14 -- 2017-02-24 06:49:32
Session 9A Paper 4

Penney, Richard: QinetiQ Ltd
Jackson-Booth, Natasha: QinetiQ Ltd

Ionospheric imaging by finite-element tomography

Being able to estimate the spatial distribution of ionospheric electron density is important to many geophysical and communications applications affected by space weather. In general, this 3D density profile is very difficult to measure directly, and must involve fitting techniques which try to reconcile relatively sparse measurements from ionosondes and dual-band GPS receivers with a parameterized model of the ionosphere. Tomographic techniques have been successfully applied to ionospheric imaging, but generally require considerable specialization to handle the irregular spatial sampling and other peculiarities of time-series derived from GPS, GLONASS, NIMS, etc.. Obtaining the best tomographic image quality requires careful consideration of how sparsely sampled sensor measurements correspond to the imaging model.

We will illustrate how unsophisticated interpolation techniques (and non-local basis-functions) used implicitly within a tomographic reconstruction severely limit the fidelity of an estimated electron-density profile. We will describe improved techniques that more self-consistently handle the interpolation of sensor data within a tomographic fitting process, based on finite-element modelling techniques and tetrahedral electron-density grids. We will consider both an idealized 2D tomographic toy problem, and a full 4D tomographic imaging system using dual-band GPS.

The 2D scenario involves trying to reconstruct Gaussian clouds on a rectangular grid, using a set of randomly placed look-directions, analogous to the complex motion of GPS satellites along which one has measurements of Total Electron Content (TEC). Each observation will typically intersect multiple grid-cells, and will generally have a rather complex pattern of lengths and vertex-offsets within each of the cells through which it passes. Fitting the parameters of one’s model to the available measurements requires one to define an interpolation scheme which allows one to integrate the fitted electron-density along an arbitrary line across the grid. We will show that the choice of this interpolation scheme exerts a huge influence on the quality of one's tomographic reconstruction, even when the final image is post-processed to smooth-out discontinuities. Popular interpolation schemes, such as piecewise-constant, are shown to lead to either very low quality reconstructions or significant spurious image features. We will show that self-consistently using a smoother interpolation scheme (e.g. bilinear) in both the fitting and rendering process leads to a much higher fidelity tomographic image, while requiring exactly the same number of numerical parameters to be estimated from the observational data. Careful choice of the interpolation function also allows much more efficient implementation if line-integrals can be performed algebraically.

It is not trivial to choose a 3D grid geometry that is compatible with the Earth’s curvature, and has an interpolation scheme that allows the algebraic manipulations necessary for high quality tomographic imaging. For example, these criteria are very poorly met by a regular latitude/longitude/altitude grid. However, a grid formed of tetrahedra, and piecewise linear interpolators, has many of the features required for high quality tomographic reconstruction: it can be made to conform to a curved ionosphere; it does not need special treatment of polar regions; it avoids discontinuities in the interpolated density; and point-density and line-integrals of density can be computed analytically over each tetrahedron.

We have implemented such a finite-element tomographic process for a number of ionospheric measurement scenarios. A particularly challenging application is trying to estimate the 3D electron density profile exclusively using TEC measurements from dual-band GPS (without any background model such as IRI). We will present results from a simulated scenario in which IRI-2016 is used to generate a set of GPS TEC time-series for a known 3D electron-density profile, and with true GPS satellite trajectories. From these, a tomographic fit is constructed using a dozen receiver ground-stations in western Europe to estimate the electron density profile over the region of satellite visibility. The reconstructed electron density profiles show that it is possible to recover many of the features of the known density profile (e.g. in terms of typical gradients, diurnal variation, etc.).

On-going work is investigating how these techniques can improve ionospheric imaging for scenarios that involve combinations of GPS and ionosonde sensors, and conservatively incorporate phenomenological models such as IRI.