

Latitudinal variation in the occurrence of GPS L-band scintillations associated with the day-to-day changes in TEC, h'F and the E×B drift velocity and their impact on GPS satellite signals

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The present study describes the day-to-day variations in the occurrence of GPS L-band scintillations from equator to the anomaly crest location associated with the changes in TEC, h'F and E×B drift velocities. The GPS–TEC and S₄ index data from an equatorial station, Trivandrum (8.47°N, 76.91°E), a low latitude station, Waltair (17.7°N, 83.3°E) and an anomaly crest location Kolkata (22.6°N, 88.4°E) during the low solar activity years of 2004 and 2005 are used. It is observed that the day-time ambient TEC is higher during scintillation days compared to that during the days on which there are no scintillations at the three different locations mentioned above. Further, the diurnal variation of TEC shows a rapid decay during 1700–2000 hr LT over the three different locations during scintillation days which is observed to be comparatively much less during no scintillation days. The average height of the F-layer in the post-sunset hours over Trivandrum is found to be higher, around 350 km during scintillation days while it is around 260 km during the days on which there is no scintillation activity. The average pre-reversal E×B drift velocity observed around 19:00 hr LT is higher (20 m/s) during scintillation days, whereas during no scintillation days, it is found to be much less (7 m/s). Further, it is observed that the GPS receivers lose their locks whenever the S₄ index exceeds 0.5 (>10 dB power level) and these loss of lock events are observed to be more around the anomaly crest location (Kolkata). It may be inferred from the present observations that the level of ambient ionization around noon-time, and a fast decay (collapse) of the ionization during afternoon hours followed by rapid increase in the height of the F-layer contributes significantly to the occurrence of scintillations. The present study further indicates that the S₄ index at L-band frequencies increases with an increase in latitude maximizing around the crest of the equatorial ionization anomaly during the post-sunset hours resulting in more loss of lock events in the GPS receiver signals around the EIA crest region.

1. Introduction

The equatorial and low-latitude ionosphere is the region where the post-sunset ionospheric dynamics

play a crucial role in the generation of irregularities in the electron density distribution. Soon after the sunset, the F-layer rapidly rises and develops a steep bottom side gradient due to the combined

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effects of recombination of electrons and ions in the F₁ and E layers followed by an increase in the vertical drift velocity. As a consequence, the ionosphere is left with a very steep plasma density gradient that makes the situation analogous to a heavier fluid being supported by a lighter fluid in the presence of gravity. These conditions result in an F-layer plasma density profile which is unstable to the Rayleigh–Taylor (R–T) instability (Ossakow *et al.* 1979), paving way for the generation of a wide range of scale sizes of density irregularities. This multi-dimensional phenomena manifests in different ways such as spread in the F-region echoes as seen in the ionograms, airglow intensity bite-outs, VHF and UHF scintillation of satellite to earth communication signals and plumes in the range time intensity (RTI) maps of the backscatter echoes from coherent scatter radars.

These plasma density irregularities cause disruptions in the satellite-to-ground communication links and degrade the performance of satellite based communication and navigation systems. The general morphological features of the scintillations reported during the past few decades revealed that the occurrence of scintillations depends on local time, season, solar cycle, latitude, longitude and geo-magnetic activity conditions (Woodman and LaHoz 1976; Yeh and Liu 1982; Basu and Basu 1985; Rama Rao *et al.* 2006; Liu *et al.* 2012; Prasad *et al.* 2012 and references therein). However, the day-to-day randomness in the occurrence of scintillations makes their prediction a challenging problem. To predict the scintillation phenomenon so as to achieve the operational forecasting capability, it is important to have a comprehensive understanding on the preceding conditions of the ionosphere leading to the generation of irregularities. Several investigations have been made in identifying the role of the pre-reversal enhancement (PRE) in the upward $E \times B$ drift and associated lifting of the F-layer in creating conditions favourable for the generation of ESF irregularities and scintillations (Rishbeth *et al.* 1978; Basu *et al.* 1996; Dabas *et al.* 2003; Anderson *et al.* 2004). It was reported that the occurrence of ESF over different seasons is evidently correlated with the variations in the magnitude of EEJ and $E \times B$ drifts (Sreeja *et al.* 2009).

A high crest-to-trough ratio of EIA developing in 270–300 km altitude range between 17:00 and 19:00 hr LT on the spread-F days is conspicuously absent on non-spread F days (Raghavarao *et al.* 1988; Sridharan *et al.* 1994; Rama Rao *et al.* 1997; Valladares *et al.* 2001; Li *et al.* 2008). Alex *et al.* (1989) reported higher values of the Total Electron Content (TEC) over Ahmedabad and lower values over Ootacamund on the days of scintillation. The occurrence of strong amplitude scintillations closely associated with a significant drop in the

ionospheric electron content (IEC), termed as electron content depletion, has been reported by many researchers at the equatorial and low latitude stations (Yeh *et al.* 1979; Das Gupta *et al.* 1983; Aarons 1993; Weber *et al.* 1996; Huang *et al.* 2001; Valladares *et al.* 2004; Dashora and Pandey 2005; Rama Rao *et al.* 2006). The time rate of change of TEC (ROT) and the rate of change of TEC index (ROTI) have been studied by several researchers to investigate the characteristics of ionospheric irregularities and the spatial variation of electron density deviation at various scale lengths (Wanninger 1993; Doherty *et al.* 1994; Aarons *et al.* 1996; Basu *et al.* 1999). Correlation between equatorial spread-F plumes and GPS-TEC fluctuations was reported by Kelley *et al.* (1996). Bagiya Mala and Sridharan (2011) have shown that the fluctuations in TEC ($dTEC$) at any given instant could be taken to represent the prevailing basic ionospheric-thermospheric conditions and these perturbations exert continuous control on the evolution of the scintillation phenomena.

In the present study, the simultaneous TEC and S₄ index measurements over three typical locations in the Indian sector, namely, Trivandrum (8.47°N, 76.91°E), an equatorial station, Waltair (17.7°N, 83.3°E), a low latitude station and Kolkata (22.6°N, 88.4°E), an anomaly crest location are used to understand the background ionospheric conditions in the post-sunset hours responsible for the generation of irregularities. It is also of interest to study the spatial and temporal variabilities of the GPS L-band scintillations in the equatorial and low-latitude sectors. A study on the behaviour of TEC with respect to the day-to-day occurrence of scintillation activity at the three different locations has been carried out during the low solar activity period 2004–2005. The time rate of fall in TEC ($dTEC/dt$) during the post-sunset hours has been investigated during different days, with and without scintillation activity and the results are discussed. The simultaneous ionosonde data over an equatorial station Trivandrum is used to study the variations in the virtual height of the F-layer ($h'F$) and the $E \times B$ drift velocities with respect to the day-to-day occurrence of scintillation activity.

Further, during the time of scintillation activity, the rapid phase variations in the trans-ionospheric signal cause a Doppler shift in the GPS signal, which may exceed the bandwidth of the phase lock loop (PLL), resulting in a loss of the phase lock (Leick 1995). In addition, the fades in the amplitude of the received signal can cause the signal-to-noise ratio (SNR) to drop below the threshold level of the receiver, resulting in loss of the code lock. The loss of code lock events in the received signals result in the codeless and semi-codeless

technologies *vs.* full code correlation (Skone and de Jong 2000). Therefore, the loss of lock events detected in the GPS receiver signals from equator to the anomaly crest are studied to illustrate the impact of ionospheric scintillations on satellite based communication and navigation system performance. Also, typical case studies are described to investigate the latitudinal variation of the loss of lock events and their dependence on the strength of the scintillation activity.

2. Database

In the present study, the Total Electron Content (TEC) and the amplitude scintillation (S_4 index) data recorded from the dual frequency GPS receivers located at three typical Indian latitudes namely an equatorial station Trivandrum (8.47°N Geog., 76.91°E Geog., 0.63°S Geomag., 0.6°S dip lat.), a low latitude station Waltair (17.7°N Geog., 83.3°E Geog., 6.4°N Geomag., 20.0°N dip lat.) and an anomaly crest location Kolkata (22.6°N Geog., 88.4°E Geog., 12.78°N Geomag., 32°N magnetic dip) during the low solar activity years 2004 (annual mean $R_z=40$) and 2005 (annual mean $R_z=30$) are considered. The GPS satellite passes with elevation angles greater than 40° are considered for deriving TEC and S_4 indices. These

GPS receivers (Model: GSV4004) are among the 18 GPS receivers installed jointly by the Indian Space Research Organization (ISRO) and the Airport Authority of India (AAI) under the Indian GAGAN programme for making continuous measurements of TEC and scintillation index. The threshold dB level of these three GPS receivers is 25 dB-Hz and 16 dB-Hz at L1 and L2 frequencies respectively. The locations of the three GPS receivers considered in the present study are shown in figure 1 along with the locations of the other set of GPS receivers installed in the Indian equatorial and low latitude sector. The virtual height of the F-layer ($h'F$) is scaled at every 15 min interval using the ionosonde (KEL, IPS-42) data at the equatorial station, Trivandrum during the considered period. The time rate of change of the virtual height of the 4 MHz return signal on the ionograms representing the $E \times B$ upward drift velocity (Bittencourt and Abdu 1981; Fejer *et al.* 2007) is also used in the present study.

3. Results and discussion

3.1 Variations of TEC during different days on which scintillations are present and absent

The diurnal variations of GPS-TEC during different days with and without scintillation activity in

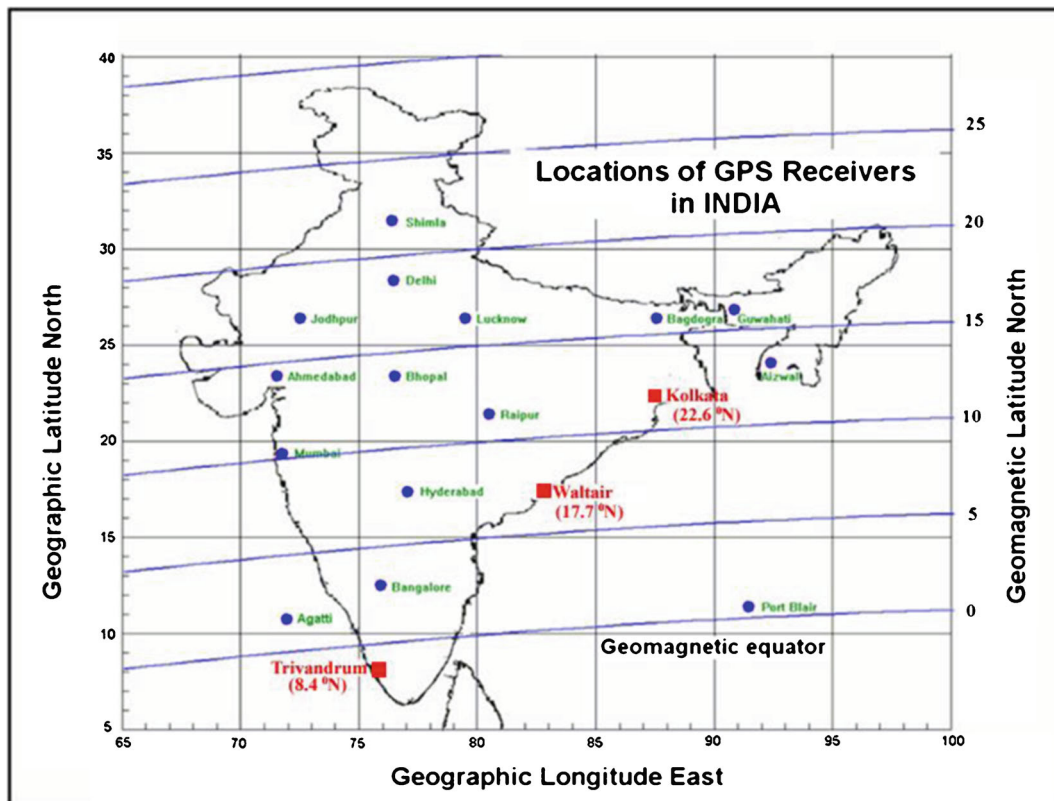


Figure 1. Locations of the GPS receivers installed under GAGAN programme in the Indian region.

equinoctial, winter and summer months of the year 2004 (annual mean $R_z=40$) are presented as mass plots in figure 2 for the three different locations Trivandrum, Waltair and Kolkata. In figure 2(a), the three panels in the first row represent the diurnal variation of TEC over Trivandrum, Waltair and Kolkata during the days on which scintillations (>6 dB) are present and the other three panels in the second row represent the diurnal variation of

TEC during the days on which scintillation activity is absent in the equinoctial months of the year 2004. Similarly, figure 2(b and c) shows the variations of TEC during scintillation days and no scintillation days in the winter and summer months of 2004 respectively. It can be readily seen from this figure that, during the three different seasons, the TEC during scintillation days is higher compared to the days on which there are no scintillations

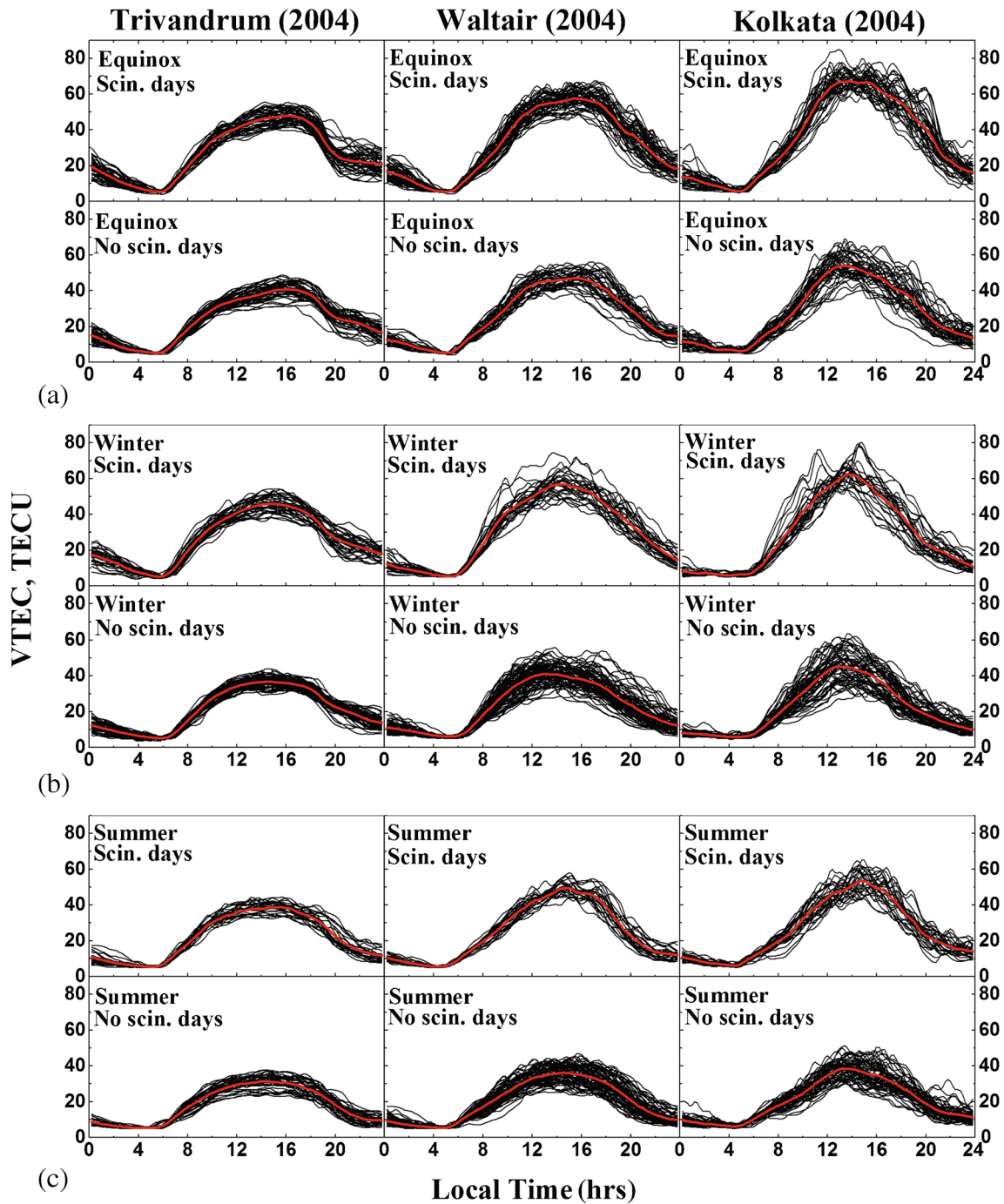


Figure 2. Mass plots showing the seasonal mean diurnal variation of TEC over an equatorial station, Trivandrum; low latitude station, Waltair and an anomaly crest location, Kolkata during scintillation days and no scintillation days of the year 2004.

at the three different stations. The day maximum values of TEC over Trivandrum vary from 30 to 55 TECU during scintillation days, while it varies from 25 to 40 TECU during no scintillation days. At a low latitude station, Waltair, the day maximum TEC varies from 40 to 65 TECU during scintillation days and from 25 to 50 TECU during no scintillation days. The TEC values over an anomaly crest location, Kolkata are higher than those over Trivandrum and Waltair varying between 45 and

75 TECU during scintillation days and between 30 and 65 TECU during the days on which there is no scintillation activity. It is observed from the red coloured mean diurnal plots that the average day maximum in TEC during the equinoctial months is found to be around 48, 57 and 65 TECU during scintillation days and around 37, 45 and 50 TECU during no scintillation days over Trivandrum, Waltair and Kolkata respectively. Similarly, during winter and summer months, the

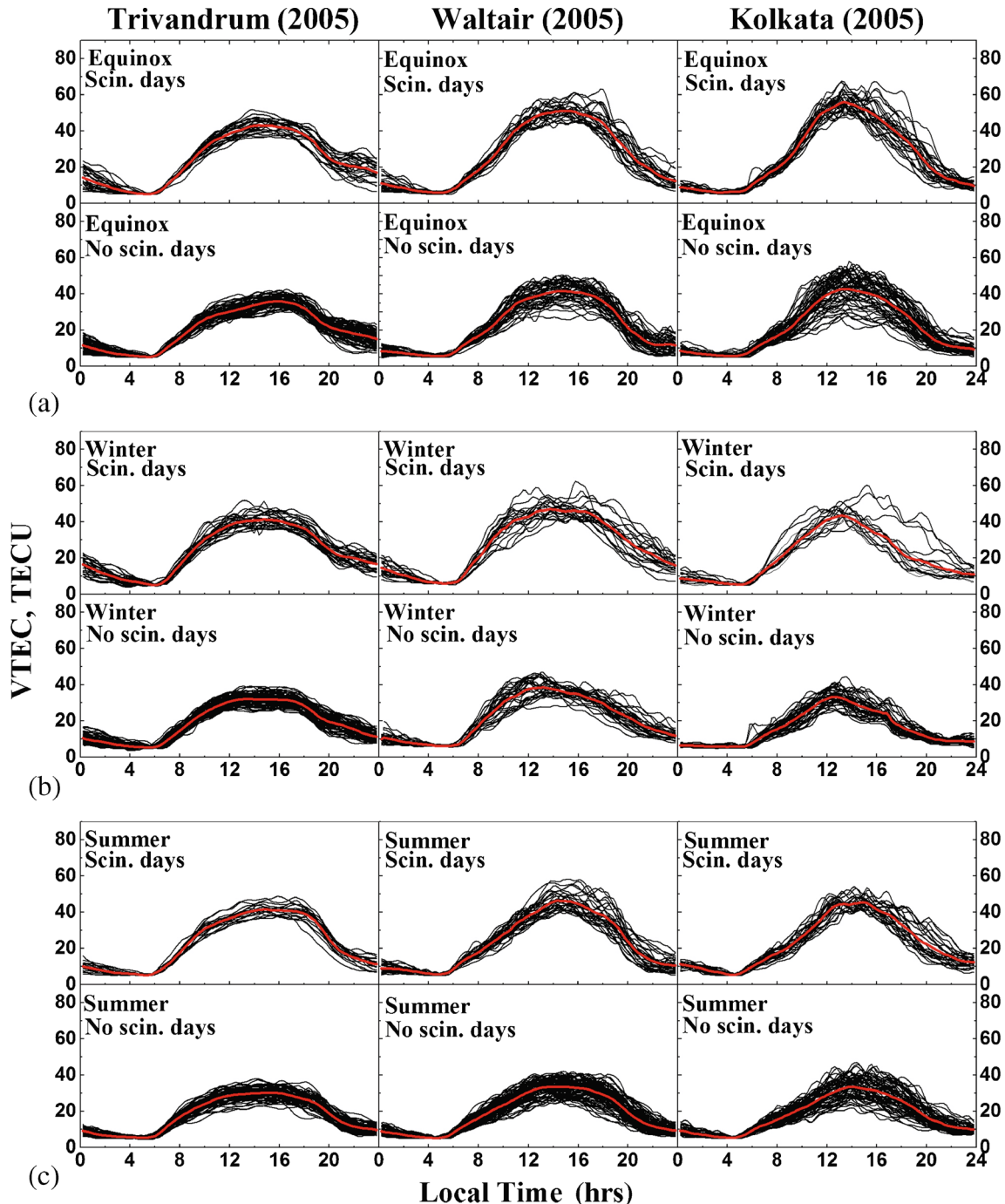


Figure 3. Mass plots showing the seasonal mean diurnal variation of TEC over an equatorial station, Trivandrum; low latitude station, Waltair and an anomaly crest location, Kolkata during scintillation days and no scintillation days of the year 2005.

mean TEC at the three different locations is found to be more during the scintillation days compared to no scintillation days with an increase from equator to the anomaly crest.

A similar analysis has been carried out using the TEC data during the year 2005 (annual mean $R_z=30$) and the results are presented in figure 3(a, b and c), respectively for equinoctial, winter and summer seasons. The day maximum values of TEC vary from 30 to 50 TECU during scintillation days and 23–38 TECU during no scintillation days over Trivandrum. Similarly, over Waltair, the day maximum TEC varies from 40 to 58 TECU during scintillation days and from 25 to 45 TECU during no scintillation days. Over Kolkata, the TEC varies from 40 to 65 TECU during scintillation days and from 20 to 50 TECU during no scintillation days. In general, it is observed from figures 2 and 3 that the maximum, mean and minimum TEC values on days of scintillations are higher than those during no scintillation days. However, it is seen that the minimum of TEC values on days of scintillations during different seasons is less than the maximum TEC value on no scintillation days during different seasons. This indicates that, in addition to day maximum level of TEC, there could be some other parameter (parameters) that also play an important role in the generation of irregularities. Further, it is also observed from figures 2 and 3

that the average diurnal variation of TEC shows a fast decay from 17:00 to 20:00 hr LT during scintillation days compared to the days on which there is no scintillation activity.

To understand these rapid variations in TEC during the post-sunset hours, two typical days on which scintillation activity is present (24 March 2004 and 29 March 2004) are considered and the diurnal variations of TEC and S_4 indices over the three stations are presented in figure 4. It is observed that the day maximum TEC as well as the scintillation indices are higher over Kolkata compared to those at Trivandrum and Waltair. On 24 March 2004, the day maximum TEC is about 50, 60 and 75 TECU over Trivandrum, Waltair and Kolkata respectively. The TEC is found to decrease at the rate of 14.2, 10.1 and 9.2 TECU/hr between 17:00 and 20:00 hr LT over Trivandrum, Waltair and Kolkata, respectively. On this day, the scintillation activity started around 19:00 hr LT and maximum scintillation indices of 0.15 (~ 3 dB) over Trivandrum, 0.45 (~ 10 dB) over Waltair and 0.8 (~ 20 dB) over Kolkata are observed. On the other scintillation day of 29 March 2004, the day maximum TEC and the rate of fall in TEC are found to be 45 TECU and 14 TECU/hr over Trivandrum, 65 TECU and 11.3 TECU/hr over Waltair and 80 TECU and 14.4 TECU/hr over Kolkata. On this day, the scintillation activity started around

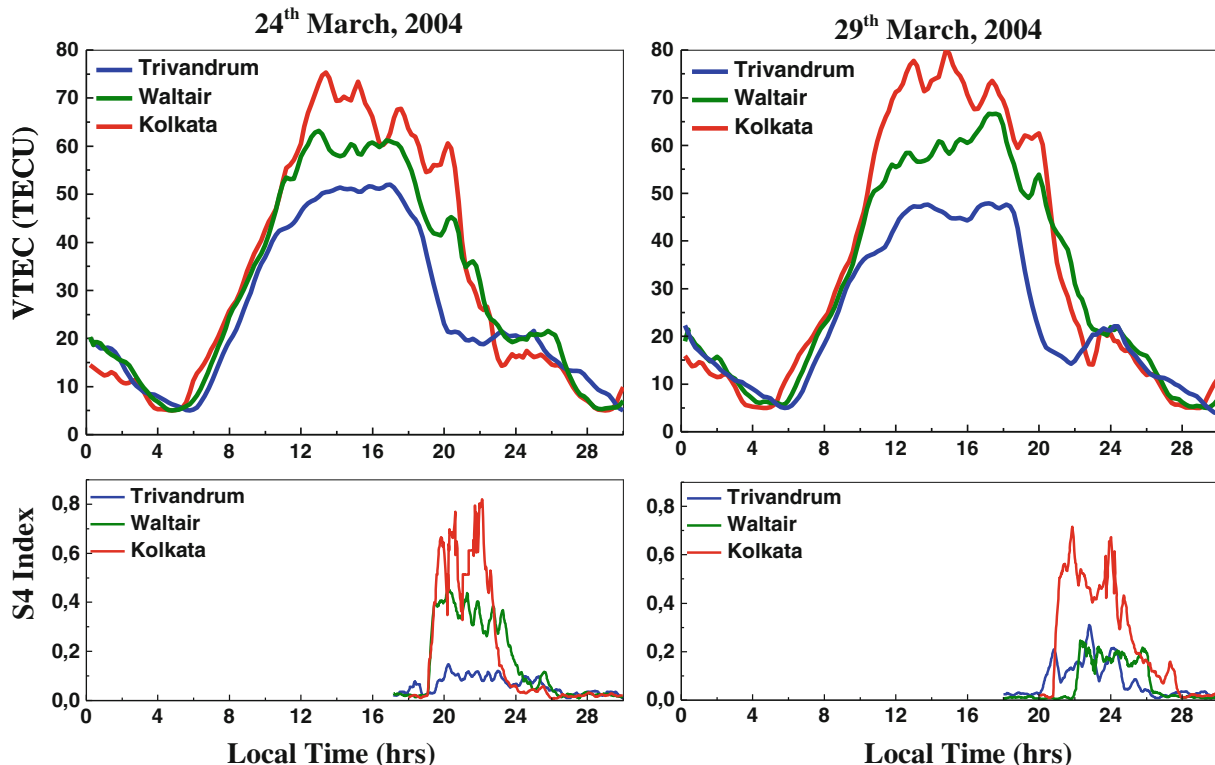


Figure 4. Plots showing the diurnal variation of TEC and scintillation index over Trivandrum, Waltair and Kolkata during two typical days on which scintillations are present.

20:00 hr LT extending up to the post-midnight hours of 02:00 hr LT and the maximum scintillation indices observed are around 0.4 (~ 8.5 dB) over Trivandrum and Waltair and 0.7 (~ 17 dB) over Kolkata.

Another set of two typical days on which there is no scintillation activity (1 September 2004 and 8 December 2004) are considered and the diurnal variation of TEC and S_4 indices over the three different stations Trivandrum, Waltair and Kolkata are presented in figure 5. It is seen from this figure that on a typical day of 1 September 2004, the day maximum TEC is around 35 TECU over Trivandrum, around 40 TECU over Waltair and Kolkata. The TEC in the evening hours decreases at the rate of 3.5 TECU/hr over Trivandrum, 3.2 TECU/hr over Waltair and 4.4 TECU/hr over Kolkata. Similarly, on the other, no scintillation day of 8 December 2004, the day-time ambient ionization is low (below 40 TECU) compared to that during the above two typical scintillation days at all the three different stations. The rate of decrease in TEC between 17:00 and 20:00 hr LT varies from 3 to 3.5 TECU/hr at the three different stations. The S_4 index values plotted for these two typical days at the three different stations show the absence of scintillation activity. From the examples presented in figures 4 and 5, it is seen that the TEC shows prominent

fluctuations on scintillation days compared to no scintillation days and significant increase from Trivandrum to Kolkata during scintillation days.

To study the latitudinal increase in TEC during scintillation days in detail, the TEC data over Trivandrum and Kolkata during the two years 2004 and 2005 is used to calculate the ratio of TEC over the anomaly crest location Kolkata to the TEC over an equatorial station Trivandrum. In figure 6, the mean diurnal variations of the ratio of TEC between Kolkata and Trivandrum during three different seasons of the years 2004 and 2005 are presented. The red and blue coloured curves represent the variations of TEC ratio during scintillation days and no scintillation days respectively. It is observed from this figure that, during scintillation days the ratio of TEC varies between 0.5 and 2 with a peak in the early morning hours. During the days on which there is no scintillation activity, the ratio of TEC varies between 0.7 and 1.3 during different seasons. It can be seen from these plots that in the early morning hours the TEC ratio during scintillation days is lower than that during no scintillation days. During the day-time hours, the ratio of TEC is found to be more during scintillation days compared to that of no scintillation days in three different seasons of both years. This indicates the existence of a strong anomaly and significant

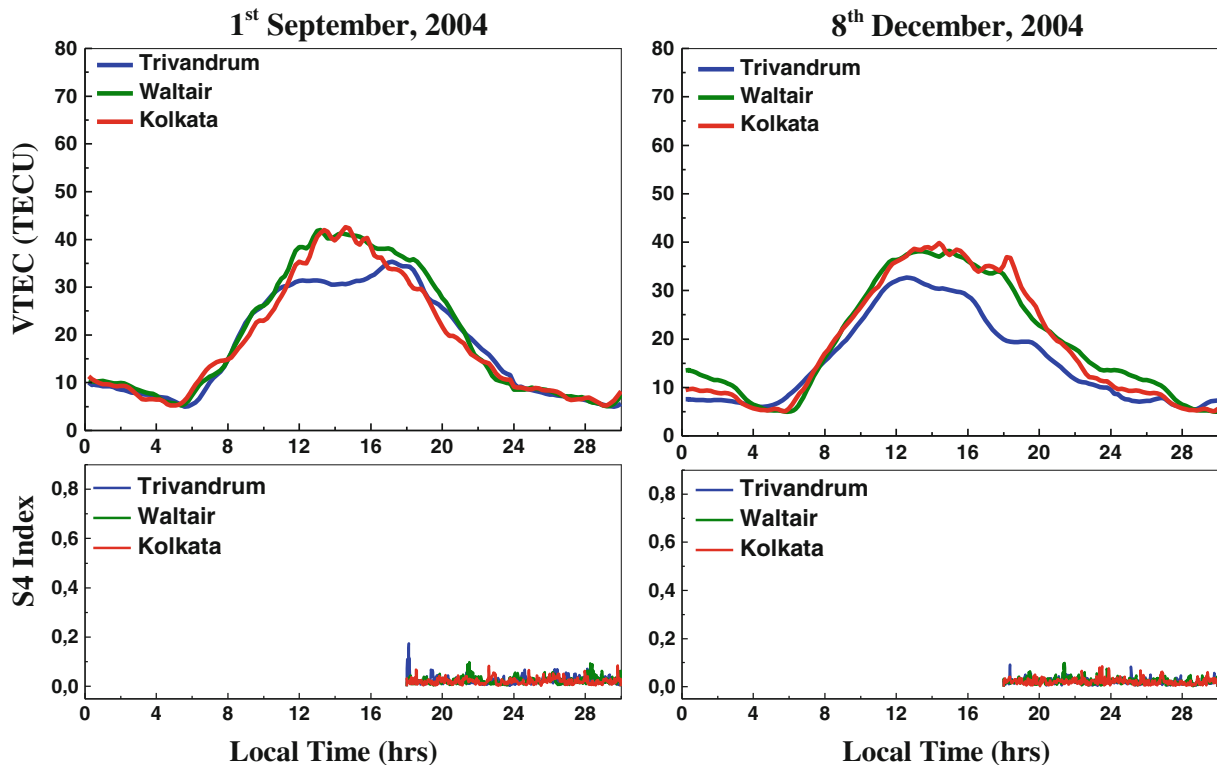


Figure 5. Plots showing the diurnal variation of TEC and scintillation index over Trivandrum, Waltair and Kolkata during two typical days on which scintillation activity is absent.

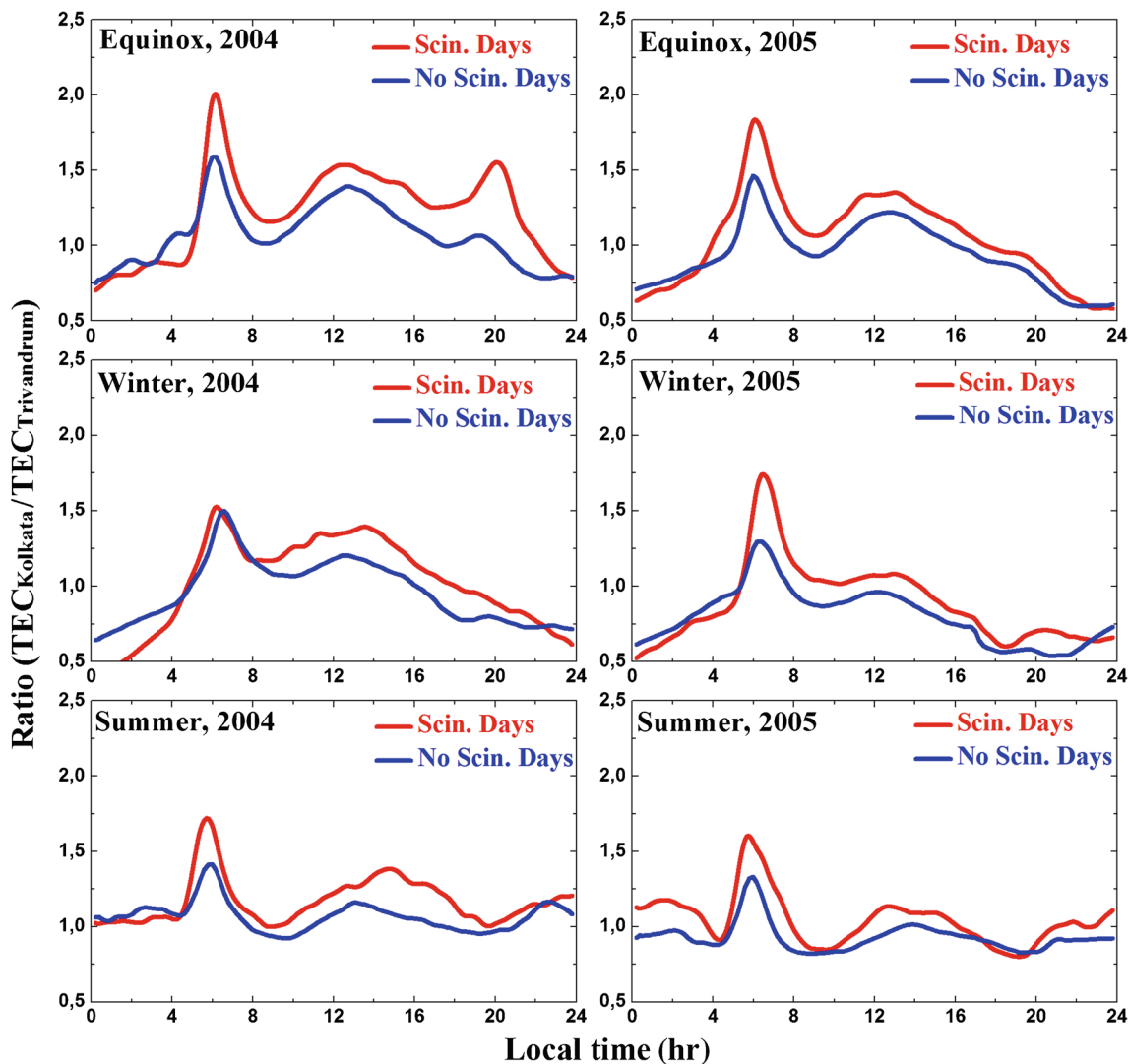


Figure 6. Seasonal mean diurnal variation of the ratio of TEC over Kolkata to TEC during scintillation days and no scintillation days over Trivandrum during equinox, winter and summer months of the years 2004 and 2005.

latitudinal gradients in TEC during scintillation days.

From the above observations, it may be inferred that the day-time ambient TEC is higher during scintillation days compared to that during no scintillation days. Secondly, it is found that the electron density decays rapidly in the post-sunset hours during scintillation days while this rapid fall in TEC is not observed during the days on which there is no scintillation activity. Further, the crest (Kolkata) to trough (Trivandrum) ratio of TEC is more during scintillation days.

3.2 Variations of $h'F$ and $E \times B$ drift velocity during different days on which scintillations are present and absent

The $h'F$ values scaled at every 15 min interval from the ionosonde data over Trivandrum are separated

into two groups; one group containing the data on the scintillation days and the other containing the data during no scintillation days and the results are presented in figure 7 as mass plots separately for the years 2004 and 2005. The average diurnal variation of $h'F$ is plotted as red coloured curves in each of the panels. In general, the diurnal variation of $h'F$ shows a double peak around 06:00 and 20:00 hr LT with higher values during the post-sunset hours (20:00 hr LT). The height of the F-layer from 18:00 to 22:00 hr LT reaches much larger altitudes during scintillation days with a maximum of 450 km while it is less than 350 km during no scintillation days. The mean diurnal variations of $h'F$ show that during the day-time hours (08:00–17:00 hr LT), the $h'F$ varies from 170 to 220 km both during scintillation and no scintillation days. Later, around the post-sunset hours, the mean $h'F$ increases rapidly attaining a maximum of about 350 km during scintillation days, while it is around

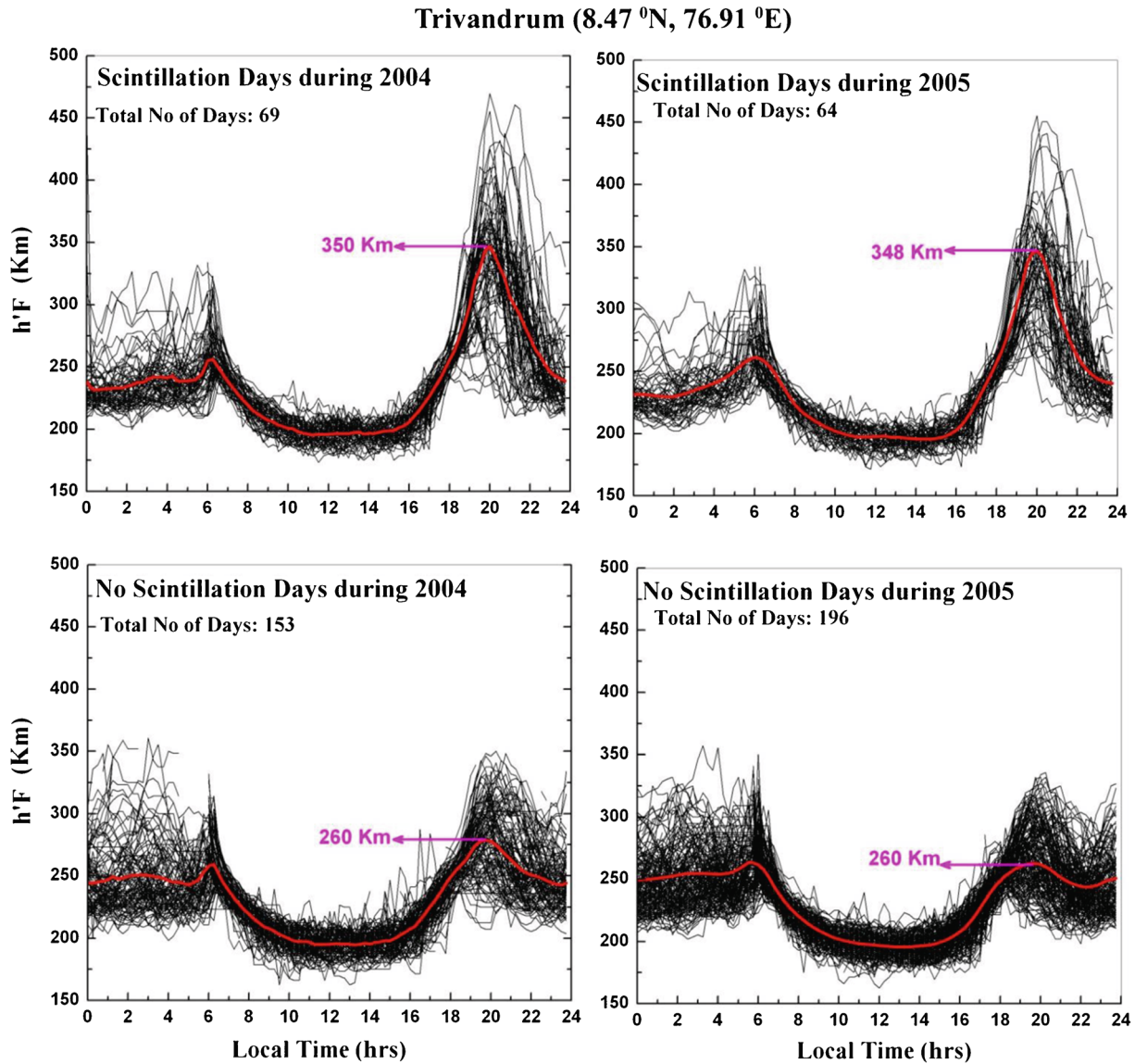


Figure 7. Mass plots showing the diurnal variation of the $h'F$ over an equatorial station Trivandrum during the scintillation days and no scintillation days of the years 2004 and 2005.

260 km during no scintillation days. This indicates that the F-layer over the equator is lifted to greater heights in the post-sunset hours during scintillation days. Alex *et al.* (1989) showed that the F-layer height over Kodaikanal rose to 300 km on days of scintillation, while it is around 250 km on days of no scintillation. Chandra *et al.* (1997) reported higher F-layer rise and later reversal on spread-F days over a low latitude station, SHAR. It is also seen from figure 7 that the maximum, mean and minimum $h'F$ values on days of scintillations are higher than those during no scintillation days. However, the minimum of $h'F$ value on days of scintillations is less than the maximum $h'F$ value on no scintillation days. This indicates that, in addition to the fast rise of the height of the F-layer over the equator, other parameters such as the background

ionization, rate of change of TEC, high crest to trough ratio of EIA and magnitude of the electrojet strength play an important role in creating the conditions favourable for the generation of irregularities (Doherty *et al.* 1994; Sridharan *et al.* 1994; Basu *et al.* 1999; Valladares *et al.* 2001; Li *et al.* 2008; Sreeja *et al.* 2009).

The seasonal mean $E \times B$ drift velocity over the equator during both scintillation days and no scintillation days for the three different seasons in each of the years 2004 and 2005 are presented in figure 8. The red coloured lines represent the average diurnal variation of $E \times B$ drift velocity during scintillation days and the blue coloured lines represent the average diurnal variation of $E \times B$ drift velocity during no scintillation days. In general, it is observed that the drift velocity is positive during

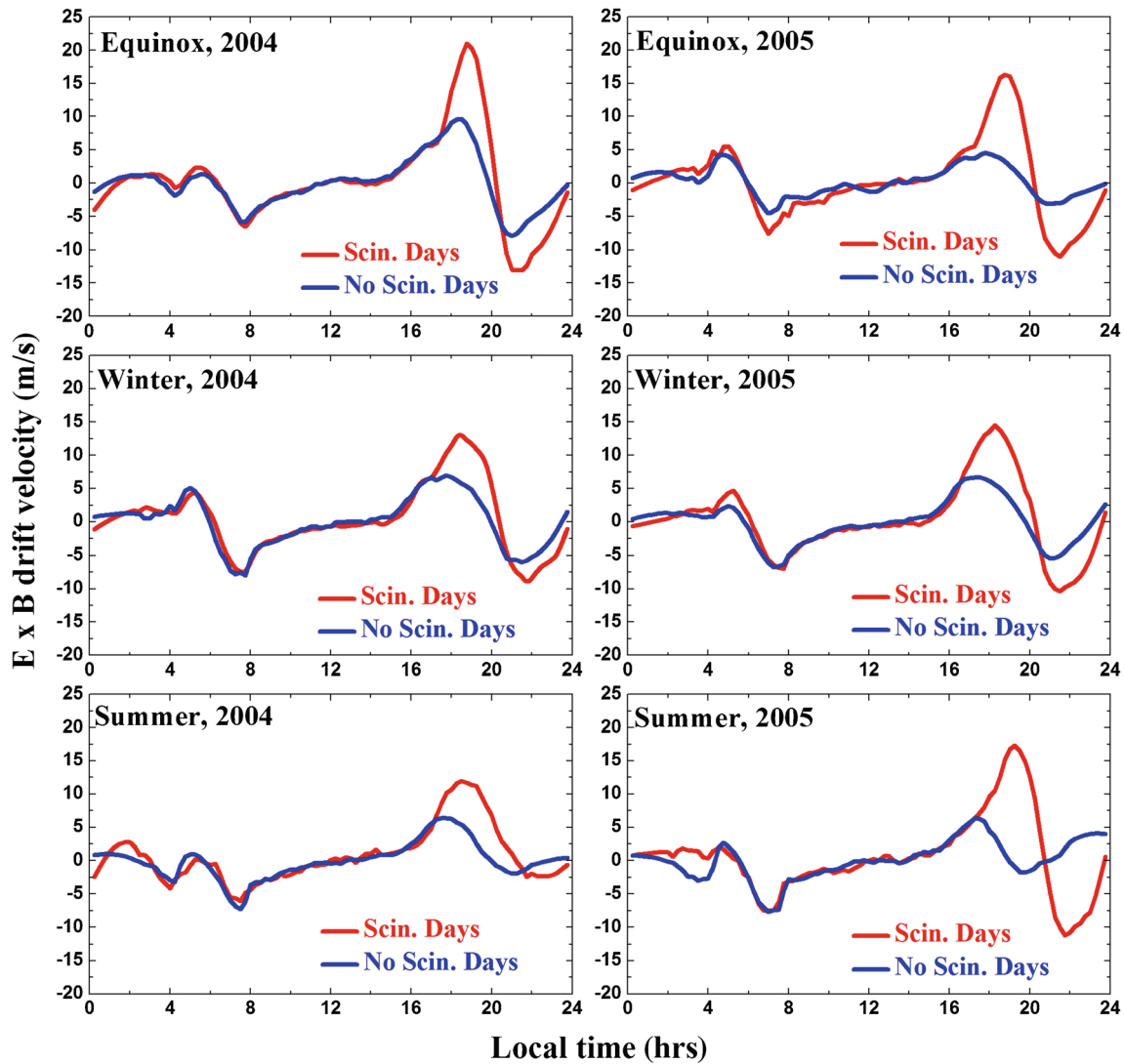


Figure 8. Seasonal mean diurnal variation of the $E \times B$ drift velocity over an equatorial station Trivandrum during scintillation days and no scintillation days of the years 2004 and 2005.

day-time hours and becomes negative during night-time hours as expected since the electric field becomes westward during night-time hours. It is interesting to note from these plots that the variations of vertical drift velocity during scintillation days and no scintillation days is nearly similar from 00:00 to 17:00 hr LT in all seasons during the two years. Later in the post-sunset hours, the maximum average vertical drift velocity observed during scintillation days vary between 15 and 20 m/s during different seasons, while it is found to be less than 7 m/s during no scintillation days. It can be mentioned here that a rapid decay in TEC is also observed in the post-sunset hours from 17:00 to 20:00 hr LT, which is in accordance with the fast rise in the height of the F-layer over the equator.

In the post-sunset hours, due to the recombination of electrons and ions in the absence of photo

ionization by solar ionizing radiations from the Sun, the E-region ionization quickly decreases resulting in a steep upward directed ionization density gradient at the bottom side of the F-layer, which becomes anti-parallel to the gravity (Kelley 1989; Hysell *et al.* 1990). Further, the rapid post-sunset enhancement in the zonal electric field leads to a large vertical $E \times B$ drift, thereby lifting the F-layer to higher altitudes where the recombination effects are negligible and collisions are also rare, resulting in a condition favourable for the development of plasma irregularities. Basu *et al.* (1996) and Fejer *et al.* (1999) reported that, when the drift velocities are large enough, the necessary seeding mechanisms for the generation of strong spread-F/scintillation always seems to be present. For forecasting the night-to-night occurrence of equatorial scintillation activity, Anderson *et al.* (2004) examined the relationship between the $E \times B$ drift

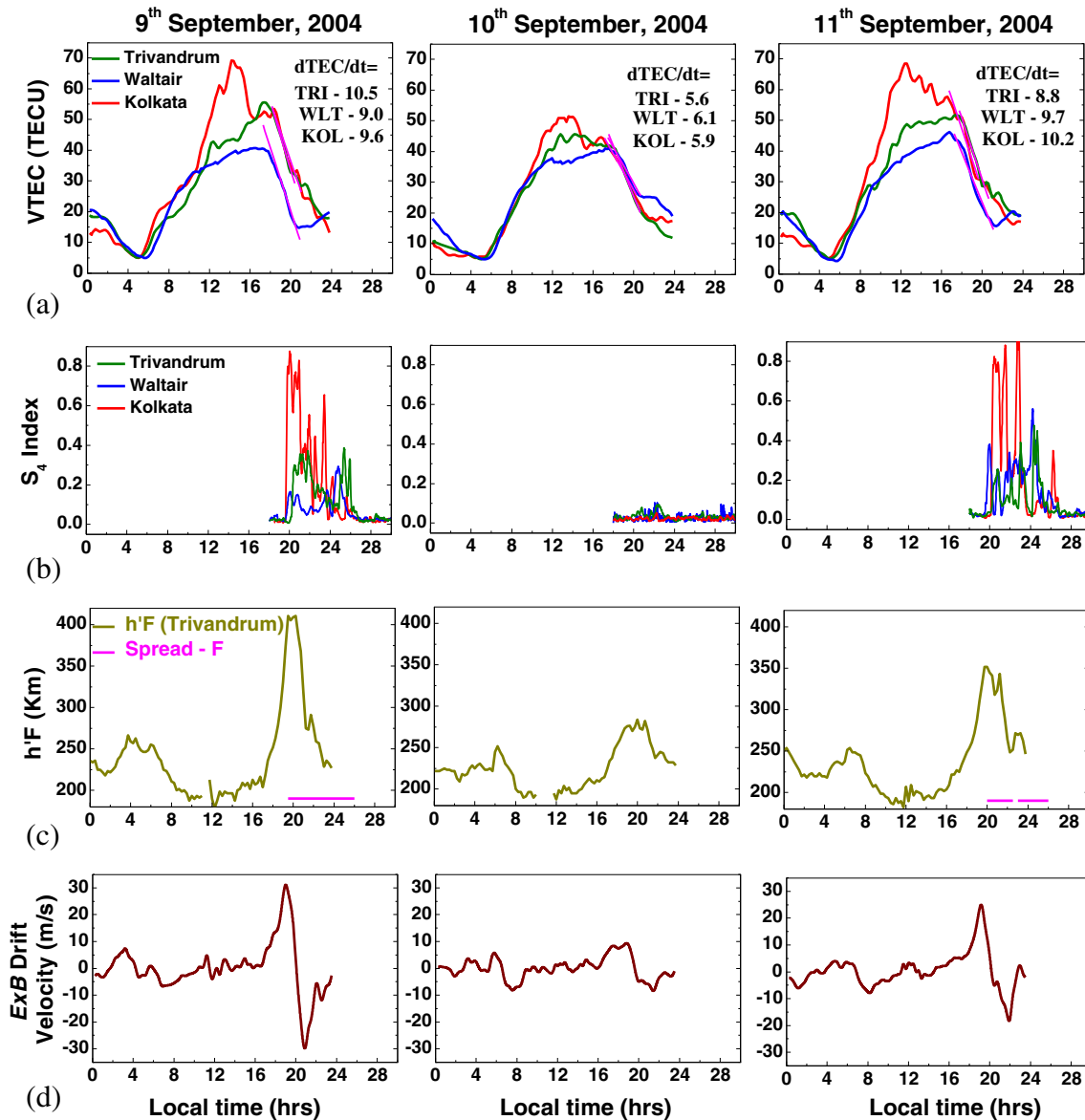


Figure 9. Plots showing the time histories of the (a) TEC, (b) S_4 index over an equatorial station, Trivandrum; low latitude station, Waltair and an anomaly crest location, Kolkata, (c) $h'F$ and (d) $E \times B$ drift velocity over Trivandrum during 9–11 September, 2004.

velocity and the occurrences of scintillation activity using the data of Jicamarca Digisonde and a network of UHF and L-band scintillation receivers and reported that the scintillations with S_4 index greater than 0.5 are observed when the $E \times B$ drift velocity exceeds 20 m/s. In the present study also, an average height of 350 km and an $E \times B$ drift velocity of 20 m/s are observed during scintillation days, which is in good agreement with the results of the earlier studies.

Seker and Kelley (1998) reported that the pre-reversal enhancement in the vertical drift velocity provides a favourable situation for the confinement of the irregularities in the bottom side of the ionosphere. Chandra and Rastogi (1978) have

reported larger F-layer rise and later electric field reversal on spread-F days than no spread-F days over Thumba. Vyas and Chandra (1991) reported later drift reversal over Tiruchirapalli on spread-F days compared to no spread-F days. Mendillo *et al.* (2001) reported that, if one assumes that the required seed perturbation for ESF onset is essentially always available, for all practical purposes, the magnitude of the eastward electric field that causes upward drift is both the necessary and sufficient parameter to forecast ESF with reasonable success. When the base height of the F-layer is high, even perturbations of small amplitude would grow faster and the converse would happen when the F-region moves down (Anderson *et al.* 2004).

3.3 Day-to-day occurrence of scintillation activity – Case study using TEC, $d\text{TEC}/dt$, $h'F$ and $E \times B$ drift velocities

For a given ionospheric and thermospheric condition, ESF and its various manifestations could occur on one day and be totally absent on another day making it difficult to predict. Therefore, the day-to-day randomness in the occurrence of scintillations is a challenging task in view of achieving the forecast capability needed for satellite based communication and navigation system applications particularly over the equatorial and low latitude sectors. A comprehensive understanding on the background ionospheric conditions leading to the generation of irregularities causing scintillations on trans-ionospheric signals is much needed to improve the prediction capabilities. To understand the day-to-day changes in the background ionospheric conditions associated with the occurrence of scintillation activity, simultaneous variation of TEC, $d\text{TEC}/dt$, S_4 index, $h'F$ and $E \times B$ drift velocities has been studied during three consecutive days from 9 to 11 September, 2004.

In figure 9, the diurnal variations of TEC and S_4 indices over the three different stations along with the variations of $h'F$ and $E \times B$ drift velocities over Trivandrum during the period 9–11 September, 2004 are presented. The variations of TEC and S_4 indices are presented as blue coloured curves for Trivandrum, green coloured curves for Waltair and red coloured curves for Kolkata (figure 9a and b). The day maximum values of TEC on 9 September, 2004 are found to be around 40 TECU over Trivandrum, 55 TECU over Waltair and 70 TECU over Kolkata, respectively. A rapid fall in TEC is observed with maximum $d\text{TEC}/dt$ values of 10.5 TECU/hr over Trivandrum, 9.0 TECU/hr over Waltair and 9.6 TECU/hr over Kolkata. On this day, the scintillation activity started around 20:00 hr LT at the three different locations and was observed till the post-midnight hours of 02:00 hr LT. The maximum S_4 indices of 0.3 (~ 6 dB) over Trivandrum, 0.4 (~ 8.5 dB) over Waltair and 0.8 (~ 20 dB) over Kolkata are observed. The simultaneous variation of $h'F$ over Trivandrum (figure 9c) shows a rapid increase in the F-layer height to a maximum altitude of 400 km between 17:00 and

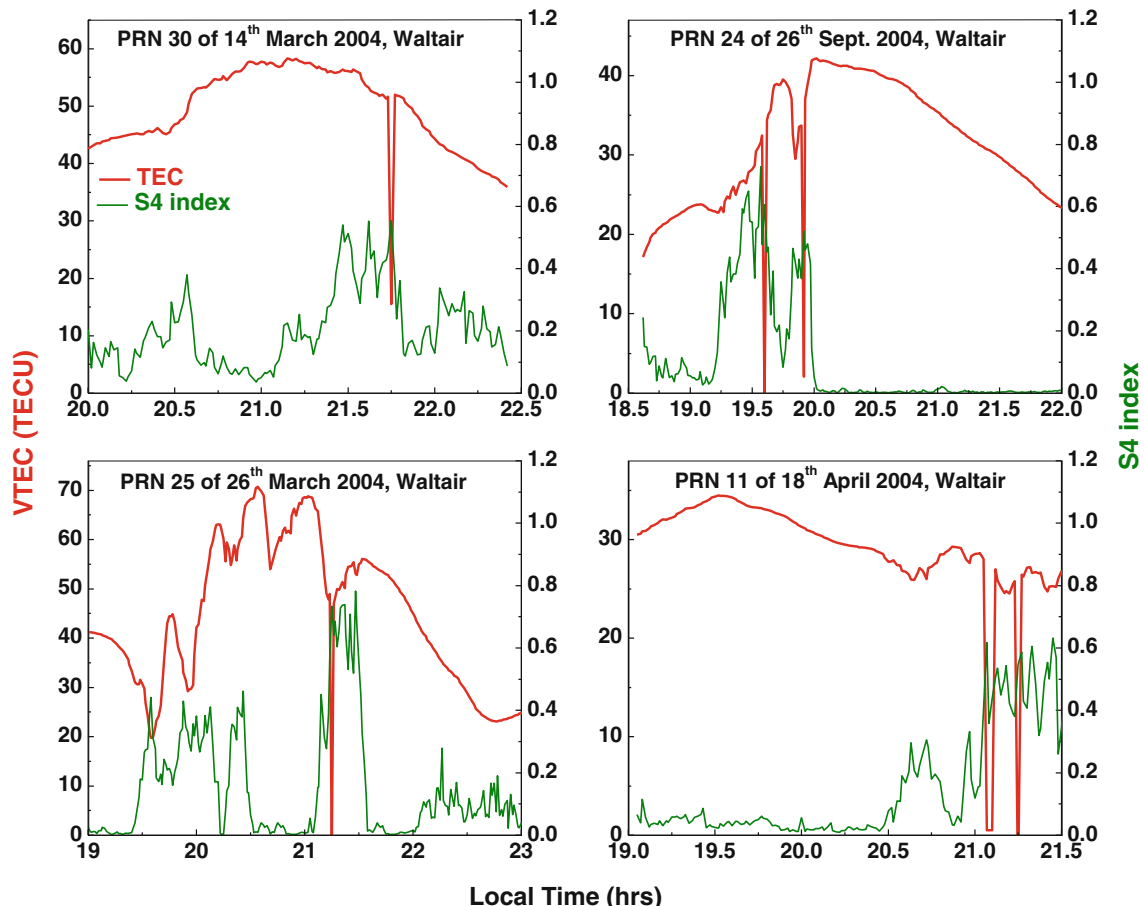


Figure 10. Typical examples of the variation of S_4 index along with TEC showing the loss of locks in the GPS receiver over Waltair.

20:00 hr LT. The variation of $E \times B$ drift velocity (figure 9d) shows a pre-reversal enhancement of about 30 m/s around 19:00 hr LT. The spread-F on the ionograms is observed from 20:00 to 02:00 hr LT simultaneously with the occurrence of scintillation activity.

On the next day (10 September, 2004), the ambient level of ionization decreases and the day maximum values of TEC vary between 40 and 50 TECU over the three different stations while the $d\text{TEC}/dt$ in the evening hours is found to vary between 5 and 6 TECU/h. The S_4 index variations plotted for this day shows no scintillation activity at the three different stations. The maximum height attained by the F-layer over the equator on this no scintillation day is about 280 km and the corresponding pre-reversal peak in the $E \times B$ drift velocity is much less (10 m/s) compared to that of the previous day. On the following day (11 September, 2004) the day-time ambient level of TEC is high compared to that on 10 September, 2004 and the day maximum values of TEC are found to be around 45 TECU over Trivandrum, 50 TECU over Waltair and 70 TECU over Kolkata. In the evening hours, the $d\text{TEC}/dt$ is about 8.8, 9.7

and 10.2 TECU/hr over Trivandrum, Waltair and Kolkata, respectively. On this day, scintillations are observed between 20:00 and 02:00 hr LT with maximum scintillation indices of 0.4 (~ 8.5 dB) over Trivandrum and Waltair and 0.9 (~ 24 dB) over Kolkata. The F-layer over Trivandrum reaches a maximum height of 350 km around 20:00 hr LT and the corresponding pre-reversal peak in the $E \times B$ drift velocity reaches a maximum of around 24 m/s. Spread-F on the ionograms is also observed between 20:00 and 02:00 hr LT simultaneously with the occurrence of scintillations.

From the above observations in sections 3.1 to 3.3, it may be inferred that there are three major factors that can create conditions favourable for the generation of irregularities. They are (i) higher values of the ambient ionization around noon time; (ii) rapid decay in the ionization in the afternoon hours; and (iii) enhancement in the pre-reversal electric fields. In the presence of these three factors or a combination of any of these factors, there seems to be a possibility for the generation of irregularities. Although similar results have been reported earlier from different Indian locations, in the present study, both the temporal and spatial

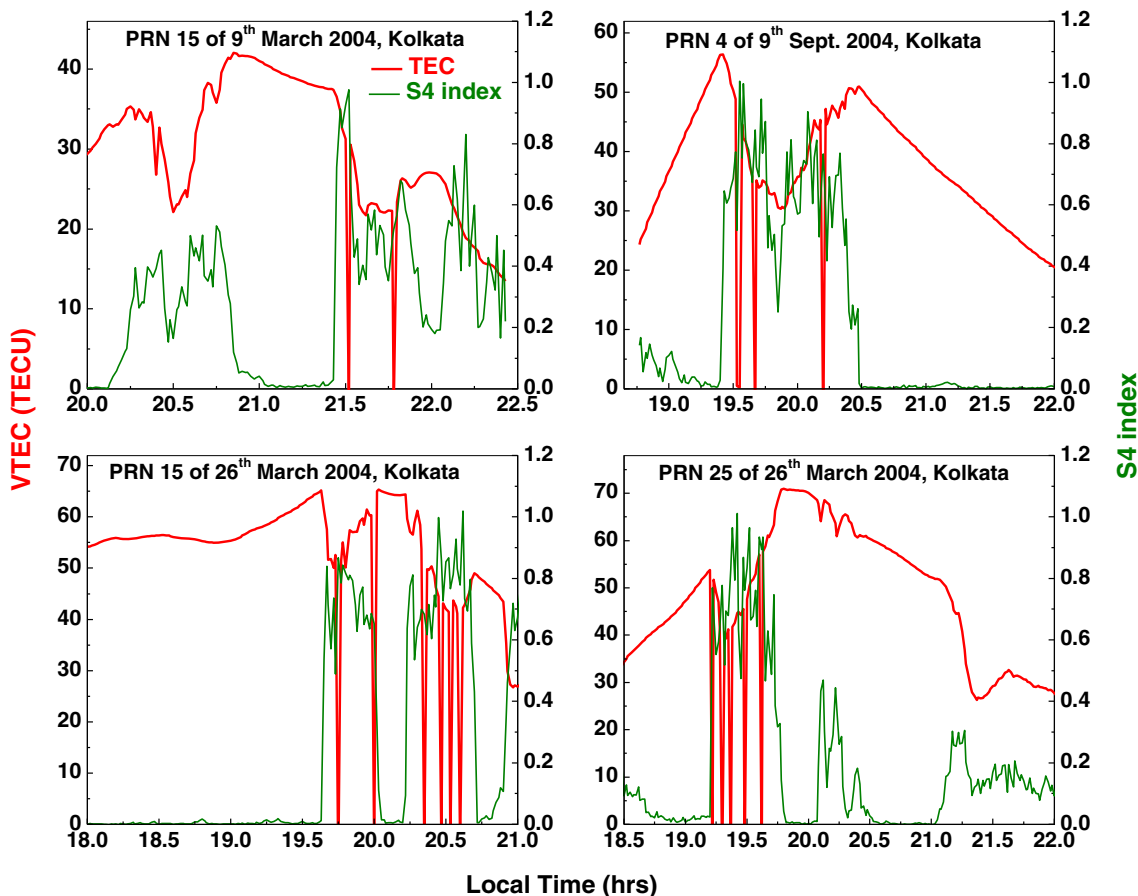


Figure 11. Typical examples of the variation of S_4 index along with TEC showing the loss of locks in the GPS receiver over Kolkata.

variability of the L-band scintillations associated with the day-to-day variations in TEC, h'F and the E×B drift velocities at the equator have been reported using simultaneous measurements over the three different chosen locations in the Indian equatorial and low latitude sectors.

3.4 Loss of lock events observed in the GPS L-band signals during intense scintillation activity

Typical examples of the loss of lock events detected in the GPS receivers over Waltair are shown in figure 10. The red coloured curves indicate the variation of TEC, while the blue coloured curves indicate the variation of S_4 index. It is seen from this figure that, whenever the S_4 index exceeds 0.5 (>10 dB power level), there is a loss of lock in the received signal. On 18 April, 2004, the receiver loses the lock of the signal from satellite PRN 11 twice within a short duration of 15 min. Similarly, typical examples of the loss of locks observed in the TEC data over Kolkata are presented in figure 11. The scintillation activity over Kolkata is severe compared to that at Waltair and the GPS receiver loses its lock more than twice in all the cases. On a typical day of 26 March, 2004, the receiver loses the lock of the signal from PRN 15 six times within a duration of about one hour and the PRN 25 losses its lock five times within a short duration of half-an-

hour. A close examination of the GPS data during the period 2004–2005 reveals that whenever the L-band scintillation activity (S_4 index) exceeds 0.5 or a 10 dB power level, the receiver loses its lock for a duration of about 1–2 min.

The TEC and S_4 index values simultaneously measured over the three different locations using the signals from the GPS satellites PRN 15 and PRN 25 on a typical scintillation night of 23 March, 2004 are presented in figure 12. Over Trivandrum, the maximum S_4 index observed from the satellite PRN 15 is 0.25 (~5 dB), while at Waltair, the S_4 index increases to 0.6 (~14 dB) and the variation of TEC shows depletions in TEC and loss of locks in the GPS receiver. The S_4 index further increases to a maximum of 0.8 (~20 dB) over Kolkata and the GPS receiver loses the lock of the signal from the satellite PRN 15, six consecutive times within a duration of about one hour. Similarly, using the signals from another satellite PRN 25 on the same day, the S_4 index observed over Trivandrum is 0.2 (~3.5 dB) and over Waltair it increases to 0.4 (~8.5 dB) whereas at Kolkata, the S_4 index increases to 0.9 (~24 dB) and the GPS receiver loses its lock six times within a short duration of half an hour, while there are no loss of locks over Trivandrum and Waltair.

Increase in the vertical drift over the equator during post-sunset hours result in the uplift of the F-layer to high altitudes creating conditions

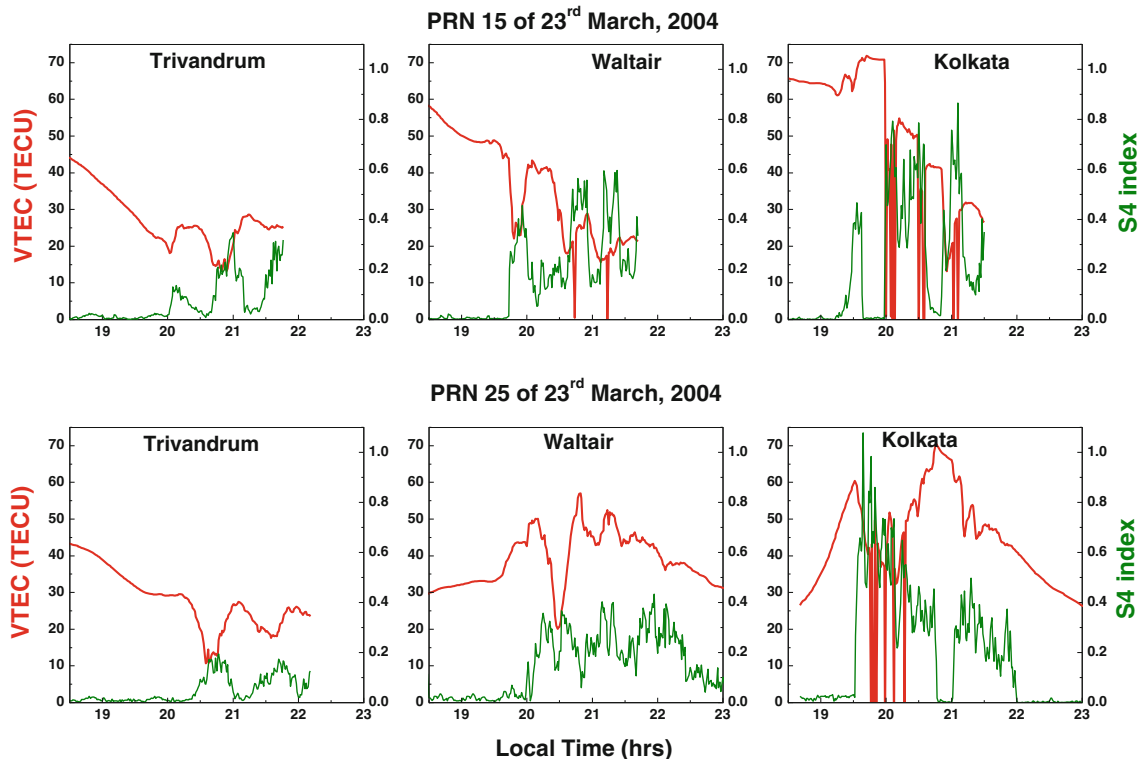


Figure 12. Variation of TEC and S_4 index over Trivandrum, Waltair and Kolkata simultaneously measured using the signals from the satellites PRN 15 and PRN 25 on a typical day of 23 March, 2004.

favourable for the generation of irregularities. These irregularities generated over the equator align along the magnetic field lines and are mapped to the latitudes away from the equator as time advances. While these irregularities are mapped from the equator along the magnetic field lines, some of the large scale structures disintegrate and form medium and small scale structures. Under this process, in addition to the large scale structures, the probability for finding the medium and small scale structures is more, at and around, the anomaly crest locations compared to that at the equator (Basu and Basu 1981; Basu *et al.* 1988). It is known that the Fresnel scale of the irregularities (Fr) is defined as $Fr = \sqrt{2\lambda z}$, where λ is the signal wavelength and z is the distance from the ground to the phase screen. Assuming a scattering layer height of 350 km, the Fresnel scale for the GPS L1 wavelength is approximately 365 m which fall under the medium scale (Kelley 1985). Thus, the GPS signals are sensitive to the medium scale size irregularities of about 400 m (Fejer 1996; Kelley 1985, 1989; Abdu 2001). Hence, at Kolkata, the scintillations in the GPS L-band signals intensify with larger S_4 index values compared to those at Trivandrum and Waltair. Basu *et al.* (1988) have also shown that the occurrence of L-band scintillation is high during the pre-midnight hours and maximizes around the EIA crest regions. Therefore, it may be expected that, at and around, the crest region of the equatorial ionization anomaly, where the S_4 index increases significantly during equinoxes and high sunspot activity periods, the loss of locks in the GPS receiver are expected to be much more. Thus, the intensified scintillations at the GPS L-band frequencies, at and around, the anomaly crest region cause more number of loss of lock events to occur in the GPS receiver signals resulting in the degradation of the performance of the communication and navigation systems.

4. Summary

The simultaneous measurements of the GPS-TEC and S_4 index over an equatorial station, Trivandrum; a low latitude station, Waltair and an anomaly crest location, Kolkata are used to study the variations of the Total Electron Content (TEC) associated with the day-to-day occurrence of scintillations. The results obtained in the present study are summarized below.

- The day-time ambient ionization is found to be higher during scintillation days compared to that during no scintillation days at the three different locations.
- The diurnal variation of TEC shows a rapid decay between 17:00 and 20:00 hr LT at a rate of more than 6 TECU/hr during scintillation days whereas it is around 4 TECU/hr during no scintillation days.
- During the post-sunset hours, the average height of the F-layer over the equator is higher (around 350 km) during scintillation days compared to that during no scintillation days (around 260 km). Simultaneously with the rapid fall in TEC, the average pre-reversal $E \times B$ drift velocity shows a maximum of about 20 m/s around 19:00 hr LT during scintillation days while it is much less (7 m/s) during no scintillation days.
- These observations reveal that (a) the level of ambient ionization around noon-time, (b) a fast decay (collapse) of the ionization during afternoon hours followed by rapid increase in the height of the F-layer contributes significantly in creating conditions favorable for the generation of irregularities.
- Further, the loss of lock events in the GPS receiver signals are observed whenever the S_4 index exceeds 0.5 (>10 dB power level) and the receiver phase lock loop recovers within a short duration of 1 to 2 min.
- It is also observed that the S_4 index at the L-band frequencies increases with latitude maximizing around the anomaly crest resulting in more loss of lock events in the GPS receiver signals.

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