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GPS Ionospheric Total Electron Content and Scintillation Measurements during the October 2003 Magnetic Storm

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Abstract: Problem Statement: Ionospheric scintillations, cause significant effects on satellite signals for communication and navigation in equatorial region and polar regions mainly during sever magnetic storms periods. This phenomenon is not fully understood due to few studies performed. The study investigates variability of Total Electron Content (TEC) and ionospheric scintillation during October 2003 magnetic storm over Antarctica using ground based GPS technique. **Approach:** The TEC/scintillation measuring system at Scott Base station, consists of Trimble TS5700 24-channel (a high-precision dual-frequency GPS receiver), a Trimble Zephyr Geodetic antenna and a notebook computer for data logging. The absolute GPS TEC was calculated from differential phase advance GPS observables (1-L2). The GPS signal-to-noise ratios (C/No) and 1/L2 carrier frequencies were employed to determine the scintillation index S_4 every 60 s, amplitude scintillation (in dB-Hz) and phase scintillation. **Results:** The GPS measurements during storm periods at Scott Base show pronounced phase and amplitude scintillation activities, sudden increase in TEC followed by trough-like figure depletions. The maximum value of phase scintillation during the main phase of third episode was 8.3 times the value during Sudden Storm Commencement (SSC) period. Measured amplitude scintillation and S4 index on both 1 and L2 signals are >15dB-Hz and >0.4dB-Hz respectively. **Conclusion/Recommendation:** The timing and intensity of TEC and scintillation measurements during the storm event were are in a good agreement with WDC measurements. For this particular event, the duration of enhanced periods were approximately 12 h while periods of TEC depletions were more than 30 h. This value implies better understanding of the polar ionospheric response to magnetic storm and eases efforts for better space weather prediction in this region.

Key words: GPS ionospheric, total electron content, magnetic storm

INTRODUCTION

The Earth's ionosphere can cause serious problems in many radio applications, especially in radio communications, navigations and space weather, which is now been the subject of active research. The ionosphere is prone to significant disturbances, which are considerably worse during periods of high solar activity, such as at solar maximum. As the radio wave signal from a satellite or radio star interact the disturbed ionosphere, the received signal will exhibit a rapid fluctuation in amplitude, phase and Faraday rotation due to the irregularities of the electron density in this medium. These fluctuations in amplitude, phase and Faraday rotation angle of the signal about mean level is known as ionospheric scintillation.

The period from 28th October-1st November of 2003 was characterized by extreme solar activity that resulted in a series of intense geomagnetic storms. This storm was the greatest storm during the 23rd solar cycle and one of the fastest traveling solar storms in the last two decades. The extreme interplanetary and geomagnetic disturbances in the 2003 magnetic storm were related to the eruptive activity of the sun. The event started to take place on 28th October around 09:51 UT when a series of X17.2/4B flares occurred accompanied by bursts of radio emissions and ejections of solar mass were observed. During 29th and 30th October, two high speed streams of the solar wind which are caused by coronal hole, produced large series of magnetic storms. During this period, huge groups of sunspots on the visible solar disk were observed (Panasyuk *et al*., 2004; Veselovsky *et al*., 2004).

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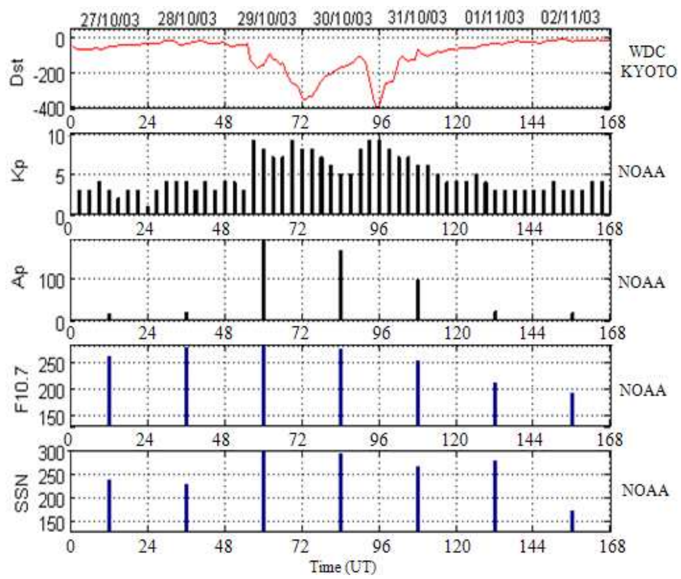

Fig. 1: The magnetic and solar indices for the October 2003 storm

Radio measurements conducted during the October 2003 storm over the northern high-latitude region showed a pronounced scintillation activity. Mitchel *et al*. (2005) observed a pronounced scintillation activity during the evening of 30th October over European high arctic region using the GPS scintillation receiver. They concluded that the gradient-drift instability is a likely mechanism for the generation of the irregularities causing some of the scintillation at L-band frequencies during the storm. A clear scintillation activity was also observed over Calgary and other sites in Canada during the storm time periods that correspond to the presence of Storm Enhanced Density (SED). The observed SED is characterized by a narrow plume of greatly enhanced Total Electron Content (TEC) values (>50 TECU) and is associated with very steep electron density gradients and high ion flux values. Forte *et al*. (2004) measured spatial spectral behaviour of small-scale plasma irregularities during the storm period based on GPS derived scintillation information.

The study of ionospheric TEC and scintillation behavior during magnetic storm periods is still lacking especially in the southern polar region. Most of the studies concentrated on high and middle latitude region of the northern hemisphere. Therefore, the ionospheric response at conjugate points in northern and southern polar regions is not completely understood. In this study, we present the results of GPS ionospheric TEC and scintillation during the October 2003 storm at Scott Base station in Antarctica. Our main emphasis of this study is to measure the ionospheric response during severe magnetic storms in the Polar Regions and its influence on the scintillation activity.

October 2003 storm conditions: The October 2003 storm occurs on 29-31st October 2003. Figure 1 shows the geomagnetic indices Dst, Kp and Ap during the period from 27th October-2nd November 2003 obtained from WDC. As shown in Fig. 1, three distinct Dst minima were recorded during 29th and 30th October 2003, on 29th October at 1200 UT (-180 nT), on 30th October at 0100 UT (-363 nT) and at 2300 UT (-401 nT) respectively. The sudden storm commencement (SSC) of the first storm took place at about 0600 UT on 29th October 2003, the second SSC occurred at about 1200 UT of the same day, while the third SSC began around 1700 UT on 30th October 2003. During this period, the 3 h Kp index recorded a maximum value of 9 for four times at 0900 UT and at 2100 UT on 29th October and at 2100 UT until 2400 UT on 30th October. During this event Ap jump abruptly from a value of 20 on 28th October to a maximum value of 189 on 29th October and decreases dramatically to a value of 21 on 1st November when the storm subside. The solar index F10.7 > 250 and SSN > 200 a few days before the storm event and maintained its high values during the whole storm event. This showed the sun has been in active conditions a few days prior to the storm event.

MATERIALS AND METHODS

The TEC/scintillation measuring system at Scott Base station, consists of Trimble TS5700 24-channel (a high-precision dual-frequency GPS receiver), a Trimble Zephyr Geodetic antenna and a notebook computer for data logging. Trimble TS5700 provides direct measurement of C/No on L1 and L2 which allows us to determine the ionospheric scintillation without extensive software development. The absolute GPS TEC can be obtained from differential time delay (P1-P2) or from differential phase advance (L1-L2). The TEC obtained from differential time delay gives the level of absolute TEC but it is highly exposed to multipath effect, while the TEC attained from differential phase advance gives high precision TEC but the level is unknown due to the initial offset called the ambiguity. Therefore, the level of TEC is adjusted to the TEC derived from the corresponding code difference for each satellite-receiver pair (Otsuka *et al*., 2002). In this study, the time delay measurements were used to remove the ambiguity term and by combining the phase and the code measurements for the same satellite receiver pair, the absolute TEC are obtained with high precision. The TEC values were corrected from the receiver and satellite biases by using the AIUB Data Center of Bern University in Switzerland (AIUB, 2000). The equivalent absolute vertical TEC, Percentage deviation of the GPS TEC and the rate of change of TEC (ROT) have been calculated using standered methods (Rashid *et al*., 2006; Momani *et al*., 2008; 2010; Abdullah *et al*., 2009).

GPS signals provide an excellent means for measuring scintillation effects on a global basis as they are available and can be measured through many points in the ionosphere simultaneously (Van Dierendonck *et al*., 1993). Dual and single frequency GPS receivers are both used for this purpose using the GPS L1 and/or L2 carrier and phase signals transmitted from the satellites. For the calculation of scintillation index S4, the amplitude and phase scintillation and, GPS signal-to-noise ratios (C/No) and L1 / L2 carrier frequencies are employed. Scintillation index or S_4 index descriptor which represents signal fade is defined as the standard deviation of the received power divided by the mean value of the received power (Van Dierendonck *et al*., 1993). Amplitude scintillation for single frequency receiver is defined as the difference of C/No of two successive readings as follows: $\Delta A(t) = C/N_o(t) - C/N_o(t-1)$. Finally, the phase scintillation is defined as standard deviation and power spectral density of the de-trended carrier phase signals received from GPS satellites (Van Dierendonck *et al*., 1993).

RESULTS

Figure 2 presents the results of daily TEC variations before, during and after the storm period, superimposed in the figure is the mean TEC calculated for the days of quiet solar and magnetic activity (9th, 10th and 11th October 2003, where Kp for these days are less than 3) referred to as mean QD. Figure 3 shows the phase scintillation (ph-scin), S4 index on L1 and L2 signal (S4-L1 and S4-L2), amplitude scintillation on L1 and L2 signal (Amp-L1 and Amp-L2) and Rate of TEC (ROT) during the same period. It should be noted that timing of the GPS extracted parameters are delayed by about 30 minutes with respect to the WDC data.

As shown in the Fig. 2, the GPS TEC profile exhibits an enhancement and depletion (positive and negative disturbance) during the storm event as can be clearly seen in the Fig. 2. During the first SSC at 0630 UT on 29th October 2003, VTEC reached a value of 22 TECU (7 TECU above the mean value). At this time, the measured phase scintillation is 0.5 m, S4-L1 is 0.08, S4-L2 is 0.07, Amp-L1 is 4.0 dBHz and Amp-L2 is 2.7 dBHz and the rate of TEC measured is 0.08 TECU/min. Following this time the TEC and scintillation activities becomes quiet.

At the time of second SSC at 1230 UT on 29th October, VTEC value is 5 TECU (2 TECU below the mean value), the phase scintillation is 0.5 m, S4-L1 is 0.06, S4-L2 is 0.06, Amp-L1 is 3.6 dBHz, Amp-L2 is 2.3 dBHz and ROT is 0.06 TECU/min, similar to the condition at the first SSC. The first TEC enhancement was observed between 2100 UT on 29th October and 0230 UT on 30th October with a maximum TEC value of 47 TECU at 2320 UT. During the period of enhanced TEC, the maximum reading of phase scintillation is 2.1 meter, Amp-L1 is 8 dBHz, Amp-L2 is 12 dBHz, S4-L1 is 0.1, S4-L2 is 0.24 and ROT is 0.62 TECU/min. Following this time, TEC depression with trough-like figure occurred which continue for more than 14 h (between 0500 UT and 1900 UT), a decreased by about 17% with respect to mean QD.

At the third SSC at 1730 UT (on 30th October 2003) the VTEC is 10 TECU (3 TECU lower than mean value), the reading of phase scintillation is 0.7 m, S4-L1 and S4-L2 both are 0.05, Amp-L1 is 3.1 dBHz, Amp-L2 is 1.8 dBHz and ROT is 0.1 TECU/min.

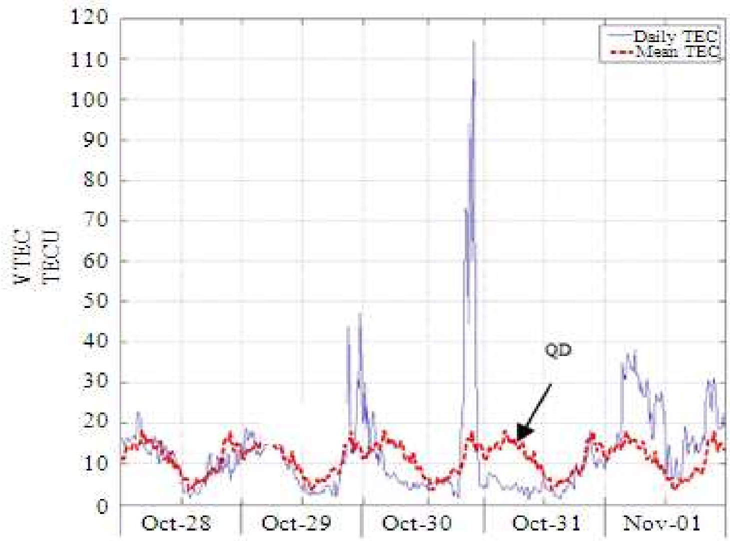

Fig. 2: The daily VTEC variation during the period from 28th October to 1st November 2003

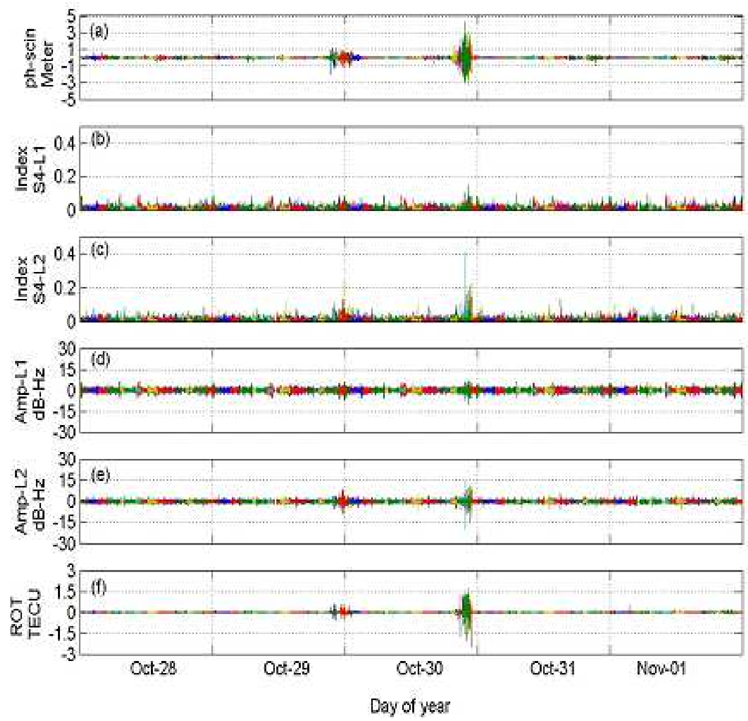

Fig. 3: The daily phase scintillation, S4 index on L1 and L2, amplitude scintillation on SNR-1 and SNR-2, the rate of TEC measurements during the period from 28th October to 1st November 2003

Table 1: The VTEC and scintillation parameters measurements during the SSC and recovery phase of October 2003 superstorm

Time	TEC	Ph-Scin	S4-L1	S4-L2	Amp- L1	Amp-L2	ROT
1st SSC	22	0.5	0.08	0.07	4.0	2.7	0.08
2nd SSC	5.0	0.5	0.06	0.06	3.6	2.3	0.06
3rd SSC	10.0	0.7	0.05	0.05	3.1	1.8	0.10
Rec. ph.	38.2	1.2	0.1	0.13	6.0	6.0	0.53

Following this time, the second TEC enhancement occurred during the period between 1900 UT and 2300 UT (4 h) with a maximum value of 114 TECU at 2200 UT, an increased of about 38% with respect to mean QD. Note that a strong TEC depletion-enhancement was observed during the recovery phase of the storm during the period from midday of 31st October to the end of 1st November. During the recovery phase of storm on 31st and 1st November 2003, VTEC reached 38.2 TECU at 0610 UT on 1st November, maximum phase scintillation of 1.2 m, 4-1 is 0.1, S4-L2 is 0.13, Amp-L1 is 6 dBHz, Amp-L2 is 6 dBHz and the rate of TEC value is 0.53 TECU/min.

DISCUSSION

For this particular storm, the total VTEC enhancement on 30th October 2003 with respect to the mean QD is about 31%, The total durations of enhanced periods were approximately 12 h while the total periods of TEC depletions or trough were more than 30 h. Several troughs were also seen during the storm period. The long TEC depression and positively high response of TEC during the storm at Scott Base station was in agreement with Yizengaw *et al*. (2004) observation at the mid-and high-latitudes of the southern hemisphere and with De Morais *et al*. (2005) who observed a high peak of TEC (over 180 TECU) during the event at Palo Alto, USA (37°N, 122 °W).

Note that, the scintillation event exhibited more pronounced activity during the recovery phase than that to the sudden storm commencement. This trend was also observed by Birsa *et al*. (2002) at Vanimo (2.4°S, 141.4°E) and Shilo *et al*. (1998) at Casey Station (66.28°S, 110.24°E). The TEC and scintillation measurements during the first, second and third SSC and during the recovery phase of storm are summarized in Table 1.

Table 2 summarizes the daily maximum readings of vertical TEC, phase and amplitude scintillation, S4 index and rate of TEC (ROT) during the period from 28th-1st November 2003. The results of vertical TEC, amplitude and phase scintillations were in good agreement with solar and magnetic data obtained from the WDC. Note that, the enhanced periods of TEC and scintillation activity during the storm episodes was coincidence with disturbed Interplanetary Magnetic Field (IMF) and extreme solar wind speed.

Table 2: The maximum VTEC and scintillation measurements during the superstorm of October 2003

Measurement	28 Oct	29 Oct	30 Oct	31 Oct	1 Nov
VTEC (TECU)	22.80	47.20	114.30	18.50	38.20
Ph Scint. (Meter)	0.60	2.10	4.30	1.00	1.20
Am-L1 Scint. (dB-Hz)	6.30	8.00	10.00	6.00	6.00
Am-L2 Scint. (dB-Hz)	4.20	12.00	20.40	6.00	6.00
S4-L1 index	0.10	0.10	0.15	0.09	0.09
S4-L2 index	0.09	0.24	0.41	0.13	0.10
ROT(TECU)	0.13	0.62	2.47	0.21	0.53

CONCLUSION

The period from October 28th-November 1st November was characterized by extreme solar activity that resulted in a series of intense geomagnetic storms. This storm was the greatest storm during the 23rd solar cycle with maximum readings of magnetic indices Dst, Kp and Ap were 9, -401 nT and 162 respectively and the maximum recorded solar indices for this particular event were F10.7 > 250 and SSN > 200. During the storm period, VTEC profile showed both an enhancement and depletion; the total durations of enhanced periods were approximately 12 hours while the total periods of TEC depletions or trough occurs for more than 30 h. The long duration trough was observed between 0500-1900 UT on 30th October 2003 which decreased by about 17% with respect to mean QD. The TEC enhancement occurs during the period between 1900 and 2300 UT, an increase of about 38% with respect to mean QD. The VTEC peak reached a significantly high value of 114 TECU at 2200 UT on 30th October 2003. Pronounced phase and amplitude scintillation and sudden increase in TEC are clearly observed during this storm. The maximum phase scintillation of 4.3 m was observed during the third storm on 30th October with a factor of 8.3 times with respect to the first sudden storm commencement (SSC). Measured amplitude scintillation and S4 index on both 1 and L2 signals were > 15 dB-Hz and > 0.4 respectively. The strong ionospheric scintillation or irregularities observed during the period of TEC enhancement, which is characterized by the narrow plume of greatly enhanced TEC. Our observation (at southern high latitude) agrees well with the observation made by other researchers (Mitchell *et al*., 2005; Forte *et al*., 2004) at the northern high latitude. Hence, supports the conjugacy phenomena of the solar- magnetic storm effect. The timing and intensity of TEC and scintillation measurements during the storm event were in a good agreement with WDC measurements. The periods of enhancement in TEC and scintillation were coincidence with the periods of extreme interplanetary magnetic field IMF and solar wind speed.

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