Reconstruction of the ionospheric electron density by geostatistical inversion

Tomography of the ionospheric electron density

- 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) 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

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

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

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

3D Simple Kriging of the electron density

- Derive the STEC measurements $\text{STEC}$ from the dual-frequency GNSS measurements and initialize the NeQuick model as background providing the expected STEC $\mu$ along a given measurement geometry
- 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 $\Sigma$
- Estimate the parameters of the spatial covariance model within a maximum likelihood estimation (MLE) by means of the available STEC measurements, i.e. maximize:

$$\arg\max_{\theta} \frac{1}{2n} \| \text{STEC} - \tilde{\mu} \|^2 \Sigma^{-1} (\text{STEC} - \tilde{\mu})$$

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

$$\text{Ne}(\tilde{x}) = \mu (\text{Ne}(\tilde{x})) + \left( \text{cov}_y (\text{Ne}(\tilde{x}), \text{STEC}) \right)^T \Sigma^{-1} \text{STEC} - \tilde{\mu}$$

Estimated covariance

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

Above: Tomography of the ionosphere

Left: Work flow of 3D Simple Kriging

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