Effect of Ionospheric Perturbation on GPS Observation over Low Latitude Region, Bhopal

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Abstract

Increased knowledge on the ionospheric structure is of important interest for precise positioning, since the ionosphere has an impact on global positioning system (GPS) L-band radio waves by its free electrons. Especially during perturbed geomagnetic conditions when the ionosphere differs from its undisturbed state, quasi real time data assimilation would be useful. On the other hand, these perturbations of the GPS signals are taken as scientific information to investigate ionospheric scenarios. In this paper we describe the occurrence of GPS phase fluctuations during January to December 2005 events on the basis of Bhopal GPS observations. This study concerns the analysis of strong phase fluctuations which were associated with geomagnetic storms. The intensive total electron content (TEC) fluctuations observed along GPS satellite passes, demonstrate a strong horizontal gradient of TEC and difficulties with the carrier phase ambiguity in relative GPS positioning. In turn, the phase fluctuations can cause cycle slips.

Keywords: Global positioning system; Phase fluctuations; Geomagnetic storms; TEC; Cycle slips.

1. Introduction

During the last decade GPS has become an interesting tool for ionospheric investigations. One-dimensional profiling [1,2] allows retrieving information on the vertical structure of the ionosphere. For this purpose, signals from GPS satellites orbiting the Earth at about 20,200 km are received during so-called occultation at LEO (low earth orbit) satellites at orbit altitudes lower than 800 km. A great advantage of this occultation technique lies in the global distribution of the retrieved profiles. Regarding the present amount of satellites profile coverage is still sparse although promising. Two-dimensional mapping of GPS data to vertical TEC [3] pose another application. Hereby, the vertical integrated

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measurements of the electron content are mapped to the Earth's surface. This method is based on ground received data and allows a regional continuous monitoring of the ionosphere. This method is expected to be a tool for retrieving vertical and horizontal information. The inversion of the integrated (total electron content) TEC values to three-dimensional electron density patterns is a third possibility of monitoring the ionosphere with GPS data. The ionospheric behavior during quiet conditions is well known and efficiently modeled by the International Reference Ionosphere (IRI) [4]. However, knowledge of the ionospheric response during geomagnetic storms and related process remains incomplete. To predict and model the ionospheric response during storms is therefore a high priority. There have been several attempts to simulate the storm-time response of the thermosphere and ionosphere using theoretical models [5] and Parameterized Ionospheric Models (PIM) [6]. There are, however, a number of physical processes operating during a storm that can result in changes in the ionosphere. During a storm, changes in the neutral wind occurred that directly impact the ionosphere, as well as through which neutral composition changes can occur. Electric field can strip away plasma to high mid-latitude and can penetrate to low latitudes. The ionospheric responses to all of the physical processes are very difficult to capture and understand even with a complex physical model, and are even more difficult to capture in a simple empirical model. The details of the ionospheric response to a particular storm therefore are unique due to the many physical processes involved and due to the complexity of the driving processes from the magnetosphere. Thus, TEC measurement is a powerful new method for studying and monitoring the processes of development of an ionospheric storm. This paper presents an analysis of the occurrence of strong phase fluctuations of GPS signals observed at Bhopal, low latitude station. The ionosphere irregularities are responsible for phase fluctuations of GPS signals. Phase fluctuations are caused by large scale irregularities. During storm intensity phase fluctuations essentially increased. Because of the depressive nature of the ionosphere the dual frequency GPS phase measurements provide useful information about variations of the ionospheric total electron content. In refs. [7-9] it has been observed that during low solar activity period also TEC shows much impact on ionosphere as well as space weather events greater at low latitude than at mid latitude. Rapid fading takes place in the two layers E and F at different epochs of solar cycle also has also been observed [8]. The close relationship between the geomagnetic indices and the ionospheric perturbations in the magnetic field can cause large gradients in the TEC at earth's altitudes have been reported in refs. [10]. So the knowledge of this gradient is important for different GPS users. The GPS can be used for the study of magnetic storms; otherwise it is a comprehension tool for the earth solar environment. Several studies used GPS observations to monitor TEC fluctuation caused irregularities [11-12].

2. Data and Methodology

For analysis of the temporal variations of different carrier phase the GPS signals passes along individual satellite were used. The indices Rate of TEC (ROT) on 1 min interval

and RMS value of TEC rate expressed in TECU/min have been used [13] as a measure of the activity of phase fluctuations. In this paper we describe the occurrence of GPS phase fluctuations during January 2005 to December 2005 events on the basis of Bhopal GPS observations. This study concerns the analysis of strong phase fluctuations which were associated with geomagnetic storms. In our study, TEC data at a rate of change of 1 min, ROT, were used to estimate phase fluctuations. When using ROT we avoid the problem of phase ambiguities. Short-term changes in ionospheric TEC were computed over a one-minute time interval. The rate of TEC (ROT) is defined as in [14]

$$ROT^i(t_k) = \frac{TEC^i(t_k) - TEC^i(t_{k-1})}{(t_k - t_{k-1})} \tag{1}$$

where i denotes the observation to the ith satellite and k is the time epoch. When computing ROT we only use the phase measurements.

To quantify the degree of the disturbances, we calculate the RMS value of ROT values within 5 min period for all satellites observed, based on the following equation,

$$RMS = \sqrt{\sum \frac{(ROT - u)^2}{n}} \tag{2}$$

where n is total number of observations in 5 min, and u is the average of ROT.

Since each storm has its separate effects on the ionosphere. The events are divided into three groups according to the strength of Dst; Strong (Dst > -90nT), Moderate (-30nT < Dst < -90nT) and Small (Dst<-30 nT). The parameter which monitors the different phases of the geomagnetic storm is the equatorial Dst (H) index. The value of equatorial Dst (H) index, AE, the auroral electrojet index and vertical component of interplanetary magnetic field values are taken from the Advance Composition Explorer (ACE) satellite Data Service of World Data Centre. In the present work we have considered 25 storms as shown in Table 1 out of which 5 are weak storms, 13 moderate and 7 strong storms during the period of January 2005- December 2005.

Table1. List of Storms during the period of January 2005 - December 2005.

Sl.	Date	Dst minimum	Time	Category
1	7 January 2005	-59 nT	0922	Moderate
2	9 January 2005	-39 nT	1041	Moderate
3	17 January 2005	-74 nT	0748	Moderate
4	21 January 2005	-99 nT	1711	Moderate
5	4 April 2005	-55 nT	1307	Moderate
6	6 May 2005	-3 nT	1307	Weak
7	7 May 2005	-29 nT	1916	Weak

Contd. Table 1

8	15 May 2005	-263 nT	0238	Strong
9	20 May 2005	-103 nT	0401	Strong
10	28 May 2005	-43 nT	0436	Moderate
11	29 May 2005	-46 nT	0952	Moderate
12	12 June 2005	-105 nT	0745	Strong
13	14 June 2005	-35 nT	1835	Moderate
14	16 June 2005	-41 nT	0847	Moderate
15	10 July 2005	-94 nT	0337	Strong
16	13 July 2005	-54 nT	0512	Moderate
17	17 July 2005	-46 nT	0134	Moderate
18	27 July 2005	-14 nT	1939	Weak
19	24 August 2005	-216 nT	1613	Strong
20	30 August 2005	-19 nT	1908	Weak
21	2 September 2005	-50 nT	1419	Moderate
22	9 September 2005	-38 nT	1401	Moderate
23	11 September 2005	-147 nT	0114	Strong
24	15 September 2005	-86 nT	0835, 0904	Moderate
25	27 October 2005	-23 nT	1156	Weak

3. Result and Discussion

The observations of total electron content (TEC) by GPS can contribute to understanding of the characteristics of ionospheric perturbations. The storm time relationship between the perturbation component of TEC and geomagnetic fields has been experimentally examined by several investigators [12, 15, 16].
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3.1. *Weak storms*

During the period of January 2005 to December 2005 there are 05 weak storms occur. Here we have considered the weak storms that occur on 27th July 2005 and 27th October 2005. Weak storms means that they have their minimum Dst <-30 nT. Figs. 1 present an example of weak storm which occurred over low-latitude region in India, during the magnetic storm of 27 July 2005. As shown in the top three panel of Fig.1 AE, Dst and the variation of interplanetary magnetic field (IMF Bz), are depicted, respectively, during 26–28 July 2005. On 27 July, the ground magnetic field measurement show that a sudden commencement occurs at 1939 UT and around 0600 UT (next day i.e. 28 July) the Dst reaches its value of -50 nT. AE also show its maximum values of 1095 nT and 1004 nT on the same day i.e. on 28 July. But on 27 July, the IMF Bz starts fluctuating over the entire

day and showed a strong negative component of 12.18 nT at 2000 UT. Now the top panel of Figs. 2 the RMS of TEC rate (RMS of ROT) and the second panel shows the equivalent vertical TEC fluctuations for the storm we have considered. Large and rapid fluctuations in TEC were observed during the storm time. It shows that during geomagnetically disturbed days, RMS of TEC rate appears quite irregular and reaches as high as 0.49 on 27 July with VTEC of 36.25 TECU.
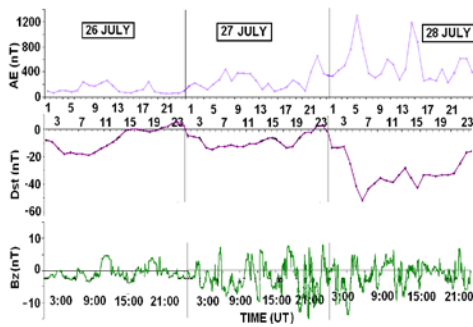

Fig. 1. Storm event of 27 July 2005 with AE(nT), Dst (nT) and Bz (nT).

Fig. 2. Magnetic disturbance period of 27 July 2005.

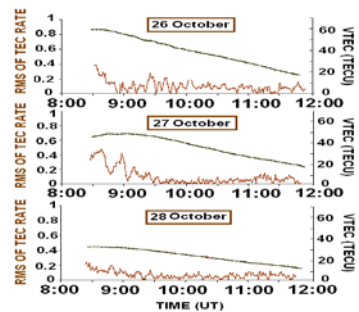Fig. 3. Storm event of 27 Oct. 2005 with AE(nT), Dst (nT) and Bz (nT).

Fig. 4. Magnetic disturbance period of 27 Oct. 2005.

Similarly we can see from Fig. 3 that during the next event of 27 October 2005, AE shows its value of 468 nT but gives the maximum value of 540 nT on the next day i.e. on 28 October. On the storm day of 27 October, the sudden storm commencement occurred at 1156 UT and Dst reached its maximum value of -51 nT at around 1700UT. During the same time the IMF Bz turned southward and showed the negative component of 4.27 nT at 1700 UT. In the same manner during geomagnetically disturbed days of 27 October, RMS of TEC rate appears quite irregular and reaches as high as 0.5 on 27 October with

51.12 TECU as shown in Fig. 4. Such a rapid change in TEC may be related to ionospheric perturbations. During the storm the intensity of the fluctuations increases dramatically relative to quiet conditions. The occurrence of TEC fluctuations depends on the geographic and geomagnetic latitude of the site. In the Bhopal region the difference between geomagnetic and geographic coordinates of the site may be bigger than 10 degrees. At lower latitudes, fluctuations of GPS signals are attributed to small and middle scale irregularities. The intensity of phase fluctuations depends on geomagnetic activity also. The ionospheric gradients increased essentially during the storm. The irregular gradients sometimes exceeded the regular ones. During the storm, this can be the cause of major errors while determining phase ambiguities of GPS observations in the Bhopal region.

3.2. *Moderate storms*

Here we combine the TEC variations of two moderate storm events in constructing a picture of the prompt effects associated with magnetospheric disturbances at low latitude region. Fig. 5 shows the period of moderate storm of 17th July, the maximum value of AE goes to 1064 nT at 2400UT on the storm day when sudden storm commencement (SSC) was at 0134UT. The main phase of the storm started about 0700UT and reached the value of -46nT on that storm day. At about 1100UT, the recovery phase started but at 2200UT again the phase of the storm goes to the southward direction and reached to its second maximum of -76nT at 0700UT on 18 July. During the storm day, the IMF Bz also got its maximum value of -11.28nT at 2300UT. Although the southward turning of the interplanetary magnetic field (IMF) Bz ensures the transportation of solar wind energy into the Earth's magnetosphere, which is the primary cause for the formation of geomagnetic storms [17].
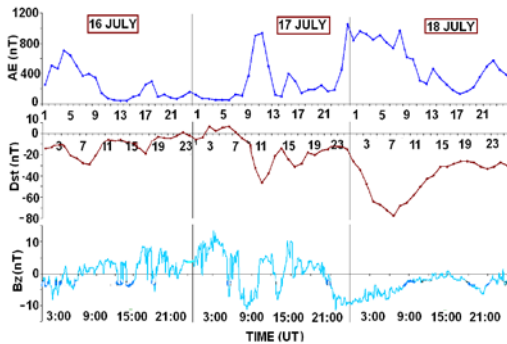

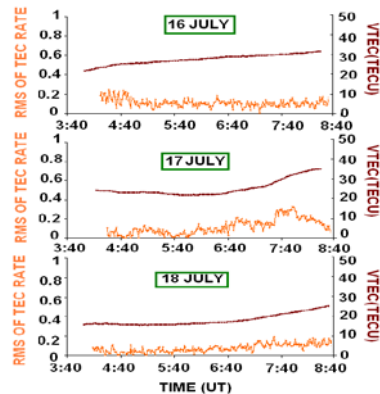Fig. 5. Storm event of 17 July 2005 with AE(nT), Dst (nT) and Bz (nT)'

Fig. 6. Magnetic disturbance period of 17 July 2005.

Again Fig. 6 depicts the value of RMS value of TEC rate and equivalent vertical TEC for the same period of time. During the period of moderate storm on 17th July the TEC shows irregular behavior and RMS of TEC rate reaches upto 0.32 whereas the variation of equivalent vertical TEC 36.37 TECU was observed. The effect of the magnetic storm seemed to create enhanced effects at lower latitude as evidence by the TEC behavior.
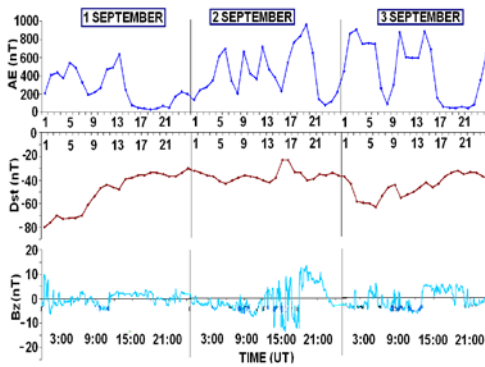

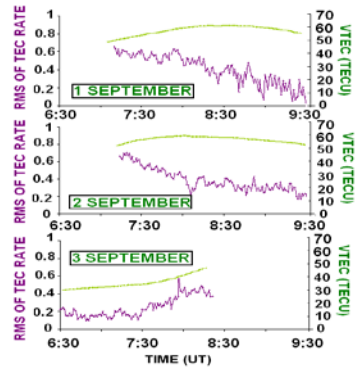Fig. 7. Storm event of 2 Sep. 2005 with AE(nT), Dst (nT) and Bz (nT).

Fig.8 Magnetic disturbance period of 2 Sep. 2005

Similarly during the next moderate storm day of 2nd September in Fig. 7, AE shows the maximum value of 947nT but later also AE shows many peaks during the next of storm day i.e. on 3rd September. Sudden storm commencement was observed at 1419UT and Dst reached its maximum value of -63nT on the next day i.e. on 3rd September. Here also during this storm day, it is evident that as time advances, IMF Bz turned southward at around 0100 UT. Except for several northward excursions, it remained negative and reached its maximum of -13.81nT.

During the period of moderate storm, the TEC shows irregular behavior and RMS of TEC rate reaches upto 0.7 on 2nd September 2005 whereas the variation of equivalent vertical TEC 57.15 TECU was observed in Fig 8.

Since the RMS of TEC rate gives an idea about the intensity and occurrence of ionospheric irregularities. It is evident from the figures that during the storm day the RMS value of ROT (TEC rate) reached its maximum value indicating the presence of strong irregularities. The study shows that the strong fluctuations in TEC were caused by the presence of large-scale ionospheric structures of enhanced electron density. At the equatorial region, due to the occurrence of intense small-scale irregularities of the ionospheric F2-layer, fast variations in TEC developed and caused the degradation of positioning accuracy and quality of GPS performance. It has been found that growth of the level of geomagnetic activity is accompanied by growth of the total intensity of TEC

variations [18]. These variations are observed due to fluctuations in TEC in the ionosphere.

3.3. *Strong storms*

In this category we have taken those storms having Dst>-90nT. During the study total of 7 strong storms occur. Out of them two storms shown here are 20th May 2005 and 10th July 2005. As shown in Fig. 9, AE show the value of 885nT at 0700UT but it reached to its maximum value of 1050 on the next day of the storm (i.e. 21st May 2005). During the storm day of 20th May, sudden storm commencement was at 0401UT and at about 0530UT the main phase of the storm started and reached its maximum excursion of -103nT at 0900UT. On the same day, IMF Bz turned southward at 0200UT to reach its maximum negative component of -11.8nT and then turned northward at 0900 UT and remained at the same direction over the several hours about 12 hours then again regain its southward direction and continue upto the 24th hour of next day i.e. (21st May 2005).

As seen from the Fig. 10 the effect of the magnetic storm seemed to create enhanced effects at lower latitudes as evidence by the TEC behavior. During the period of strong storm the TEC shows irregular behavior and RMS of ROT reaches upto 0.6 with equivalent vertical TEC of 70 TECU on 20th May.
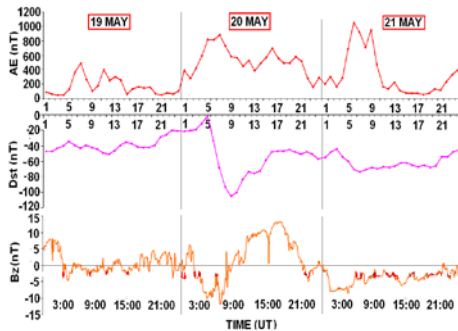

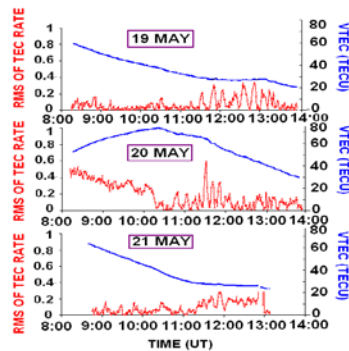Fig. 9. Storm event of 20 May 2005 with AE(nT), Dst (nT) and Bz (nT).

Fig. 10. Magnetic disturbance period of 20 May 2005.

During the next event of 10th July, all the three indices show their maximum excursion on the storm day itself i.e. (10th July). Fig. 11 shows that AE had its value of 1592nT. On the storm day sudden storm commencement was at 0337UT and main phase of the storm started at about 1200UT and reached to its maximum value of -94nT at 2100UT. During this storm day, IMF Bz started fluctuating and turned to northward direction at 0300UT then again turned to southward for few hours before the turning of northward direction. Then finally turned to southward with maximum negative value of -21.8nT throughout the day and last upto the next day (i.e. 11th July 2005). The sudden simultaneous turn in IMF

Bz possibly suggests that there is a prompt penetration of eastward electric fields into low latitudes that augmented the normal F-region dynamo induced PRE, thereby lifting the F-layer to higher altitudes and creating conditions favorable for the development of irregularities.

During the period of strong storm on 10th July, the TEC shows irregular behavior and RMS of ROT reaches upto 0.56 with equivalent vertical TEC of 53.66 TECU as shown in Fig. 12. It is observed from the figure that the fluctuation is high for strong storm, so it is clear that depending on the intensity of storms the fluctuation in ROT increases or decreases. Also whenever there is change in TEC this give rise to fluctuations in ROT, so it can be interpreted that there is perturbations in the ionosphere during geomagnetically disturbed days.
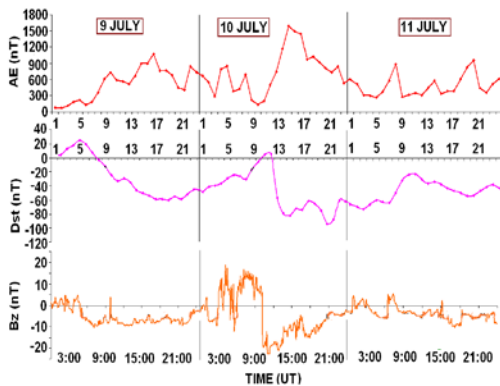

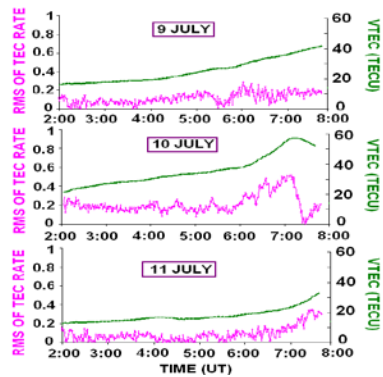Fig. 11. Storm event of 10 July 2005 with AE(nT), Dst (nT) and Bz (nT).

Fig. 12. Magnetic disturbance period of 10 July 2005.

The GPS data provide adequate information on phase fluctuations associated with middle and large-scale ionospheric irregularities. It is well established that the variation of GPS derived total electron content (TEC) due to geomagnetic storm effect, local low latitude electrodynamics response to penetration of high latitude convection electric field and effect of modified fountain effect on GPS–TEC in low latitude zone [19]. In ref. [20-21] it has been mentioned the outstanding features produced during the storms are significant positive storm effects delayed positive effects during the night-time hours in the trough of the equatorial anomaly ("dusk" effect). To investigate the effect of perturbations on the ionosphere several scientists have focused their work showing the relation between TEC variation and ROT variation [22-23] concerning ionospheric storms.

4. Conclusion

It has been shown that TEC is a quiet useful parameter to design perturbations in the Magnetosphere/ionosphere/thermosphere systems. This study was undertaken using GPS

data during the period of geomagnetic disturbances. When a perturbation appears in the ionosphere the calculated TEC will fluctuate in addition to the quick variation in the ROT. On the day of the storm, the rapid variation in ROT became more intense and occurs continuously. The ionospheric disturbances during magnetic storms are generally explained in terms of the thermospheric changes in both neutral air winds and composition, which result in changes of the rates of production and loss of ionization. In particular, geomagnetic activity of a given magnitude, as measured by standard geomagnetic indices, is seen to elicit different responses from the ionosphere in the same region, depending on the local time, season, and solar activity. To quantify the strength of ionospheric perturbations, we propose to derive temporal and spatial gradients from the generated TEC maps. In addition to solar and geomagnetic activity indices TEC map derived ionospheric perturbation indices would be helpful especially for system operators to estimate the perturbation degree of the ionosphere.

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