Topside ionosphere modelling using GPS data: possibilities for South Africa

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Abstract

Successful modelling of the topside ionosphere relies on the availability of good quality measured data. The Alouette, ISIS and Intercosmos -19 satellite missions provided large amounts of data, but with limited coverage of relevant geophysical conditions by each individual mission. Recently, methods for inferring the electron density distribution in the topside from Global Positioning System (GPS)-based total electron content (TEC) measurements have been developed. This paper attempts to review recent progress in topside ionospheric modelling focusing on GPS-TEC based modelling techniques and explores the possibility of using GPS measurements for the topside modelling efforts in South Africa.

1 Introduction

Relative scarcity of experimental data for the topside ionosphere greatly limits modelling efforts for this region of the ionosphere. Sounding the topside requires a satellite-borne topside sounder. Only a few such missions, such as ISIS 1 & 2 and Intercosmos 19, have been undertaken and have provided sets of topside data, but with a limited coverage of the relevant geophysical conditions. A small percentage of these datasets have been processed into electron density profiles [*Huang et al.*, 2002], and coverage of the Southern African region is sparse within the database presenting a challenge in topside modelling efforts for this region.

Since the late 1990s, the Global Positioning System (GPS) has been used to measure the total electron content (TEC) along a ray path between the satellite and the receiver. Researchers have developed techniques that use GPS-TEC to provide vertical profiling of the Earth's ionosphere such as: (a) Ionospheric tomography, (b) GPS Radio occultation [*Jakowski et al.*, 2002] and (c) the approach proposed by *Stankov and Muhtarov* [2001] which uses a combination of GPS-TEC, ionosonde and the upper transition height measurements to reconstruct the electron density profile. The technique uses a profiler, such as Chapman, sech-squared, or exponential, to construct a system of equations from which the unknown ion scale heights can be calculated and then an electron density profile at a specified location can be constructed.

TEC is an important characteristic of the Earth's ionosphere. It is defined as the integral value of the electron density along a path. GPS-TEC has proved to be useful as a sensor of ionospheric climatology. Applications include data assimilation techniques in ionospheric modelling where the GPS-TEC can be used as an anchor point to adapt models for the locations and epochs of interest.

This paper follows the approach presented by *Stankov and Muhtarov* [2001] and presents preliminary results for the application of this method to the Southern African region using the Epstein function to approximate the individual ion density distributions in the topside ionosphere. GPS-TEC measurements in South Africa present a new data resource for an effort to improve the modelling of the topside ionospheric electron density.

2 Determining the profile function

The technique presented in this paper uses a combination of GPS-TEC measurements calculated using the Adjusted Spherical Harmonic Analysis (ASHA) model [*Opperman et al.*, 2007], ionosonde measurements, and the upper transition height provided by the Field Line Interhemispheric Plasma (FLIP) model [*Richards et al.*, 2000].

Topside TEC (up to the height of the GPS satellite), TEC_t, is taken to be the difference between the GPS-TEC and the bottomside TEC_b TEC (up to hmF2).

Assuming negligible contribution from He^+ ions [*Carlson and Gordon*, 1966], the major ion species present in the topside ionosphere are the O^+ and the H^+, [*Titheridge*, 1972], and expressing the topside electron density as a sum of the constituent ion densities,

$$N_e(h) = N_{0^+}(h) + N_{H^+}(h)$$

The Epstein functions are used to analytically approximate the individual ion density distributions of the ions to give the reconstruction formula, equation 1.

$$N_e(h) = N_{0^+}(hmF2)sech^2(\frac{h - hmF2}{2H_{0^+}}) + N_{H^+}(hmF2)sech^2(\frac{h - hmF2}{2H_{H^+}}) \quad (1)$$

Defining the plasma scale height as $H_j = kT_j/m_j g$ [*Liu et al.*, 2007] and assuming isotropic conditions and equal ion temperatures, the H^+ ion scale height will be approximately 16 times larger than the O^+ ion scale height along a geomagnetic field line. Thus the ion scale height, $H_{H^+} = 16O_{O^+}$ [*Stankov and Muhtarov*, 2001]. Expressing H_{H^+} in terms of the H_{O^+} in equation 1 and integrating from hmF2 to infinity gives us equation 2 for topside TEC.

The upper transition level and the F2 layer peak are used as reference points to simplify the problem. At the upper transition level, h_{tr}, the O^+ and H^+ ion densities are equal, represented by equation 3. This is the level where the electron density profile changes its slope and serves as a base for finding the relative quantity of H^+ and O^+ ions in the topside ionosphere.

At the F2 layer peak, the sum of the O^+ and H^+ ion densities is equal to the measured electron density, NmF2, shown in equation 4, a system of equations is constructed.

$$TEC_t = 2H_{O^+}N_{0^+}(hmF2) + 32H_{O^+}N_{H^+}(hmF2) \quad (2)$$

$$N_{0^+}(hmF2)sech^2(\frac{h_{tr} - hmF2}{2H_{0^+}}) = N_{H^+}(hmF2)sech^2(\frac{h_{tr} - hmF2}{32H_{O^+}}) \quad (3)$$

$$NmF2 = N_{0^+}(hmF2) + N_{H^+}(hmF2) \quad (4)$$

To solve this system, three key inputs are required, NmF2, TEC_t and the upper transition height h_{tr}, the system has three unknowns; $N_{0^+}(hmF2)$, $N_{H^+}(hmF2)$ and H_{0^+}.

This system of equations is solved numerically using a Newton iterative procedure to obtain the O^+ ion scale height which is then used in the reconstruction equation 1 to obtain the electron density as a function of height.

3 Results and discussions

The reconstruction procedure was performed using the data from the Grahamstown, South Africa ($33.3^o S, 26.5^o E$), ionosonde and co-located GPS receiver for midday on day 92 in 2005. The resulting electron density profile compared with the ionosonde profile is presented in figure 1. The topside profile shown in the ionosonde profile is derived with the α-Chapman function using a scale height derived from the bottomside profile [*Huang and Reinisch*, 1996; *Reinisch and Huang*, 2001].

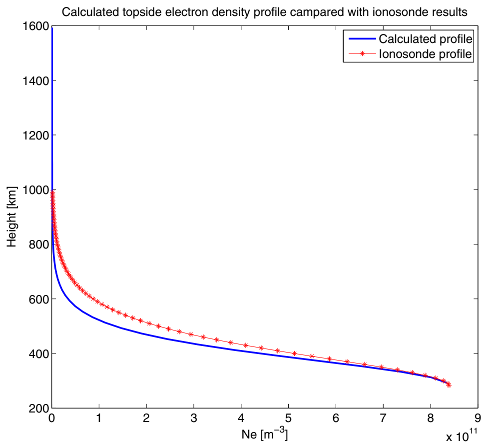

Figure 1: Reconstructed topside electron density profile for daytime. Values for the input parameters used are, TEC_t = 8.39x10^{16}m^{-2}, h_{tr} = 826km, NmF2 = 11.81x10^{11}m^{-3}

These results show that the electron density profile can be reconstructed from its integral quantity, TEC. This approach offers an opportunity to improve topside modelling efforts and provide valuable information about the topside ionosphere, a region that is difficult to model due to the scarcity of measured data. The approach has an advantage in that the constructed profile is tied to reliable measured TEC offering a higher level of confidence in the resulting electron density.

From the figure it can be seen that the electron density, in general, shows a smooth and continuous decrease with altitude. There was no measured topside electron density data to compare the results with measured data.

4 Discussion and conclusion

A single value of scale height is determined for the whole topside ionosphere and plasmasphere. This assumes that the scale height is constant in the topside and plasmasphere. A more accurate approximation of the topside profile will require the construction of a suitable scale height function that will represent the altitude variation of the scale height.

Future work should involve applying the technique at a location with an ionosonde co-located with a GPS receiver and also having measured topside profiles to validate this topside reconstruction technique. This would show how the calculated profiles compare with measurements.

The results presented show that this approach can be a useful tool in modelling the topside ionosphere over the Southern African region where measured data is sparse and does not represent the various geophysical conditions. GPS based techniques offer a powerful tool for ionospheric characterisation. They provide a combination of dense global coverage, and the capability to give continuous measurements of TEC values as well as being a relatively inexpensive technique.

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