Chapter 3

TEC variations during low solar activity period (2005-2009) near the EIA crest region in India

3.1 Introduction

As mentioned earlier, when the GPS satellite signals propagate through the ionosphere, the carrier experiences a phase advance and the code experiences a group delay due to the total number of free electrons along the path of the signals from the satellite to receiver at the ground. Therefore, the carrier phase pseudoranges are measured too short and the code pseudoranges are measured too long compared to the geometric range between the satellite and the receiver. This results in the degradation of the positional accuracy provided by the GPS receiver [Hofmann-Wellenhof et al., 1992]. The domain of the effect on the range may vary from the furthest distance of more than hundreds of meters (at mid day, during the period of maximum sunspot activity, with the satellite near the horizon of the observer) to the closest distance of less than a few meters (at night, during the period of minimum solar activity, with the satellite at the zenith). Among the different sources of GPS positional errors, ionospheric delay, which is proportional to the TEC, is the highest contributor. Therefore, in order to get better GPS positional accuracy, it is necessary to have a precise knowledge of the accurate values and variations of the TEC at different geographical locations under different geophysical conditions.

3.2 Historical background

During past few decades an extensive study of TEC variations with local time, seasons, and solar activity has been made [Rastogi et al., 1971; da Rosa et al., 1973; Van Velthoven, 1990; Feichter and Leitinger, 1997; Warnant et al., 2000; Gupta and Singh, 2000; Wu et al., 2008]. In the past three decades, several individual measurements of TEC at various locations in India have been made using the available low earth orbiting satellites as well as geostationary satellites.
[Rastogi and Sharma, 1971; Das Gupta and Basu, 1973; Rastogi et al., 1975; Rama Rao et al., 1977; Davies et al., 1979]. All these studies have shown the characteristic features of the TEC for the Indian region.

Equatorial Ionosphere exhibits large spatial gradients in electron density due to the well-known EIA with a trough at the equator and a crest at ±15° north and south geomagnetic latitudes of it. Rastogi and Klobuchar [1990], using ATS-6 TEC measurements from India, have shown a large day to day variability in the location of EIA crest in the Indian sector and its dependence on the EEJ and CEJ. Sethia et al., [1980] and Balan and Iyer [1983] have shown that the EEJ has a pronounced influence on the development of EIA in TEC, based on the sparse data of previous satellites of opportunity.

With the advent of GPS satellites, a network of GPS stations monitoring TEC and scintillations in the Indian subcontinent have been established jointly by Indian Space Research Organisation (ISRO) and Airport Authority of India (AAI). This network is known as the GAGAN (GPS Aided Geo Augmented Navigation). Using GAGAN GPS TEC measurements [Rama Rao et al., 2006] and other individual GPS TEC measurements [e.g. Pandey and Dashora, 2006], ionospheric TEC variations have been investigated at few Indian stations.

The dual frequency GPS signals recorded at Rajkot near the EIA northern crest in India have been analyzed to study the ionospheric variations in terms of TEC during the low solar activity period of April 2005 to April 2009. In this study, we describe the diurnal and seasonal variations of TEC, solar activity dependence of TEC. Some limited data set from the GAGAN GPS receivers is used to study the control of EEJ on EIA. The details of GAGAN GPS stations used in the present study are given in Appendix I (Table I.1). The observed low latitude L-band scintillation during the descend phase of the solar activity is also discussed.
3.3 Diurnal variations of TEC

The diurnal variations of TEC exhibit a steady increase from about sunrise to an afternoon maximum and then fall to attain a minimum just before sunrise. The diurnal characteristics of TEC have seasonal, solar activity, geomagnetic activity and latitudinal dependence. Figure 3.1 shows the diurnal pattern for a typical quiet day of 17 April 2005 (Ap=4) derived from per minute TEC values. It is derived for ±2° latitude and ±2° longitude bin from the Rajkot for all the visible satellites. The variations can be divided into three different regions, namely: the build up region, the day time plateau and the decay region. The diurnal variations in TEC at Rajkot exhibits many characteristics typical to low latitude ionosphere such as TEC minimum at pre-dawn hours and gradual increase with the time of the day, attaining maximum in the afternoon and gradual decrease after sunset. The daily peak occurs around 14:00 IST hours (IST=UT+5.5 hrs).

At low latitude ionosphere the highest daytime peak TEC values greatly depend on the strength of the EIA. Figure 3.2 (a) and (b) shows the mass plots of TEC diurnal variations for the months of years 2005 to 2009.
Figure 3.1: Diurnal variations of TEC observed for a ±2° latitude and ±2° longitude bin from the observing station Rajkot
Figure 3.2 (a): Mass plot of Diurnal variation of TEC at Rajkot from April 2005 to May 2007 with the exception of May to August 2006 due to instrument failure.
Figure 3.2 (b) : Mass plot of Diurnal variation of TEC at Rajkot from June 2007 to May 2009 with the exception of February to March 2008 (because during this period, GPS receiver operated from Gadanki for ESF campaign)
These curves show appreciable day to day variability. The day to day variability of TEC is contributed by the various parameters like EUV flux, geomagnetic activity [Dabas et al., 1984], EEJ strength and local atmospheric conditions in the thermosphere [Rama Rao et al., 1980] etc. It can be noticed that the day to day variability in TEC decreases with the phase of the solar activity. During 2005 to 2007 significant day to day variability is observed while during 2008 and 2009 the day to day variability is less. This is may be due to the variations of EUV flux with the phase of the solar activity.

3.4 Seasonal variations of TEC

The mean diurnal TEC variations during different seasons recorded at Rajkot for the years of 2005–2009 are shown in Figure 3.3. The equinox represents March, April, September, and October; the summer represents May, June, July, August; and the winter represents the January, February, November and December.

It can be seen from Figure 3.3 that TEC values are high in equinoctial months followed by summer and winter. Seasonal variations of TEC depend not only on production and loss of ionization but also on the transport of plasma through winds and on thermospheric neutral composition variations. The higher values of TEC in equinox months are due to high values of solar flux. During summer the meridional winds are equatorward. The equatorward winds push the plasma along the geomagnetic field lines i.e. at higher altitudes where production and loss ratio is high. This behavior increases the electron density at low latitudes [for e.g. Ramarao et al., 1996]. During winter the meridional winds are poleward. The poleward winds push the plasma to lower altitudes where production and loss ratio is comparatively low. This behavior decreases the electron density.

The changes in the ratio of thermospheric [O]/[N₂] due to differential heating between two hemispheres also influences the seasonal variations of TEC [for e.g. Bhuyan and Borah, 2007 ; Mukherjee et al., 2010]. It is observed that at Rajkot, the winter anomaly is absence. Winter anomaly represents the higher
values of electron density in the winter months than in the summer. The detail
description on winter anomaly can be found in literature.

There is a sharp daily maximum during 2005–2006 for all the seasons
which is not seen for other observations. During the low solar activity period the
seasonal variability of daily peak TEC is comparatively low. This agrees with the
results shown by Modi and Iyer [1989]. One more interesting point here is that
during 2008-2009 the observed TEC values for each season are little higher than
the values observed during 2007-2008. This may be because the sun is
approaching the next active solar cycle period and TEC at low latitudes has started
to show the signatures of its. Figure 3.4 shows the month to month variations of
monthly mean diurnal peak TEC values. This monthly mean diurnal peak TEC
shows semiannual variations with a peak during the equinox period and a trough
during the solstice period.
Figure 3.3: Seasonal mean diurnal variations of TEC during (a) 2005–2006 and (b) 2006–2007 at Rajkot
Figure 3.3: Seasonal mean diurnal variations of TEC during (c) 2007–2008 and (d) 2008–2009 at Rajkot
3.5 Solar activity dependence of TEC

The sun emits a wide spectrum of radiation along with the high energy particles. In addition to the sunspot number, the flux of the sun’s radio emission at a wavelength of 10.7 cm (2.8 GHz) is also a useful indicator to show the phase of the solar activity. We have used the solar F10.7 flux values to observe the variations of the present solar cycle. Figure 3.5 shows the correlation between the yearly mean daytime peak TEC and respective year’s average solar flux values. The yearly mean TEC is derived from the average of each month’s daily peak TEC.

*Rama Rao et al., [1985]* reported the direct control of solar activity on the ionization level, with high electron density values during a high solar activity
period and low values during a low solar activity period. Although the range of solar flux variations during the present study is very limited but Figure 3.5 shows high positive correlation (Correlation Coefficient R=0.97) between daytime peak TEC and the solar F10.7 flux.

During the period of low sunspot numbers, TEC builds up quite slowly, resulting in the low values of day maximum. This can also be observed in Figure 3.4 where TEC values are decreasing consistently with the period of the years. But for the year of 2008-2009 it is observed that TEC values are increasing gradually. This shows clearly the solar activity dependence of electron density. Warnant et al., [2000] have reported higher values of TEC with increasing solar activity.

![Figure 3.5: Solar cycle dependence of TEC observed at low latitude station Rajkot](image)

Figure 3.5: Solar cycle dependence of TEC observed at low latitude station Rajkot
3.6 EEJ control on development of EIA

In order to see the EIA development and influence of EEJ on it we have derived the contour plots of TEC with respect to local time and magnetic latitudes on three quiet days for different EEJ conditions, using GAGAN GPS data of five stations: Trivandrum (0.5° N Geomagnetic), Bangalore (4.32° N Geomagnetic), Hyderabad (9.22° N Geomagnetic), Bhopal (14.21° N Geomagnetic) and Delhi (20.32° N Geomagnetic). All these stations are around the common longitude belt of 77–78° E. The details of these stations are given in Appendix-I (Table I.1).

In Figure 3.6, the first panel represents the contour TEC plot on 25 December 2005 along with the diurnal variations of EEJ on the day. It can be seen that due to the presence of CEJ, EIA peak occurred at lower value of ~35 TECU at ~1600 IST. This is the case of morning counter Electrojet. On the day anomaly is totally inhibited with a spatial extent of ~6° N. Due to inhibition of EIA, plasma does not get transfer to more extended latitudes. Hence maximum of EIA occurs at lower latitude with low magnitude.

The second panel represents the contour TEC plot on 23 October 2005 along with the diurnal variations of EEJ on the day. This is the case of weak EEJ and EEJ peak value is ~ 31 nT. On the day, the EIA peak occurred at ~45 TECU at ~15:00 IST and it extended up to 10° N.

The third panel represents the contour TEC plot on 20 October 2005 along with the diurnal variations of EEJ on the day. This is the case of strong EEJ and EEJ peak values is 78 nT. On the day, the EIA peak occurred at ~55 TECU at ~13:00 IST. The latitudinal extent of EIA is up to ~14° N.

The observed results clearly show the control of EEJ on development of EIA Dabas et al., [1984] also reported that EEJ has a pronounced influence on TEC over a large latitudinal belt starting from the equator to 25°N dip latitude. Rama Rao et al., [2005] have shown that EEJ controls the altitude of the lifted plasma over the equator and hence the location of the crest of EIA. The higher the
EEJ strength, the higher the altitude to which plasma gets lift over the equator and farther the location of the crest of the EIA. They have shown the spatial variation of TEC and dependence of EIA on EEJ using GPS data of seven stations of the GAGAN network. Our results agree with this and showing positive dependence of EIA on EEJ.

The statistical correlation between EIA strength and EEJ strength is presented in Figure 3.7. The correlation (correlation coefficient (R) value of 0.71) shows that EIA strength increases with EEJ strength. There is a good linear correlation between EIA strength and EEJ peak value. The scattered points around the regression line may be due to other factors contributing to the day-to-day variability of TEC, although only magnetically quiet days are considered in this analysis.

**Figure 3.6: EIA development during three different EEJ conditions**
As discussed in the previous section, the strong EEJ results in to the strong $\mathbf{E} \times \mathbf{B}$ drift. Hence, EIA strength increases and more plasma will get transfer at low latitudes from equatorial latitudes. This process increases the low latitudes TEC. Now, in order to see the low latitude TEC variations during different EEJ conditions we have plotted the diurnal variations of TEC at Rajkot during strong, weak and counter EEJ conditions. Figure 3.8 shows these results.

Figure 3.8 (a) represents the diurnal variations of TEC on 9 April 2005 (Ap=3), a strong EEJ day with EEJ peak value of 81 nT. TEC attains the peak value of ~70 TECU on the day and the daily peak occurred at ~13:00 IST. On strong EEJ day, obviously the EIA strength will be high. The observed high value of TEC diurnal peak on 9 April 2005 is in agreement with this.
Figure 3.8 (b) represents the diurnal variations of TEC on 5 December 2005 (Ap=3), a day of weak EEJ. The TEC diurnal variations show two peaks one at ~12:30 IST with value of ~35 TECU and other at 16:30 IST with value of ~41 TECU on the day. As observed in the case of 23 October 2005 in the previous section, the EIA peak occurs at delayed time of ~15:00 IST. The observed two TEC peaks on 5 December 2005 day require further investigations.

Figure 3.8 (c) represents the diurnal variations of TEC on 3 July 2005 (Ap=7), an afternoon CEJ day. Here also two peaks have been observed with very short time gap. Diurnal TEC maximum occurred at 14:00 IST with value of ~50 TECU. Figure 3.8 (d) represents the diurnal variation of TEC on 31 December 2006 (Ap=2), a morning CEJ day. On the day, prominent daytime TEC peak has not seen. The broad and flat TEC curve is observed. This may be due to the inhibition of EIA on this day. The morning CEJ results in to the downward $\mathbf{E}\times\mathbf{B}$ drift in the fore noon hours.

On strong EEJ days, EIA intensifies and transfers more plasma in to the crest regions. On CEJ days, EIA suppressed and TEC shows low values near the crest region. Thus the results suggest that EEJ fully controls the EIA development, and hence the distribution of F region plasma in the low latitude ionosphere. This agrees with the results shown by Rama Rao et al. [1983] and Rastogi and Klobuchar [1990].
Figure 3.8: EEJ influence on diurnal variations of TEC on the day of (a) 9 April 2005, (b) 5 December 2005, representing strong and weak EEJ conditions respectively
Figure 3.8: EEJ influence on diurnal variations of TEC on the day of (c) 3 July 2005 (d) 31 December 2006, representing afternoon CEJ and morning CEJ conditions respectively.
3.8 Low Latitude L-band scintillation and associated TEC depletion

When a radio wave propagates through electron density irregularities presence in the ionosphere, it suffers from phase and amplitude fluctuations. As we have discussed in Chapter 1, if the ionospheric irregularities are present in the path of the radio wave signals, they experience phase and amplitude fluctuations, onset angle variations and also the signal loss on some occasions. The understanding of these signal fluctuations i.e. ionospheric scintillation is necessary in order to provide the better and accurate GPS positioning and navigation and also to study the nature and dynamics of ionospheric irregularities. The detailed discussion on ionospheric F region irregularities i.e. ESF responsible for radio wave scintillation is given in Chapter 4. In this section we present GPS L-band scintillation and associated TEC depletion observed at low latitude station Rajkot during April-2005 to April-2009.

The GPS observations from April – 2005 to April - 2009 at Rajkot show only 30 scintillation days. Almost all the events are observed during post-sunset-preamidnight hours. The observed scintillation by different PRN’s for four different days during April 2005 to April 2009 are presented in Figure 3.9. The left panel of each figure shows the temporal variations of TEC and scintillation index S4. The right panel of each figure shows the temporal variations of satellite elevation angle and geomagnetic latitude (solid line) and geographic longitude (broken line) of the ionospheric pierce point (IPP) computed from the elevation and azimuth angles of the satellite at each instant of its pass, as seen from Rajkot. For IPP computations a thin ionospheric shell at an altitude of 350 km has been understood. The observations below 30° have been omitted in order to take care the effect of multipath reflections.

Figure 3.9 (a) represents the scintillation event observed by PRN 5 on 06 October 2005. It can be seen that TEC depletion of magnitude ~3 TECU has been observed between 2125 IST and 2150 IST. On the occasion S4 enhanced up to the magnitude of ~0.18. At 2150 IST, TEC enhancement is observed. The noteworthy feature here is that TEC enhancement is associated with the depletion in S4 to
~0.025. After this again TEC depletion of ~4 TECU is seen with S4 enhancement up to ~0.24. The elevation information describes that the depletion is observed at high elevation angles (between 45° and 65°). The latitude-longitude (lat-long) information describes that the depletion is observed at lower latitudes than the Rajkot i.e. equatorward and west of Rajkot.

Figure 3.9 (b) represents the scintillation event observed by PRN 31 on 24 December 2006. TEC depletion of magnitude ~1 TECU and S4 enhancement of ~0.12 is observed between 2200 IST and 2300 IST. The temporal variations of elevation angle describes that the depletion is observed at elevation angles between 65° and 50°. The lat-long variations describe that depletion is observed between 8° N and 13° N and east of Rajkot.

The strongest scintillation event observed during 2005-2009 is on 25 September 2007 which is shown in Figure 3.9 (c) and Figure 3.9 (d). TEC depletion of ~6 TECU and S4 enhancement up to 0.29 is observed by PRN 5 between 2075 IST hrs and 2125 IST hrs as shown in Figure 3.9(c). TEC depletion of ~2 TECU and S4 enhancement up to 0.12 is observed by PRN 30 in Figure 3.9(d) almost at the same time. The elevation angle variations of PRN 5 show that the depletion is occurred at elevation angles between 55° and 40°. The latitude-longitude curves of PRN 5 shows that the depletion is occurred between latitude range of ~12° N to ~11° N and west of Rajkot. The elevation variations of PRN 30 describes that the depletion is occurred at elevation angles between 55° and 50°. The lat-long variations of PRN 5 describes that the depletion is occurred between latitude range of 13.5° N and 12.5° N and west of Rajkot. PRN 30 has come across of two TEC depletions. The second is observed at quite low elevation angle of ~30°-35°. The depletion magnitude is ~4 TECU which is accompanied by S4 value of ~0.18. It is observed at lower latitudes than the Rajkot and west of it.
Figure 3.9: Low latitude L-band scintillation observed on (a) 06 October 2005 (b) 24 December 2006 at Rajkot
25 September 2007, PRN 5

25 September 2007, PRN 30

Figure 3.9: Low latitude L-band scintillation observed on (c) and (d) 25 September 2007 at Rajkot
Figure 3.9 (e) represents the scintillation event observed by PRN 24 on 08 September 2008. Three clear depletions are observed between 2200 IST and 2350 IST. The magnitude of TEC depletion is ~ 1 TECU. The S4 values are not showing any noticeable enhancement during this event. The depletions are at quite high elevation angles and higher latitudes than the Rajkot. The low S4 values indicate that the observed TEC depletions might be due to some ionospheric wave like features which require further investigations.

In this investigation, it has been observed that on most of the days scintillation is observed between 21:00 to 22:00 IST. The observed scintillation amplitude is very low and only 30 events of scintillation are observed during 2005-2009. One of the reasons for the low scintillation amplitude and less occurrence frequency is the current low solar activity period. Due to the low solar activity period, the occurrence frequency of ESF also becomes low. Even if the irregularities occur at the equator, the height which they attain over the equator...
that only decides the latitudinal extent of irregularities and hence scintillation if any.

An attempt has been made to describe the latitudinal extent of L-band scintillation in Chapter 4. The results from the multitechnique campaign conducted for the study of ESF irregularities are discussed in Chapter 4. During the campaign period, it is observed by radar, located at off equatorial station Gadanki (13.5°N, 79.2°E; geomagnetic dip 6.5°N) in India, that the ESF irregularities’ height mostly confined to 500-600 km. Thus, due to this lower confined height of ESF irregularities, they may not expand up to Rajkot latitude and die out over lower latitudes only. The observed lower occurrence frequency of L-band scintillation at Rajkot may be due to this reason.

Dasora and Pandey [2005] reported the UHF scintillation and associated TEC depletions near the northern crest region of EIA, Udaipur (26.4°N 73.7°E, Geographic, 15.6°N Geomagnetic), in India. They have shown a one to one correspondence between the TEC depletion and the increase in $S_4$ index.

3.9 Conclusion

The present chapter describes the temporal and spatial variations of GPS derived TEC during the low solar activity period (2005–2009). The temporal variations are recorded at Rajkot (22.29°N 70.74°E, sub-ionospheric dip latitude 15.8°N) near the northern crest of EIA. The diurnal variations of TEC show a steady increase from about sunrise to an afternoon maximum and then fall to attain a minimum just before sunrise. A significant day to day variability in diurnal pattern has been observed which decreases with descend phase of solar activity. The seasonal variations of TEC show that TEC values are high in equinoctial months followed by summer and winter. The month to month variations of mean diurnal peak TEC shows semiannual variations with a peak during the equinox period and a trough during the solstice period. The high positive correlation between TEC peak and solar F10.7 flux shows high solar
cycle dependence of TEC. The gradual increase in TEC observed in the year 2009 provides the indication of the starting of new solar cycle.

The latitudinal variations of TEC derived from the GAGAN GPS stations, further show that the EIA parameters, viz, the anomaly peak value, time and latitudinal extent are greatly controlled by EEJ. Our results indicate that low latitude TEC magnitude and daily peak time depends on the EEJ conditions. EIA is completely inhibited on the day of morning CEJ, resulting in a lower TEC value at Rajkot. The low latitude L-band scintillation is low both in amplitude as well as occurrence frequency due to the low solar activity period. Most of scintillation events are observed between post sunset and pre-midnight hours.