The NeQuick ionosphere electron density model: a historical overview

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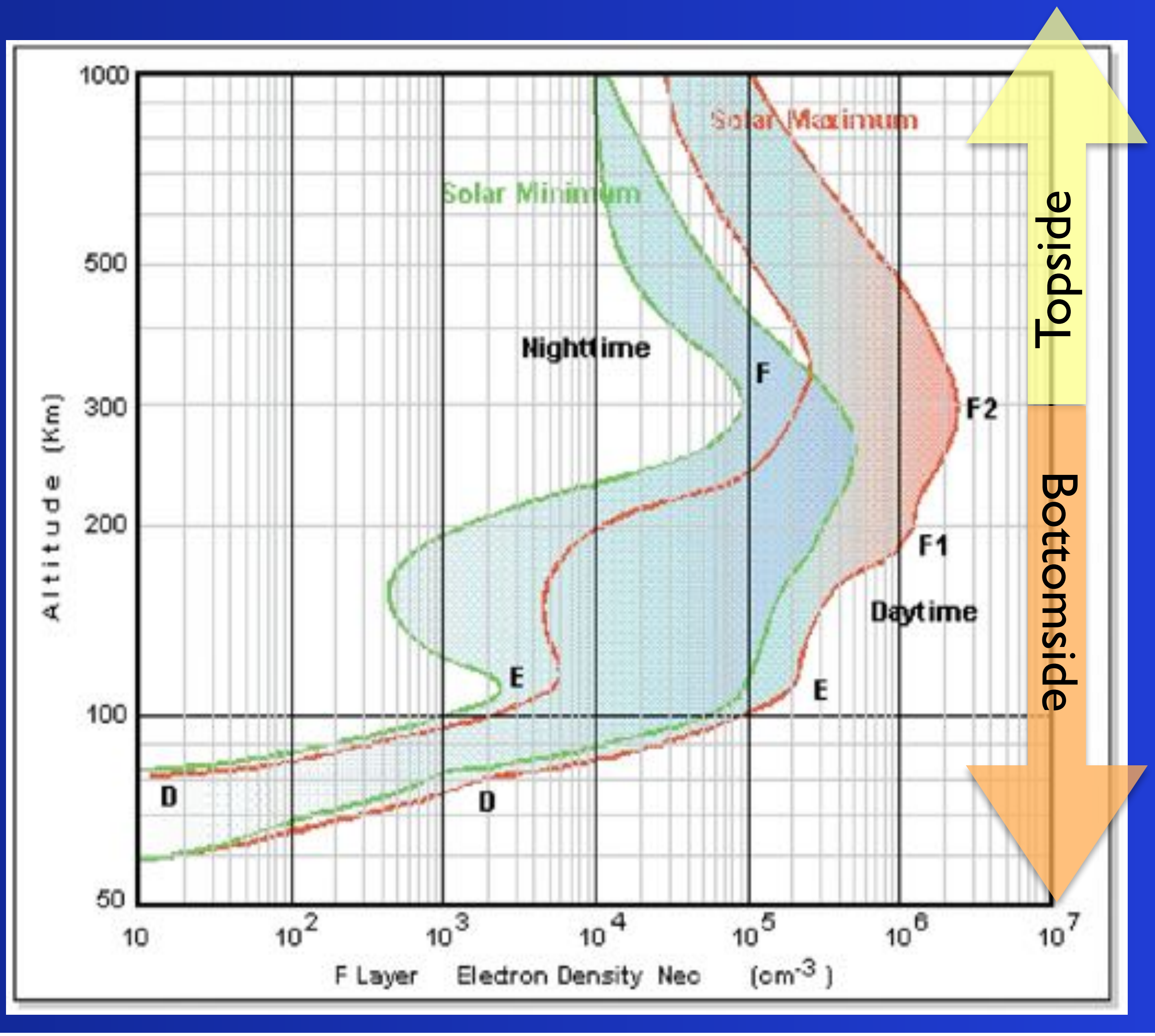
Morphology of the ionosphere

The Earth's ionosphere is defined as that part of the upper atmosphere where sufficient free electrons and ions exist to affect the propagation of radio waves. It is mainly produced by solar UV and X-radiation which dissociates and ionizes the mixture of gases (such as N2, O2, O) in the upper atmosphere.

The understanding of the behaviour of the ionosphere and its effects on human activity is determined by the ability to model at least the height, geographical and time distributions of the electron density (Ne).



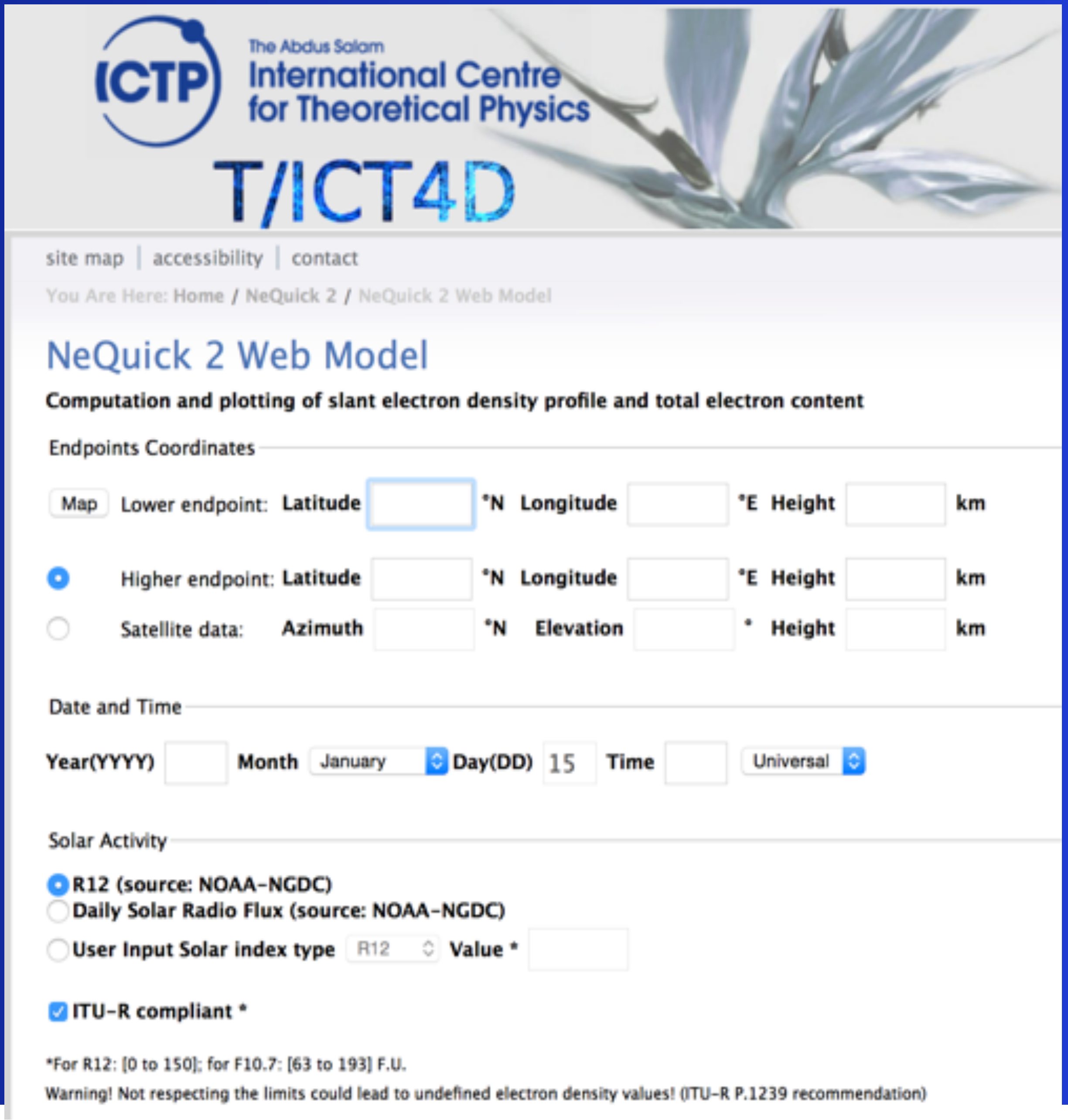
credit: http://gbailey.staff.shef.ac.uk/researchoverview.html

The NeQuick model

- The NeQuick is an ionospheric electron density model developed at the T/ICT4D 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 a quick–run empirical model particularly designed for trans–ionospheric propagation applications, conceived to reproduce the median behavior of the ionosphere.

- http://t-ict4d.ictp.it/nequick2

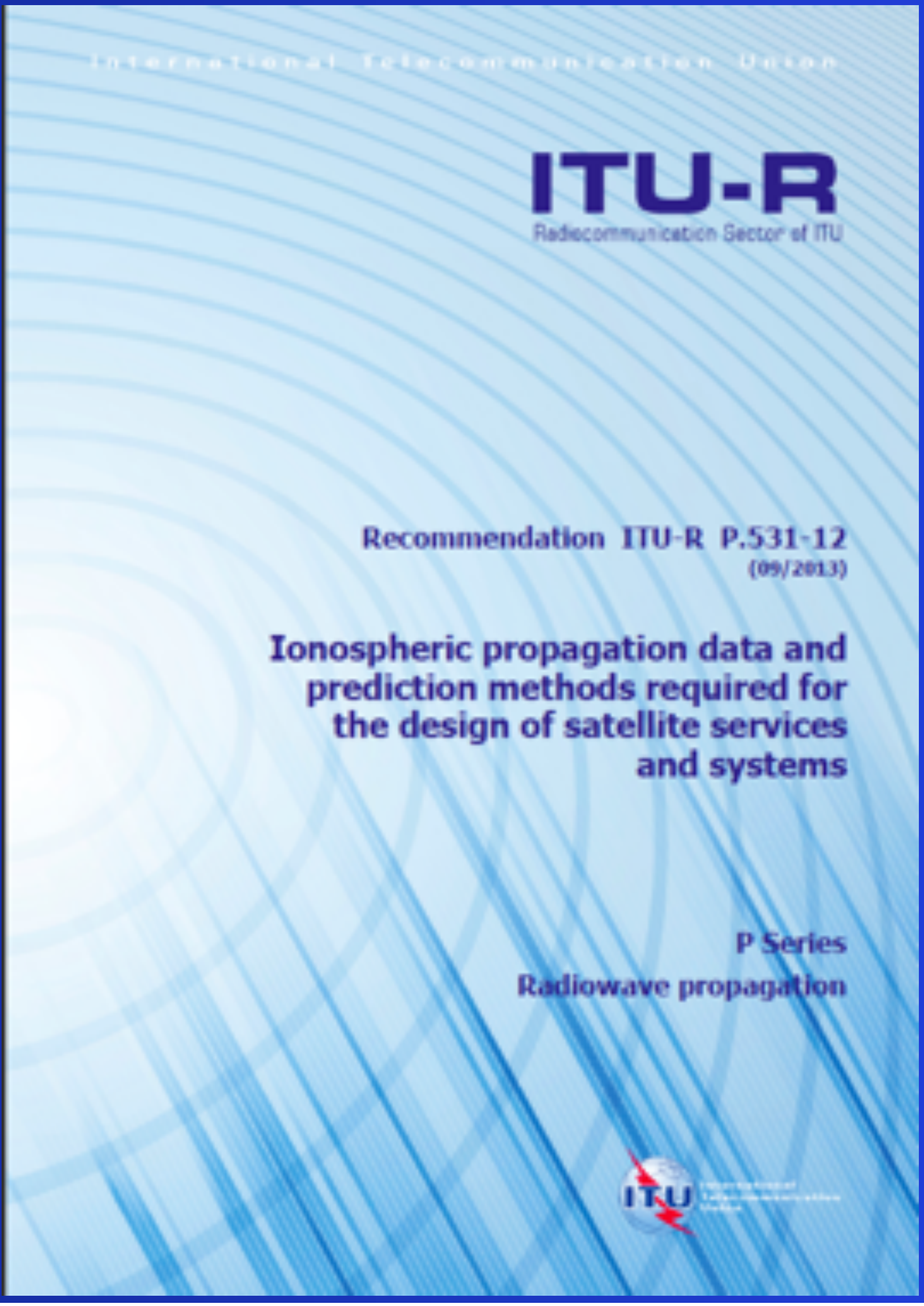


The NeQuick model

- It is based on the DGR “profiler” proposed by Di Giovanni and Radicella (1990) and subsequently modified by Radicella and Zhang (1995).
- It is described by Hochegger, et al. (2000).
- Further improvements have been implemented by Radicella and Leitinger (2001).
- A modified bottomside has been introduced by Leitinger et al. (2005).
- A modified topside has been proposed by Coïsson et al. (2006).
- All these efforts (including relevant modifications of the source code) directed toward the developments of a new version of the model, have led to the implementation of the NeQuick2 (Nava et al., 2008).

NeQuick developments

- The NeQuick (v1) has been adopted by Recommendation ITU-R P. 531 as a procedure for estimating TEC.
- Subsequently, the NeQuick 2 has substituted the NeQuick (v1) and it is the one currently recommended by ITU (ITU-R Recommendation P.531-12).
- 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)).



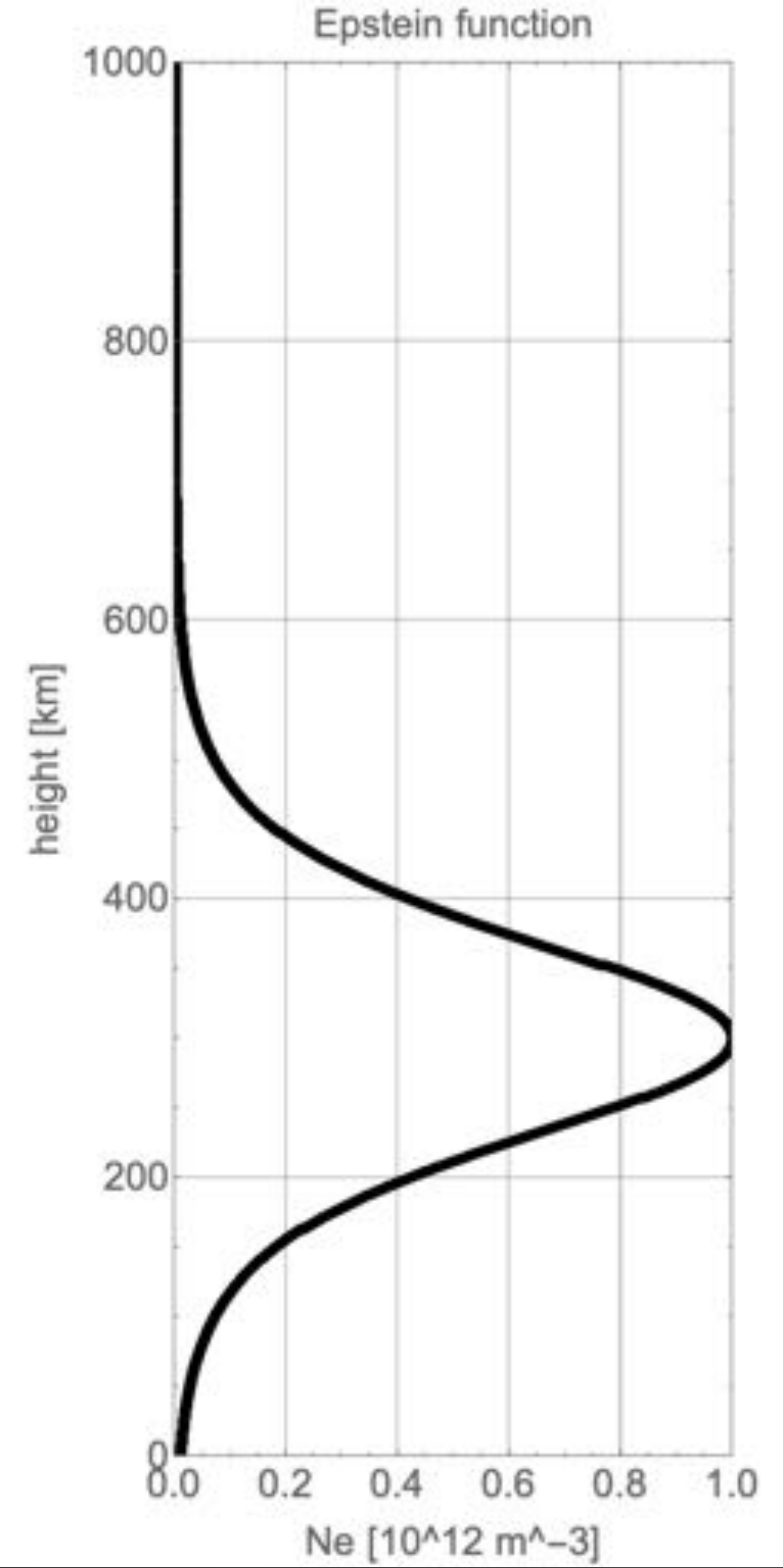
NeQuick 2

- 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.

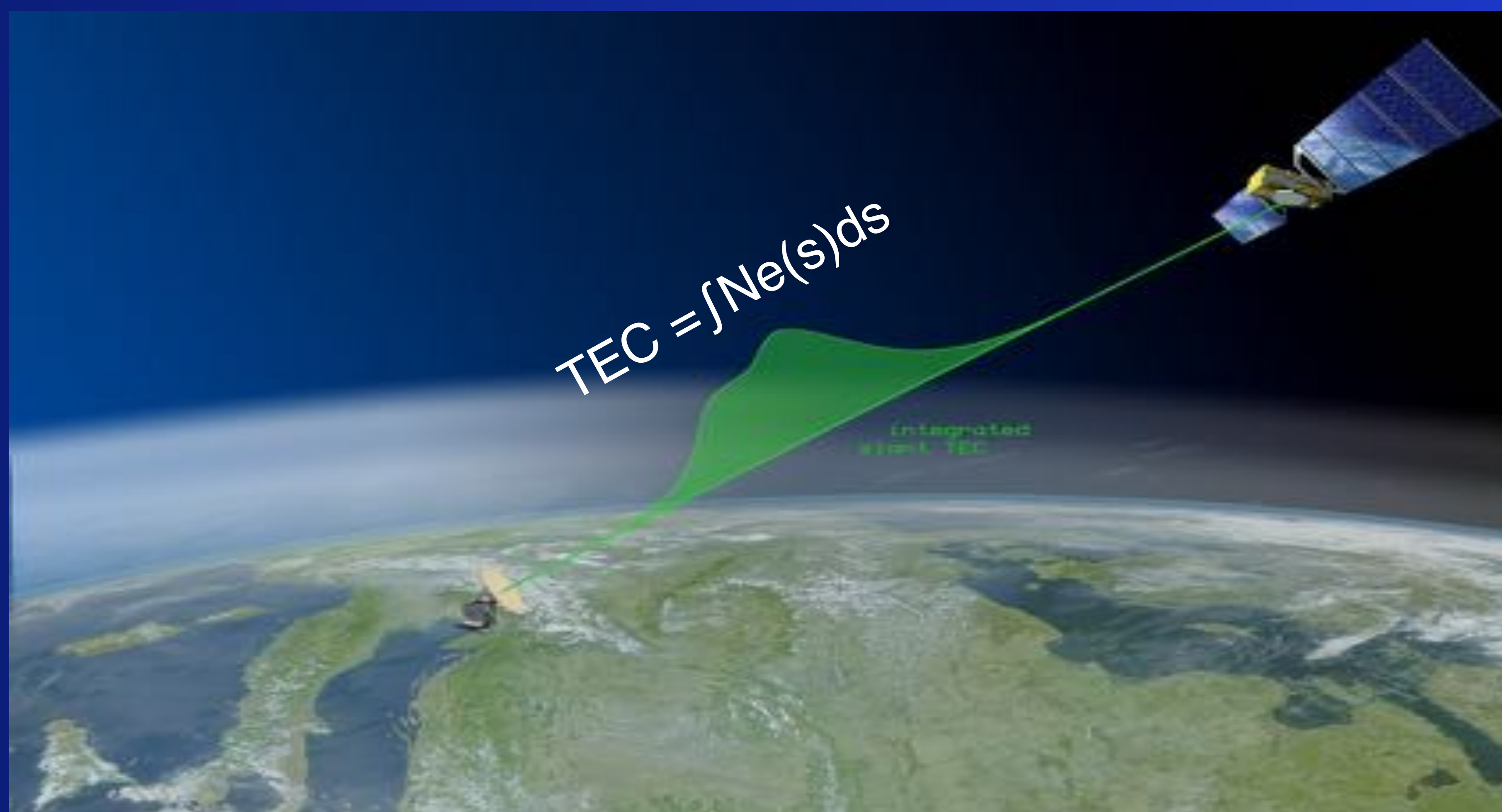
- NeQuick inputs are: position, time and solar flux; the output is the electron concentration at the given location and time.

$$N(h; hmax, Nmax, B) = \frac{4Nmax}{(1 + \exp(\frac{h-hmax}{B}))^2} \exp(\frac{h - hmax}{B})$$



NeQuick 2

- 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.

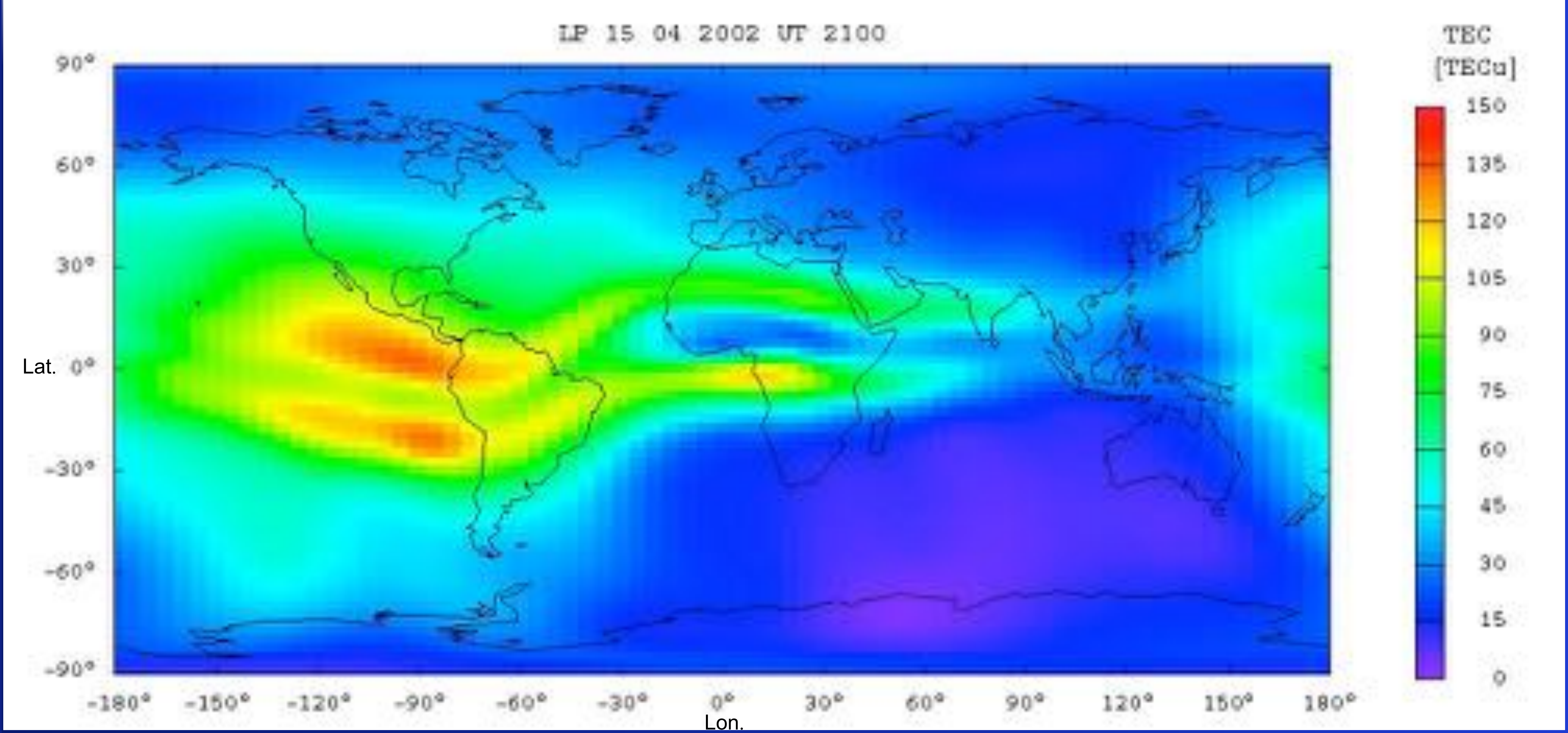


The TEC is the number of free electrons in a column of one square-metre cross-section along a given ray-path.

Data ingestion into NeQuick

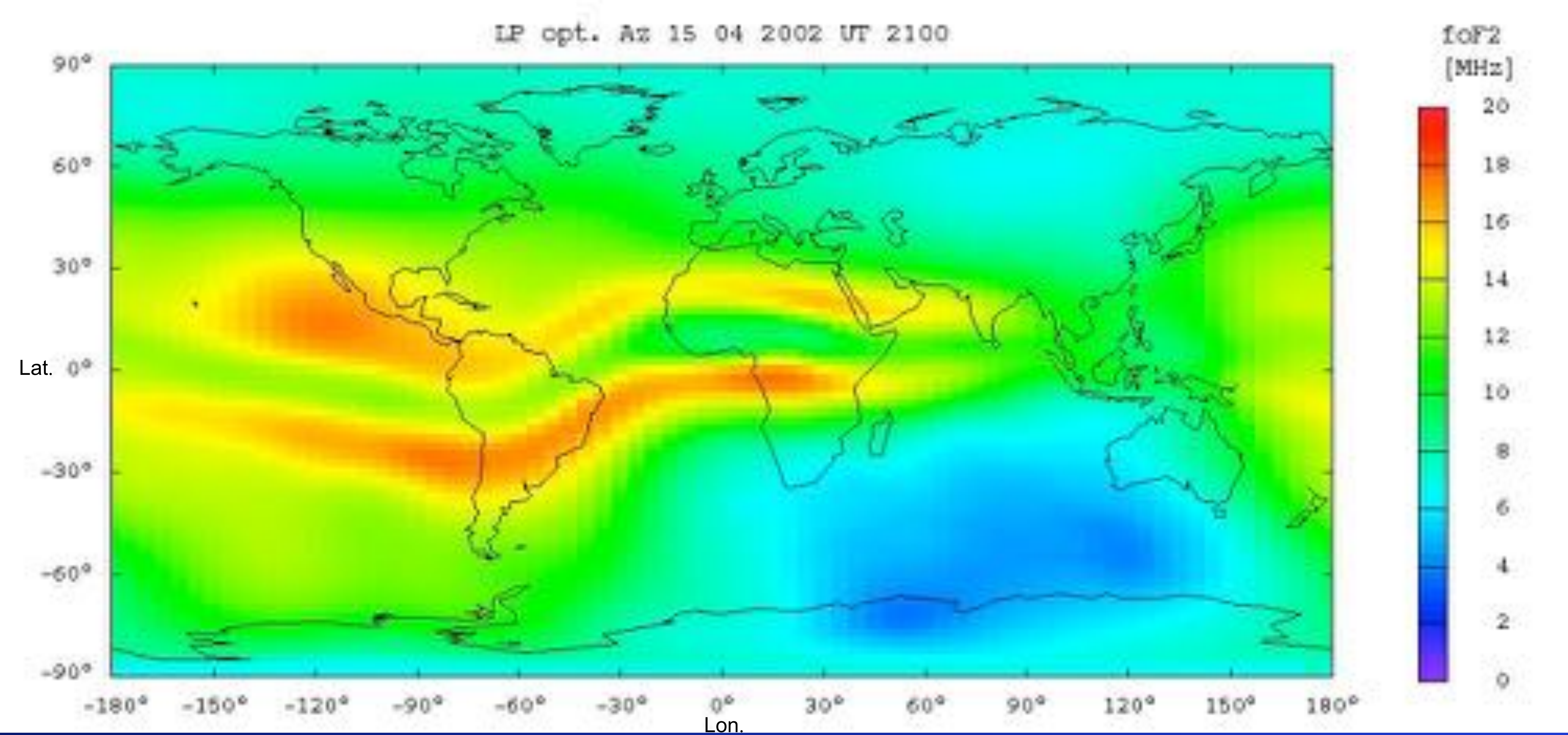
- Empirical models like IRI and NeQuick have been conceived to reproduce the median behavior (“climate”) of the ionosphere.
- For research purposes and practical applications, there is a need to estimate the 3-D electron density of the ionosphere for current conditions ("weather").
- Considering the increasing availability of experimental data even in real time, several assimilation schemes have been developed. They are of different complexity and rely on different kinds of data.
- In the case of NeQuick, (multiple) effective parameters have been utilised to adapt the model to GNSS-derived TEC data (and ionosonde measured peak parameters values). In the following, as an example, vTEC map data ingestion is considered.

Adapt to vTEC map



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

Reconstruct foF2 map

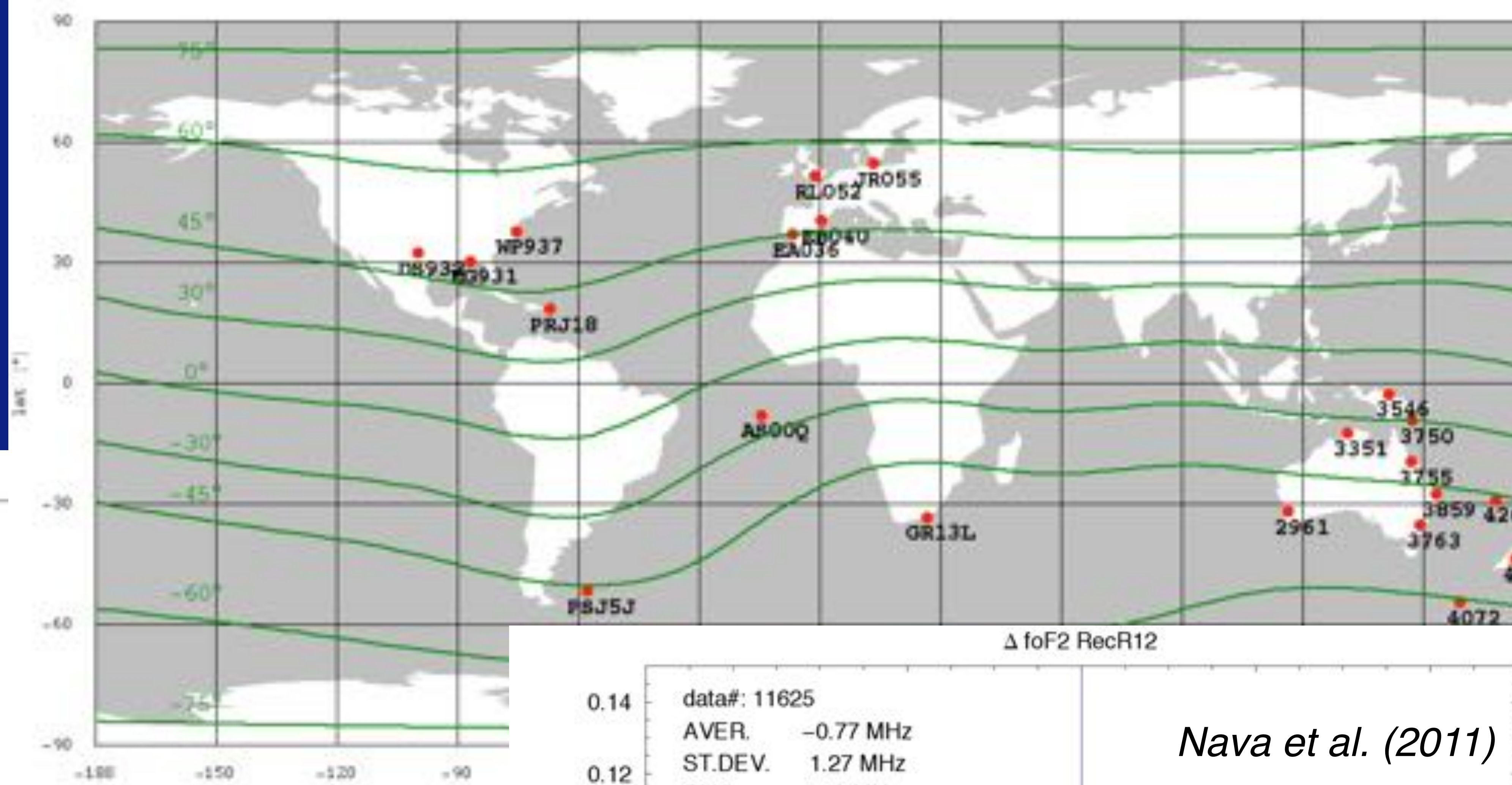


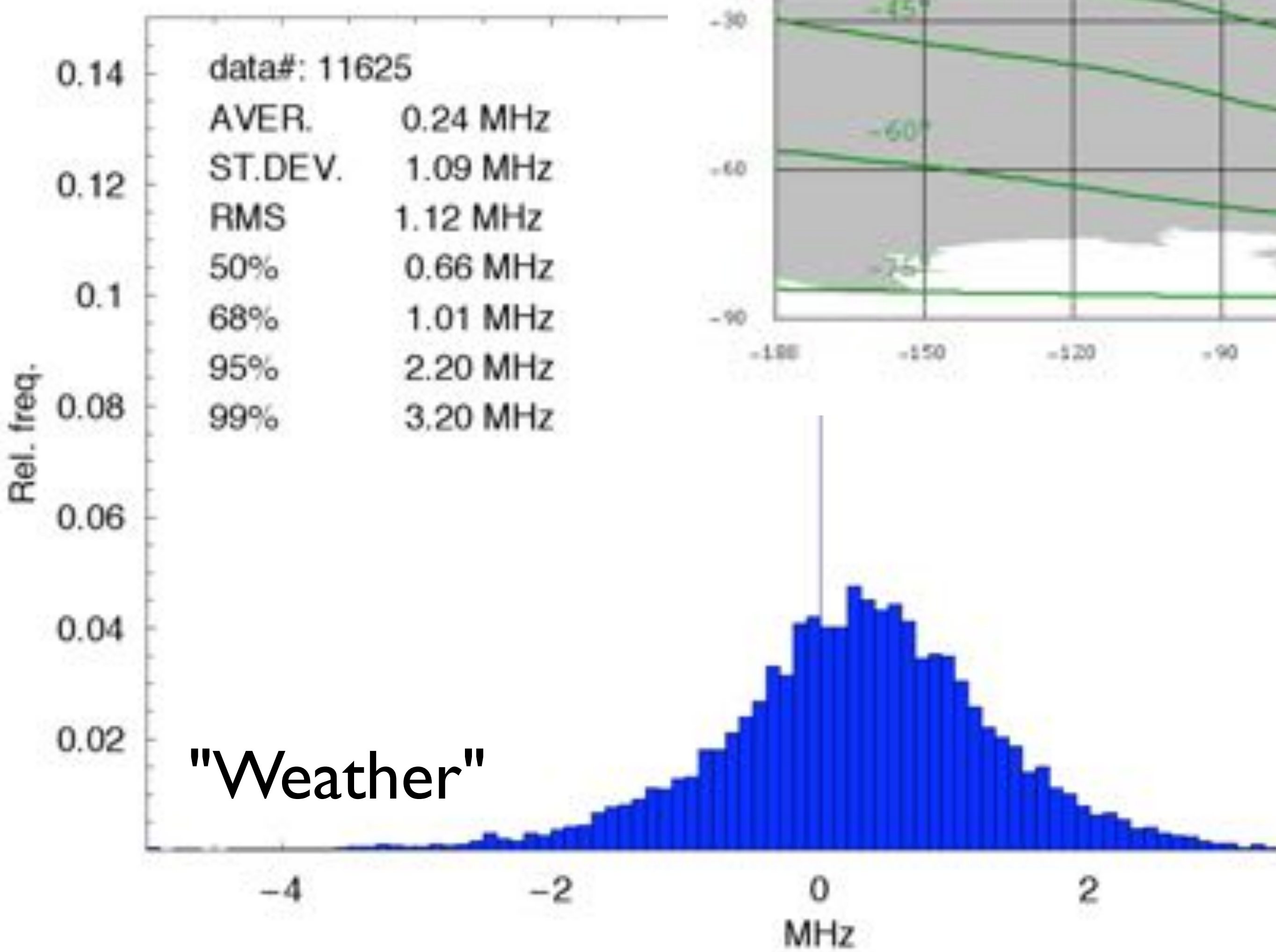
grid points:
lat.=-90°, 90° step 2.5°
lon.=-180°, 180° step 5°

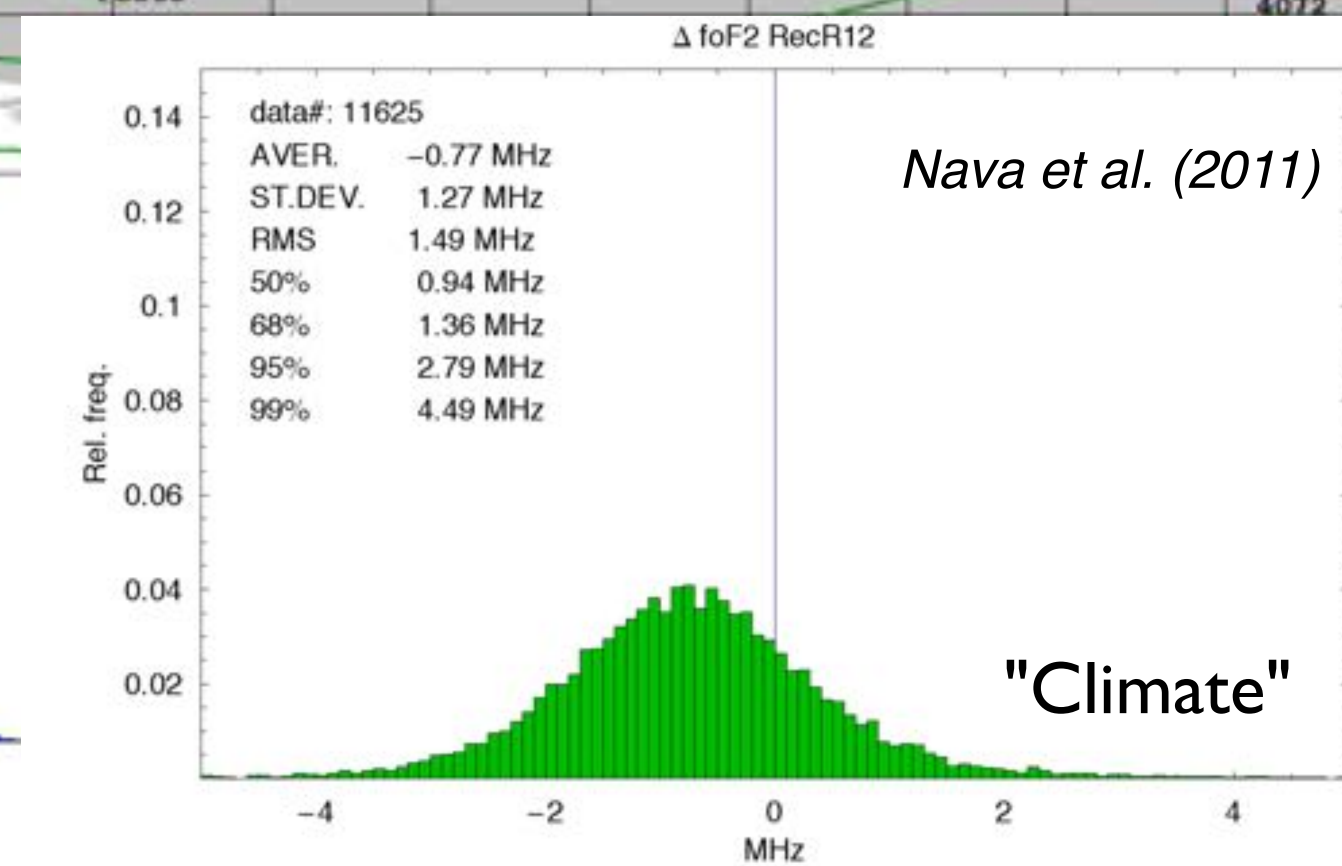
NeQuick2: validation results (example: HSA)

April 2000

foF2 error statistics







Least Square Estimation

To further improve the NeQuick performance in retrieving the 3D electron density of the Ionosphere, a minimum variance least-squares estimation has also been utilised to assimilate ground and space-based TEC data into NeQuick 2, considered as a background (like in e.g. Minkwitz et al., 2018).

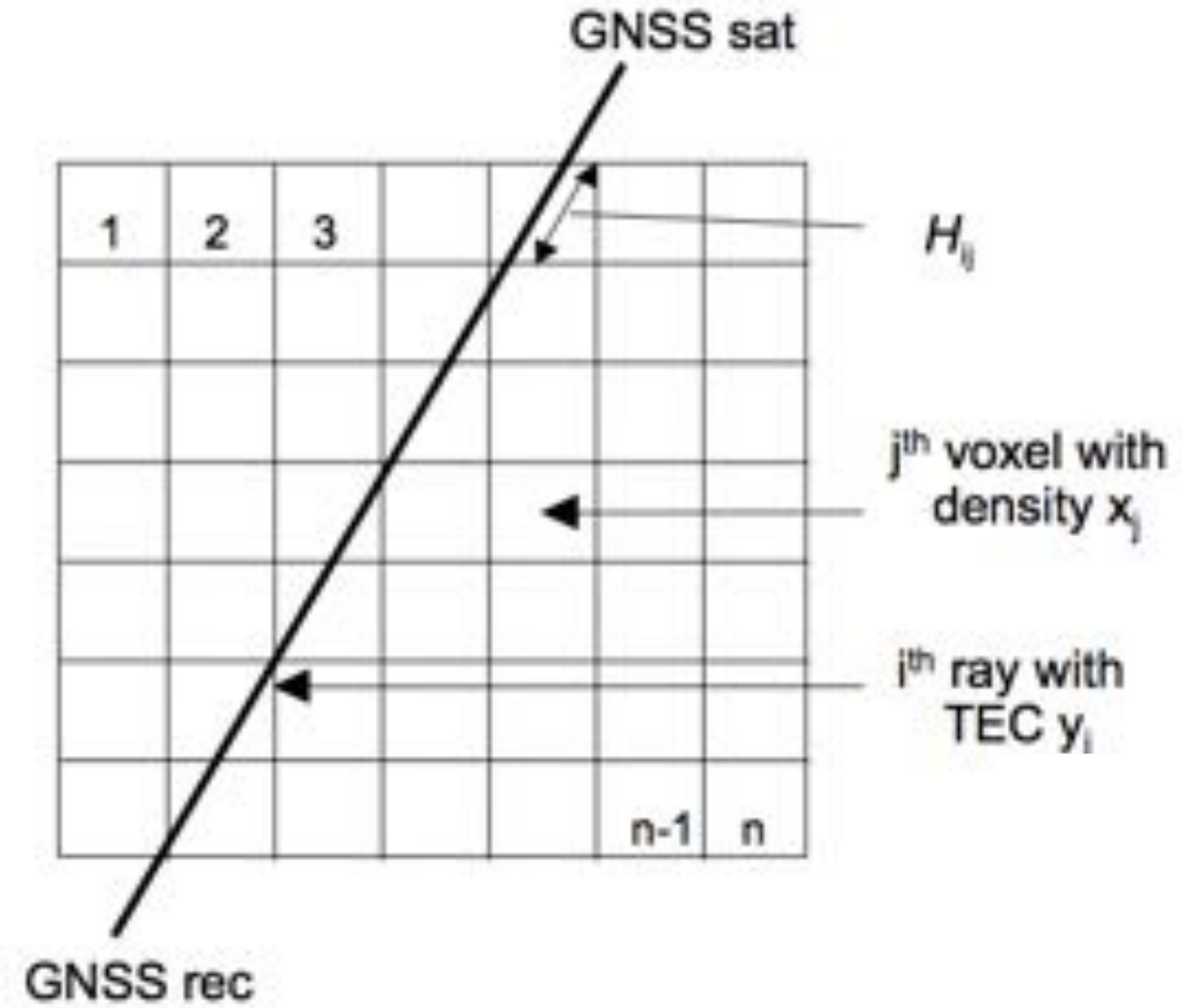
The optimal least-square estimator (BLUE analysis, x_a) is defined by

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

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

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

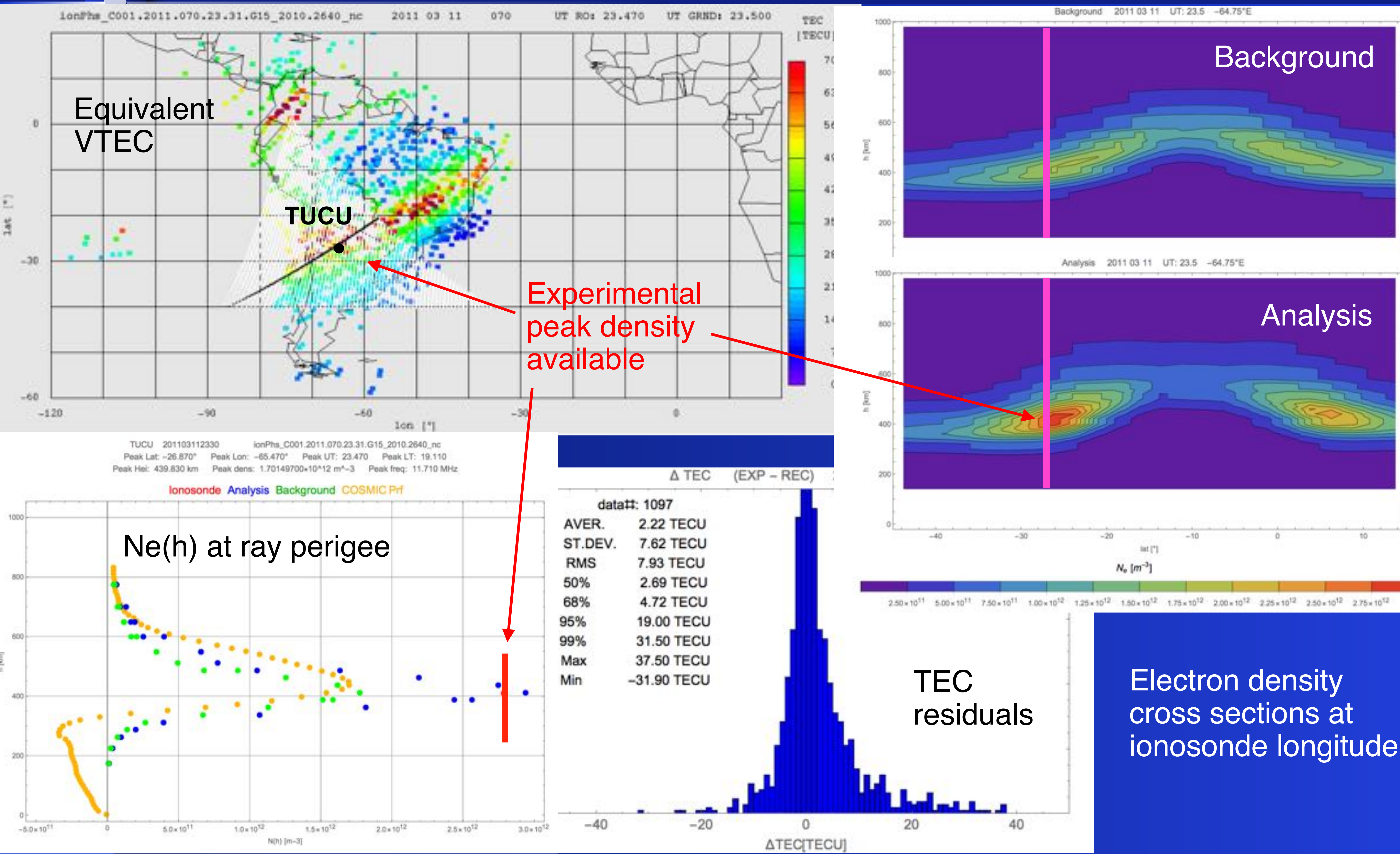
K is the *gain* of the analysis



In our case:

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

TEC DA into NeQuick

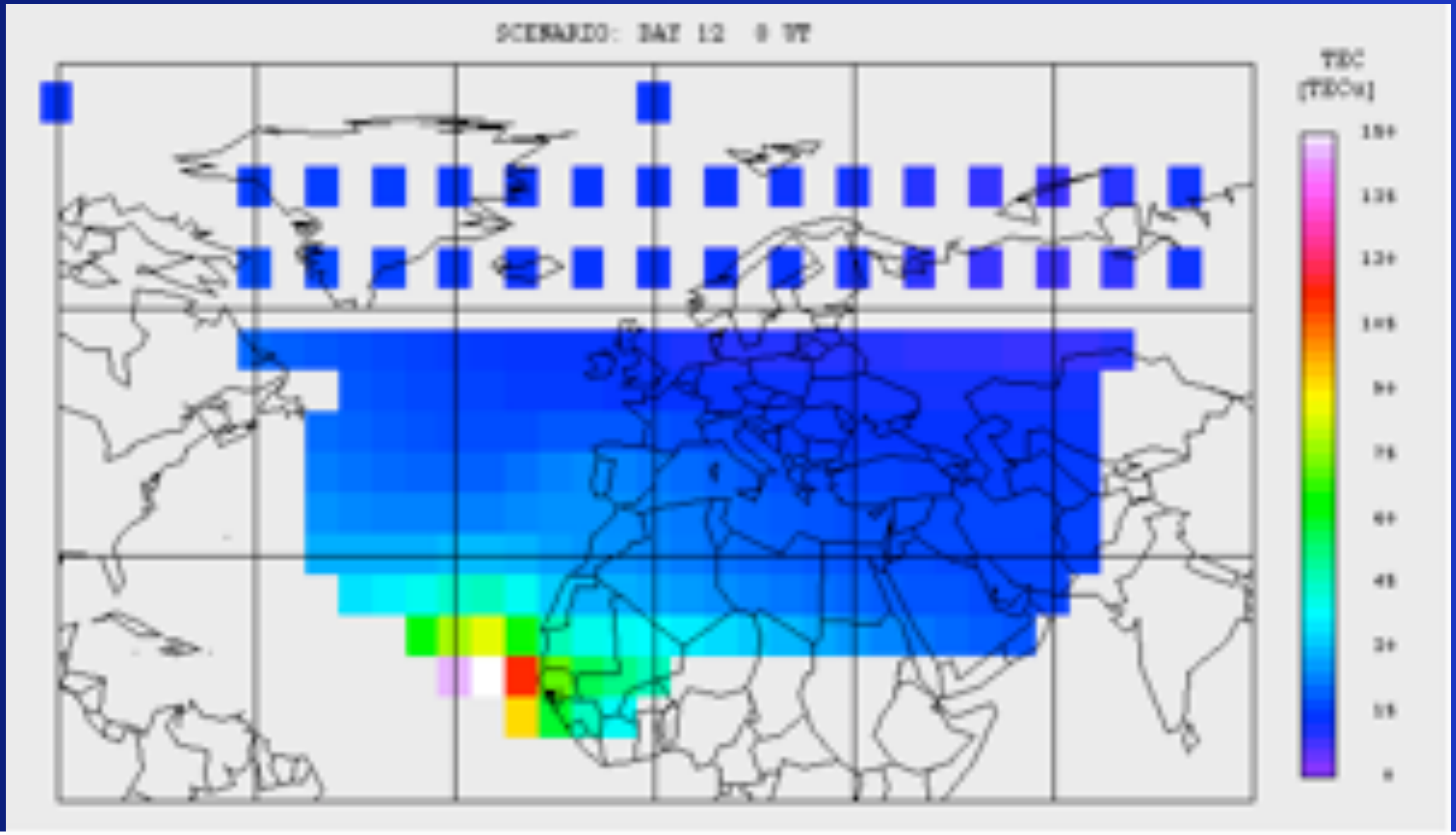


NeQuick for assessment studies

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).

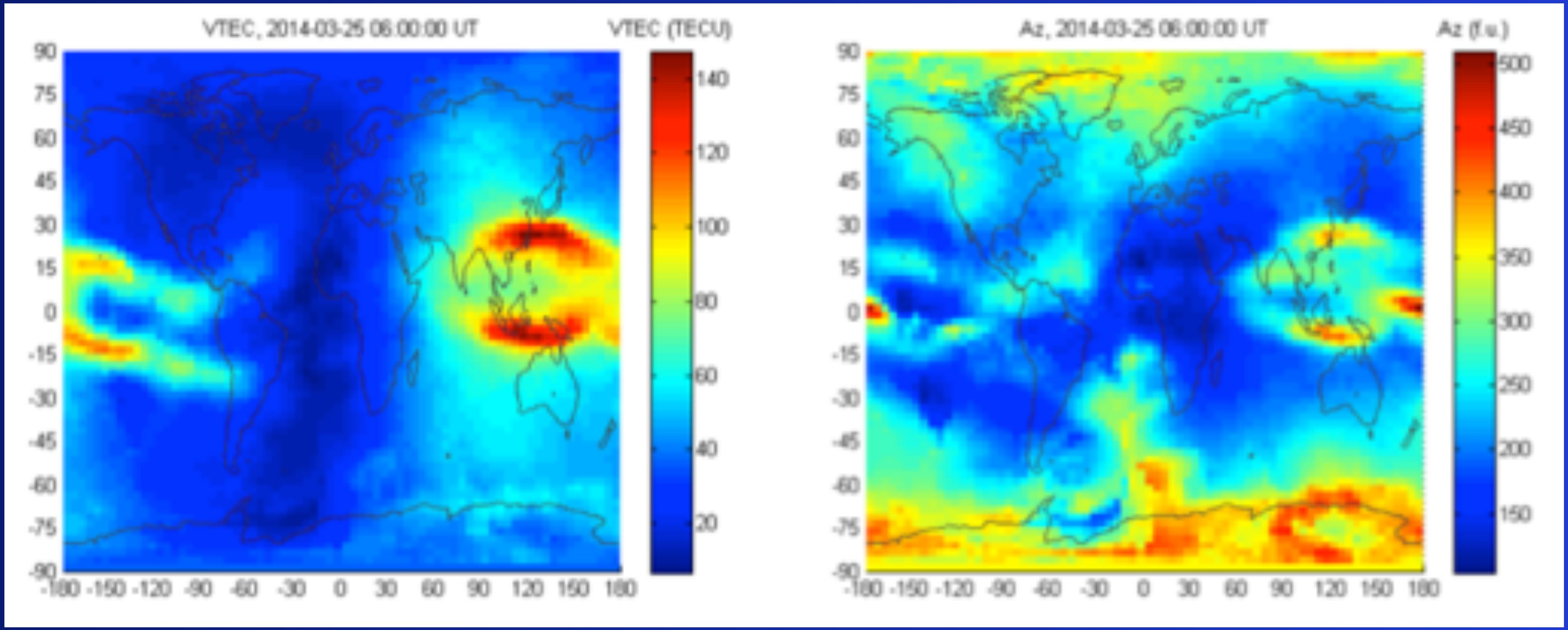
In particular NeQuick was used:

- to generate “worst case” ionospheric scenarios (including geomagnetically disturbed conditions) for assessment of the operational ionospheric algorithms of EGNOS.



NeQuick for assessment studies

- To generate "high accuracy" ionospheric scenarios in the framework of MONITOR 2 project (funded by ESA).

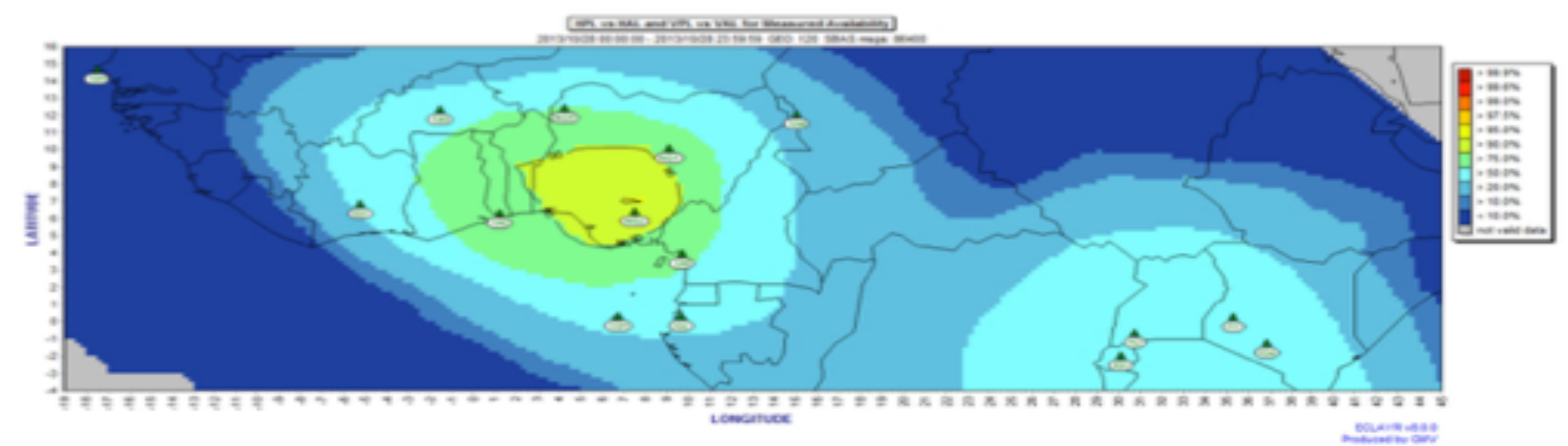


- To test and tune the "ESA UGI (Unified-GNSS-Ionosphere): An Open-source software to compute precise ionosphere estimates" (Orus-Perez et al., 2020).
- The basic methodology relies on the NeQuick 2 model adaptation to vertical TEC maps to obtain effective ionization parameter grids (Nava et al., 2011) and use them to compute slant TEC along any ground-to-satellite ray-path.

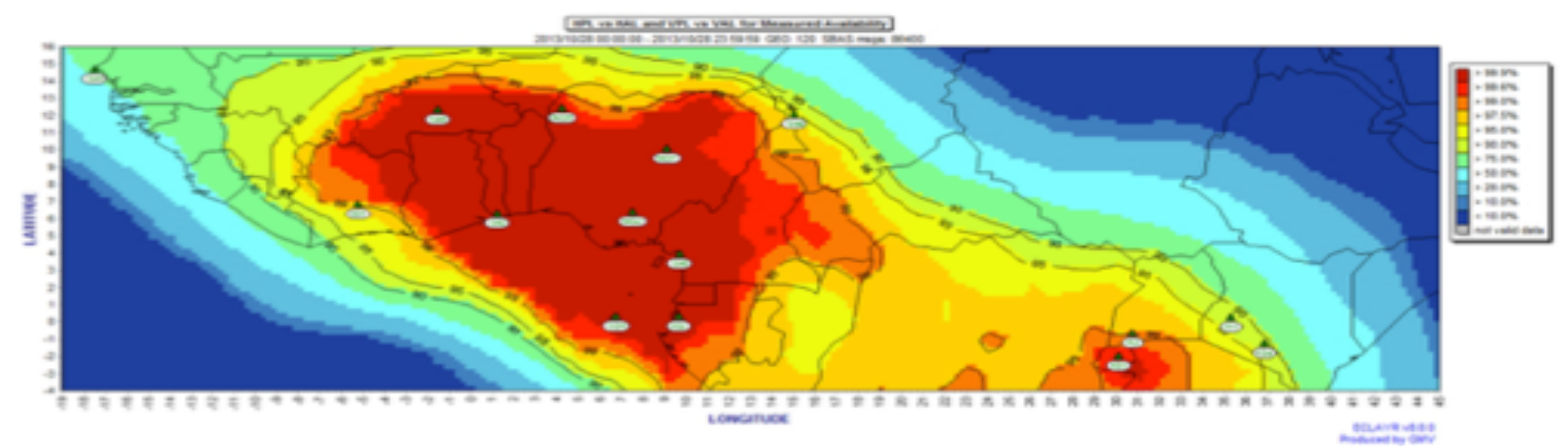
NeQuick for assessment studies

- For the TREGA Project (funded by EC) a Testing Platform / Software Simulator has been acquired by ICTP.
- The platform is able to generate GNSS observations in any area of the globe using multi-frequency, multi-constellation Raw Data Generator.
- The embedded NeQuick 1 has been used to compare different ionospheric algorithms.

Standard algorithm



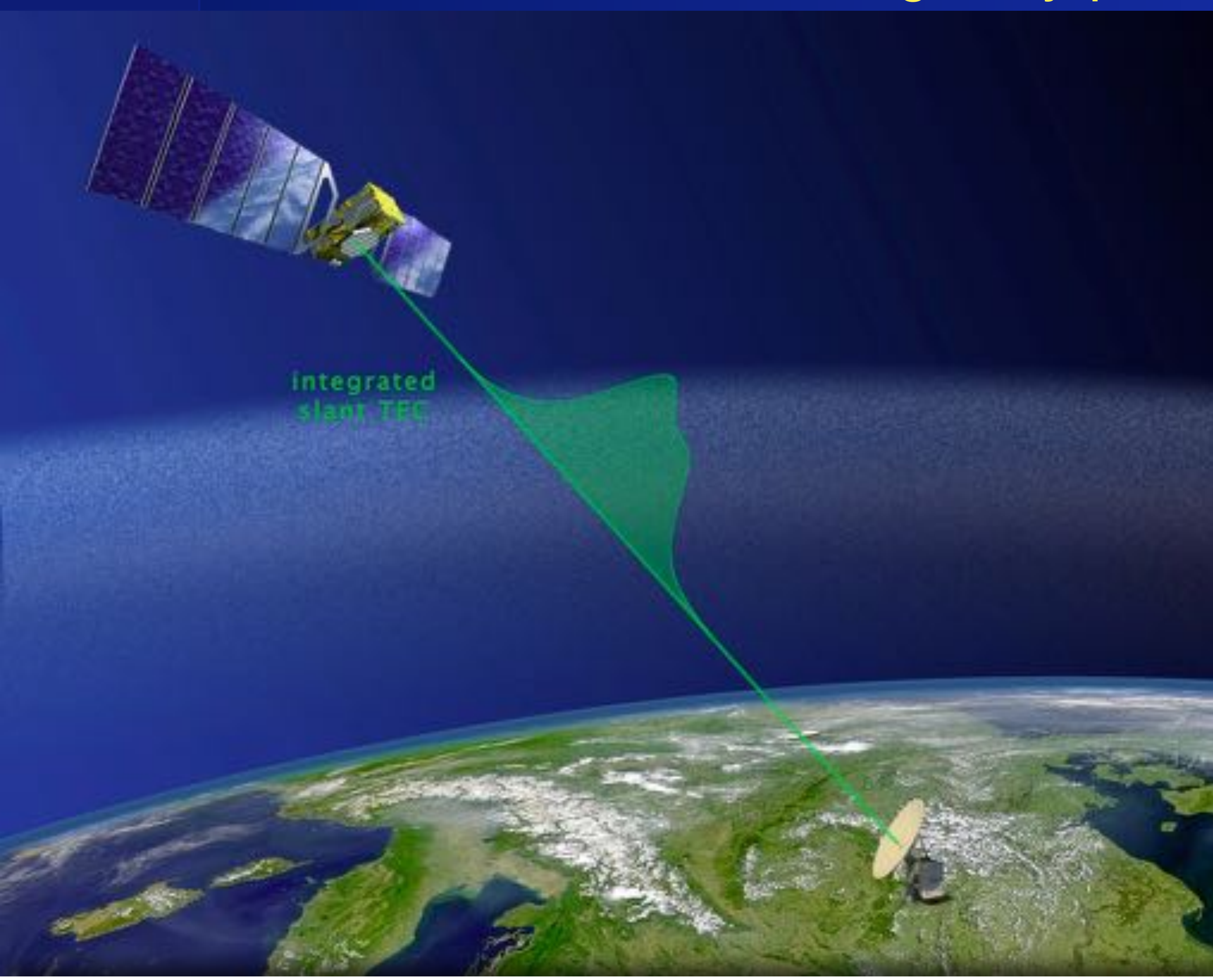
Low Latitude algorithm

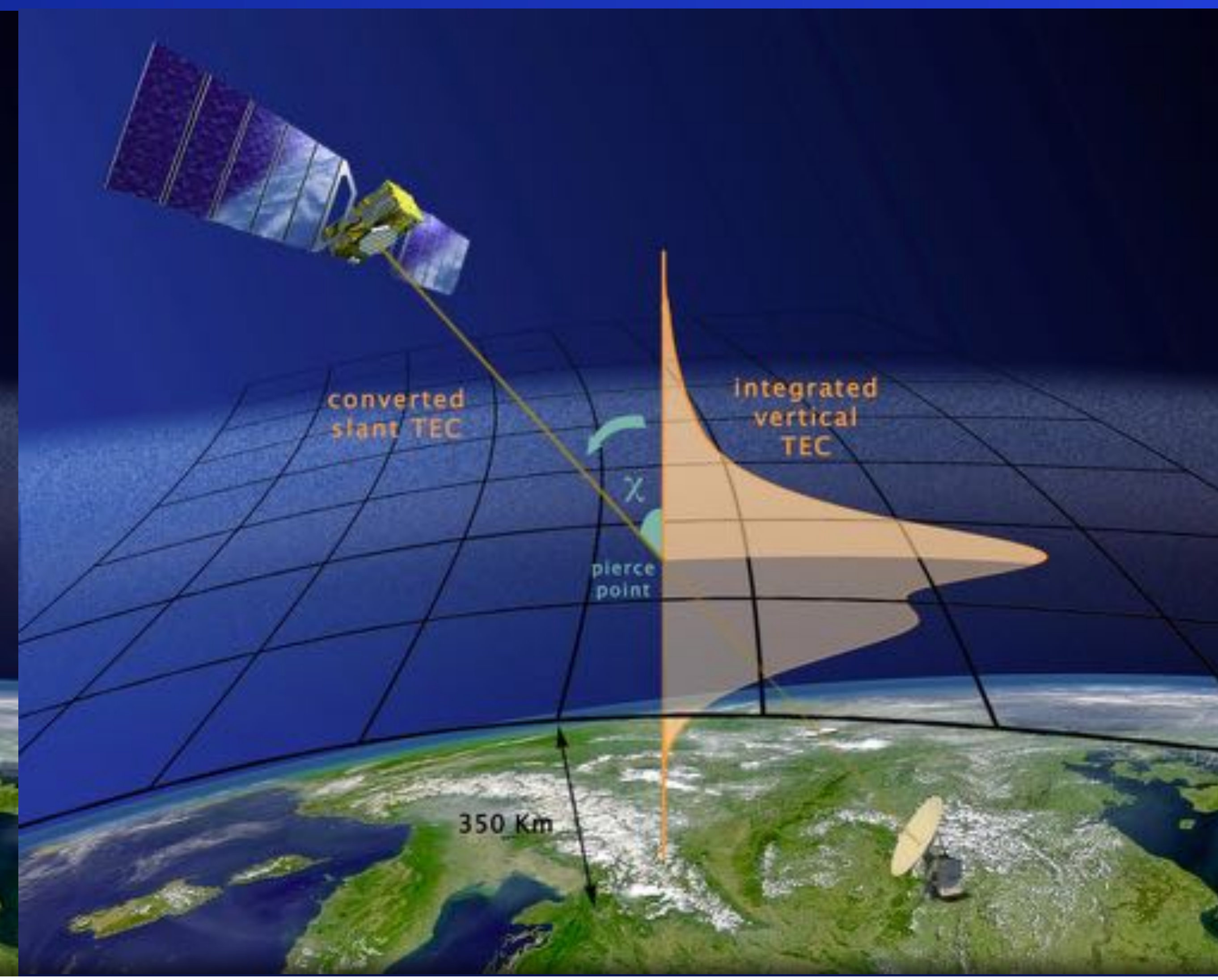


NeQuick for assessment studies

- To 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





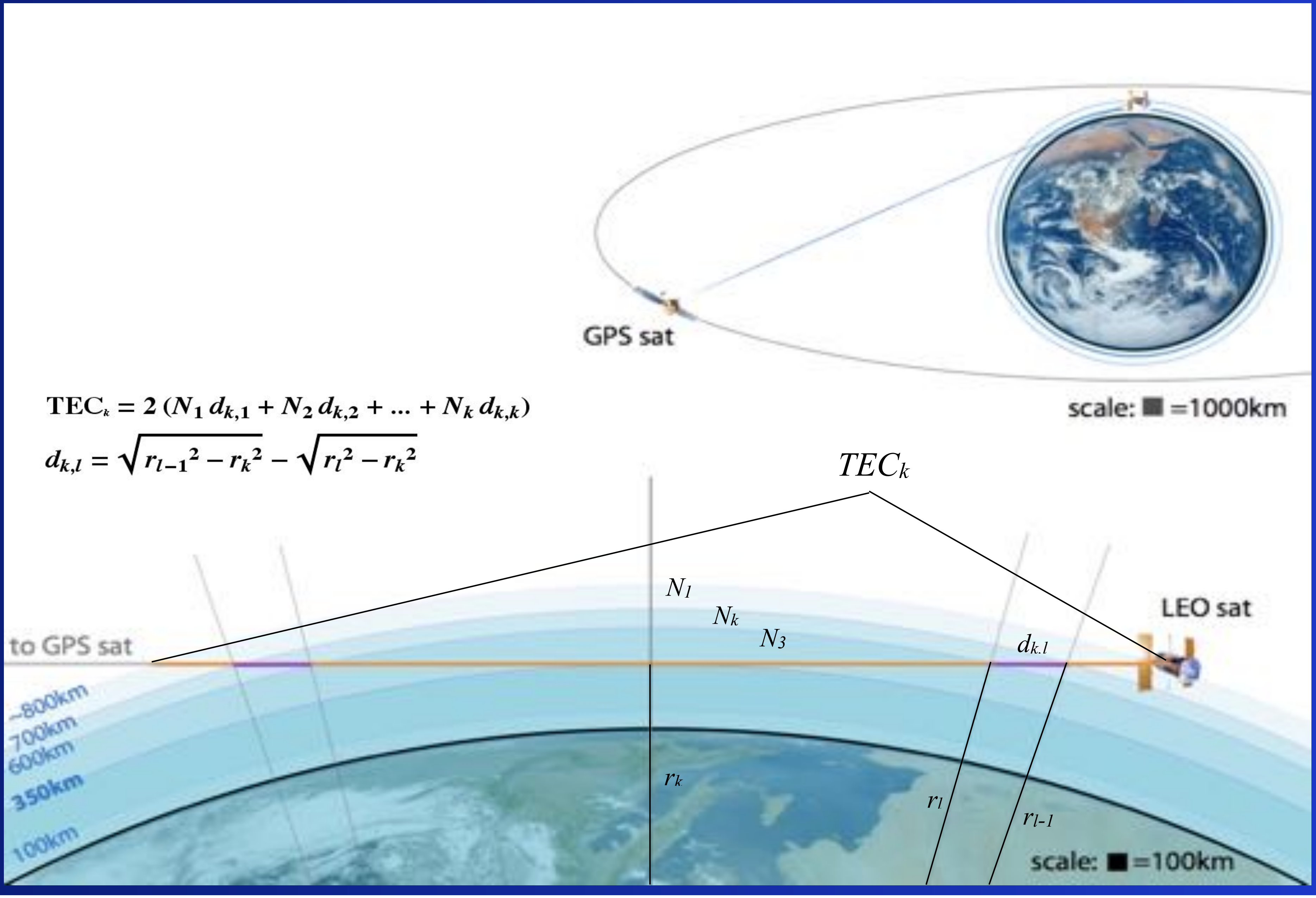
$$\mathrm{sTEC} = \int_{\mathrm{ground}}^{\mathrm{satellite}} N_e(s)\,ds$$

$$\mathrm{vTEC}_{\mathrm{pp}} = \int_{0}^{20000} N_e(h)\,dh$$

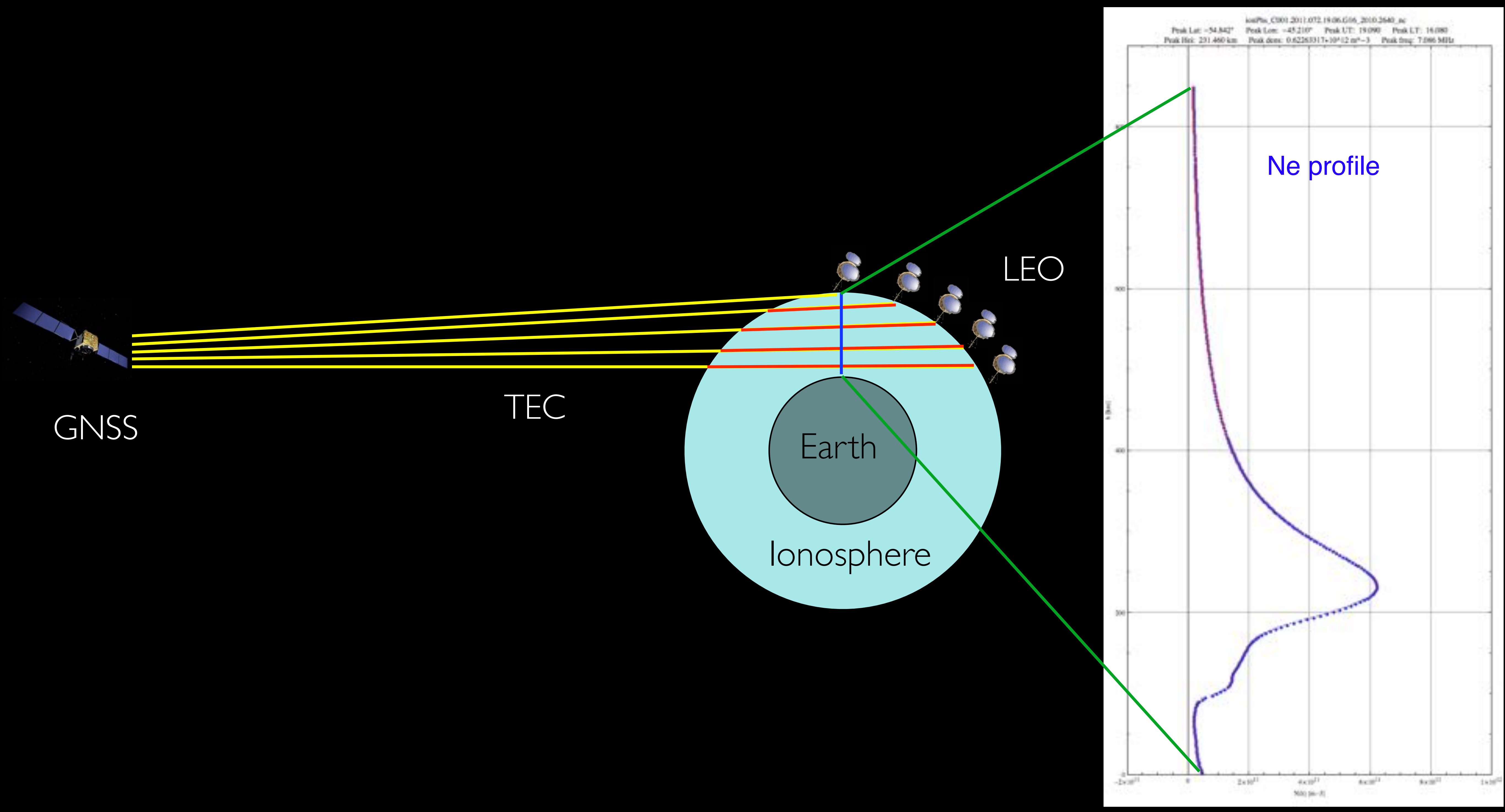
$$\mathrm{err} = \mathrm{sTEC} - \mathrm{vTEC}_{\mathrm{pp}} / \cos\chi$$

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);

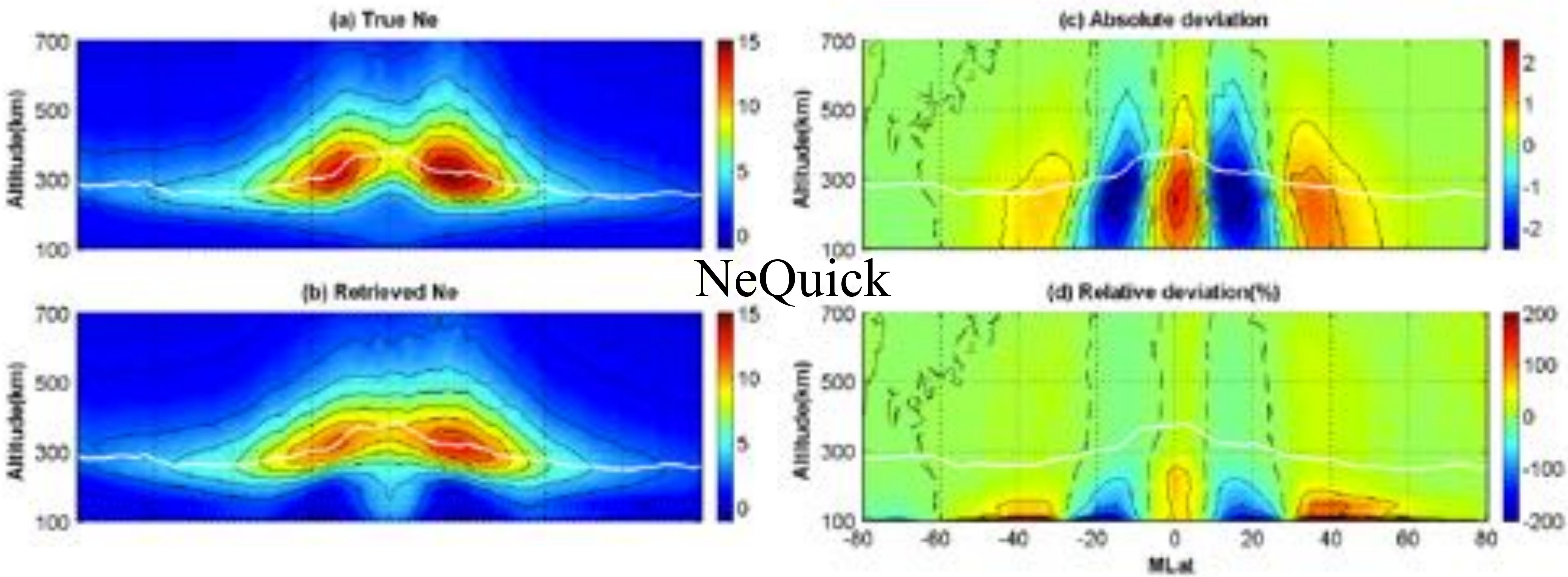


RO data inversion

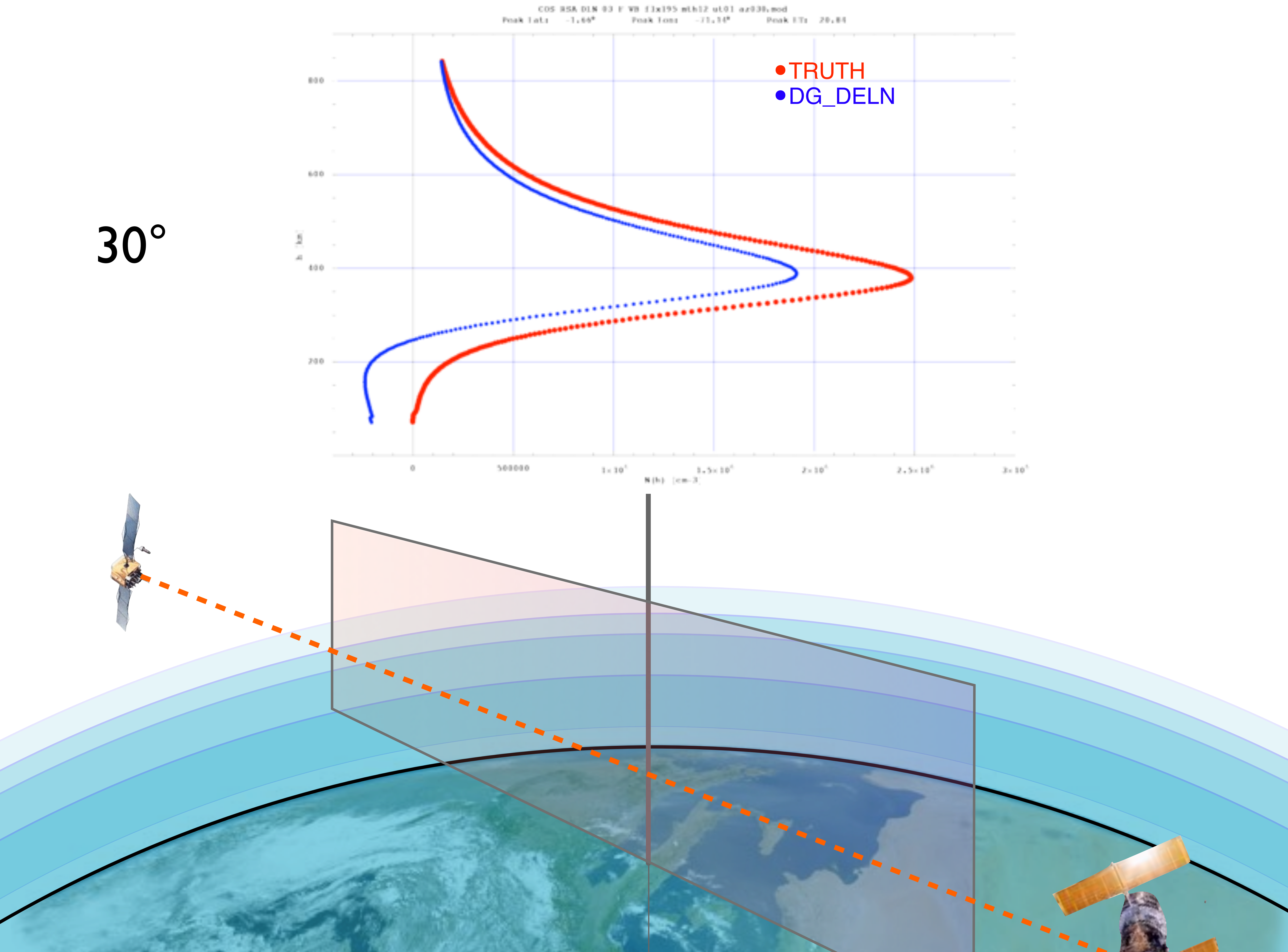


Plasma “caves”

Chu et al. (2009) reported that "there are three geomagnetic latitude regions where striking enhancements of the E region electron density occur".
Lei et al. (2010) suggested that these enhancements could be "potentially associated with the retrieval error of RO".



X. Yue, et al. (2010), based on NeQuick simulation, conclude that "Abel retrieval method overestimates electron density to the north and south of the crests of the equatorial ionization anomaly, and introduces artificial plasma caves underneath the EIA crests".


30°
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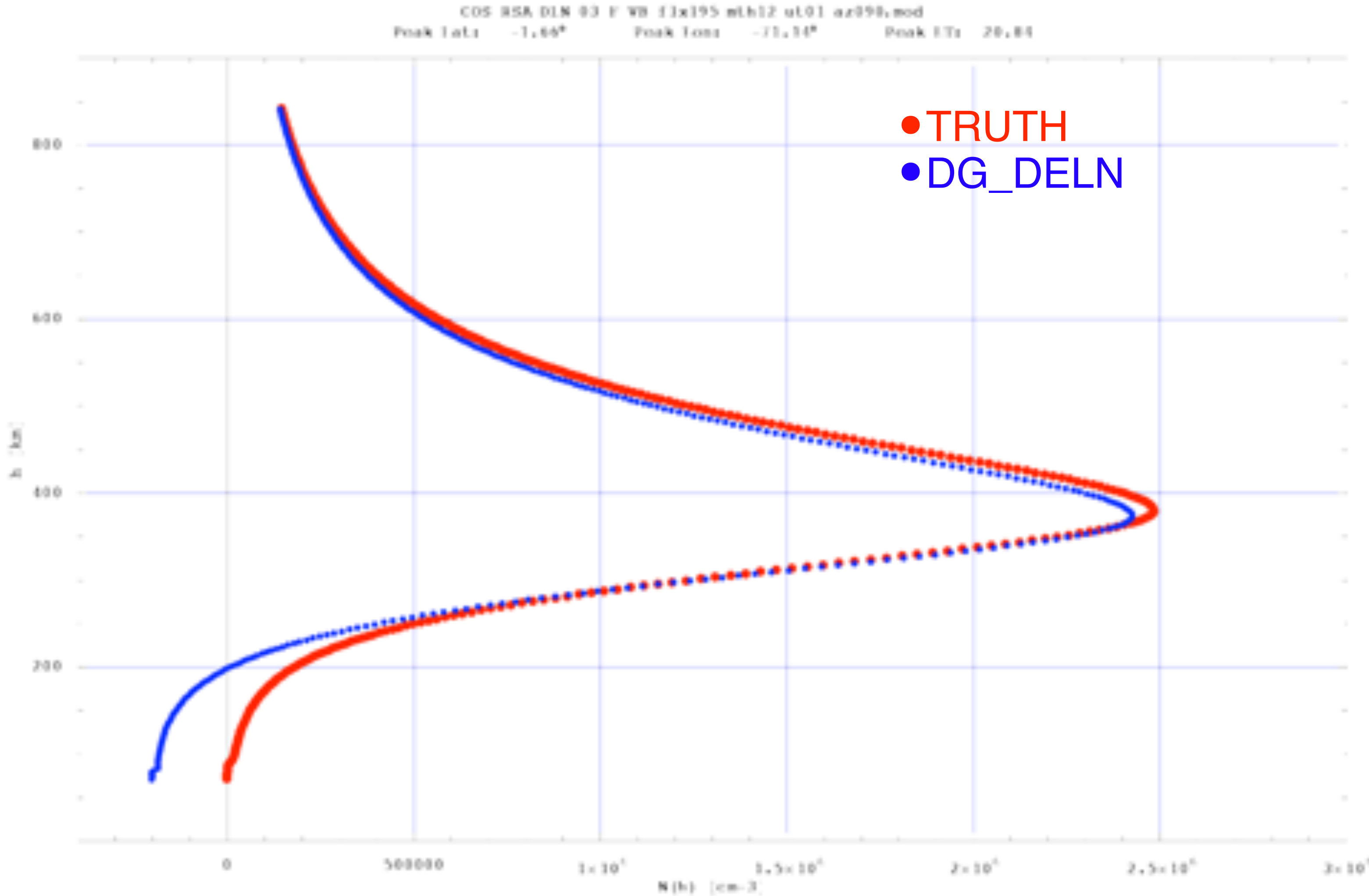
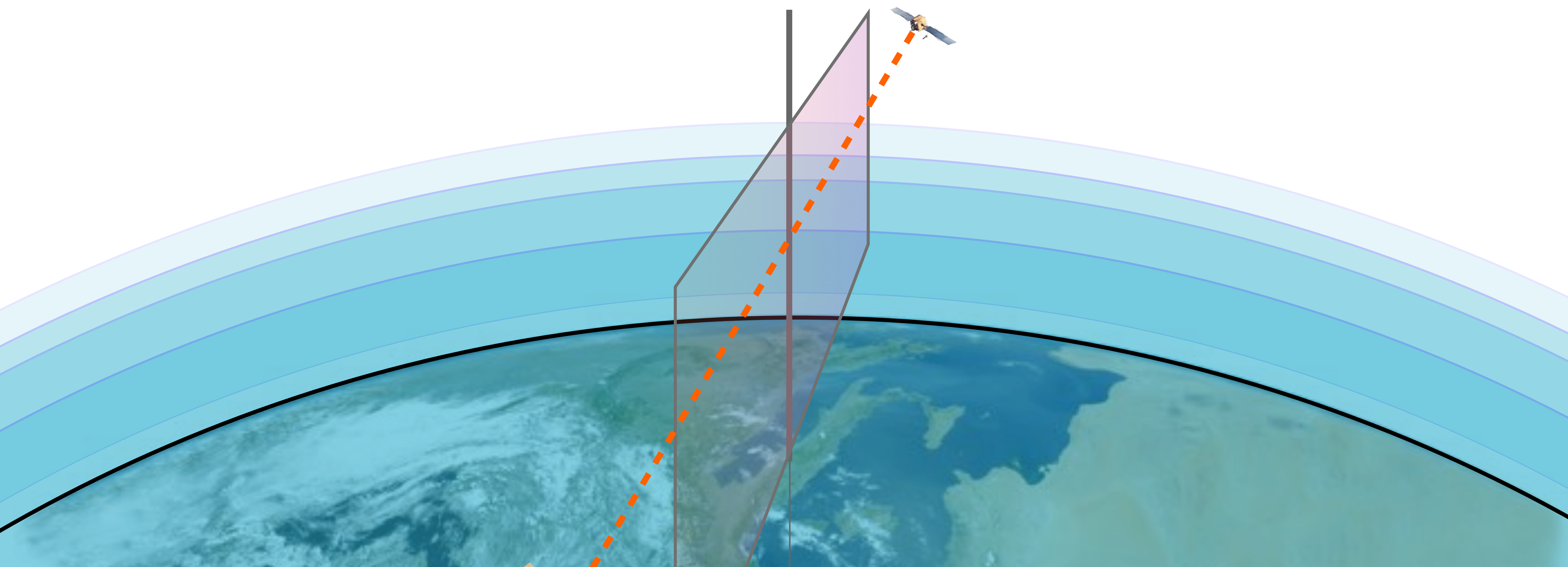
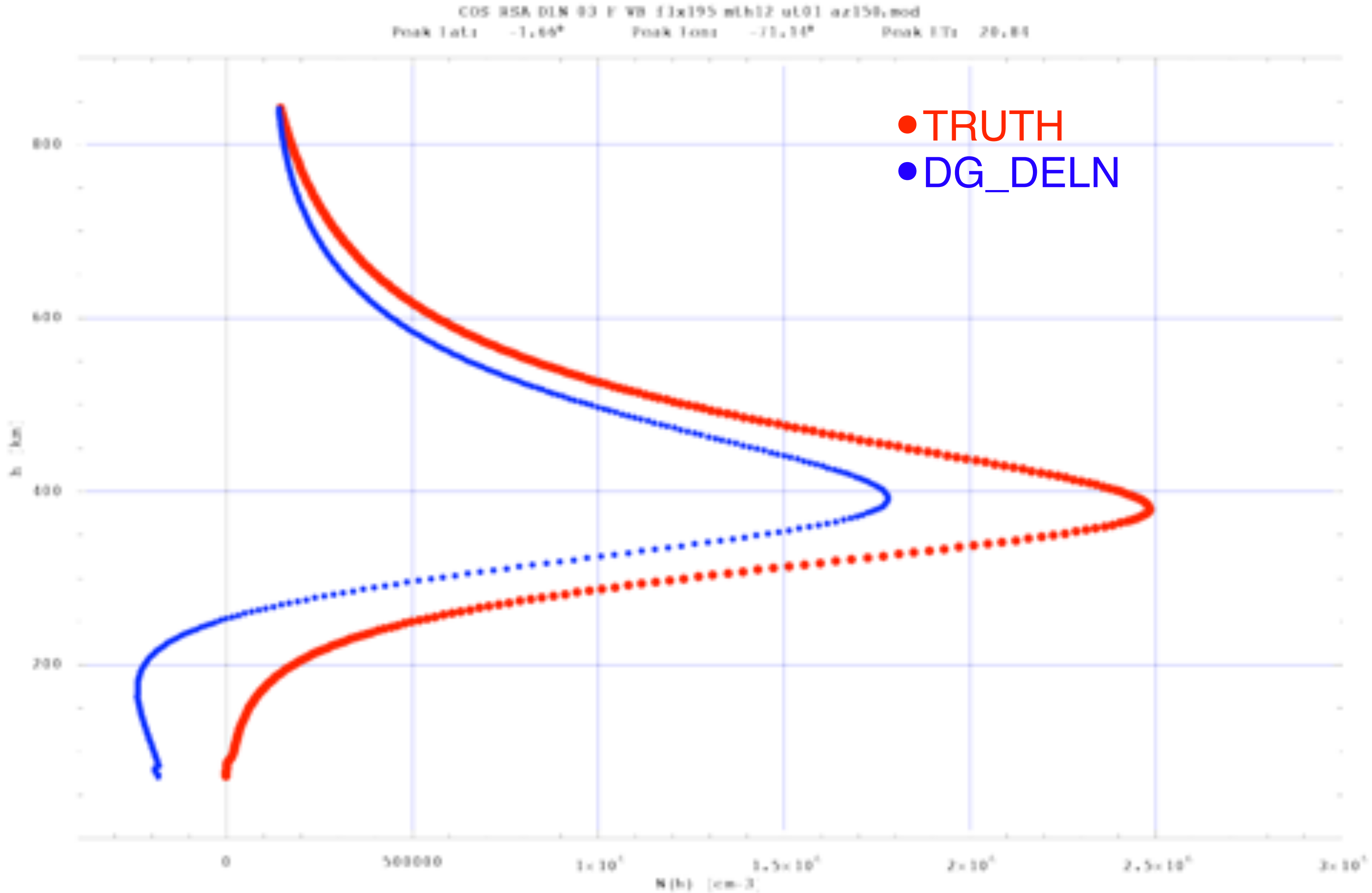
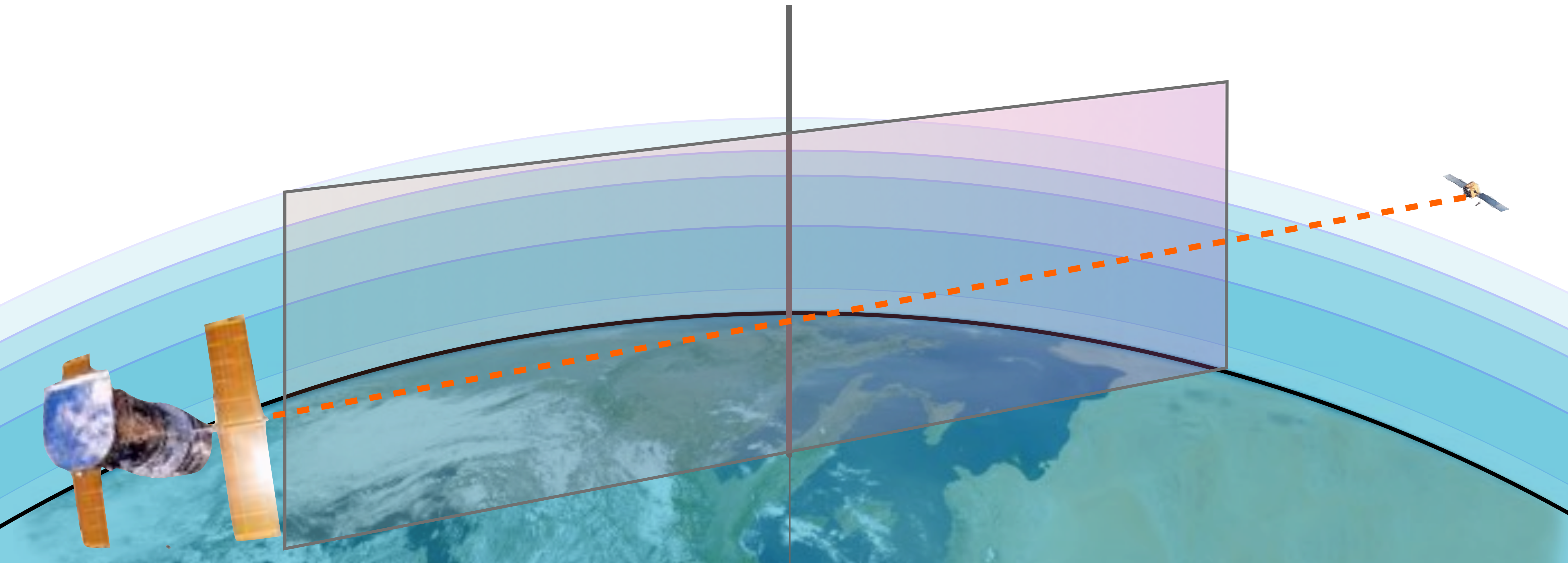




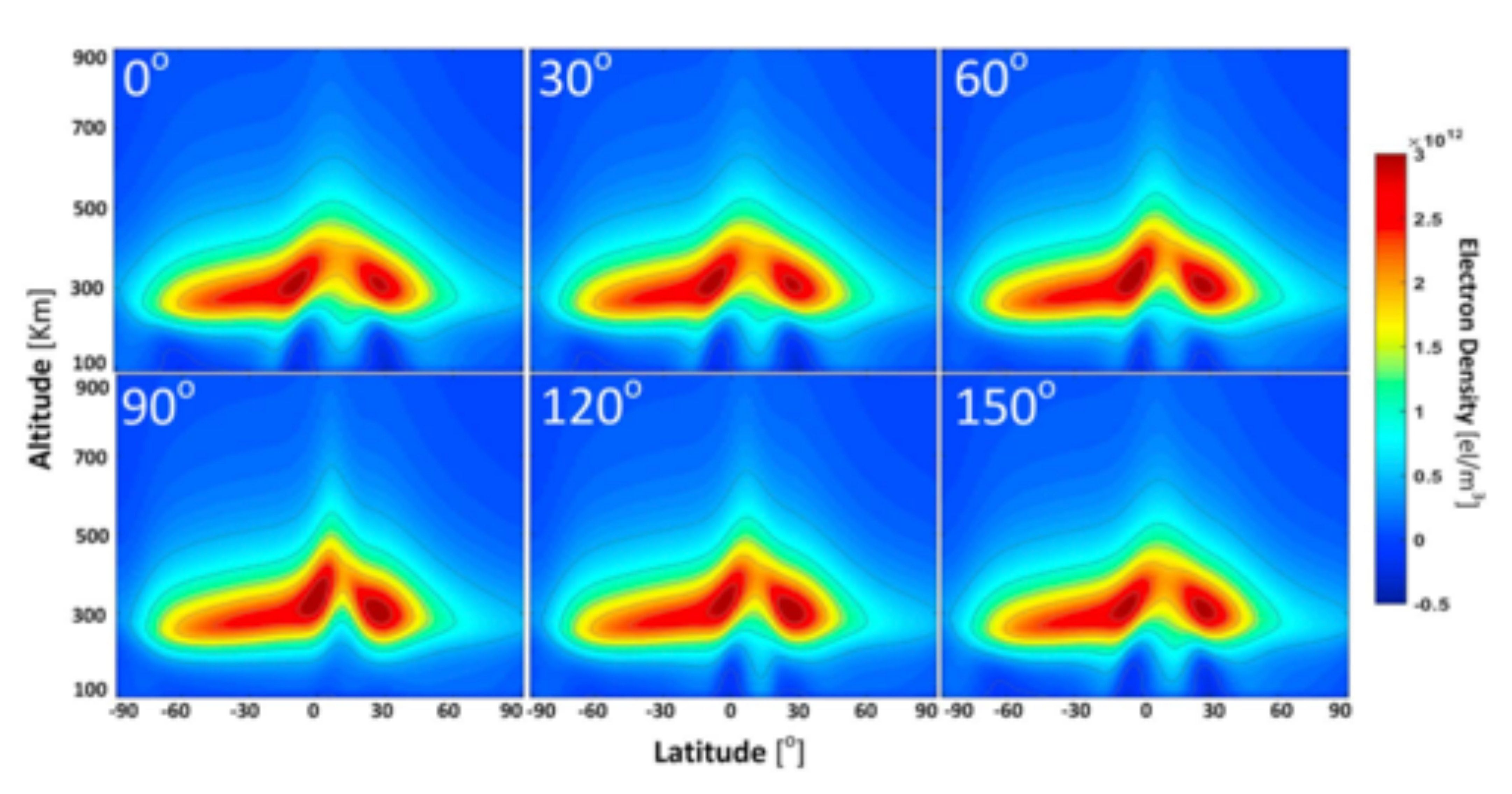
150°





NeQuick for assessment studies

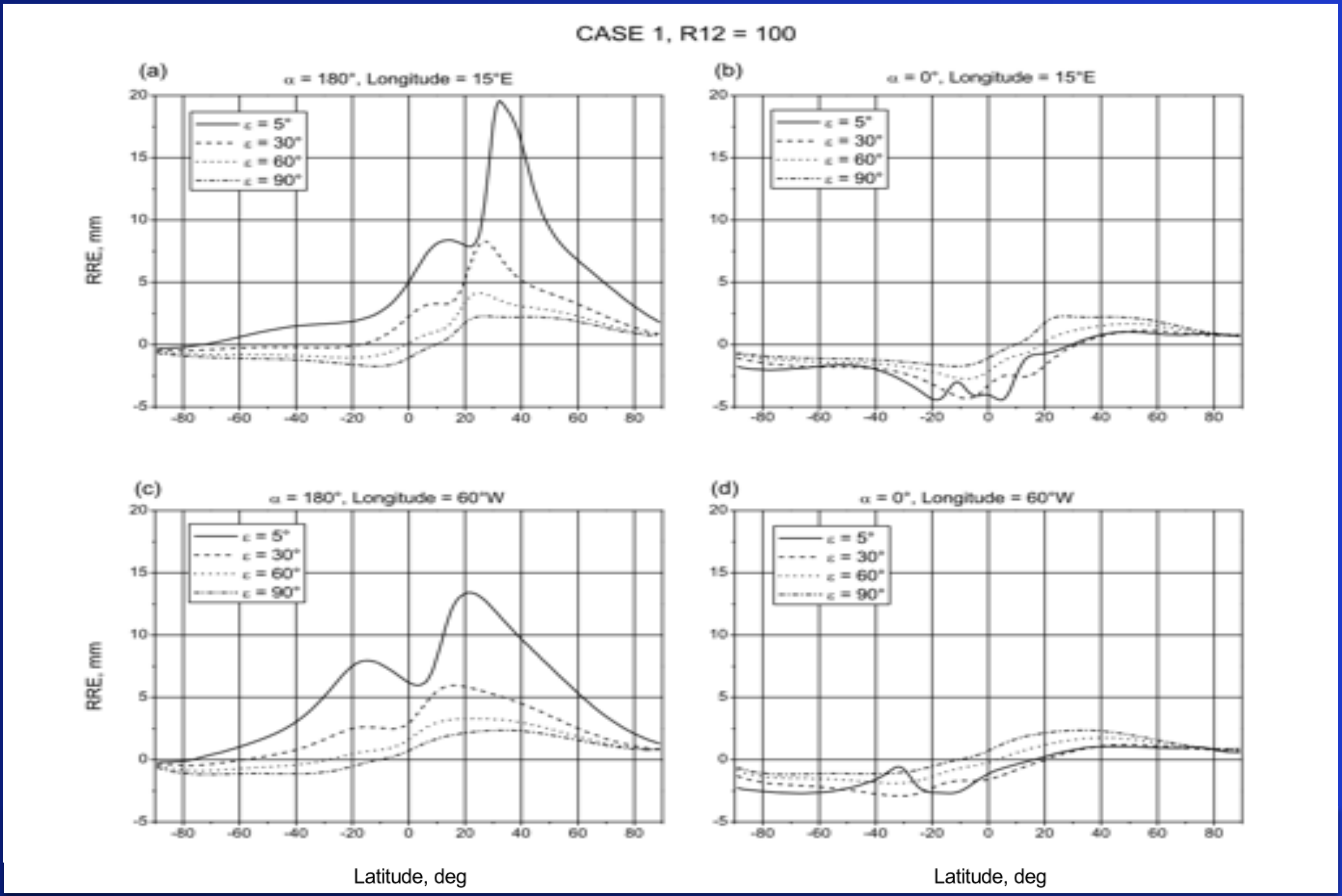
In order to verify the possibility to use topside RO-derived electron density for model validation, a preliminary assessment on the impact of spherical symmetry assumption on RO data inversion has been performed (Shaikh et al., 2018).



NeQuick2-based simulation: Abel inversion-derived Ne for April, 1400 UT, F10.7 = 190 s.f.u., 0°E longitude for azimuth of the occultation plane indicated at the top left corner of the plot.

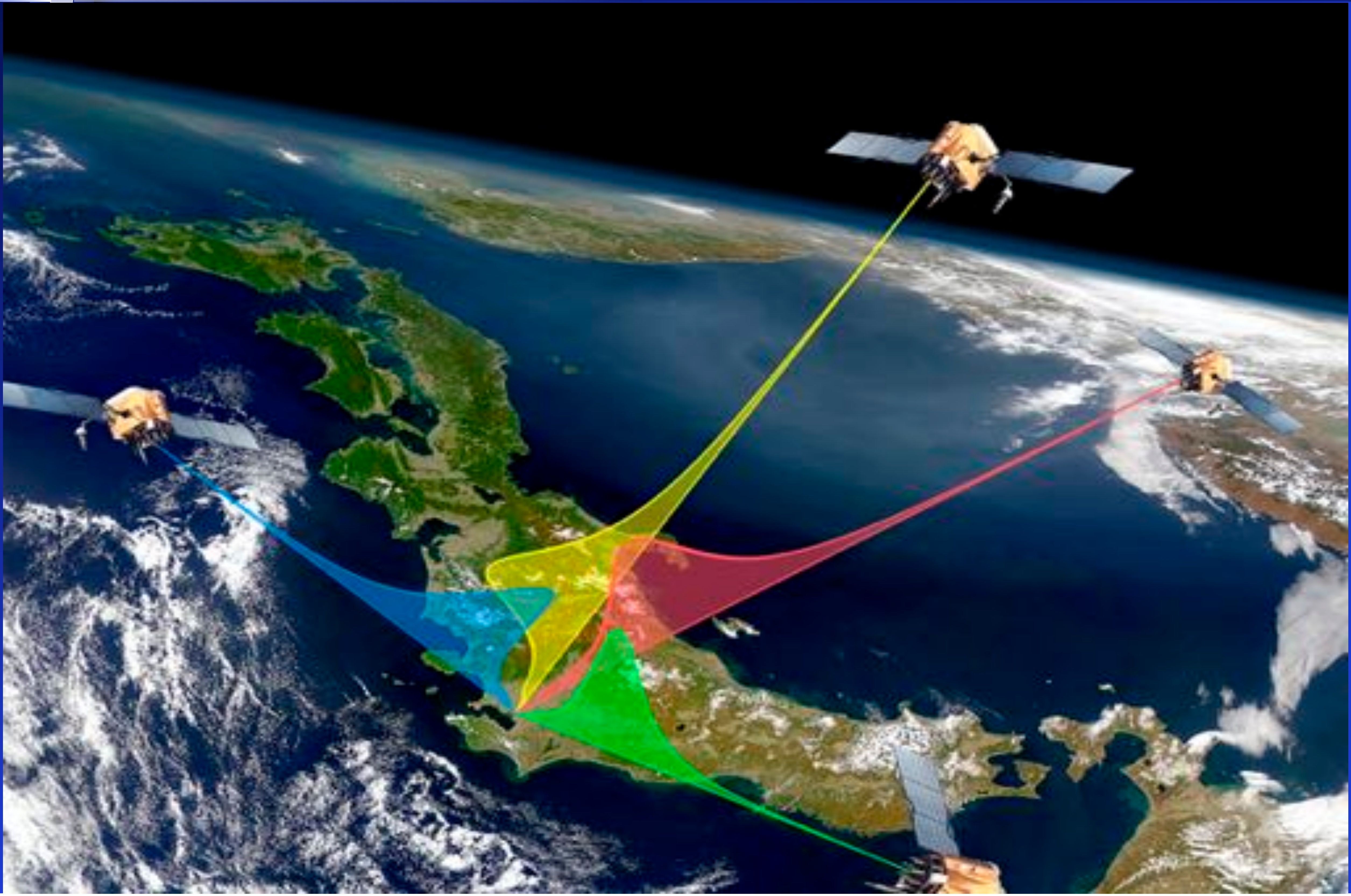
NeQuick for assessment studies

Higher-order ionospheric errors in GNSS positioning have been estimated using NeQuick (Kashcheyev et al., 2012).

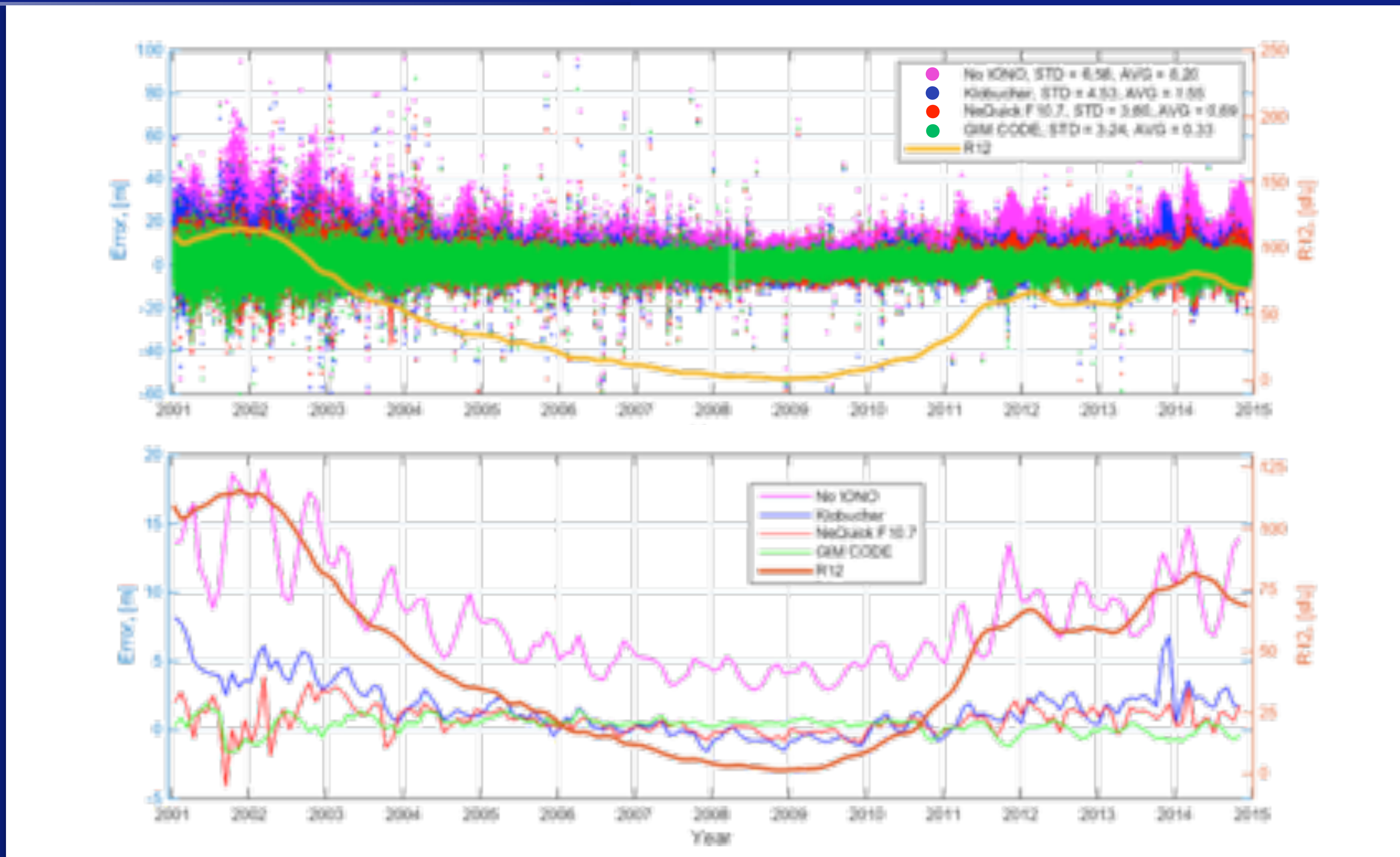


Variations of the residual range error, RRE

Applications (Positioning)



Height Error, Station = thti (low-lat)



Position for ~ 20 GNSS receivers during more than one solar cycle and using 3 different kinds of ionospheric corrections has been computed. 15 min (upper panel) and monthly averaged data (lower panel). Results for *thti* station are shown (Kashcheyev et al., 2015).

NeQuick for Galileo

- A specific version of NeQuick (NeQuick G, implemented by ESA) has been adopted as Galileo Single-Frequency Ionospheric Correction algorithm and its performance has been confirmed during In-Orbit Validation (Roberto Prieto-Cerdeira et al.; GPS World, June 2014).
- The correction capabilities of NeQuick G for single frequency users in low earth orbit (spaceborne platforms) has been also assessed (Montenbruck and Gonzalez-Rodriguez, 2020).
- Ionospheric correction algorithm for Galileo single frequency users; Issue1.2; European Commission (September 2016).

Conclusions

- Different versions of the NeQuick model have been implemented and used in GNSS related applications.
- In terms of scientific applications, the NeQuick model can provide realistic “weather-like” descriptions of the 3-D electron density of the ionosphere if suitable data ingestion and assimilation techniques are used.
- In terms of assessment studies, NeQuick has indicated that a “synthetic” ionosphere can be used to evaluate the effects of specific algorithms/assumptions in ionospheric parameters retrieval.
- The different NeQuick model implementations have demonstrated their capabilities in mitigating ionospheric effects in single-frequency positioning operations.

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Thank you for your attention