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Mapping GPS-derived ionospheric Total Electron Content over Southern Africa during different epochs of solar cycle 23

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Abstract

The Southern African Development Community and the International Global Navigation Satellite Systems Service (GNSS) network of dual frequency Global Positioning System (GPS) receivers provide an opportunity to determine Total Electron Content (TEC) over Southern Africa by taking advantage of the dispersive nature of the ionospheric medium. For this task, the University of New Brunswick (UNB) ionospheric modelling technique which applies a spatial linear approximation of the vertical TEC above each station using stochastic parameters in Kalman filter estimation, primed with data from the Southern Africa GPS network, was used for mapping TEC at South African locations during selected days and hours of different epochs of solar cycle 23. Significant enhancements in the TEC value and features, which could be associated with frequent solar events, are evident around a day of extreme solar maximum. These observations are discussed and further investigated by analyzing the GOES 8 and 10 satellites X-ray flux (0.1–0.8 nm) and SOHO Solar EUV Monitor (26.0–34.0 nm) higher resolution data. Comparison of these physical quantities reveals that for each X-ray flare observed, there is an associated EUV flare event. The latter phenomenon causes photoionisation in the daytime ionosphere which results in significant TEC enhancement. The daytime UNB TEC compared with the International Reference Ionosphere (IRI) 2001 predicted TEC found both models to show a good agreement.

Keywords: Solar Terrestrial Physics; Solar cycle; Solar flares; Global Positioning System; Ionosphere; Total Electron Content; UNB model; International Reference Ionosphere

1. Introduction

The current trend in ionospheric physics research has proven that the dual frequency ($L1 = 1575.42$ MHz and $L2 = 1227.60$ MHz) signals transmitted by the Global Navigation Satellite Systems (GNSS), and received by the network of Global Positioning System (GPS) receivers distributed worldwide provide a unique opportunity to determine the high resolution spatial and temporal ionospheric Total Electron Content (TEC) at regional and global level (e.g. Klobuchar, 1991; Komjathy and Langley, 1996; Jakowski, 1996; Komjathy, 1997; Mannucci et al., 1998). This is possible due to the dispersive nature of the ionospheric medium. Electromagnetic waves, such as GPS signals, experience time delays when traversing the ionosphere (Ratcliffe, 1959). The delay of the GPS broadcasting signals is directly proportional to the integrated free-electron density (TEC) along the signal path from the broadcasting position in space to the receiver on Earth. The magnitude of TEC is highly variable and depends on several factors such as local time, geographical location,

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season, and solar activity cycle (e.g. Jakowski, 1996; Jakowski et al., 1999, 2002; Immel et al., 2003; Tsurutani et al., 2004; Skoug et al., 2004; Jee et al., 2005; Mannucci et al., 2005; Fedrizzi et al., 2001). Recent studies (Jakowski et al., 2001, 2002) illustrate that TEC monitoring using the GNSS network, can contribute to space weather monitoring. The unit for TEC used in this work is TECU where 1 TECU = 10^{16} electrons/m^2.

This paper presents an attempt to study the solar cycle variations of TEC observed over the southern African region with the aid of the University of New Brunswick (UNB) ionospheric modeling technique (Komjathy, 1997). Komjathy (1997) developed and applied this model for mapping the global and regional ionospheric TEC using the worldwide GPS network with stations mainly densely distributed in the northern hemisphere. This model was developed to provide ionospheric corrections to single frequency users (Komjathy et al., 1998). Most recently, Fedrizzi et al. (2005) also used the same model to study TEC variability associated with geomagnetic storm activity over locations in the South American Sector. The current data available from the Hartebeeshoek Radio Astronomy Observatory (HartRAO) International GNSS Service and the Chief Directorate Surveys and Mapping (CDSM) Trignet network of dual frequency GPS receivers distributed over southern Africa make this study possible (Cilliers et al., 2003; Combrink et al., 2004).

For the purpose of this work, the monthly averaged sunspot number was used as a proxy for solar activity cycle 23 as shown in Fig. 1. From these monthly averaged values, it is well established that the Sun has a quasi-periodic ~11 year activity cycle (e.g., Smith and Marsden, 2003). Approximately every 11 years the Sun moves through a period of fewer and smaller sunspots, which is called 'solar minimum' followed by a period of larger and more sunspots which is called 'solar maximum'. Different epochs of the solar cycle were selected based on the availability of GPS data within southern Africa as follows: epoch "(a)" the moderate solar activity conditions around 1998 (left shaded band) during the ascending phase of the solar cycle; epoch "(b)" the extreme solar maximum conditions around 2001 (middle shaded band); and epoch "(c)" the moderate solar activity conditions around 2004 (right shaded band) during the descending phase of the solar cycle 23. Subsequent effects of these different epochs on TEC maps over southern Africa are discussed. TEC observations around a selected day and hour during an extreme solar maximum period display interesting features which could be associated with frequent solar activity events. These observations are further investigated by analyzing the GOES 8 X-ray flux (0.1–0.8 nm) data and the Solar and Heliospheric Observatory (SOHO): Charge, Element and Isotope Analysis/Solar Extreme Ultraviolet Monitor (CELIAS/SEM) 26.0–34.0 nm higher resolution data. The latter instrument's detailed description can be obtained from Hovestadt et al. (1995), Judge (1998), and Judge et al. (2001, 2002). The daytime TEC computed with the UNB model are comprehensively compared with TEC values computed with the recent version of the International Reference Ionosphere (IRI) 2001 model (Bilitza, 2001).

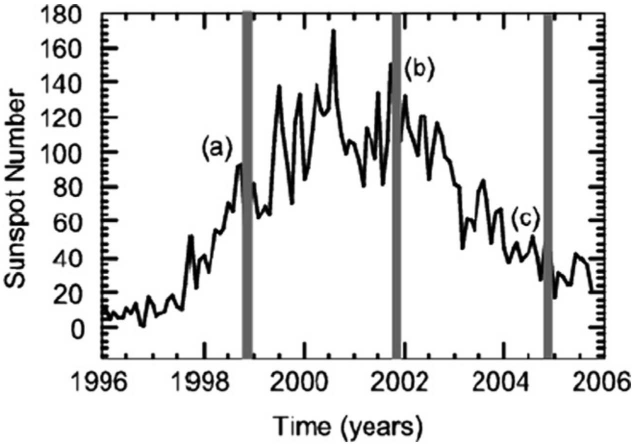

Fig. 1. Monthly averaged sunspot number for solar cycle 23. The shaded regions depict selected day 345 at 14:00 UT for different epochs of solar cycle 23. Epoch "(a)" represents intermediate solar activity conditions during the ascending phase; "(b)" represents extreme solar maximum conditions during the peak; and "(c)" represents the descending phase of the solar cycle.

2. UNB ionospheric modelling technique

The UNB ionospheric modelling technique uses the single-layer ionospheric (shell) model to compute TEC from dual frequency GPS receivers, according to the following observation equation (Komjathy, 1997):

$$I_{\mathrm{r}}^{\mathrm{s}}(t_k) = M(e_{\mathrm{r}}^{\mathrm{s}})[a_{0,\mathrm{r}}(t_k) + a_{1,\mathrm{r}}(t_k)\mathrm{d}\lambda_{\mathrm{r}} + a_{2,\mathrm{r}}(t_k)\mathrm{d}\varphi_{\mathrm{r}}] + b_{\mathrm{r}} + b^{\mathrm{s}} \tag{1}$$

where $I_{\mathrm{r}}^{\mathrm{s}}(t_k)$ represent the line-of-sight L1–L2 phase-leveled measurements obtained by receiver r and observing satellite s at epoch t_k. $M(e_{\mathrm{r}}^{\mathrm{s}})$ is the mapping function, $e_{\mathrm{r}}^{\mathrm{s}}$ represents the satellite elevation angle, $a_{0,\mathrm{r}}$, $a_{1,\mathrm{r}}$, and $a_{2,\mathrm{r}}$ are stochastic parameters for spatial linear approximation of TEC to be estimated for receiver r and assuming a first-order Gauss-Markov stochastic process (Gail et al., 1993). Furthermore, $\mathrm{d}\lambda_{\mathrm{r}} = \lambda_{\mathrm{r}} - \lambda_0$ is the difference between a sub-ionospheric point and the mean longitude of the Sun, $\mathrm{d}\varphi_{\mathrm{r}} = \varphi_{\mathrm{r}} - \varphi_0$ is the difference between the geomagnetic latitude of the sub-ionospheric point and the geomagnetic latitude of the station, b_{r} and b^{s} refer to the receiver and satellite instrumental biases, respectively. For further information on how these biases are estimated, see Komjathy (1997).

The PhaseEdit version 2.2 automatic data editing program was used to detect bad points and cycle slips, as well as repair the cycle slips and adjust phase ambiguities using the undifferenced GPS data. The program takes advantage of the high precision dual frequency pseudorange measurements to adjust L1 and L2 by an integer number of cycles