Ionospheric 4-D Multi-Instrument Tomography with Gaussian Markov Random Field Priors

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The ionospheric tomography problem suffers typically from two major complications. First, the problem is mathematically ill-posed and requires some additional information for a stable and unique solution. Second, with necessary spatio-temporal resolution, the problem can become very high dimensional and computationally infeasible.

Here a Bayesian statistical algorithm is used to stabilise the ill-posed problem. The approach is generally analogous to the well known 3-dimensional variational method, where the available a priori information is described as a probability distribution and updated with new measurements to obtain the current state of the system. The method provides a transparent scheme for the model calibration as the parameters have physical and probabilistic interpretation. It can also utilise any ionospheric measurements that can be represented as a linear model of the electron density.

However, in rigorous modelling of the prior distribution, the resulting prior covariance matrix can become so large that even its allocation in computer memory is impossible. Here Gaussian Markov Random Fields (GMRF) are applied to overcome the computational issues. With GMRF the covariance information can be implemented as a sparse precision matrix [1]. The sparse matrix format allows low memory storage and the use of parallel sparse linear system solvers. This makes the computation of relatively high resolution reconstructions feasible with a normal PC.

The presented approach can be used as a normal assimilation method. Any ionospheric electron density model can be selected as the background model and updated with the available measurements. However, typically in the situations where the model is accurate, such as normal day-time ionosphere, also the tomographic algorithms work well and do not require that much additional information. Then again, in disturbed situations, especially in the high-latitude night-time ionosphere, the models can be drastically off. In consequence, the analysis can be performed also without an actual background model. Instead, a zero electron density is assumed as a prior mean and the prior covariance then indicates how likely the ionospheric electron density is to deviate from it. With the GMRF approach the modification of the prior covariance can be carried out without additional computational expenses, allowing very detailed and dynamical modification of the prior covariance. Here ionosonde measurements and general physical characteristics of ionosphere are used in the construction of the covariance structure.

In the presented results GNSS, LEO beacon satellite and ionosonde measurements are employed for ionospheric tomography over Northern Europe. We validate 24h 4-dimensional tomographic analysis results with EISCAT incoherent scatter radar measurements and demonstrate the performance in disturbed ionospheric conditions.

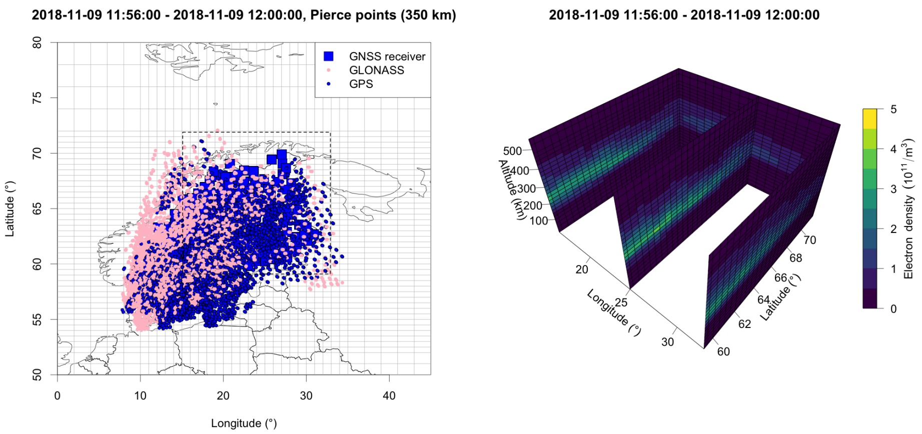

Figure 1: Snapshot from a 24h tomographic analysis. Here ground-based measurements of GPS and GLONASS signals are used.

References

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