4.1. Introduction

The low latitude ionosphere is highly variable because of existence of equatorial ionization anomaly (EIA) and irregularities like spread-F and sporadic E. In addition, it is also influenced by geophysical phenomena like solar flares and magnetic storms and various anthropogenic sources like nuclear explosions, volcanic activities, dust storms, and seismic activities (Pulinets and Davidenko, 2014). These factors bring out substantial variation in structure and dynamics of the low latitude ionosphere. In view of the occasional existence of the ionization anomalies produced by these factors, it is sometimes difficult to identify the anomalies produced by seismic events. Hence, a morphological study of the low latitude ionosphere is essential so that anomalies produced by earthquakes may be clearly identified and separated from those produced by other sources.

Globally, a number of researchers have studied the morphological features of the ionosphere using GPS based TEC measurements and found very interesting and valuable results (Warnant et al., 2000; Wu et al., 2008, 2012; Natali and Meza, 2011; Akala et al., 2013; Huy et al., 2014). In India, due to existence of the EIA, researchers have studied the low latitude ionosphere extensively using GPS based TEC measurements and also compared their results with ionospheric IRI models (Gupta and Singh, 2000; Bhuyan and Borah, 2007; Bagiya et al., 2009; Chauhan and Singh, 2010; Mukherjee et al., 2010; Kumar et al., 2012; Prasad et al., 2012; Sharma et al., 2012; Chakraborty et al., 2014; Karia et al., 2015; Rathi et al., 2015). Recently, the studies of GPS-TEC measurements have achieved a great success to predict the behaviour of the ionosphere and also proved to be very useful to detect the effects of solar events (Lastovicka, 2002; Dashora et al., 2009; Trivedi et al., 2011, 2013; Xu et al., 2012; Adebiyi et al., 2014). The results of some morphological studies have also been reported excellently by Indian workers. For example Rama Rao et al. (2006a) have investigated the temporal and spatial variations of TEC data taken from the Indian GPS network during the period of low solar activity of 2004-2005. The diurnal variation in TEC in the equatorial ionization anomaly (EIA) region shows its maximum value between 13:00 and 16:00 LT and the day minimum between 05:00 and 06:00 LT at all the observing stations from the equator to the EIA crest region. The seasonal variations of TEC have shown maximum during the
equinox months and minimum during the summer. Prasad et al. (2012) have also studied the variations of TEC at four Indian GPS stations during the year 2004. The higher and lower TEC values are found during equinoctial and summer months, respectively. The significant day-to-day variability have also been observed. The variations are found more at the anomaly crest locations and less at the equatorial stations which are supported well by IRI-2007 model over the four Indian GPS stations. The variations with solar activity indices (SSN, F10.7 and EUV) have shown good correlations during equinoctial months but unsatisfactory correlation during summer months.

In this chapter, the results of analysis of TEC data for two years from 01 January-31 December, 2007 (period-I) and 01 January-31 December, 2011 (period-II) recorded at the low latitude GPS station Agra, India during low and high solar activity periods are presented. The study of diurnal and seasonal variations of TEC data indicate the significant variations from low to high solar activity periods. The results also validate with recent ionospheric model IRI-2012 and find a very good agreement in trends (strong correlation) but IRI model is overestimated during each of the three seasons (winter, summer and equinox) for both the periods. The effects of magnetic storms have also been examined on TEC data and found significant change. The data of $\Sigma$Kp, solar flux (F10.7 cm) indices and IRI-2012 model are taken from the NASA website of http://omniweb.gsfc.nasa.gov/form/dx1.html and http://omniweb.gsfc.nasa.gov/vitmo/iri2012_vitmo.html respectively. Finally, it is suggested that these results must be taken into consideration while examining the earthquake induced TEC anomalies.

4.2. Experimental setup and method of analysis

The details of experimental setup of TEC measurements are same as mentioned in chapter 2. In brief, the experimental setup includes an $L_1/L_2$ GPS antenna (Novatel’s Model GPS 702), a GPS receiver (Novatel’s Euro Pak 3-M), connecting cables imported from GPS Silicon Valley, USA and relevant software (novatel.com). The analysis procedure is to convert slant-TEC (STEC) into vertical-TEC (VTEC) by multiplying with a suitable mapping function given by;

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

where $R_E$ is the mean radius of the earth in km, $h_s$ the ionosphere (effective) height above the earth’s surface, $z$, the zenith angle and $E$, the elevation angle in degrees. The effective
ionospheric height of 350 km is used for determination of IPP locations (Rama Rao et al., 2006b).

4.3. Results

4.3.1. Diurnal variations

The four contour diagrams shown in Fig. 4.1 depict the average monthly variations of TEC data for each period from 01 January-31 December, 2007 and 01 January-31 December, 2011 at our Agra station and their comparison with IRI-2012 model. Here, one TEC unit (1TECU) is $\approx 10^{16}$ electrons per meter$^2$. The diurnal pattern of VTEC increases during sunrise to an afternoon maximum and then decreases to attain a minimum just before sunset.

Fig. 4.1. Upper panel (left) shows the contour plot of average monthly GPS-TEC variations during period-I (2007) over a low latitude station, Agra, India and the upper panel (right) presented the IRI-2012 model TEC data variations over the same station and for the same period. The lower panel presented the same as above but for the period-II (2011).

The usual features of low latitude ionosphere as appeared in diurnal variation of TEC data like VTEC values show a minimum during morning hours and they gradually increase with the time of the day attaining a maximum in the afternoon and again a steady decrease after sunset. These features are similar to those obtained by earlier workers (Mukherjee et al., 2010;
Kumar et al., 2012; Sharma et al., 2012). The peak value of the VTEC lies between 14:00 and 16:00 hrs. These plots show the monthly variations of VTEC, mostly during the mid-day to morning hours which are helpful in forecasting and navigation (Bagiya et al., 2009; Rama Rao et al., 2006a). The monthly variations of VTEC at Agra may be credited due to the changes in the intensity of the arriving solar radiations (Natali and Meza, 2011; Akala et al., 2013). The highest GPS-TEC values are found in equinoctial month of April for period-I and are also supported by corresponding IRI-TEC variation. The highest GPS-TEC values for period-II are also found in equinoctial months of November and October. Here, it can be noticed that IRI model supports to our results but it also shows the same variations in the first equinox period (March and April) which is not shown in our data. Both the GPS-TEC and IRI-TEC show the similar trends and IRI-2012 model shows higher values of TEC as compared to our data for equinoctial months for period-I. So it may be concluded here that TEC values are enhanced in equinox than in winter and summer season.

4.3.2. Seasonal Variations

The seasonal variations of TEC and their comparison with IRI model are shown in Figs. 4.2 and 4.3. Here, the three seasons are considered i.e. summer, equinox, and winter. The months of April, May, June, and July are taken in summer solstice. The average of TEC data is taken for the months of March, April, and September, October corresponding to two equinoxes. Another combination of months of November, December, January, and February,
corresponds to winter solstice. In these figures, the upper panels show the variation of TEC data in each of three seasons (winter, summer, and equinox) and their comparison with seasonal IRI-TEC shown by solid and dotted lines respectively and the lower panels present the correlation plot between GPS-TEC and IRI-TEC for two periods. The peak GPS-TEC values are found in the range of 15-25 TECU for all the seasons. Here, the IRI model is overestimated during peak hours and underestimated during morning and afternoon hours in case of winter and equinox season. It is underestimated during morning and afternoon hours in summer season. To validate our results, the correlation coefficients are calculated between GPS-TEC and ionospheric IRI-2012 model TEC data for each of the three seasons and found strong correlation between them $\approx 0.98$ except for winter where it is 0.85 during period-I.

Fig. 4.3. shows the same as Fig. 4.2 but for the period-II (2011).

In Fig. 4.3, one can see that the TEC values are higher in period-II as compared to that in period-I. It may be because of the direct effect of solar activity. The peak TEC values lie in the interval of 25-30 TECU. From this figure, it can be seen that IRI model is overestimated in this period also but shows strong correlation $\approx 0.98$ for all the seasons. One more interesting point that may be noticed here is that there is a change in TEC values from period-I to period-II. So these changes may be interpreted in the light of solar activity which will be discussed later. The GPS-TEC and IRI-TEC show higher values during equinoxes and lower values in winter relative to those in summer for both the periods. These results are similar to the findings of earlier workers (Kumar et al., 2012; Sharma et al., 2012). The mechanisms which are related to these variations are discussed later. This study is consistent with the studies of other low latitude stations which are nearer to our station. For example, Sharma et al. (2012) have
investigated the TEC variations over Delhi (beyond the EIA region and closer to Agra) in addition to Trivandrum equatorial station during low and high solar activity and found similar variations.

4.3.3. Solar activity dependence and geomagnetic storm effect

![Graph of Sun Spot Numbers and F10.7 flux for periods I and II.](image)

Fig. 4.4. Upper panel shows the variations of Sun Spot Numbers (SSNs) for the period-I (2007) and period-II (2011) by solid and dotted lines respectively. The lower panel shows the variations of F10.7 flux for the same periods.

To see the effect of solar activity on TEC data during the period under consideration, sun spot numbers (SSNs) and solar flux F10.7 indices are plotted for period-I and period-II by solid and dotted lines respectively. The results are shown in Fig. 4.4. The upper panel of this figure shows the variation of SSN which is almost quiet for period-I but shows large variations for period-II in equinoctial months. As it may be seen here, the maximum values of SSN are ≈ 30 and ≈ 140 during period-I and period-II respectively. The lower panel of this figure shows the variation of solar flux F10.7 during both the periods. We can clearly see that the maximum values of solar flux F10.7 are ≈ 90 for period-I and ≈ 190 for period-II. Here, a large change in maximum values of solar activity parameters can be seen between the two periods. It confirms that the solar activity affects largely during period-II in comparison to period-I.
To see the effect of geomagnetic storms on the TEC data at our low latitude station Agra, we examine the correlation between the monthly TEC variations and geomagnetic activities for which the correlation coefficient between TEC data and $\sum K_p$ index is calculated for each month of year 2011. The results are shown in Fig. 4.5. Here, it is noted that values of correlation coefficients are not so good for the period under consideration, so we can say that geomagnetic activity does not affect the TEC data largely.
While the monthly correlation does not produce a satisfactory result, four cases of magnetic storms are selected to see the effect of magnetic storm on TEC data such as those occurred on 06 August, 27 September, 25 October and on 01 November, 2011 respectively. On these days ΣKp index values are high from the normal days values. For the first case, the VTEC variations (upper panel) and corresponding ΣKp index (lower panel) are plotted for the period of 03 August to 16 August 2011 in Fig. 4.6a. It can be seen that the enhancement in VTEC data occurs on 07 August one day after the occurrence of a magnetic storm. In the second case, the period of 25 September to 08 October 2011 is considered and plotted the same as above corresponding to this period. One can notice in Fig. 4.6b that ΣKp index values (lower panel) are > 30 between 26-29 September, whereas the major enhancements occur in TEC data during 2-3 October (5-6 days after). Similarly, two other cases of VTEC variations in relation to magnetic storms during 23 October-05 November are shown in Fig. 4.6c. In the lower panel of this figure it can be seen that ΣKp values are high (≥ 30) on 25 October and 01 November. The
enhancements occur in the data corresponding to these two moderate magnetic storms 1-4 days after the occurrence of these storms. However, it is well known that geomagnetic storm can produce large perturbations in the ionospheric F-region in the form of enhancements and depletions in the electron density during periods of positive and negative phases of a magnetic storm, respectively.

4.4. Summary of the results

The results obtained from the analysis of the GPS-TEC data over Agra during low and high solar activity periods are summarized in the following table;

<table>
<thead>
<tr>
<th>S. N.</th>
<th>Type of variation</th>
<th>Quiet Period (2007)</th>
<th>High Solar Activity period (2011)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>General variation</td>
<td>In summer, the TEC values are high.</td>
<td>In both summer and equinox TEC values are high.</td>
</tr>
<tr>
<td>2.</td>
<td>Solar activity variation (a) Sunspot Numbers</td>
<td>In summer TEC is relatively higher than other months of seasons.</td>
<td>TEC is much higher during equinoctial months.</td>
</tr>
<tr>
<td></td>
<td>(b) F10.7 cm</td>
<td>Similar as above</td>
<td>Similar as above</td>
</tr>
<tr>
<td>3.</td>
<td>Magnetic storms (moderate)</td>
<td>-----</td>
<td>TEC enhanced one day after the storm in summer and four days after in equinoxes.</td>
</tr>
</tbody>
</table>

Table 4.1. Main points of the interpretation of results.

4.5. Application of the results for interpreting earthquake induced TEC anomalies

From the summary of the results presented above it is clear that there are significant variations in TEC values with season and solar activity during quiet periods TEC shows enhancement in summer, while during disturbed periods it shows enhancements in equinoxes also. A particular point to be noted is that TEC shows anomalously enhanced values after few days of occurrence of magnetic storms.

As mentioned in the first chapter, several workers have reported enhancements in TEC a few days before the occurrence of earthquakes (Dabas et al., 2007; Chauhan et al., 2012; Singh et al., 2012). In order that such results may be authenticated it is necessary to examine the variation in TEC with respect to season and solar activity so that there may not be misunderstanding in reaching a conclusion.
4.6. Discussion

The enhancements in TEC data can be attributed to solar extreme UV ionization coupled with the upward vertical E × B drift. Our station is located in the equatorial ionization anomaly region in which two crests in the ionospheric electron density often show a minimum nearby magnetic dips 15° north and south respectively (Appleton, 1946). In this study, we find that the GPS-TEC and IRI-TEC show higher values during equinoxes and lower values in winter relative to those in summer for both the periods. Here, it may be noticed that the large difference in magnitude of VTEC exists between period-I and period-II because of the low to high solar activity period. Generally, during the daytime, the equator is hotter than the North and South poles which causes meridional wind flow towards the poles from the equator. The flow of meridional wind changes the neutral composition and O/N\textsubscript{2} decreases at equatorial stations. This decrease in O/N\textsubscript{2} ratio, which is maximum during the equinox months, will result in higher electron density. Hence equinox VTEC will be highest (Bagiya et al. 2009; Kumar et al., 2012).

Solar activity affects the magnetospheric dynamics, and influences the plasma density distribution within the ionosphere. The variations of ionospheric VTEC with solar activity can be studied, using solar flux F10.7 cm and SSN which are the useful indicators of solar activity relevant for ionospheric effects and widely used. The F10.7 cm flux may be defined as the radio power of sun at a frequency of 2800 MHz commonly measured in solar flux unit (1 sfu = 10\textsuperscript{-22} Wm\textsuperscript{-2} Hz\textsuperscript{-1}). Generally, the ionization level varies to higher values during a high solar activity period and lower values during a low solar activity period. SSN is a temporary phenomenon but it is very important to define the solar activity effect. The changes in the TEC data variations at our station are attributed to the changes in the solar activity period which is confirmed by the variations of solar activity factors (F10.7 and SSN) and the earlier workers have also found similar interesting results associated with the solar activity. For example, Warnant et al. (2000) have reported higher values of TEC with increasing solar activity. Balan et al. (2002) have also investigated the TEC variation over Japan using the GEONET GPS array during quiet conditions and high solar activity period. They have found that the most significant changes in GPS-TEC occur with respect to the time variation of a day. This change was smallest around 12% in daytime during equinox and attain a highest value around 60% in nighttime during winter season.

The enhancements during the periods of magnetic storms may be attributed to the delayed effects of the induced electric field penetrating the low latitude ionosphere and
magnetosphere (Jain and Singh, 1977; Rastogi and Klobuchar 1990; Lakshmi et al., 1983, 1997; Jain et al., 2010). Basically, two main factors may affect the ionosphere during a magnetic storm: First is thermospheric heating mainly caused by storm-induced thermospheric winds (Danilov and Lastovicka 2001), which results at low latitudes, ionization level increase short of any noteworthy changes in the ratio of atom to molecule (Fuller-Rowell et al., 1994). Second is the penetration of an eastward electric field to low latitudes which results in the enhancements in the fountain effect and the EIA poleward. The enhanced fountain effect is responsible for the enhancements in TEC data measured at low latitudes.

There are numerous reports showing TEC anomalies a few days prior to the occurrence of earthquakes. It has been suggested that earthquake induced electric fields penetrate the ionosphere and cause such anomalies. However, as mentioned in section 4.4, TEC anomalies occur with season and magnetic storms also. It is interpretive to examine TEC variations carefully.

4.7. Conclusion

The GPS-TEC data have been analyzed at a low latitude station Agra, India for two periods from of 01 January-31 December, 2007 and 01 January-31 December, 2011 corresponding to low and high solar activities. The diurnal and seasonal VTEC variations have been studied for both the periods of observation. The solar dependence on TEC data have also been investigated from low to high solar activity and it is found that solar activity directly controls the variation of TEC. The maximum values of VTEC have been found during equinox and minimum in winter solstice. The results have shown a strong correlation with IRI-2012 model for each season. Here, it may be concluded that the TEC values maximizes during equinox and minimizes during winter season which may be attributed to solar activity for each period. The effects of magnetic storms have also been examined and significant enhancements in TEC data associated with them as the delayed effect at low latitudes are found. It is finally suggested that TEC anomalies attributed to earthquakes must be examined in the light of anomalies caused by above factors.