Comparison of ionospheric Total Electron Content derived from collocated GNSS receivers over HartRAO during solar X-ray flares

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ABSTRACT

The International Global Navigation Satellite Systems (GNSS) and the South African ground based network of dual frequency Global Positioning System receivers provide a unique opportunity to monitor the space weather effects on the ionospheric total electron content (TEC) over South Africa. In particular, using the University of New Brunswick ionospheric modelling software, TEC was computed over collocated HRAO (27.69°E, 25.89°S) ASTECH X-ZII3 and HARB (27.71°E, 25.89°S) TRIMBLE 4000SSI GNSS receivers located at Hartebeesthoek for the solar X17 flare which occurred on day 301, 2003 and the recent solar X9 flare which occurred on day 339, 2006. TEC values were compared by computing the TEC differences between these stations for the two selected flares. It was found that the TEC difference between HRAO and HARB is large (~9 TECU) for the X17 flare compared to the X9 (~6 TECU). The possible reasons for the TEC difference between the two receivers could presumably be attributed to the receivers' instrumental differences, inaccuracy associated with the single-layer ionospheric model, and inaccuracy within the geometric mapping function. Furthermore, a comparison of the TEC values over South Africa for these flares show evidence of solar cycle dependence. This is important for future application in high frequency radio communication, navigation, positioning, frequency management and long term studies of impact of solar outputs on climate change over South Africa.

Introduction

The international Global Navigation Satellite Systems (GNSS) Service (IGS) and the South African Chief Directorate Surveys and Mapping (CDSM) TrigNet network of ground based Global Positioning System (GPS) receivers provide a unique opportunity for permanent monitoring of the temporal and spatial variations of the electron content of the ionosphere over South Africa (20°S ≤ λ ≤ 35°S; 15°E ≤ φ ≤ 35°E) (e.g. Cilliers et al., 2004; Ngcobo et al., 2005; Moeketsi et al., 2007). This is possible due to the dispersive nature of the ionospheric medium (Ratcliffe, 1959). The dual frequency (L1 = 1575.42 MHz, L2 = 1227.60 MHz) signals of GNSS experience time delays and phase advances when traversing the ionosphere, in particular due to interaction with free electron gas. The net effect of this delay is directly proportional to the integrated electron density (TEC) along the signal path from the position of the satellite (~22,200 km) to the receiver on Earth (e.g. Klobuchar, 1991; Langley, 1996). The unit for TEC used consistently in this paper is TECU (1 TECU = 10¹⁶ electrons.m⁻²). Decades of ionospheric research has shown that TEC is highly variable and depends on several factors such as local time, geographical location, season and solar cycle (e.g. Jakowski, 1996; Jakowski et al., 1999; Tsurutani et al., 2005; Mannucci et al., 2005; Fedrizzi et al., 2005, Moeketsi et al., 2007). Recently, Jakowski et al. (2001; 2002) illustrated that TEC monitoring using the GNSS network can contribute to space weather monitoring.

In this work, the University of New Brunswick (UNB) Ionospheric model (Komjathy and Langley 1996; Komjathy, 1997; Fedrizzi et al., 2005) is applied, using 30s data from the IGS and the GPS networks over South Africa (Combrinck et al., 2003; Cilliers et al., 2003; Combrink et al. 2004) to compute TEC over the collocated HRAO (27.69°E, 25.89°S) and HARB (27.71°E, 25.89°S) receivers for the X17 and X9 solar flares which occurred on day 301, 2003 and day 339, 2006, respectively. The HRAO (ASHTECH X-ZII3) and the
HARB (TRIMBLE 4000SSI) GNSS receivers are located ~3 km apart at Hartebeesthoek, South Africa. The main aim of this study is to compare TEC derived from both receivers by computing the TEC difference between them during the two solar flares considered in this work.

The UNB Ionospheric TEC Model
The UNB Ionospheric Modelling Technique Unix-compatible version was developed in 1997, in the Department of Geodesy and Geomatics Engineering at the University of New Brunswick (UNB), to compute global and regional TEC from GNSS observables at both L1 and L2 frequency bands in order to provide ionospheric corrections to communication, surveillance and navigation systems operating at a single frequency (e.g. Komjathy and Langley, 1996; Komjathy, 1997; Komjathy et al., 1998). Efforts were undertaken at the Space Geodesy Programme, HartRAO to modify the Unix version of the UNB Model Unix version to compile and execute on a Linux platform in order to compute TEC over South Africa (Ngcobo et al., 2005; Moeketsi et al., 2007). The UNB model estimates the coefficients of a linear approximation of TEC over each station in addition to the satellite and receiver differential biases, modelling the ionospheric measurements from a dual frequency GNSS receiver with a single-layer ionospheric model. The technique used to estimate these biases is described by Sardon et al. (1994).

The used UNB approach uses the single-layer model, which assumes that the vertical TEC can be approximated by a thin spherical shell located at the average height (400 km) of maximum electron density (e.g. Komjathy, 1997). The mapping function used in this work is a standard geometric mapping function (Mannucci et al., 1993), that computes the secant of the zenith angle of the signal geometry ray path at the ionospheric pierce point, and then projects the line-of-sight measurements to the vertical of the sub-ionospheric point. The elevation cut-off angle was set to 10°. It is important to mention that recent studies of comparison of different TEC mapping techniques (e.g. MIDAS) reported an improvement in accuracy of the determination of TEC compared with the thin shell.

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method (e.g. Meggs et al., 2004; Meggs and Mitchell, 2006).

As a result of the ionospheric dependence on solar radiation and the geomagnetic field, the model uses a solar-geomagnetic reference frame to compute TEC at each grid point. TEC values change at a slower rate in this reference frame compared to an Earth-fixed one. The ionospheric model was evaluated for the four closest stations to a grid node at which a TEC value is computed. Consequently, the inverse-distance-squared weighted averages of the individual TEC data values for the four stations were computed. The closer a particular grid node is to a GPS station, the more weight was placed on the TEC values computed by evaluating the temporal and spatial variation of the ionosphere above the particular station. The ionospheric TEC maps are produced using a 5-degree grid spacing. Each fifteen minutes map reflects the observations obtained from 7.5 minutes before to 7.5 minutes after the respective quarter hour (Fedrizzi et al., 2005).

Observations and data analysis

The data sampled at 30s from 17 IGS and South African dual frequency GPS receivers, were used in this study as an input to the UNB code described above. The IGS data used are obtained from the HartRAO data server ftp://geoid.hartrao.ac.za, while the South Africa CDSM Trignet data were obtained from http://www.trignet.co.za. It was ensured that the quality of the GPS data was checked for all stations using the UNAVCO Translate/Edit/Quality Check (TEQC) software (Estey and Merteens, 1999). The software module “EditObs” developed locally (Ngcobo et al., 2005) was used to extract the GPS observables used by UNB code from the Receiver Independent Exchange (RINEX) format GPS observation file. Furthermore, data pertaining to the two solar X-ray flares (X17 and X9), which occurred on day 301, 2003 and day 339, 2006 were used in the analysis, was obtained from http://goes.ngdc.noaa.gov/data/plots.

Figure 1 is an example of an image recorded at 10:44 UT of the X9 flare observed by the Solar X-ray Imager (SXI) onboard GOES – 13 (http://sxi.ngdc.noaa.gov/images/). This flare emanated from active region 930 as seen on the solar disk. A white horizontal line has been reported to be due to a CCD anomaly and the cause thereof is under review and is not of interest to this work.

Results and discussions

Two solar X-ray flare events which occurred on day 301, 2003 during moderate solar activity conditions and Day 339, 2006 during solar minimum conditions, are selected in this work to compare the behaviour of ionospheric TEC over two collocated GNSS receivers, namely HRAO and HARB. The classification and duration of these flares are summarised in Table 1.

Figure 2. Panels (a) and (c) shows comparison of TEC over collocated HRAO and HARB GNSS stations during the solar X17 (day 301, 2003) and X9 (day 339, 2006) flares. Panels (b) and (d) show the corresponding computed TEC difference between HRAO and HARB for (a) and (c), respectively.
Table 1. Summary of time duration of two X-ray flares studied in this work

<table>
<thead>
<tr>
<th>Flare Class</th>
<th>Onset time (UT)</th>
<th>Peak time (UT)</th>
<th>End time (UT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>X17</td>
<td>11:00</td>
<td>11:10</td>
<td>11:30</td>
</tr>
<tr>
<td>X9</td>
<td>10:18</td>
<td>10:35</td>
<td>10:45</td>
</tr>
</tbody>
</table>

The X17 is the most intense flare which occurred on day 301, 2003, around 11:00 UT and reached peak intensity within 10 minutes, thereafter took longer to decay as shown in Table 1. The X9 flare occurred on day 399, 2006 at 10:18 UT and peaked at 10:35 UT and then decayed slowly back to the initial background values measured before the onset of the flare. The ionospheric TEC response due to these flares over HRAO and HARB is discussed below.

X17 flare on day 301, 2003

Figure 2(a) shows a comparison of the five minute averaged TEC over HRAO (dashed lines) and HARB (solid line) between ~6:00 and ~18:00 UT for the X17 flare. The TEC over these stations are compared by

Figure 3. Panels (a), (b) and (c) show TEC maps over South Africa before (~10:15 UT), during (~11:15 UT) and after (~12:00 UT) the X17 flare occurred on day 301, 2003. Panels (d) at ~10:15 UT, (e) at ~10:30 UT and (f) and ~11:15 UT show similar scenarios as panels (a), (b) and (c) for the X9 flare which occurred on day 399, 2006. The red triangles on the TEC maps indicates geographical location of HRAO (27.69°E, 25.89°S) and HARB (27.71°E, 25.89°S).
computing the TEC difference $\Delta TEC = HRAOTEC - HARBTEC$ as shown in Figure 2(b). It is evident that the TEC over HRAO ($HRAOTEC$) is slightly (~5 TECU) higher than TEC over HARB ($HARBTEC$) during the early hours between ~6:00 and ~8:00 UT. However, the TEC value recorded between the (~8:00 – 10:00 UT) and (~13:00 to 15:00 UT) periods over both stations is comparable. The TEC over HARB and HRAO display a rapid increase from the onset of the X17 flare and reach the peak within ~10 minutes, after which it decreases gradually to reaches the background values before the onset of the flare at ~13:00 UT. The difference between $HRAOTEC$ and $HARBTEC$ is large (~9 TECU) during the peak of the flare and after ~15:00 UT towards the night as shown in Figure 2 (b).

X9 flare on day 339, 2006

Figure 2(c) shows comparison of ionospheric TEC over HRAO (dashed lines) and HARB during the recent X9 flare which occurred on day 339, 2006. Coinciding with the flare onset (~10:18 UT), the TEC value rapidly increases over both stations and reaches a peak at ~10:35 UT, after which it decreases gradually as the flare decays. The TEC values over these stations for the X9 flare are compared by computing the TEC difference $\Delta TEC$ for the daytime ionosphere as shown in Figure 2(d). The $HRAOTEC$ is slightly higher than the $HARBTEC$ during the early hours (~8:00 – 10:00 UT). A significant difference (~6 TECU) between $HRAOTEC$ and $HARBTEC$ is evident around the peak.

Recent studies of the flare-ionosphere relations (e.g. Tsurutani et al., 2005; Zhang and Xiao, 2005; Moeketsi et al., 2007) have shown that the daytime ionosphere responds dramatically to the X-ray and Extreme Ultraviolet (EUV) flare inputs by an abrupt enhancement of TEC with respect to the prior flare background values. Furthermore, the EUV component of the flare is responsible for the TEC enhancement, which lasts far longer than the duration of the flare. This interpretation holds for ionospheric the TEC response to the two flares discussed in this work.

Of major interest is the pronounced difference of ~6 TECU and ~9 TECU between collocated $HRAOTEC$ and $HARBTEC$ for the X9 and X17 solar flares. The two GNSS receivers are located ~3 km apart from each other and the ionosphere is not expected to behave differently over such a short distances. However, possible causes for the TEC difference between the two could be due to the following:

- Two different types of collocated GNSS receivers used could possibly have different biases.
- Some inaccuracy associated with the single-layer ionospheric model as reported by Meggs et al. (2004) and Meggs and Mitchell (2006), could be expected in calculations.
- Some inaccuracies within the geometric mapping function in projecting the line-of-sight TEC into vertical TEC above each station particularly at high solar activity could be expected (e.g. Komjathy, 1997).

In order to investigate TEC differences between the two collocated receivers, further studies using additional data are needed.

Comparison of the TEC difference between the two flares indicates evidence of solar cycle dependence (e.g. Moeketsi, et al., 2007). The TEC difference is larger for the X17 flare than for the X9 flare. The former occurred in 2003 during moderate solar activity conditions; the latter occurred in 2006 during solar minimum conditions.

TEC maps during X-ray flares

Shown in Figure 3 are the ionospheric TEC maps of South Africa computed with the UNB model for the two solar X-ray flares considered in this work. Panel (a), shows the TEC map at 10:15 UT before the onset, (b) near the peak (11:15 UT) and (c) after the decay phase (12:00 UT) of the X17 flare. The TEC values on the TEC map around the peak are significantly enhanced compared to the TEC map before and after the flare. Panel (d), shows the TEC map prior (10:15 UT) to the onset of the X9 flare, (e) shows the TEC map during (10:30 UT) the flare and (f) shows the TEC map after the decay phase (11:15 UT) of the flare respectively. It is also evident that TEC values computed during this flare are enhanced compared to the period before and after the flare. The latter holds for both flares due to the high rate of solar radiation input causing photo-ionisation, which results in a sudden TEC enhancement within the daytime ionosphere during solar flares (Tsurutani et al., 2005; Moeketsi et al., 2007). This is direct evidence of space weather effects on the terrestrial ionosphere.

Conclusions

It has been shown that there exist considerable differences between TEC observed by the two different but collocated (HRAO (27.69°E, 25.89°S) and HARB (27.71°E, 25.89°S)) GNSS receivers during the X17 and X9 solar flares selected for the purpose of this study. This could presumably be attributed to the following reasons: (a) the instrumental differences in receivers, (b) inaccuracy associated with the single-layer ionospheric model as reported by Meggs et al. (2004) and Meggs and Mitchell (2006), and (c) inaccuracies of the geometric mapping function used in projecting the line-of-sight TEC into vertical TEC above each station particularly at high solar activity (e.g. Komjathy, 1997). In order to investigate TEC differences between the two collocated receivers, further studies using additional data are needed. However, a comparison of TEC for these flares showed evidence of a solar cycle dependence (e.g. Moeketsi et al., 2007), and direct evidence of space weather effects on the ionosphere over South Africa. This is important for future application in high frequency radio communication, navigation, positioning, frequency management and long term studies of impact of solar outputs on climate change over South Africa.

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