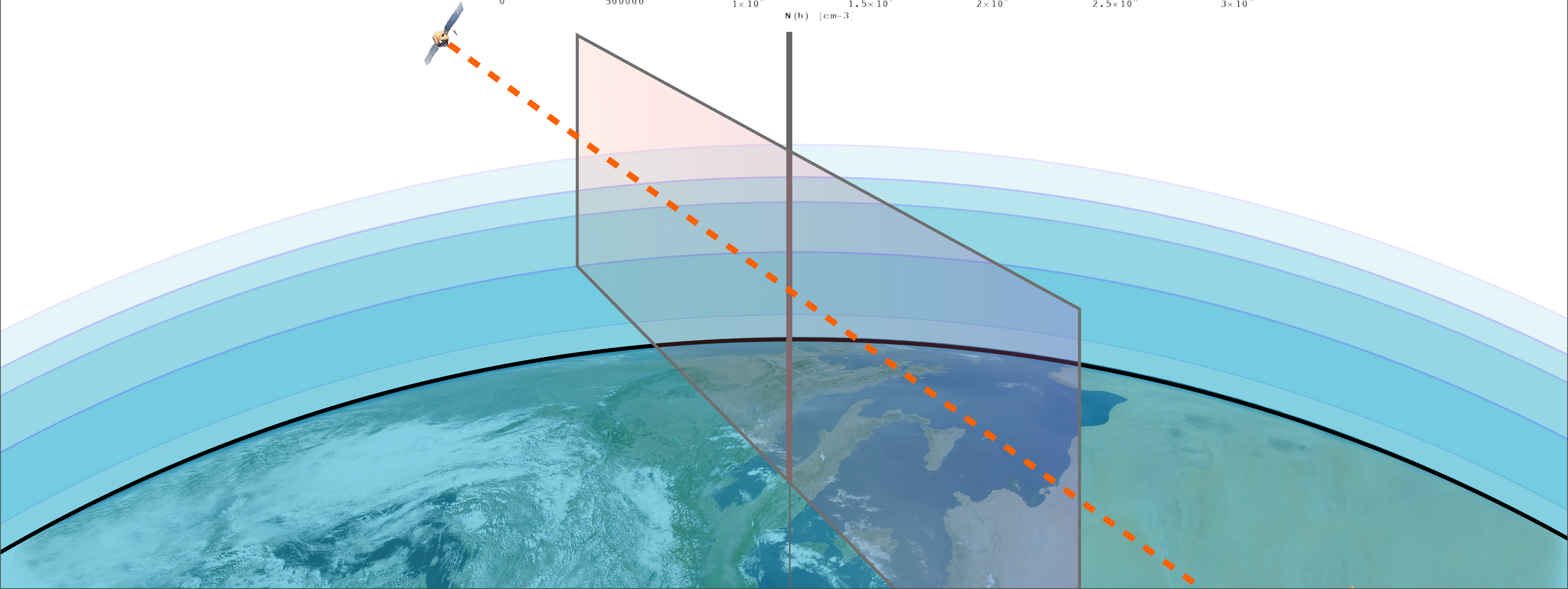
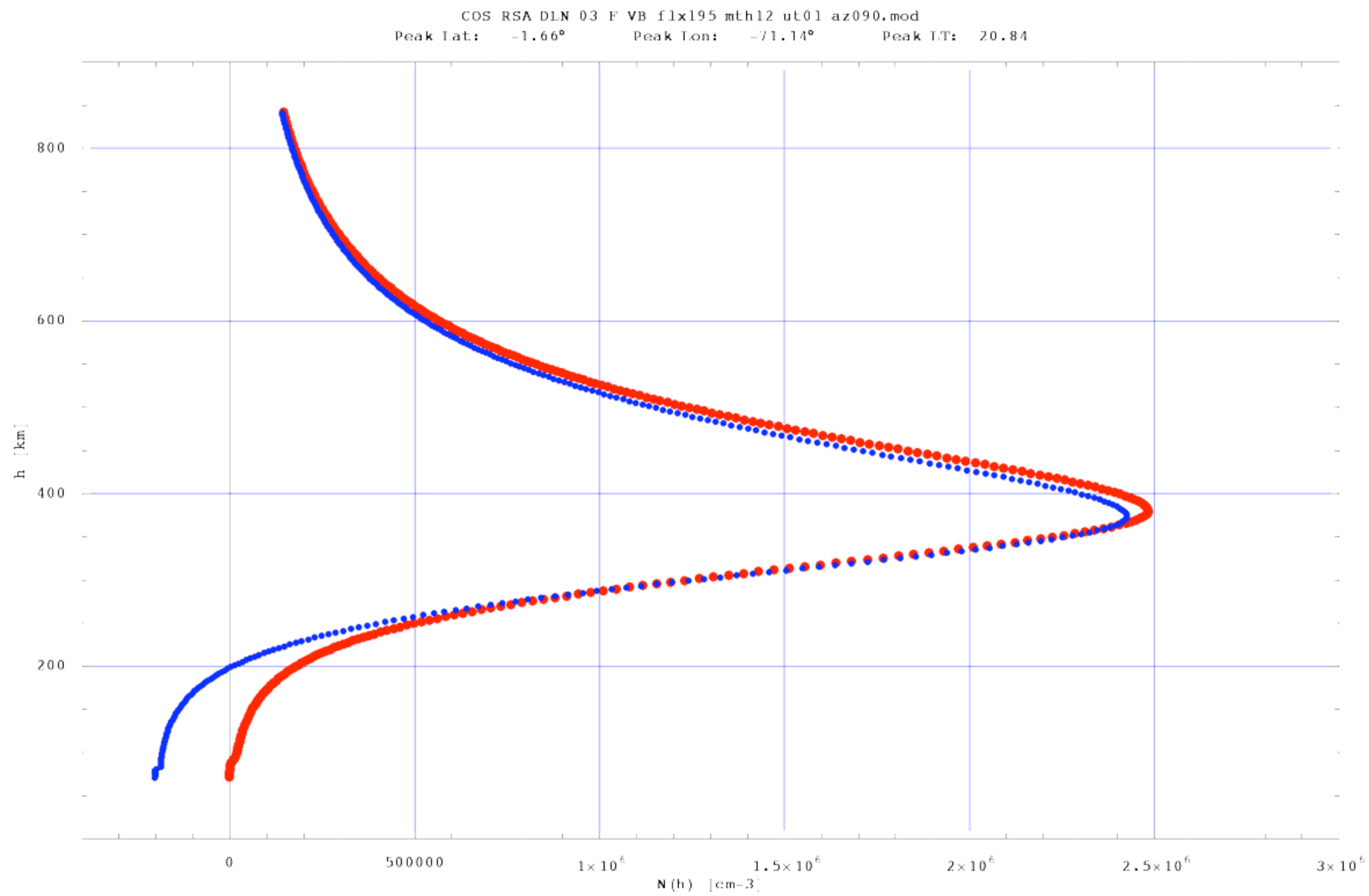
N(h) [cm-3]



90°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Peak Lon: -71.14°
Peak LT: 20.84
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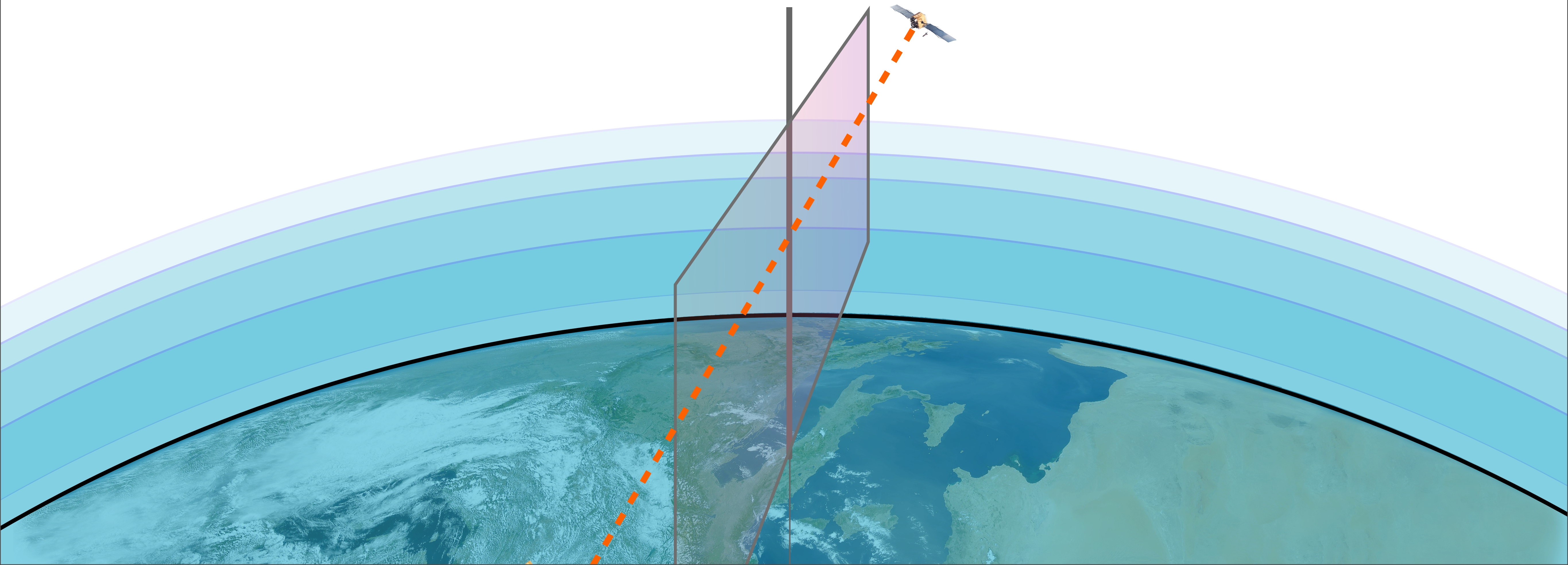
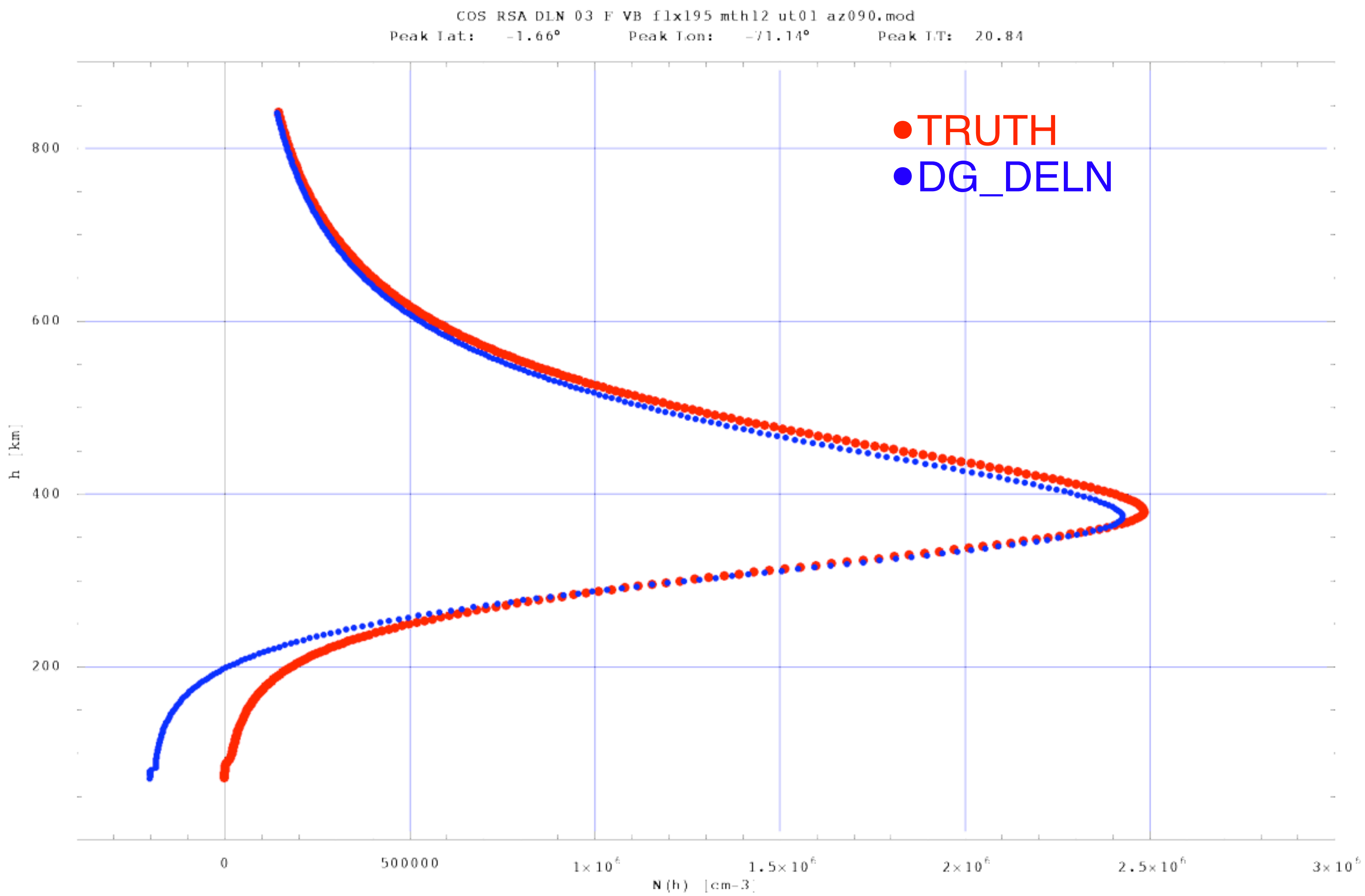
N(h) [cm-3]



90°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Peak Lat: -1.66° Peak Lon: -71.14° Peak LT: 20.84
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h [km]
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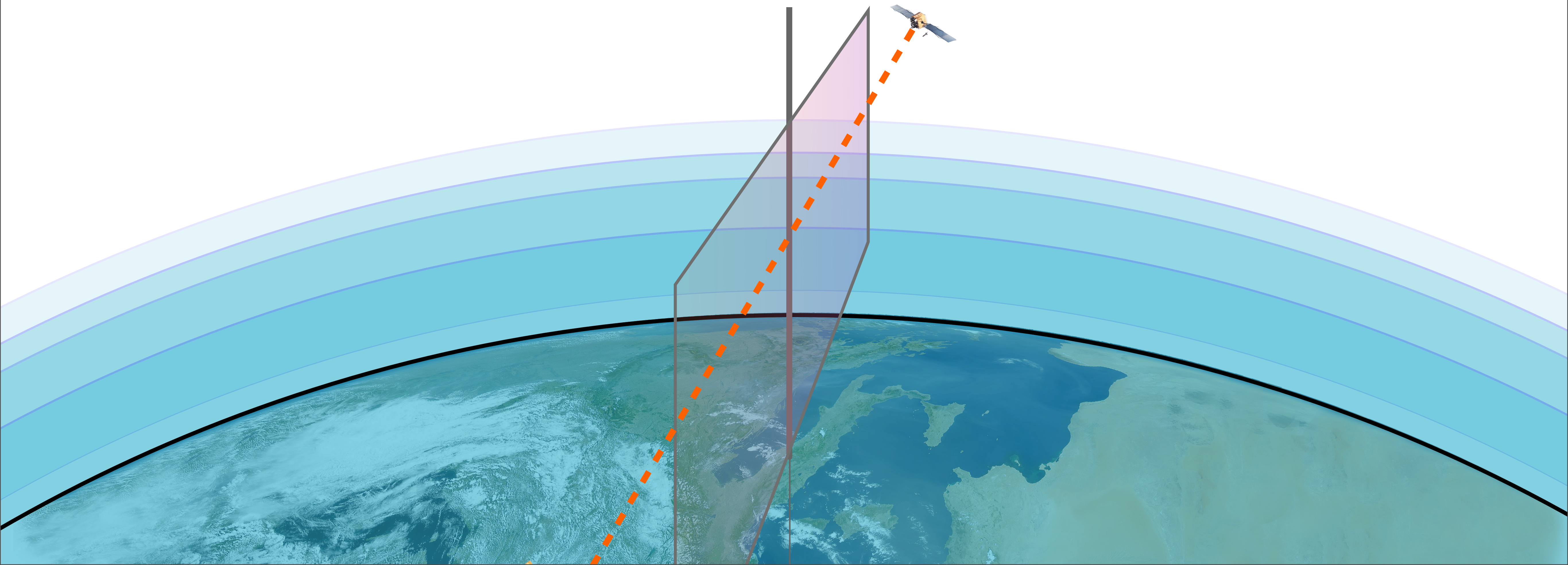
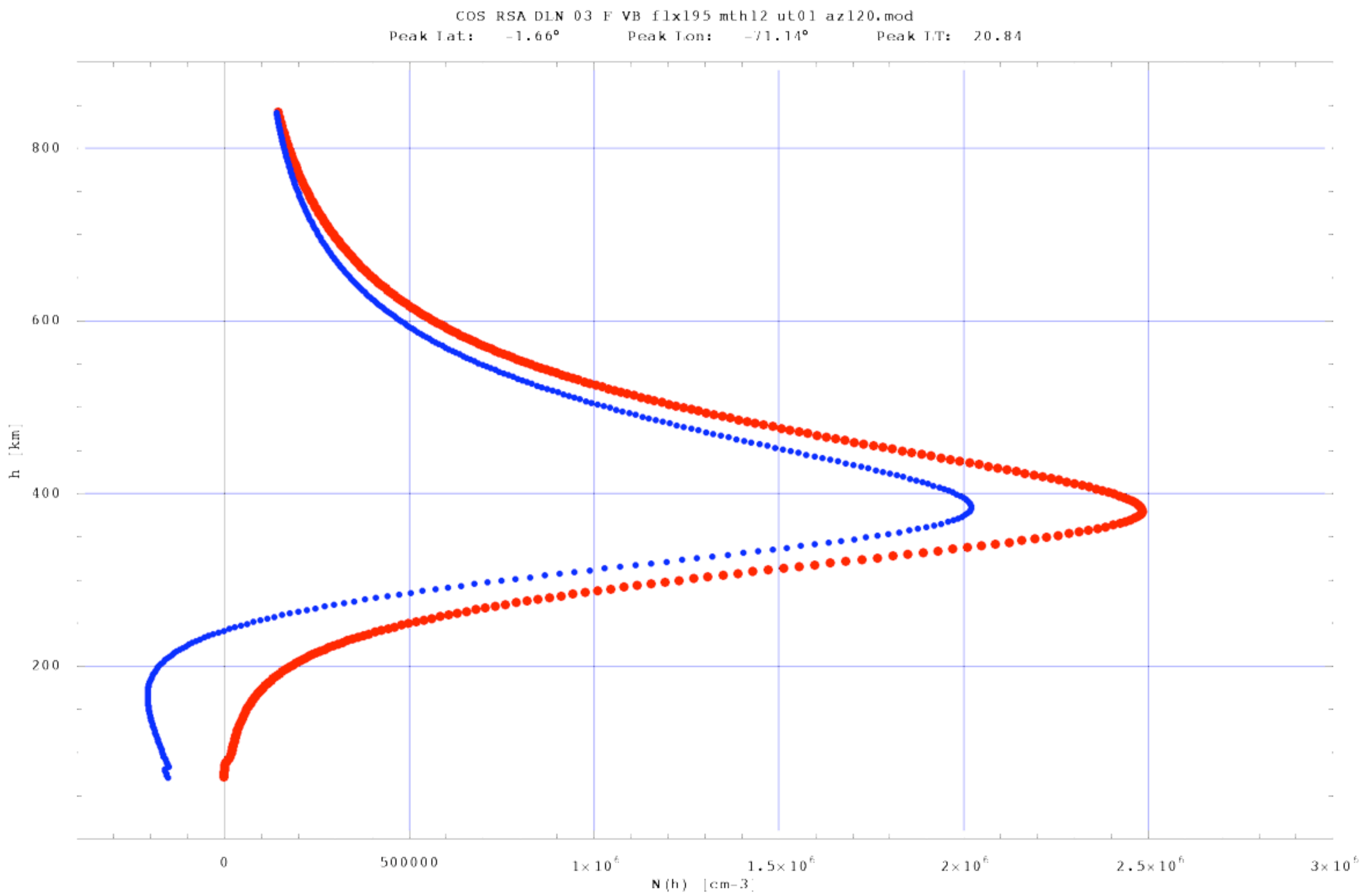
3×10^6
N(h) [cm-3]



120°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h [km]
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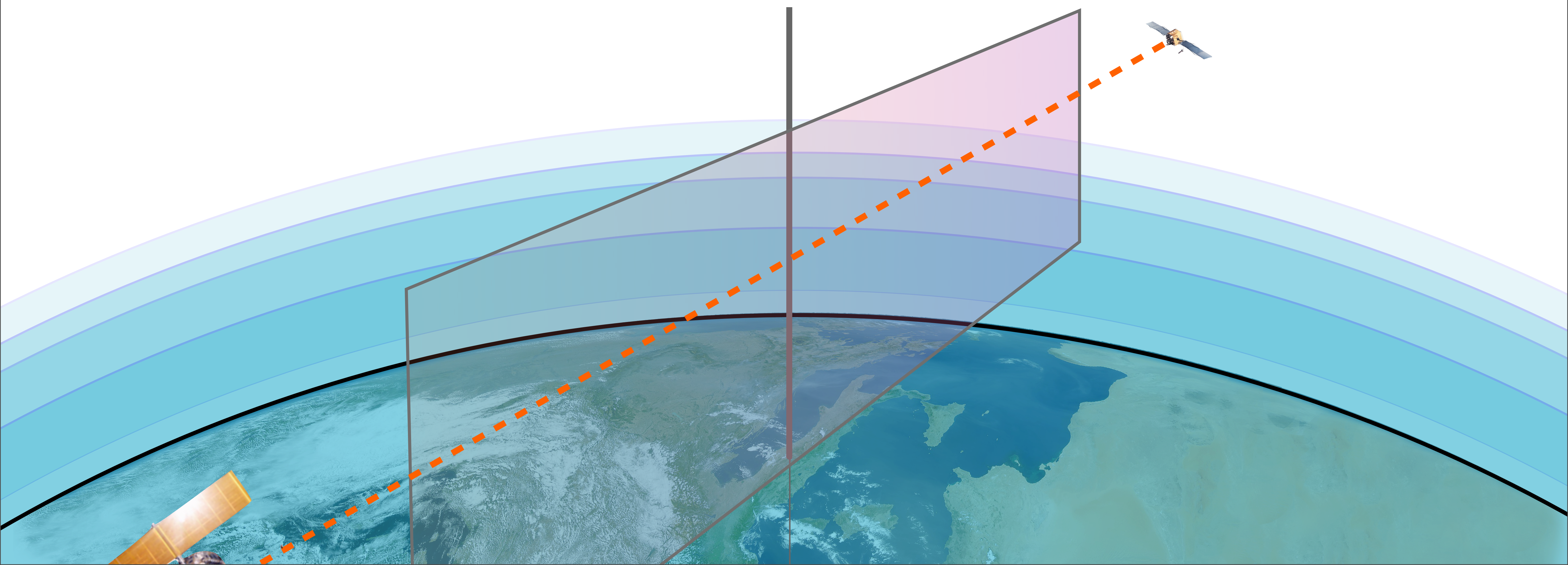
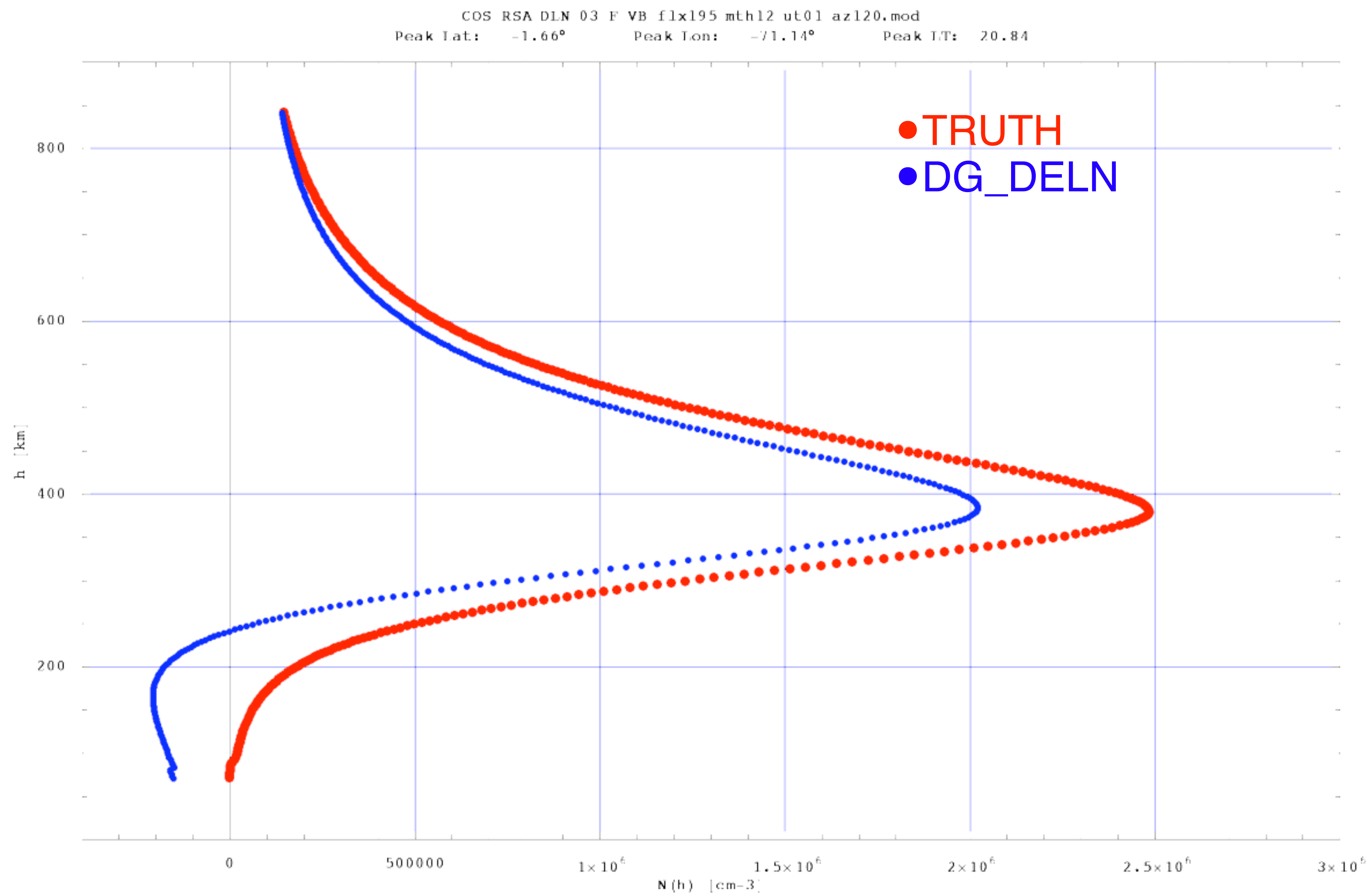
2×10^6
2.5×10^6
3×10^6
N(h) [cm-3]



120°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Peak Lat: -1.66° Peak Lon: -71.14° Peak LT: 20.84
●TRUTH
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h [km]
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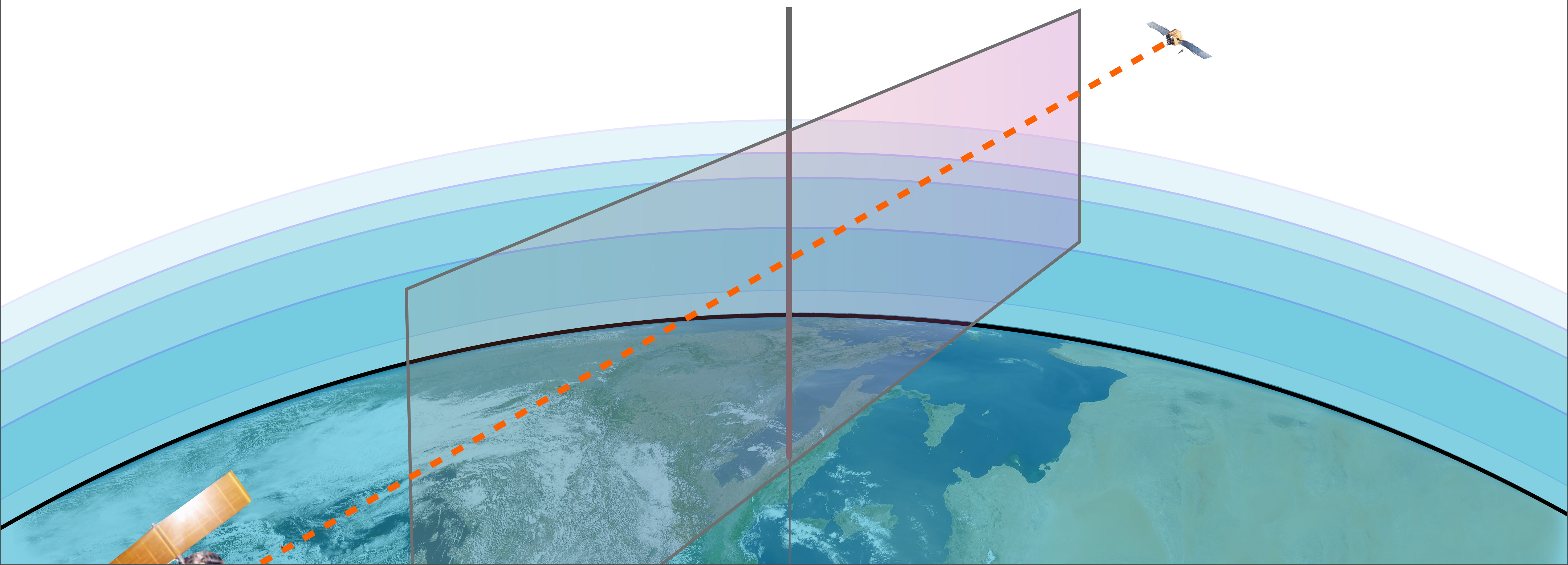
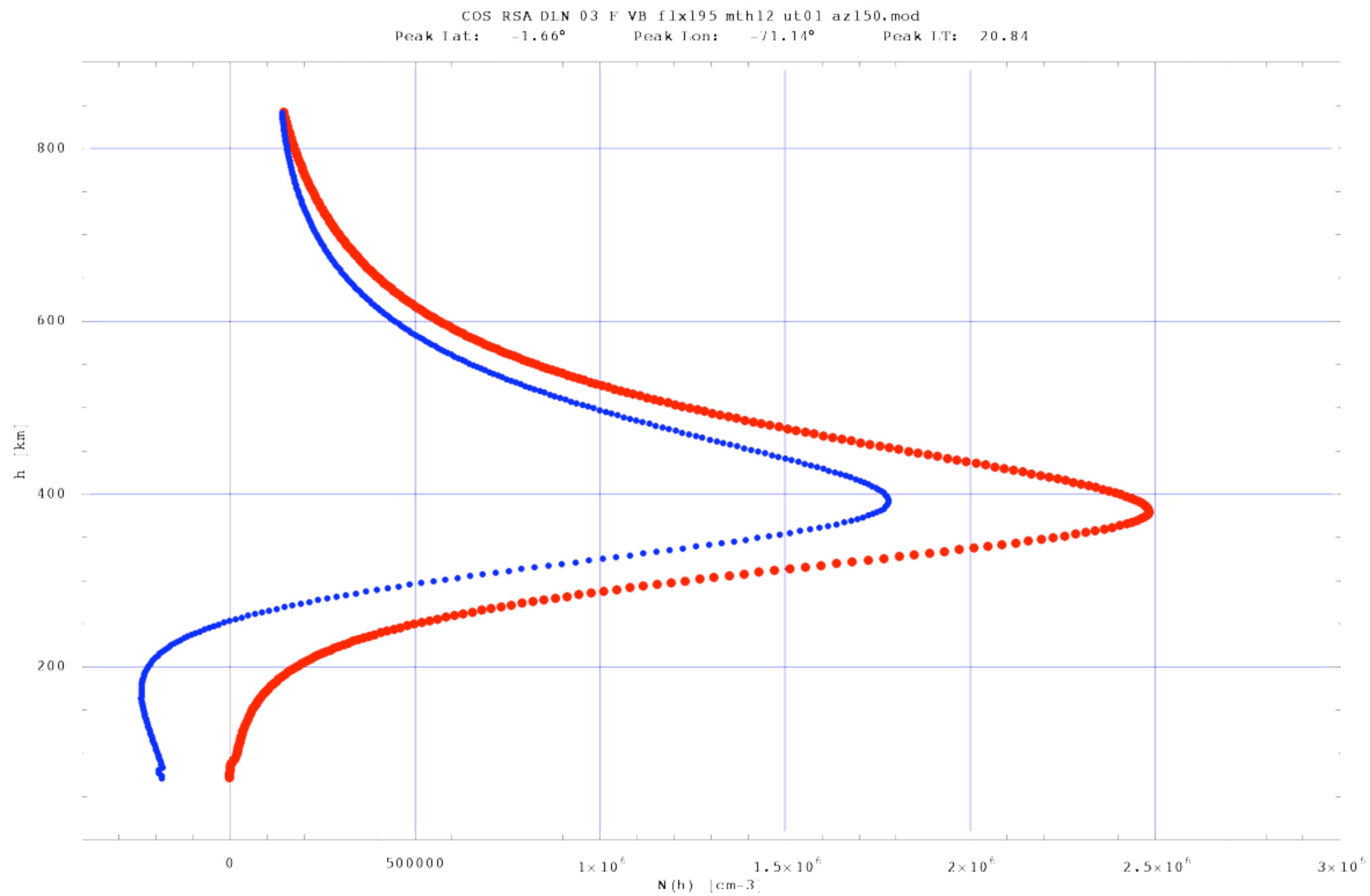
3×10^6
N(h) [cm-3]



150°



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Peak lon: -71.14°
Peak I/T: 20.84
h [km]
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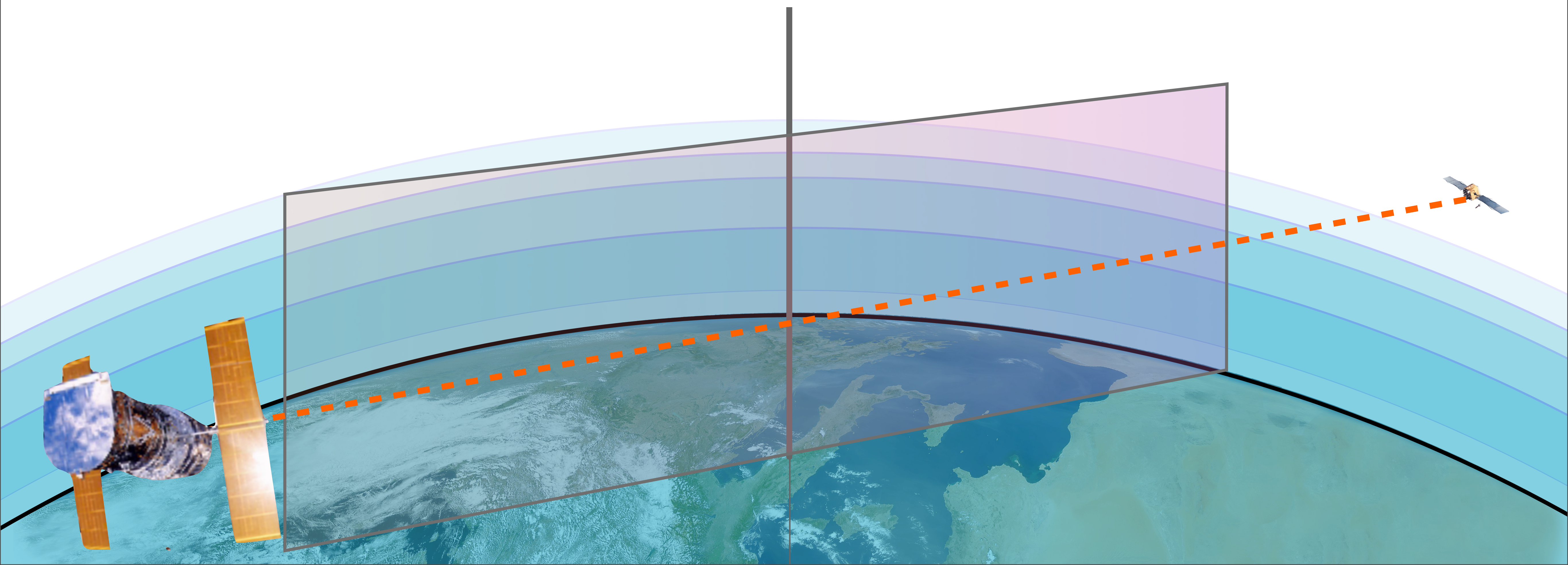
1.5×10^6
2×10^6
2.5×10^6
3×10^6
N(h) [cm-3]



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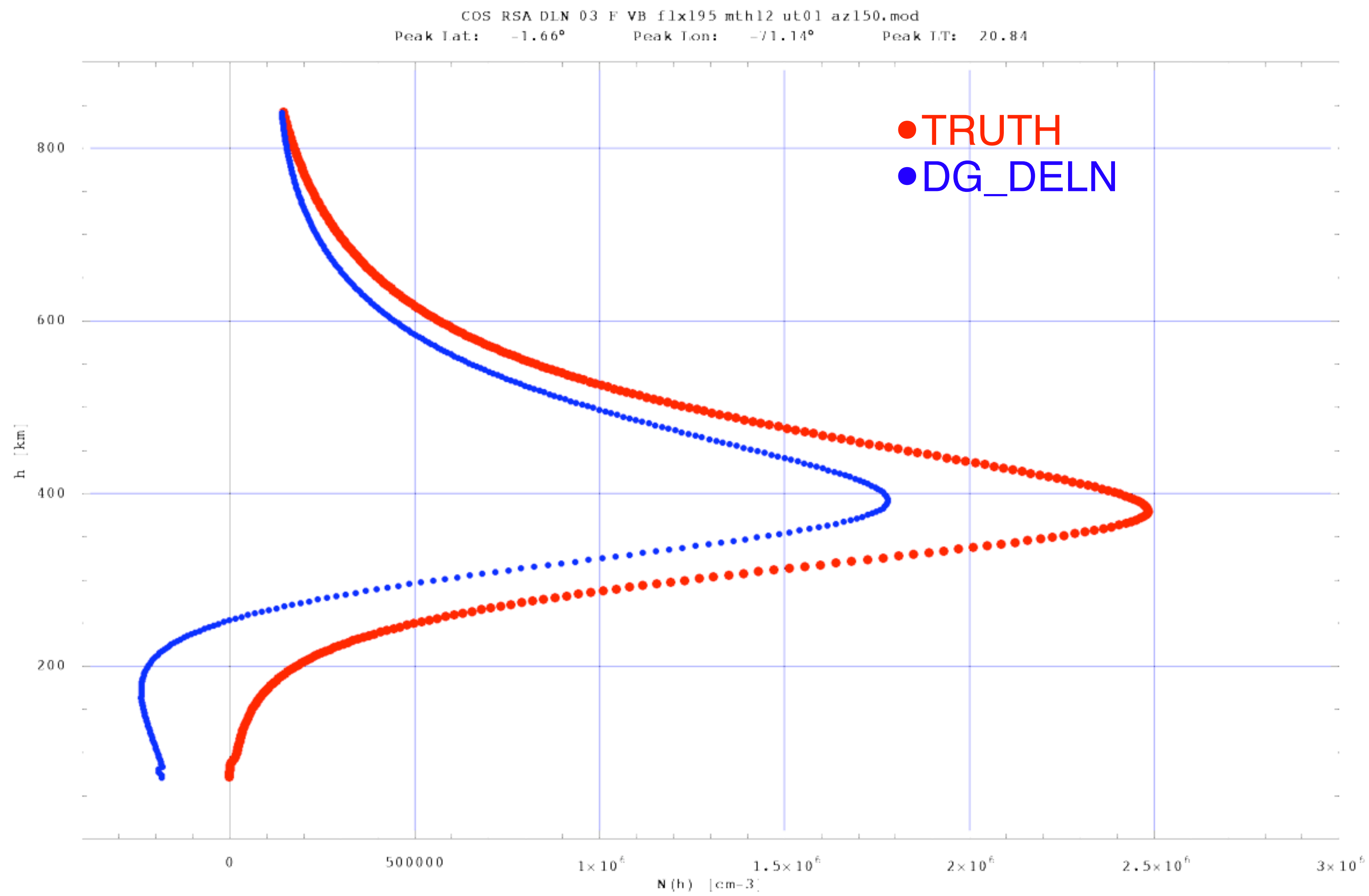
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Peak Lat: -1.66° Peak Lon: -71.14° Peak LT: 20.84
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h [km]
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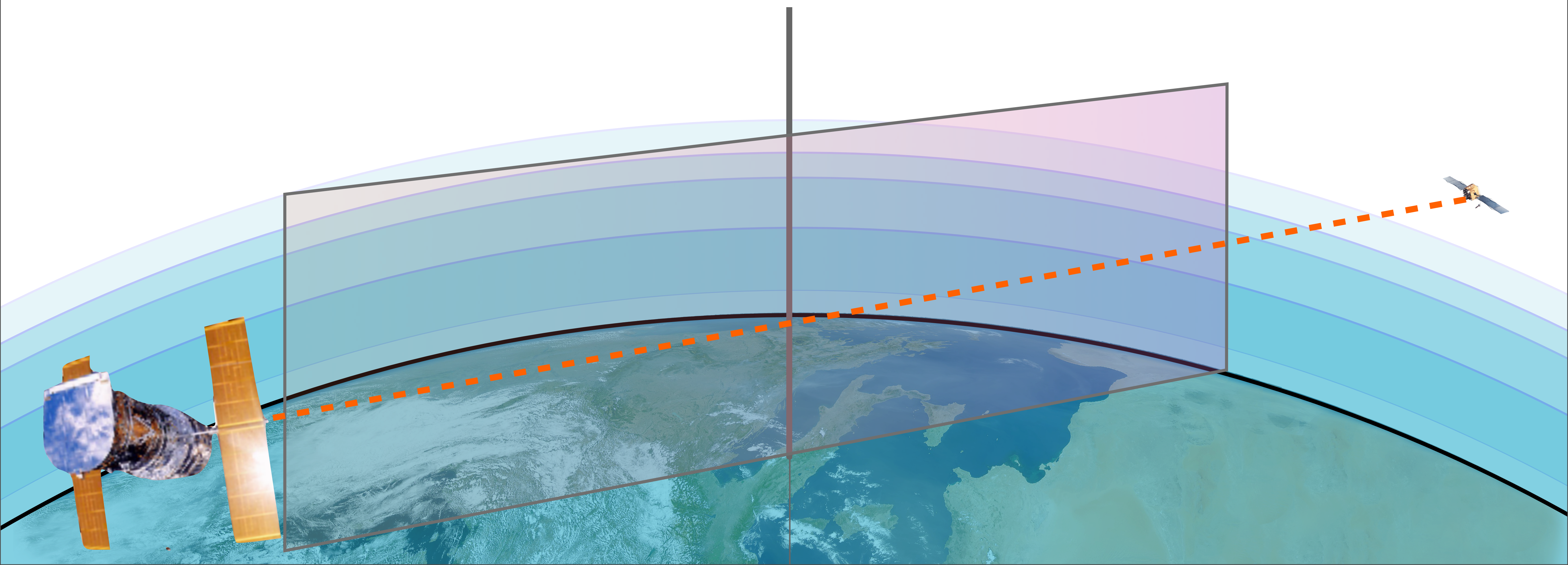
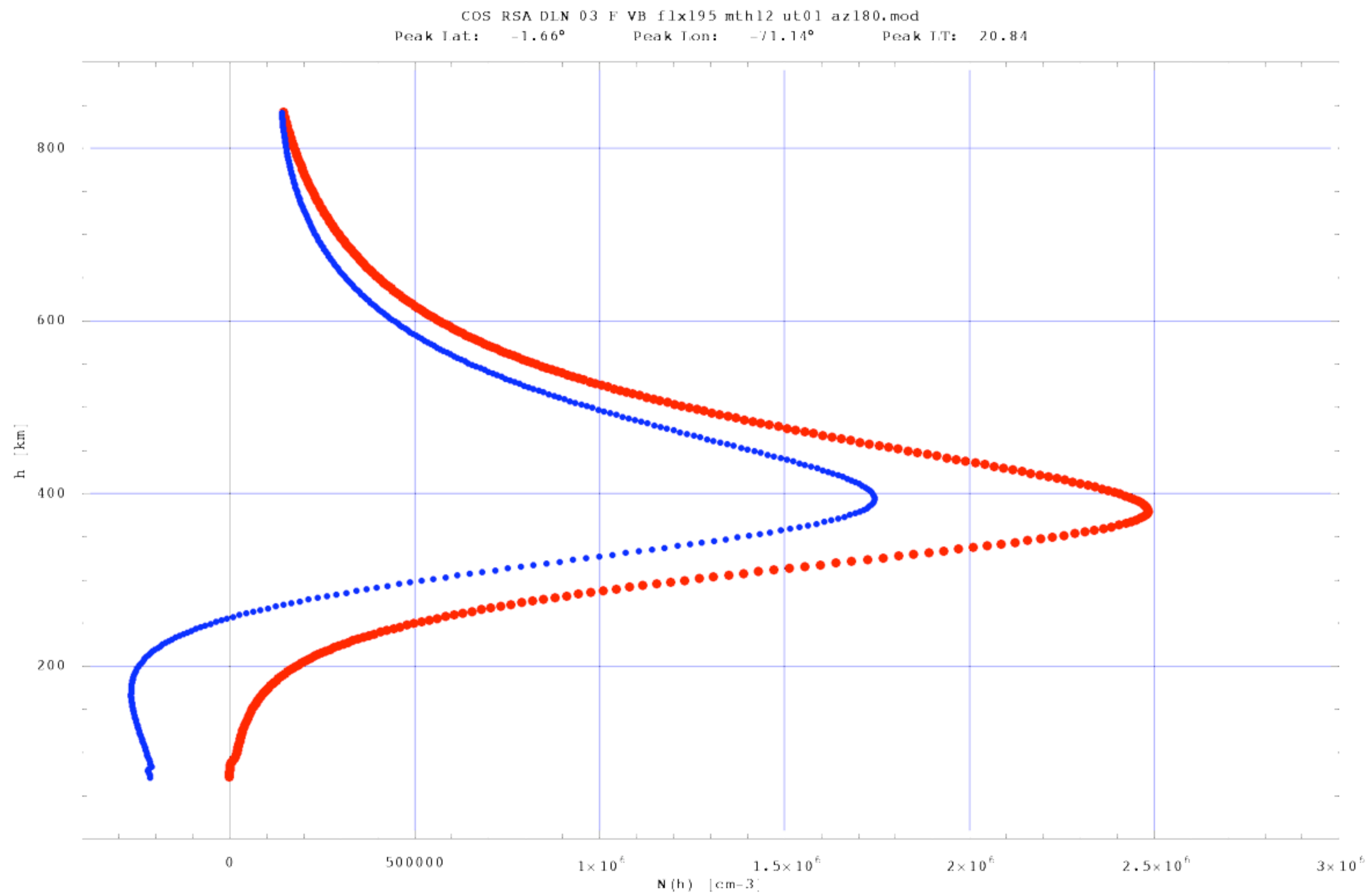
2×10^6
2.5×10^6
3×10^6
N(h) [cm-3]



180°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h [km]
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500000
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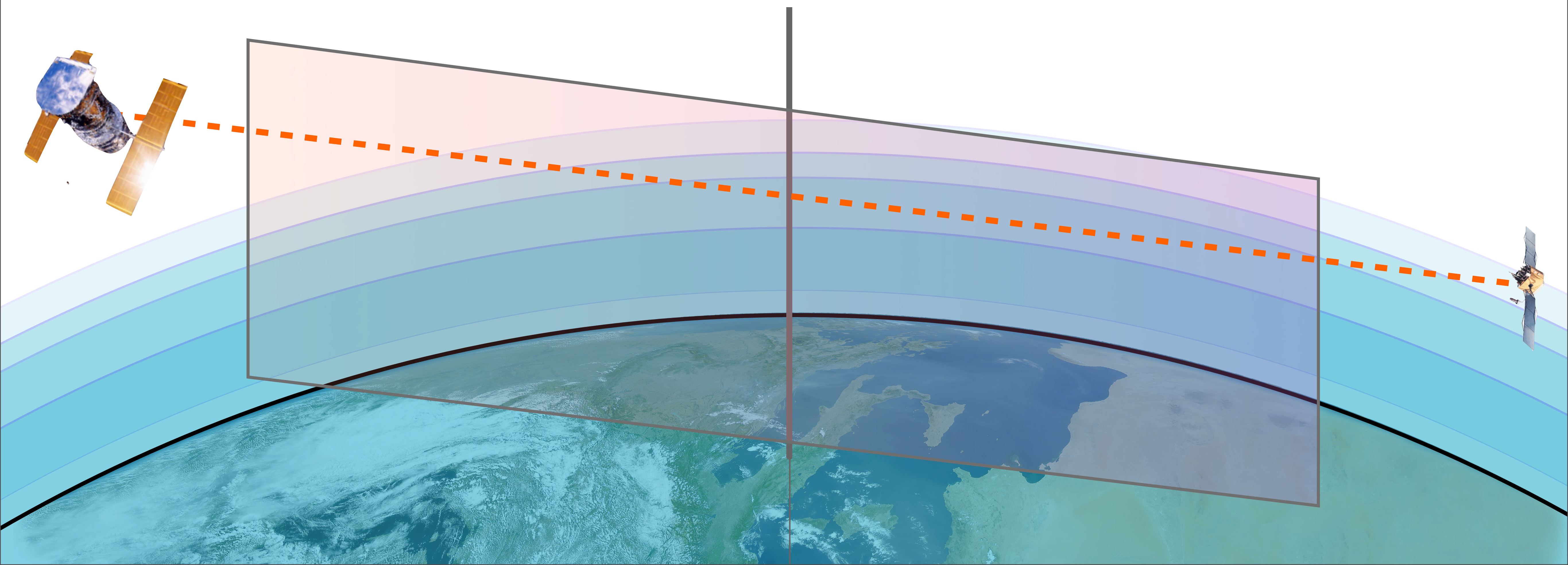
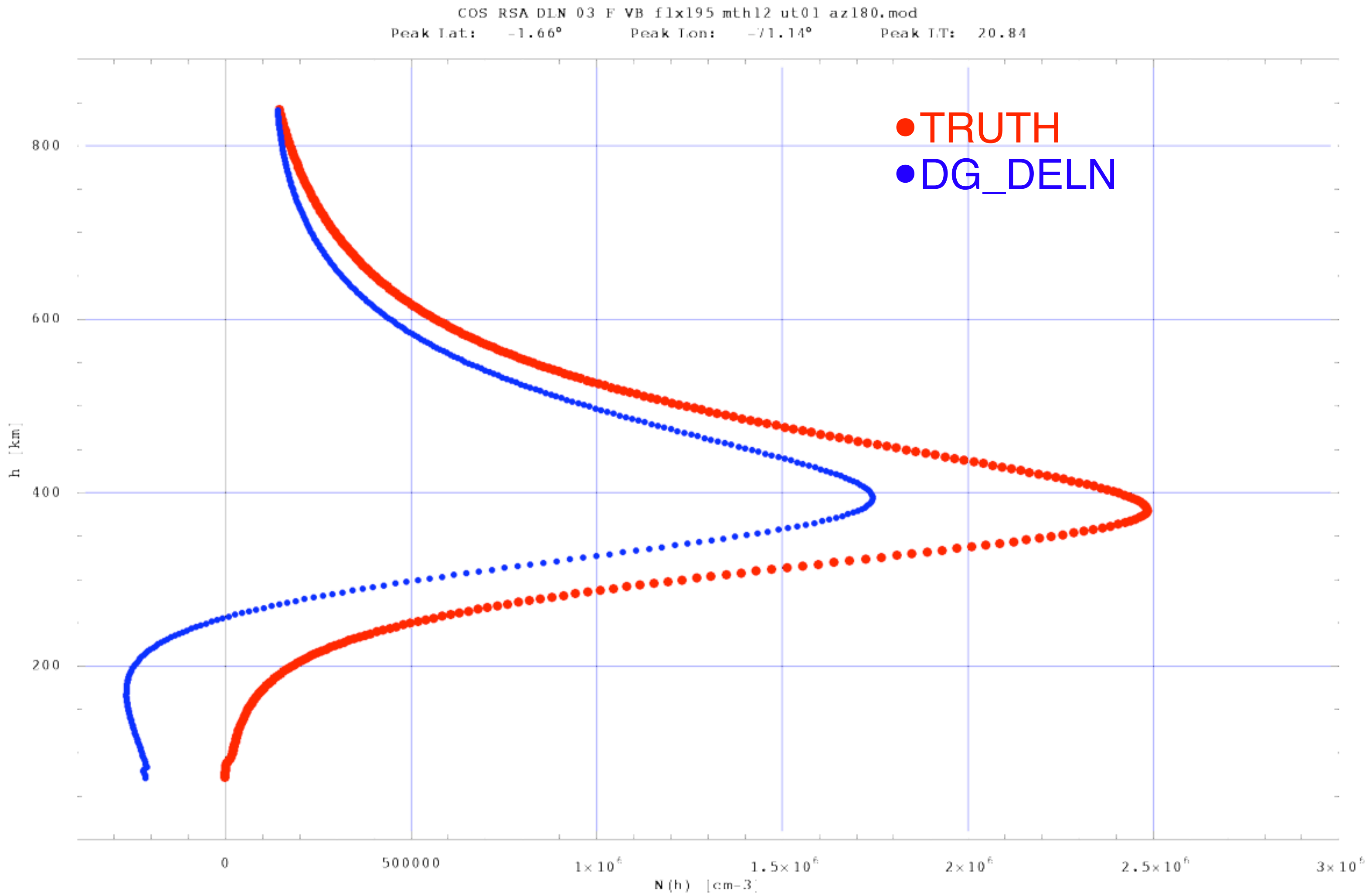
1.5×10^6
2×10^6
2.5×10^6
3×10^6
N(h) [cm-3]



180°



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TRUTH
DG_DELN
800
600
400
200
h [km]
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500000
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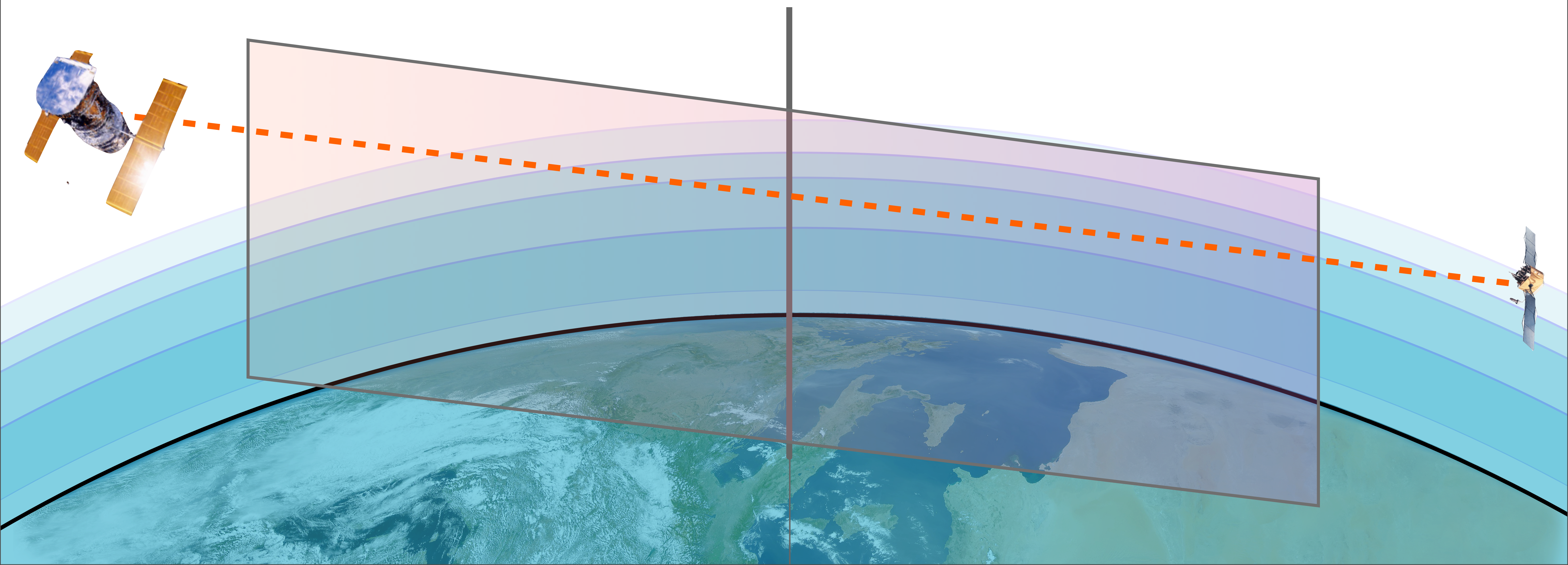
1.5×10⁶
2×10⁶
2.5×10⁶
3×10⁶
N(h) [cm-3]



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)

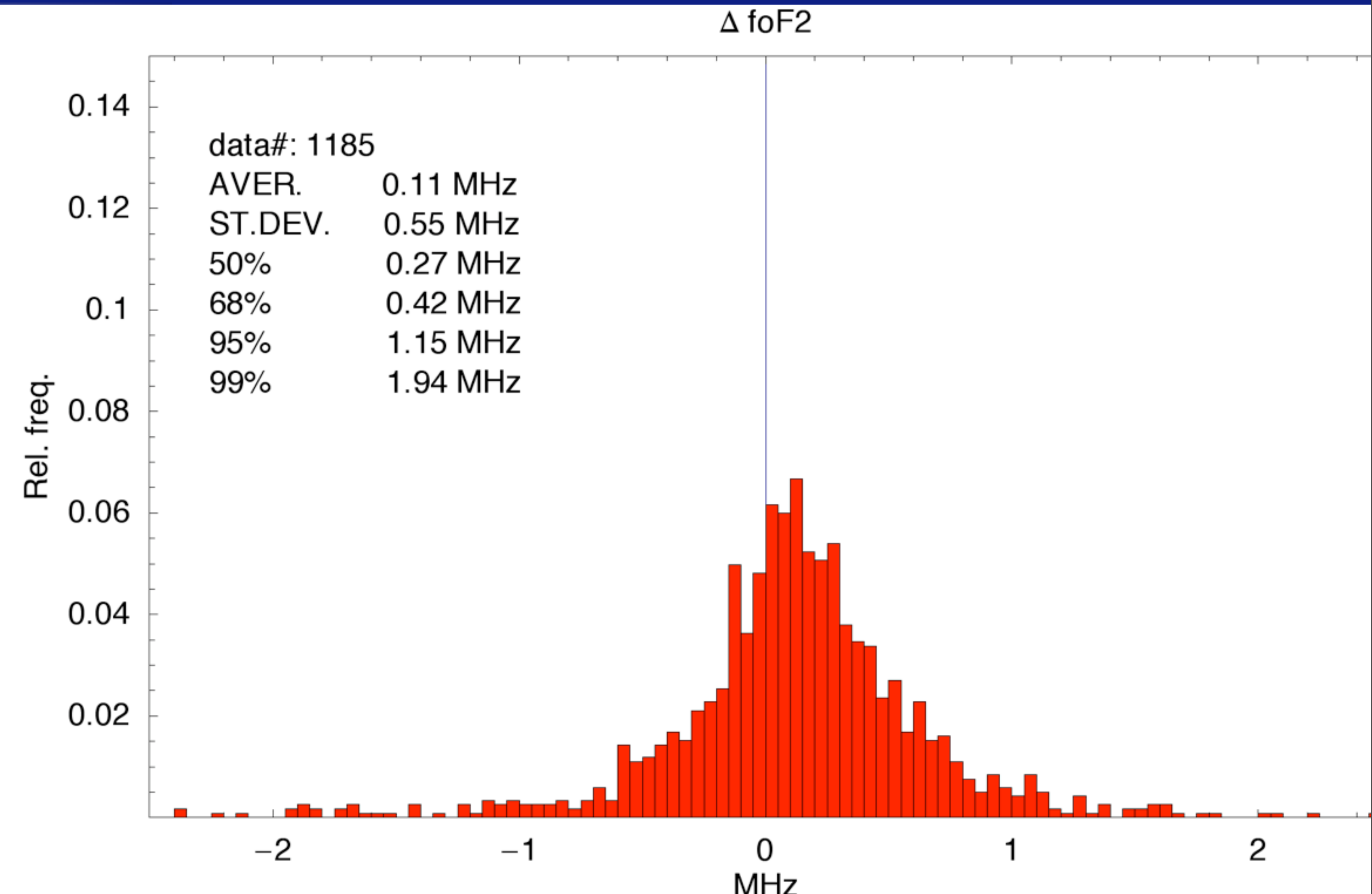
↓

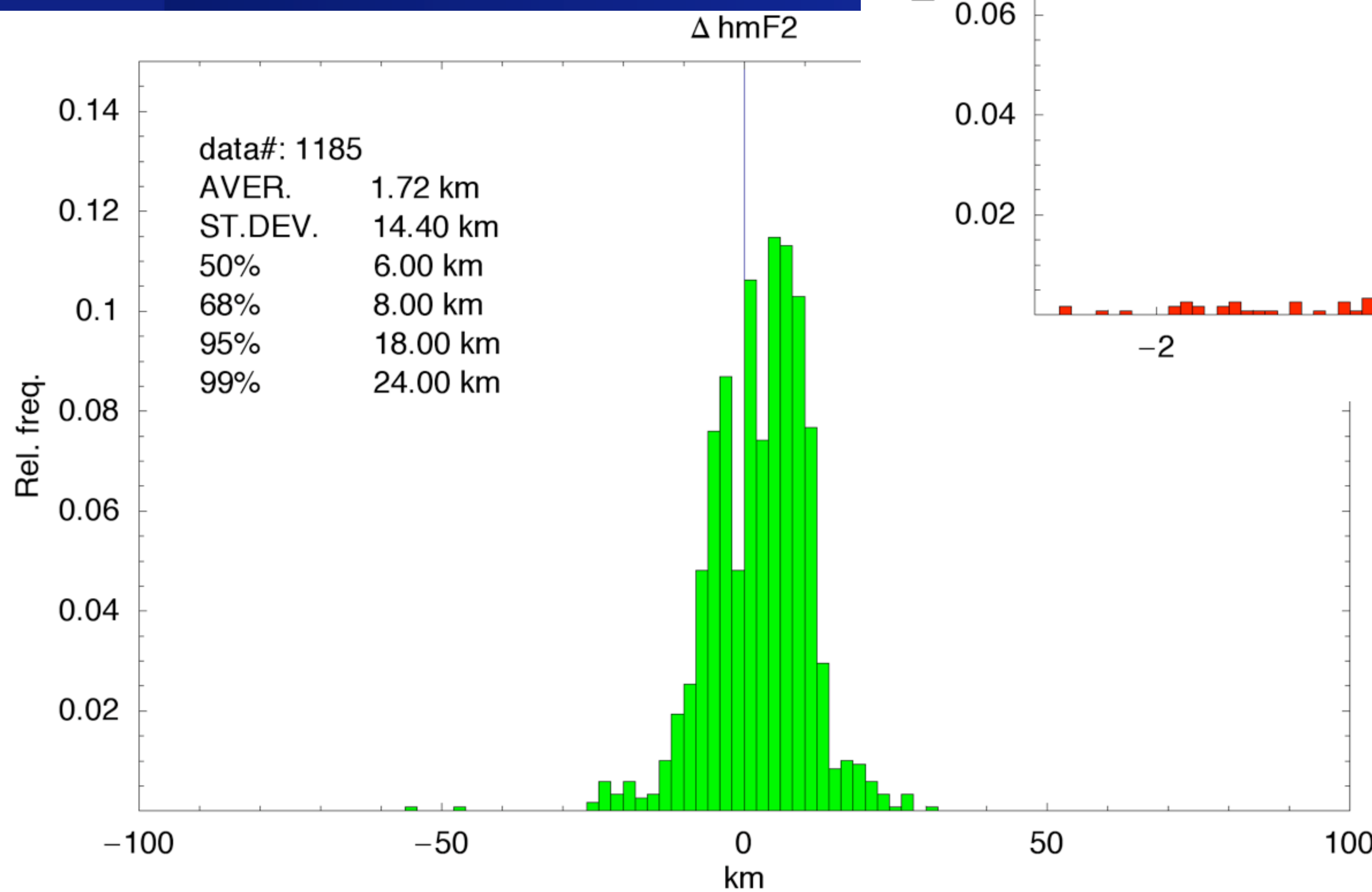
Onion Peeling
vs
True profile
(Ionosonde)

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

Simulation results (HSA)

foF2 and hmF2
errors statistics





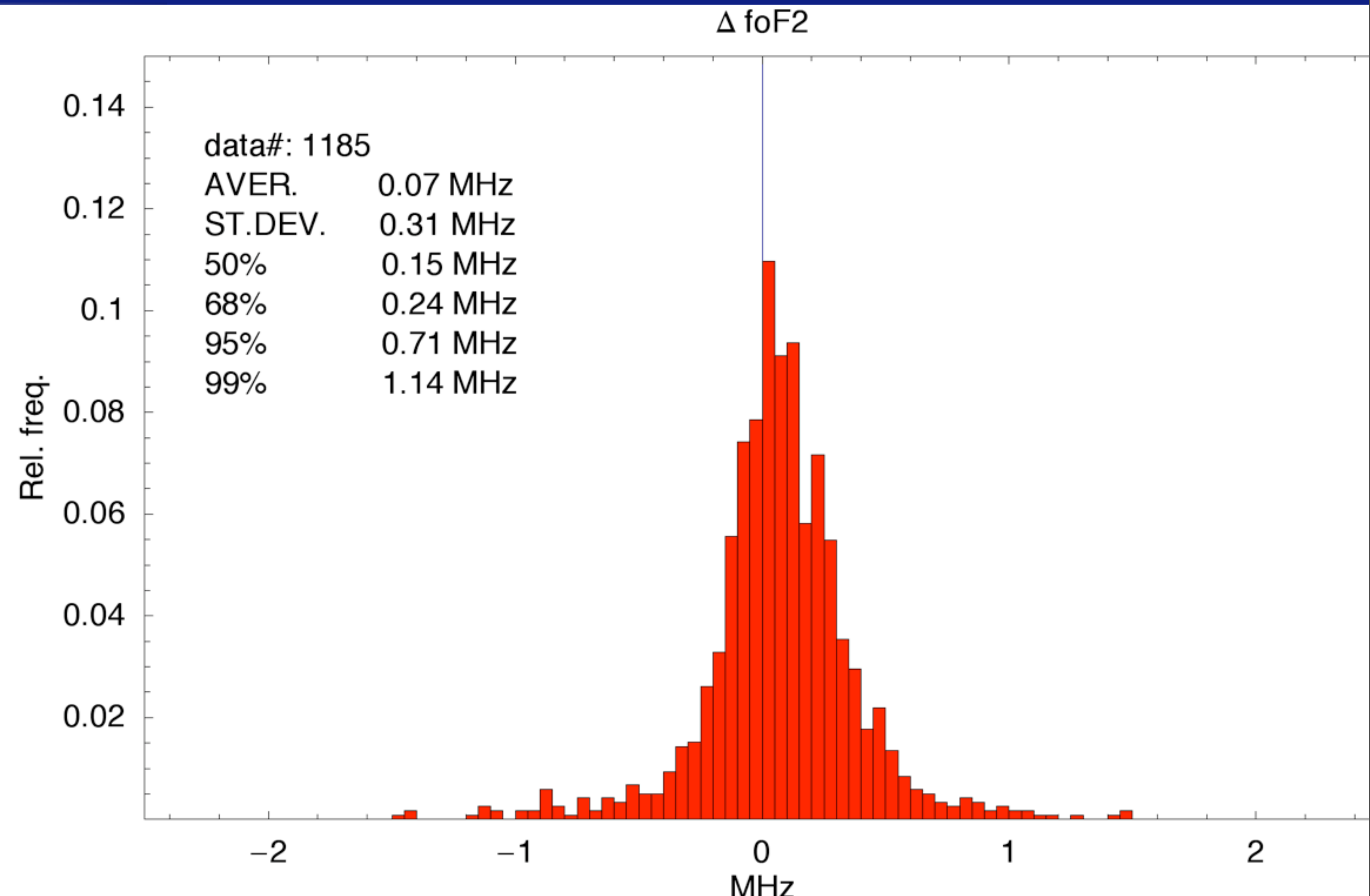
Co-location criteria for true profile and Onion Peeling derived profile

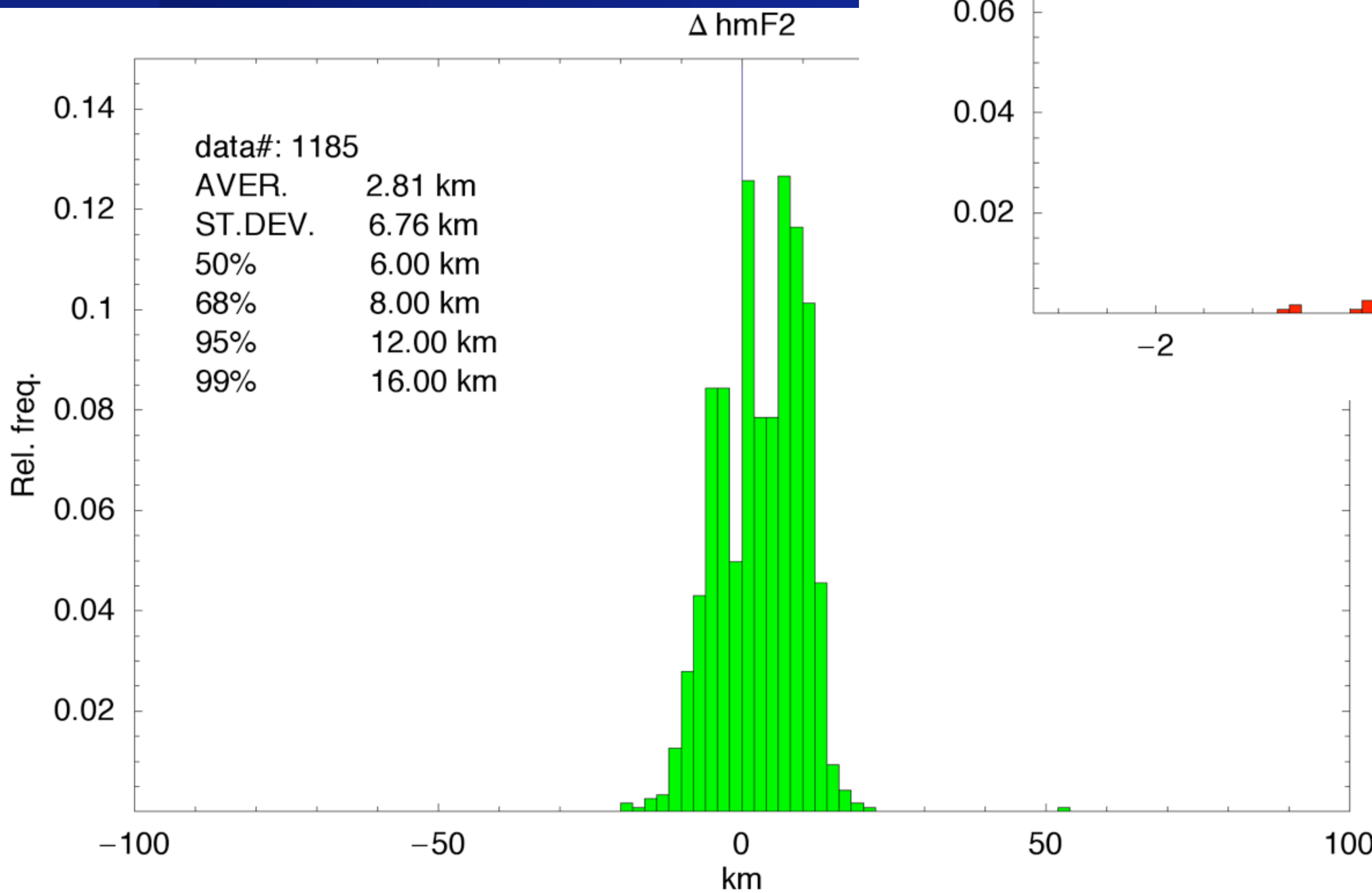
↓

exact matching

Simulation results (LSA)

foF2 and hmF2 errors statistics





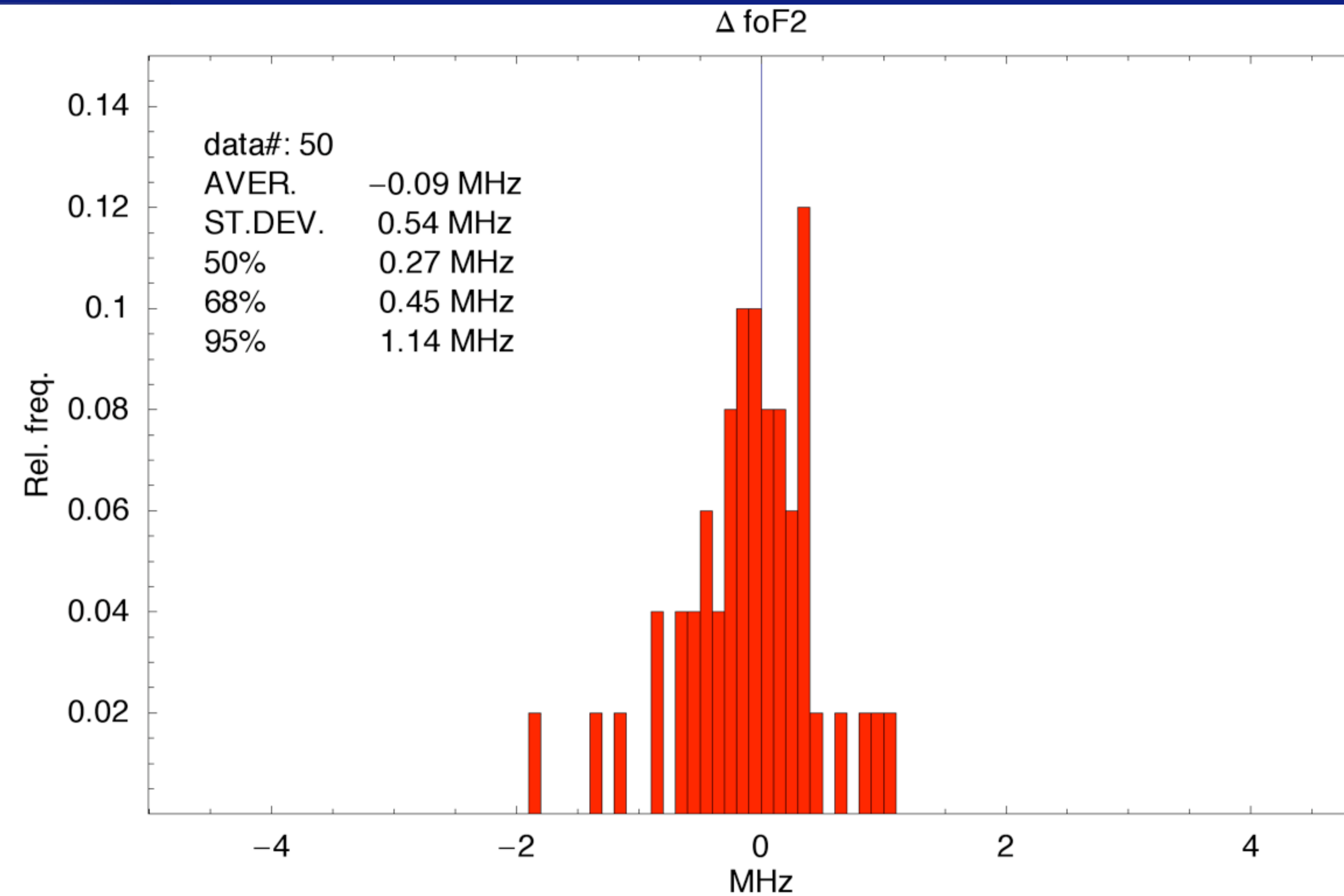
Co-location criteria for true profile and Onion Peeling derived profile

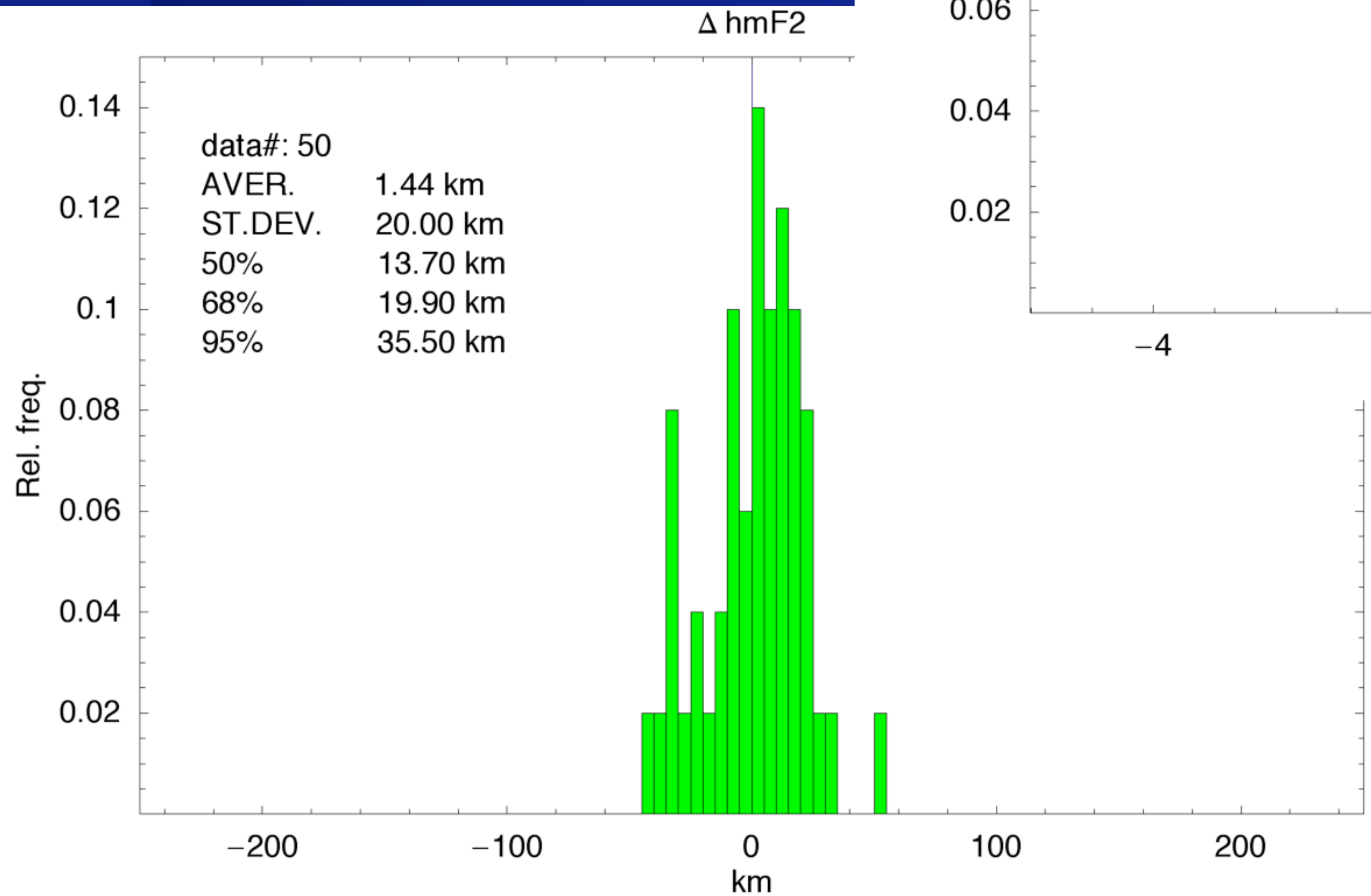
↓

exact matching

Experimental data (LSA)

foF2 and hmF2 errors statistics





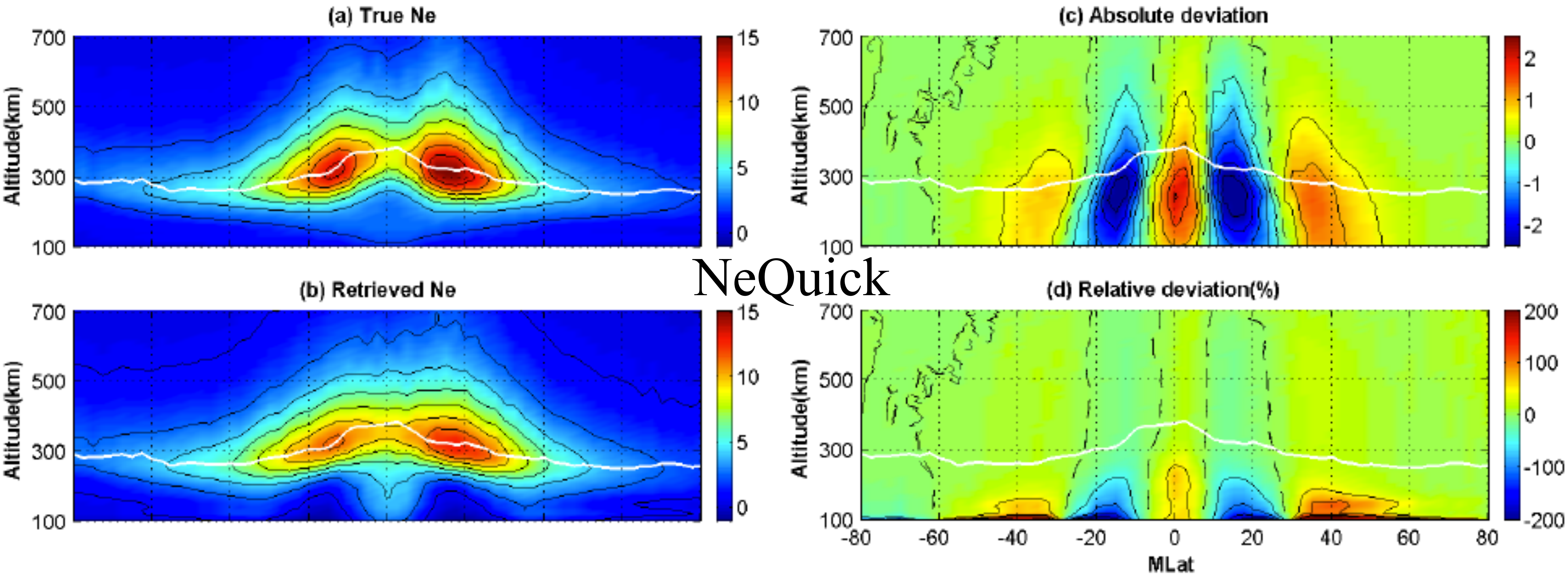
Co-location criteria for true profile and Onion Peeling derived profile

↓

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

Plasma "caves"

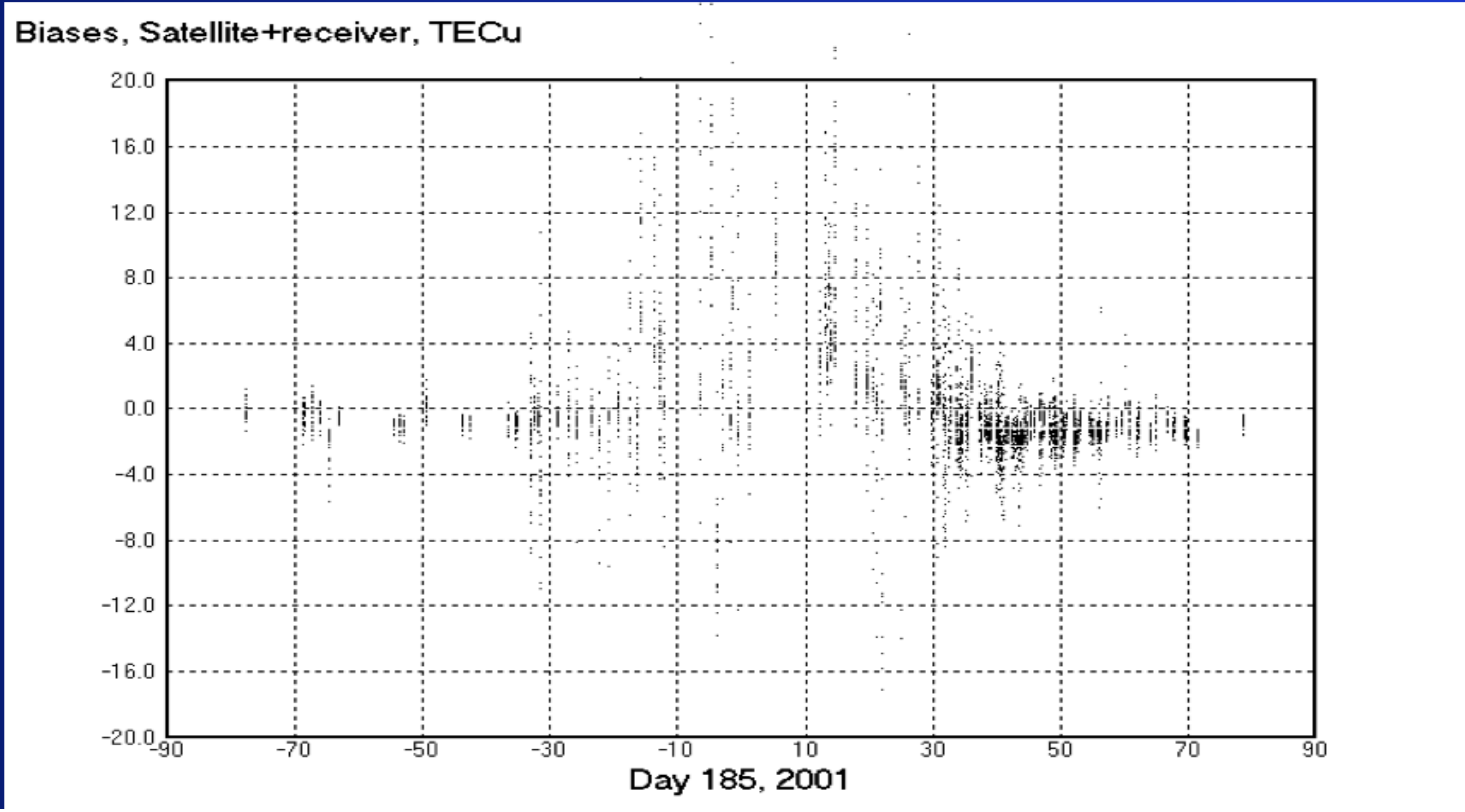
Comment on "A new aspect of ionospheric E region electron density morphology" by Yen-Hsyang Chu, Kong-Hong Wu, and Ching-Lun Su
Jiuhou Lei, Xinan Yue and William S. Schreiner; JGR, 2010



Error analysis of Abel retrieved electron density profiles from radio occultation measurements
X. Yue, et al.; Ann. Geophys., 28, 217–222, 2010

NeQuick for assessment studies

- to validate specific TEC calibration techniques
  - using model derived slant TEC directly (e.g. with bias = 0)
  - using model derived slant TEC to produce RINEX files (to be implemented; also including other effects; e.g. troposphere);



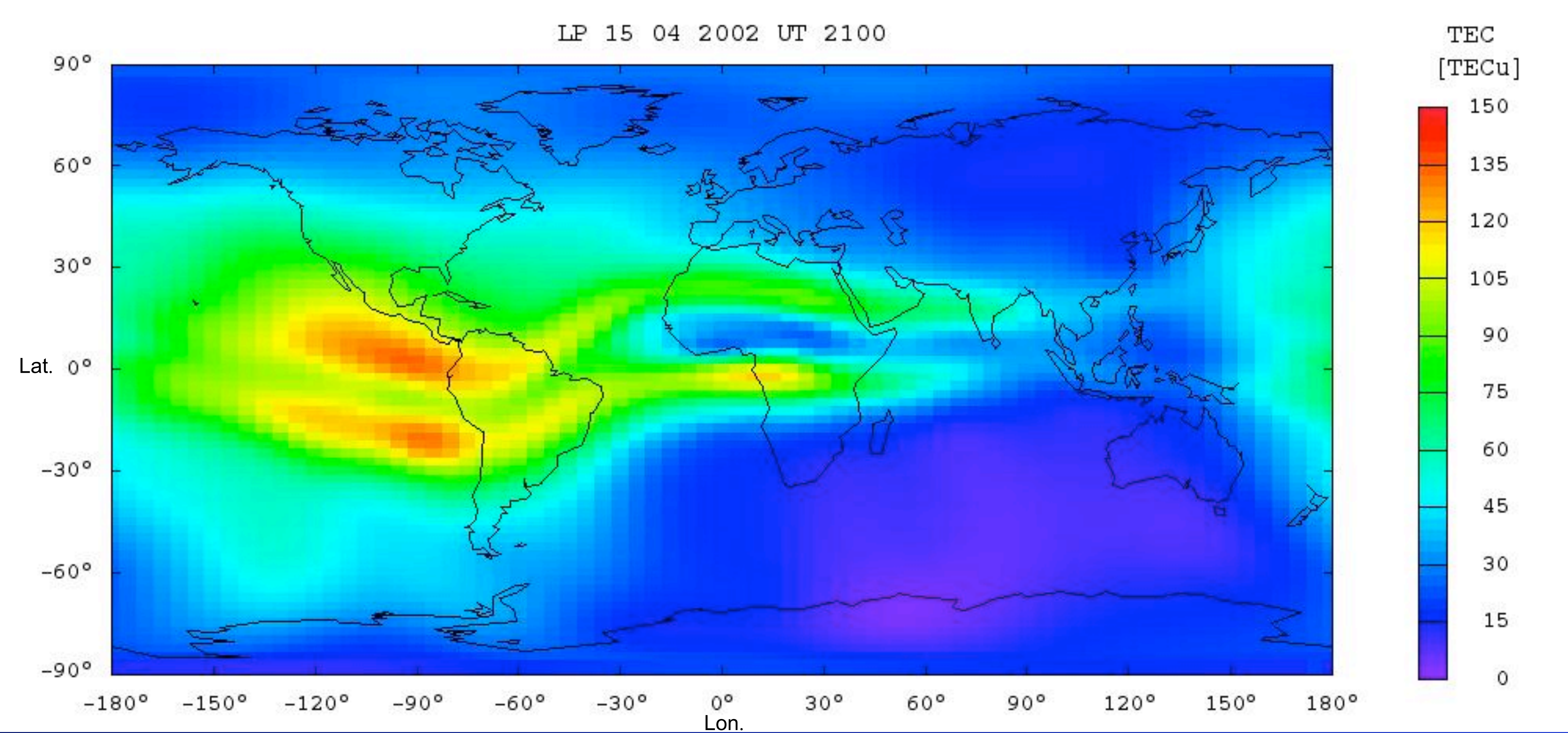
Data ingestion into NeQuick

- Empirical models like NeQuick have been conceived to reproduce the median behavior of the ionosphere ("climate").

- For research purposes and practical applications, to provide the 3-D electron density of the ionosphere for current conditions ("weather"), different retrieval techniques have been implemented.

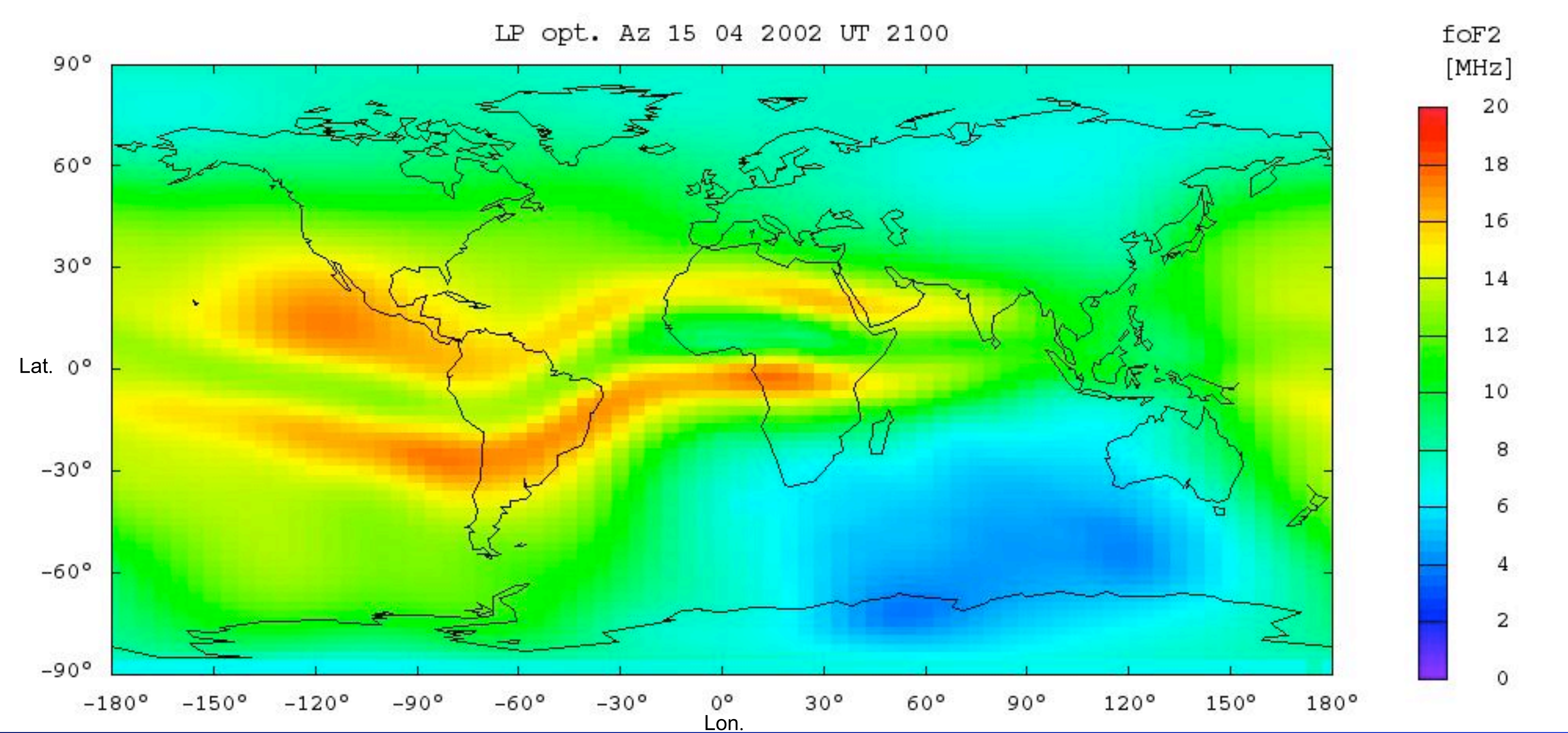
- They are based on the use of (multiple) effective parameters to adapt the NeQuick to GNSS-derived TEC data (and ionosonde measured peak parameters values). The adaptation can be performed using TEC values from:
  - a single GNSS receiver
  - multiple receivers
  - maps

Adapt to vTEC map



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

Reconstruct foF2 map



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

vTEC map data ingestion validation

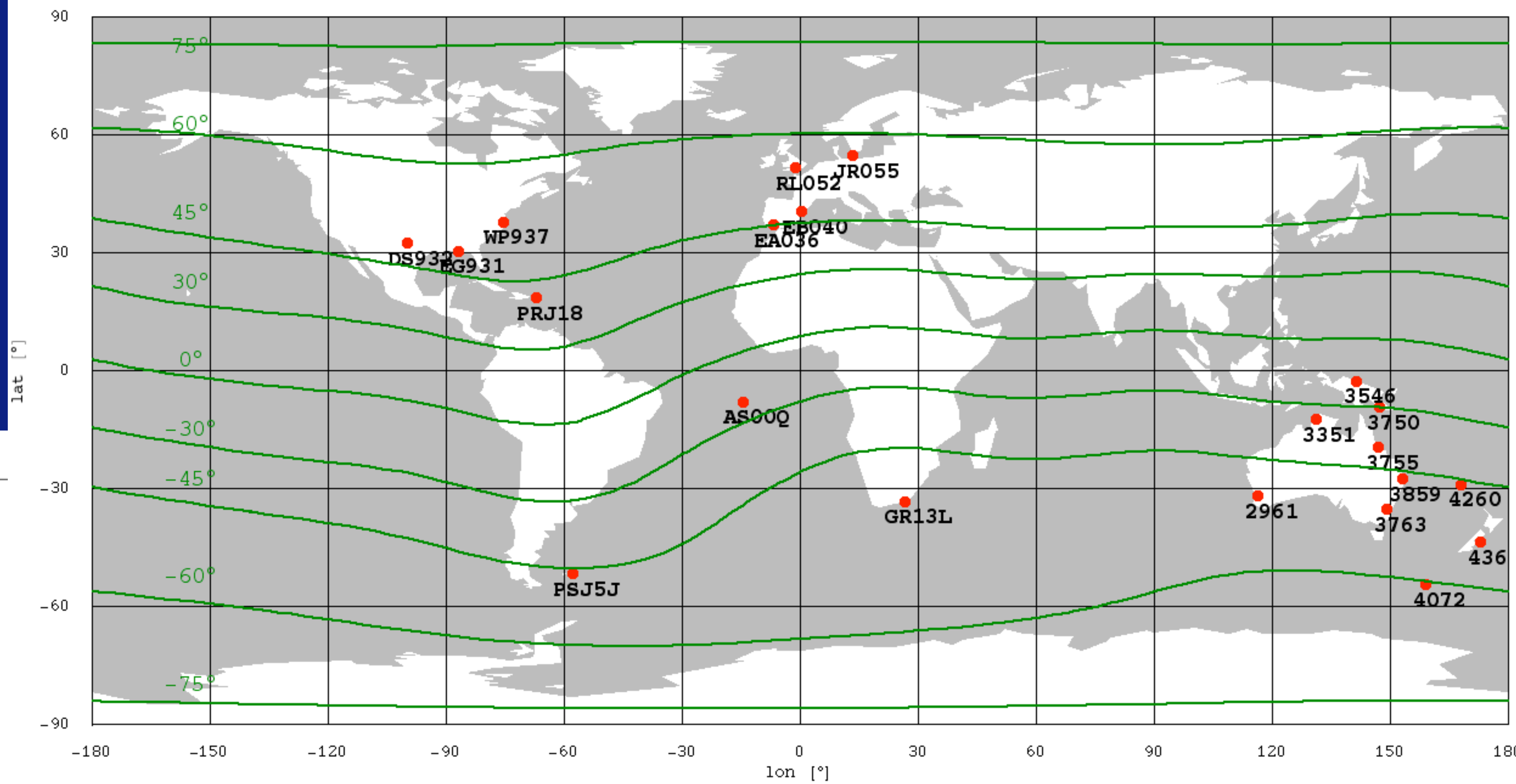
- Data at one hour time interval for Apr. 2000 (HSA) and Sep. 2006 (LSA) have been used.
  - In particular, LaPlata global vTEC maps have been used for the assimilation.
  - Manually scaled foF2 values have been used as independent “ground truth” measurements for comparison with the model-retrieved values.
- The statistical analysis has been carried on:

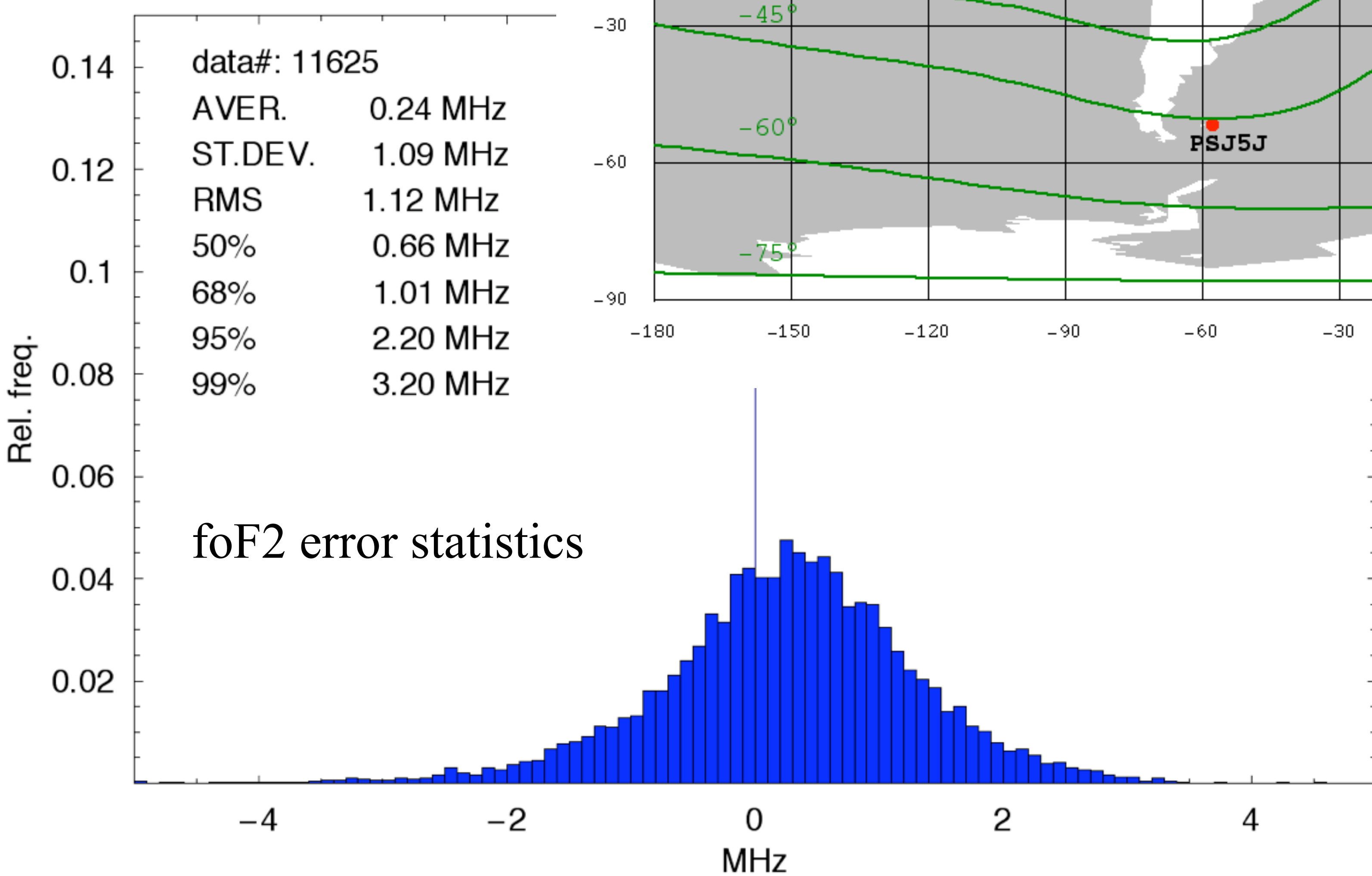
$$\Delta foF2 = foF2_{NeQ2} - foF2_{exp}$$

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

NeQuick2: validation results (example: HSA)

Apr. 2000





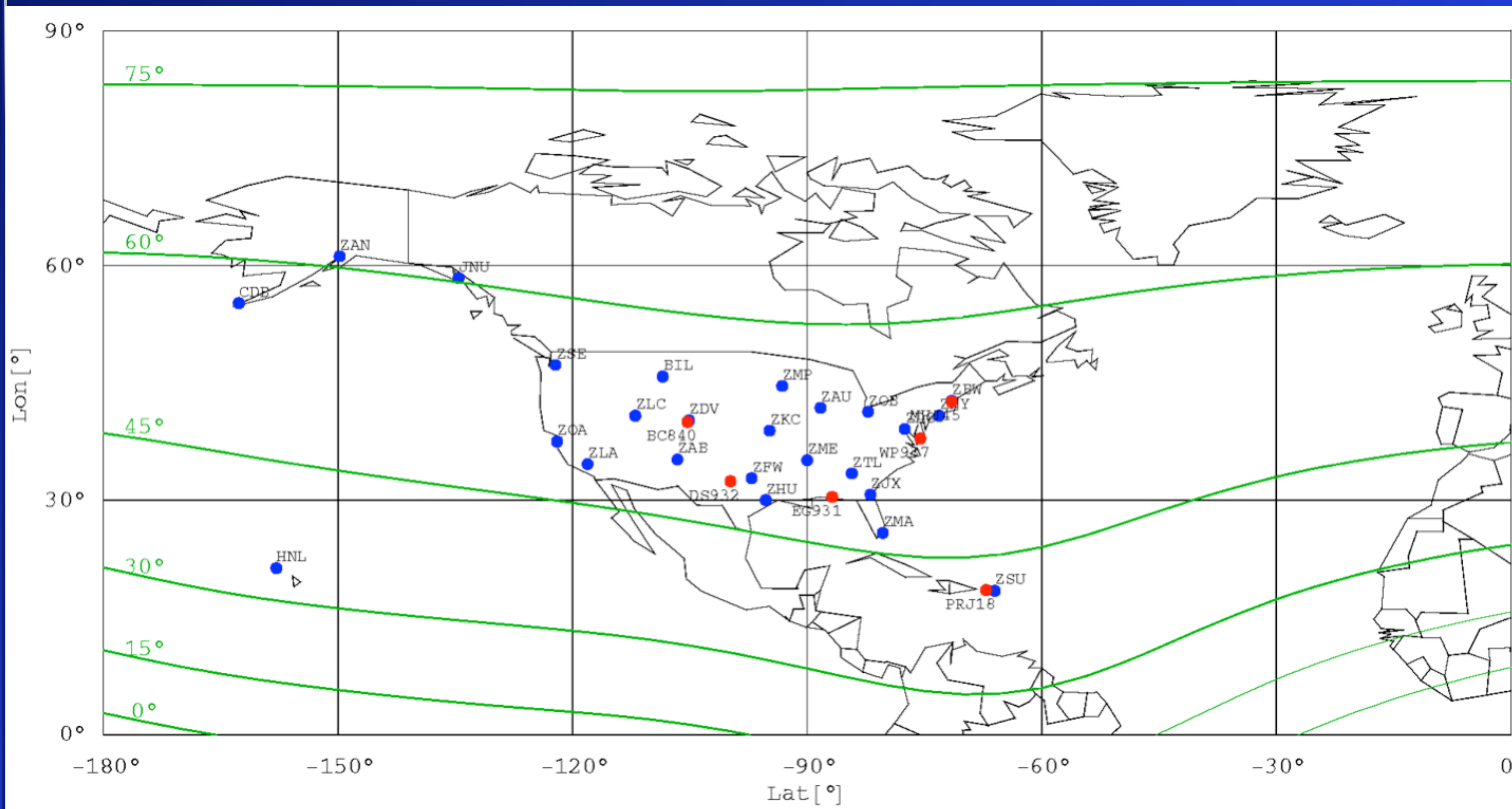
Nava, B., S. M. Radicella, and F. Azpilicueta (2011), Data ingestion into NeQuick 2, Radio Sci., 46, RS0D17, doi: 10.1029/2010RS004635

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

(For possible near real time applications)

Nava, B., S. M. Radicella, R. Leitinger, and P. Coïsson (2006), A near-real-time model-assisted ionosphere electron density retrieval method, Radio Sci., 41, RS6S16, doi:10.1029/2005RS003386

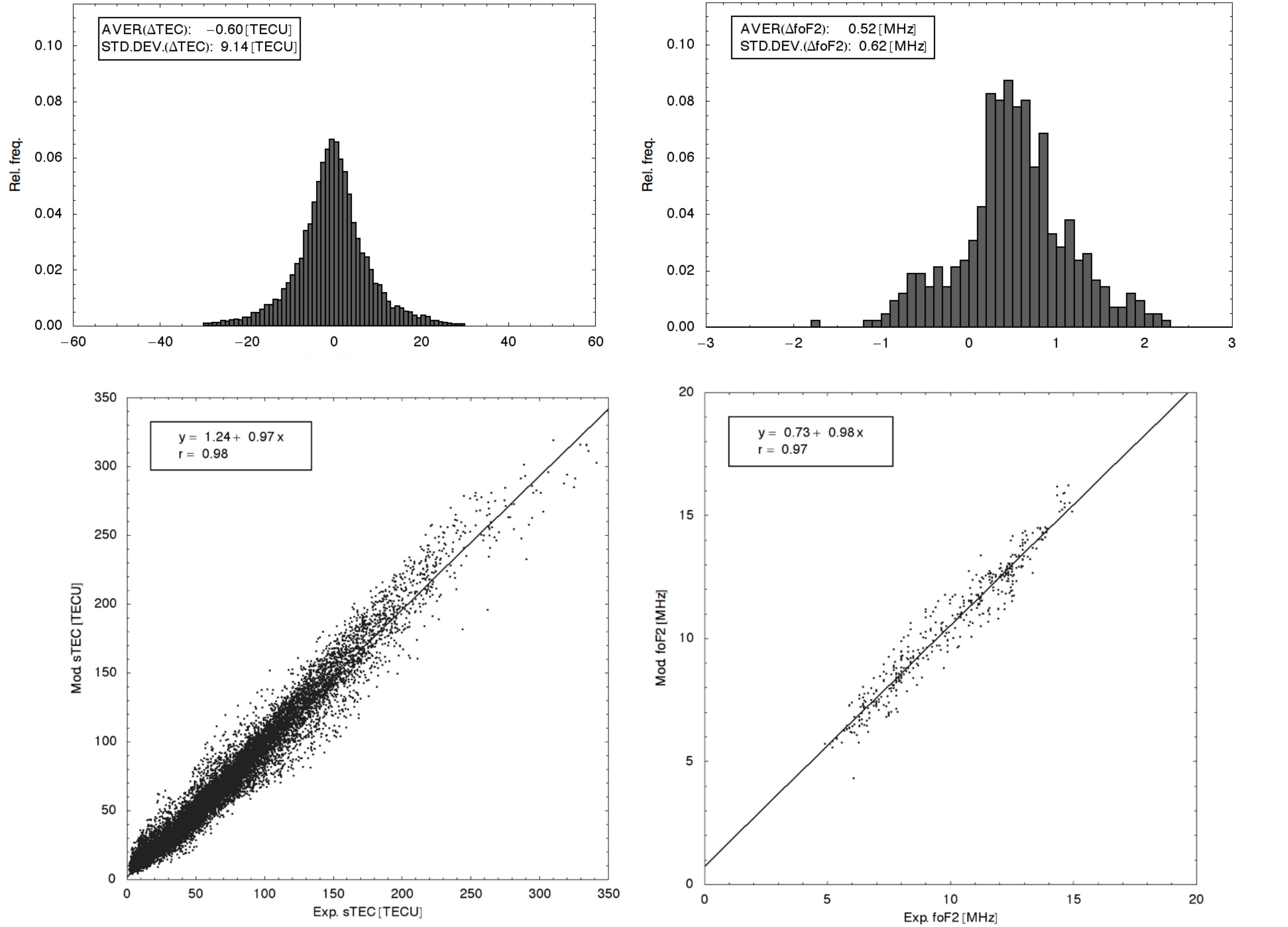
Stations & ionosondes locations



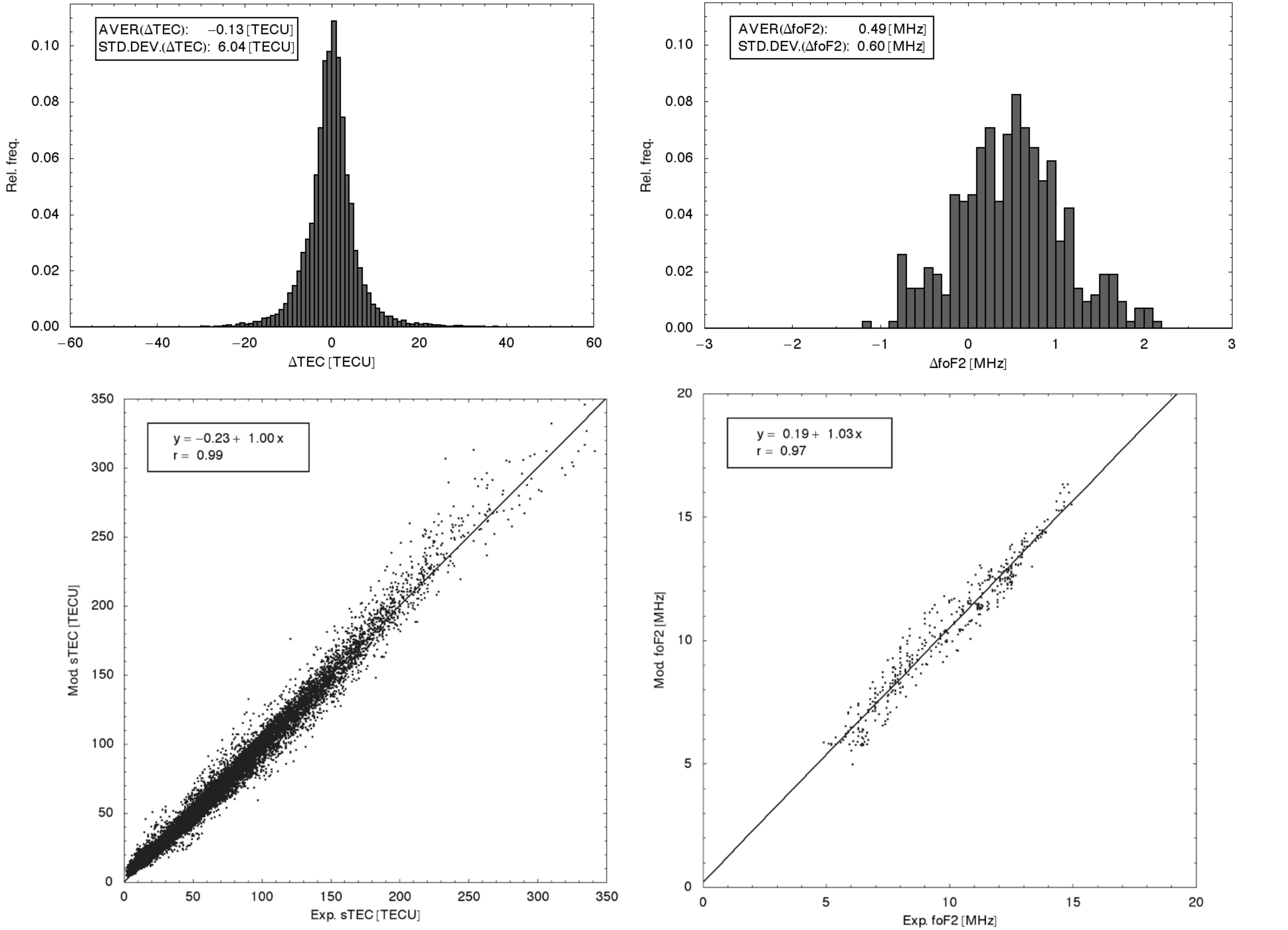
- GPS receivers
- Ionosondes

Modip isolines

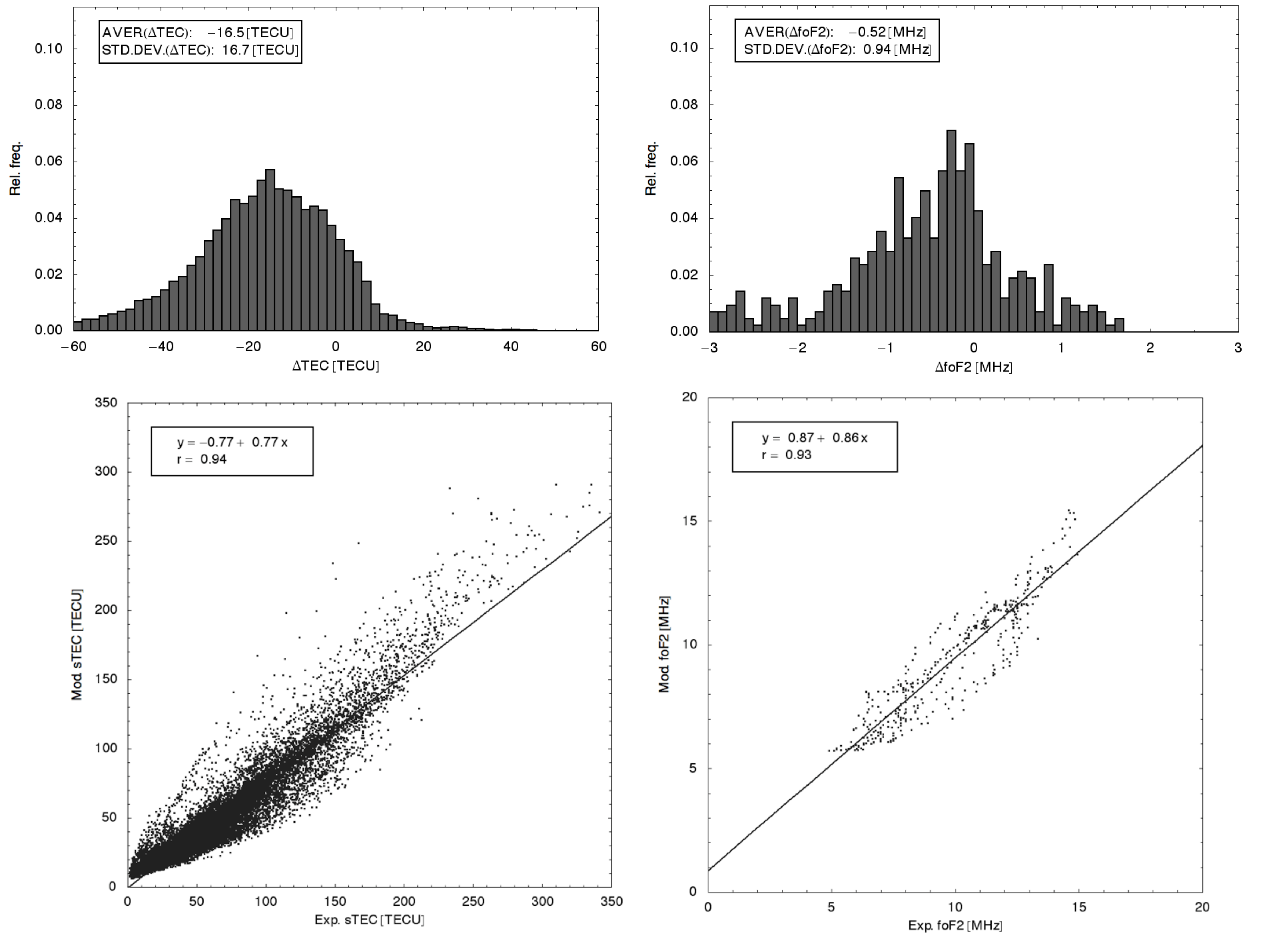
(6) Single station statistics (000405)



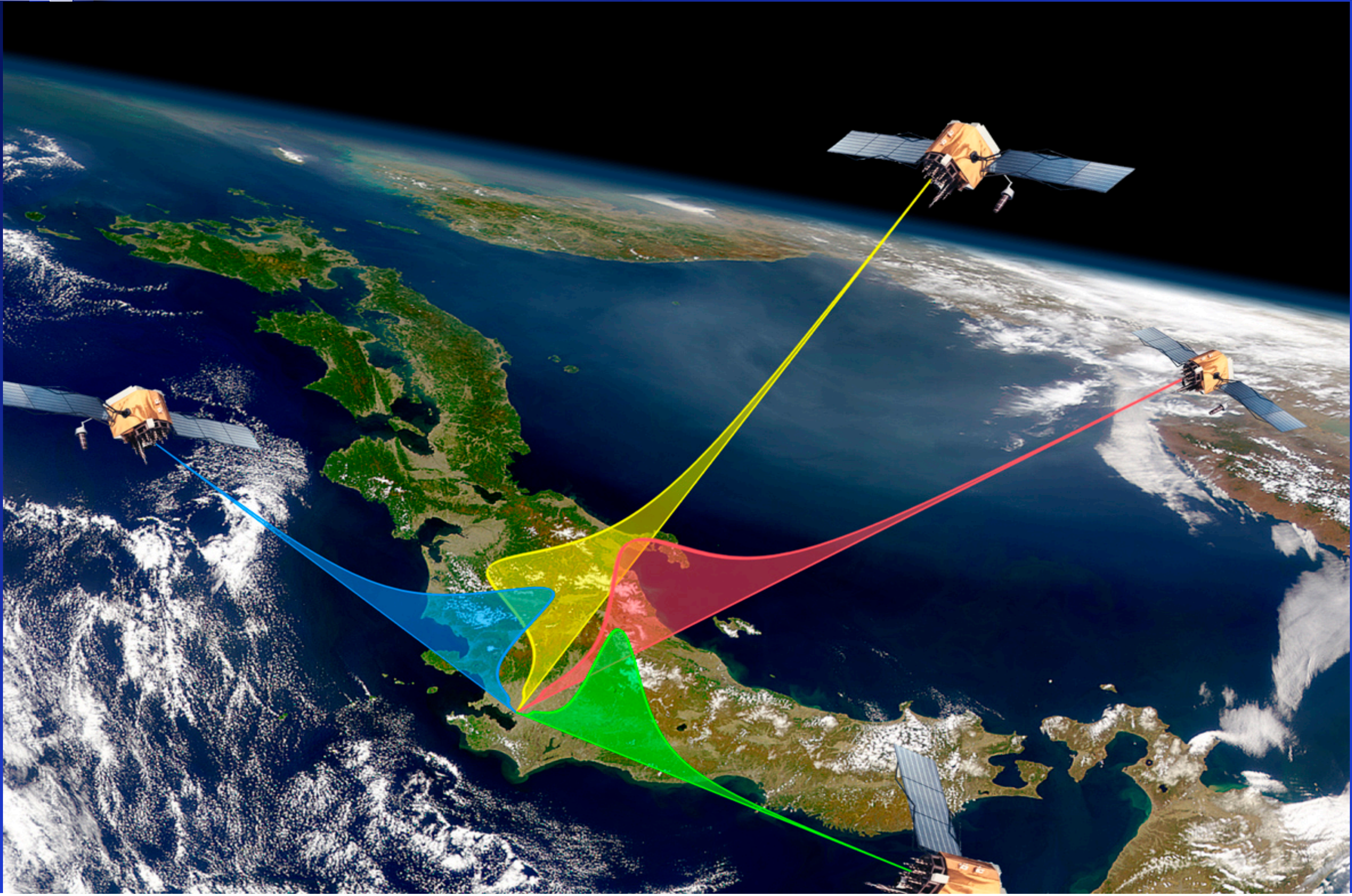
Multiple station statistics (000405)



Flux of the day statistics (000405)



Applications



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

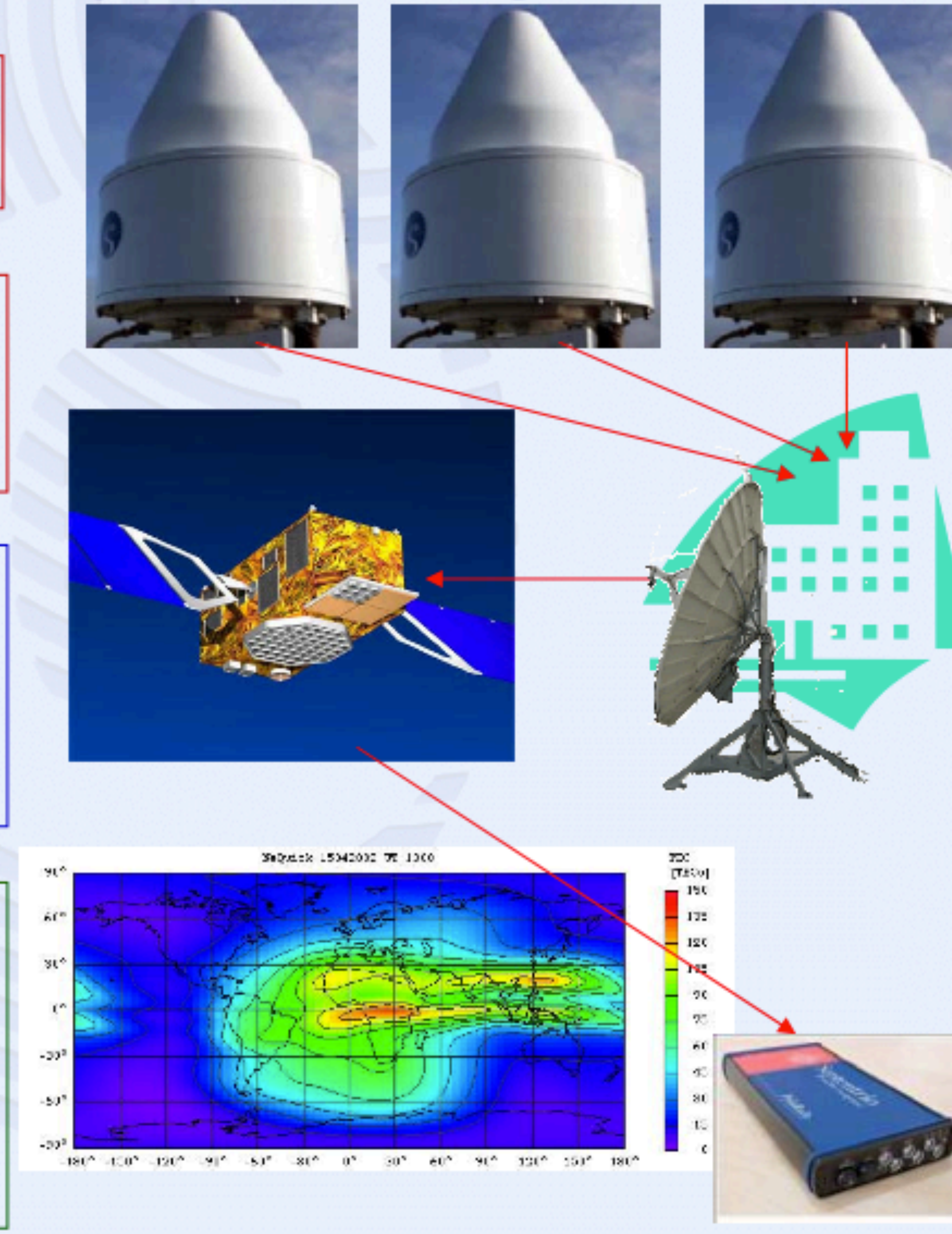
Transmit effective ionisation parameter in Navigation message

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

↓

USER RECEIVER

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



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

Mitigation of ionospheric effects

Position calculation mitigating
the ionospheric effect with:

↙ ↘

ICA, Klobuchar model
(driven by 8 coefficients)

NeQuick 2 model
(driven by f10.7)

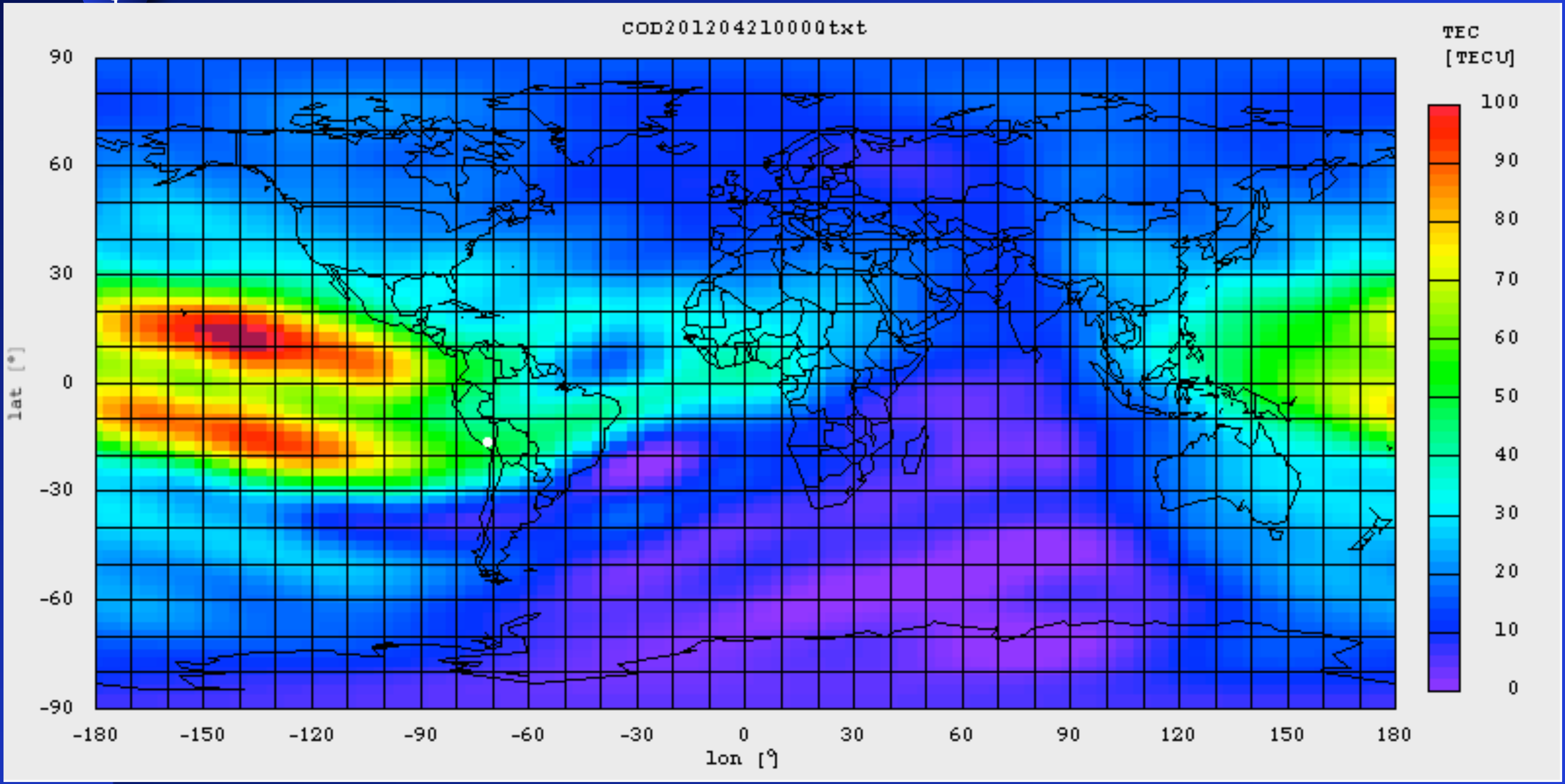
CODE VTEC maps
(SBAS-like approach)

NeQuick 2 model
(driven by Az grids)

areq (-16.46°N; -71.48°E)

2012 Apr 21; (doy 112)

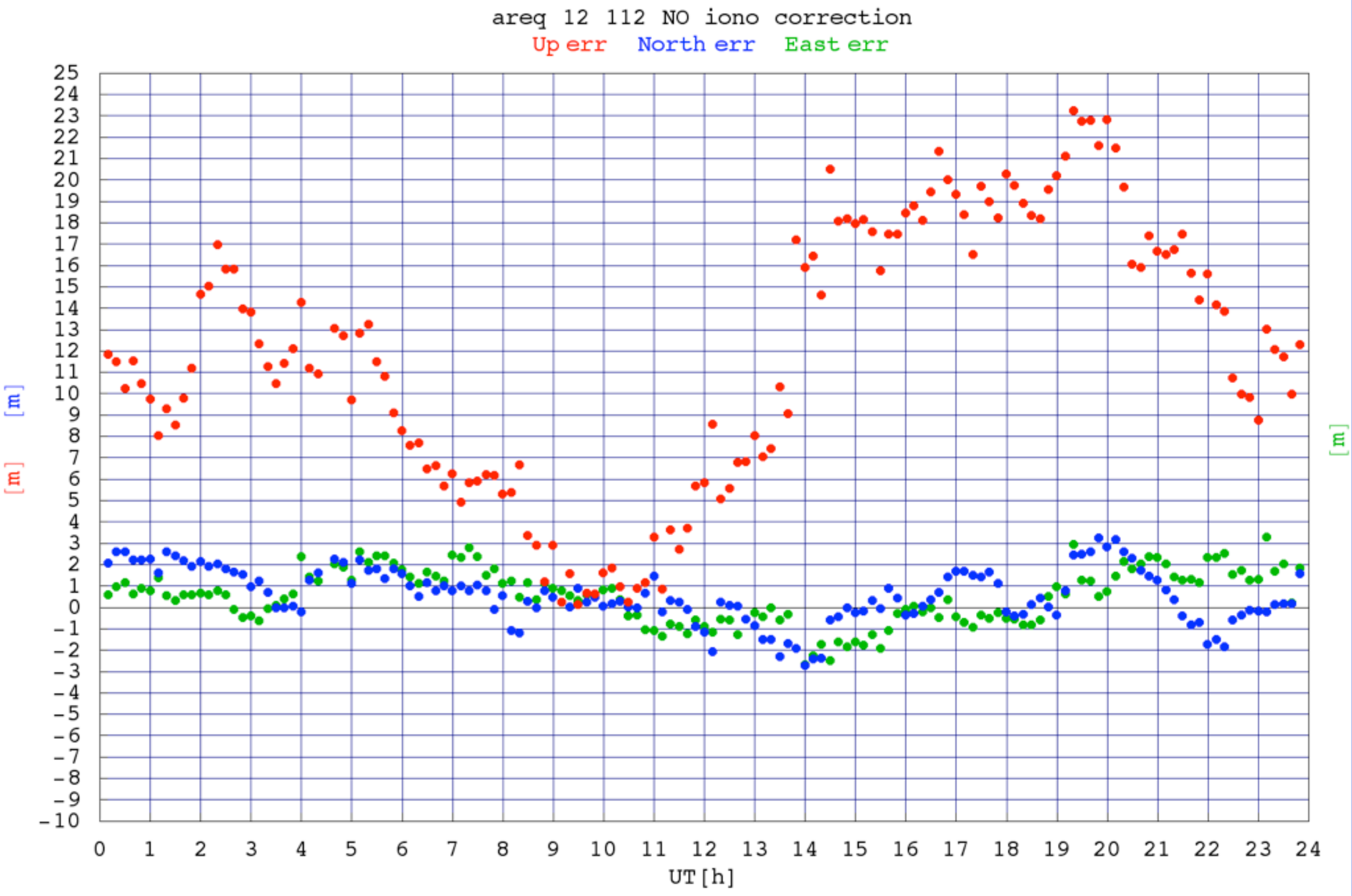
CODE VTEC map 2012 04 21



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

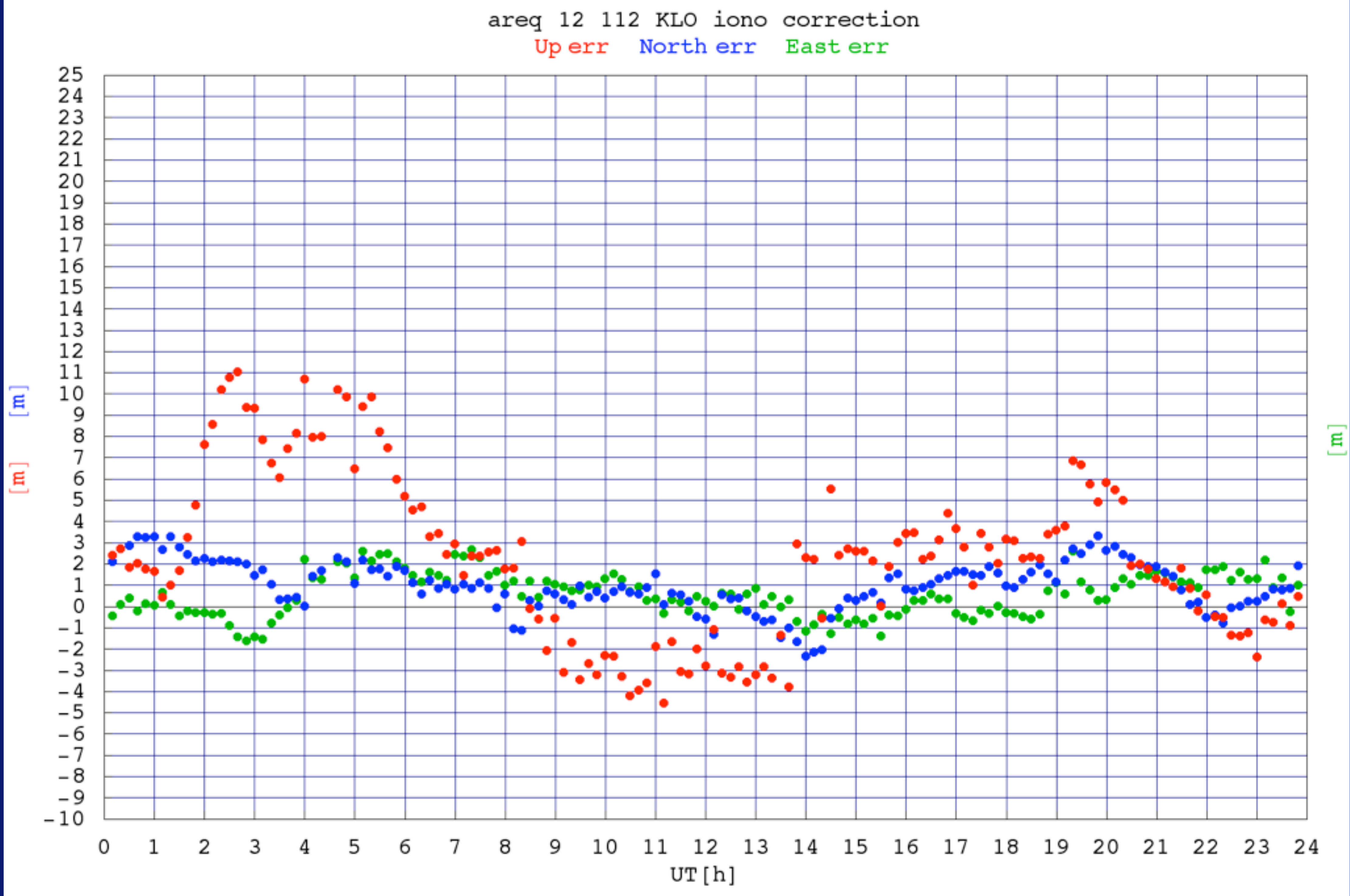
time interval:
10 min.
(interpolation)

Results



areq 12 112 NO iono correction
Up err North err East err
[m]
[m]
[m]
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
UT [h]

Results


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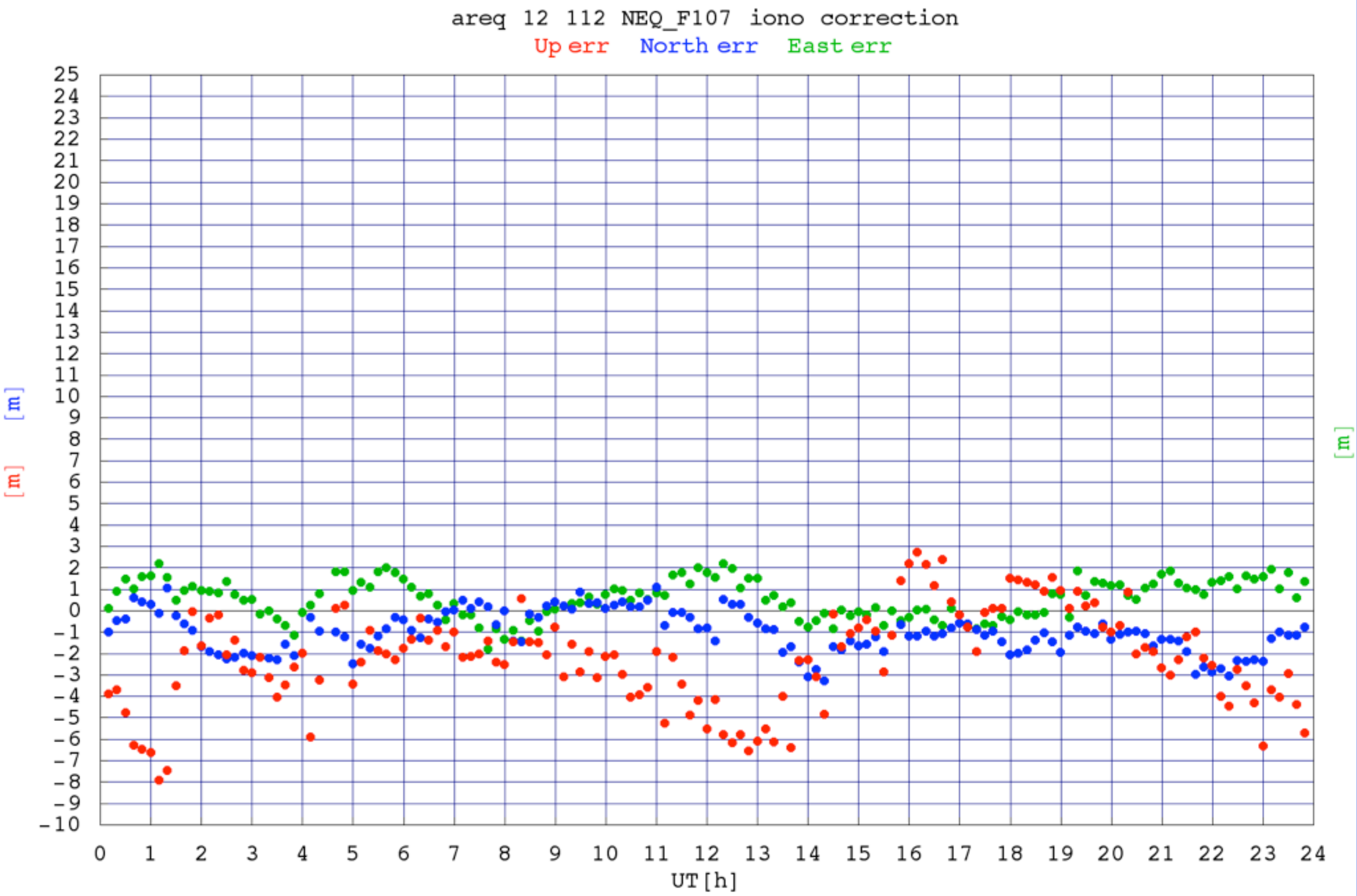
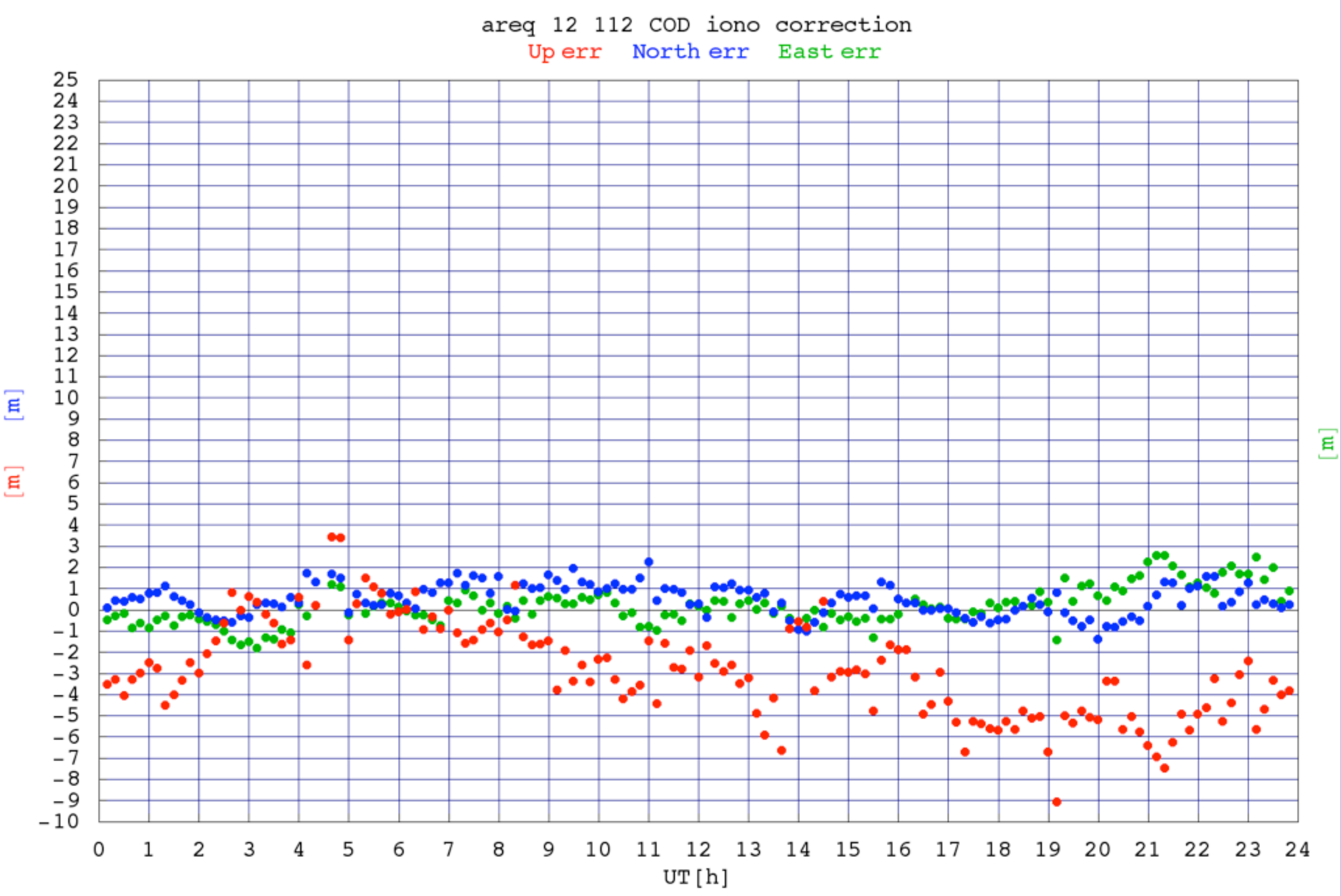
-8
-9
-10
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24

Results

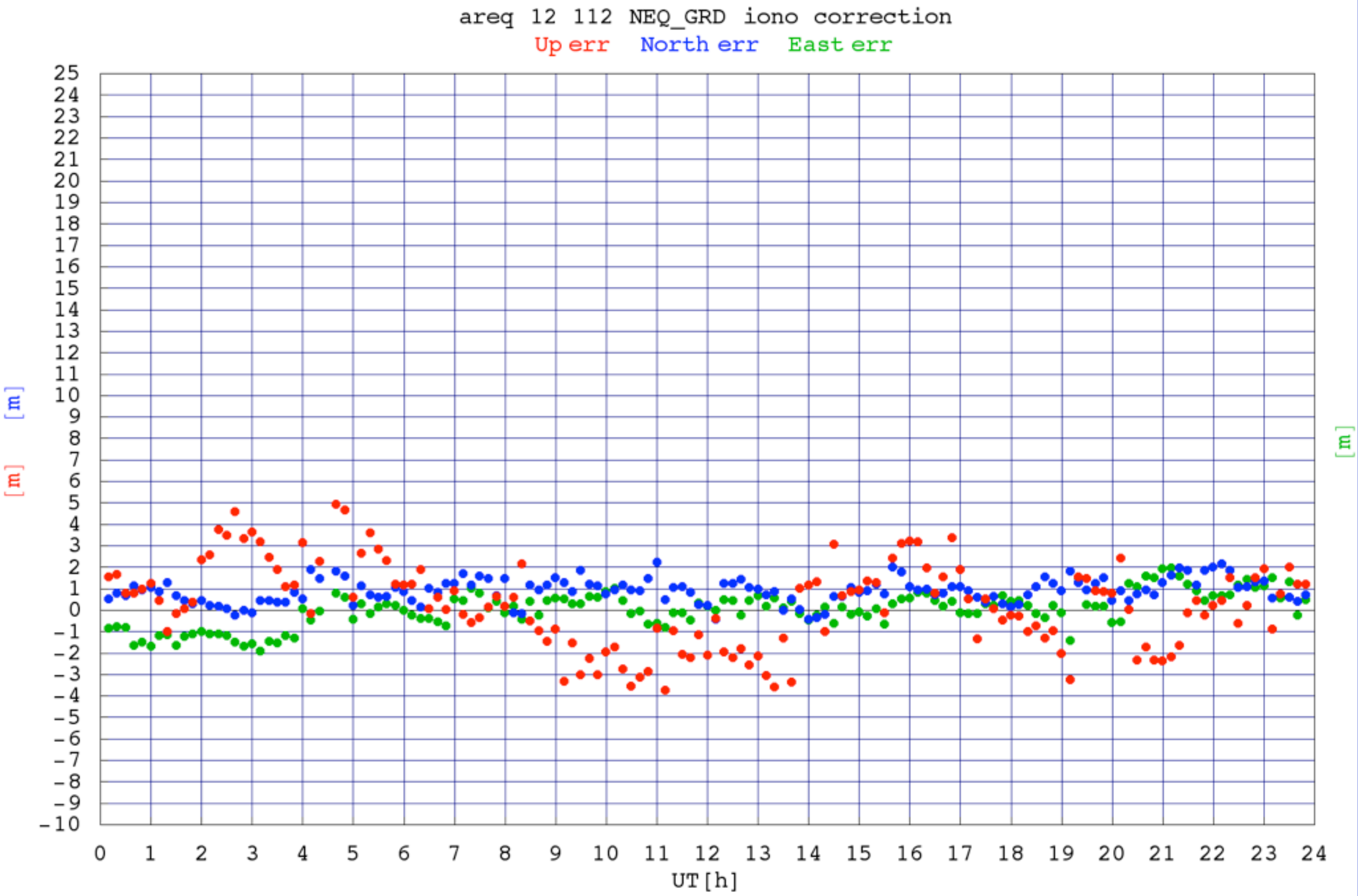

areq 12 112 NEQ_F107 iono correction
Up err North err East err
[m]
[m]
[m]
UT [h]

Results



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

Results



areq 12 112 NEQ_GRD iono correction
Up err
North err
East err
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-6
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-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]

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

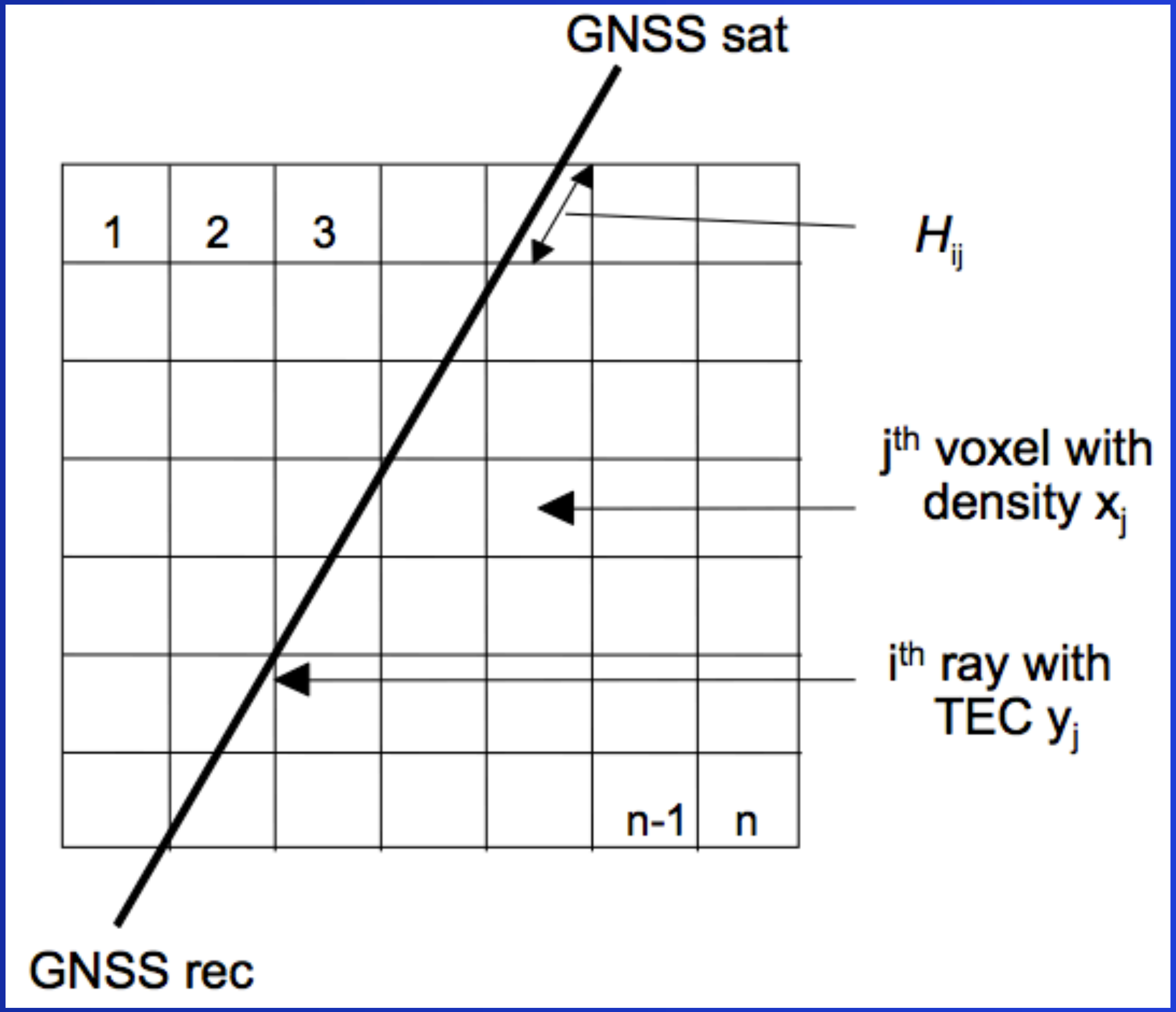
A covariance matrix of analysis errors

*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

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



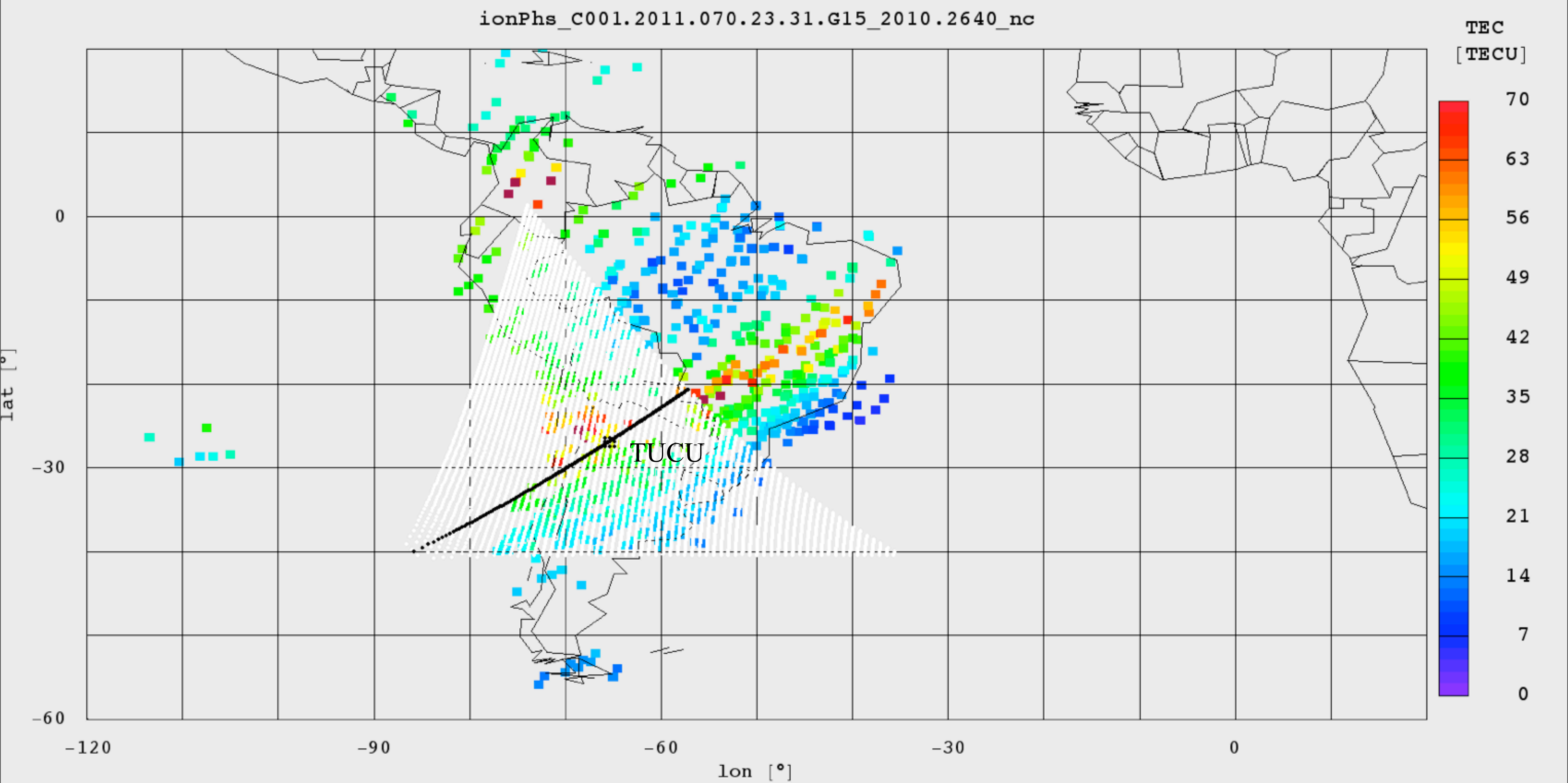
K is called *gain* of the analysis

In our case:

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

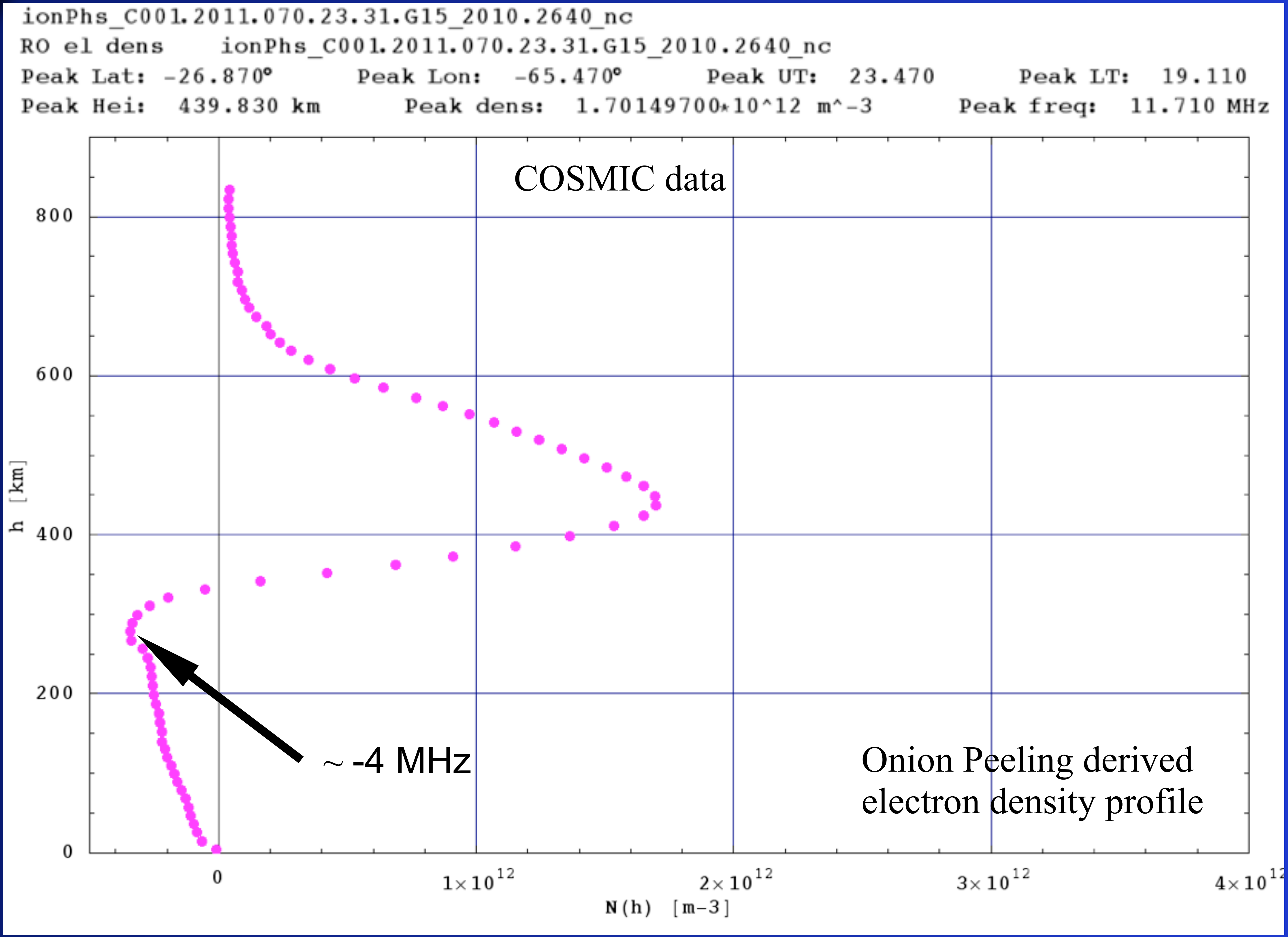
e.g. bckg_TEC = $\mathbf{Hx_b} = \sum_j H_{ij}\, x_{bj}$

LS solution: a challenging case

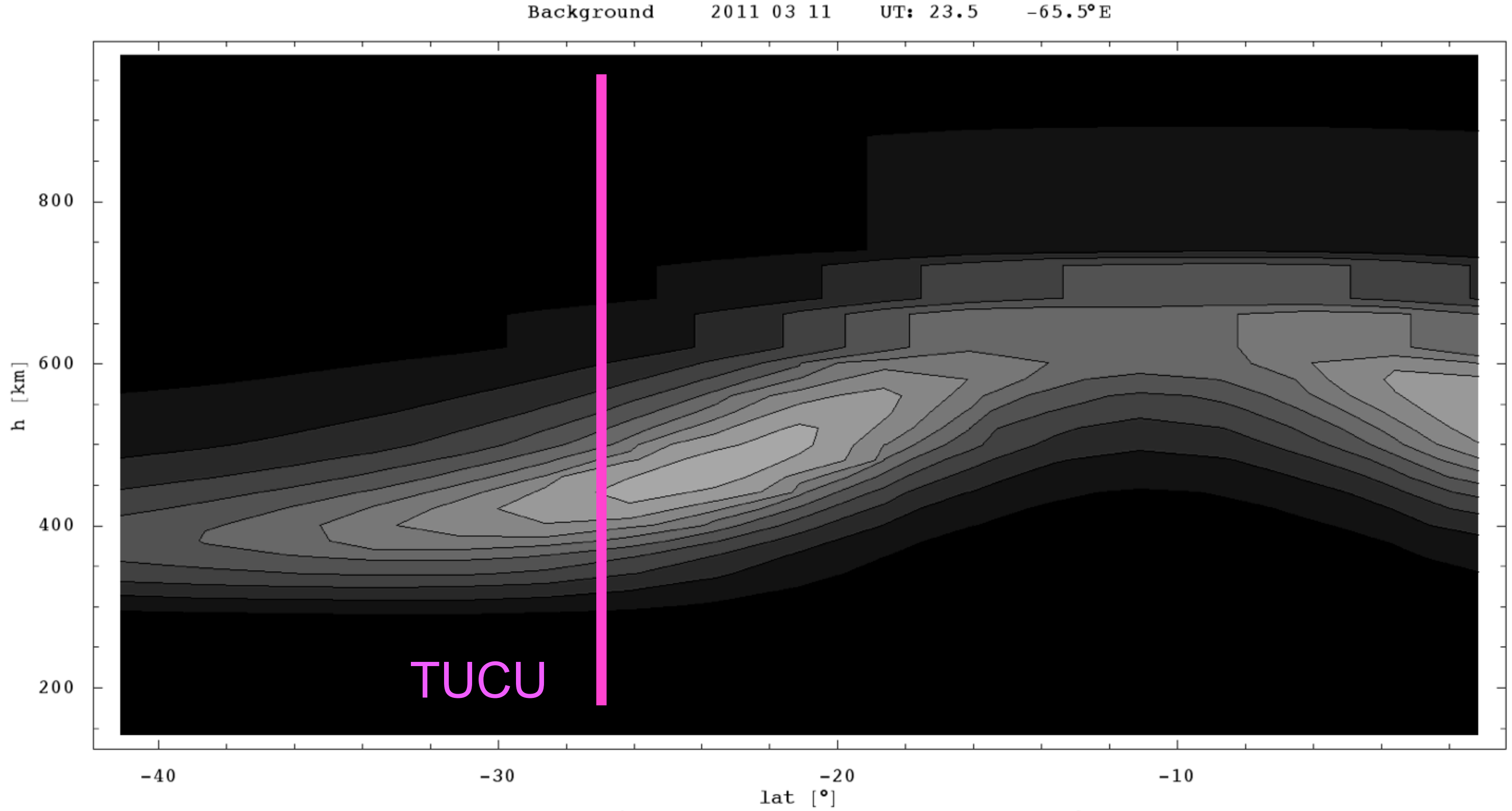


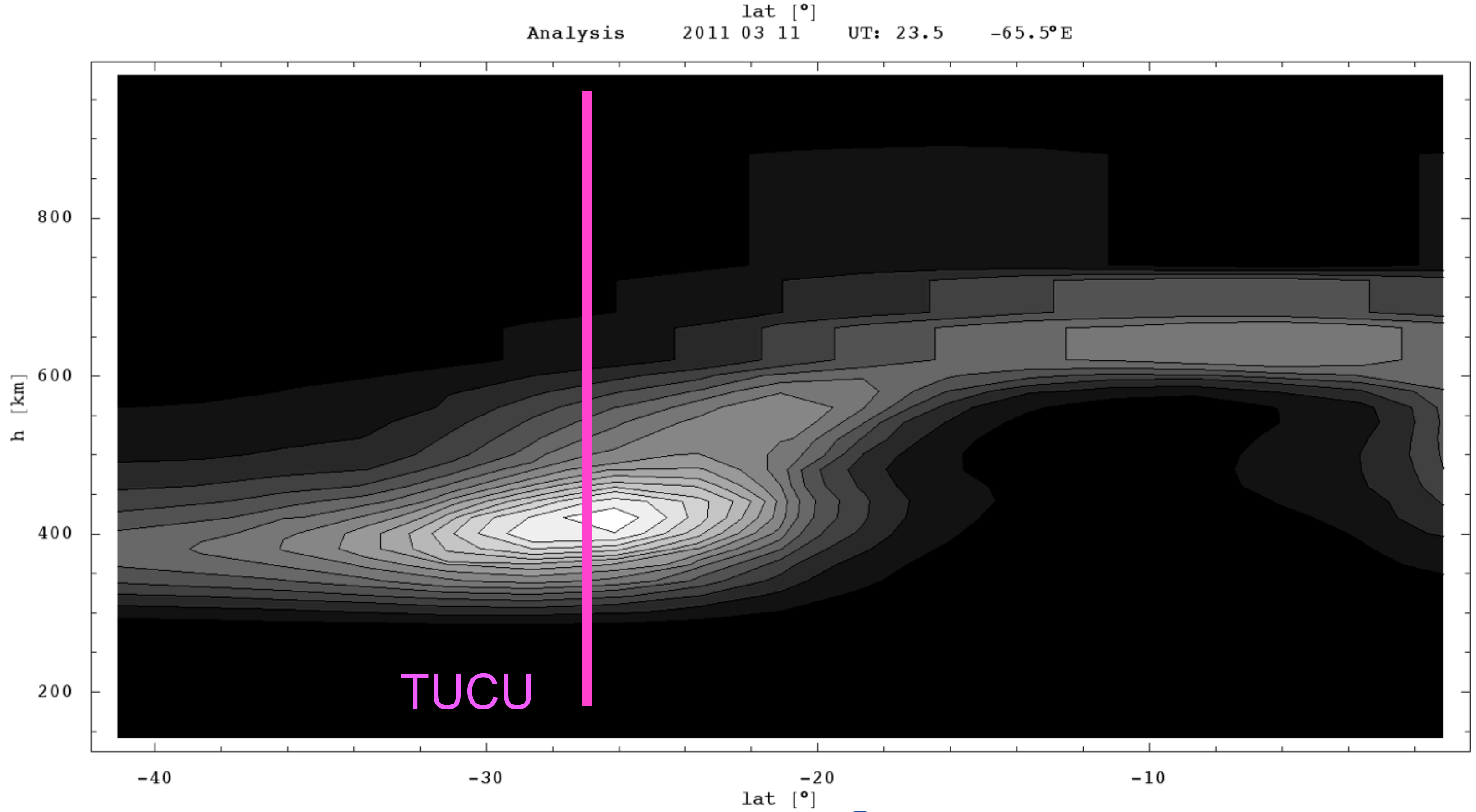
- projections of the LEO -> GPS links below the LEO orbit
- tangent points of the LEO -> GPS links

LS solution: a challenging case



Results: retrieved electron density



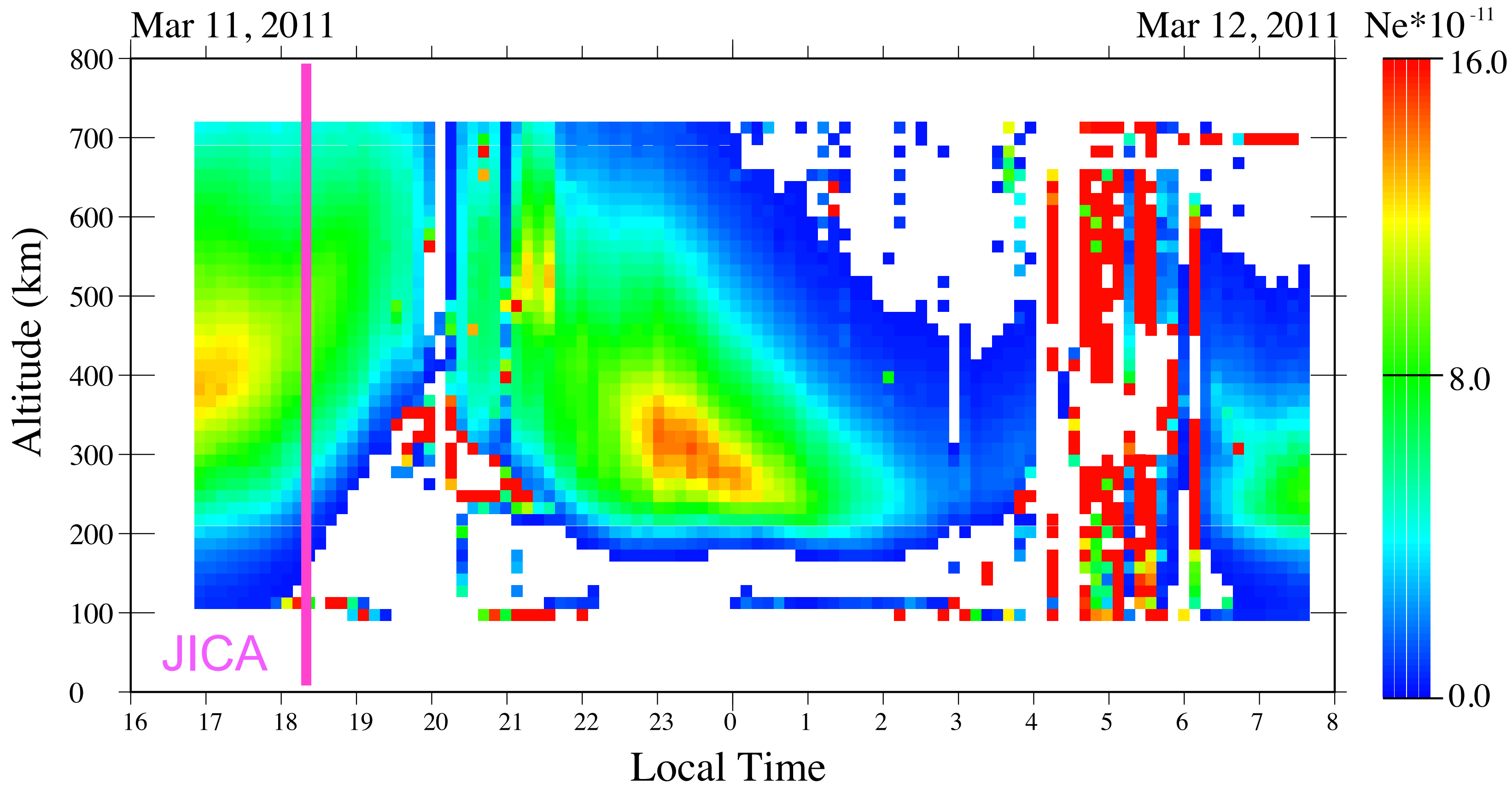


Cross section
23:30UT; -65.5°E
from -40°N to -2°N

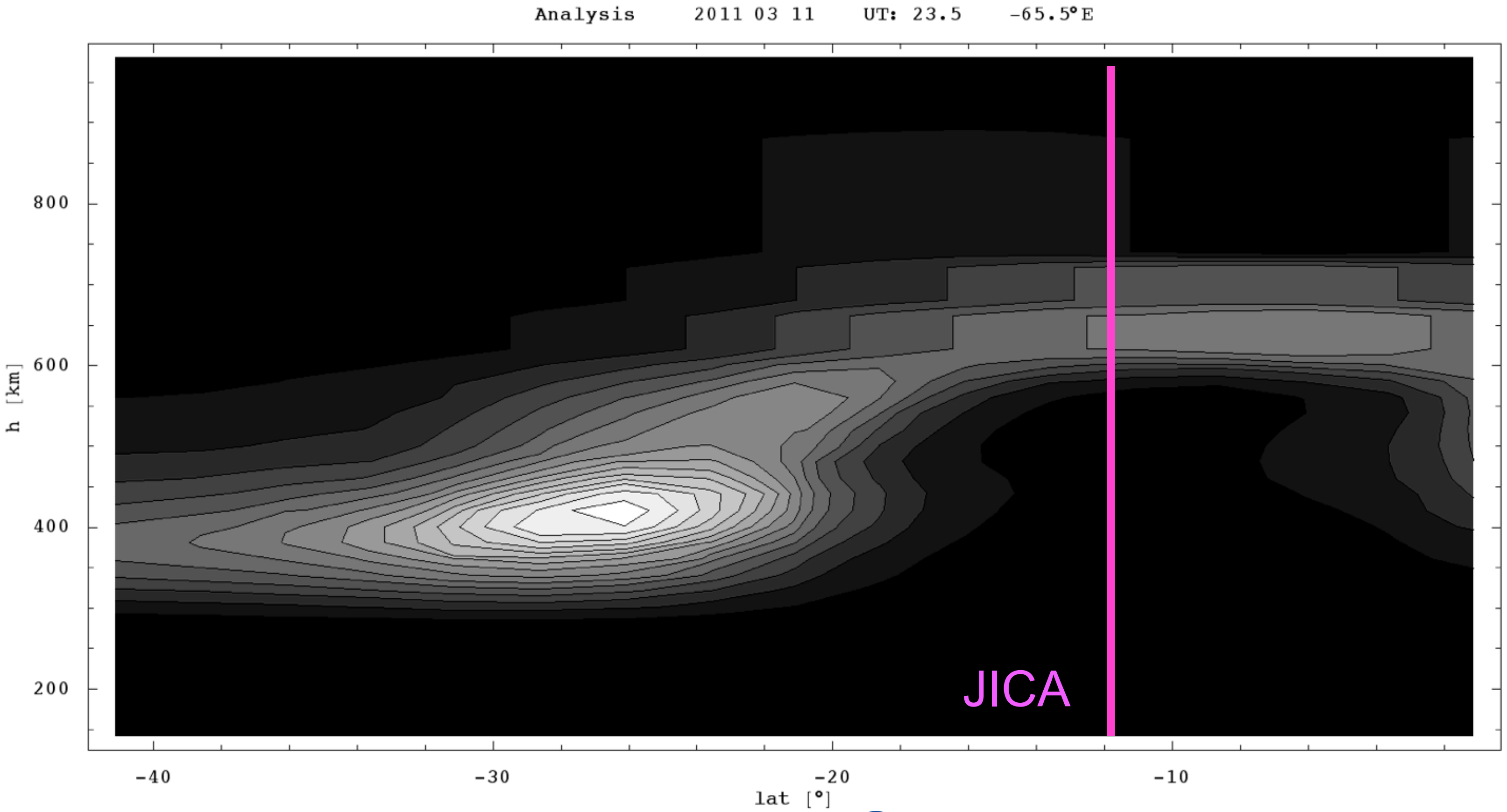
Background model
(before the assimilation)

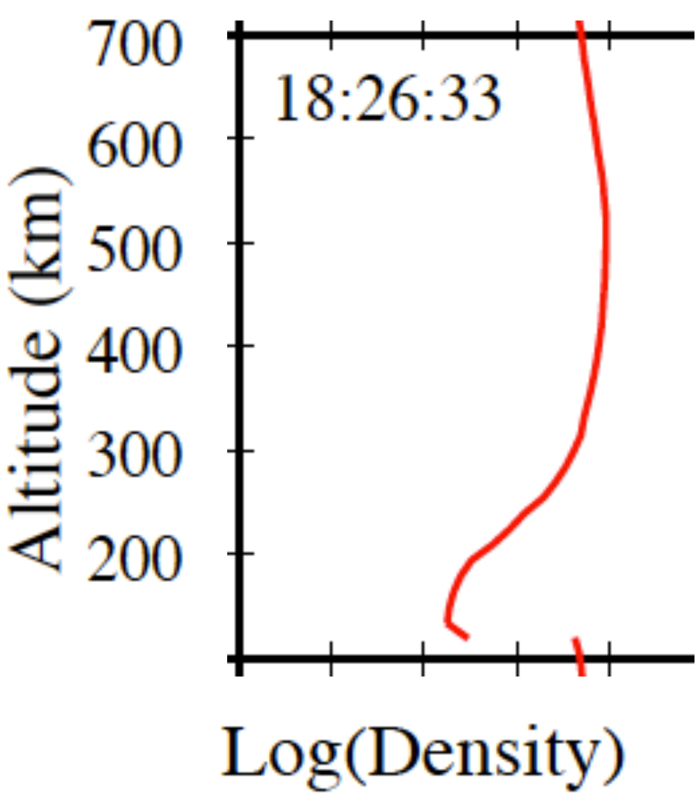
Analysis
(after the assimilation)

Results: retrieved electron density

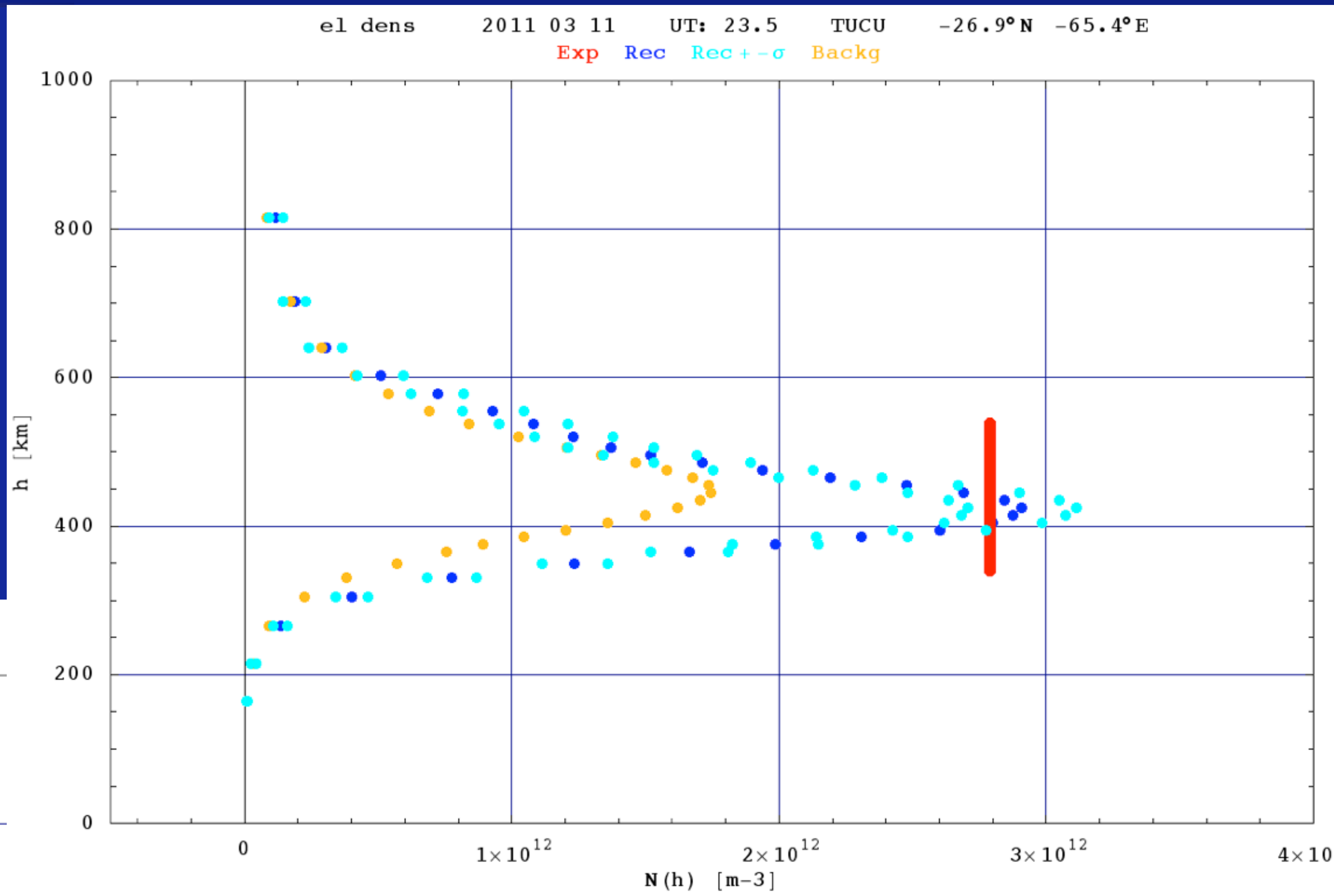


Jicamarca data
(C. Valladares)

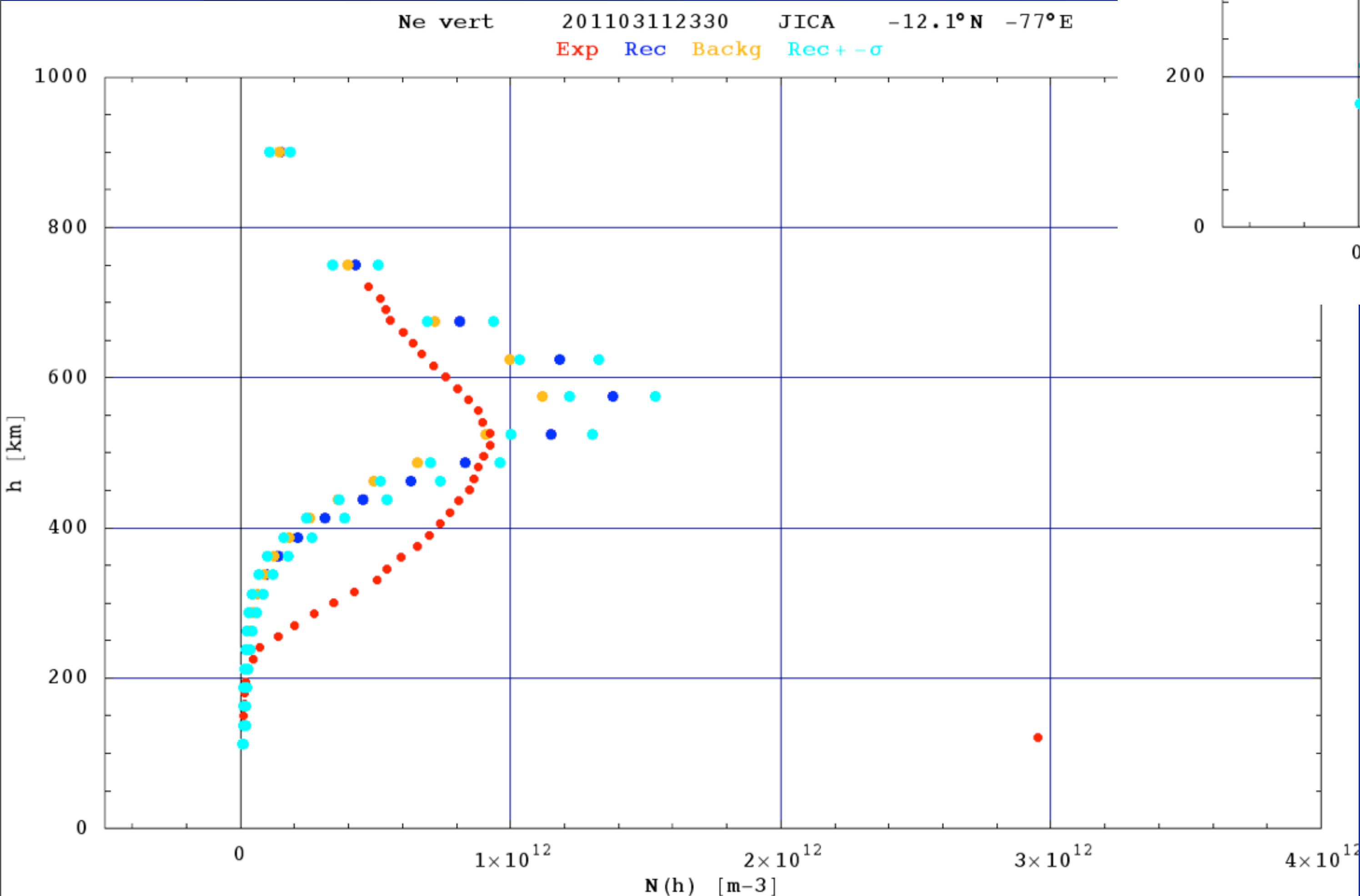




Method validation



Electron density profiles at JRO location



Electron density profiles at Ionosonde location

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; Gigi Ciraolo; Marta Mosert, ICATE - CONICET; Italian Space Space Agency (ASI), Air Navigation Service Company (ENAV); 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