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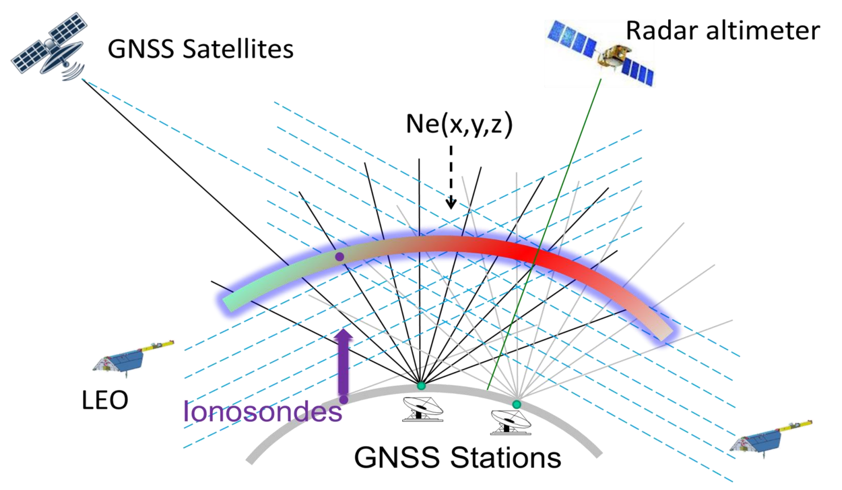
HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

Reconstruction of the ionospheric electron density by geostatistical inversion

David Minkwitz[1], Karl Gerald van den Boogaart[2, 3], Mainul Hoque[1] and Tatjana Gerzen[1]

[1]German Aerospace Center (DLR), Institute of Communications and Navigation, 17235 Neustrelitz, Germany, [2]Helmholtz Zentrum Dresden-Rossendorf, Helmholtz Institute Freiberg of Resource Technology and [3]Technical University Bergakademie Freiberg, 09599 Freiberg, Germany

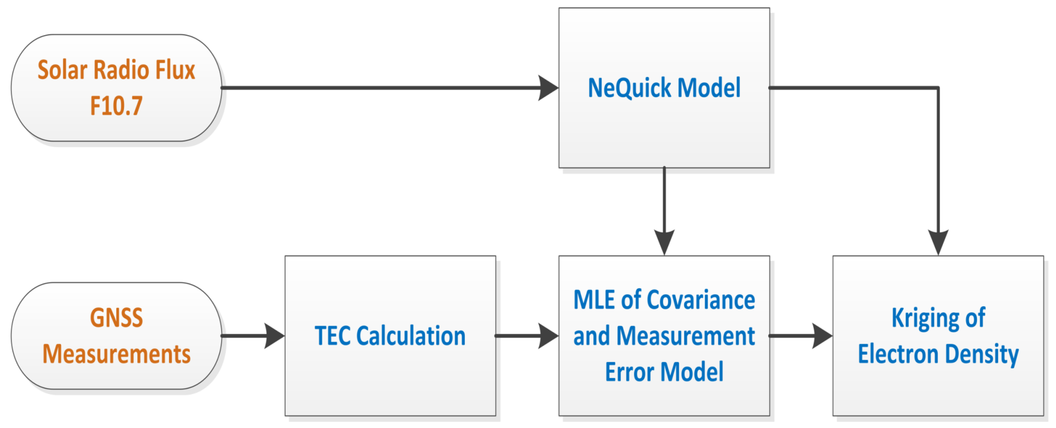
Tomography of the ionospheric electron density



Above: Tomography of the ionosphere

- 3D electron density distribution of the ionosphere is of crucial importance for different applications like GNSS Positioning and Remote Sensing
- Different direct (e.g. ionosondes, in-situ) and indirect measurements (ground- and space-based slant Total Electron Content [STEC]) of the ionospheric electron density are available
- The estimation of the ionospheric electron density by STEC measurements is a strongly underdetermined and ill-posed inverse problem with limited angle geometry

3D Simple Kriging of the electron density



Left: Work flow of 3D Simple Kriging is based on the incorporation of a background model, in this case the NeQuick model, and ground-based STEC measurements

1) Derive the STEC measurements $\overrightarrow{STEC}$ from the dual-frequency GNSS measurements and initialize the NeQuick model as background providing the expected STEC $\vec{\mu}$ along a given measurement geometry

2) Establish a parametric spatial covariance model of the electron density representing the ionosphere's behavior, e.g. anisotropic correlation lengths and non-stationarity, and derive its relation to the spatial covariance of the STEC measurements Σ_θ

3) Estimate the parameters of the spatial covariance model within a maximum likelihood estimation (MLE) by means of the available STEC measurements, i.e. maximize:

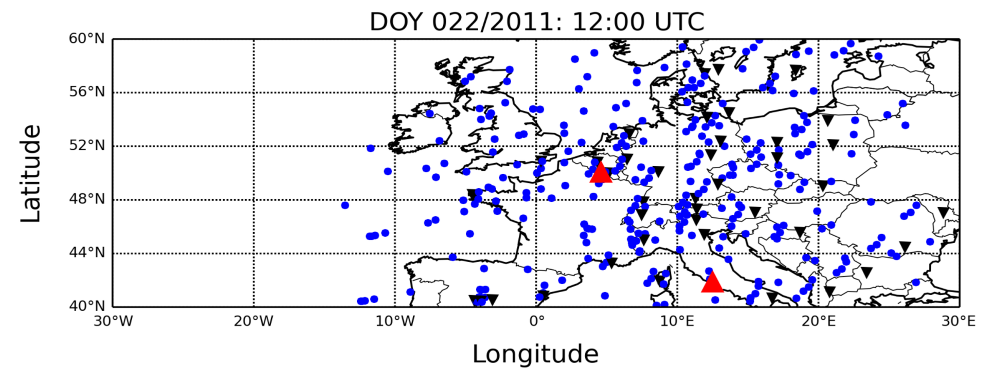
$$\arg\max_{\theta} \frac{1}{\sqrt{(2\Pi)^n \cdot |\Sigma_\theta|}} \exp\left(-\frac{1}{2}\left(\overrightarrow{STEC}-\vec{\mu}\right)^T \Sigma_\theta{}^{-1}\left(\overrightarrow{STEC}-\vec{\mu}\right)\right)$$

4) Estimate the electron density for an arbitrary WGS84 coordinate $\vec{x}$ by the 3D Simple Kriging of linear functionals, i.e. STEC measurements:

$$Ne(\vec{x}) = \mu(Ne(\vec{x})) + \begin{pmatrix} cov_\theta(Ne(\vec{x}), STEC_1) \\ \vdots \\ cov_\theta(Ne(\vec{x}), STEC_n) \end{pmatrix}^T \Sigma_\theta{}^{-1}\left(\overrightarrow{STEC}-\vec{\mu}\right)$$

Regional application

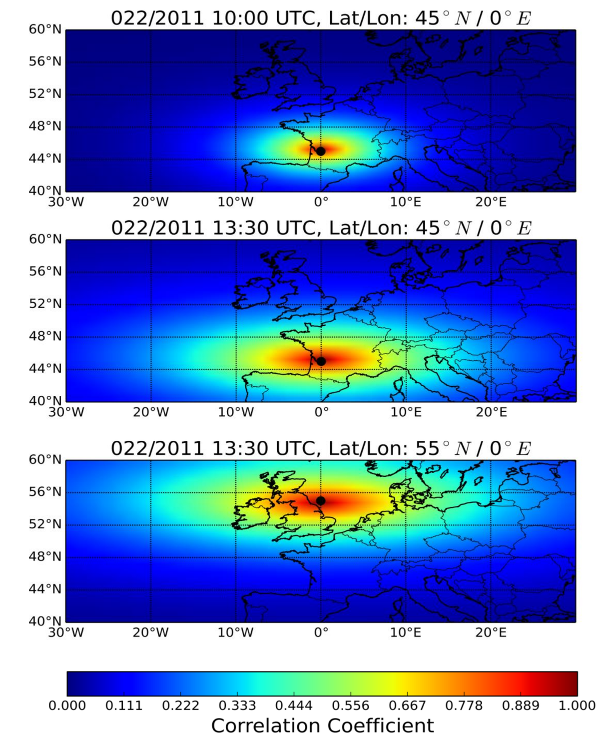
- European region is chosen as validation environment for DOY 022/2011
- Measurement geometry reveals strongly underdetermined inverse problem
- 3D Simple Kriging of the electron density with about 300 STEC measurements of 50 IGS stations
- Comparison of derived electron density profiles to ionosonde profiles



Left: Typical measurement geometry over Europe: IGS ground stations (black triangles), ionospheric piercing points of the STEC measurements (blue circles) and ionosondes Rome/Italy and Dourbes/Belgium (red triangles)

Estimated covariance

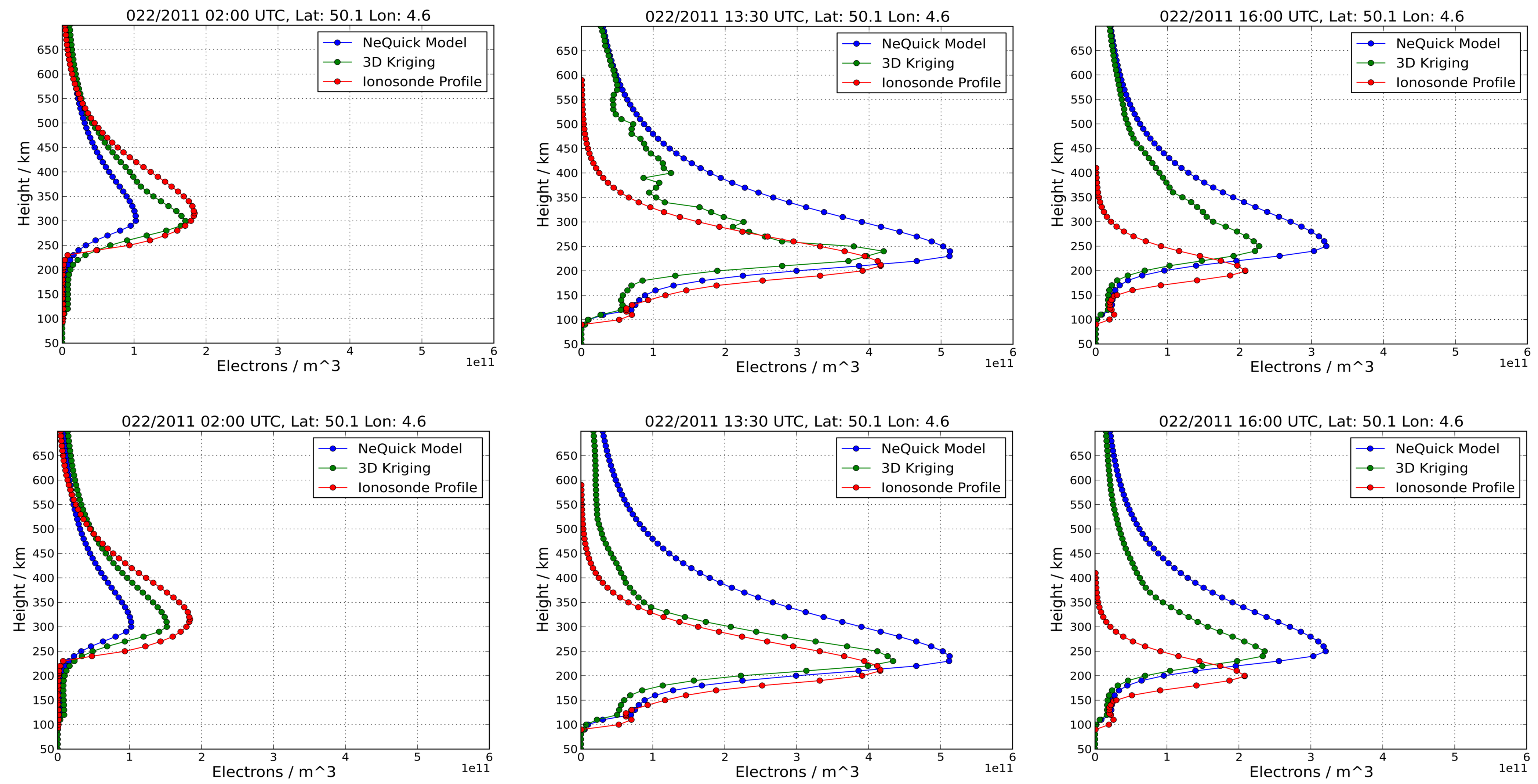
- The parametric covariance model is composed of a horizontal and vertical component
- Correlation lengths depend on local time and latitude

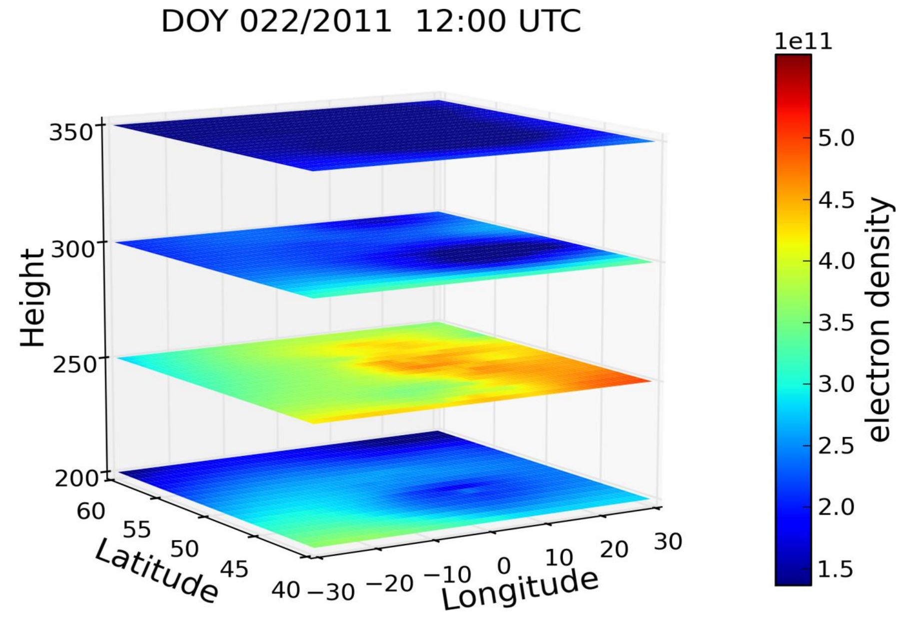


Right: Estimated horizontal correlation lengths for DOY 022/2011 at an altitude of 300 km for two different times and coordinates (black dots)

Preliminary results

- The 3D Simple Kriging fits the background model electron density profiles towards the STEC measurements
- The comparison with independent ionosonde profiles illustrates the achieved improvements regarding the F2 layer characteristics on DOY 022/2011
- Artifacts can be reduced by the estimation of the measurement error model parameter





Above: Electron density reconstruction over Europe at DOY 022/2011 12:00 UTC for the altitudes between 200 – 350 km

Left: Reconstructed electron density height profiles at Dourbes/Belgium during DOY 022/2011 without (upper) and with (lower) measurement error model: Electron density profiles of the NeQuick background model (blue), the 3D Simple Kriging electron density profiles (green) and the ionosonde electron density profiles (red) at 02:00 13:30 and 16:00 UTC

Conclusions & Outlook

- A novel tool for the ionospheric electron density reconstruction is developed based on the estimation of the electron density's covariance
- Electron density covariance is crucial for data assimilation methods
- Preliminary results indicate a promising gain compared to the background model
- Approach is able to ingest direct and indirect measurements of the ionosphere
- Future work will focus on incorporation of additional measurements and the inclusion of a temporal aspect, for instance by means of an Ensemble Kalman Filter

Contact:
David Minkwitz (email: david.minkwitz@dlr.de)
German Aerospace Center (DLR), Institute of Communications and Navigation, Kalkhorstweg 53, 17235 Neustrelitz, Germany
http://www.dlr.de/kn/en/

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