The NeQuick ionosphere electron density model: GNSS applications

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Outline

• The NeQuick model

• Different uses of NeQuick
  • Assessment studies
  • Applications
    • NeQuick G
  • Data assimilation
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.
• 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.

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 (NeQuick G, implemented by ESA) has been adopted as Galileo Single-Frequency Ionospheric Correction algorithm (http://gpsworld.com/galileo-update-ionospheric-model-shared-at-enc/) 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 used:

• to generate “worst case” ionospheric scenarios for assessment and tuning 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).

- The basic methodology will rely on the NeQuick 2 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 can be computed.
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

EGNOS Processing Set v.2.3.2

Low Latitude algorithm
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);

\[ TEC_i = 2 \left( N_1 d_{k,1} + N_2 d_{k,2} + \ldots + N_k d_{k,k} \right) \]

\[ d_{k,l} = \sqrt{r_{l-1}^2 - r_k^2} - \sqrt{r_l^2 - r_k^2} \]
30°
150°
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
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)
NeQuick for assessment studies


Variations of the residual range error, RRE
Applications
Considering that 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"
Galileo Ionospheric 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.

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<th>Definition</th>
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<th>Unit</th>
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Correction Algorithm: End-to-End Overview

- Observe slant TEC in Sensor Stations for 24 hours
- Optimise effective ionisation parameter for NeQuick to match observations
- Broadcast effective ionisation parameter in Navigation message
  \[ \Delta z = a_0 + a_1 \cdot \mu + a_2 \cdot \mu^2 \]
- Calculate slant TEC using NeQuick G with broadcast parameter. Correct for Ionospheric delay at frequency in question.
FOC Results: Iono. Corr. Capability (%)

Galileo broadcast

Doy 2015_76, Mean Correction 79.4%

GPS broadcast

Doy 2015_76, Mean Correction 76.2%

Doy 2015_80, Mean Correction 82.9%

Doy 2015_80, Mean Correction 80.3%
IOV+FOC: Residual RMS error ($m_{L1}$) - daily 2013-2015

- Broadcast NeQuick G performance very good despite the low number of satellites used to drive the model

Ground segment update

IOV
Towards FOC
Specifcation document - Contents

- Full step-by-step methodology and description
- Complementary files
- Input / Output validation files
- Appendix with pseudo-code implementation

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)*

\( \mathbf{y} \) vector of observations
\( \mathbf{x}_b \) background model state
\( \mathbf{x}_a \) analysis model state
\( \mathbf{H} \) observation operator
\( \mathbf{R} \) covariance matrix of observation errors
\( \mathbf{B} \) covariance matrix of background errors
\( \mathbf{A} \) 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

\[ x_a = x_b + K(y - Hx_b) \]

\[ K = BH^T(HBH^T + R)^{-1} \]

\[ A = (I-KH)B \]

\( K \) is called *gain* of the analysis

In our case:

- \( y = \text{TEC} \)
- \( x_a = \text{retrieved electron density} \)
- \( x_b = \text{background electron density} \)
- \( H \rightarrow \text{“crossing lengths” in “voxels”} \)

\[ \text{e.g. } \text{bckg}_\text{TEC} = Hx_b = \sum_j H_{ij} x_{bj} \]
LS solution: a test case

- projections of the LEO -> GPS links below the LEO orbit
- tangent points of the LEO -> GPS links
Results: retrieved electron density

Cross section
23:30UT; -65.5ºE
from -40ºN to -2ºN

Background model
(before the assimilation)

Analysis
(after the assimilation)
Results: retrieved electron density

![Graph showing electron density changes over time and altitude.](image)
Method validation

Electron density profiles at JRO location

Electron density profiles at Ionosonde location
Conclusions

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

• 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.

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

• 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.
Acknowledgments

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Thank you for your attention