The Abdus Salam International Centre for Theoretical Physics

European Space Agency

Navigation solutions powered by Europe

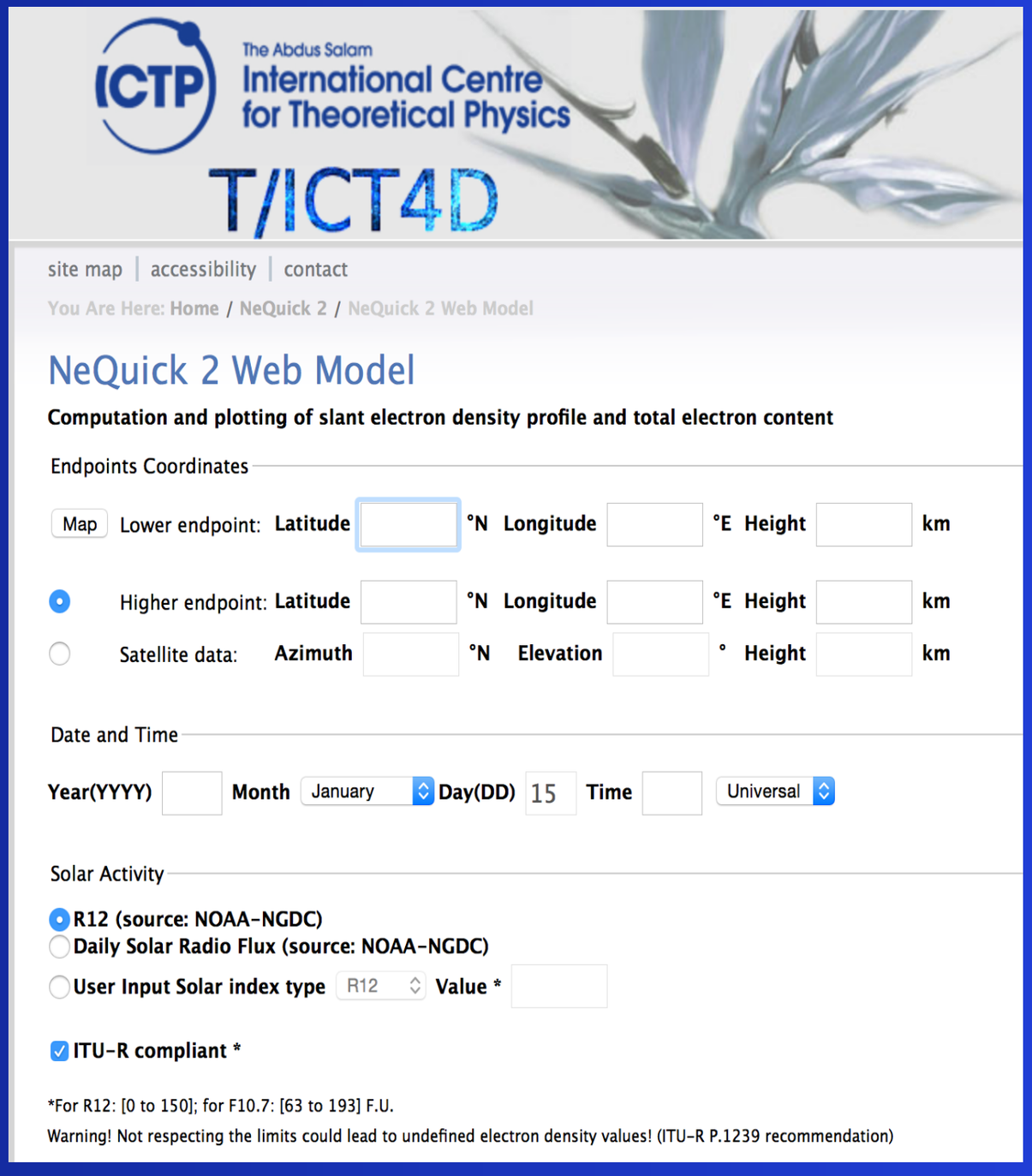
The NeQuick ionospheric electron density model: developments and applications

B. Nava [1]; R. Orus-Perez[2]
[1] STI Unit - ICTP; Trieste, Italy
[2] TEC-EFW - ESA/STEC; Noordwijk, The Netherlands

15th Meeting of the International Committee on Global Navigation Satellite Systems
Vienna, 27 Sep - 1 Oct, 2021

The NeQuick model

- NeQuick 2 (Nava et al., 2008) is the ionosphere electron density model developed at the Abdus Salam International Centre for Theoretical Physics, Trieste, Italy in collaboration with the University of Graz, Austria.
- It is a quick-run model particularly designed for trans-ionospheric propagation applications that has been conceived to reproduce the climatological behaviour of the ionosphere.
- It is based on the Di Giovanni and Radicella "profiler", which has been subsequently modified by other co-authors (Coïsson, Leitinger, Nava, Zhang).

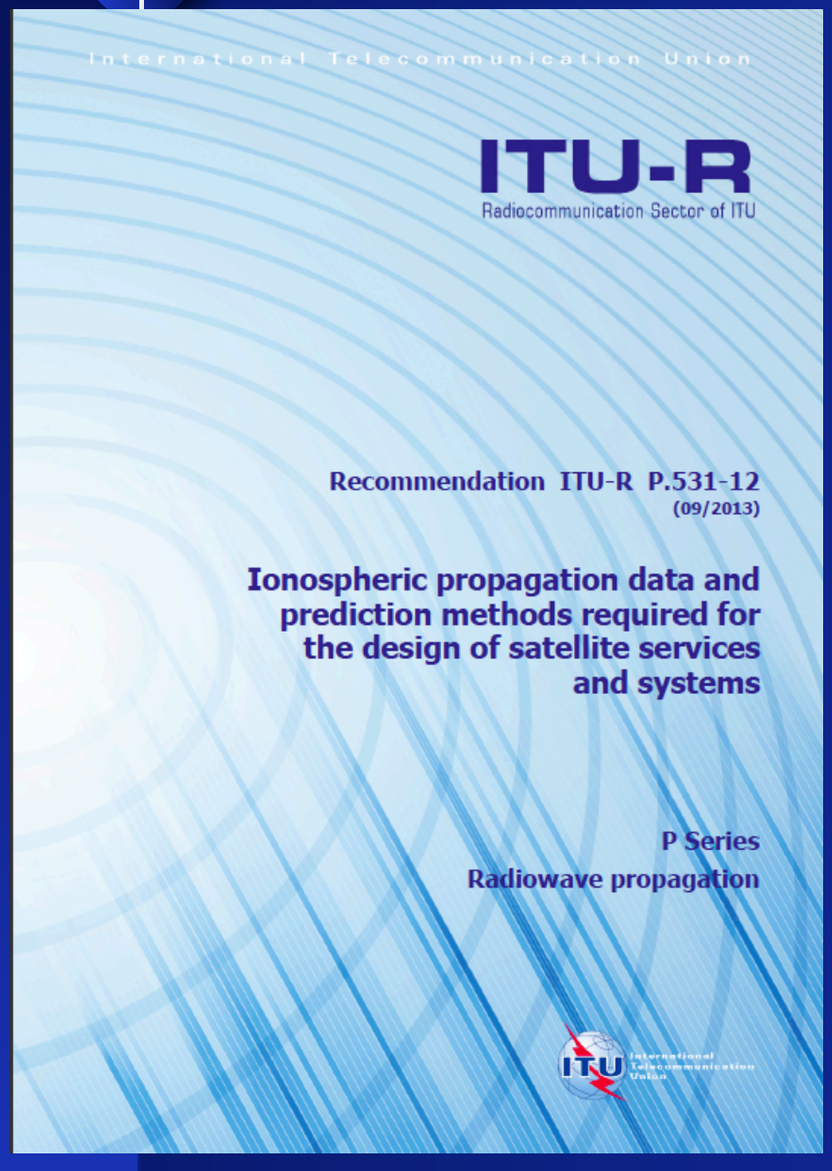


https://t-ict4d.ictp.it/nequick2/

The NeQuick model

- 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 developments



- The first version of the model has been adopted by the International Telecommunication Union, Radiocommunication Sector, as a procedure for estimating TEC (Recommendation ITU-R P. 531).
- Subsequently, NeQuick (v1) has been substituted by NeQuick 2, which is currently the model recommended by ITU (Recommendation P.531-14; 08/2019).

SPENVIS
The Space Environment Information System

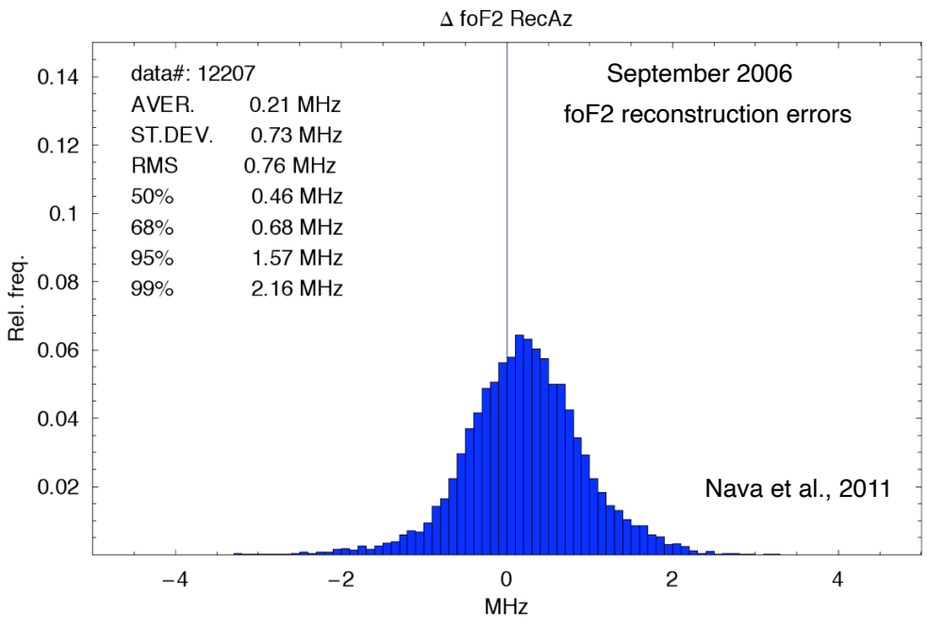
- ESA has included NeQuick 2 into Space Environment Information System (SPENVIS).

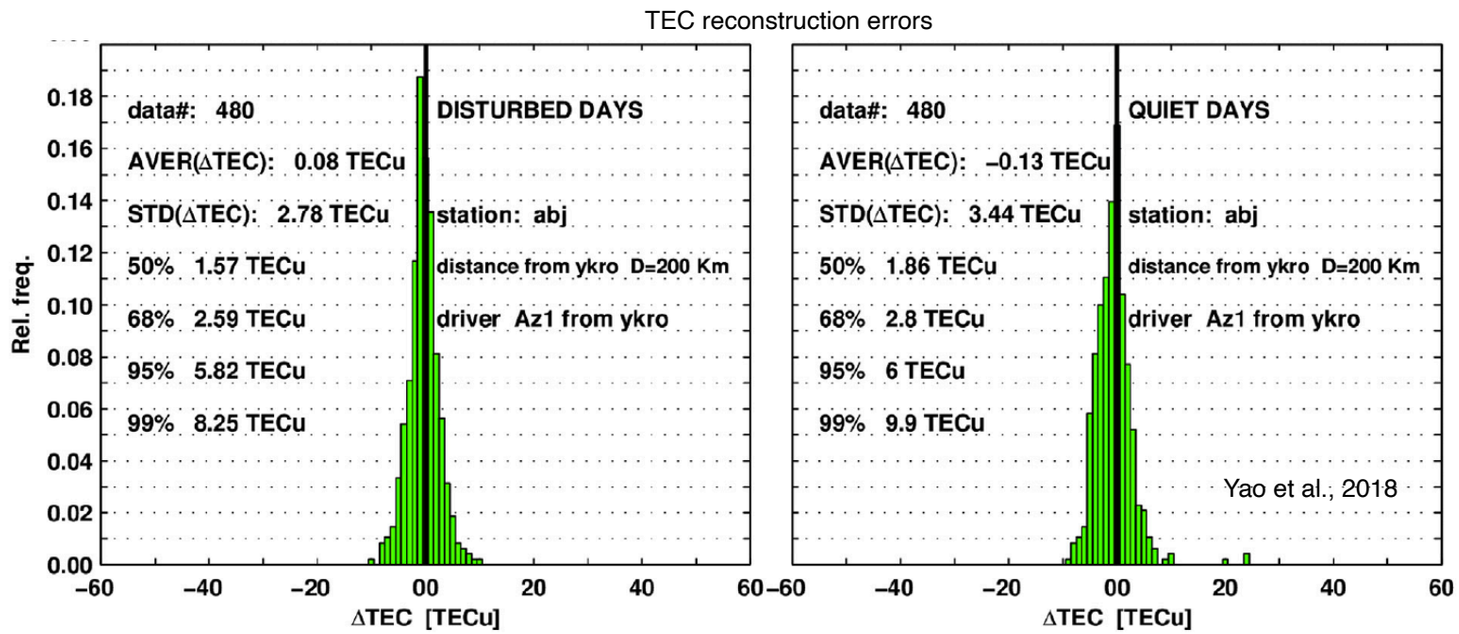
NeQuick developments

- A specific version of NeQuick (NeQuick G, implemented by ESA) has been adopted as Galileo Single-Frequency Ionospheric Correction algorithm.
- Its performance has been confirmed during In-Orbit Validation (Prieto-Cerdeira et al., 2014).
- More recently, Montenbruck and González Rodríguez (2020) have demonstrated that NeQuick G can as well be used for ionospheric correction of single-frequency observations from spaceborne platforms.

NeQuick implementations

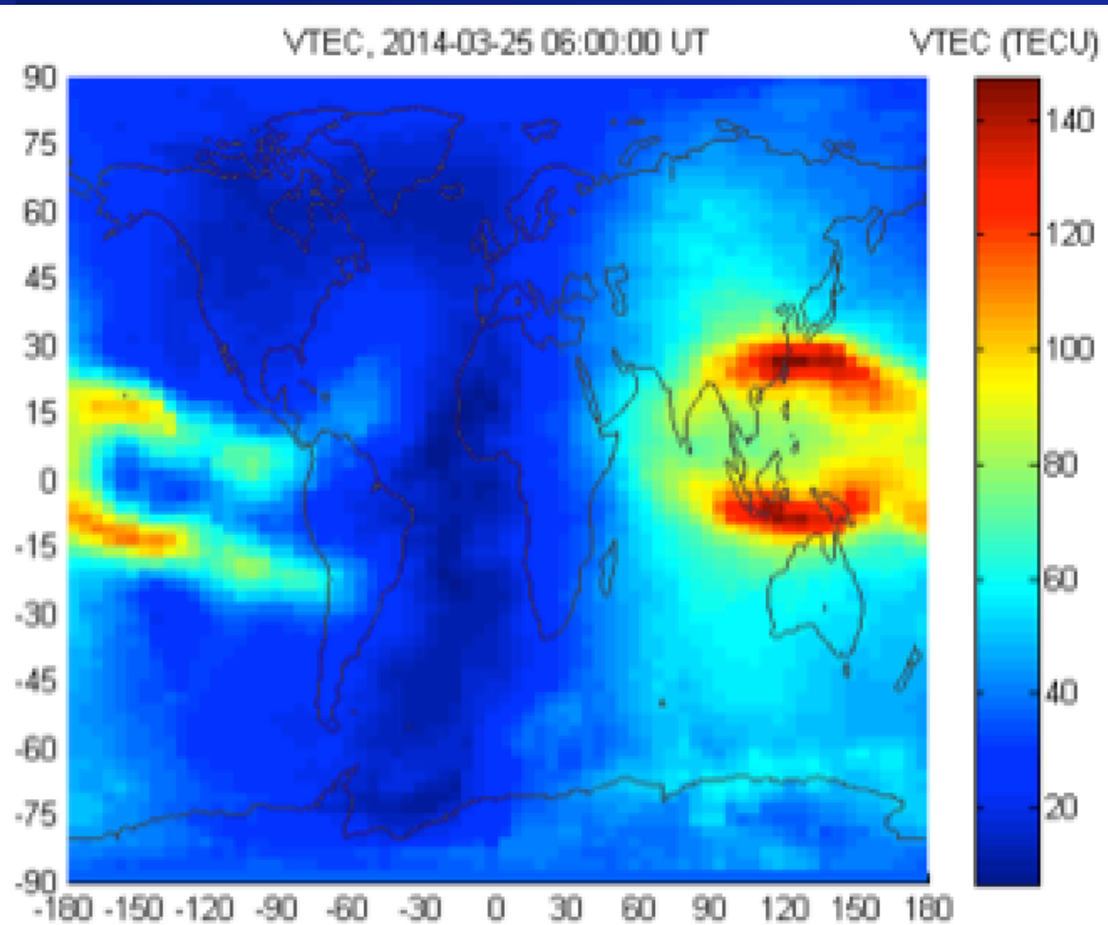
- To reconstruct the 3-D ionosphere electron density for current conditions, different data ingestion techniques based on the NeQuick adaptation to GNSS-derived TEC data have been implemented (Nava et al. 2011).
- These techniques have demonstrated to improve the model performance, also during geomagnetically disturbed periods (Yao et al., 2018).
- NeQuick has also been used as a part of very sophisticated assimilative models, which are able to incorporate (direct and) indirect measurements of the ionosphere electron density (Elvidge and Angling, 2019).

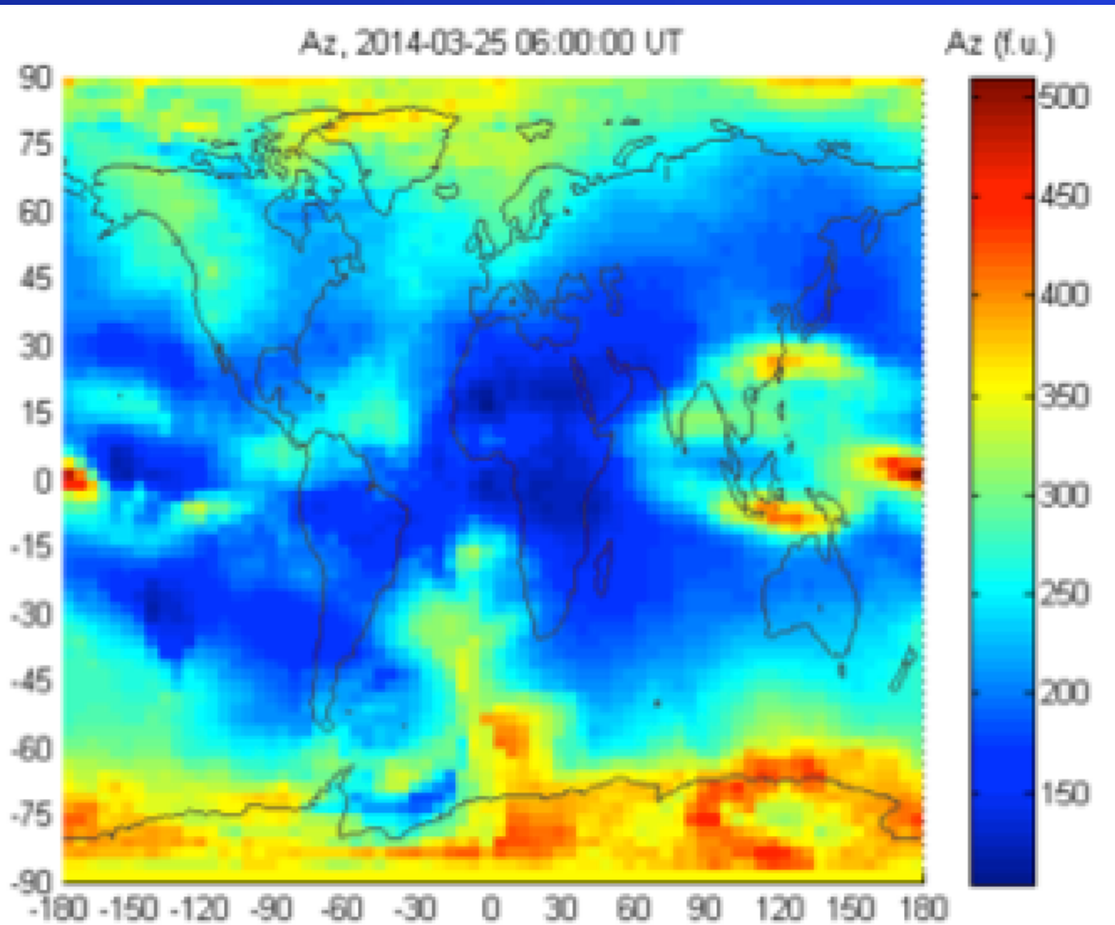




NeQuick for assessment studies

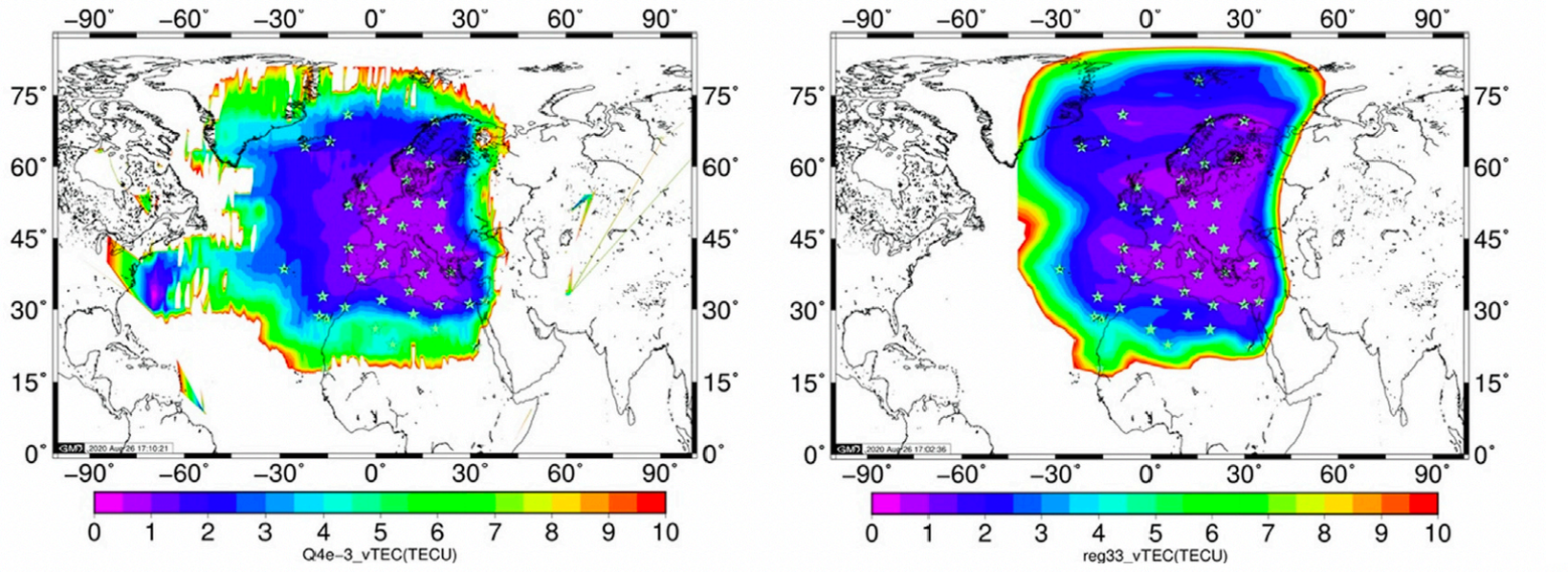
- Taking advantage of these ingestion techniques, NeQuick 2 has e.g. been used to generate “high accuracy” ionospheric scenarios in the framework of the MONITOR 2 project (funded by ESA).
- The basic methodology relied on the model adaptation to vertical TEC maps to obtain effective ionization parameter (Az) grids (Nava et al., 2011). Using these Az grids and the relevant NeQuick package, slant TEC values for any ground-to-satellite link could be computed.



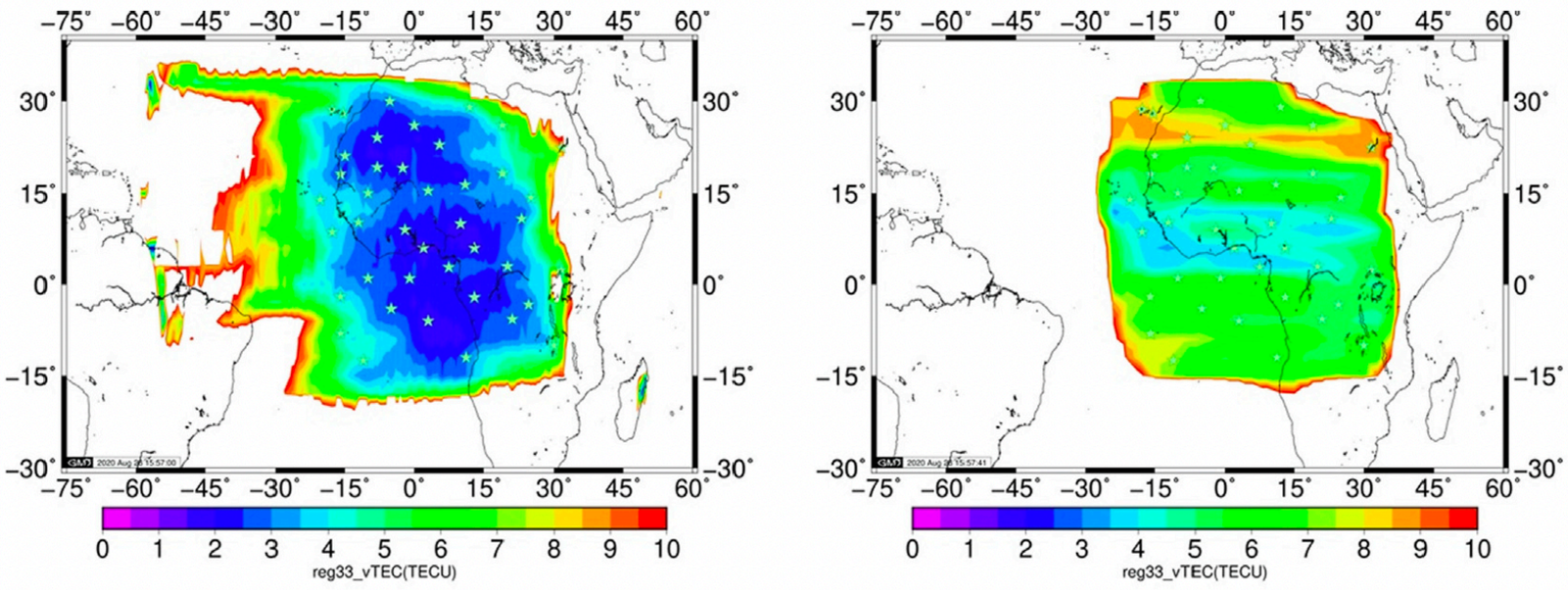


NeQuick for assessment studies

a)



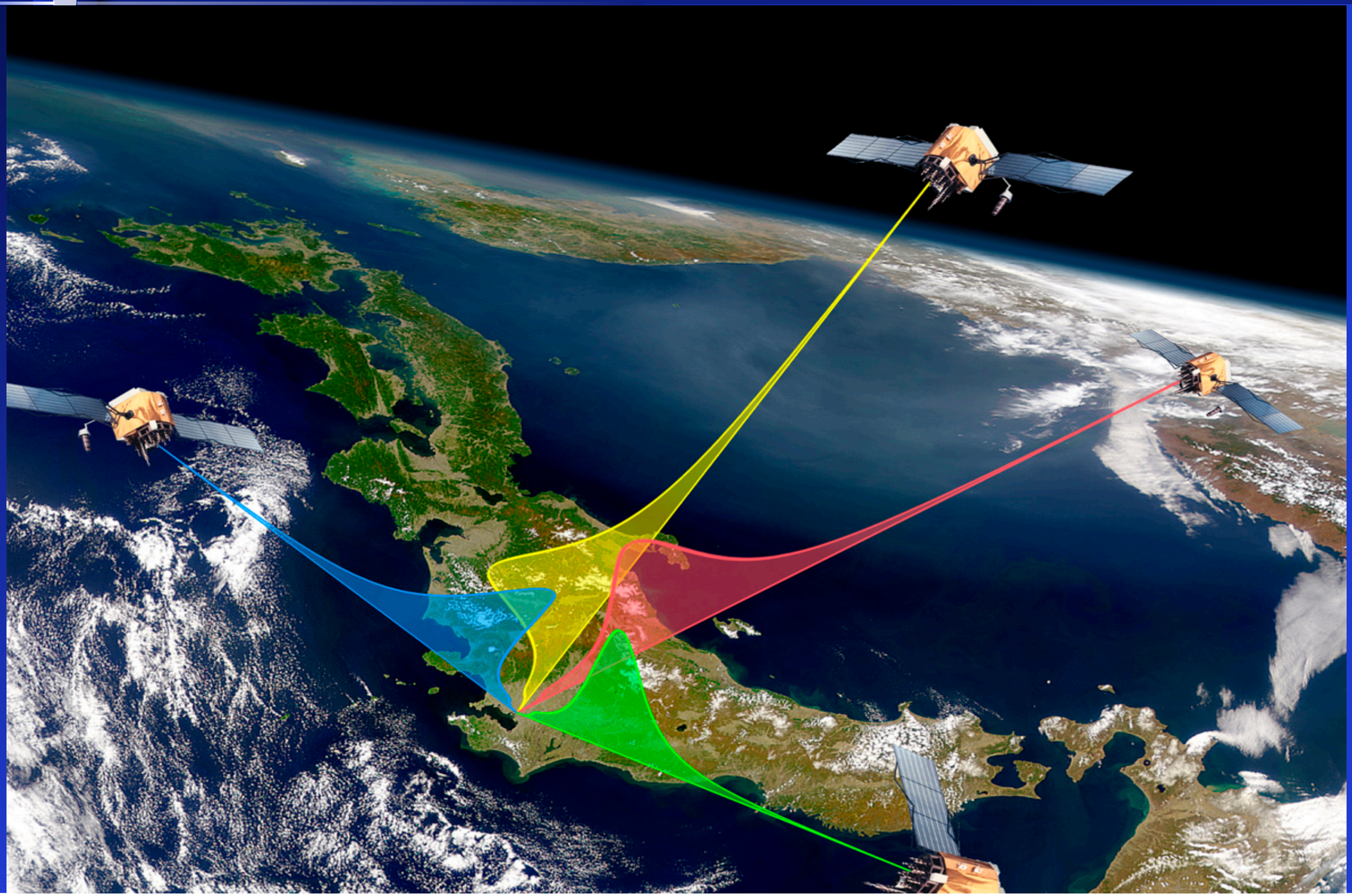
b)



RMS TEC error for the voxel (left) and spherical harmonics (right) models used over European (a) and African (b) region.

- The previously mentioned ingestion methodology has been used by Orus et al. (2021) construct a realistic modelled ionosphere.
- This allowed evaluating different algorithms/ models aimed at estimating vertical TEC from GNSS dual frequency observables, including the relevant Inter Frequency Biases (also called Differential Code Biases) and phase ambiguities.

NeQuick applications (GNSS)



Considering that in Nov. 2014 the International Committee on Global Navigation Satellite Systems Working Group B has recommended:

- to distribute …"the document providing the detailed description of the NeQuick algorithm implemented in Galileo" ….and
- …"to assess the performance and usability of a NeQuick ionospheric correction algorithm for the single frequency users similar to the one adopted by Galileo"….

NeQuick G

Galileo Ionospheric Correction Algorithm for Single-Frequency Users

- Navigation message broadcast:
  - 3 Az (Effective ionisation level) coefficients.
- Based on an adaptation of the 3D empirical climatological electron density model NeQuick → ***NeQuick G***
  - From monthly-mean climatological modelling to real-time corrections.
  - Including a number of evolutions from NeQuick 1.
  - Galileo specific version of geomagnetic field model (modip file)
  - Adaptations due to software engineering process.

Parameter	Definition	Bits	Scale factor	Unit
a_{i0}	Effective Ionisation Level 1st order parameter	11	2^{-2}	sfu**
a_{i1}	Effective Ionisation Level 2nd order parameter	11*	2^{-8}	sfu**/degree
a_{i2}	Effective Ionisation Level 3rd order parameter	14*	2^{-15}	sfu**/degree^2
SF_1	Ionospheric Disturbance Flag for region 1	1	N/A	dimensionless
SF_2	Ionospheric Disturbance Flag for region 2	1	N/A	dimensionless
SF_3	Ionospheric Disturbance Flag for region 3	1	N/A	dimensionless
SF_4	Ionospheric Disturbance Flag for region 4	1	N/A	dimensionless
SF_5	Ionospheric Disturbance Flag for region 5	1	N/A	dimensionless
Total Ionospheric Correction Size		**41**		

Correction Algorithm: End-to-End Overview

SENSOR STATION

Observe slant TEC in Sensor Stations for 24 hours

↓

Optimise effective ionisation parameter for NeQuick to match observations

↓

SATELLITE

Broadcast effective ionisation parameter in Navigation message

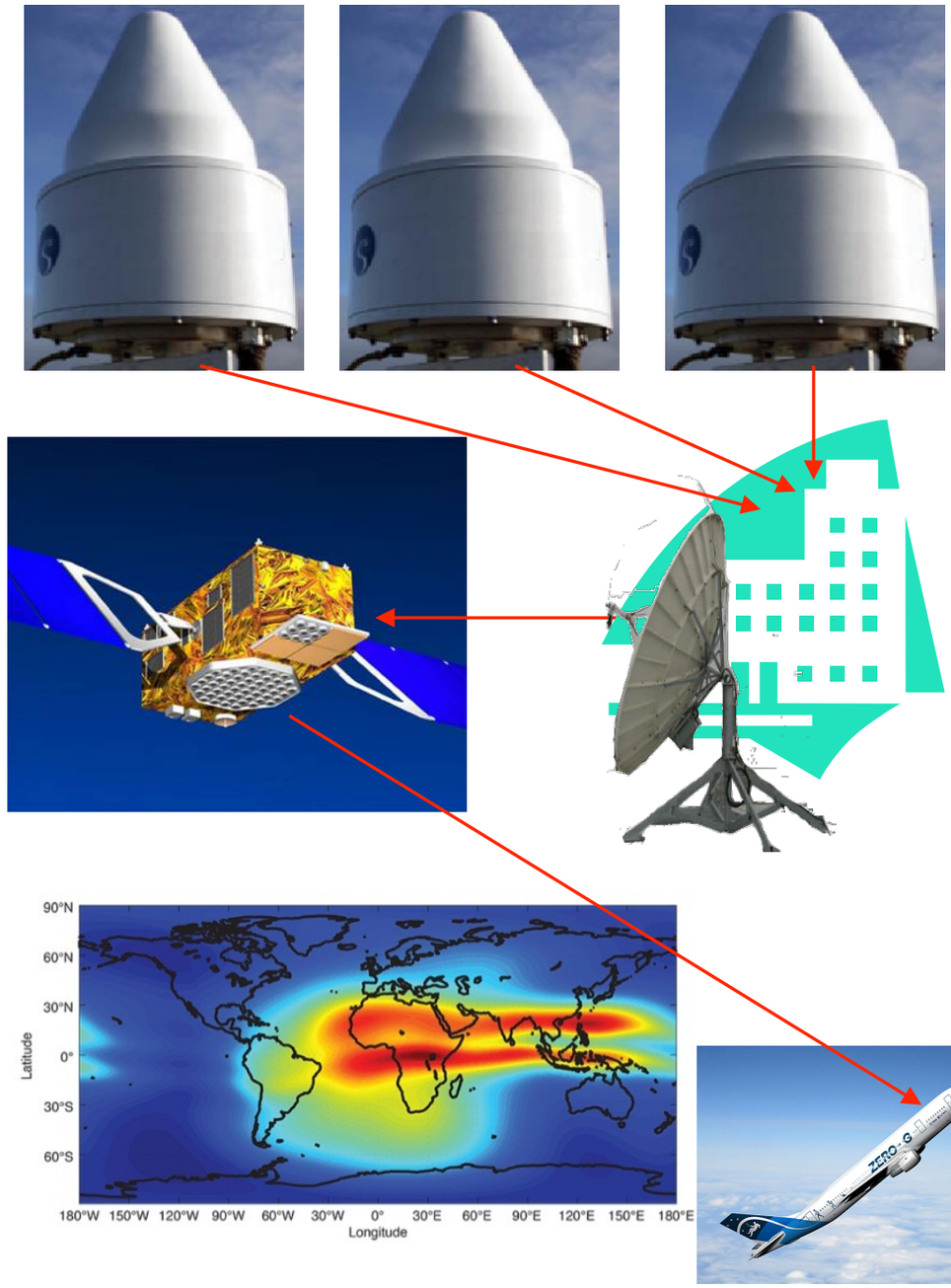
$$Az = a_0 + a_1 \cdot \mu + a_2 \cdot \mu^2$$

↓

USER RECEIVER

Calculate slant TEC using NeQuick G with broadcast parameter. Correct for Ionospheric delay at

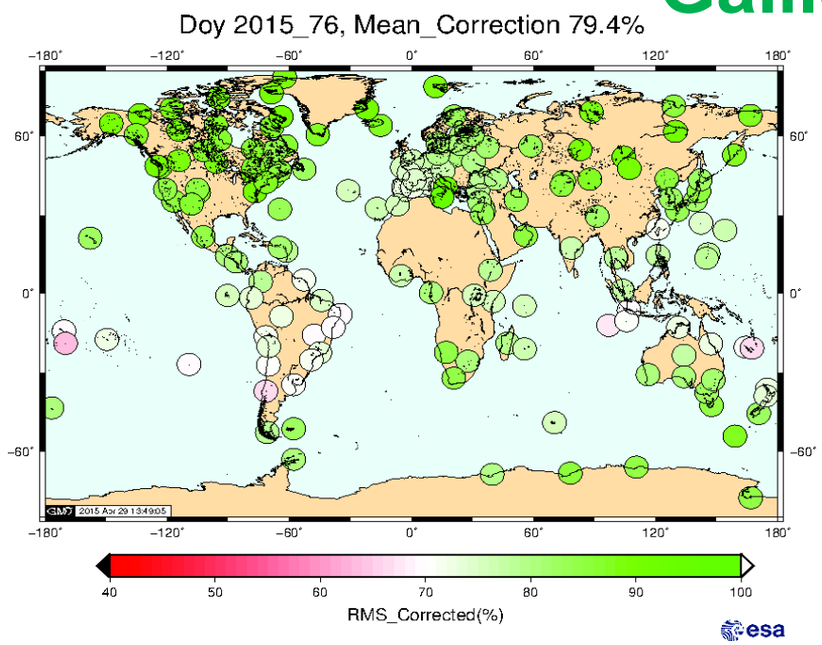
frequency in question.



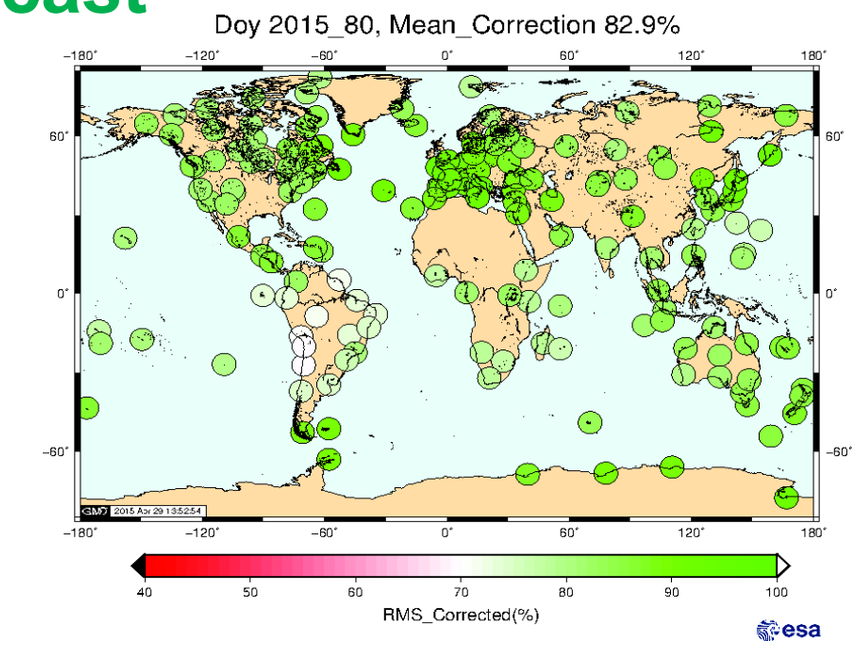
GALILEO EGNOS

FOC Results: Iono. Corr. Capability (%)

Galileo broadcast

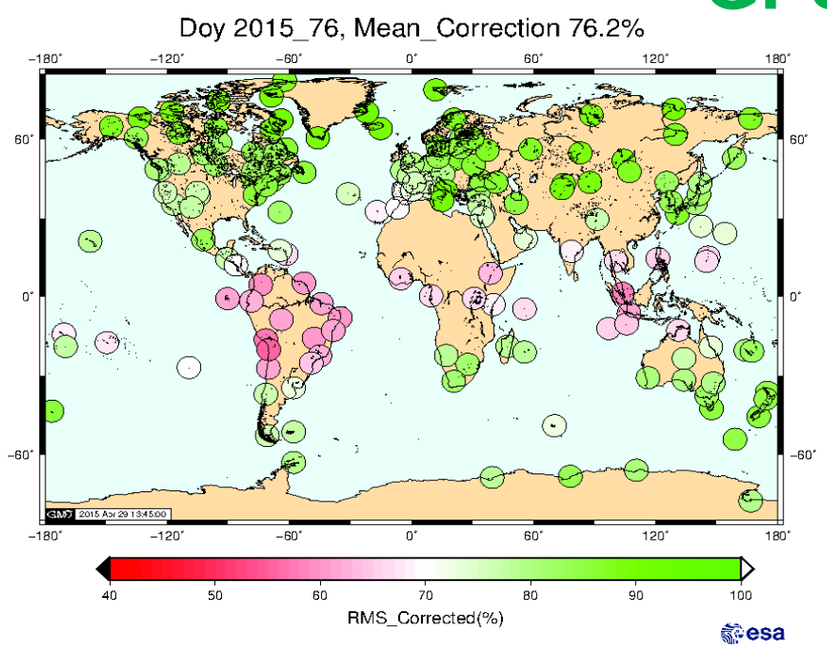


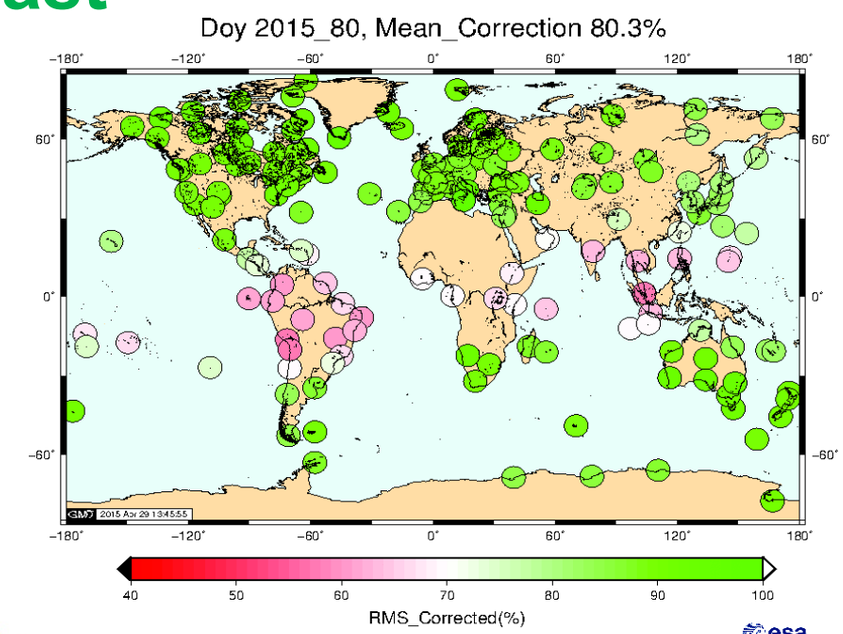
Doy 76/2015 (St. Patrick's storm)



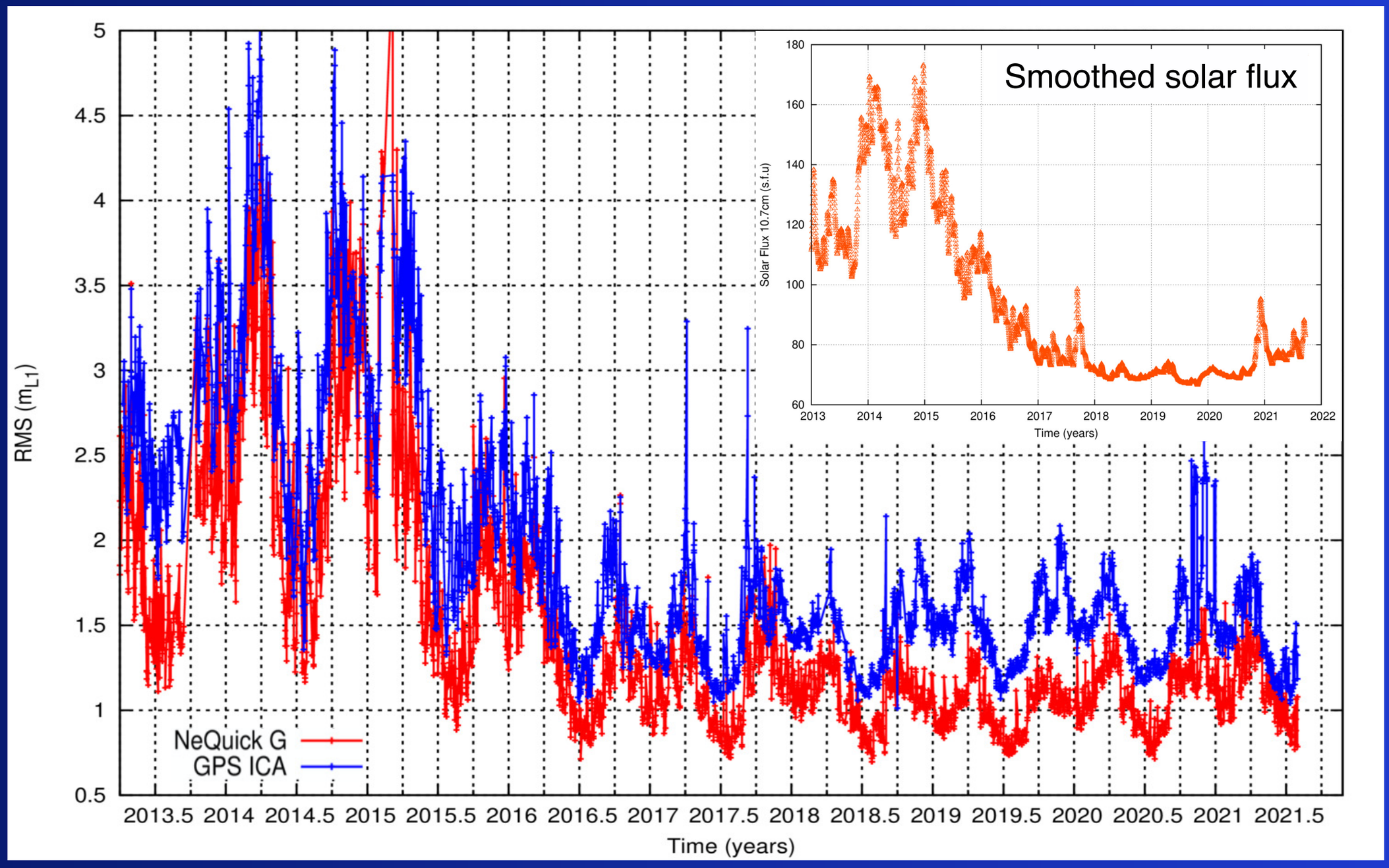
Doy 080/2015

GPS broadcast



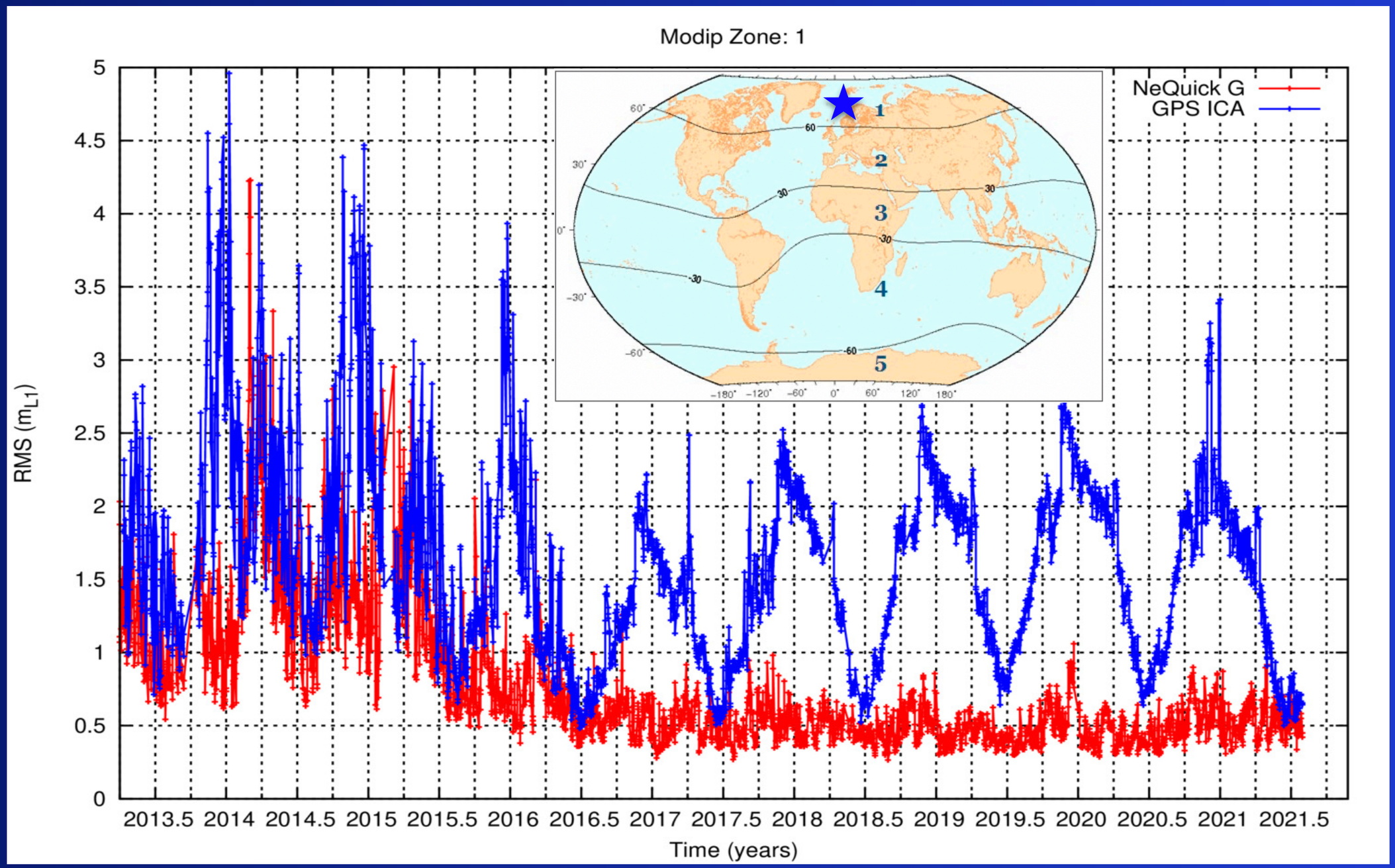


NeQuick G performance - Global



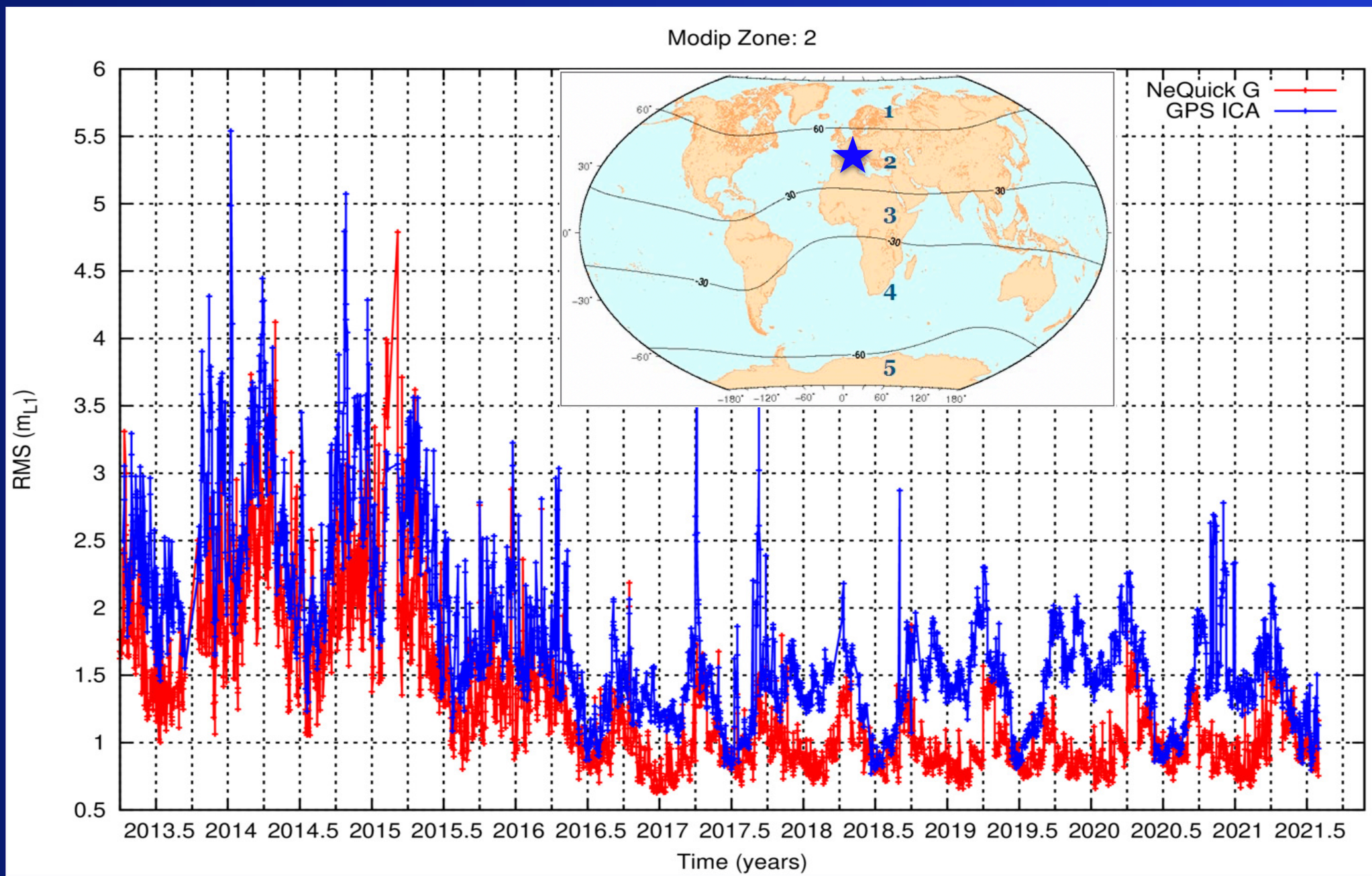
NeQuick G and ICA daily RMS TEC error@L1 [m] as a function of time; Global

NeQuick G performance - Zone 1



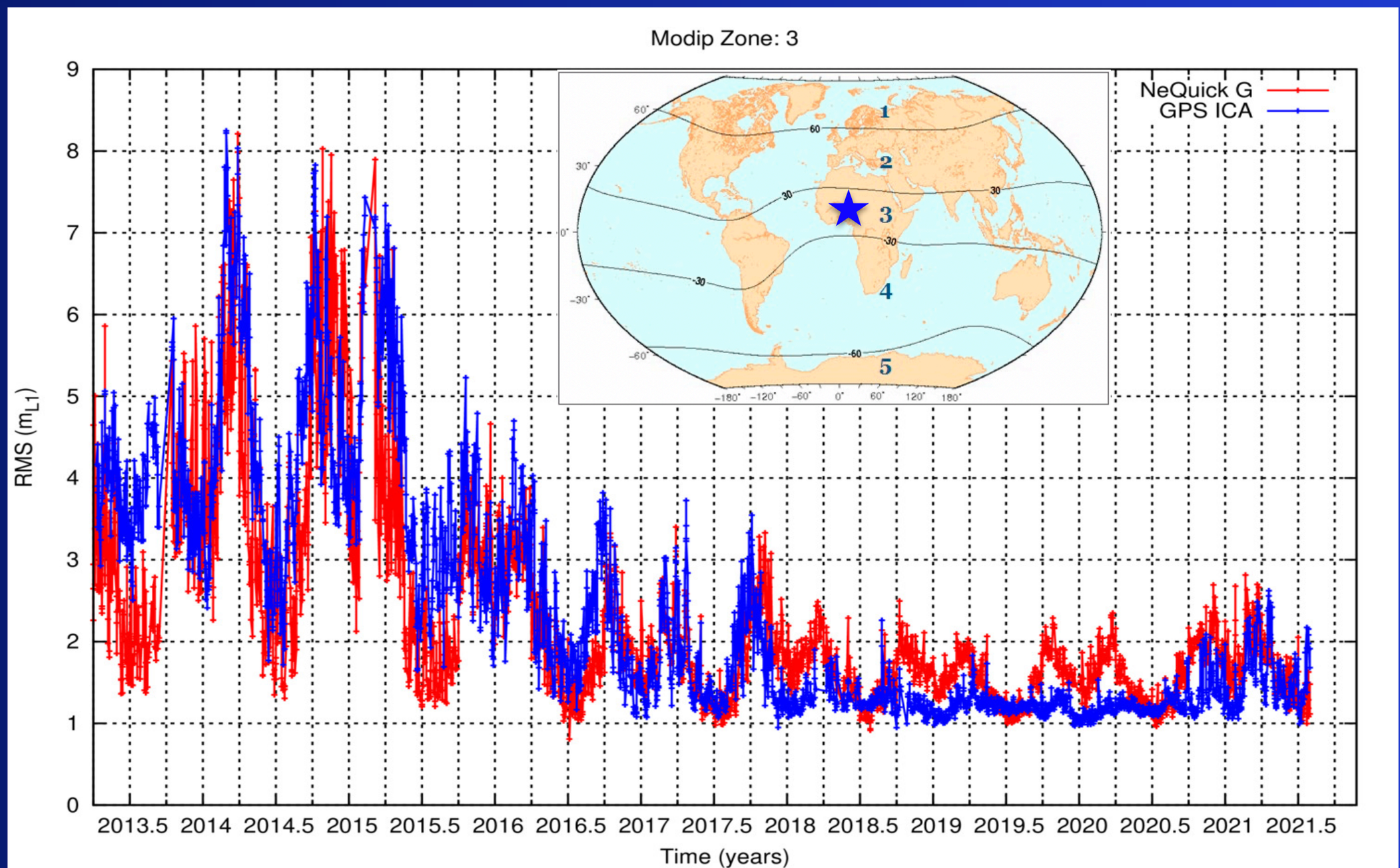
NeQuick G and ICA daily RMS TEC error@L1 [m] as a function of time; Zone 1

NeQuick G performance - Zone 2



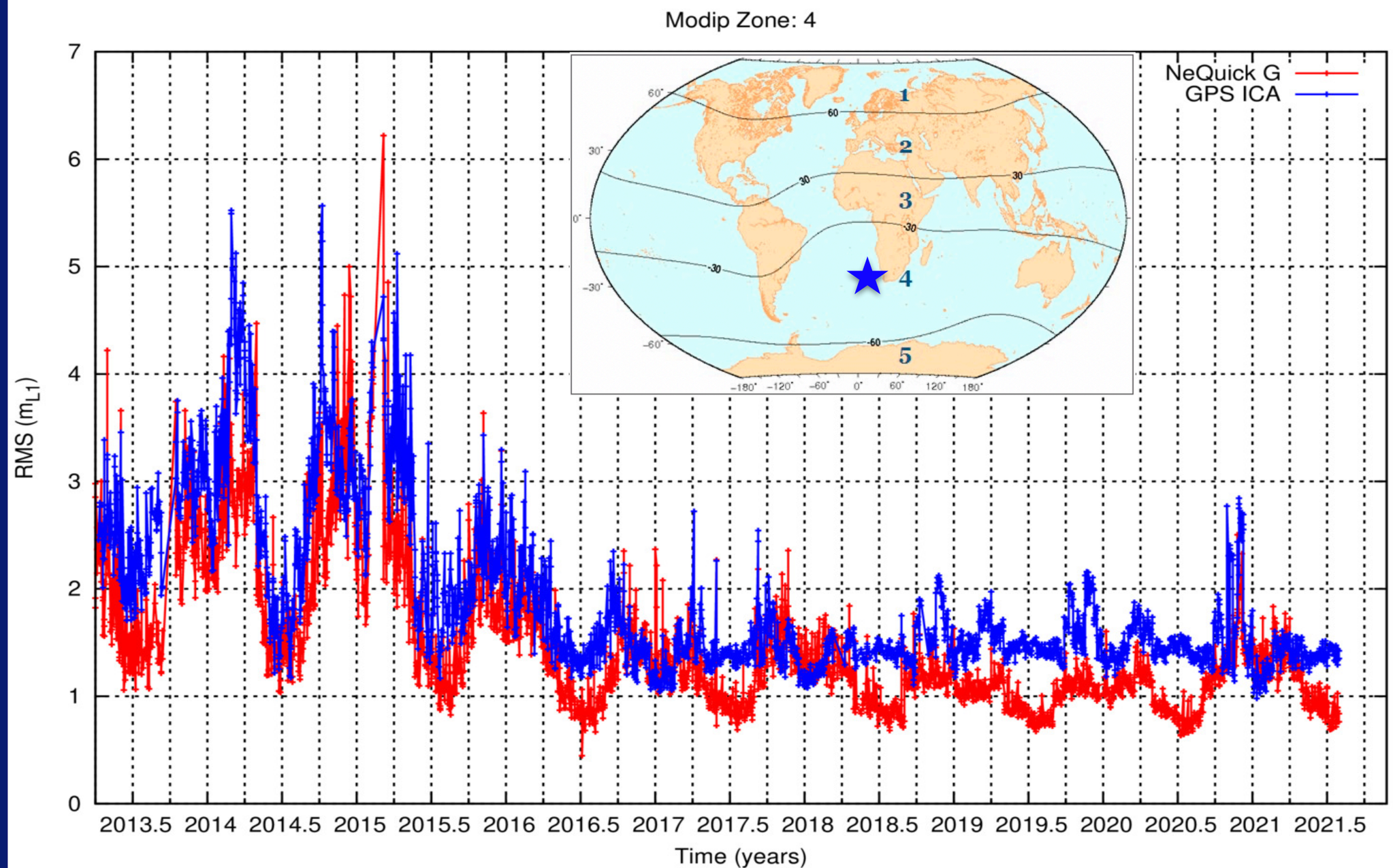
NeQuick G and ICA daily RMS TEC error@L1 [m] as a function of time; Zone 2

NeQuick G performance - Zone 3



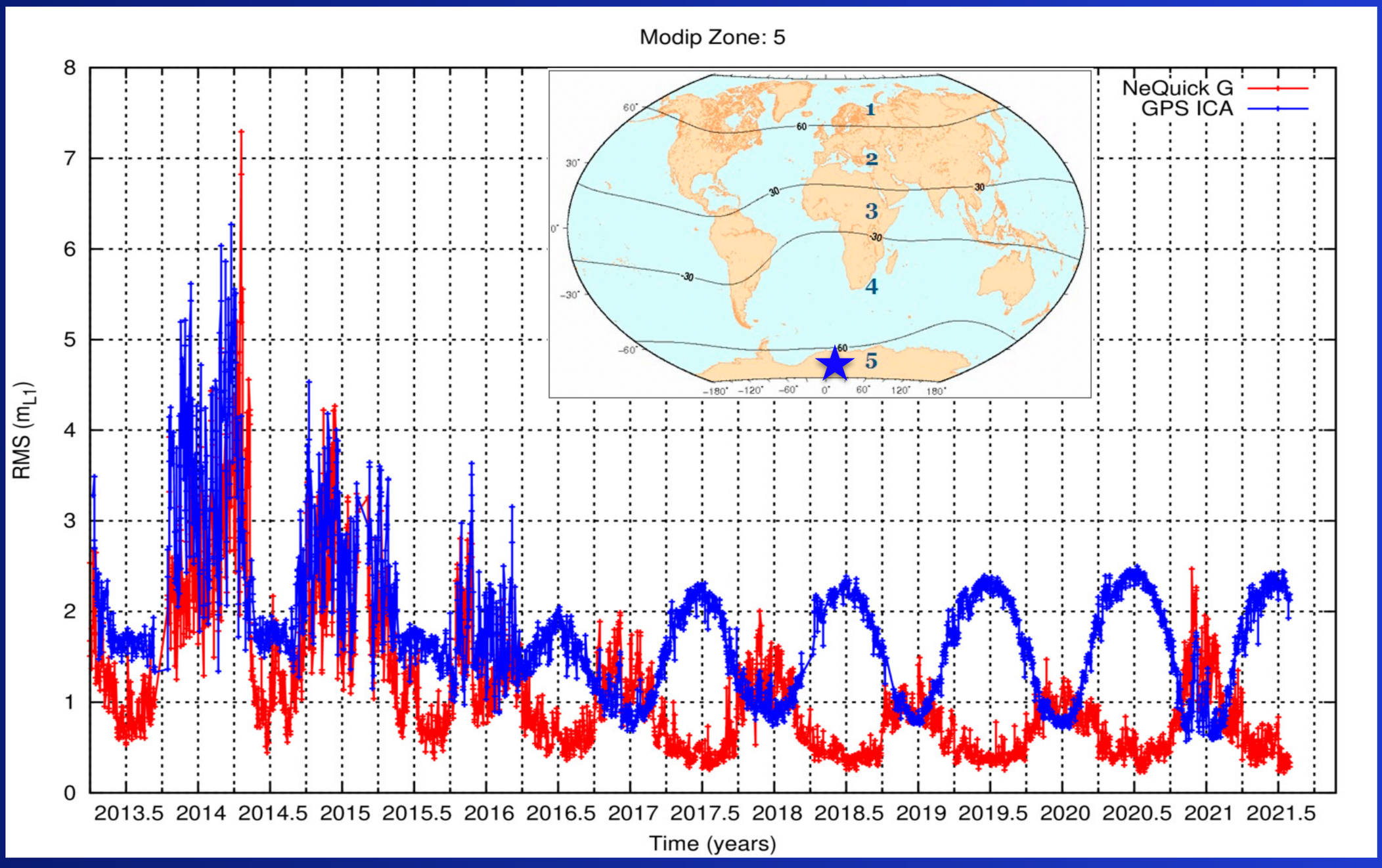
NeQuick G and ICA daily RMS TEC error@L1 [m] as a function of time; Zone 3

NeQuick G performance - Zone 4



NeQuick G and ICA daily RMS TEC error@L1 [m] as a function of time; Zone 4

NeQuick G performance - Zone 5



NeQuick G and ICA daily RMS TEC error@L1 [m] as a function of time; Zone 5

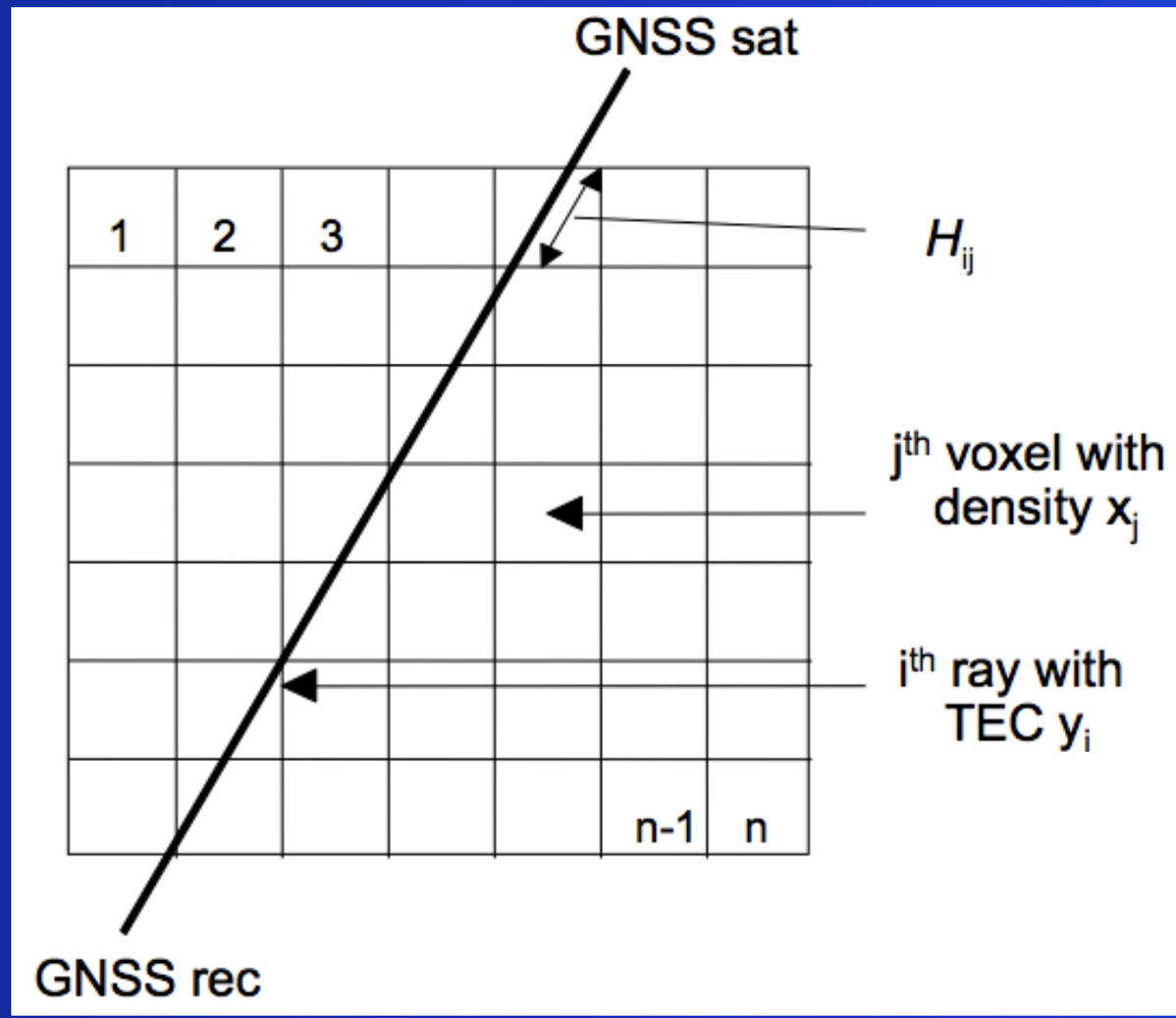
Data assimilation: the BLUE algorithm

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

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

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

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

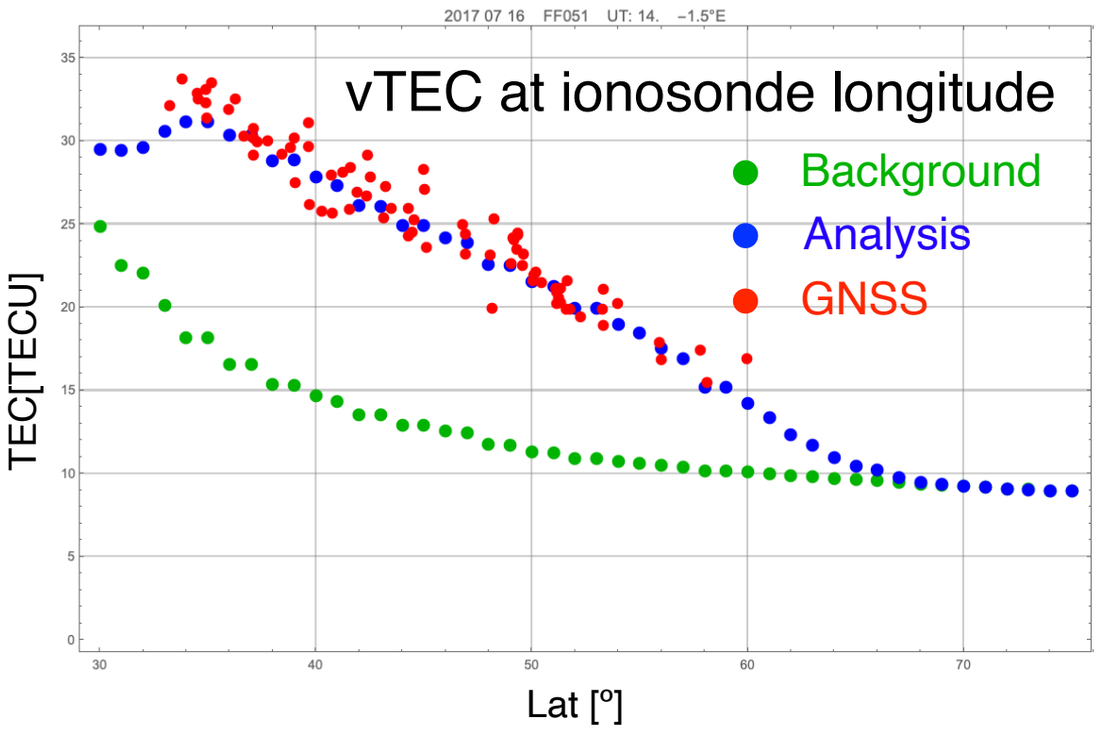


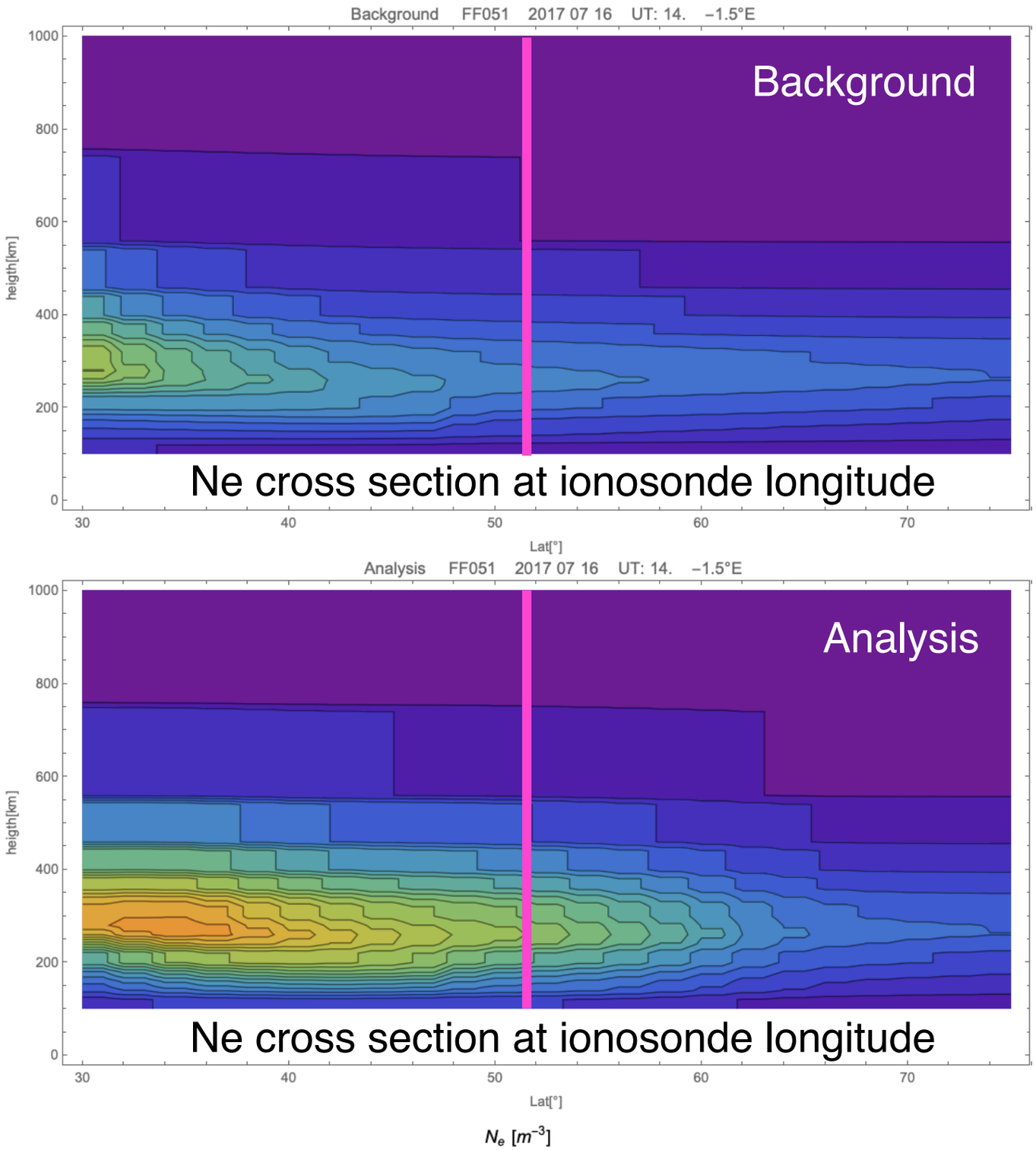
In our case:

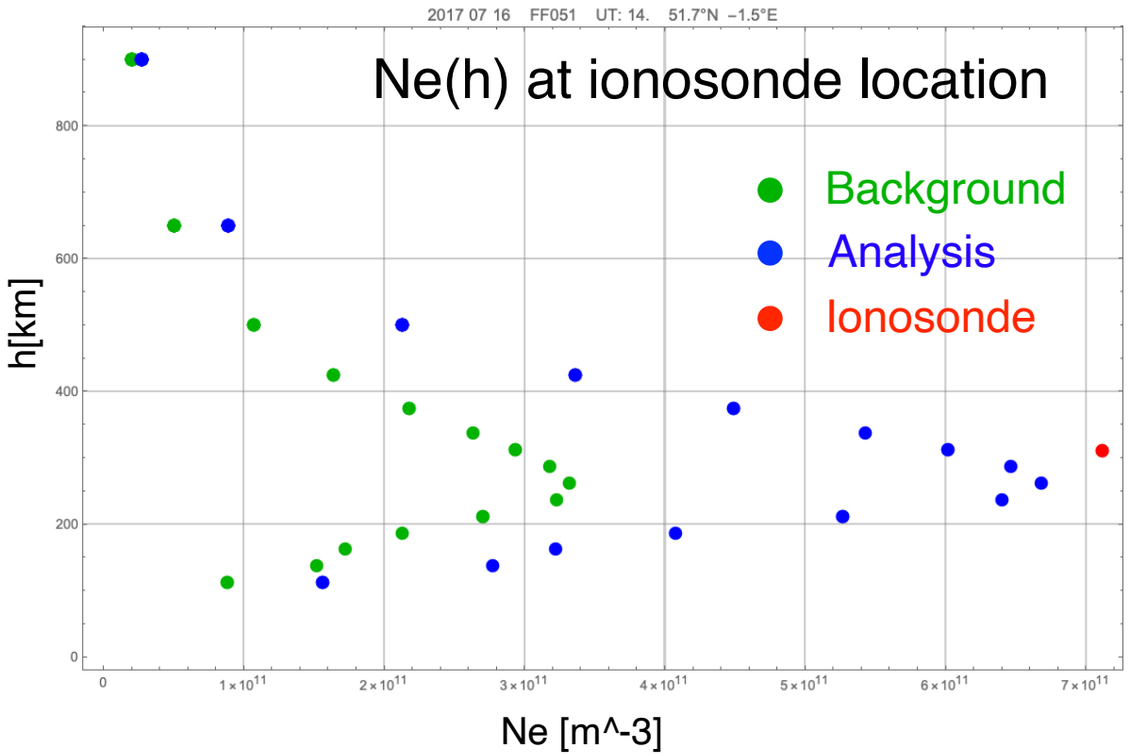
y = GNSS sTEC
$\mathbf{x_b}$ = NeQuick electron density
$\mathbf{x_a}$ = retrieved electron density
H -> “crossing lengths” in “voxels”

Simple formulation for **B** has been adopted (**R** is diagonal)

Results: 16 July 2017 (*); 14:00UT; FF051







Conclusions

- Different versions of the NeQuick model have been implemented and used in GNSS related applications.

- In terms of assessment studies, using NeQuick (e.g. with ingestion capabilities) it has been indicated how a “synthetic” ionosphere can be used to assess the effectiveness of specific algorithms/models in retrieving ionospheric parameters.

- As far as positioning applications are concerned, the NeQuick G has confirmed its very good performance as ionospheric correction algorithm for single-frequency users.

- In terms of scientific applications, the NeQuick model can provide realistic the 3-D representations of the electron density of the ionosphere if suitable data ingestion and assimilation techniques are used.

References

- Elvidge S., and M. J. Angling, "Using the local ensemble Transform Kalman Filter for upper atmospheric modelling", J. Space Weather Space Clim. 9 A30, 2019, doi: 10.1051/swsc/2019018.
- Montenbruck and González Rodríguez (2020) NeQuick-G performance assessment for space applications. GPS Solutions. https://doi.org/10.1007/s10291-019-0931-2
- Nava, B., P. Cosson, and S. Radicella (2008), "A new version of the NeQuick ionosphere electron density model", Journal of Atmospheric and Solar-Terrestrial Physics, 70 (15), 1856-1862; https://doi.org/10.1016/j.jastp.2008.01.015.
- Nava, B., S. M. Radicella, and F. Azpilicueta (2011), "Data ingestion into NeQuick 2", Radio Sci., 46, RS0D17; https://doi.org/10.1029/2010RS004635.
- Orus-Perez, R., B. Nava, J. Parro, A. Kashcheyev (2021). ESA UGI (Unified-GNSS-Ionosphere): An open-source software to compute precise ionosphere estimates, Advances in Space Research, Volume 67, Issue 1, Pages 56-65. https://doi.org/10.1016/j.asr.2020.09.011.
- Prieto-Cerdeira, Roberto & Orús Pérez, Raül & Breeuwer, Edward & Lucas-Rodriguez, Rafael & Falcone, Marco. (2014). Performance of the Galileo Single-Frequency Ionospheric Correction During In-Orbit Validation. GPSworld. 25. 53-58.
- Yao J.N., B. Nava, O.K. Obrou, S.M. Radicella, "Validation of NeQuick2 model over West African equatorial region using GNSS-derived Total Electron Content data", Journal of Atmospheric and Solar-Terrestrial Physics, Volume 181, Part A, December 2018, pp 1-9. https://doi.org/10.1016/j.jastp.2018.10.001.

Thank you for your attention