Ionospheric irregularities at Antarctic using GPS measurements

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The purpose of this work is to study the behaviour of the ionospheric scintillation at high latitude during geomagnetically quiet and disturbed conditions which is one of the most relevant themes in the space weather studies. Scintillation is a major problem in navigation application using GPS and in satellite communication at high latitudes. Severe amplitude fading and strong scintillation affect the reliability of GPS navigational system and satellite communication. To study the effects of the ionospheric scintillations, GPS receiver installed at Antarctic station Maitri (Geog. 70.76°S; 11.74°E) was used. The data is collected by using GISTM 4004A, NOVATEL'S GPS receiver during March 2008. Studies show that percentage occurrence of phase scintillation is well correlated with geomagnetic activity during the observation period. The result also shows that very intense scintillations can degrade GPS based location determination due to loss of lock of satellites. These findings indicate that the dependence of scintillations and irregularity occurrence on geomagnetic activity is associated with the magnetic local time (MLT). Large number of patches are reported and their activity depends on the magnetic activity index.

1. Introduction

High latitude ionosphere is highly dynamic owing to the direct precipitation of highly energetic particles. The geomagnetic field lines being vertical at high latitude region causes the polar areas to be characterized by the presence of ionospheric irregularities. The high latitude plasma structures associated with auroral and polar cap F-region patches and sun-aligned arcs are sources of scintillation that have been observed at UHF frequencies (Basu *et al* 1987; MacDougall 1990; Coker *et al* 2004). Sometimes when a radio signal passes through the disturbed ionosphere, the received signal will show rapid fluctuations in amplitude and phase that are not consistent with the source strength or modulation. These fluctuations of the radio signals are known as scintillations. Occurrence of scintillations at high latitude relates with auroral oval, cusp and polar cap patches. Polar cap patches are large regions of enhanced F region plasma density and were observed to travel through the ionospheric polar caps (Pederson *et al* 2000). It is well known that the scintillation of satellite radio signal is a consequence of the existence of random electron density fluctuations within the ionosphere. These large scale polar patches are responsible for the formation of horizontal TEC gradients along with the enhancement of TEC with respect to the background ionization which leads to phase as well as amplitude scintillation as reported by many researchers (Krankowski *et al* 2006; Mitchell 2007; De Franceschi *et al* 2008). Since ionospheric scintillation can cause considerable communication hazards on radio systems and is therefore of great practical interest (Banerjee *et al* 1992). It is generally

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recognized that further research about scintillation and irregularities that produce scintillation is required.

In recent years, observation of GPS scintillations at high latitudes were reported by many authors (Wernik *et al* 2004; De Franceschi *et al* 2006; Meggs *et al* 2008; Spogli *et al* 2009; Li *et al* 2010; Gwal and Jain 2011). Evidence indicates that the dayside auroral oval plays a major role in the formation of large scale ionization structures (patches) in the polar ionosphere (Weber *et al* 1984). These structures convect across the polar cap and cause destabilization of the plasma, then develop intermediate scale irregularities (responsible for scintillation of radio signals) by the action of the gradient drift instability mechanism (Tsunoda 1988). The destabilization process also includes the current convective and the Kelvin–Helmholtz instability (Basu *et al* 1986). It is established that precipitation of soft particles into the F-region may play a direct role in irregularity formation (Basu 1983; Kersley *et al* 1988). Using GPS observations from 11 high latitude stations, Aarons (1997) noted that phase fluctuation activity has a daily pattern mainly controlled by the motion of the receiver location into the auroral oval. Geomagnetic storms produce strong ionospheric irregularities at auroral latitudes and also affect ionosphere at equatorial latitudes particularly in post-midnight period (Basu *et al* 2001). Our present study focuses on the construction and discussion of 'scintillation occurrence maps' for both the scintillation indices over the period under investigation, also considering the contribution of disturbed and quiet days. The scintillation maps provide information on the cusp/cap effect and on the expansion of the auroral oval.

We used data from the Indian station Maitri (70.76°S; 11.74°E), at Antarctica, which occupies a subauroral location during magnetically quiet conditions ($\Sigma Kp < 10$), but attains an auroral position when the auroral oval shifts equatorwards with increasing strength of magnetic disturbance. The aim of our analysis is to better understand the morphology of irregularities at auroral region.

2. Data selection and processing

Scintillation and TEC data are recorded during March 2008 by a GPS Ionospheric Scintillations and TEC monitor system (GISTM); model GSV4004A (Van Dierendonck *et al* 1993) installed at Maitri (MAIT) in Antarctic has been used to study the scintillation activities. The GISTM receiver is modified high performance NOVATEL OEM4 dual frequency GPS C/A code receiver equipped with wide bandwidth tracking loop that measures amplitude and phase scintillation parameters in real time. This system is capable of tracking up to 11 GPS satellites at the L1 frequency of 1575.42 MHz and L2 frequency of 1227.60 MHz. Amplitude scintillation is measured by S4 index defined as the standard deviation of the received signal power normalized to average signal power and is computed over 60-second intervals which we call as $(\mathrm{S4})_{\mathrm{tot}}$. Receiver also computes the correction to S4 which includes the ambient noise denoted as $(\mathrm{S4})_{\mathrm{cor}}$ (NovAtel 2003). The corrected S4 (ambient noise free) is then calculated as follows:

$$(\mathrm{S4}) = \sqrt{(\mathrm{S4})_{\mathrm{tot}}^2 - (\mathrm{S4})_{\mathrm{cor}}^2},$$

where $(\mathrm{S4})_{\mathrm{tot}}$ and $(\mathrm{S4})_{\mathrm{cor}}$ are total and corrected S4, respectively. In the present study, we have considered only those cases which have amplitude scintillation index $\mathrm{S4} > 0.25$. Phase scintillation measurements are obtained by monitoring measurements of the standard deviation and the power spectral density of detrended carrier phase from received signals. The phase scintillation index σ_φ are computed over 1, 3, 10, 30 and 60-second intervals and our analysis is based on the 60 s σ_φ values. The value of σ_φ can vary from 0.05 radians for very weak scintillation to 1.0 radian for a strong scintillation.

We have plotted maps of occurrence of the scintillation indices in magnetic latitude (MLat) *vs.* magnetic local time (MLT) similar to the maps constructed by Spogli *et al* (2009). MLT is the time given with the sun's position relative to the magnetic pole. Universal Time (UT) measures time using the rotation of the earth around its axis whereas MLT measures not time but position relative to the sun. The UT variation depends on the separation of the geographic and magnetic poles (Hunsucker and Hargreaves 2003). The daily variation of the F-region depends on universal time as well as on local time. The UT variations when viewed in terms of MLT will be physically meaningful. The percentage of occurrence is evaluated for each bin of 2 hrs MLT × 2° MLat, as:

$$\frac{N(\mathrm{S}_4 \text{ or } \sigma_\varphi > \text{threshold})}{N_{\mathrm{tot}}},$$

where $N(\mathrm{S4} \text{ or } \sigma_\varphi > \text{threshold})$ is the number of data points corresponding to a scintillation index above a threshold, while N_{tot} is the total number of data points in the bin. The selected thresholds are 0.2 radians for σ_φ and 0.25 index for S4. A threshold value of 0.25 and 0.2 rad for amplitude and phase scintillation satisfies the need of a meaningful sample and the necessity of distinguishing moderate/strong scintillations. The scintillation occurrence maps are superimposed to the position of the

Feldstein auroral oval (Feldstein 1963; Holzworth and Meng 1975) for two different levels of magnetic activity (IQ), to investigate the ionospheric regions more affected by scintillation. We choose IQ = 3 as representative of the quiet ionosphere and IQ = 6 for the disturbed ionosphere, and we refer this two ovals as quiet oval (IQ = 3) and disturbed oval (IQ = 6). The elevation angle of the satellites is taken greater than 30° for scintillation studies in order to minimize the errors due to multipath, which generally occurs for lower elevation angle.

TEC is the measure of the number of electrons in a vertical column having a one square meter cross section, extending all the way from the GPS satellite to receiver and is reported in TEC units ($1 \text{ TECU} = 1 * 10^{16}$ electrons/m^2). The TEC is computed from the combined L1 and L2 pseudo ranges and carrier phase. This slant TEC (STEC) was then converted to an equivalent vertical TEC (VTEC) and is therefore mathematically given by:

$$\text{VTEC} = \cos \chi . \text{ STEC},$$

where χ is the angle of incidence at 400 km altitude of GPS ray path from satellite to ground receiver; $\cos\ \chi$ an oblique factor, is defined as (Jakowski 1996):

$$\cos\ \chi = \sqrt{1 - \left(\frac{R_E . \cos(e)}{R_E + H_{\text{iono}}}\right)^2}$$

where R_E is the radius of the Earth, e is the elevation angle of the satellite and H_{iono} is the height of ionospheric penetration point usually assumed to be 400 km. The elevation angle of the GPS satellite plays an important role in determination of the ionospheric pierce point (IPP) altitude. For the purpose of TEC analysis, ionospheric data is considered above 20° elevation of satellites. To detect the presence of the irregularity we used phase fluctuations, and rate of change of TEC (ROT) is used to calculate the size of irregularity which is measured in TECU/min (Aarons and Lin 1999; Krankowski *et al* 2006).

3. Results and discussion

3.1 *GPS scintillation in the auroral region*

Figure 1 shows the contour of percentage occurrence of amplitude scintillation (S4) and percentage occurrence of phase scintillation σ_φ with the overlapping of Feldstein disturbed (red) and quiet (grey) ovals. The left plot shows S4 and right plot shows σ_φ over Maitri. It is clear from figure 1 that the auroral region covered by the station gives rise to more signal phase scintillation than the amplitude scintillation (∼0.18% peak occurrence for amplitude and ∼1.5% for phase), confirming the results of several studies (Doherty *et al* 2000; Li *et al* 2009; Spogli *et al* 2009). The general behaviour of both the indices is significantly different; the S4 map seems to be confined in well defined region while the σ_φ map shows a strong characterization both in MLat and MLT.

Amplitude scintillations were caused by irregularities in the range of Fresnel dimension to a dimension smaller by about a decade which constitutes irregularities with scale sizes of the order of several hundred meters to several tens of meters

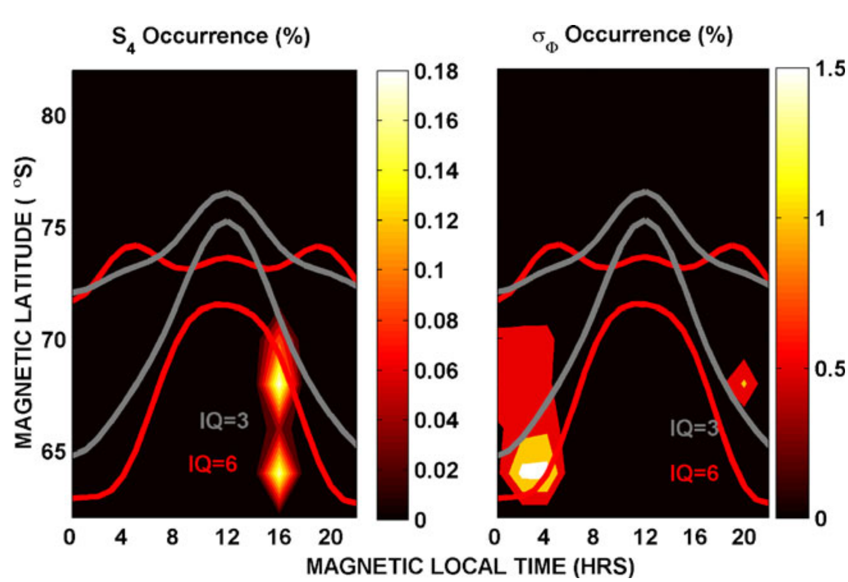

Figure 1. Contour of occurrence of amplitude scintillation (left panel) and phase scintillation (right panel) at Maitri during March 2008. Maps are overlapped with the Feldstein auroral ovals for quiet (grey) days and disturbed (red) days.

(Aarons 1997; Basu *et al* 1998). These irregularities are common at high latitude regions which suggests that the occurrence of weak amplitude scintillation may be due to small scale irregularities present in the auroral regions. Figure 2 shows the contour of occurrence of S4 for quiet and disturbed days mapped with the Feldstein ovals. It is clear from figure 2 that at Maitri, the percentage occurrence of S4 for both quiet and disturbed days is enhanced around 16 MLT hrs and is not confined to the area. The observed noon peak in scintillation occurrence possibly indicates that the irregularities producing scintillation may be caused by the precipitation into the daytime cusp/cleft region. During the quiet days, the S4 activity is maximum (∼62°–70°S) and is shifted towards pole during disturbed days (71°–76°S). It is clear that S4 enhances after magnetic noon at Maitri. Thus there is a clear latitudinal shift on disturbed days in the region of occurrence of S4 as seen from figure 2 and the magnitudes are also different (0–0.2 for quiet days and 0–2 for disturbed days).

The phase scintillations are caused by ionospheric irregularities of scale size of hundreds of meters to few kilometers (Basu *et al* 1998). Left panel of figure 3 shows quiet day conditions of Maitri where maximum percentage occurrence of phase scintillation is found around magnetic midnight and is confined to 67°–69°S MLat. During disturbed days (right panel of figure 3), σ_φ activity is prominent in the magnetic morning sector and shifted towards the equator. During magnetic storm, large scale irregularities develop, which are attributed to the large σ_φ values. The percentage occurrence of σ_φ is large and the scintillation activity shifts to lower magnetic latitudes. This shifting may be due to the displacement of auroral oval under disturbed conditions as shown in figure 3. The occurrence of phase scintillation is mainly due to the electron density gradients (polar patch structures). It is clear from figure 3 that occurrence of phase scintillation was generally found low (∼1.5) for quiet days ($\Sigma Kp < 24$) and high (∼9) for disturbed days. From figure 3 it is evident that percentage occurrence of σ_φ increased 2–4 times during geomagnetic disturbed days as compared to quiet days over auroral region. The occurrence of phase scintillation increases as Kp index increases which indicates its dependency on magnetic activity. We found a significant correlation between the occurrence of phase scintillation with the daily sum of Kp ($r = 0.70$ for Maitri). The higher value of phase scintillation activity is due to the fact that σ_φ increases with increasing $\mathrm{d}N/N$ as well as the velocity (V km/s) of the irregularities. In contrast, S_4 is dictated by the Fresnel scale which is about 400 m. Since Power Spectral Density (PSD) at 40 km is much larger than 400 m, σ_φ comes out to be much larger (Gwal and Jain 2011).

3.2 *Example of polar patch*

A Sudden Storm Commencement (SSC) occurred at 1142 UT on 8 March 2008. The Kp index reached its maximum up to 6. The north-south component (Bz) of the interplanetary magnetic field (IMF) exhibited incursion to the south and intermittently flipped to northward and southward for 5 hours (0100–0600 UT), reaching its minimum to −9 nT

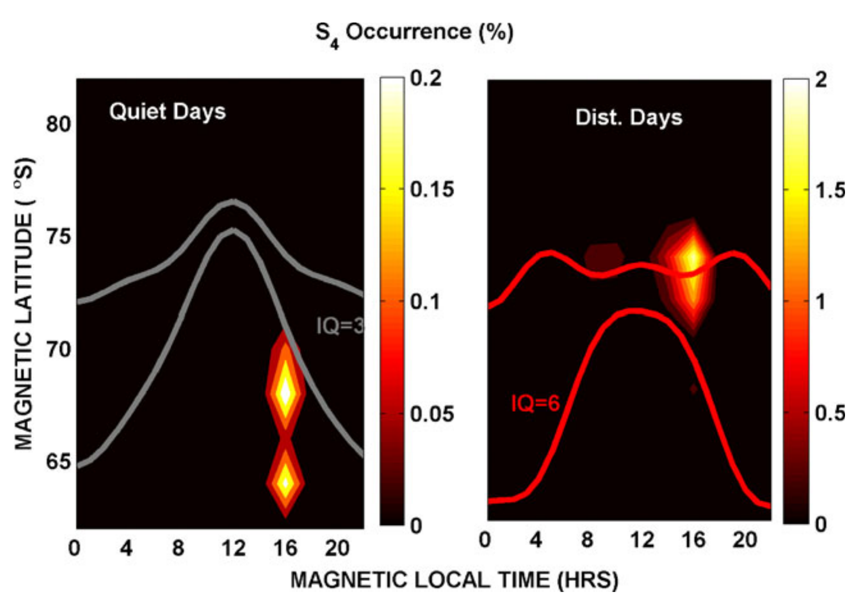

Figure 2. Contour of occurrence of amplitude scintillation for quiet days (left panel) and for disturbed days (right panel) as a function of MLT. Maps are overlapped with the Feldstein auroral ovals for quiet (grey) days and disturbed (red) days during March 2008.

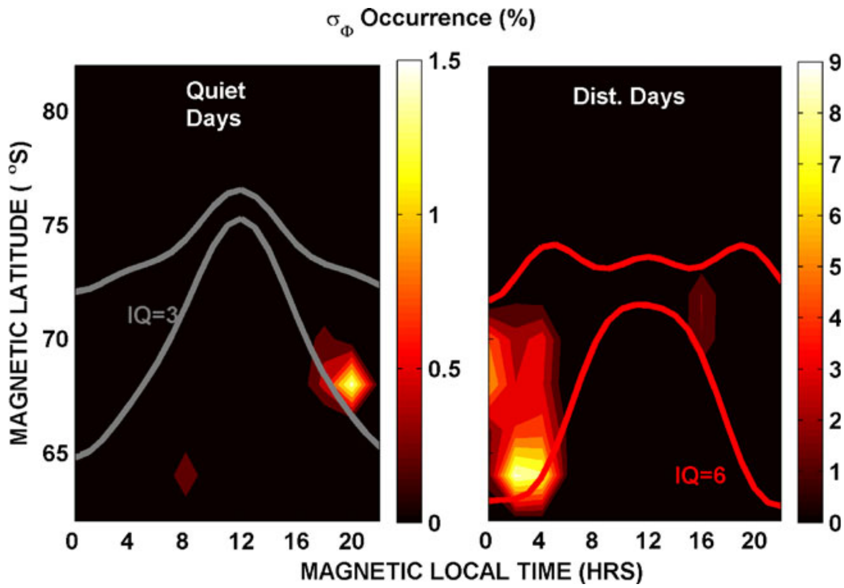

Figure 3. Contour of occurrence of phase scintillation for quiet days (left panel) and for disturbed days (right panel) as a function of MLT. Maps are overlapped with the Feldstein auroral ovals for quiet (grey) days and disturbed (red) days during March 2008.

as shown in figure 4. During the storm, variations in TEC increased from 4 to 10 TECU relative to the quiet conditions. Large variations in VTEC are caused by the large scale ionospheric structure of enhanced electron density in the polar ionosphere. These variations were associated with the occurrence of the polar patches. In figure 5, VTEC (brown line) of individual satellite pass over Maitri for PRN #12 and PRN #17 is presented from 0500 to 0900 UT along with the VTEC (black line) to control quiet day (7 March 2008). The path of satellite (green line) with magnetic local time (MLT) in top abscissa is also shown in figure 5. Rate of TEC (ROT), which is a measure

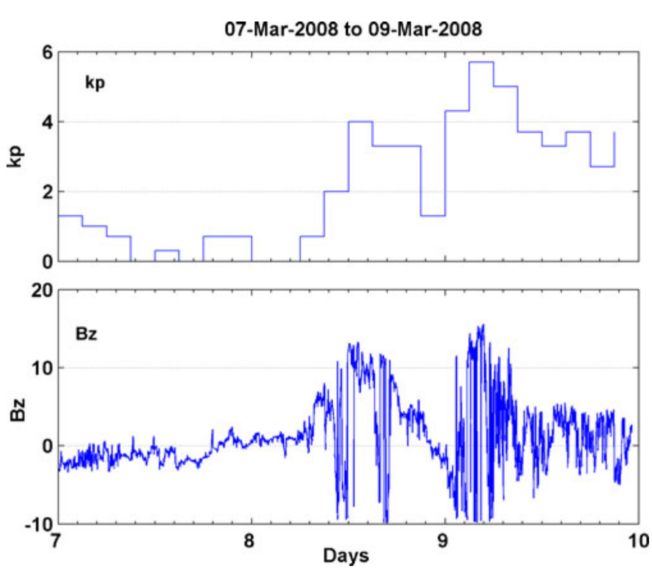

Figure 4. *Kp* and IMF Bz indices during 7–10 March 2008.

of the size of the irregularity (Aarons and Lin 1999; Krankowski *et al* 2006) is found around −4 to 4 TECU/min between 0500 and 0700 UT for PRN #12 and PRN #17 (figure 5, right panel). The geomagnetic latitude ranges from ∼68°–73°S for PRN #12 and between ∼68° and 71°S for PRN #17 in Antarctic region.

Polar patches are typically considered to be of the order of 100–1000 km in horizontal extent. Basu *et al* (1998) found that on an average, the patches are related with an increase of TEC by about 2 TEC units and duration of about 30 minutes. The polar patches of high electron density produce scintillation in the signal and large enhancement in TEC. The increase of 5–10 TECU relative to background have been observed at Maitri (figure 5). The alternate increase and decrease of TEC signify the transit of polar cap patches across the GPS propagation path (Basu *et al* 1998). It is clear from figure 5 that 3–7 patches were observed at Maitri during 0500–0800 UT hr with the duration of about 10–20 minutes. By assuming the drift of the patches of around 600 ms^{-1} (Basu *et al* 1998), the horizontal dimension of the patches was around 360 to 720 km at Maitri.

Amplitude and phase scintillation show significant fluctuations during disturbed condition as shown in figure 6. Amplitude scintillation (S4) shows variation in all PRN's above the threshold value of 0.25, whereas increased phase scintillation (σ_φ.) was observed in most of the visible PRN's on 9 March 2008. We attribute these phase scintillations to polar cap patches along the satellite paths as large plasma drifts allow irregularity scale length to contribute to σ_φ. For a power law irregularity

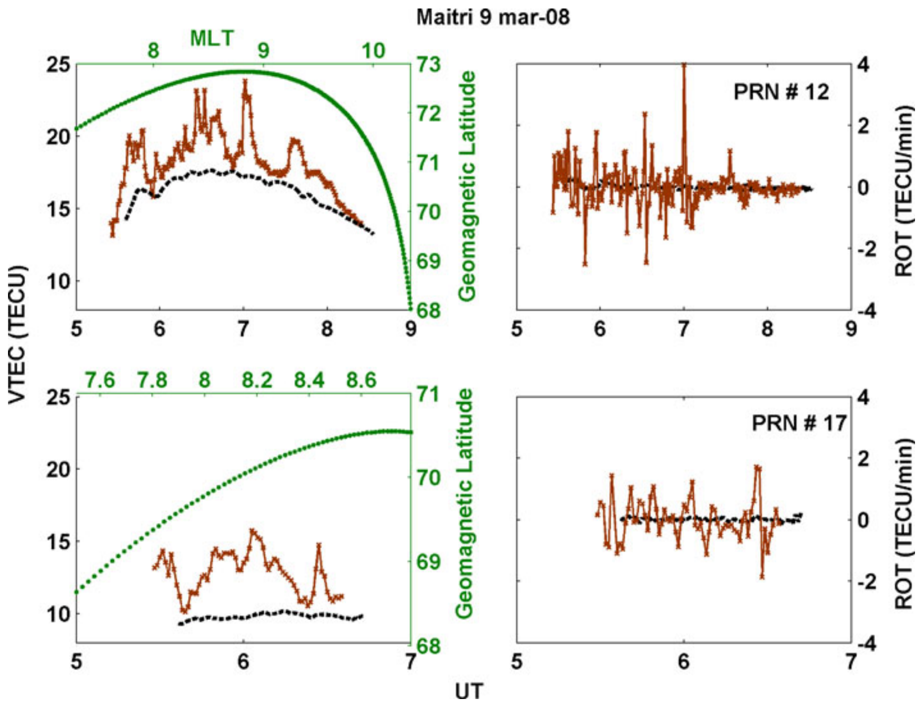

Figure 5. Variations of VTEC (top left panel) and Rate of TEC (ROT) (top right panel) along the satellite pass of PRN#12 and PRN#17 at Maitri (bottom panel) along the satellite pass for 9 March (brown line) and quiet day 7 March (black broken line). Satellites path (green line) on left panel can also be seen.

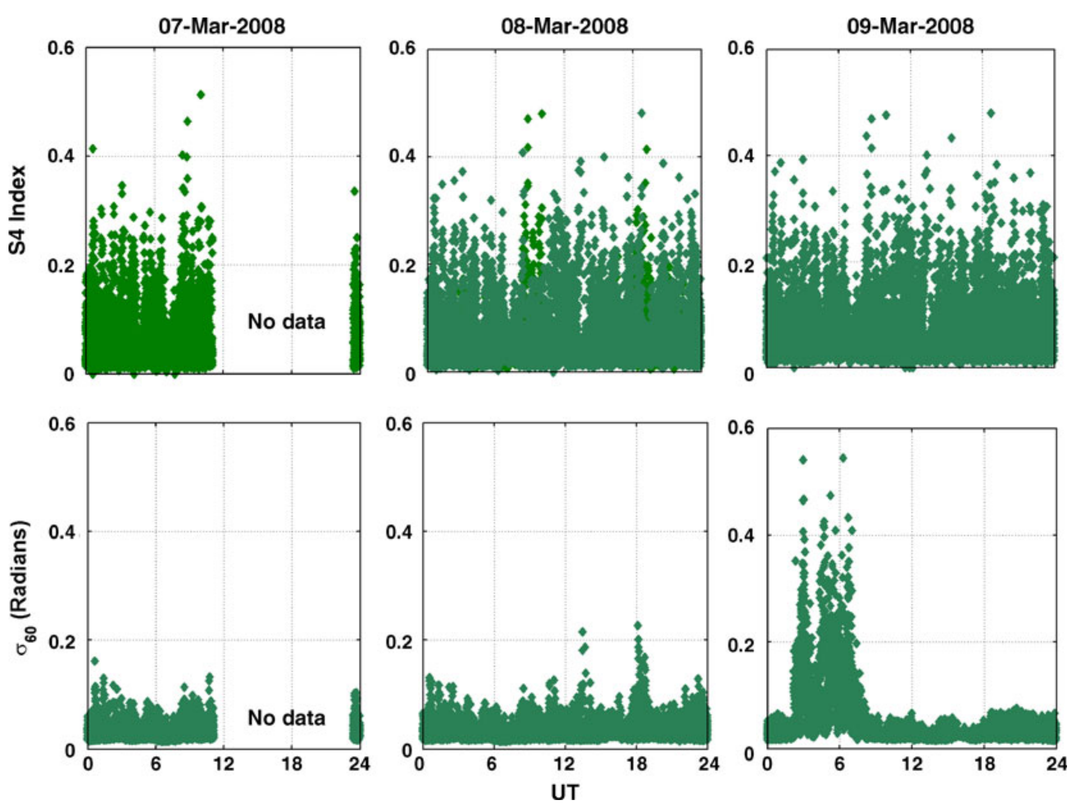

Figure 6. Variations in amplitude scintillation (S_4) and phase scintillation (σ_φ) during 7–9 March, 2008 for all visible satellites.

spectrum, large irregularity wavelength will greatly enhance σ_φ values. This is a clear case of positive correlation of phase scintillation with the magnetic activity at auroral regions. It can be clearly seen from figure 7 that losses of lock occur during the encounter of irregularity and the signal strength

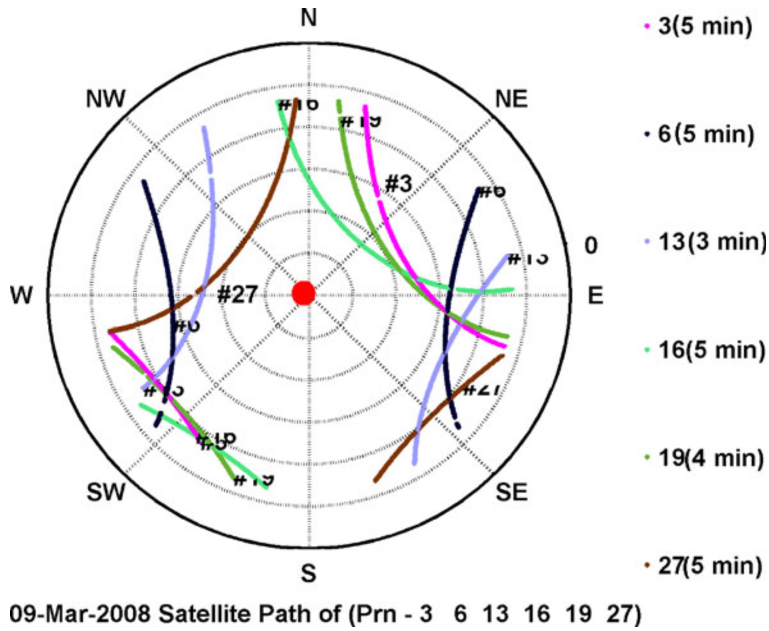

Figure 7. Sky plots of PRNs have loss of lock during 9 March 2008. Red dot shows the location of the receiver.

degrades while the signal passes through the irregularity region. Loss of lock was reported in PRNs' #3, #6, #13, #16, #19 and #27 during the disturbed day. In figure 7, path of all satellites in view during the period 0000–0900 UT on 9 March, 2008 are shown with different colours and duration of loss of lock are shown in legend in right. These observations suggest that large scale moderate intensity patches were developed during the storm.

3.3 *Discussion*

The ionospheric behaviour at high latitude is dependent on the factors under the control of geomagnetic conditions, like polar cap convection, geographic location, solar production and the neutral wind. The percentage occurrence of phase scintillation is well correlated with the geomagnetic activity (ΣKp) for the observation period. Several authors (Aarons 1997; Aarons and Lin 1999; Tsunoda 1988; Krankowski *et al* 2006) found good correlation of phase scintillation with the geomagnetic storms especially at high latitudes. The percentage occurrence of phase scintillation was increased by a factor of 2–4 times during the disturbed geomagnetic periods. Deep TEC fluctuations are detected in phase scintillation along individual GPS satellite passes and the fluctuations were well associated with polar patches. These patches occur due to scintillations in satellite signals which arise from the scattering of radio waves of intermediate scale irregularities (Weber *et al* 1986). Due to the precipitation of high energy electrons in the E layer and low energy electrons in the F layer (Kelley and Vickrey 1982), irregularities in the polar region exist in the form of large-scale patches of several hundred kilometers. The irregularity region expands poleward and equatorward during the magnetic storm. The storm effects on the development of irregularities combine the entry of the station into the irregularity oval with the dynamics of the individual magnetic storm (Aarons 1997). These patches move predominantly antisunward across the polar region and are associated with the phase scintillation. We have also observed that enhancement of TEC exceeds 4–8 TECU relative to the background similar to the observations of Gwal and Jain (2011) at high latitude. The horizontal dimension of the patches measured at Maitri during the magnetically disturbed conditions is 360–720 km. It may be due to the location of stations in auroral region (Maitri). Maitri at Antarctic, occupies a sub-auroral location during magnetic quiet conditions ($\Sigma Kp < 10$), but attains an auroral position when the auroral oval shifts equatorwards with increasing strength of magnetic disturbance. It is found that the position of station (Maitri) changes with magnetic activity with respect to the auroral oval.

4. Conclusion

Following conclusions are drawn from the analysis:

- Phase scintillation was always accompanied by at least a moderate level of amplitude scintillation but amplitude scintillation can occur with or without it. It is observed that phase scintillation occurs more frequently (2 to 4 times) during geomagnetic disturbed days as compared to quiet days during March 2008.

- Occurrence of phase scintillation is well correlated ($r = 0.70$) with the ΣKp index during the observation period, indicates that the auroral region is sensitive to phase scintillation.
- Occurrence of amplitude and phase scintillation increases during disturbed days compared with quiet days.
- The scintillation region displaced towards lower latitudes during magnetically active periods indicates that the auroral region is more sensitive to phase scintillation than the amplitude scintillation.
- VTEC fluctuations are stronger (4–10 TECU) and more frequent during the storm resulting from a large number of polar patches. The horizontal dimension of the patches measured at Maitri during the magnetic storm is 360–720 km. It is now confirmed that the existence of polar patches at auroral region is the main source of scintillation during low-solar-activity period. The losses of lock occur during the encounter of the irregularity and the signal strength degrades during passes of the irregularity.
- It is the first attempt to study ionospheric irregularities at the Maitri station during low-solar-activity period, the existence of polar patches and loss of signal lock during moderate level of geomagnetic storms affect GPS positioning and navigation. This situation might be worse during severe geomagnetic storms and during high solar activity period.

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