Preliminary results for the assimilation of forward oblique ionosonde data into the Electron Density Assimilative Model.

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Abstract

A strong understanding of the spatial and temporal variation of the Earth's ionosphere is paramount for the effective operation of radio systems for communication and navigation. Ionospheric measurements can be assimilated into models, such as the Electron Density Assimilative Model (EDAM) to produce three-dimensional global nowcasts of the ionospheric electron density. Conventional measurement techniques, such as vertical ionosondes and global navigation satellite systems (GNSS), are prohibitively expensive and difficult to implement in areas such as oceans and are therefore sparse over vast expanses of the Earth. Information about these under-observed regions can instead be found by assimilating data from forward oblique ionosondes (FOIs) into background ionospheric electron density models. Here we present preliminary results for the assimilation of FOI data into EDAM, demonstrating that the background electron density can be successfully modified using data from FOIs to capture the bottomside structure of the ionosphere.

1. Introduction

The Electron Density Assimilative Model (EDAM) has been developed by QinetiQ (Angling & Cannon, 2004) to assimilate a variety of ionospheric measurements into a background ionospheric model, such as the empirical International Reference Ionosphere (IRI-2007, (Bilitza & Reinisch, 2008)). EDAM produces full three-dimensional global nowcasts through assimilation of empirical data via a Gauss-Markov Kalman filter approach which utilises a form of minimum variance optimal estimation. EDAM can use a number of data sources to estimate the three-dimensional global ionosphere, including radio occultation (Angling, 2008), total electron content (TEC) measurements derived from global positioning system (GPS) data and vertical electron density profiles from ionosondes.

EDAM can be used to provide real time estimations of HF propagation conditions, however the performance of such tools is limited by the accuracy of the bottomside electron density profile. Whilst EDAM has been shown to perform very well when compared to other models (Angling & Khattatov, 2006; McNamara, et al., 2013), the observational data currently assimilated are obtained from measurement techniques that prove difficult to implement over vast expanses such as oceans. This is because data from vertical ionosondes and GPS are sparse in these areas, and radio occultation measurements are unable to provide any detail about the bottomside ionosphere. To enhance EDAM in these areas, forward oblique ionosondes (FOIs) can be used. FOIs consist of a receiver and transmitter pair with a known separation distance and can therefore be used to measure the group delay of the radio signal at a range of frequencies between these positions, enabling measurements over areas where it is prohibitively difficult or expensive to place a GPS receiver or vertical ionosonde.

In this paper we outline a new technique to assimilate FOI data into EDAM. We present results for the preliminary implementation of the assimilation of FOI data into EDAM. To demonstrate the performance of this technique, we compare simulated electron density grids with those created by assimilating FOI data synthesised from the simulated electron density grid into a background electron density grid. For further verification, the resulting electron density grid after assimilation of the FOI data is also compared to electron density grids output by EDAM after the assimilation of GPS data.

2. Overview of the FOI assimilation technique

To assimilate FOI data into EDAM using the FOI assimilation technique, an initial prediction of the ionospheric electron density is firstly made. This is forecast from a background ionospheric model and the known previous state of the ionosphere. A ray is then synthesised through the predicted ionosphere at a measured frequency and the group delay and total electron content over the synthesised ray path is calculated. The group delay along the synthesised ray path is compared to the group delay measured by the FOI and used to update the total electron content along the ray path. This new value of total electron content is then assimilated into the background electron density grid using minimum variance optimal estimation, thus allowing for the prediction of the ionosphere to be updated.

An iterative assimilation procedure is followed when assimilating FOI data. The group delay measured at the lowest frequency is assimilated first, before the remaining measured group delays are assimilated with increasing frequency (and thus increasing altitude). The FOI assimilation technique is therefore applied to the E-layer trace prior to the F-layer trace.

3. Test scenarios

To verify that the FOI assimilation technique is capable of returning an accurate ionospheric electron density grid, we simulate an ionosphere and synthesise FOI data by ray tracing through the simulated ionosphere. These data are then assimilated into a background ionosphere and compared to 'truth' data (synthesised FOI data that were not assimilated into the background ionosphere) to measure how well the assimilation process has performed. As well as comparing to 'truth' FOI data, the resulting electron density grid is also compared to 'truth' GPS slant TEC data.

For these tests, the FOI data were created by ray tracing between a number of locations in Scandinavia (shown in Figure 1). The GPS slant TEC data were created using true satellite trajectories for the receivers shown in Figure 1.

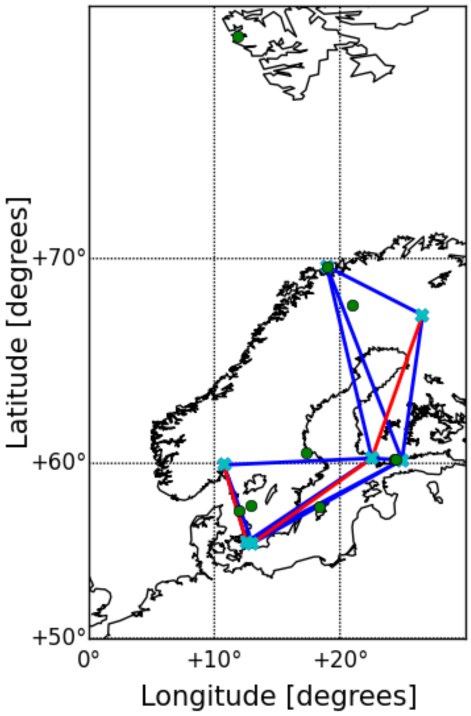

Figure 1: Map of Scandinavia with ray paths marked between transmitters and receivers in Oslo, Malmö, Tromsø, Karuna, Helsinki, Copenhagen and Sodankylä (cyan crosses). The ray paths highlighted in red (Oslo to Copenhagen, Sodankylä to Karuna and Karuna to Malmö) are removed from the assimilation process and used as truth data sets. The green dots indicate the receiver stations used for the GPS slant TEC data.

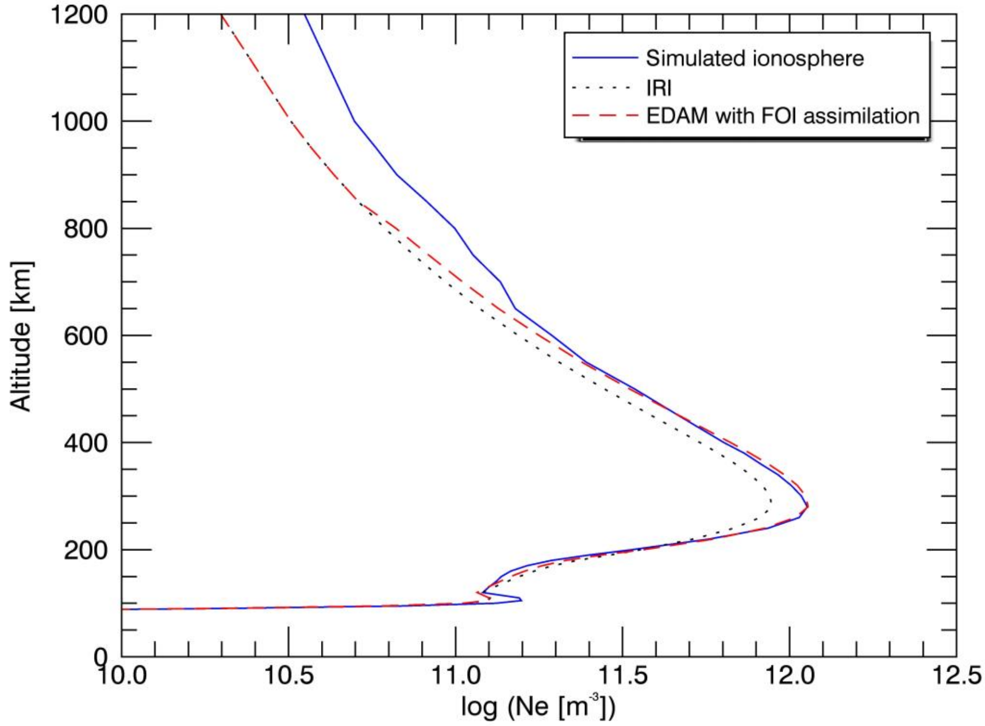

Figure 2: Vertical electron density profile as produced by FOI assimilation into a background electron density grid (red dashed line). The electron density profiles for the simulated electron density grid (solid blue line) and the background electron density grid (IRI-2007, dotted black line) are also shown for comparison.

3.1. Comparison to truth FOI data

Three 'truth' data sets were chosen for this initial test and were therefore not assimilated during the assimilation process. These are marked in Figure 1 by red lines between the transmitters and receivers. The FOI data for the remaining ten ray paths shown in Figure 1 were assimilated into the background electron density grid using the FOI assimilation technique outlined in Section 2, and the resulting vertical electron density profiles were then compared to the corresponding vertical electron density profiles from the simulated (truth) ionosphere.

A typical vertical electron density height profile is shown in Figure 2. It shows a comparison between the background electron density profile (IRI), with that of the simulated ionosphere and the profile produced after FOI data have been assimilated into the background profile (EDAM). It can be seen that the electron density profile produced by the assimilation of FOI data into a background electron density grid matches well with the bottomside of the simulated (truth) ionosphere.

As well as comparing electron density height profiles, we also present FOI data synthesised for the transmitter/receiver circuits not included in the FOI assimilation (the ray paths marked with red lines, Figure 1). Figure 3 shows the resulting F-layer oblique ionograms for these three transmitter/receiver circuits, created by ray tracing through the simulated electron density grid, the background electron density grid and the grid after the FOI data have been assimilated into the background (EDAM with FOI assimilation). From Figure 3 it can be seen that the assimilation of FOI data into a background ionosphere successfully brings the F-layer trace of the resulting ionogram closer to the F-layer trace on the truth ionogram. This reinforces that the bottomside of the electron density profile after FOI assimilation matches well with the bottomside of the simulated (truth) ionosphere, as seen in Figure 2.

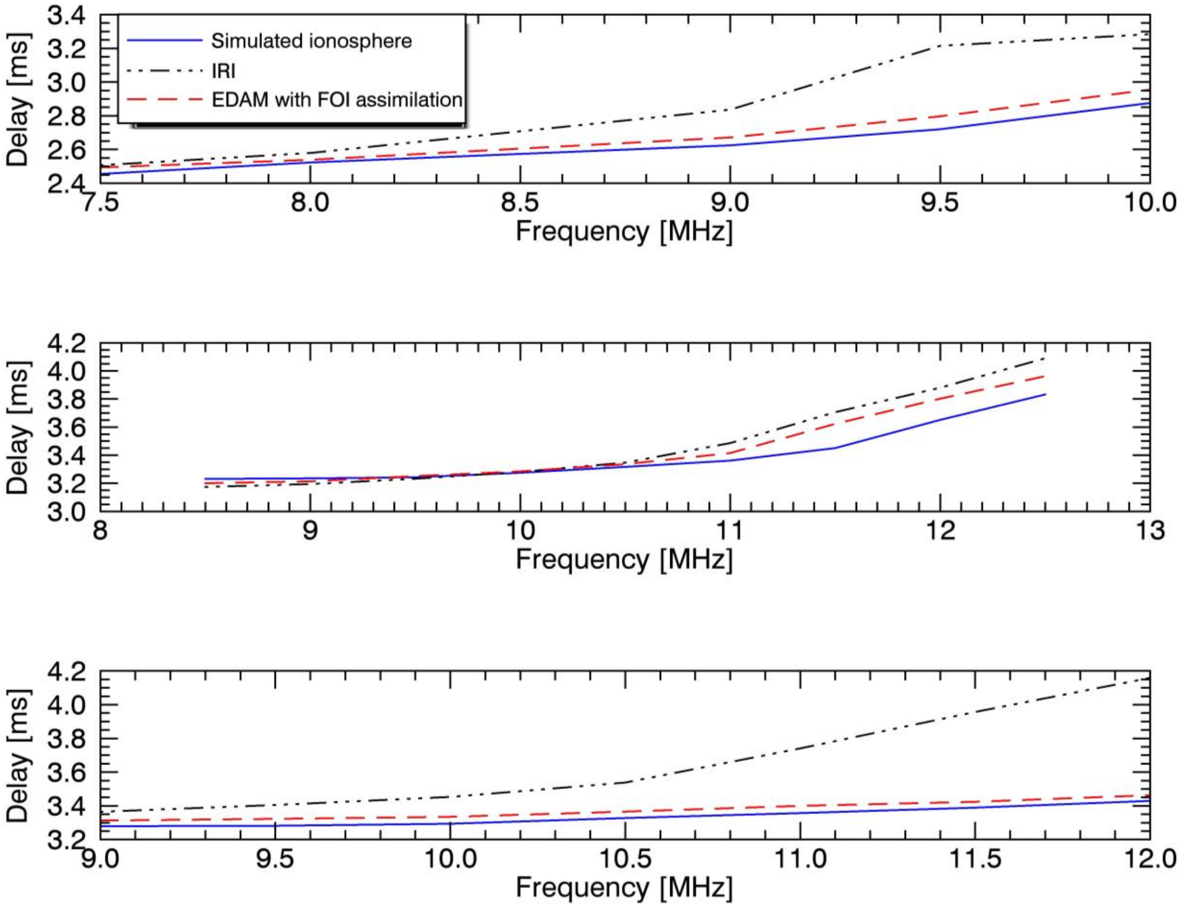

Figure 3: F2-layer oblique ionograms for ray paths between Sodankylä and Karuna [TOP], Karuna and Malmö [MIDDLE], and Oslo and Copenhagen [BOTTOM], showing group delay against frequency for the simulated electron density grid (blue solid line), the background electron density grid (IRI-2007, black dashed and dotted line) and the FOI assimilation into the background electron density grid (red dashed line).

3.2. Comparison to truth GPS data

Slant TEC data were calculated between a selection of GPS satellites and the receiver stations shown in Figure 1 for the background electron density grid, the simulated electron density grid, EDAM with GPS assimilation and EDAM with FOI assimilation. These data allow us to compare how well the FOI assimilation technique performs with respect to the assimilation of GPS data into EDAM (a tested, and verified, method (Feltens, et al., 2011)). Typical results for three satellite/receiver pairs are shown in Figure 4.

From the slant TEC plots in Figure 4, it can be seen that the assimilation of FOI data causes the slant TEC to move away from the background and towards the truth values. Unlike EDAM with GPS assimilation, EDAM with FOI assimilation does not fully reproduce the expected slant TEC because FOIs only provide information about the bottomside ionosphere. Whilst the assimilation technique does alter electron density above hmF2 (as seen in Figure 2), the amount of change decreases with altitude, eventually reverting back to the background electron density grid.

It can be seen in Figure 4 that as you move away from the area over which the FOI data were measured, the model reverts to the background electron density grid (IRI-2007). This is demonstrated at the start of the measurement period for the Onsala receiver/satellite link, and for the entirety of the measurement period for the Ny-Ålesund receiver/satellite link.

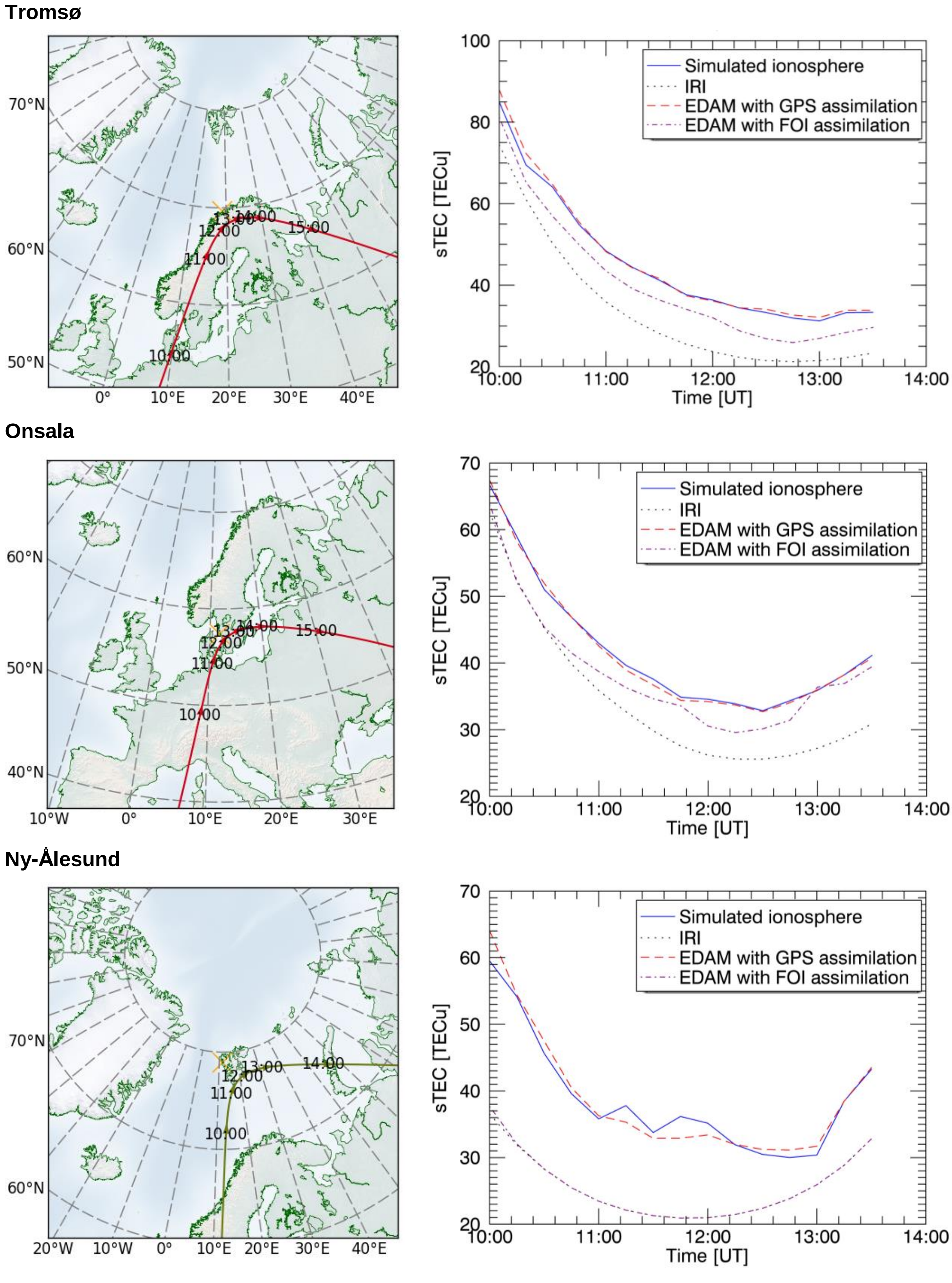

Figure 4: LEFT: Map of the position at which the ray path between a GPS satellite and a GPS station intersects the ionosphere at an altitude of 400 km. RIGHT: Slant TEC plot between the satellite and the GPS receiver. The black dotted line is the slant TEC through the background grid, the blue solid line is the slant TEC through the simulated ionosphere, the red dashed line shows the resulting slant TEC through an EDAM electron density grid that has had GPS data assimilated into it, and the purple dashed and dotted line shows the resulting slant TEC through an EDAM electron density grid that has had FOI data assimilated into it.

4. Outlook

We have presented the first successful assimilation of FOI data into EDAM. Comparisons have been made between simulated electron density grids and those created by assimilating FOI data synthesised from a simulated electron density grid into a background grid. We have qualitatively demonstrated through these comparisons that the FOI assimilation technique is capable of producing electron density grids that show good agreement with the simulated (truth) ionosphere, and are closer to the simulated (truth) ionosphere than they are to the background electron density grid. We have also demonstrated that the FOI assimilation technique produces results that are comparable to those output by EDAM when it is assimilating GPS data.

The successful assimilation of FOIs into EDAM has the capability to drastically improve the three-dimensional electron density grid over oceans and other areas where a dearth of ionospheric observation stations impacts the model. This will enable space track radars and navigation systems to be operated with increasing accuracy, as well as improving radio communications by enhancing estimations of HF propagation conditions.

5. Acknowledgements

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6. References

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