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Accurately Modelling the Ionosphere at High Latitudes Using the Electron Density Assimilative Model (EDAM)

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Abstract

The high latitude (>60°) ionosphere is challenging to model due to many different processes, such as the auroral oval. This creates problems using radio frequencies in the region, such as for radio communications and navigation. This paper discusses ionospheric model testing performed in the high latitude region. The models tested here are the Electron Density Assimilative Model (EDAM) and the International Reference Ionosphere – 2007 (IRI2007). Outputs from the models were compared against a truth data set to determine their respective performances. It was found that EDAM improved on IRI2007 in modelling the high latitude ionosphere.

1. Introduction

The ionosphere is a region of the Earth's atmosphere which is ionised by extreme UV solar radiation and fluctuates in response to events such as solar flares, geomagnetic storms and lightning. All of these can have a high, and often adverse, impact on the performance of trans-ionospheric radio systems due to changes in electron density leading to signal loss and reduction of service. Systems affected include Global Navigation Satellite Systems (GNSS), where delays of rays through the ionosphere causes positional errors, which can make GNSS unsafe for use on automated processes such as aircraft landing.

High latitude (>60°) regions of the ionosphere are notoriously difficult to model. Reasons for this include, but are not limited to, converging longitudinal and magnetic field lines and the auroral oval. The variability and difficulty of modelling the region poses problems with communications and the use of GNSS in this area, as it is hard to accurately specify the ionosphere.

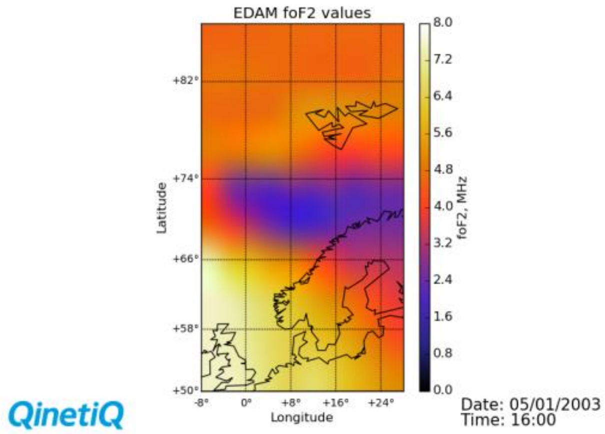
There are many distinguishing features of the region, one of which is the mid-latitude trough, first described in 1965 as the F-layer ionospheric trough [1]. Although named the mid-latitude trough this phenomenon is often seen at high latitudes, representing itself as a region of depleted electron density extending longitudinally (~30°) but narrower in latitude (~10°).
This is a daily feature which appears mid-afternoon at very high latitudes (~75°), then moves southward during the afternoon and evening to the mid-latitude region. At dawn the rising of the sun causes the trough to quickly retreat northward and disappear. The trough is seen in total electron content (TEC) measurements and foF2, the highest frequency of an ordinary wave reflecting off the F2 layer. These measurements can be used to determine the performance of different ionospheric models in the high latitude region.

The Electron Density Assimilative Model (EDAM) is an ionospheric assimilative model which produces global 3D grids of electron density in real time at 15 minute intervals [2]. Data sources assimilated by EDAM include; Global Positioning Satellite (GPS) data from dual frequency receivers, incoherent scatter radar, ionosonde measurements and radio occultation data. The various data sources give information on different characteristics of the ionosphere; GPS TEC data provides the number of electrons along a path, ionosonde data gives structural information up to the F2 peak and radio occultation provides topside information. By assimilating these different data types into a background model EDAM is able to produce a physical representation of the ionosphere. EDAM uses the International Reference Ionosphere – 2007 (IRI2007) as the background model for assimilation, and uses a Gauss Markov Kalman filter to assimilate data into this background. IRI2007 is an empirical model which uses historical data to produce an estimate of global 3D electron density [3].

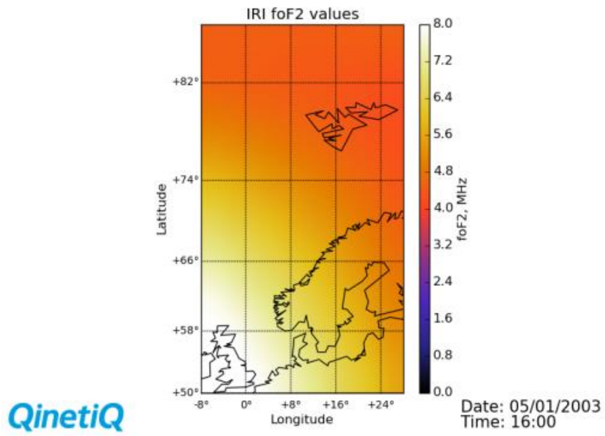
In this paper we test both EDAM and IRI2007 by calculating TEC and foF2 in the high latitude ionosphere and comparing against a truth data set.

2. Mapping the trough with foF2

For the foF2 comparisons, EDAM was run for the week 2nd to the 8th January 2003, assimilating GPS data from 93 European stations for a selected high-latitude region; 50° to 86° latitude and -8° to 28° longitude. EDAM (with GPS data assimilated) shows a trough-like feature in foF2 as a reduction in foF2, as seen in Figure 1a. The equivalent IRI2007 foF2 map shown in Figure 1b produces no trough-like features. Maps of foF2 produced for the specified location using EDAM grids show the movement in the trough to be consistent with those describing the mid-latitude trough, which is seen moving southward during the afternoon and evening before being pushed northward by the rising sun. No trough-like features were produced by the IRI2007 foF2 maps for the week studied.



(a)



(b)

Figure 1 (a) Map of foF2 in high-latitude ionosphere using EDAM showing a trough-like feature between 66° and 74° latitude. This feature appeared daily in the EDAM maps during early afternoon. **(b)** Equivalent map of IRI2007 foF2, showing no trough-like feature.

To study the trough shape and movement foF2 map data was plotted at constant longitudes at 4° degree steps in longitude from -8° to 28° over the latitude range 50° to 86°. Every 15 minute step for an hour was placed on the same plot, as this allowed the movement of the trough and the change of shape of the trough to be measured over each hour. These plots were created for EDAM and IRI2007, where again the trough feature was clearly seen in the EDAM plots. EDAM shows the trough movement in time and also the evolution of the shape of the trough. The trough can be seen to move southward from mid-afternoon until the sun-rise, around 7:00 UTC where it then retreats northward and loses its structural definition. For the duration of the morning and into the early afternoon the EDAM foF2 plots have a much closer resemblance to IRI2007. This behaviour coincides with the foF2 maps produced for EDAM and IRI2007.

3. Slant TEC calculations

For the TEC validations EDAM was run for a one year period between September 2002 and September 2003 assimilating data from the same 93 European GPS stations used in the foF2 test. Data from the GPS station HERS, located at latitude 51° north, 0.3° east on the south-eat coast of England, was not included in any EDAM assimilations as this was to be used as the truth data set for EDAM and IRI2007 validations.

Slant TEC is the total number of electrons along the line of sight between a GPS satellite and receiver. For this test slant TEC was calculated for the HERS receiver for the period of September 2002 to September 2003 at 5 minute intervals throughout the year for every available GPS satellite. For the EDAM and IRI2007 comparative slant TEC values were extracted from 15 minute global electron density grids. The times and positions of the satellites available to the HERS receiver were used to calculate equivalent EDAM and IRI2007 slant TEC arcs.

GPS satellites and receivers have unknown differential code biases (DCBs), so it is not possible to accurately use slant TEC directly for comparisons. Differential slant TEC measurements were used instead; these are defined as the difference along a satellite path at the point of closest approach subtracted from each point along the arc. The benefit of this is the accuracy is increased to less than 0.1TECu, where $1TECu=10^{16}m^{-2}$, as the DCBs have been effectively removed.

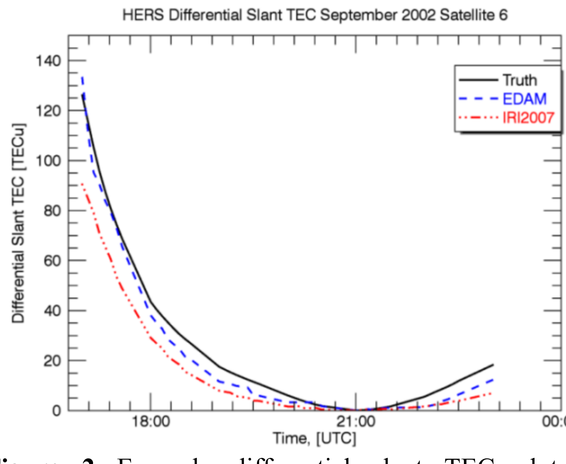


Figure 2 Example differential slant TEC plot for September 22nd 2002 using GPS satellite number 5, the truth arc (black solid line), EDAM (blue dashed line) and IRI2007 (red dots and dashes) can be seen. This plot shows the EDAM TEC values before 18:00 have a closer relationship to the truth values than IRI2007.

Differential slant TEC plots were produced for the month of September 2002 for each GPS satellite. Truth, EDAM and IRI2007 were shown on the same plot, to determine how well each model performed. Both models gave results consistent with the truth data, however statistical analysis was required to provide a better method of showing the performance of the models. An example of the differential slant TEC plots can be seen in Figure 2 where EDAM has a closer relationship to the truth arc than IRI2007 does.

4. Slant TEC Results

Taylor diagrams provide a useful way of displaying the performance of different models with respect to truth data on the same plot [4]. This is achieved by comparing normalised standard deviation, correlation and the normalised error standard deviation of the different models to a truth data set. Modified Taylor diagrams have the addition of comparing bias by using a colour scale [5], with an ideal model having a normalised standard deviation and correlation of 1 and a bias of 0. Modified Taylor diagrams were created for two different scenarios; the whole data set combined, and the data split into day and night (10am to 3pm and 10pm to 3am UTC respectively). It can be seen from the modified Taylor diagram of the whole data set EDAM improves on IRI2007 by bringing the electron density grids closer to the truth, with EDAM having a closer normalised standard deviation and correlation to 1 than IRI2007 as shown in Figure 3, where it can be seen EDAM performs better than IRI2007.

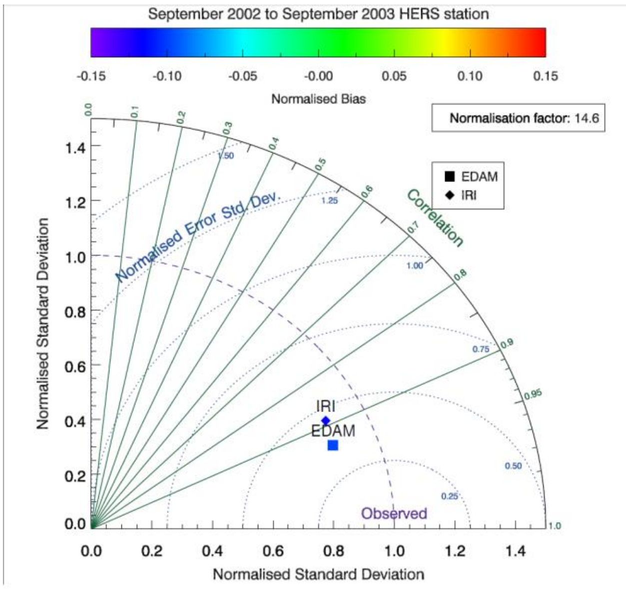


Figure 3 Modified Taylor diagram showing the year September 2002 to September 2003, EDAM (squares) has a higher correlation than IRI2007 (diamonds), an improved standard deviation and a smaller bias.

When split into day and night it can be seen that both models perform best during the day when the trough is a less prominent feature of the ionosphere. For both day and night EDAM outperforms IRI2007, as shown in Figure 4. At both times of day EDAM is less biased than IRI2007, has a higher correlation and a marginally better standard deviation.

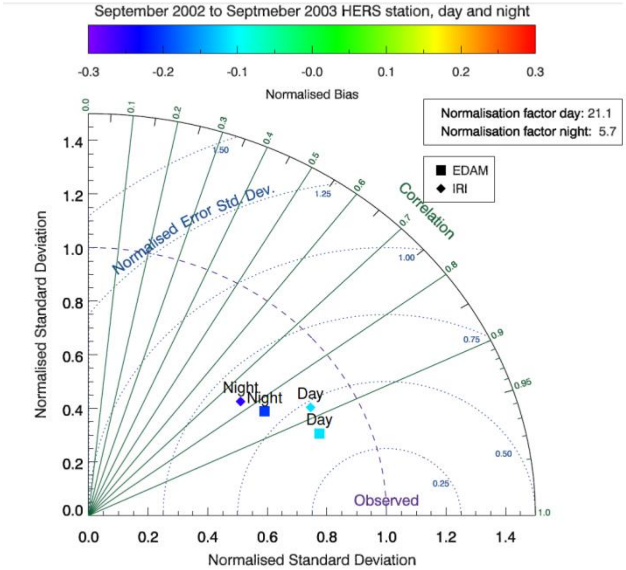


Figure 4 Modified Taylor diagram showing the year data split into day and night (10am to 3pm and 10pm to 3 am UTC respectively). It can be seen EDAM's (squares) performance is best during the day, and is closer to the truth values than IRI2007 (diamonds) at both times of day.

5. Discussions and Conclusions

This study showed EDAM was able to detect a daily trough-like feature in foF2 which represented the mid-latitude trough. The same plots using the background empirical model IRI2007 did not show any trough-like features. When the differential slant TEC for EDAM and IRI2007 were compared to a truth data set from the GPS station HERS, it was seen EDAM showed improvements on IRI in terms of standard deviation, bias and correlation to the truth. Splitting the data into day and night also showed how EDAM improved on IRI2007 at both times of day. It can therefore be said that EDAM was able to improve on IRI2007 in a select mid to high-latitude region of the ionosphere, which can be used to mitigate the unusual effects of the high-latitude region.

6. Acknowledgements

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7. References

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