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Investigation of the Relationship Between the Storm Enhanced Density and Ionospheric Scintillation at Conjugate Points Over the Polar Regions

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Abstract: The conjugacy effects of the ionospheric scintillation obtained from GPS measurements during the geomagnetic storms of October 2003, November 2003 and July 2004 have been investigated at the approximately geomagnetically conjugate points over the polar regions: Scott Base station; Antarctica (SBA) (GC: 77.85°S, 166.76°E; CGM:-79.94°S, 327.23°E) and Resolute Cornwallis Island station (RESO) at the high Arctic region (GC: 74.69°N', 265.12°E'; CGM: 83.17°N', 320.95°E'). The measurements aims at investigation of the similarities and differences of the storm time ionospheric scintillation activities occurring at the conjugate points and study its relationship with the Storm Enhanced Density (SED) over the polar regions. The statistical measurements during these storm events over both hemispheres showed asymmetrical occurrences of the ionospheric scintillation at the conjugate points. During these magnetic storms, pronounced scintillation activity was observed at the nightside hemisphere with the total daily scintillation were higher by a factor of 1.1, 4.2 and 32, respectively and the periods of the ionospheric scintillation are longer by a factor of 1.6, 2.5 and 3.8, respectively. The measurements showed that the periods of intense scintillation at both stations were corresponding to the presence of the SED events which were more pronounced over the nighttime hemisphere. The SED magnitudes over the nightside hamisphere were higher by a factor 1.5-2.1 during the October 2003 storm, factor of 2 during the November 2003 and factor of 5 during July 2004 storm.

Key words: Geomagnetic storm, scintillation, TEC, GPS, SED

INTRODUCTION

The response of the ionosphere provides us some indications about the processes and geophysical changes of the Sun-Heliospheric system during the intense geomagnetic storm period. When the sun erupts it can suddenly and violently release bubbles of gas and magnetic fields called Coronal Mass Ejections (CMEs). The solar events such as solar flares, CME, filament, disappearance and eruptive prominences are able to initiate intense geomagnetic storms (Siqing *et al*., 2001). In the Earth's magnetosphere, the charged particles tend to be trapped on the same field line and therefore conjugate points could be affected by the same population (NASA, 2005; Rodger and Aarons, 1988). Any two points on the Earth's surface are geomagnetically conjugate if they are on opposite ends of the same field line (NASA, 2005). In the polar regions, the locations perceive six months of sunlight and six months night where these conditions are opposite at the conjugate points. The precipitation of the plasma particles into the polar ionosphere causes magnificent aurora that illuminates the northern and southern polar skies as well as causes significant heating of the polar upper atmosphere (SCAR, 2005). Several studies have been conducted to quantify and understand the similarities and differences between the ionospheric response at northern and southern polar upper atmospheres using several techniques including the radio sounding techniques and GPS measurements (Coster *et al*., 2006; Parkinson *et al*., 2005; Tsugawa *et al*., 2004; Hunsucker and Hargreaves, 2003; Ho *et al*., 1998; Balan *et al*., 1994; Titheridge and Buonsanto, 1988; Jakowski *et al*., 1981; Jani and Kotadia, 1969). However, most of these studies focused on the seasonal variations of inter-hemispheric ionospheric Total Electron Content (TEC) and on the inter-hemispheric behaviour during storm periods.

The study of inter-hemispheric conjugacy effects of ionospheric scintillation behaviour is still lacking. Many of the research studies in this area of study have concentrated on the single hemispheric regions (Coster *et al*., 2006; Mitchell *et al*., 2005; Biktash, 2005; Coster *et al*., 2004; Tate and Essex, 2001; Shilo *et al*., 2001; Kumar and Gwal, 2000). Thus, the complete picture of the ionospheric seasonal behaviour between the two hemispheres is not very much clear. Kumar and Gwal (2000) showed that the southward Interplanetary Magnetic Field (IMF) Bz and solar ion dynamic pressure are the primary causes of the intense magnetic storms that can generate strong and long duration scintillation with higher fading rates on VHF signals. Study made by Shilo *et al.* (2001) during two years period from 1997 to 1998 over Casey station in Antarctica showed that the TEC and phase scintillation activities are quite disturbed when the IMF Bz component turned to southward direction (Bz<0). Measurements made by Tate and Essex (2001) showed occurrence of strong scintillation activity in the southern polar region when the TEC rise significantly with respect to background levels. Tate and Essex (2001) suggested that the TEC enhancement is associated with the polar patches which originate near or equatorward of the dayside aurora zone and enter the polar cap as Tongue of Ionization (TIO). The ionospheric patches are mostly occur when IMF Bz is southward or when the 3 h planetary K-index (Kp) >4 (Tate and Essex, 2001). Coster *et al.* (2004) observed a clear scintillation activity during the October 2003 superstorm over Calgary University and other sites in Canada during the time periods that correspond to the presence of Sudden Enhanced Density (SED) event. The SEDs are defined as the plume-like structure of greatly enhanced TEC values of >50 TECU (1 TECU = 1×10^{16} electron m^{-2}) and associated with large gradients and high ion flux values and related to the polar patches (Coster *et al.*, 2004). Mitchell *et al.* (2005) observed a pronounced scintillation activity during the evening of 30th October 2003 superstorm over European high arctic region using the GPS scintillation receiver. Mitchell *et al.* (2005) 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. Statistical study made by Coster *et al.* (2006) presents the statistics observations of the SED at magnetically conjugate stations over northern Europe and American sector and at the associated stations over southern hemisphere during several storms between 2000-2005. Their methodology compares the TEC magnitude, location, size of gradients and time evolution of the SED events in both hemispheres. Biktash (2005) showed a strong relation between the equatorial scintillation activity and the magnetospheric and ionospheric currents and the magnetic indices (IMF Bz, disturbance storm time index (Dst), Kp, aurora electrojet indices AU and AL). The results showed that scintillation almost took place when IMF Bz is negative.

The availability of the low cost GPS receivers at the polar regions provide an excellent opportunity to investigate the interhemispheric similarities and asymmetrical properties of the ionosphere scintillation at both hemispheres which are related to the solar effects. In this study, the similarities and asymmetries or unbalance proportion of the ionized medium causing scintillation activity at both hemispheres as well as the impact of SED on the interhemispheric conjugacy effects of the scintillation activities will be investigated. In the analyses, the GPS scintillation measurements from the polar GPS receivers at Scott Base station, Antarctica (SBA) (GC: 77.85°S, 166.76°E; CGM: -79.94°S, 327.23°E; LT = UT+12) and the Canadian Resolute Cornwallis Island station (RESO), high Arctic region (GC: 74.69°N, 265.12°E (94.88°W); CGM: 83.17°N, 320.95°E; LT = UT-5) during the Halloween storms of October 2003 storm, November 2003 and July 2004 storm will be analyzed. The geographical location for both SBA and RESO stations is shown in Fig. 1.

Geomagnetic storms conditions: The period from 28th October to 1st November of 2003 was characterized by extreme solar activity that resulted in a series of intense geomagnetic storms. This storm was considered as the greatest storm during the 23rd solar cycle and one of the fastest traveling solar storms in the last two decades (Spectrum, 2003). Three distinct Dst minimum were recorded during this storm with the first Dst minimum (-180 nT) occurred around 12:00 UT on 29th October, the second Dst minima occurred at 01:00 UT (-363 nT) on 30th October 2003 and the third Dst minimum occurred at 23:00 UT (-401 nT) on the same day. The Sudden Storm Commencement (SSC) of the first storm episode took place around 06:00 UT on 29th October 2003, the second SSC event occurred around 12:00 UT of the same day, while the third SSC event took place around 17:00 UT on 30th October 2003. During this period, the 3 h Kp index reached its maximum value of 9 for 3 times at 09:00 UT and between 21:00 UT on 29th October and between 21:00 UT until 24:00 UT on 30th October. During this event the planetary index Ap jumped abruptly from a value of 20 on 28th October to a maximum value of 189 on 29th October and decreased dramatically to a value of 21 on 1st November when the storm subsided. The readings of the solar indices, 10.7 cm solar flux (F10.7) and Sun Spot Number (SSN) began high a few days before the storm event with maximum values of 250 for F10.7 and 200 for SSN and maintained its high values during the whole storm event. This indicates that the sun has been in active conditions a few days prior to the storm event.

The November 2003 magnetic storm took place on 20th November with SSC occurred at around 10:00 UT. The maximum magnetic Dst, Kp and Ap indices during this day were -465 nT, 9 and 117, respectively. The recorded solar activity was high during the day of the storm and on the following day and becomes low during the days 22nd, 23rd and 24th November, respectively (IPS, 2003). The readings of the solar indices (F10.7/SSN)

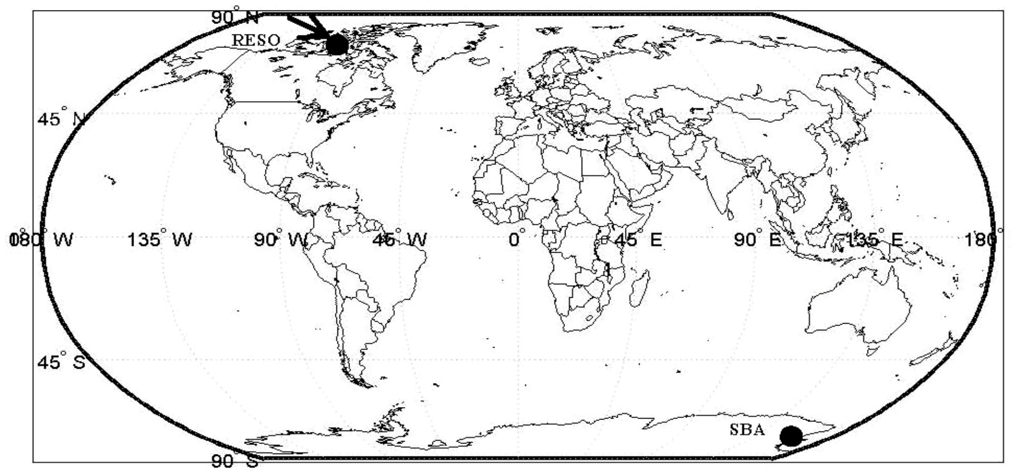

Fig. 1: The geographical location of SBA and RESO GPS stations illustrated on the world map

for the day of the storm and the following days (20th-24th November) were 175/129, 177/131, 176/130, 178/131 and 177/131, respectively. The observed geomagnetic field levels for this period were quiet to severe on 20th November, quiet to major on 21st November, quiet to minor on 22nd November and quiet to active during the days of 23rd and 24th November, respectively. On the day of 20th November 2003, the X-ray solar flare was categorized as a M3 class.

The July 2004 storm event consists of three main episodes with three distinct Dst minima on the days 23rd, 25th and 27th July 2004. However, the maximum storm effect was observed during the third episode of the magnetic storm on the 27th July 2004. The effect of the storm was observed before the midday UT time of 22nd July 2004 particularly around 10:00 UT when a rapid fluctuation in the polar cap index and IMF Bz components were clearly seen (IPS, 2004). Significant M 9.1 X-ray flares were also observed around 0:015 UT which were produced from the AR 652 on the solar disk (IPS, 2004). The summary of the maximum values of solar and magnetic indices (Kp, Ap, Dst, F10.7, SSN, IMF Bz, X-ray flares, plasma velocity, density and temperature) during the October 2003, November 2003 and July 2004 geomagnetic storms are shown in Table 1. The numbers in the table represent the maximum recorded values during the event.

Data processing: The GPS phase scintillation can be determined from the standard deviation of the power spectral density of the de-trended carrier phase signals received from GPS satellites (Shilo *et al*., 2001; Van Dierendonck *et al*., 1993). The phase scintillation is

Table 1: Daily maximum solar and magnetic indices and solar wind parameters for October 2003, November 2003 and July 2004 geomagnetic storms

Index/Parameters	October 2003 storm	November 2003 storm	July 2004 storm
Kp-index	9.00	9.00	9.00
Dst-index	-401.00	-465.00	-197.00
Ap-index	189.00	117.00	162.00
F10.7	279.00	175.00	165.00
SSN	330.00	129.00	130.00
X class X-flare (W m^{-2})	1.00	0.00	0.00
M class X-flare (W m^{-2})	3.00	3.00	4.00
C class X-flare (W m^{-2})	9.00	9.00	12.00
PCN	28.00	15.00	10.00
IMF-Bz (nT)	-56.30	-53.00	-24.00
Plasma velocity (km sec^{-1})*	530.00	730.00	550.00
Plasma density (No. cm^{-3})*	2.50	0.13	0.32
Plasma temperature (K)*	2.3×10^5	1×10^5	0.5×10^5

*: From ulysses spacecraft measurements

measured over 1, 3, 10, 30 and 60 sec intervals, these five values are averaged over 1 min and displayed or the stored (Shilo *et al*., 2001). In dual-frequency GPS receivers, phase scintillation can be calculated using the previous method or from the difference between the carrier phase frequencies L1 and L2 signals for each satellite receiver group as shown by Fu *et al*. (1999) using the Eq. 1 and 2:

$$\Delta\phi_r^s = \phi_{r1,2}^s(t) - \phi_{r1,2}^s(t-1) \quad (1)$$

$$\phi_{r1,2}^s(t) = C(\phi_{r,2}^s(t) - \phi_{r,1}^s(t)) \quad (2)$$

The subscripts r and superscripts s in Eq. 1 and Eq. 2 represent the receiver and satellite, respectively, $\phi_{r,1}^s$ and $\phi_{r,2}^s$ are the GPS carrier phase measurements (in cycles), C is a constant for converting the measurements to ϕ_1 or ϕ_2 ionospheric phase delay (in meter). The $\phi^s_{r\,1,2}$ term in the unit of length is expressed using the following formula:

$$\phi^s_{r\,1,2} = c(\frac{f_1\phi^s_{r,2} - f_2\phi^s_{r,1}}{f_1 f_2}) \text{ (in meter)} \quad (3)$$

Where:
c = The speed of light 299792458 m sec^{-1}
f_1 = 1575.42 MHZ
f_2 = 1227.60 MHZ are the GPS carrier frequencies derived from the fundamental frequency 10.23 MHZ

The following steps are used to calculate the absolute GPS TEC and TEC irregularities:

- Calculate the Geometry-Free Combination (GFC) of dual frequency code and phase measurements of the dual frequency GPS receiver by using Eq. 4 (Hofmann *et al*., 1994; Warnant and Pottiaux, 2000):

$$\begin{aligned} P^s_r &= P^s_{r,1} - P^s_{r,2} \\ \phi^s_r &= \phi^s_{r,1} - \frac{f_1}{f_2}\phi^s_{r,2} \end{aligned} \quad (4)$$

Where, $P^s_{r,1}$ and $P^s_{r,2}$ are the GPS pseudorange observables (in meter).

- Calculate the geometry-free linear combination of code and phase measurements as a function of TEC from Eq. 5 (Warnant and Pottiaux, 2000; Ephishov *et al*., 2000):

$$\begin{aligned} P^s_r &= -0.105TEC^s_r + (Dg_r - Dg^s) \\ \phi^s_r &= -0.552TEC^s_r + N^s_r \end{aligned} \quad (5)$$

Where, Dg^s and Dg_r are the satellite and receiver differential group delay and N^s_r is the ambiguity term in cycle.

- Resolve the ambiguity term by combining the geometry-free code with phase measurements for each satellite path using Eq. 6 (Warnant and Pottiaux, 2000):

$$P^s_r - \lambda_1\phi^s_r = (Dg_r - Dg^s) - \lambda_1 N^s_r \quad (6)$$

Where, λ_1 is the wavelength of the frequency f_1.

- Obtain the equivalent Vertical Total Electron Content (VTEC) for each satellite path using Eq. 7:

$$VTEC^s_r = TEC^s_r \cos\chi \quad (7)$$

Where, χ is the zenith angle of the line of sight at the sub ionospheric point. The zenith angle of the line of sight at the sub ionospheric point is calculated by using Eq. 8:

$$\chi = \arcsin\left(\frac{R}{R + h_m}\cos\theta\right) \quad (8)$$

Where:
θ = The elevation angle
R = The mean radius of the earth (6378.137 km)
h_m = The height of sub-ionospheric point which is assumed at 400 km above the Earth's surface

- The perturbation components of TEC are derived by subtracting the quiet-time TEC values from the storm-time TEC values and expressed by ΔTEC%. The quite day TEC (the TEC when the Kp index ≤2) can be estimated as the average TEC of 3 days before or after the storm period, for each satellite receiver group. The parameter ΔTEC% is used to determine the TEC gradients represented by positive or negative storm phases (TEC enhancement or TEC depletion phases) which is expressed by using Eq. 9 (Forster and Jakowski, 2000).

$$\Delta TEC\% = \frac{TEC_{dist} - TEC_{quiet}}{TEC_{quiet}} \times 100\% \quad (9)$$

Where:
TEC_{dist} = The storm time (disturbed)
TEC and TEC_{quiet} = The quiet day TEC values

RESULTS AND DISCUSSION

The relationship between the SED and scintillation activity at nearly geomagnetically conjugate points over the polar regions is investigated during the October 2003 storm (Section A), November 2003 storm (Section B) and July 2004 storm event (Section C). In the analysis, the durations and magnitudes of SED, the intensity and durations of ionospheric scintillation in addition to the time delay between SED events and scintillation occurrences between the northern and southern polar regions are the main parameters that will be analyzed, compared and quantified. As mentioned earlier the geomagnetically coupled polar regions perceive six months sunlight called summer season and six months darkness called winter season where this response is opposite in both hemispheres. At the southern polar region, the summer season is observed during the period from 23rd September and 21st March every year, while the winter season at this region is outside this period. At the northern polar region, the months of summer and winter seasons are reversed.

The relationship between SED and scintillation during October 2003 storm: Figure 2 shows the measurements of the solar wind IMF-Bz obtained from the Magnetic Fields Investigation (MFI) magnetometer onboard the WIND spacecraft (panel a), ionospheric phase scintillation (panel b and c) and absolute VTEC measurements (panel d and e) at SBA station and at geomagnetically conjugate point RESO station during the period between 15:00 UT on 29th October 2003 and 06:00 UT on 30th October 2003 (2nd episode of the storm). As shown in the Fig. 2, the enhanced periods of scintillation activity during this period were coincident with the southward IMF-Bz component between 18:30 UT on 29th October 2003 until 02:30 UT on 30th October 2003. The Fig. 2 also shows that the sudden increase of electron content TEC at both stations was also coincident with the periods of southward solar wind IMF-Bz. Comparison of the phase scintillation measurements during this storm at both stations showed clear asymmetrical occurrence of scintillation activity at both sites. At the dayside SBA station, the intense scintillation activities lagged behind the IMF activity by about 3 h while it only lagged by about 1.5 h at the nightside RESO station. This indicated that the influence of the storm at RESO conjugate station was faster than the influence at SBA station by about 1.5 h as shown in Fig. 2. The earlier occurrence of ionospheric scintillation at RESO station was probably induced by the particle precipitation mechanism which is more pronounced over the nighttime hemisphere as suggested by Baran *et al.* (2001).

Figure 3 shows the measurements of the IMF Bz component (panel a), ionospheric phase scintillation (panel b and c) and absolute VTEC measurements (panel d and e) during the period between 12:00 UT and 24:00 UT on 30th October 2003 at SBA and RESO stations (the 3rd episode of the storm). As shown in the Fig. 3, the IMF-Bz response began to turn southward at around 17:00 UT and continued in southward direction until 23:00 UT of the same day. During this period, pronounced phase scintillation and TEC activities were observed. It was also observed that the intense scintillation activities at SBA station lagged behind the IMF Bz activity by about 2 h while it only lagged by about 0 h at RESO station.

The results during the 2nd and 3rd episodes of the October 2003 storm showed that the severe ionospheric scintillation activities at the conjugate stations were mainly observed during the time periods which corresponded to the presence of sudden enhanced density periods which has a different response observed

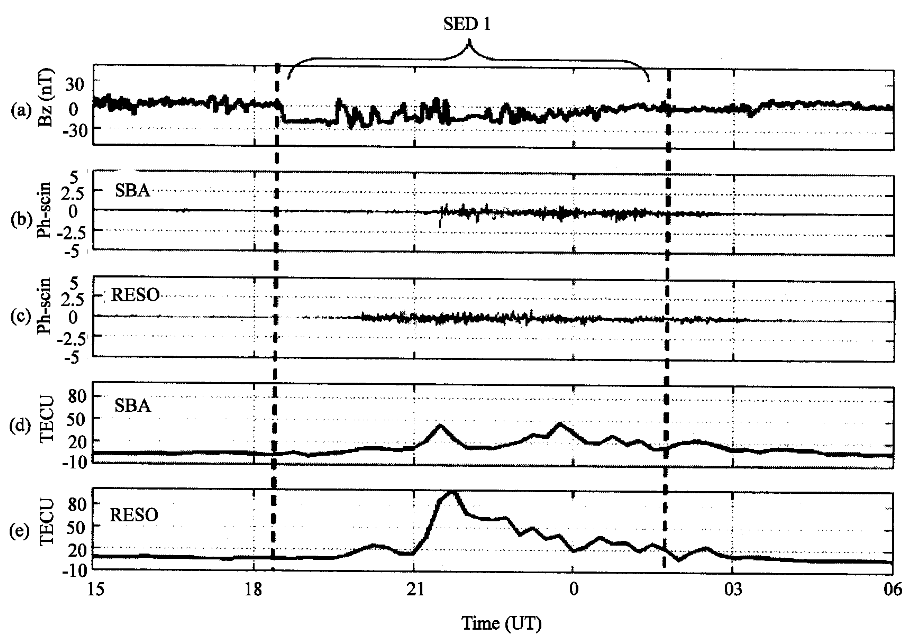

Fig. 2: The IMF-Bz component with the GPS phase scintillation and TEC measurements during the period between 15:00 UT on 29th October and 06:00 UT on 30th October 2003 (2nd episode of the storm)

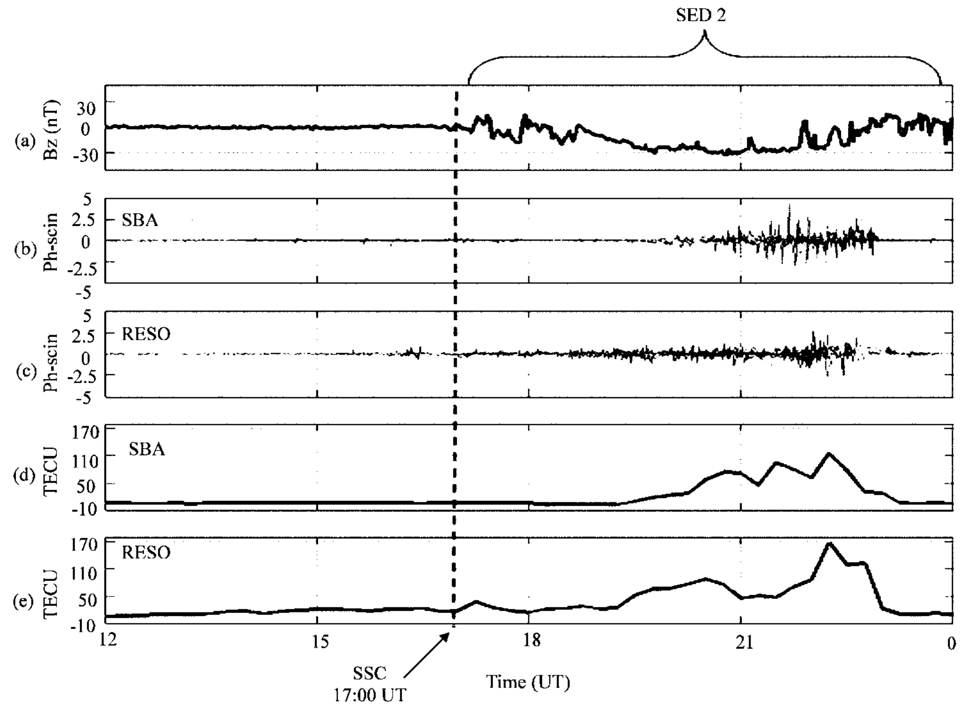

Fig. 3: The IMF-Bz component with the GPS scintillation and TEC measurements during the period between 12:00 UT and 24:00 UT on 30th October (3rd episode of the storm)

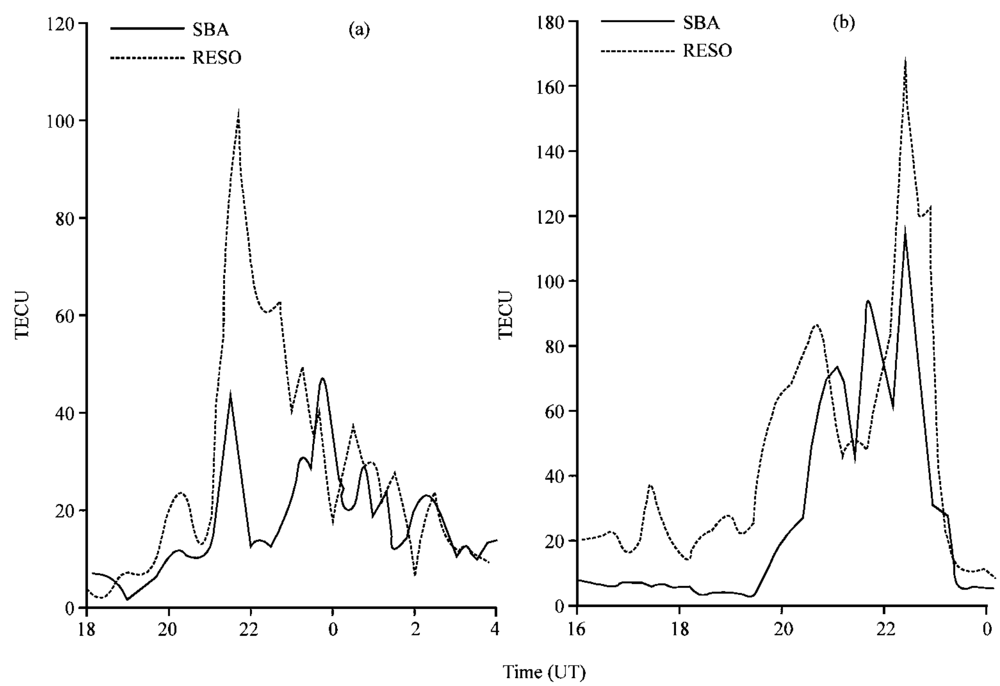

Fig. 4: The sudden increase of TEC at SBA and RESO stations on (a) 29th October 2003 (b) 30th October 2003 showing higher TEC level occurred at the nightside RESO station by a factor of 1.5-2

over the dayside and nightside hemispheres. Two SEDs events were observed during the October 2003 storm as shown in Fig. 4: The 1st SED period at SBA was observed between 20:00 UT on 29th October and 02:00 UT on

30th October with a duration of 6 h and a magnitude of 47 TECU (ΔTEC% is 200%) while at the nightside conjugate station RESO, the SED period was observed between 19:00 UT on 29th October and 02:00 with a duration of 7 h and a magnitude of 100 TECU (ΔTEC% is 400%). As shown in the Fig 4a, the sudden increase of TEC is observed almost simultaneously at SBA and RESO stations with the magnitude of SED is higher at RESO station than at SBA station by a factor of 2. The duration of SED at both stations was 6 h at SBA and 7 h at RESO, with an increase factor of 1.2. The 2nd SED period at both stations is shown in Fig. 4b. The 2nd SED event at the dayside SBA station was observed between 20:00-23:00 UT on 30th October 2003 with duration of 3 h and magnitude of 110 TECU (ΔTEC% is 420%) while at the nightside RESO station it was observed between 17:00-23:00 UT with a duration of 6 h and 170 TECU magnitude (ΔTEC% is 580%). As shown in the Fig. 4b, higher TEC magnitude was observed at RESO station with a factor of 1.5 and the total enhancement period of about 3 h at SBA and 6 h at RESO station (factor of RESO/SBA is 2). The significant activity at the nightside site was probably induced by the particle precipitation mechanism which is dominant over the nighttime hemisphere as suggested by Baran *et al.* (2001).

The relationship between the phase scintillation and sudden enhanced density periods during the October 2003 storm has not been reported before. As discussed earlier, the previous radio scintillation measurements during the October 2003 superstorm have been conducted over northern hemisphere only. Mitchell *et al.* (2005) observed intense scintillation activity over European high Arctic region using the GPS scintillation receiver and concluded that the gradient-drift instability was a likely mechanism of generation the irregularities causing some of the scintillation at L-band frequencies during the storm. During the same event, Coster *et al.* (2006) observed a clear scintillation activity over Calgary University and other sites in Canada and then concluded that the scintillation occurrence corresponded to the presence of SED. Finally, Forte *et al.* (2004) measured the spatial spectral behavior of small-scale plasma irregularities based on its spatial and temporal distributions over 3 sites in Canada during the period using GPS derived scintillation information.

The relationship between SED and scintillation during November 2003 storm: The measurements of solar wind IMF Bz component, phase scintillation measurements and percentage deviations of the absolute TEC (ΔTEC%) during the 20th November 2003 storm are presented in Fig. 5. Rapid variations of IMF-Bz component due to the arrival of Coronal Mass Ejections (CME) associated with M3-solar flare that were detected on 18th November 2003 were clearly observed around 09:00 UT on 20th November which continued until around 12:00 UT on the same day.

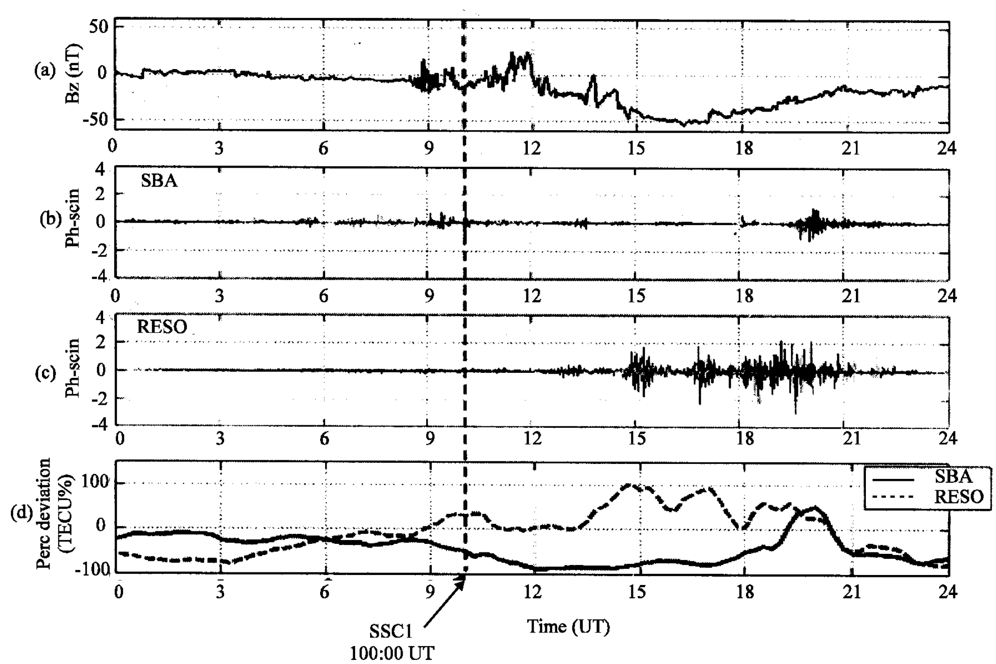

Fig. 5: The IMF Bz, phase scintillation and ΔTEC% measurements at SBA and RESO stations during 20th November 2003 storm

Following this time, the IMF-Bz direction turned to southward which persisted until the end of the day as shown in the panel (a) of Fig. 5. The enhanced periods of phase scintillation activities (panel (b) and (c) of Fig. 5) at both stations were coincidental with the periods of southward IMF Bz component. Comparison of the scintillation activity at both hemispheres during this particular storm showed longer and more intense scintillation occurrence at the nighttime hemisphere represented by RESO station which mainly occurred during the southward direction of IMF-Bz. As mentioned earlier, the significant activity at the nightside site was probably induced by the particle precipitation mechanism which is dominant over the nighttime hemisphere as suggested by Baran *et al.* (2001). The intense phase scintillation at RESO station mainly occurred between 12:00 UT and 23:00 UT with total duration of 11 h, while at the dayside SBA station, the intense phase scintillation activity was observed between 18:00 UT and 22:00 UT with total duration of 4 h. At RESO station, zero time delay between scintillation and IMF-Bz was observed, while at SBA station the scintillation activity lagged behind the IMF Bz by about 6 h as shown in Fig. 5.

The measurements also show that the TEC enhancement indicated by SED event at RESO station (panel d of Fig. 5) was observed during the whole period of southward IMF Bz particularly between 12:00 UT and 23:00 UT on 20th November 2003 (11 h duration) whereas at the dayside SBA station, the SED event was only observed during the period between 18:00 UT and 22:00 UT (4 h duration) on the same day. The periods of intense phase scintillation activity at both dayside and nightside stations were coincidental with the periods of the TEC enhancements as shown in Fig. 5. Results also show that weak scintillation activity was observed during the periods of TEC depletion which was more pronounced at SBA station. The observations during the November 2003 storm show that the scintillations occur only during the time periods which corresponded to the presence of SED event as was suggested by Coster *et al.* (2006). During this particular storm, the analysis showed that, the timing of the scintillation activities and SED events at both stations were in good agreement.

The relationship between SED and scintillation during July 2004 storm: Opposed to the storm conditions during October 2003 and November 2003 storms, the southern polar region during July 2004 storm perceived winter season and therefore night conditions were observed all over the region whereas the northern polar region perceived summer season and therefore all sites observed sunlight conditions. Figure 6 shows the measurements of solar wind southward IMF-Bz component (panel a) ionospheric phase scintillation

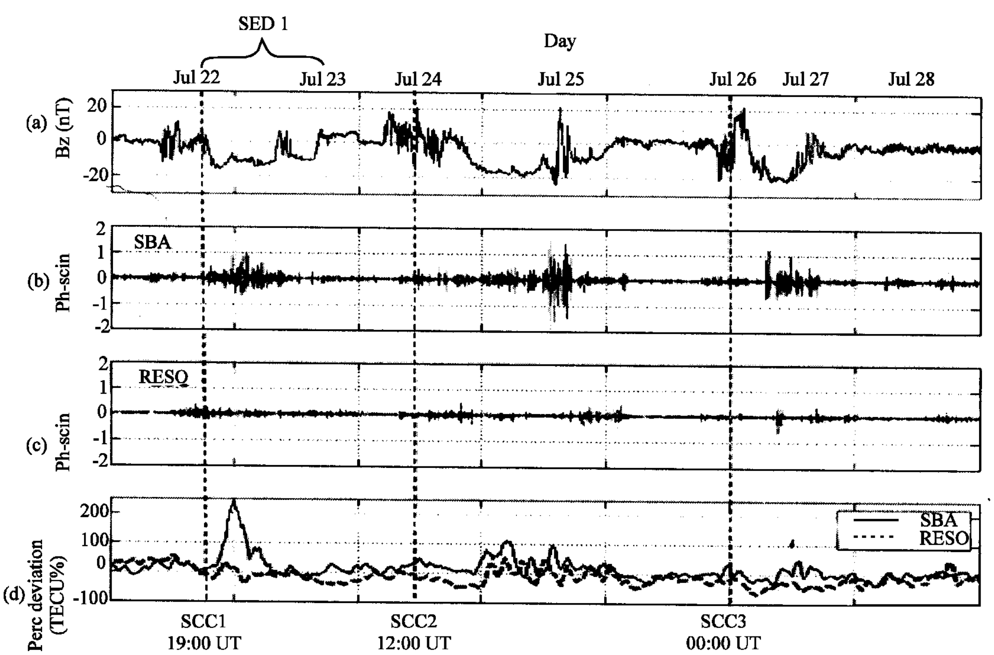

Fig. 6: The IMF-Bz component with the GPS scintillation and ΔTEC% measurements at SBA and RESO during the July 2004 magnetic storm between 22nd and 28th July 2004

(panel b, c) and ΔTEC% measurements (panel d) during the July 2004 storm between 22nd and 28th July 2004 at SBA station and at the conjugate point represented by RESO station. As shown in the figure, the periods of intense TEC and scintillation activity during the July 2004 storm were coincidental with the periods of southward IMF-Bz which mainly occurred during the three storm periods namely between 19:00 UT on 22nd July and 10:00 UT on 23rd July 2004 (the 1st episode of the storm), between 18:00 UT on 24th July and 03:00 UT on 26th July 2004 (the 2nd episode of the storm) and between 06:00 UT and 18:00 UT on 27th July 2004 (the 3rd episode of the storm). The measurements during July 2004 storm show that the periods of strong scintillation activities at both stations are coincidental with the positive storm periods while only weak scintillation activities were observed during the negative storm periods as shown in Fig. 6. It was also found that, the periods of intense scintillation periods are corresponded to the presence of SED events that were observed during 23rd, 25th and 27th July 2004, respectively. As shown in Fig. 6d, the more pronounced SED activity were observed over the nightside hemisphere with a maximum effect observed during the 1st episode of the storm particularly between 19:00 UT on 22nd July and 10:00 UT on 23rd July 2004 with 15 h duration. During this period, strong phase scintillation activities were also observed at SBA station where the timing of both measurements is in good agreement.

Comparison of the total phase scintillation measurements (total scintillation is obtained by adding all daily scintillation values that exceeded 0.3 m threshold) during the October 2003, November 2003 and July 2004 geomagnetic storms at the geomagnetically conjugate stations SBA and RESO showed higher scintillation occurrences over the nightside (winter side) hemisphere with increase factor of 1.1, 4.2 and 32, respectively. It was also found that, the durations of intense scintillation at the nightside hemisphere were longer than the activity at the dayside hemisphere by a factor of 1.6, 2.5 and 3.8, respectively. The results of daily total scintillations intensity and durations are shown in Table 2. As shown in the table, the strongest scintillation and TEC activities at the conjugate stations were observed at the nightside hemisphere. The strongest scintillation activity at the nightside hemisphere occurred almost simultaneously with the southward IMF Bz and Dst responses whereas at the dayside hemisphere stations, the enhanced scintillation periods were found to be lagging behind the timing of southward IMF and Dst responses by about 2-3 h during the October 2003 storm, 6 h during November 2003 storm while no scintillation effect was observed during the July 2004 storm. The analyses during the storm events also showed that the intense scintillation periods corresponded to the presence of the SED. More pronounced SED events were observed at the nighttime hemisphere, with the SED magnitude was higher by about 1.5-2.1 times during October 2003 storm, 2 times during November 2003 and 5 times during July 2004 storm. These SEDs events and scintillation activities during these storm periods can be explained by the effect of the polar patches which originate near the equatorward of the dayside aurora zone and enter the polar cap as a TIO as suggested by Coster *et al*. (2006) and Tate and Essex (2001). The main features of the measured SED during the three investigated storm events are shown in Table 3.

Table 2: Summary of ionospheric scintillation activities during the magnetic storms of October 2003, November 2003 and July 2004

		October 2003 storm		November 2003 storm		July 2004 storm	
Parameters	Hemisphere	Total value (m)	Factor winter/summer	Total value (m)	Factor winter/summer	Total value	Factor winter/summer
Σ Scintillation (m)	Winter season	826.0		390		212 m	
	Summer season	774.0	1.1	92	4.2	6.5 m	32.0
Duration (h)	Winter season	13.5		10		15 h	
	Summer season	8.5	1.6	4	2.5	4 h	3.8

Table 3: The duration time and peak magnitude of the SED during the main phase of October 2003 storm, November 2003 and July 2004 at winter and summer hemispheres

Parameters	Hemisphere	29th Oct 2003	Factor winter/summer	30th Oct 2003	Factor winter/summer	20th Nov 2003	Factor winter/summer	23rd Jul 2004	Factor winter/summer
Duration (h)	Winter season	7.0	6.0	1.2		11	2.75	15	3.75
	Summer season	6.0		3.0	2.0	4		4	
Magnitude (%)	Winter season	400.0		580.0		100		200	
	Summer season	200.0	2.0	420.0	1.4	50	2.00	40	5.00
Scintillation lagging behind IMF-Bz (h)	Winter season	1.5		0.0		0		0	
	Summer season	3.0		2.0		6		-	

Table 4: Total durations of positive and negative storm effects during the October 2003, November 2003 and July 2004 severe storms

		October 2003 storm		November 2003 storm		July 2004 storm	
Magnetic storm phase	Hemisphere	Duration (H)	Factor winter/summer	Duration (H)	Factor winter/summer	Duration (H)	Factor winter/summer
Positive storm phase (h)	Winter season	+63		+11.5		+128	
	Summer season	+44	1.4	+3	3.8	+34	3.8
Negative storm phase (h)	Winter season	-33		-12.5		-40	
	Summer season	-52	1.6	-21	1.7	-134	3.4

Comparison of the storm time positive and negative storm phases during these storm events obtained from ΔTEC% at each station showed longer duration of positive storm effects occurred over the nightside hemisphere with a factor of 1.4-3.8. These are probably due to the mechanism of penetration of the disturbance solar wind energy to ionospheric heights other than by auroral precipitation as was suggested by Danilov and Lastovicka (2001). Longer durations of negative storm effects were observed over the dayside hemisphere with a factor of 1.6-3.4 which could be related with the impulsive precipitation particle energy or Joule heating event at the dayside cusp region which accordingly causes sharp density depletion. According to Idenden (1998), the increase in the recombination rate due to ion neutral friction heating which is caused by the rapid ion flow through the dayside convection throat in the cusp region could produce significant depletion in the F-region. As a result, the positive phase storm during winter season and negative phase storm during summer season were explained by composition changes, downwelling in winter and upwelling in summer as shown by Fuller-Rowell *et al.* (1996) and Buonsanto (1999). The periods of positive and negative storm effects during the October 2003, November 2003 and July 2004 severe storms are shown in Table 4.

CONCLUSIONS

The measurements of the interhemispheric conjugacy effects of the GPS scintillation activities have been conducted at nearly two magnetically conjugate stations SBA, Antarctica and RESO station in high Arctic during the October 2003, November 2003 and July 2004 magnetic storm. This study aims at investigation of the similarities and/or asymmetries or unbalance of the storm time scintillation activities occurring at the conjugate points and examine the relationship between the SED and the bipolar scintillation activity during storm periods. The measurements of daily scintillation activities during these storm events at both hemispheres show asymmetry in the scintillation occurrence at the conjugate points. Pronounced scintillation activity was observed at the nightside hemisphere while only weak scintillation activity was observed at the conjugate dayside hemisphere. The measurements of total phase scintillation at the nightside hemisphere during these storms were stronger by a factor of 1.1, 4.2 and 32, respectively and the scintillation durations were longer by a factor of 1.6, 2.5 and 3.8, respectively. The strong scintillation and TEC activities at the conjugate stations were coincident with the long duration southward IMF-Bz component with a different response was observed at both hemispheres. At the nightside, the scintillation and TEC enhancement occurred almost simultaneously with the timing of southward IMF Bz while at the conjugate dayside it is always lag behind the southward IMF-Bz by about 2-3 h as was seen during October storm and by 6 h during November 2003 storm. The results show that the intense scintillation periods are corresponding to the presence of the SED that was more noticeable over the nightside station and weak at the conjugate dayside station.

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