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Study of ionospheric variability during geomagnetic storms

Rakhee Malik, Shivalika Sarkar, Shweta Mukherjee and A.K. Gwal
Space Science Laboratory, Department of Physics, Barkatullah University, Bhopal - 462 026
Email: sslakg@gmail.com

ABSTRACT
The dual frequency Global Positioning System (GPS) receivers provide an opportunity to determine Total Electron Content (TEC) over the crest of equatorial ionization anomaly region Bhopal by taking advantage of the dispersive nature of the ionospheric medium. The TEC values observed for eight geomagnetic storms of the period 2004-2005 is used in this paper to discuss the behaviour of ionospheric total electron content (TEC) during geomagnetically disturbed periods. Variation of TEC is studied in correlation with the geomagnetic index Dst and southward component of interplanetary magnetic field Bz. The main purpose of this study is to know how TEC varies from its average values with geomagnetic storms. The TEC variability is found to vary between 49%-104% with the maximum negative excursion of Dst index during the geomagnetic storms days. Positive phases are observed for all the storms studied. Maximum TEC variability is observed during the recovery phase of the storms. The study of storm time TEC behaviour is very important due to recent increase in satellite-based navigation applications.

INTRODUCTION

During a geomagnetic storm, the solar wind energy deposited into the magnetospheric polar cap region will eventually be dissipated into the ionosphere and thermosphere. Meanwhile, various physical and energy transport processes within the ionosphere become extreme and more complicated (Mendillo 1971; Fuller-Rowell et al., 1996; Buonsanto & Fuller-Rowell 1997). Interactions of the various near Earth space plasma regions with the interplanetary magnetic field and solar wind has been known for decades. Various aspects of this process continue to attract intensive research even today. In particular, one of the major indications of the magnetosphere-ionosphere coupling is the significant variation of electron density during a storm (Buonsanto 1999; Danilov 2001). A number of instruments have been used to investigate the electron density variation during such events. Several investigators have shown that the observations of total electron content (TEC) by GPS can contribute to understanding of the characteristics of ionospheric variations during geomagnetic storms (Jakowski 1996, Lu, Richmond & Roble 1998). Drastic changes in low latitude and equatorial ionospheric TEC can be produced by intense disturbance electric fields (Fejer & Scherliess 1997). There are several studies on low latitudinal ionosphere responses during magnetic storms events (Sastri, Niranjan & Subba Rao 2002; Pincheira et al., 2002; Abdu 2001; Lobzin & Pavlov 2002a, 2002b; Pavlov, Fukao & Kawamura 2004; Lynn et al., 2004 and Lima et al., 2004). A number of studies by Indian workers have been conducted on low latitudinal ionospheric responses during magnetic storm periods that have significantly advanced our knowledge on this subject (Jain & Singh 1977; Dabas & Jain, 1985; Lakshmi et al., 1997). The study in this paper is related to the TEC changes during eight magnetic storms at the crest of equatorial ionization anomaly (EIA) region. The ionization in this region is known to be high compared to relatively moderate levels of electron content in mid latitude ionosphere. The purpose of this work is to examine the TEC variations in EIA crest region for eight geomagnetic storms of varying intensity during the period 2004-2005 and how this variability can affect users of satellite based navigation systems. The results of the study have revealed the characteristic features of the variation of TEC in this region during magnetic storms.

DATA AND METHOD OF ANALYSIS

TEC derived from GPS signals is a powerful method of studying the ionospheric response to geomagnetic storms, Total Electron Content (TEC) data obtained from dual frequency GPS receiver is used to study the ionospheric variability during minor, moderate and severe magnetic storms. For the present study GPS data has been obtained from GPS receiver GSV 4004A stationed at Bhopal (23.2º N, 77.4º E, Dip lat. 18.4 º N) a station at the equatorial ionization anomaly crest. The TEC data are corrected for receiver and satellite (instrumental) biases. The variability of the ionosphere can be estimated by different ways (Forbes, Palo & Zhang 2000; Rishbeth & Mendillo 2001) but the changes in the ionosphere are more evident in TEC deviation from the monthly average. The disturbance degree was estimated by the deviation from the monthly average:

$$\delta TEC = (TECobs\text{-}TECavg) \times 100/TECavg.\ \%$$

where TECobs is the observed value of the total electron content and TECavg is the average value.

We have selected eight storm events during the year 2004-2005. The summary of all these events is listed in Table 1.

Slant TEC measurement at one minute interval from the GPS receiver are converted into VTEC from elevation angle greater than 35° using the formula given in Rama Rao et al. (2006). The purpose of our work is to examine the behavioral change in Z component of interplanetary magnetic field (IMF), Bz, and TEC data for several sudden commencements that occurred in the low latitude region. According to Gonzalez et al. (1994) "the geomagnetic storm is an interval of time when a sufficiently intense and long lasting interplanetary convection electric field leads, through a substantial energization in the magnetosphere-ionosphere system, to an intensified ring current sufficiently strong to exceed some threshold of the quantifying storm time Dst index". This index is a quantative measure of the ring current forming around the earth during the geomagnetic storm. It is commonly agreed that the magnetic storm can develop when Dst index exceeds the threshold –50 nT (which corresponds to the interplanetary magnetic field Bz component –5 nT) and stays over this threshold at least 2 hours (Gonzalez et al., 1994). Minimum values of Dst, which are indicators of geomagnetic storm, can be used to classify the magnetic storms: weak (-30nTe"Dste"-50nT), moderate (-50nTe" Dste"-100nT), intense (-100nTe"Dste"-200nT) and very intense (Dstd"-200nT).

The storms are classified with the negative intensity of Dst (intensity of ring current) index as can be seen from Table 1. The values of Dst index and Bz have been taken from the Space Physics Interactive Data Resource, Boulder website http://spidr.ngdc.noaa.gov.

Results

Ionospheric variability during the magnetic storms of November 7-10, 2004

One of the most extreme geomagnetic storm of the current solar cycle was observed in the month of November 2004. Figure 1 shows the TEC deviations from November 5 to 15, 2004. TEC deviations are plotted alongwith Bz component and Dst index as function of hours (UT) in Fig.1. The storm of November 7 started with SSC at 18:27 UT (23:57LT). It can be seen from Figure 1 that the maximum Bz value is -44.93 nT at 02:00 UT (07:30 LT) on November 8, and just after four hrs of southward turning of Bz the maximum negative excursion of Dst ~ -373 nT is observed on November 8 at 06:00 UT (11:30 LT) followed by the recovery phase. A good degree of enhancement in the äTEC ~ 104% is observed on November 9 at 15:00 UT (20:30 LT). Another storm set in morning hours

Table 1. Selected magnetic storm events for 2004-2005 for this study.

Year	Month	Starting date	SSC	Minimum Dst (nT)
2004	November	7 November	18:27 UT	-373 nT
2004	November	9 November	9:30 UT	-289 nT
2005	January	17 January	7:48 UT	-121 nT
2005	January	21 January	17:11 UT	-105 nT
2005	May	7 May	19:16 UT	-127 nT
2005	May	15 May	02:38 UT	-263 nT
2005	June	12 June	7:45 UT	-106 nT
2005	August	24 August	6:13 UT	-216 nT

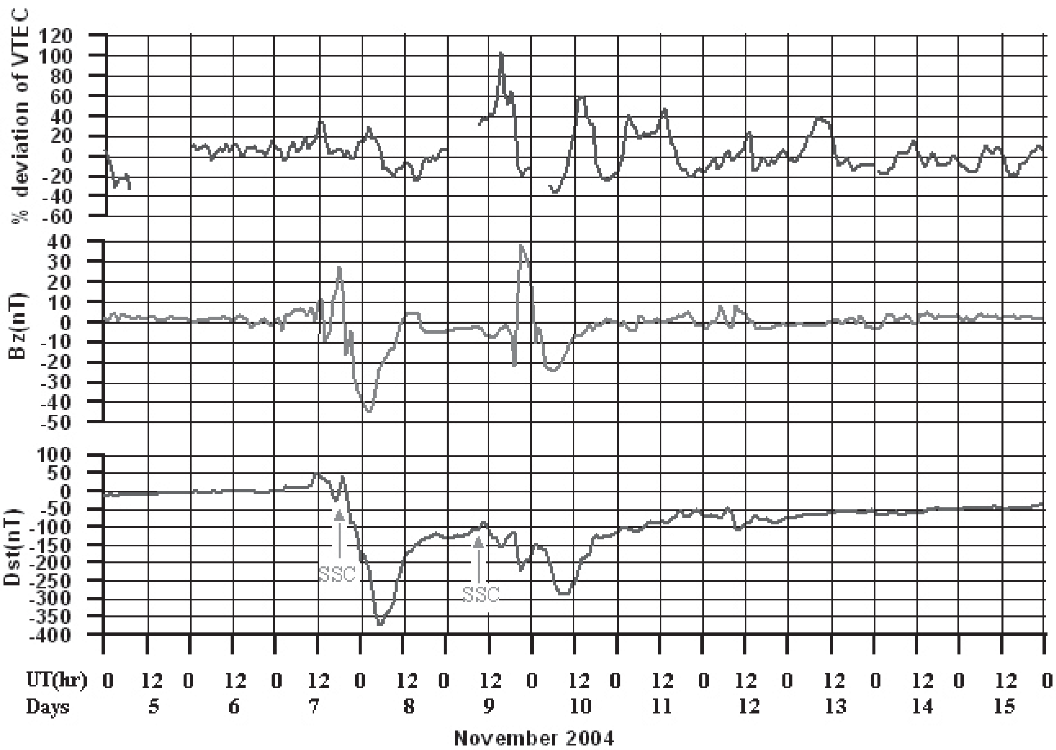

Figure 1. Hourly variation of TEC (in percentage) in top panel, IMF Bz component (middle panel) and Dst geomagnetic index (bottom panel) during the storm period from 5-15 November 2004.

of November 9 with SSC at 09:30 UT (15:00 LT) with Bz turning southward to reach a maximum negative value of –22 nT at 19:00 UT (00:30 LT). The maximum negative excursion of Dst reached –289 nT at 09:00 UT (14:30 LT) on November 10. Five hours after the maximum negative value of Dst the äTEC reached 59.72% at 14:00 UT (19:30 LT) on November 10.

Ionospheric variability during the magnetic storms of January 17-22, 2005

Two intense storms were observed in the month of January 2005. Hourly TEC deviations from January 15 to 24 are plotted alongwith Bz component and Dst index in Fig. 2. The intense storm of January 17 started with SSC at 07:48 UT (15:18 LT). with Bz turning southward and maximum value in the negative direction ~ –13.54 nT observed at 06:00 hrs UT (11:30 LT) on January 18. Two hours later at 08:00 hrs UT (13:30 LT) maximum negative excursion of Dst ~ –121 nT is noted and the storm lasted until January 19 which was followed by the recovery phase on January 20. δTEC values started increasing in the positive direction from 07:00 UT i.e. one hour before the maximum negative excursion of value of Dst and reached its maximum variation of 63.78% at 10:00 UT (15:30 LT) on 18 January. During the recovery phase of the storm TEC showed positive deviations (~ 40% to 47.85%) on January 19 and 20. One day later on another storm started with SSC at 17:11 UT (22:41 LT) on January 21 and the maximum value of Bz component in the negative direction is –7.70 nT at 18:00 UT (23:30 LT) on January 21. The Dst value reached a maximum negative value of –105 nT at 06:00 UT (11:30 LT) on January 22. The percentage variation in the TEC values from its average values reached maximum at 45.69% at 05:00 UT on January 22.

Ionospheric variability during the magnetic storms of May 7-9 and May 14-17, 2005

There were two magnetic storms in the month of May 2005. The first storm is intense and the other one is of very intense category. . Hourly TEC deviations from May 5 to 17 are plotted from alongwith Bz component and Dst index in Fig. 3. The intense storm of May 7 started with SSC at 19:16 UT (00:46 LT) and resulted in southward turning of the Bz component of IMF to reach a maximum negative value of –12 nT at 23:00 UT (04:30 LT) on the same day. The corresponding Dst values also start decreasing and maximum negative excursion of

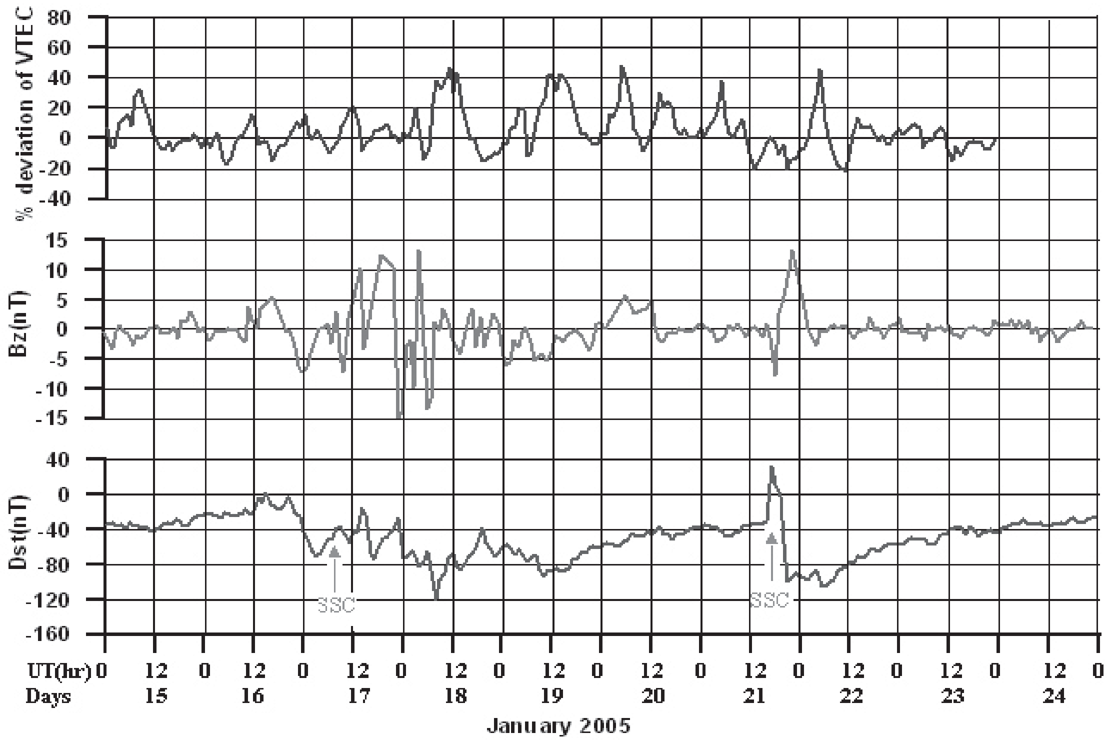

Figure 2. Hourly variation of TEC (in percentage) in top panel, IMF Bz component (middle panel) and Dst geomagnetic index (bottom panel) during the storm period from 15-24 January 2005.

Dst ~ –127 nT is observed at 18:00 UT (23:30 LT) on May 8. This was followed by the recovery phase on May 9. The TEC values show enhanced variability starting from 15:00 UT up to 19:00 UT and the maximum variability ~ 76% is observed at 19:00 UT (23:30 LT) on May 8.

Another important storm event that affected the ionospheric variability started with SSC at 02:38 UT (08:08 LT) on May 15 and resulted in a sharp turning of Bz to reach a maximum negative value ~ –37.01 nT at 6:00 UT (11:30 LT). This resulted in a prompt decrease of Dst and maximum excursion in the negative direction ~ –263 nT is observed at 08:00 UT on May 15. This variation had a noticeable effect on the TEC values. The TEC deviation increased just one hour after to reach a maximum value ~ 57% at 10:00 UT (15:30 LT) on May 15.

Ionospheric variability during the magnetic storms of June 11-14, 2005

Hourly TEC deviations from June 10 to 25 are plotted alongwith Bz component and Dst index in Fig. 4. A storm of moderate intensity occurred on June12 with SSC at 07:45 UT (13:15 LT). On June12, the first polarity change was observed in Bz at 12:00 UT with the value of –4.77 nT and it remained in that direction for a long duration. Bz reached to the maximum negative value ~ –17.02 nT at 17:00 UT on June12. After a few hours the Dst index started decreasing to reach a maximum negative value ~ –106 nT at 00:00 UT (05:30 LT) on June13. Around the same time TEC values show a positive deviation with maximum value ~ 76% observed at 17:00 UT (22:30 LT). Another moderate storm occurred on June 23 but owing to lack of data the ionospheric variability associated with this storm could not be studied.

Ionospheric variability during the magnetic storms of August 23-25, 2005

Figure 5 shows the hourly TEC deviations from August 21 to 31 alongwith Bz component and Dst index.. The intense storm of August started with SSC at 06:13 UT (11:43 LT) on August 24, 2005. This resulted in sharp southward turning of the Bz and a maximum negative value of –39.01 nT was reached at 09:00 UT (14:30 LT) on the same day. Just after

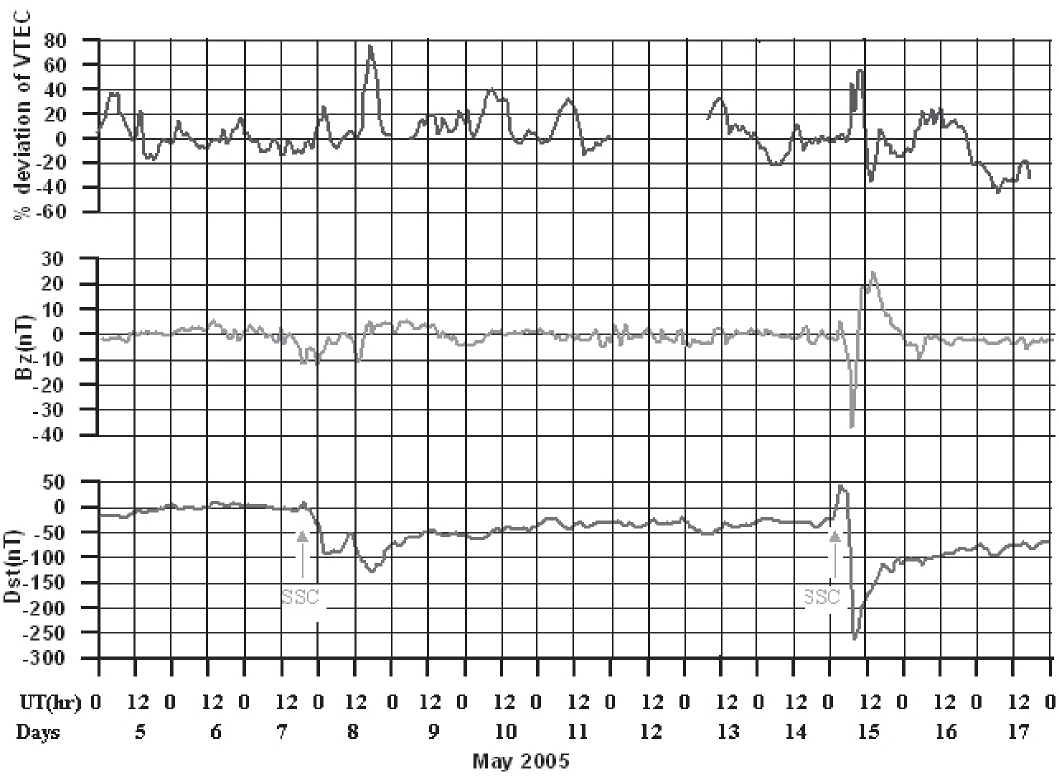

Figure 3. Hourly variation of TEC (in percentage) in top panel, IMF Bz component (middle panel) and Dst geomagnetic index (bottom panel) during the storm period from 5-17 May 2005.

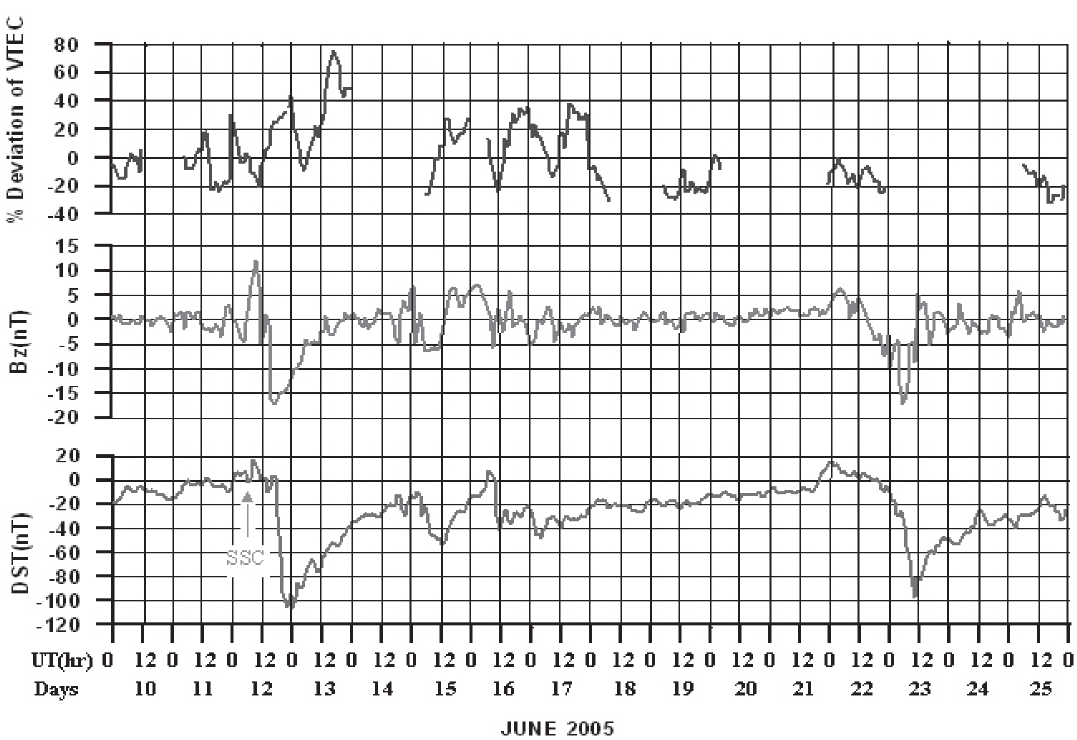

Figure 4. Hourly variation of TEC (in percentage) in top panel, IMF Bz component (middle panel) and Dst geomagnetic index (bottom panel) during the storm period from 10-25 June 2005.

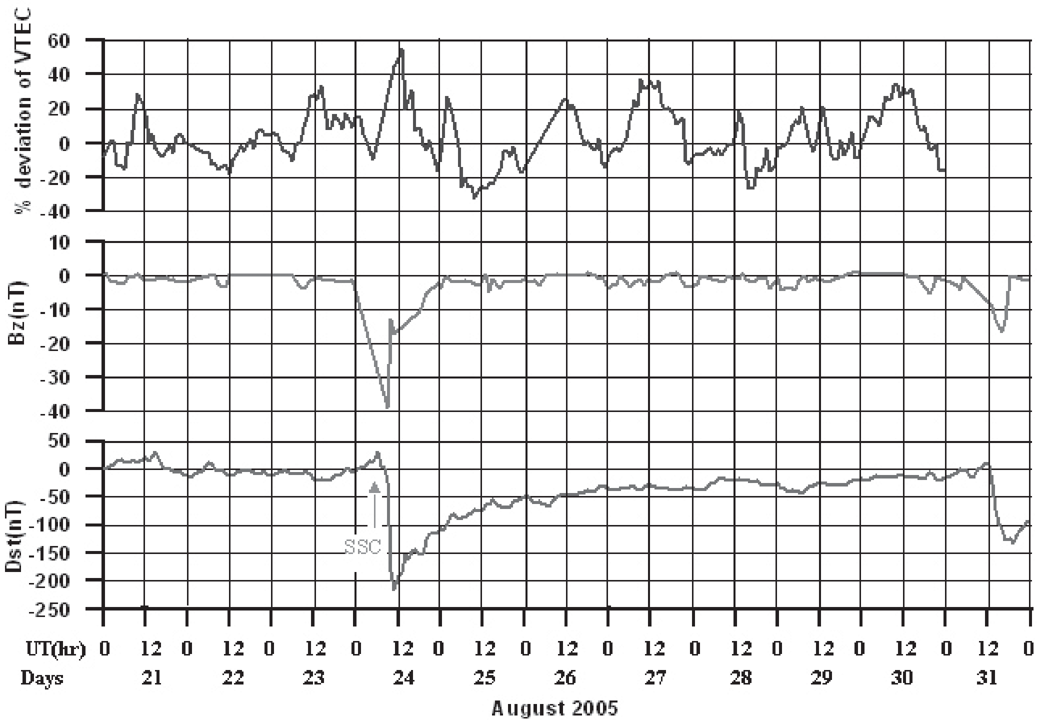

Figure 5. Hourly variation of TEC (in percentage) in top panel, IMF Bz component (middle panel) and Dst geomagnetic index (bottom panel) during the storm period from 21-29 August 2005.

one hour Dst starts decreasing and the maximum negative excursion in Dst ~ –216 nT is observed at 11:00 UT on August 24. Correlated with the negative excursion of Dst we observe positive enhancement in the TEC values from 10:00 UT to 13:00 UT and the maximum deviation ~ 56% was observed at 13:00 UT (18:30 LT). Another intense storm with Dst minimum ~ 131 nT occurred on August 31 but due to lack of data the TEC variability during this period could not be studied.

DISCUSSION AND CONCLUSIONS

The ionospheric variability during storm events of varying strengths for the period 2004-2005 is discussed in this paper. Increase in the total electron content from the average values that is the background VTEC values is being observed for all the eight storms, which represent positive storm effect. This effect is observed consistently for all the storms at the crest of EIA region. The response of the ionosphere to these storms can be summarized as follows.

Effect of prompt penetration of electric field

For the storms of May 2005 and August 2005 we observe a sudden rise in VTEC values shortly after the commencement of the main phase of the storm. These variations in VTEC can be explained by the fact that the high latitude convection electric field penetrated to the equatorial and low latitudes associated with sudden southward and then northward turning of IMF-Bz. The sudden southward turning of the z-component of the interplanetary magnetic field (i.e. IMF-Bz), from a steady northward configuration, produces a dawn to dusk convection electric field at high latitudes (Kikuchi et al., 1996, 2008). This creates the so-called under-shielding condition and the region-1 electric field penetrates instantaneously to the equatorial and low latitudes (Kikuchi et al., 1996). It operates on time scales of an hour or so and is called the prompt penetration electric field (Fejer et al., 2007). However, after a steady southward configuration, the IMF-Bz turns northward again and the over-shielding condition occurs. In this case, the existing region-2 electric field penetrates the equatorial and low latitudes (Kikuchi et al., 2008). Disturbed electric fields from high latitudes can promptly penetrate to equatorial and low latitudes with timescales of about an hour (Richmond & Lu 2000).

Effect of traveling atmospheric/ionospheric disturbances

The intial VTEC variations for the storms of May 2005 and August 2005 may be attributed to the prompt pentration of high latitude electric field to lower latitude however enhanced levels of VTEC afterwards and sustenance to higher levels suggests some other mechanism operating at low latitudes. The impulsive high-energy inputs in the high latitudes during the main phase of geomagnetic storms are known to launch the traveling atmospheric disturbances (TADs). These disturbances travel equator ward with high velocities (Bauske & Prolss 1997) and may result in the uplifting of the Flayer (Prolss & Ocko 2000). It has been emphasized that the TADs affect the ionosphere primarily through their equatorward meridional winds, which drag the ionization along the inclined magnetic field lines, higher in altitude. The TADs manifest as TIDs in the ionosphere and the effect of TIDs in ionospheric TEC has been observed as increased levels of VTEC.

Delayed storm effect

For the severe storms of November 2004 a positive storm effect was observed several hours after the SSC onset and southward turning of IMF Bz. Similarly for the storms of January and June 2005 a delayed positive phase was observed. An additional source of ionization arises from equatorial latitudes: the enhancement of the zonal electric field during perturbed periods increases the upward drift and the subsequent drainage from equatorial region followed by the ambipolar diffusion down the magnetic field lines toward low latitudes. This effect could be also responsible for the delay and the maintenance of positive effects at the crests (Mansilla 1999). Delayed positive ionospheric storms have been attributed to changes in neutral gas composition (Chandra & Stubbe 1971; Rishbeth 1991). The storm-induced circulation transports air rich in atomic oxygen from higher latitudes toward lower latitudes. The enhanced oxygen density will affect the ionization production, thus producing the positive effects.

The study of storm time behavior of TEC at EIA region is very important for Satellite Based Navigation System (SBAS) using Wide Area Differential GPS (WADGPS) technique over Indian Airspace, which is popularly known as GAGAN (GPS And Geo Augumented Navigation). Change of ionospheric range delay, which is directly proportional to change of total electron content during geomagnetic storms, is a potential limitation in precise positioning using radio waves from Global Positioning System (GPS). The positive deviations in TEC during intense and severe storms can lead to range corrections at L1 frequency in crest of EIA region can vary from 4m to 18m for navigational applications. This feature is of interest for Satellite-Based Augmentation System (SBAS) developers. Without knowledge of this feature's existence the GAGAN broadcast error bounds might not be wide enough to protect against such features.

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Ms. Rakhee Malik did her M.Sc. (Physics) from C.C.S. University, Meerut in 2005 with 78.3%. She has also done M.Phil from C.C.S. University, Meerut in 2007. She worked as a project fellow in the department of Physics, Barkatulla University, Bhopal for more than one year under the supervision of Prof. A.K.Gwal. In National Physical Laboratory, new Delhi she worked as Assistant (Level II). At present she is working as a Junior Research Fellow in the Department of Physics, IIT Delhi.

Dr. Shivalika Sarkar obtained M.Sc. in Electronics with First Class in 2000 and did herPh.D. in Electronics from Department of Physics, Barkatulla University, Bhopal in 2007. She was awarded research associateship by CSIR, New Delhi in 2008. Presently she is working as UGC- Dr. D.S. Kothari post doctoral fellow under the supervision of Prof. A.K.Gwal in Department of Physics, Barkatullah University, Bhopal. Her fields of interest include the study of ionospheric irregularities using satellite and ground based observations, study of seismo-electromagnetic effects, space weather effects on GPS receiver performance. She has six papers to her credit, mostly research papers published in national and international journals, seven papers in proceedings and three articles in book. She has presented several papers in national and international conferences.

Ms. Shweta Mukherjee has done her post graduation (M.Sc. Electronics) from Department of Physics and Electronics UTD, Barkatullah University. Presently she is working as Assistant Professor in Sadhu Vaswani College,Bairagarh, Bhopal. She is pursuing her Ph.D.in Electronics under the guidance of Prof. A.K.Gwal, Head, Department of Physics, Barkatullah University, Bhopal. Her area of interests is study of ionospheric morphology and space weather effects on satellite based navigation systems.

Prof. A.K.Gwal was bornin 1949 at Varanasi, India. He did his Ph.D. in Space Plasma Physics from the Institute of Technology, Banaras Hindu University, Varanasi in 1977. After doing his Ph.D. he joined as Scientific Officer atthe Radar Communication Center at Indian Institute of Technology, Kharagpur. In 1981, he was Visiting Scientist under NSERC at the Department of Physics and Astronomy, University of Victoria, Canada. In 1983, he joined as CSIR Pool Scientist under Laser Technology Research Programme, Indian Institute of Technology, New Delhi. In 1987, he joined Barkatullah University as Lecturer in the Department of Physics and established the Space Science Laboratory. In 1997, he participated in the 17th Indian Antarctica Expedition and established his lab at Maitri, Antarctica. At present he is the Head of the Department of Physics pursuing several national projects with ISRO, DST and international projects with France, Russia and South Africa. His interest includes Ionospheric Physics, Seismo-electromagnetics, Antarctic Geophysics and Whistler Phenomena. Prof. Gwal was the first participant from M.P. in Indian Antarctic Expedition (IAE) programme of Department of Ocean Development, Government of India, New Delhi. It was a proud occasion when he lead the First Winter Team of Indian Arctic Expedition, Ministry of Earth Science, Govt. of India, New Delhi. He is Fellow of Indian Geophysical Union and member of various scientific societies of national and international levels. Dr. Gwal has large number of research papers published in journals of repute in India and abroad and presented and presented in different National and International conferences.