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Use of varying shell heights derived from ionosonde data in calculating vertical total electron content (TEC) using GPS – New method

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Abstract

The dispersive nature of the ionosphere makes it possible to measure its total electron content (TEC). Thus Global Positioning System, which uses dual-frequency radio signals, is an ideal system to measure TEC. When data from an ionosonde situated in polar region was observed, the height of an approximated thin shell of electrons (shell height) used in GPS studies was seen not to be fixed but rather changing with time. Here we introduce a new method in which we included the varying shell heights derived from the ionosonde to map the slant total electron content from GPS to obtain a more precise vertical total electron content of the ionosphere contrary to some previous methods which used fixed shell heights. In this paper we also compared the ionosonde derived TEC with the GPS derived vertical TEC (vTEC) values. These GPS vTEC values were obtained from GPS slant TEC (sTEC) measurements using both fixed shell height and varying shell heights (from ionosonde measurements). For the polar regions, the varying shell height approach produced better results than the fixed shell height and compared to exponential function, Chapman function seems to be a better function to model the topside ionosphere.

Keywords: Polar ionosphere; GPS; Ionosonde; Total electron content; Chapman function

1. Introduction

The Global Positioning System's availability both spatially and temporarily and also its usage of dual-frequency signals ($F1 = 1.575$ GHz and $F2 = 1.228$ GHz) make it a very suitable system for ionospheric research. The phase advance and the group delay in the GPS signals produced by the ionosphere depend on its total electron content (TEC). Using these advances and delays one can calculate the total electron content along the path the ray has traveled from the satellite to the receiver through the ionosphere (Komjathy, 1997).

The point at which the ray path intersects the ionosphere is called the ionospheric pierce point (IPP) and the electron content derived from the advances and delays along that ray path is assumed to be present at that point. Some previous studies (Komjathy, 1997) have assumed the ionosphere to be a thin layer around the earth at a height called the shell height.

The shell height is defined as the height at which the electrons are distributed equally below and above it, and this height is close to the peak height of the F layer in the ionosphere (Komjathy, 1997; Horvath and Crozier, 2007). In many previous studies (e.g. Komjathy, 1997), the shell height is approximated to be 350 km. However, for the polar regions the fixed shell height assumption may not be valid since the polar ionosphere is very dynamic because of the solar wind–magnetosphere–ionosphere

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interaction and presence of ionospheric structures such as polar patches (MacDougall and Jayachandran, 2007).

The electron content derived at the Ionospheric Pierce Point (IPP) is called the slant total electron content (sTEC) since the ray path makes an angle with the vertical. This sTEC is then mapped to the vertical using a mapping function to obtain the vertical total electron content (vTEC) at the same height of the IPP (shell height).

The ionosonde is another device which is generally used to profile the ionosphere. It is a vertical sounder of the ionosphere which sweeps over a frequency range of 1–20 MHz and works on the principle of reflection (Davies, 1990). From ionosonde vertical sounding profiles, one can obtain the peak frequency and peak heights which correspond to the plasma frequency and height of the maximum electron density at that epoch, respectively. These peak heights obtained from the ionosonde were used as shell heights for mapping the slant TECs to the vertical in our analysis of the GPS data. We used sun-fixed solar geomagnetic coordinates in our calculations since the ionosphere varies much more slowly in these coordinates (Bregstrand and Haas, 2004).

We compared the TEC values obtained from ionosonde profiles (bottomside + modeled topside) with the GPS derived vTEC values. The topside profiles from the ionosonde were modeled using a Chapman and exponential functions (Chapman, 1931; Davies, 1990).

2. Data analysis

In this study, we have used GPS measurements from Resolute Bay (74°41′51″ N, 94°49′56″ W geog), an International GNSS Service (IGS) site which is in the polar cap. We have used data from three days in 2006 (11th November, 12th November, and 15th November 2006). The IGS provides 30-s dual-frequency RINEX observational files. These observational files contain information about range measured in meters on P1, P2 (P-code pseudo-ranges on L1, L2 frequencies, respectively) and C1 (C/A code pseudo-range on L1). They also have phase information (L1 and L2) measured in cycles on L1 and L2 frequencies. We calculated the slant absolute total electron content (SATEC) from pseudo-ranges and slant relative total electron content (SRTEC) from the carrier phases using Eq. (1) and (2), respectively (Horvath and Crozier, 2007).

$$\mathrm{SATEC} = \left(\left[\left(\frac{P_2}{c}\right) - \left(\frac{P_1}{c}\right)\right] \times 2.852 \times 10^{+9}\right), \tag{1}$$

$$\mathrm{SRTEC} = \left(L_2 - \left(\frac{60}{77}\right)L_1\right) \times (-2.3247), \tag{2}$$

The relative slant total electron content is relative in the sense that there is an ambiguity in the phase which does not give an absolute value but it is very precise. The absolute total electron content from the pseudo-range is absolute but noisy. To obtain a better result we combined them using a method called phase leveling (Komjathy, 1997; Horvath and Crozier, 2007). To minimize the multipath effect, we have used the phase and pseudo-range values which correspond to ±15° from highest elevation angle of the respective satellite pass to obtain the mean difference between the phase and pseudo-range values. This bias was then used to level the whole satellite pass. Since GPS hardware have their inherent delays (satellite bias and receiver bias), they should also be taken into consideration (Komjathy, 1997; Horvath and Crozier, 2007).

We obtained these bias values from the University of Bern website (http://www.aiub-download.unibe.ch/CODE/) and combined them with our slant absolute total electron content values before we did phase leveling (Horvath and Crozier, 2007). This phase leveled slant total electron content is called the slant total electron content. While analyzing the data, cycle slips, where the phase is lost for a certain period of time, were checked for and corrected before phase leveling was done. After obtaining the slant total electron content, we used the mapping function, $M(E)$ (Eq. (3)) (Komjathy, 1997), to obtain the vertical slant total electron content at the ionospheric pierce point at the shell heights obtained from ionosonde measurements. We then mapped the vertical TEC (vTEC) from the pierce point to the point above the receiver using the angle between them. Later, we averaged the vertical total electron content from each satellite to obtain the averaged vertical total electron content. This averaging would smooth out variations caused by horizontal gradients in the ionosphere. These horizontal gradients in the ionosphere are assumed to be small for a particular site and epoch. The elevation angles (E) between the receiver and satellites were obtained from the GPS Toolkit designed by the University of Texas, Austin (Gaussiran et al, 2004).

$$M(E) = \frac{1}{\cos\left(\arcsin\left[\cos(E)\frac{R_e}{R_e+h}\right]\right)}, \tag{3}$$

where R_e is the radius of earth and h is the shell height (Komjathy, 1997).

In our study we also used the Canadian Advanced Digital Ionsonde (CADI) installed at Resolute Bay. For the details of the CADI system please see MacDougall and Jayachandran (2007). Given the dispersive nature of the ionosphere, the heights we obtained from the ionosonde are called the virtual heights. To obtain the real heights from these virtual heights, one has to use numerical methods and we have used a commonly used method called the Polynomial Analysis (POLAN) method (Titheridge, 1985). CADI can provide peak height of F layer/shell height every 1 min. Fig. 1 shows the distribution of shell heights for the three days we have used for this study. One can see that this height varied between 240 km and 380 km during the time period used in this study. So using a fixed shell height will obviously introduce some errors in the vTEC calculations. Instead of using a fixed shell height we have incorporated the peak height obtained from ionosonde as the shell height