The assimilation of Forward Oblique Ionosonde profiles into the Electron Density Assimilative Model (EDAM)

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Abstract

A strong understanding of the spatial and temporal variation of the Earth's ionosphere (a magneto-ionic, refractive medium 50-1000 km above the Earth's surface) is paramount for the effective operation of radio systems for communication. 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 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 ionospheric models. Here we present preliminary results for the assimilation of FOIs into EDAM, demonstrating that the background electron density can be successfully modified using FOIs to capture the bottomside structure of the ionosphere.

1. Introduction

The Electron Density Assimilative Model (EDAM) has been developed by QinetiQ [1] to assimilate a variety of ionospheric measurements into a background ionospheric model, such as the empirical International Reference Ionosphere (IRI-2007, [2]). EDAM produces full three-dimensional global nowcasts through assimilation of empirical data via the Gauss-Markov Kalman filter approach which utilises a form of minimum variance optimal estimation. EDAM uses a number of data sources to recreate the three-dimensional global ionosphere, including radio occultation [3], total electron content (TEC) measurements derived from global navigation satellite systems (GNSS, operating in the L-band) data and vertical electron density profiles from ionosondes (transmitter and receiver pairs that operate in the HF-band).

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 [3] [4], 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 GNSS are sparse in these areas, and radio occultation measurements are unable to provide any detail about the bottomside ionosphere.

Forward oblique ionosondes (FOIs) consist of a receiver and transmitter pair with a known separation distance and can therefore be used to enable measurements over previously under-observed regions. They measure the group delay of the radio signal at a range of frequencies to infer the total electron content along the ray path.

In this paper we outline the technique used to assimilate FOI data into EDAM. Results are presented from the preliminary implementation of the FOI assimilation technique. FOI data are generated from a simulated ionosphere prior to being assimilated into a background ionosphere. Comparisons are then made between the simulated ionosphere and that output after FOI assimilation to demonstrate that the FOI assimilation technique is capable of recreating a known ionosphere

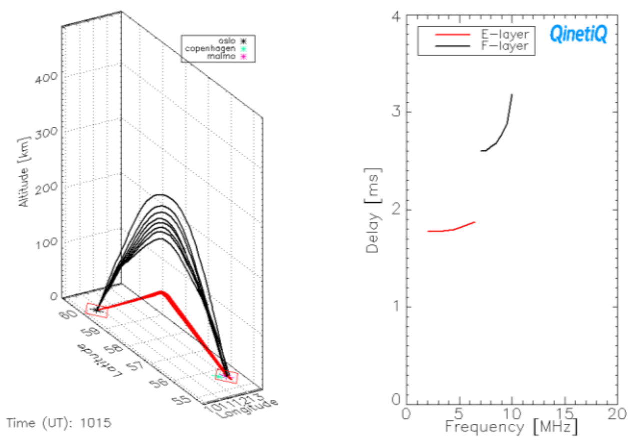

Figure 1: Left: An example of simulated ray paths between Tromsø and Karuna for a forward oblique ionosonde at a range of frequencies (0-20 MHz), showing reflections from both the E and F layers (red and black lines respectively). Right: The simulated ionogram corresponding to the oblique rays traced between Tromsø and Karuna.

2. Overview of the FOI assimilation technique

To assimilate FOI data into EDAM using the FOI assimilation technique, an initial prediction of the ionosphere 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 synthesized ray path is compared to the simulated group delay (as shown in Figure 1) 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 scenario

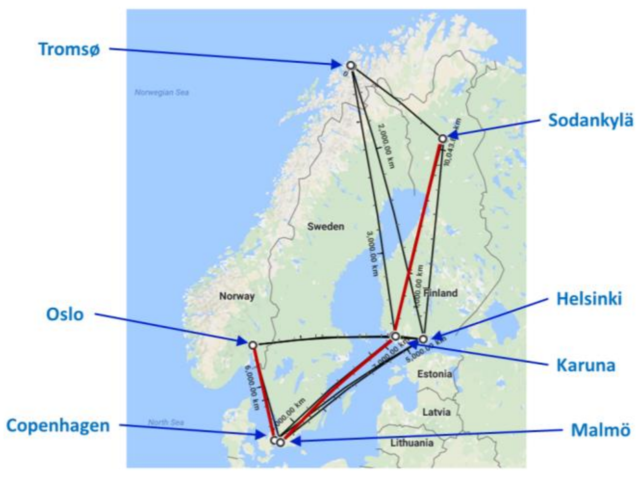

Figure 2: Map of Scandinavia with ray paths marked between transmitters and receivers in Oslo, Malmö, Tromsø, Karuna, Helsinki, Copenhagen and Sodankylä. The ray paths highlighted in red (Oslo to Copenhagen, Sodankylä to Karuna and Karuna to Malmö) are removed from the assimilation process and used as truth data sets.

To ensure 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 this simulated ionosphere between a number of locations in Scandinavia (Tromsø, Sodankylä, Oslo, Helsinki, Karuna, Copenhagen and Malmö). Figure 2 shows the ray paths between these locations. An example of an ionogram from one of these ray paths is shown in Figure 1, showing the oblique ray paths for both the E and F layers. We extract some of these data sets as 'truth' data sets and do not assimilate them during the assimilation process. The ray paths extracted as truth data sets are marked in Figure 2 by red lines between locations. The FOI data for the remaining nine ray paths are then assimilated into the background electron density grid using the FOI assimilation technique outlined in Section 2 and the resulting electron densities are compared to the 'truth' data.

A vertical electron density height profile is shown in Figure 3. 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. The FOI data does not provide any information about the ionosphere above the F2-layer peak in electron density, therefore above this point the electron density is reverted to the background electron density.

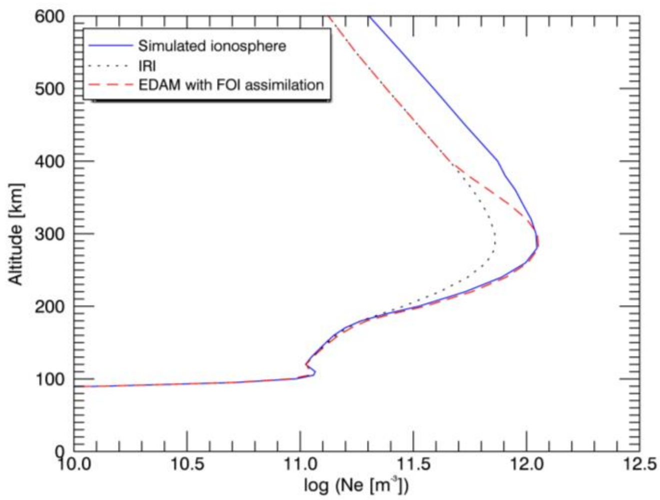

Figure 3: Vertical electron density height profile as produced by FOI assimilation into a background electron density grid (red dashed line). The electron density height profiles for the simulated electron density grid and the background electron density grid (IRI-2007) are also shown for comparison (the blue solid and black dotted lines respectively).

As well as comparing electron density height profiles, we also present oblique ionogram data synthesised for the transmitter/receiver circuits not included in the FOI assimilation (the ray paths marked with red lines, shown

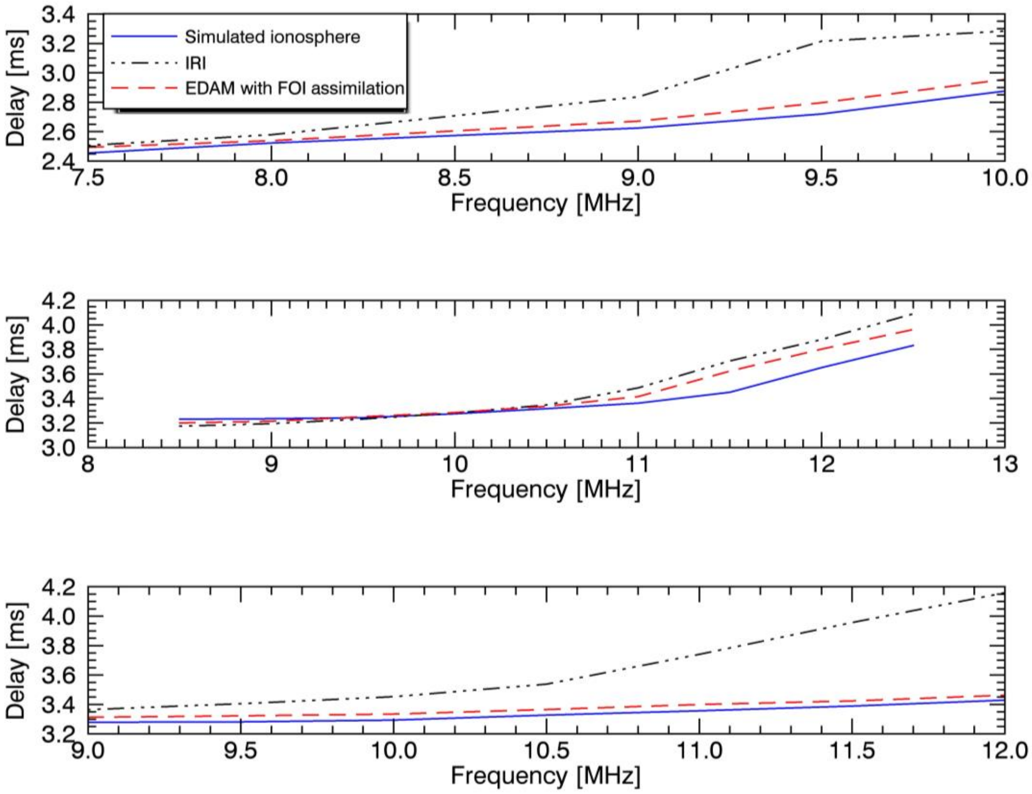

Figure 4: F2-layer oblique ionograms for ray paths between Sodankylä and Karuna [TOP], Karuna and Malmö [MIDDLE], and Oslo and Copenhagen [BOTTOM], showing group delay against frequency for the simulated electron density grid (blue solid line), the background electron density grid (IRI-2007, black dashed and dotted line) and the FOI assimilation into the background electron density grid (red dashed line).

in Figure 3). Figure 4 shows the resulting F-layer oblique ionograms for the simulated electron density grid, the background electron density grid and the grid after the FOI data have been assimilated. From Figure 4 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. The fit to the truth data is better at lower frequencies because at higher altitudes (which correspond to higher frequencies) the electron density is reverted back to the background electron density, as shown in Figure 3.

4. Discussion and conclusions

Here we have presented the first successful assimilation of oblique ionosonde data into EDAM. Comparisons have been made between simulated electron density grids and those created by assimilating FOI data synthesised from the 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 are closer to the truth grid than the background electron density model. The FOI assimilation technique produces results that are comparable to those output by EDAM when it is assimilating other data sources.

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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