Study of GPS-TEC related to Wenchuan earthquake (M=7.9) of 12 May 2008 and their fractal analysis

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Abstract. Daily variation of vertical TEC data recorded at Bichpuri Agra station (Geographic Lat. 27.2°N, Geographic Long. 78°E, Geomagnetic Lat. 17.10°N) employing a GPS receiver has been studied for a period of three months from 1 April to 30 June 2008 in relation to Wenchuan earthquake (M=7.9) of 12 May 2008. A significant enhancement has been observed in TEC 22 days before this earthquake. This result is interpreted in terms of E×B drift mechanism, where E is electric field of seismic origin. Further, fractal analysis of TEC data has also been carried out using Burlaga- Klein method and it is found that fractal dimension gradually increases long before the occurrence of this earthquake. These results are not influenced by magnetic storms and are attributed strongly to earthquake.

Keywords: TEC, Earthquake, Fractal Analysis

1. Introduction

Ionospheric anomalies prior to the occurrence of Alaskan earthquakes of 28 March 1964 were first reported by Moore (1964) and Devis and Baker (1965). Since then several workers have reported anomalies in various ionospheric parameters such as critical frequencies of the ionospheric F₂ region (f0f2) and E-region (f0fe₃), and total electron content (TEC). Such anomalies have also been observed before the occurrence of many earthquakes using ground and satellite based techniques (Fatkullin et al., 1989; Singh and Singh, 2004; Singh et al., 2004; Li and Parrot, 2006; Sharma et al., 2008). The ionosphere is disturbed by other sources like solar flare, magnetic storm etc (Davies, 1980; Liu et al., 2006) and while investigating precursory effect of seismic activities on the ionosphere, one has to examine the effect of these sources also. A detailed study in this direction can be found in Hayakawa (1994), Hayakawa and Molchanov (2002), Molchanov and Hayakawa (2008), Singh (2008) and references therein.

During the last decade GPS (Global Positioning System) based TEC anomalies have been widely used for investigating ionospheric precursors of earthquakes (Jung et al., 2006; Mannucci et al., 1999). GPS based TEC provides an overall description of the ionisation and is measured in TEC units where one TEC unit is equal to 1 X10¹⁶ el/m². From various studies it has been found that earthquakes of magnitude M ≥ 5.0 show significant ionospheric signatures prior to and after their occurrence. Many workers have reported apparent reduction and enhancement in GPS-TEC a few days before the earthquake (Liu et al., 2001, 2004; Devi et al., 2001, 2004).

Some step-like changes take place in earth crust as a result of lithospheric processes in the preparatory zone (Ida and Hayakawa, 2006). Such a nonlinear dynamics occurring in earth crust toward the rupture can be investigated with the use of fractal
dimension (Yonaiguchi et al., 2007a, b). Fractal dimension of geophysical time series data give important information about the earthquake preparation processes (Gotoh et al., 2003). Hayakawa et al (1999) first time used this technique on ULF data and found significant changes in the spectral slope, a few days to weeks before the occurrence of the earthquake. Later on this technique has been applied by other workers also to examine the precursory effect of the earthquakes on the time series data in other frequency ranges including DC and ULF/VLF emissions (Smirnova et al., 2004; Gotoh et al., 2004; Varatsos, 2005).

In this paper we study TEC data obtained at Agra (Geographic Lat. 27.20°N, Geographic Long. 78.00°E, Geomagnetic Lat.17.10°N) for a period of three months from 1 April to 30 June 2008 in relation to Wenchuan earthquake (M=7.9) of May 2008 (Zhao et al, 2008; Liu et al, 2009) and results obtained are discussed. Further, in order to confirm our results fractal analysis of TEC data has also been carried out using Burlaga - Klein method. It is found that fractal dimension increases before the occurrence of earthquake. These results are found in good agreement with those of earlier workers.

2. Experimental set up

The experimental set up employed for TEC measurements are shown in Fig.1. Equipments used for this purpose have been imported from USA which include a L1/L2 GPS antenna (Novatel’s Model GPS 702), a GPS receiver (Novatel’s Euro Pak 3-M), relevant softwares and connecting cables. The GPS receiver is able to locate upto 11 GPS signals at two frequencies of 1575.42 MHz and 1227.6 MHz. It measures phase and amplitude at 50 Hz rate and code/carerrier divergence at 1-Hz rate for each satellite being tracked and computes TEC from combined frequencies pseudo range and carrier phase measurements. To collect ionospheric scintillation and TEC data for all visible satellites is the main objective of the GPS receiver. The output data contain four pairs of TEC, amplitude scintillation index S4, and the phase scintillation index computed over 1-minute. In this paper only TEC data have been utilised for fractal analysis.

Fig.1: Experimental set up employed for TEC measurements at Agra.
3. **Method of observation and analysis of TEC data**

Employing a dual frequency GPS receiver TEC measurements have been started at our Agra station (Geographic Lat.27.2\(^\circ\)N, Long. 78\(^\circ\)E, Geomagnetic Lat. 17.10\(^\circ\)N) since 24 June, 2006 on a continuous basis. The data for the period of three months from 1 April to 30 June have been analysed specially to examine the effect of Wenchuan earthquake (M=7.9) which occurred on 12 May 2008. The obtained values of TEC are slant TEC which are converted into vertical TEC (VTEC) using following mapping function at different Ionospheric Pierce Point (IPP) locations (Mannucci et al., 1993; Langley et al., 2002).

\[
S(E) = \frac{1}{\cos(z)} = \left\{1 - \left(\frac{R_E \times \cos(E)}{R_E + h_s}\right)^2\right\}^{-0.5}
\]

Here, \(R_E\) and \(h_s\) stand for mean radius of the earth and the ionosphere (effective) height above the earth’s surface in km while \(z\) and \(E\) stand for the zenith angle and the elevation angle in degrees. In order to determine IPP locations the effective ionospheric height equal to 350 km is taken into consideration which is found to be valid for higher elevation angles in a low latitude sector (Rama Rao et al., 2006). The IPP obtained at Agra employing GPS receiver cover the ionospheric region about +12\(^\circ\) geographic latitudes and +2\(^\circ\) geographic longitudes from the geographic coordinates of the observing station located at Bichpuri, Agra. TEC values obtained at higher elevation angles (>50\(^\circ\)) are taken into consideration to remove the effects due to multipath, troposscatter and water vapor on TEC at low elevation angles. Data are recorded at a sampling rate of 60 seconds. An example of diurnal variation of TEC data recorded on 01 May 2008 is shown in Fig.2. Other details of the figure will be presented later.

![Fig.2: An example of diurnal variation of TEC recorded on 01 May 2008.](image-url)

4. **Sources of earthquake and magnetic storm data**

In Fig. 3 we show the map of India and China in which location of Wenchuan earthquake (M=7.9, Geographic Lat. 31\(^\circ\)N, Geographic Long. 103.32\(^\circ\)E, depth 7.9 km) which occurred on 12 May 2008 is shown by a large solid circle in China and the
observing station for TEC data is shown by a star at Agra in India. A small solid circle in the same figure indicates the location of another earthquake (M=6.6, Geographic Lat. 10.01°N, Geographic Long. 91.71°E, depth 17 km) occurred on 27 June 2008 in Indian ocean at a distance of 2284 km from Agra (Wenchuan earthquake occurred at a distance of 2498 km from Agra). Except the above two earthquakes, no other earthquake (M>6 with depth < 50 km) occurred in the study area during the period of study. Liu et al. (2009) have shown in their study that the earthquake preparation area was about 1650 km and 2850 km from the epicenter in the latitudinal and longitudinal directions, respectively. Therefore, this distant earthquake of large magnitude in China region is found suitable to be studied at Agra station. Details of both of these earthquakes are taken from the USGS website (http://neic.usgs.gov). In order to separate the effect of magnetic storms on TEC from that of the effect of earthquake, we examine the changes in TEC in the light of magnetic

![Fig.3: Map of India and China. The big solid circle indicates the location of Wenchuan earthquake (M = 7.9) while a small solid circle gives the location of earthquake which occurred in Indian Ocean. Star in the Indian region indicates the location of the observing station at Bichpuri Agra.](image)

storms. For this, we consider the Dst index data which are obtained from the World Data Centre (WDC), Kyoto, Japan through the website (http://swdcdb.kugi.kyoto-u.ac.jp).

5. Results and discussion

We have already mentioned that the TEC measurements using a GPS receiver have been in progress at Agra station since 24 June 2006. Here, we analyse the data for a period of three months from 1 April to 30 June 2008 in the light of Wenchuan earthquake (M=7.9) of 12 May 2008. From the diurnal variation shown in Fig. 2 it is clear that vertical TEC continuously increases from 0600 hrs to 1200 hrs LT (LT = UT + 5.5 h) and then decreases. Almost similar variation is obtained in the vertical TEC on each day in normal condition (when there is no magnetic storm or seismic activity). Possible cause for this maximum value of vertical TEC in the midday hours is that additional ionisation
takes place in the ionosphere due to solar radiations during this period. In morning and evening hours Sun radiations are not too intense, hence ionisation (VTEC) values are less during these periods.

In order to examine the effect of Wenchuan earthquake (M=7.9) daily variation of TEC data for the three months from 1 April to 30 June has been shown by the solid lines in the top panel of Fig. 4. Further, for studying the effect of magnetic storm on TEC, Dst data are considered and plotted in the bottom panel of this figure.

![Graph](image)

Fig.4: Daily variation of TEC data for a period of three months from 1 April to 30 June 2008 (top panel). Solid lines with square points indicate the daily variation of Dst index data (bottom panel).

From a glance at the lower panel of the figure, it is clear that the whole period under consideration is magnetically quiet since Dst is less than -30nT throughout the period of observation. TEC variation shown in the top panel indicates a marked enhancement on 20 April 2008. Since there are no other sources which may cause this enhancement, the only possible source for this anomaly is Wenchuan earthquake (M=7.9) which occurred on 12 May 2008. As shown in the top panel of figure there is another earthquake (M=6.6) occurred on 27 June 2008 in the Indian Ocean (Geographic Lat. 10.01⁰ N, Geographic Long. 91.71⁰ E). However, a very minor enhancement is seen in the TEC data 13 days before the occurrence of this earthquake. A minor enhancement in TEC compared to that of 20 April is due to the reason that the latter is influenced by Wenchuan earthquake. Another possibility is that the earthquake of 27 June occurred in the Indian Ocean so that electric field is attenuated due to highly conducting sea. In order
to support the precursor effect of Wenchuan earthquake in the TEC data that occurred as anomaly on 20 April, 2008 one is required to examine the multistation data such as those of IGS stations, nearby ionosonde or GIM. Unfortunately, relevant data corresponding to days of anomaly are not available, hence the results of such study can not be presented here.

Our finding that TEC shows anomalous variation 22 days before the occurrence of earthquake is consistent with the results of earlier workers also. For example Liu et al. (2001) have shown that TEC values decreased 1, 3 and 4 days before the Chi-Chi earthquake of Taiwan (M=7.7) occurred on 20 September, 1999. Liu et al. (2004) observed anomalous variation in TEC before all the 16 earthquakes (M ≥ 6.0) which occurred in Taiwan area from 1999 to 2002. Zakhrenkova et al. (2007) observed enhancements in GPS TEC data 05 days before the Hokkaido earthquake (M=8.3) occurred on 25 September, 2003. Zakhrenkova et al. (2008) observed enhancements in TEC 4-5 days before the Peru earthquake (M=7.5) of 26 September 2005.

Now the question arises that how anomalous state (change in TEC) is produced in ionosphere before and during the seismic activity and how it is observed at such a long distance (2500 km) at the observing station, Agra. In order to answer this question one may mention here that the E×B drift mechanism is one of the significant contributors to seismo-ionospheric effects, where the electric field is triggered by earthquake preparatory process and generates E×B drift (Depueva and Ruhzin, 1993; Devi et al., 2002). Depletions or enhancements in density profile may be the result of earthquake associated E×B drift when electron density may flow into or out of the observing station depending upon the location of the epicenter of the earthquake (Larkina et al., 1983; Parrot and Mogilevsky, 1989). Pulinets (2004) has proposed an elaborate mechanism in which the radon emission ionises the near earth atmosphere over the seismic zone. He suggested formation of quasi-neutral ion-clusters as a first stage of seismo-ionospheric coupling and then the generation of electric field in next stage. It is found that the concentration of green house gases is enhanced over the earthquake preparation zone (Voitov and Dobrovalsky, 1994) which plays two fold roles; first it creates instabilities which are able to stimulate-aoustic gravity wave generation through generating air motion, and second the air motion destroys the ion clusters as a result of which the near ground layer of atmosphere becomes rich in ion (the estimated concentration is 10^2-10^6 cm^{-3}) within a short time. The charge separation process leads to generation of anomalously strong vertical electric field (~1 kV/m) in comparison with the fair weather electric field (~100 Vm^{-1}) which triggers the ring current resulting E×B drift.

6. Fractal Analysis of TEC data

In the preceding section it is shown that the TEC data show a significant enhancement 22 days before the Wenchuan Earthquake (M=7.9). The fractal behavior of this time series data is examined by using Burlaga- Klein approach (Burlaga and Klein, 1986). This method has also been used by other workers who found convincing results (Gotoh et al., 2004). In order to provide a stable estimation of fractal characteristics i.e. fractal dimension (D_0) and fractal exponent (β) from a time series geophysical data, Burlaga- Klein defined the length of the curve representing a geophysical time series B(t_k) (k = 1, 2, 3, ......n) between time interval 0≤ t≤T_0 (where T_0 = nt) as follows,
where \( \overline{B}(t_k) \) represents the mean value of \( B(t) \) between \( t = t_k \) and \( t = t_k + \tau \). This length of the curve is a function of \( \tau \). For statistically self-affine (fractal) curves length is given by the relation \( L_{BK} \propto \tau^{D_0} \). Using this relation fractal dimension can be calculated as the log-log plot of the length \( L_{BK}(\tau) \) versus the time interval. Then fractal exponent is computed using Berry equation (Berry, 1979)

\[
\beta = 5 - 2D_0
\]

Using equation (2) we calculate the length of the curve of the different time intervals and then find a log-log plot of length and time by using 6 data for one day. This shows a straight line the slope of which gives fractal dimension \( (D_0) \). An example of this log-log plot on a particular day is shown in Fig.5.

![Log-log plot](image)

**Fig.5:** An example of estimating fractal dimension from the slope of the straight line computed on 1 May, 2008.

This approach is applied on all the other days and the fractal dimension for whole period of the data is determined. It may be mentioned here that since TEC anomaly appears mostly during the peak period of the data we have chosen two hour data between 1200-1400 LT for the calculation of fractal dimension.

In order to make a statistical study of the fractal dimension of the TEC we have adopted the mean and standard deviation around the mean \( (m \pm \sigma) \) approach from the whole analysed data which are presented by the solid lines in the top panel of Fig. 6. Such an approach has been adopted by Ida and Hayakawa (2006). Daily variation of fractal dimension of TEC data for a period of three months from 1 April to 30 June 2008 has been shown by the solid curve with square points in the upper panel of Fig.6. Unfortunately, such a study can not be taken from 24 June, 2006 (starting date of measurement of TEC) due to the reason that the data are influenced by other earthquakes in the region which may not help in examining the effect of Wenchuan earthquake.
convincingly. We have already mentioned that the whole period of three months is free from magnetic storms and hence TEC variation is not affected under the influence of magnetic storm. The anomalous peak in fractal dimension on 1 May 2008 above m+σ line and its increasing tendency before this day show the critical behavior of the earth as a result of Wenchuan earthquake. Fractal exponent (β) is computed by using Berry equation (β = 5 - 2D₀) for each day and its daily variation is shown in the lower panel of Fig.6. As stated above, m±σ are the thresholds for normal variations of D₀ and β. Hence, any outward departure from these thresholds will indicate the critical behavior of the data. Since both are related linearly by Eq.3 (one increases while the other decreases simultaneously), it is worthwhile to show their behavior in the figure. These parameters are not influenced by magnetic storms also because the period of analysis was magnetically quiet.

Fig.6: Daily variation of fractal dimension between 1 April and 30 June 2008 by solid curve with square points (a), the same for fractal exponent (b).

Here it may be shown that fractal exponent shows a complimentary behavior with that of fractal dimension as expected. From Fig.6 it may also be seen that the fractal dimension and fractal exponent show a large enhancement and depletion around 27 June 2008. This may correspond to increase in the TEC data 13 days before this earthquake (see Fig.4)

On comparing the results presented in Fig. 4 with that of the Fig. 6 it is found that the TEC anomaly occurs on 20 April whereas fractal dimension shows large peaks between 01 and 05 May 2008. Here the question arises how the fractal behavior shows anomalies after the TEC anomaly. In order to answer this, it may be mentioned here that
if we examine the fractal behavior closely we find fractal dimension shows enhanced occurrences above $m + \sigma$ line on five occasions between 2 and 17 April 2008 much before the TEC anomaly. This explains satisfactorily fractal behavior of rupture area before the TEC anomaly.

Our finding that fractal dimension of TEC data increases and fractal exponent decreases before the occurrence of the earthquake is consistent with the results of the earlier workers also. For example, scaling characteristics (fractal dimension and fractal exponent) of ULF geomagnetic data were computed by Smirnova et al. (2001) in relation to Guam earthquake ($M = 8.2$) of 13 August 1993 in Japan and they found that fractal exponent fluctuated periodically during the course of time and gradually decreases when approaching to the date of earthquake. They also observed a gradual increase in fractal dimension before the main shock. Gotoh et al. (2003) reported an enhancement in fractal dimension and depletion in fractal exponent of the ULF data observed at Izu Peninsula, Japan before the swarm of strong nearby earthquake. Yonaiguchi et al. (2007b) performed multifractal analysis of the VHF electromagnetic data (at 49.5 MHz) observed at three stations in the light of strong earthquake ($M = 7.2$) occurred in the off sea of Sendai (Japan). They found a significant enhancement in the multifractalal complexity before the main shock only at one station (Kunimi). Such changes observed at this station might be related with geophysical structures around the station because there are no fault regions around the station.

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References

Davies, K., Recent progress in satellite radio beacon studies with particular emphasis on the ATS-6 radio beacon experiment, Space Science Reviews, 25, 357-430, 1980.


Li, F. and M. Parrot, Total electron content variations observed by DORIS station during 2004 Sumatra Andman earthquake, J. Geodesy, 80 (8-11), 487-495, 2006.


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