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Modelling plasma structures in the high-latitude ionosphere

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ABSTRACT

The ionosphere is a highly complex plasma containing electron density structures with a wide range of spatial scale sizes. Large-scale structures with horizontal extents of tens to hundreds of km exhibit variation with time of day, season, solar cycle, geomagnetic activity, solar wind conditions, and location. Whilst the processes driving these large-scale structures are well understood, the relative importance of these driving processes is a fundamental, unanswered question. The large-scale structures can also cause smaller-scale irregularities that arise due to instability processes such as the gradient drift instability (GDI) and turbulence. These smaller scale structures can disrupt trans-ionospheric radio signals, including those used by Global Navigation Satellite Systems (GNSS).

Statistical modelling techniques have been used to generate models of various measures of large-scale plasma structuring in the polar ionosphere using 15 years of data gathered by the EISCAT Svalbard Radar (ESR). These models quantify the relative importance of the dominant driving processes in four time sectors (noon, dusk, midnight and dawn). In every sector the dominant process is the seasonal variation, but additional secondary processes have a significant influence upon the amount of plasma structuring.

The same statistical modelling techniques have been applied to the auroral ionosphere using data from both Incoherent Scatter Radars and GNSS scintillation receivers. The dominant driving processes of these models are compared to those observed for large-scale plasma structures in the polar ionosphere. The models have the potential to make real time predictions for GNSS applications. The steps required to develop predictive models are discussed.

Key words: High latitude ionosphere, Ionospheric structures, Modelling, GNSS, Incoherent scatter radar.

Introduction

The ionosphere is a weakly ionised plasma forming the part of the Earth’s atmosphere which extends from an altitude of around 60km to around 1000km where it merges with the outer regions of the Earth's environment. The plasma is structured on a wide range of horizontal spatial scale sizes from several hundreds of kilometres to tens of metres, due to numerous physical processes including the solar cycle, the Interplanetary Magnetic Field (IMF) carried by the solar wind, geomagnetic activity, time of day, thermospheric composition, season and longitude of observations[1]. The processes causing the large-scale structures are reasonably well understood, but the relative importance of each of these processes is an open question.

The large-scale structures can cause smaller-scale irregularities. The irregularities grow due to the irregularity-wave cascade process driven by the gradient drift instability (GDI) and/or turbulent processes[2]. Small-scale irregularities in the ionospheric plasma cause scintillation of received signals, with consequent fading to a depth that disrupts the communication channel. A direct connection between large-scale plasma structuring caused by auroral precipitation and the loss of signal lock at a GNSS receiver has been observed[3,4].

Modelling technique

The technique of Generalised Linear Modelling is used in this study. The method used is a development of the Transport Research Laboratory models, used to predict road accidents in parts of the UK[5]. In essence, this is a form of multiple regression analysis where the dependent variable is related to a range of explanatory variables. An appropriate parameter estimate is made for each of the explanatory variables to relate it to the dependent variable. In this study, observations of the amount of plasma structuring in the ionosphere were related to a range of geophysical variables, thus providing a model for examining the relative importance of the driving processes.

Large-scale plasma structures in the polar ionosphere

Fifteen years of observations from the EISCAT Svalbard Radar were used to build a database of the amount of plasma structuring, broken into four time sectors (noon, dusk, midnight and dawn). Various measure of the amount of large-scale plasma structuring were used. One example was to take a three hour window of observations (19-22 UT) approximately centred on local magnetic midnight (20:45 UT) in the F-region (indicated by the pink box in figure 1) and establish the altitude at which electron density took its highest average value (270 km in this example). Only data at this altitude were considered further. The mean value of the largest 25% of the electron density measurements at this altitude was set as the ‘high’ value and the mean value of the 25% of the electron density measurements at this altitude was set as the ‘low’ value. The ratio of the high:low values gave a measure of the amount of plasma structuring. This process was repeated for all available data sets.

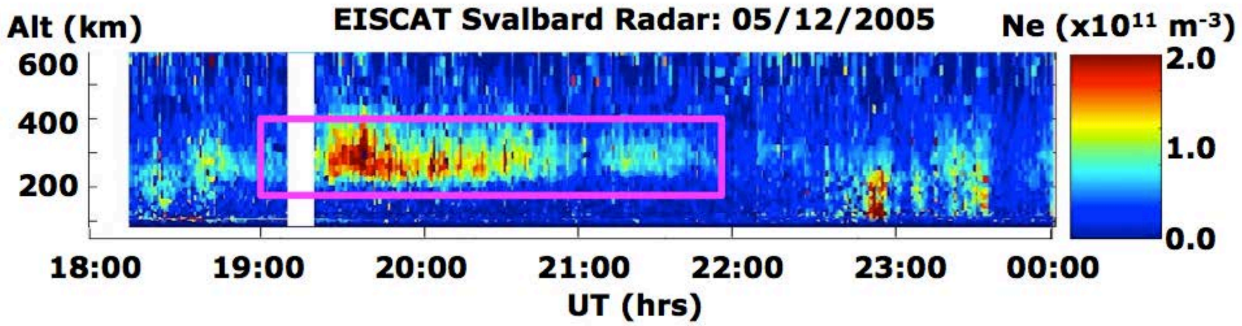

Figure 1. Electron densities measured by the 42 m dish of the EISCAT Svalbard Radar observing along the geomagnetic field between 18:00 UT and 23:59 UT on 5 December 2005. The pink box indicates a number of plasma structures observed in the F-region.

Generalised linear modelling was used to relate these measures of plasma structuring to various variables which were proxies for the geophysical processes. These were:

- Season, represented by a sine function with a value of -1 at midwinter and +1 at midsummer.
- Solar activity, represented by the F10.7 solar flux and the solar sunspot number
- Geomagnetic activity, represented by Kp and AE.
- IMF, represented by observations made by the ACE spacecraft.

This analysis was repeated for time windows of different lengths (1-hr to 6-hr), for the Total Electron Content of the F-region and was then extended to the E-region. In every time sector the dominant process was the seasonal variation, and this difference was attributed to both the variation in the chemical composition of the atmosphere and the maintenance of the background ionosphere by photoionization in summer. Secondary processes for the best fitting models varied with time sector:

- Noon sector: Geomagnetic activity (Proxy: Kp).
- Dusk sector: Strength and orientation of the IMF, geomagnetic activity (Proxy: AE).
- Midnight sector: Strength and orientation of the IMF, geomagnetic activity (Proxy: AE).
- Dawn sector: Strength and orientation of the IMF.

Large-scale plasma structures & scintillation in the auroral ionosphere

The same statistical modelling techniques have been used to generate models of large-scale plasma structures in the auroral ionosphere using data gathered by the EISCAT UHF radar across more than two solar cycles. These techniques have also been used to generate models of phase scintillation in the auroral ionosphere using GNSS data. The dominant driving processes of these models are compared to those observed for large-scale plasma structures in the high-latitude ionosphere.

Predictive capability

In theory the statistical models should be able to make predictions of the amount of large-scale plasma structuring and scintillation in the ionosphere at the geographic locations where the models were developed. However current results suggest that there is at least one driving process missing from the models. It has been shown that the thermosphere can have a substantial effect upon the ionosphere[6]. Proxies to represent thermospheric processes are being added to the models and these results are discussed.

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