Effect of Ionosphere Scintillations on the Loss of Lock-In GPS Signals at Antarctica Region

A. K. Gwal, Suryanshu Choudhary, and Ritesh Yadav

Abstract We studied the effect of amplitude and phase scintillations on the loss of lock during five most disturbed days of the December 2006. During all the disturbed days weak, moderate or intense geomagnetic storms were observed. The main findings of the study are following; during all the disturbed days the amplitude and phase scintillations of moderate intensity were observed. The amplitude and phase scintillation become frequently, the visible PRNSs does not remains stable for longer periods. The loss of lock occurs frequently whenever the GPS signals scintillate. In present studies the diurnal variation of TEC goes higher during the daytime but it decreases gradually in the Antarctica region.

Keywords Scintillations · Loss of lock · Geomagnetic storms · GPS · Radio wave

1 Introduction

Antarctica is a land of extremes; it is the highest, driest and coldest continent. In many ways, it is a Paradise of Science, and many scientific phenomena have happened, having weird and unknown facts about earth and sun relation. In between the Magnetosphere and Ionosphere, incoming solar wind particles disturb the earth ionospheric condition. Ionospheric scintillation studies in the polar region are also fascinating and provide scientific results for space weather phenomena. Many instruments and scientific payloads are capable of delivering valuable and real-time information of the polar ionosphere. The Global Positioning System (GPS) has accuracy and reliability, and its GPS receiver's performance gives a perfect image of the earth ionosphere. When a radio wave (either from the satellite or the cosmic noise, especially from the

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radio star) traverses in an irregular ionosphere (i.e. ionospheric irregularities of electron density), it develops a random phase of fluctuations across the wave-front. As the wave-front travels towards the ground, phase mixing occurs. Due to relative motion between the satellite, ionospheric irregularities and the receiver on the ground, the spatial pattern of amplitude and phase variations sweeps past the receiver and the temporal variations of phase and amplitude, which is known as scintillations. It is the single most crucial deleterious factor in utilising the earth-space propagation path.

The occurrence of scintillation occurs when the earth's ionised upper atmosphere often becomes turbulent and develops electron density. These irregularities scatter radio waves from satellites in the frequency range of 100 MHz–4 GHz (Basu et al. 1988; Aarons 1993). Scintillations are strong at high latitudes, weak at mid-latitudes and intense in the equatorial region. Scintillation at all margins attains its maximum value during the maximum solar period when the F-region ionisation density increases and the irregularities occur in a background of enhanced ionisation density. Variability of ionospheric irregularities is of grave concern to the GPS because these irregularities affect the amplitude and phase of trans-ionospheric radio (satellite) signals. Amplitude scintillation may induce signal fading, and when the depth of fading exceeds the fade margin of a receiving system, message errors are introduced in satellite communication systems. It leads to loss of lock by degrading the carrier-to-noise ratio (C/N_o) to below the receiver lock threshold (De Oliviera Moraes et al. 2011), requiring the receiver to attempt reacquisition of the satellite signals. Losing signal is a significant concern in GPS receiver navigation performance (Doherty et al. 2000; Phoomchusak et al. 2003; Aquino et al. 2005; Kintner et al. 2007). If navigation is Global Positioning System (GPS) dependent, then amplitude scintillations may lead to data loss and cycle slips (Aarons and Basu 1994). Phase scintillation, characterised by rapid fluctuations of carrier-phase, can be a source of cycle slips and sometimes affect the receiver's ability to hold a lock on a signal. Fortunately, many of the essential characteristics of scintillation are already well known (Basu et al. 1988). These studies revealed that scintillation activity varies with Season, local time, operating frequency, geographic location, magnetic activity and 11-year solar cycle. Most severe scintillations occur for a few hours after sunset in the months of equinoxes at equatorial latitudes during the peak years of the solar cycle.

It is essential to clearly understand the location, magnitude, and frequency of scintillation effects on GPS. It is desirable to have statistical tools to recognise scintillation occurrence and classify its characteristics as effectively as possible. During the high solar activity period, equatorial scintillation is adequately severe, capable of disabling many communication and navigation systems (Groves et al. 1997). The effects of small-scale plasma density irregularities on trans-ionospheric radio signals constitute a problem for a wide range of military and civilian users. The WBMOD computer code was developed beginning in the early 1970s to model these effects to provide planners and system operators a tool for assessing these irregularities' impact on their systems. The WBMOD program uses a collection of empirically derived models to describe the global distribution and behaviour of naturally occurring ionospheric irregularities and a power-law phase screen propagation model to calculate the intensity and phase scintillation estimates irregularities would impose on a user-defined system and geometry. The model outputs are estimates of intensity and phase scintillation levels and occurrence statistics for the user-defined scenario. A report on improvements made to the equatorial sections of the WBMOD model was presented at the 1993 Ionospheric Effects Symposium (Secan et al. 1995). Thus to determine the role of space weather events on scintillations is essential. Many types of research (Aarons et al. 1980; Rastogi et al. 1981,1990; Pathan et al. 1991; Kumar et al. 1993; Kumar and Gwal 2000; Banola et al. 2001; Biktash 2004; Li et al. 2006; Bhattacharya et al. 2010, 2011) have studied the geomagnetic activity effects on the occurrence of scintillation over equatorial and low latitude. A moderate amplitude scintillation (S4 ~ 0.6) may cause more than 10 m error in GPS C/A code positioning (Phoomchusak et al. 2003). Severe scintillation (S4 ~ 0.7) can lead to up-to 22 m latitude error and 14 m longitude error in GPS C/A code positioning (Dubey et al. 2006). Single point precise positioning error may reach several meters in vertical and tens of centimetres horizontally during intense ionospheric scintillation events (Moreno et al. 2010). Scintillation is severe in the equatorial region, strong at high latitudes and weak at mid-latitudes (Basu et al. 1988). High latitude aurora irregularities are formed from the precipitation of energetic electrons along terrestrial magnetic field lines into at high latitude ionosphere. These electrons are energised through a complex interaction between the solar wind and the earth magnetic field, resulting in optical and UV emissions commonly known as the auroras. This phenomenon characterises the magnetosphere sub-storm, where associated irregularities in electron density lead to scintillations (Aarons 1982). Ionosphere irregularities at high latitude are of interest for users of transmissions and those studying aeronomy. With the advent of GPS and GPS use for geodesy, a network of stations has continuously reported data.

In the polar region, irregularities are typical. These irregularities on different scale cause fluctuations in a signal whose scale is more extensive than 100–300 km and occur as deep spatial variations of TEC. High latitude and polar cap scintillation are mainly produced by geomagnetic storms associated with Coronal Mass Ejections (CME) and coronal hole. Compared to equatorial scintillation, high latitude scintillations show slight diurnal variation in their rate of occurrence. They can last from a few hours to days, and they can begin at any time (Klobuchar 1991). The development of TEC fluctuations over the Antarctica region of the earth has been studied with different satellite transmissions over several years. It is found that the intermediate phase and amplitude scintillation occurrence at high latitudes while working with three stations. He found maximum phase scintillation at Churchill studied amplitude and phase scintillation at high latitudes for seasonal patterns and distinct storms. These studies have shown correction between amplitude and TEC fluctuation occurrence. High margin and polar cap scintillation also offer a seasonal variation opposite to that observation at low latitude region, being peaked during autumn equinox through winter to the vernal equinox and found maximum during summer (Since the occurrence of geomagnetic storms is solar activity-dependent through sunspot numbers, solar flares and coronal mass ejections, aurorally and polar cap scintillation also enormously varies with the 11-year solar cycle, being on the peak during solar maxima and least occurred during solar minima.

Recently, several types of research used GPS permanent observations to study irregularities in the auroral region and utilised the GPS data at 30 s intervals to study ionospheric irregularities of electron density by computing the time rate of change of the differential carrier phase. This is equivalent to the quality of change of the total electron content, termed ROT, in units of TEC/min have demonstrated the utility of such dataset for studying the evolution of different scale irregularities during magnetic storms at high latitude. A rate of change of TEC index (ROTI) based on a standard deviation of ROT over a 5 min period. This index statistically quantifies the ROT measurements (Pi et al. 1997). The intensive phase fluctuations observed along GPS satellite passes are caused by dramatic changes in total electron content (TEC) and a solid horizontal gradient of TEC. Fluctuation effects and TEC gradient can have a different impact on GPS measurements and data processing for high-precision GPS positioning. They affect phase ambiguity resolution, increases the number of undetected and uncorrected cycle slips and loss of signal lock (Wanninger 1993; Krankowski et al. 2002). In the high latitudes phase, scintillation can be more severe than amplitude scintillation.

At low latitudes, both amplitude and phase scintillations may occur, but in general, amplitude scintillation is more severe than phase scintillation (Gwal et al. 2006; Forte 2012). Both amplitude and phase scintillations can degrade the GPS positioning performance by increasing the tracking error, number of cycle slips and the probability of losing lock. In precise GPS positioning, based on double differenced (DD) carrier-phase observables, the vital issue is to resolve the ambiguities to their integer values and derive an improved estimator of the baseline coordinates (i.e., fixed solution). Therefore, the ambiguity resolution (AR) performance determines the quantity of the resulting position coordinates. The development of TEC fluctuations and their impact on GPS signal loss of lock is presented from the data collected at Indian Antarctic Base Station, Maitri, during the solar activity period 2006.

2 Datasets and Methodology

This study evaluates GPS performance during extreme or disturbed ionospheric conditions; consequently, we have chosen five troubled days of December 2006. At the same time, we have also selected the five quietest days of the same month. During these disturbed days, the GPS performance was evaluated by considering the loss of GPS signals during the scintillation events. Irregularities of different scales characterise the disturbed ionosphere. When the GPS signals encounter these irregularities, significant changes occur in their phase and amplitude, commonly known as scintillations. The ionospheric scintillations were monitored using NovAtel's dual-frequency GISTM- (GPS Ionospheric Scintillation and TEC Monitor) based GPS receiver GSV4004A. The receiver has been widely used to monitor ionospheric scintillations and TEC in the past as well. The receiver performs amplitude and phase measurements at a 50 Hz sampling rate and measures carrier-code divergence at the 1 Hz rate for each satellite tracked on L1. It computes TEC from combined L1 L2 pseudorange and carrier phase measurements. The 12 channel is used to measure noise for C/N_o as well as scintillations computations. The receiver was installed in the sub auroral region at the Indian Antarctic Base station, Maitri (70.45°S, 11.45°E), Antarctica, during the low solar activity period 2006. Disturb and quiet days are considered for investigation and calculation of Vertical Total Electron Content (VTEC), measurement of phase and amplitude scintillation during the loss of lock for each PRN, carrier to noise ratio (C/N_o) is also measured.

3 Results

The small-scale irregularities in the electron density that usually occur during disturbed solar and geomagnetic conditions can diffract the signal, leading to rapid fluctuations in signal intensity and phase, known as amplitude and phase scintillations, respectively. Amplitude and phase scintillations can be severe enough for the received GPS signal intensity to drop below a receiver's lock threshold, forcing the receiver to lose lock. We have considered five geomagnetically disturbed days of December 2006 and investigated the effect of scintillations on lock loss during high geomagnetic activity.

3.1 15th December 2006

The 15th of December 2006 was the most disturbing day in December, as indicated by the geomagnetic indices. On this day, an intense geomagnetic storm was observed. The DST index's maximum or peak value occurred at 07:00 hrs UT with a peak value of −162 nT. The other geomagnetic indices like Kp and AE also underwent a significant increase in achieving peak values of 8.3 and 1372 nT. Therefore, this day was identified as a disturbing day. We now show the occurrence and effect of scintillation during this event on the loss of lock. Figure 1 represents the 15 min Averaged Total Electron Content's hourly variation using all visible PRNs during the 15th of December 2006. It means a usual diurnal patter with TEC achieving a peak of about 28 TECU around 12:00 hrs UT.

3.2 Average VTEC (15 Min) 15 Dec 2006

Figure 2 shows the temporal variation of amplitude and phase scintillation indices along with the VTEC observed by all visible PRNs at Maitri, Antarctica, on the 15th of December 2006. The S4 represents the amplitude scintillation, and the Phi

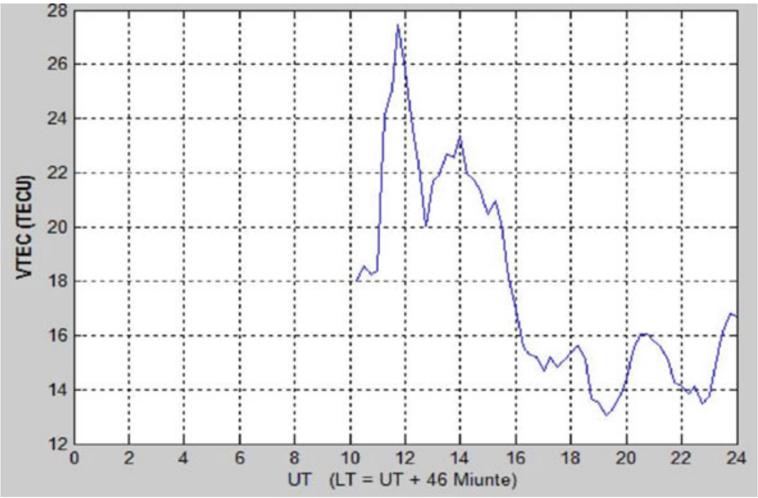

Fig. 1 The diurnal variation of total electron content (VTEC) on the 15th of December 2016

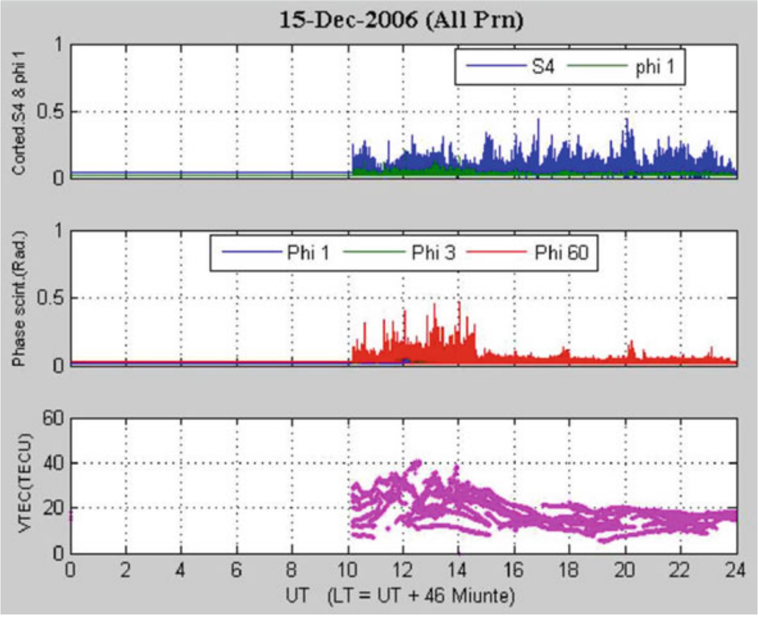

Fig. 2 Temporal variation of amplitude and phase scintillation indices along with VTEC

1, Phi 3 and Phi 60 represent the phase scintillation at 1, 3 and 60 s, respectively. From the figure, we find that all the S4 index undergoes rapid fluctuation, and it reaches a threshold of about 0.5 between 16:00 to 20:00 hrs UT. Similarly, the phase scintillation indices also reach the point of 0.5 during 10:00 to 15:00 hrs UT, indicating moderate scintillation during this period. The bottom panel of the figure shows the variation of VTEC calculated from different PRNs visible at Maitri. The value of VTEC is highest during 10:00 to 14:00 hrs UT with an apparent dip around 12:30 hrs. During this dip of VTEC, the scintillation activity increases.

3.3 15 Dec, 2006 (All PRN)

The relevant effect of these scintillations on the loss of lock can be seen in Fig. 3, where the product is described by the C/N_o ratio and safety time for different visible PRN's. The C/N_o ratio goes less than 40 dB and remains disturbed during the time of occurrence of scintillations. The locked PRN's do not seem to be stable for more extended periods, as shown in blue colour and breaking of lock occurs continuously during the amplitude and phase scintillation of the signals.

Different PRNs showing loss of lock (in TEC curve) with the rise in scintillation have been demonstrated in Fig. 4. Their Azimuth and Elevation angle has also been shown in Figs. 5a, b, c, d, e, respectively.

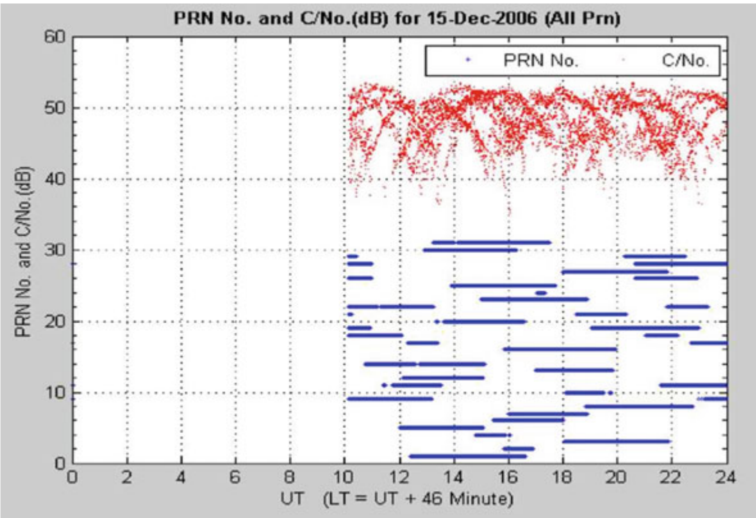

Fig. 3 The C/N0 ratio and lock time for different visible PRNs

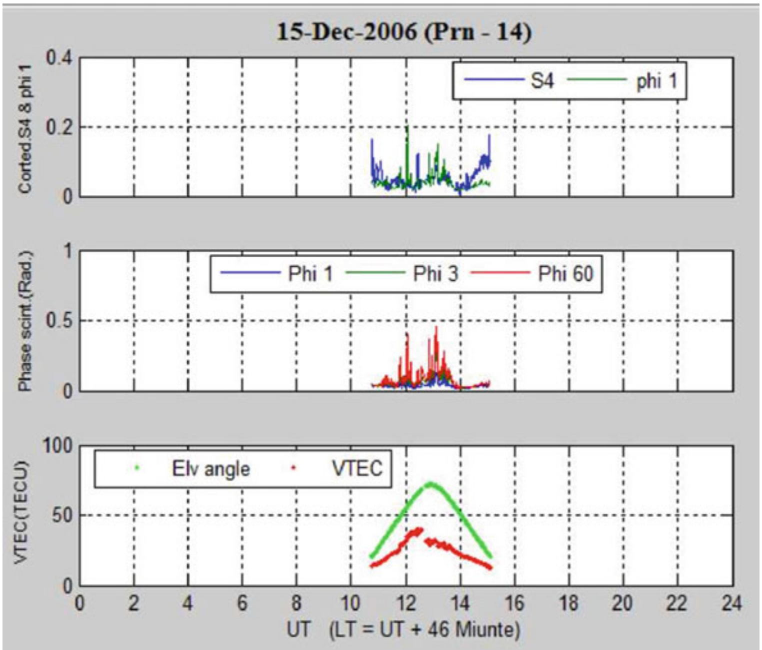

Fig. 4 RNs showing loss of lock-in TEC curve with the rise scintillation

3.4 14th December 2006

We then identified another disturbing day and presented the effect of geomagnetic activity on the loss of lock. The 14th of December 2014 was selected as the second case for this investigation. It was the second most disturbing day of December 2006, as indicated by various geomagnetic indices. The variation of Storm intensity index Dst showed a moderate geomagnetic storm. The peak value of Dst was found to be −69 nT at 23:00 hrs UT. The interpretation of other indices also showed that geomagnetic activity was high on this day. The peak values achieved by the Kp index and the AE index were 5.3 and 1616 nT, respectively. Therefore the day was designated as a disturbing day. Then the effect of increased geomagnetic activity was evaluated on the occurrence of scintillations and loss of lock. The temporal evolution of Total Electron Content (TEC) is represented in Fig. 6. It shows the 15 min averaged TEC computed from all the PRNs. The maximum value of TEC occurred at 08:00 hrs UT and the peak value achieved is 25 TECU. Apart from the daily peak, two other peaks can also be noticed in the diurnal pattern, one at 15:00 hrs UT and the other at 20:00 hrs UT. Moreover, a steep and sharp decrease in TEC can also be noticed around 18:00 hrs UT.

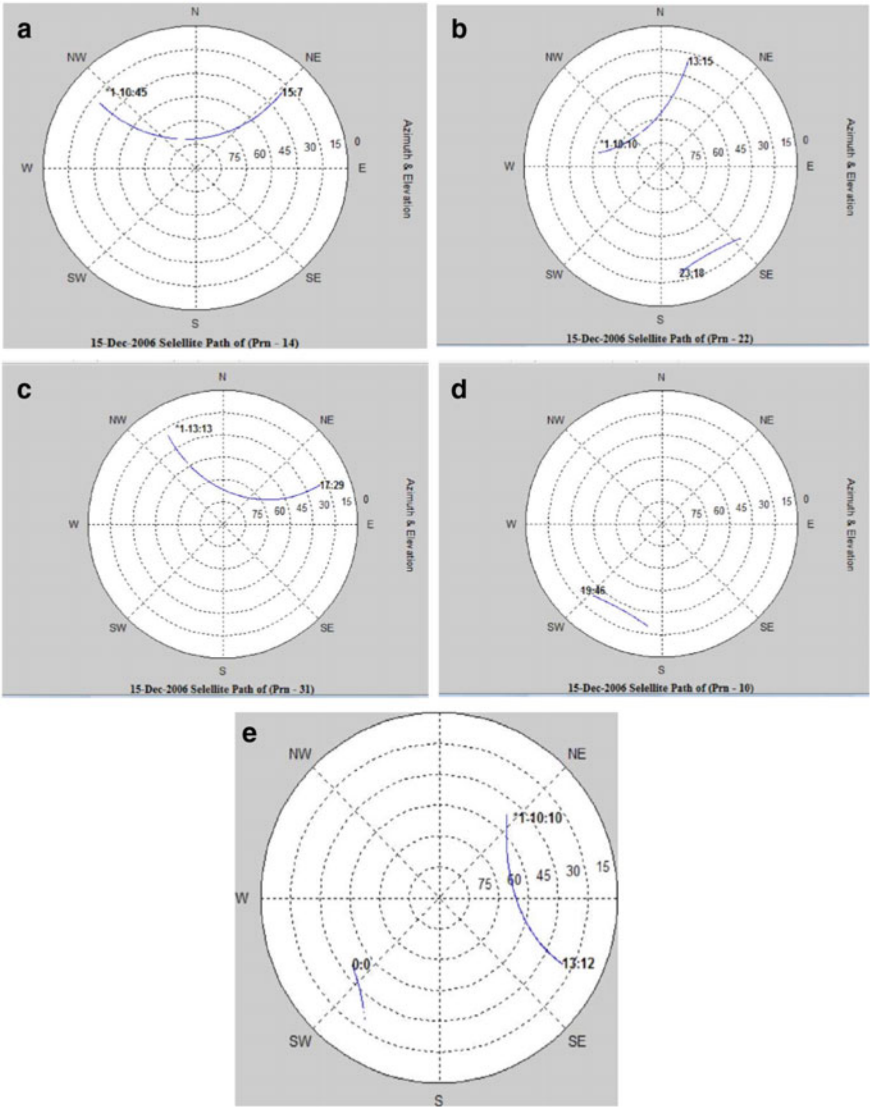

Fig. 5 **a**: Polar plot showing Azimuth and Elevation for PRN-14 during the 15th of December 2006. **b**: Azimuth and Elevation for PRN-22 during the 15th of December 2006. **c**: Azimuth and Elevation for PRN-31 during the 15th of December 2006. **d**: Azimuth and Elevation for PRN-10 during the 15th of December 2006. **e**: Azimuth and Elevation for PRN-09 during the 15th of December 2006

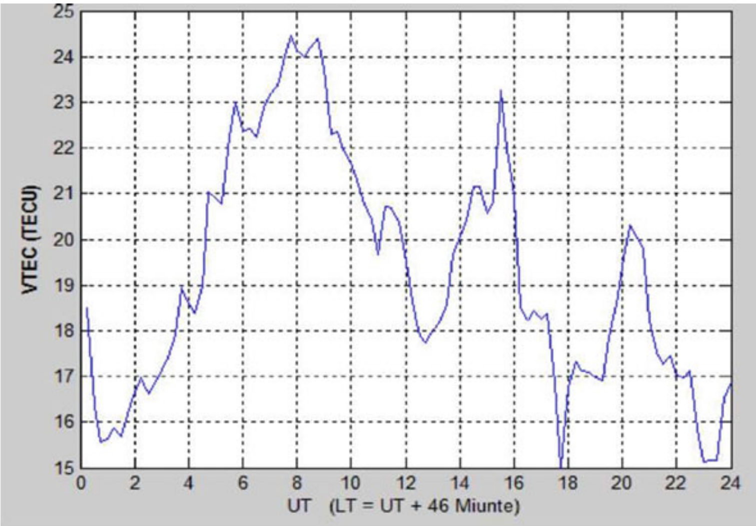

Fig. 6 The diurnal variation of total electron content during the 14th of December 2006

3.5 Average VTEC (15 Min) 14 Dec 2006

The occurrence of scintillations and the VTEC from different visible PRNs is shown in Fig. 7. It shows the temporal changes in the amplitude scintillation index S4 and phases scintillation index phi. The phase scintillation index phi is calculated at 1, 3 and 60 s. From the figure, we notice that both the scintillation indices increase around 18:00 hrs UT to about 0.5 thresholds indicating the occurrence of moderate amplitude and phase scintillations. The scintillation was also observed around 23:00 hrs UT when the geomagnetic storm was in its peak phase. The occurrence of this scintillation corresponds to the depletion in TEC. The values of the S4 index fluctuate continuously throughout the day, indicating the event of weak scintillations.

The effect of amplitude and phase scintillations on the loss of lock is shown in Fig. 7 and changes in the C/N_o ratio along with locked PRN's during the 14th of December 2006. The red dots show the C/N_o ratio, while the blue diamond's show the lock of locked PRNs. From the figure, we notice that C/N_o falls below 40 dB and shows rapid fluctuations during the scintillations.

The lock time of the visible PRN's at Maitri during the time of scintillation, particularly during the main phase of the geomagnetic storm, is not stable for more extended periods. The lock brakes regularly. Therefore, we conclude that the occurrence of amplitude and phase scintillation during the 14th of December 2006 resulted in the loss of locks of the visible PRNs at Maitri, Antarctica, and at different PRN's their Azimuth and Elevator angle has been shown in Figs. 8a, b, c, d, e respectively.

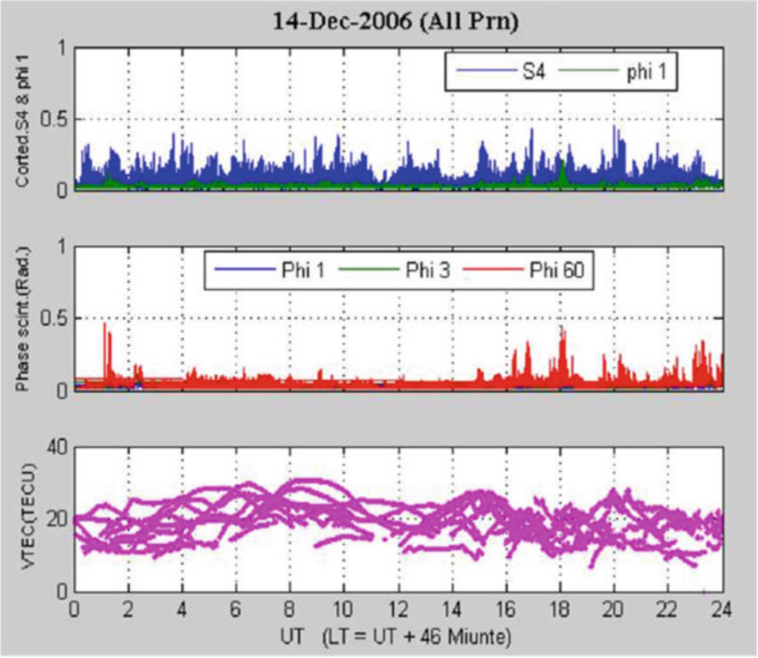

Fig. 7 The C/N_0 ratio and lock time for different visible PRN

3.6 12th December, 2006

The occurrence of amplitude and phase scintillation is shown in Fig. 9, along with the time profile of VTEC of the different PRNs visible at PRNs during the 12th of December 2006. The S4 index describes the occurrence and intensity of amplitude scintillations while the phase scintillations are described by Phi 1, Phi 3 and Phi 60 at 1, 3 and 60 s, respectively. We can quickly notice amplitude scintillations of moderate intensity of 0.5 around 17:00 hrs UT and 21:00 hrs UT from the figure. Similarly, phase scintillations can also be found to occur between 20:00 hrs UT to 23:00 hrs UT. The occurrences of these scintillations correspond to the recovery phase of the geomagnetic storm. Around the same time, the AE index, specific to high latitude regions, peaked at its peak value. Thus during increased geomagnetic activity, particularly at high latitudes, the occurrence of scintillations is quite frequent. At the same time, we found that there is a decrement in VTEC.

The relevant effect of the scintillations of moderate-intensity is evaluated in Fig. 10 and demonstrates the impact of the C/N_0 ratio and the loss of lock. The red dots represent the C/N_0 ratio in decibels, while the blue diamond's show the lock time of different PRN's visible on the 12th of December 2006 at Maitri station. From the figure, we find that the C/N_0 ratio falls below 40 dB and fluctuates rapidly around the time when the amplitude and phase scintillation become frequent. We also notice

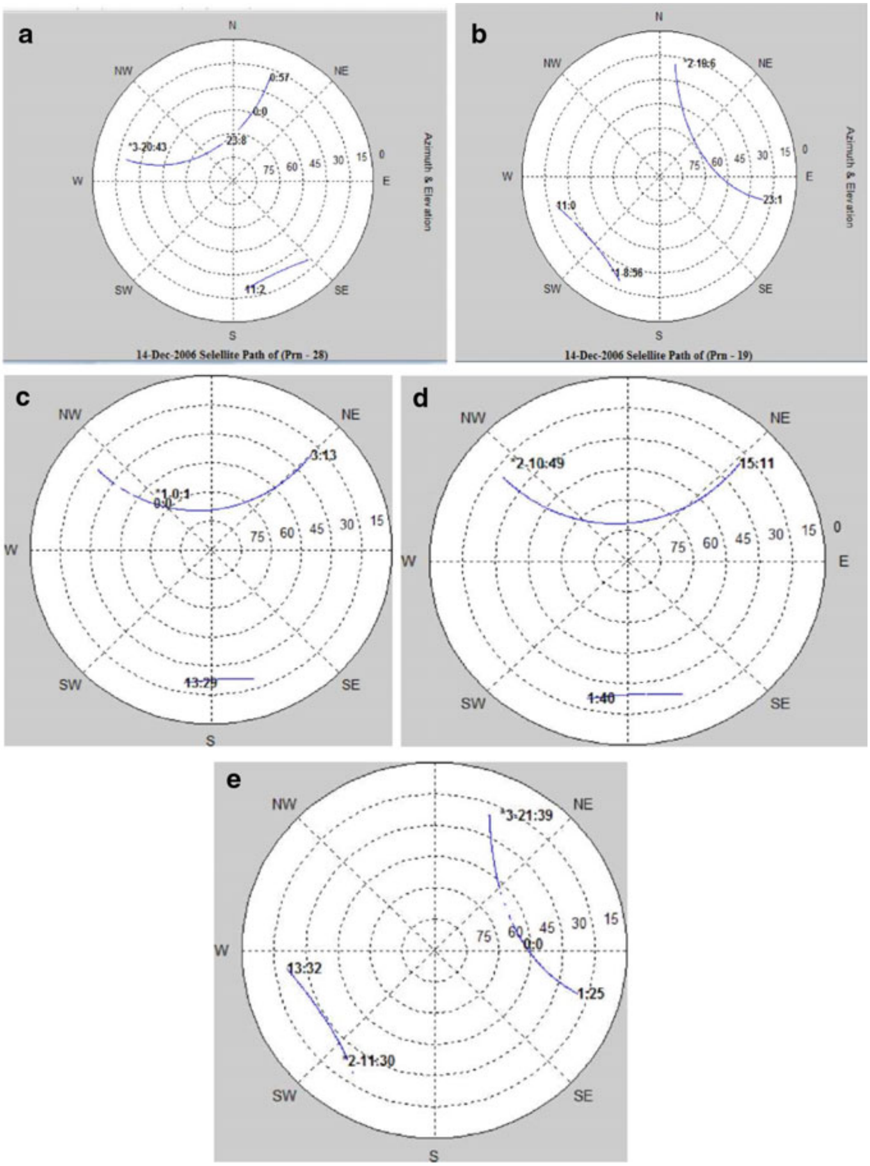

Fig. 8 **a**: Azimuth and Elevation for PRN-28 during the 14th of December 2006. **b**: Azimuth and Elevation for PRN-19 during the 14th of December 2006 **c**: Azimuth and Elevation for PRN-17 during the 14th of December 2006. **d**: Azimuth and Elevation for PRN-14 during the 14th of December 2006. **e**: Azimuth and Elevation for PRN-11 during the 14th of December 2006

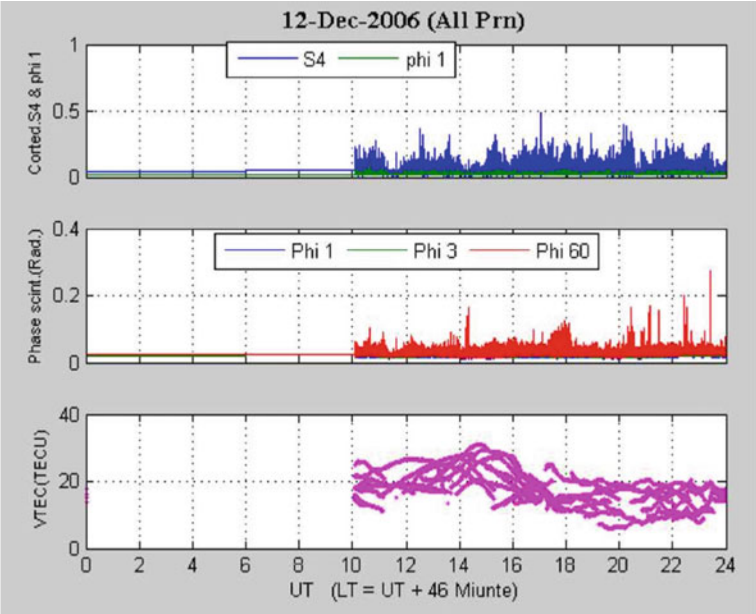

Fig. 9 Temporal variation of amplitude and phase scintillation indices along with VTEC

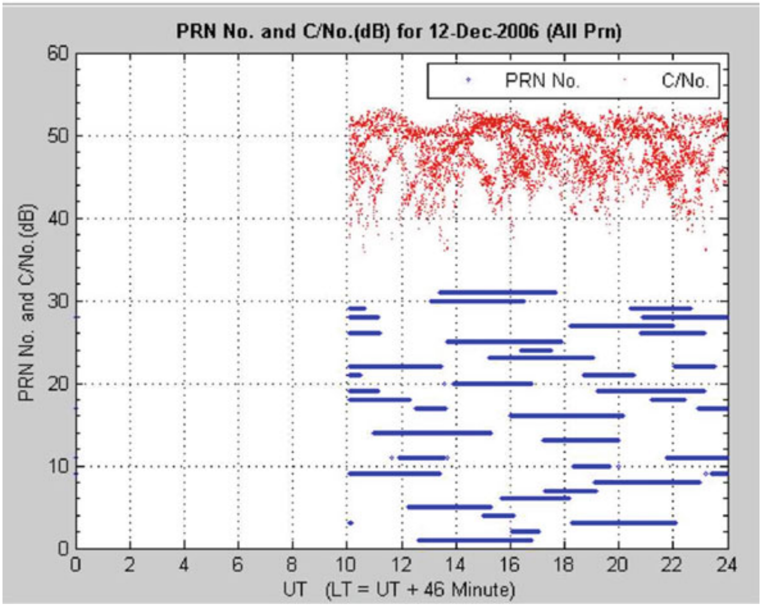

Fig. 10 The C/N_0 ratio and lock time for different visible PRN's

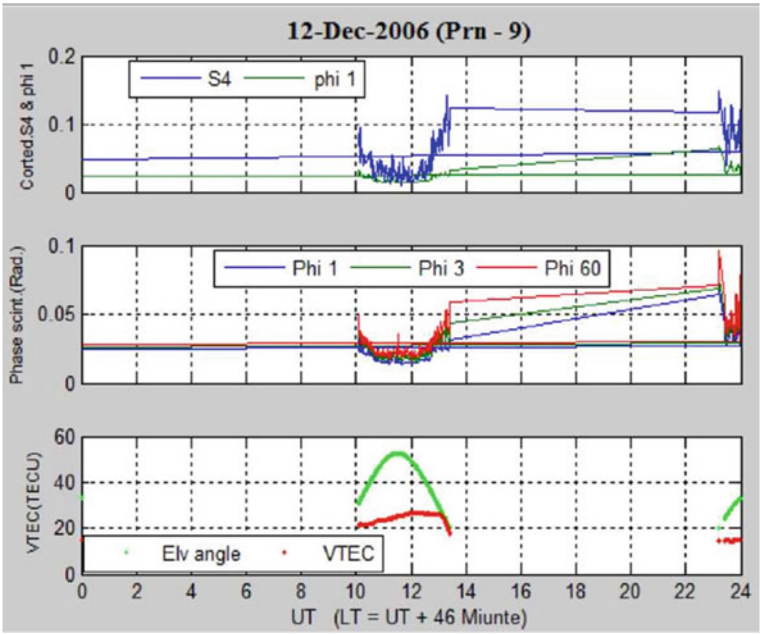

Fig. 11 PRN's showing loss of lock-in TEC curve with the rise scintillation

that the PRN lock is also not stable for more extended periods during the existence of phase and amplitude scintillations. The certainty of the PRN's visible at this particular time is lost frequently. Different PRN's showing loss of lock (in TEC curve) with the rise in scintillation has been shown in Fig. 11.

3.7 06th December 2006

The last event considered for this study is the 06th of December 2006. It was also a disturbing day, as indicated by the temporal variation of different geomagnetic indices like Dst, Kp and AE. It was identified as the fifth most worrisome day of December 2006. The Dst achieved its peak value of −55 nT at 12:00 hrs UT indicating a geomagnetic storm of moderate intensity. Kp and AE indices' value was also well above their typical or average values and recorded 4.7 and 810 nT's peak values. Therefore, from the variation of all these geomagnetic indices, we conclude that the 06th of December 2006 was disturbing.

The hourly variability of the VTEC during the 06th of December 2006 is shown in Fig. 12. The figure describes the behaviour of 15 min averaged TEC calculated from the observations of all the visible PRNs at Maitri, Antarctica. From the model, we find that the VTEC follows a regular diurnal pattern with a daily peek at 14:00 hrs

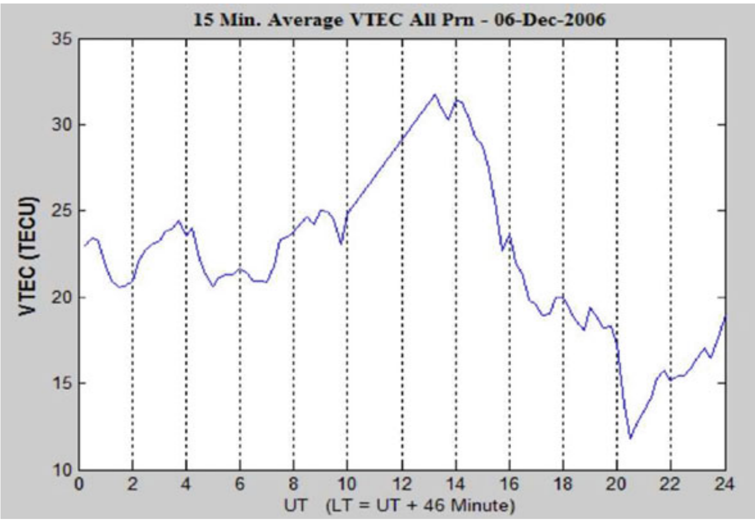

Fig. 12 The diurnal variation of total electron content during the 06th of December 2006

UT and takes a peak value of 32 TECU, which is comparatively higher than observed in previous events. A sharp decrement can also be observed in VTEC around 20:00 hrs UT with TEC's value decreasing to 12 TECU. The Azimuth and Elevator angle has been shown in Figs. 13a, b, respectively.

3.8 PRN No. and C/No. (dB) for 07-Dec-2006 (All PRN)

The occurrences of scintillations are shown in Fig. 14. It describes the amplitude scintillation by the S4 index while phi1, phi 3 and phi 60 relate phase scintillations at 1, 3 and 60 s, respectively. From the figure, we notice that the phase scintillations of moderate-intensity at all three thresholds occur around 20:00 hrs UT as well as 04:00 hrs UT. It is the same time at which the decrement is VTEC can be observed from the bottom panel. The weak amplitude scintillations are frequent throughout the day; however, amplitude scintillation of moderate to vigorous intensity can occur between 18:00–22:00 hrs UT. Different PRNs showing loss of lock (in TEC curve) with the rise in scintillation has been demonstrated in Figs. 15a, b, c, d, e.

4 Conclusions and Discussion

We studied the effect of amplitude and phase scintillations on lock loss during the five most disturbing days of December 2006. During all the hectic days, weak,

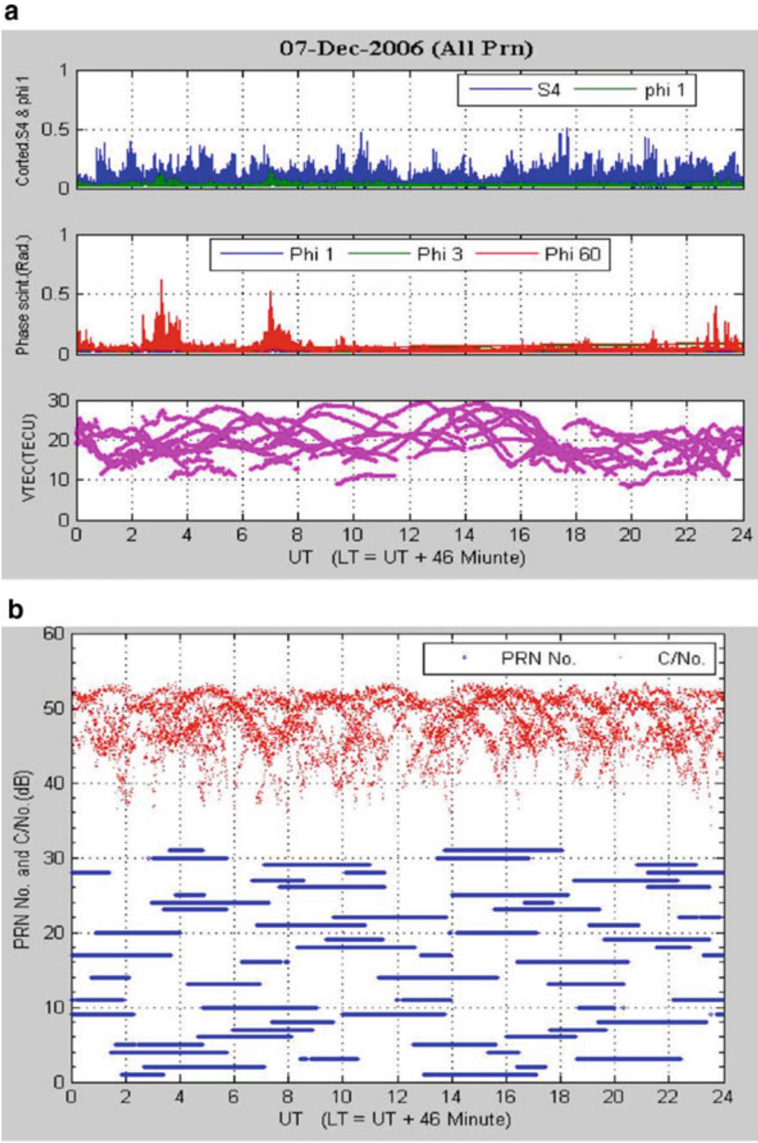

Fig. 13 **a**: Temporal variation of amplitude and phase scintillation indices along with VTEC. **b**: The C/N_0 ratio and lock time for different visible PRN's

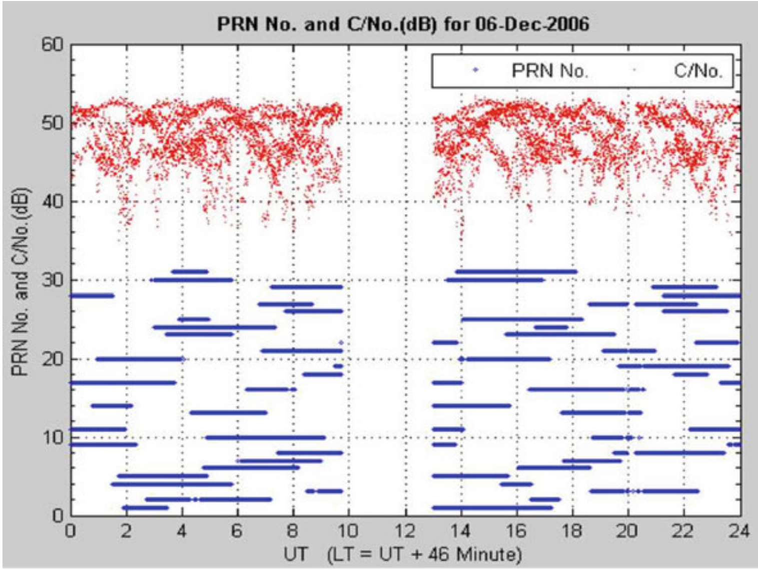

Fig. 14 The C/N_0 ratio and lock time for different visible PRN's

moderate or intense geomagnetic storms were observed. The study's main findings are summarised below: During all the disturbed days, the amplitude and phase scintillations of moderate-intensity were observed. The occurrence of these scintillations usually corresponds to the decrement in the value of VTEC. The value of the C/No ratio describing the effect of the scintillations was found to fall below 40 dB during all the selected events.

Moreover, it was also found to fluctuate rapidly during the occurrence of both amplitude and phase scintillations. The loss of lock was significantly affected by the occurrence of scintillation during all the events. The amplitude and phase scintillation become frequent, and the visible PRNSs do not remain stable for more extended periods. The loss of lock frequently occurs whenever the GPS signals scintillate. In present studies, TEC's diurnal variation goes higher during the daytime, but it decreases gradually in the Antarctica region. Temporal variations were also observed in amplitude and phase scintillation indices. This study presents the daily and seasonal variation in GPS-measured TEC over the Antarctica region using simultaneous GPS receivers measurements. Observations revealed that the diurnal variation at high latitude station reached its maximum value between 12:00 and 14:00 LT.

Similarly, the daily minimum in GPS TEC occurs between 05:00 and 06:00 at the same station. The diurnal variation in GPS TEC shows a range of about 0–60 TECU. The latitudinal and longitudinal variations show a sharp, steep increase of about 12–16 TECU occurring between 01:00 and 02:00 LT. An intense and short-lived daytime minimum of about 0–2 TECU occurs between 04:00 and 06:00 LT. TEC increases with time across all the longitudes until noon-time. The speed and

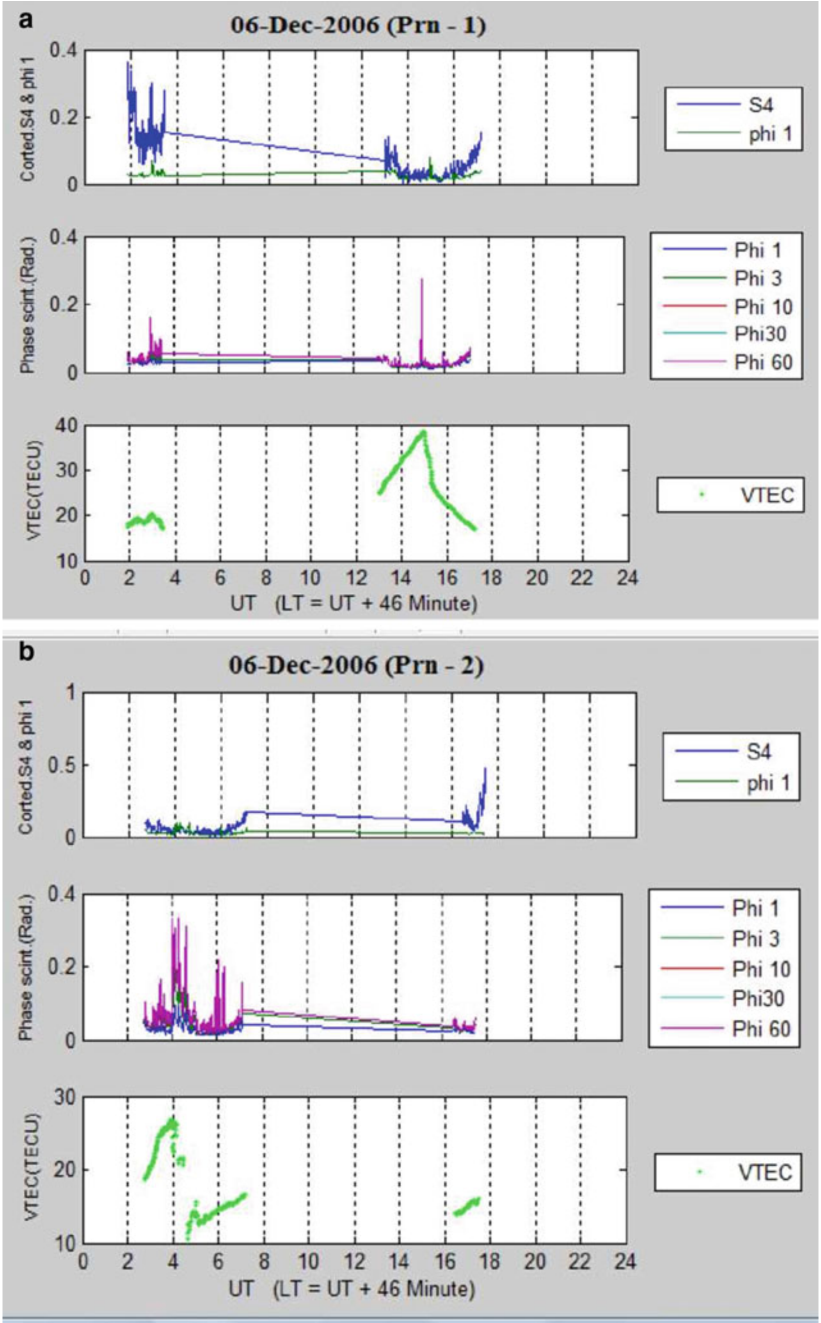

Fig. 15 **a**: PRNs showing loss of lock-in TEC curve with the rise scintillation. **b**: PRNs showing loss of lock-in TEC curve with the rise scintillation. **c** PRNs were showing loss of lock-in TEC curve with the rise scintillation. **d**: PRN's showing loss of lock-in TEC curve with the rise scintillation. **e**: PRNs showing loss of lock-in TEC curve with the rise scintillation

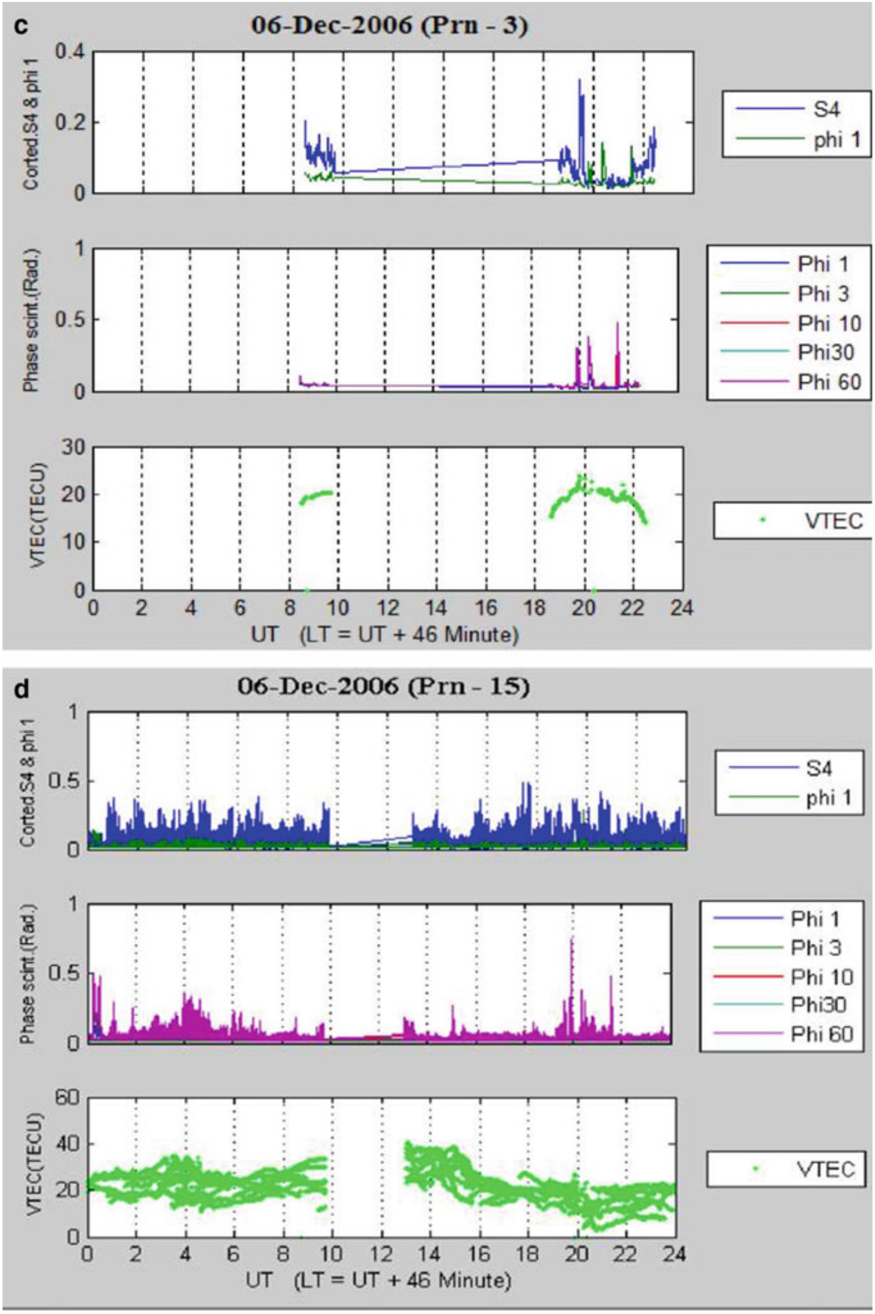

Fig. 15 (continued)

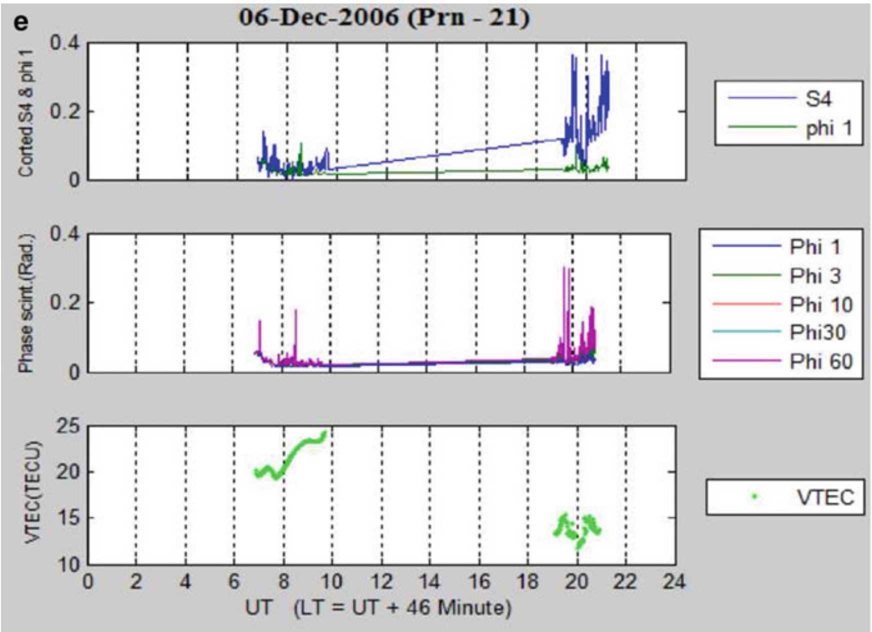

Fig. 15 (continued)

propagation path of the GNSS signals in the ionosphere depend upon the number and distribution of free electrons in the course, or Total Electron Content (TEC). Changes in the TEC result in variable time delays in the signal propagation due to refraction. The interplanetary electric field's increase drives an eastward electric field on earth's dayside that reaches equatorial latitudes. The near-horizontal magnetic field at low latitude combined with the eastward electric field renders the vertical plasma transport (E × B) very effective in lifting the plasma to higher altitudes. The seasonal variations show that TEC reaches a maximum during the equinox months and is lowest during the solstice months, revealing an asymmetric semi-annual pattern.

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