Morphological Characteristics of L-Band Scintillations and Their Impact on GPS Signals – A Quantitative Study on the Precursors for the Occurrence of Scintillations

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ABSTRACT

The scintillation data (S4-index) at the L-band frequency of 1.575 GHz recorded from 18 GPS receivers installed at different locations in India under the GAGAN project has given an unique opportunity, for the first time in the Indian region, to make a simultaneous study of spatio-temporal and intensity characteristics of the trans-ionospheric scintillations during the low sunspot activity (LSSA) period from January 2004 to July 2005. During this period the occurrence of intense (S4 > 0.45 ≈ 10 dB) scintillations are found to be mostly confine to the pre-midnight hours of equinoctial months and around the equatorial ionization anomaly (EIA) region of geographic latitudes from 15^o to 25^o N in the Indian sector. These scintillations are often accompanied by the TEC depletions with durations ranging from 5 to 25 minutes and magnitudes from 5 to 15 TEC units that are found to affect the positional accuracy of GPS by about 1 to 3 meters. Further, during the times of intense scintillations, the GPS receivers are found to loose their lock for a short duration of 1 to 4 min increasing the error bounds and thus effecting the integrity of the SBAS operation, which may substantially increase during the high sunspot activity periods.

The pre-reversal enhancement (PRE) in ExB drift is the most important parameter in controlling the occurrence of scintillations. Also, these drifts are found to decrease with increasing geomagnetic activity (Kp), more significantly during equinoctial months. On a day-to-day basis, it is found that an upward drift velocity ≥ 30 m/s at the equator, is the necessary condition for strong scintillations to occur over Waltair (20^{o}N dip) on magnetically quiet days with average Kp ≤ 2 (6 hrs prior to the local sunset) during the high sunspot year of 2001. This threshold value of the upward drift reduces to 20 m/s during the low sunspot activity year of 2004.

Further, it is found that the post sunset vertical drifts at the equator are found to increase linearly with the increase in the anomaly gradients in TEC during afternoon hours. Also, strong (≥ 10 dB) L-band scintillations are observed during the days on which this afternoon anomaly gradient exceeds 1.25 and the PRE ExB drift exceeds 20 m/s, suggesting that a well developed anomaly around the afternoon to early evening hours is a precursor for large post sunset vertical drifts at the equator and a subsequent occurrence of scintillations.

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1. INTRODUCTION

The equatorial and low latitude ionosphere is the region where the postsunset ionospheric dynamics play a significant role in the generation of irregularities causing scintillations, which will adversely affect the trans-ionospheric radio communication signals. These processes are known by the generic name of Equatorial Spread-F (ESF). Measurement of scintillations is the simplest, most efficient and inexpensive diagnostic tool for probing the characteristics of the ESF irregularities, which are of serious concern in the recent times under the space weather and related applications.

The Global Positioning System (GPS) is a satellite based navigation system, which provides a good positional accuracy of the user at any point of the globe, and at any given time using the L-band frequencies of L1 (1575.42 MHz) and L2 (1227.60 MHz). The GPS positioning accuracies can be severely degraded due to the ionospheric scintillations caused by small scale density irregularities, which is of serious apprehension for certain navigation applications like aircraft's landing using Category-I (CAT-I) precision approach. With the increasing applications of GPS based communication and navigational systems, a comprehensive knowledge on the precise characteristics of scintillations and their impact on trans-ionospheric signals at L-band frequencies have gained much attention in the recent past.

Several earlier studies (Woodman and LaHoz, 1976; Aarons, 1982; Yeh and Liu, 1982; Basu and Basu, 1985) on the general morphological features of scintillations revealed that the occurrence of scintillations is controlled by local time, season, solar cycle, latitude, longitude and geo-magnetic activity. But, the day-to-day randomness in the occurrence of scintillations makes their prediction still a challenging problem.

It is known that the height of the nighttime equatorial F-layer is the most important parameter in controlling the generation or inhibition of scintillations (Farley et al, 1970; Ossakow et al, 1979; Rastogi, 1980; Kelley and Maruyama, 1992), that is largely driven by the magnitude of the equatorial vertical plasma drift (ExB) velocity. The rapid pre-reversal enhancement of zonal electric field leads to a large vertical plasma (pre-reversal enhancement in ExB) drift, thereby lifting the F-layer to higher altitudes resulting in a condition conducive for the generation of ESF.

This paper, for the first time, reports the spatio-temporal and intensity characteristics of L-band scintillations over the entire Indian region, and their impact on GPS signals using the data from a network of eighteen GPS receiver stations in India. Further, we present the results of a systematic study carried out on the role of pre-reversal enhancement in the upward (PRE ExB) drift and geo-magnetic activity (Kp-index) in predicting the scintillations and quantitatively defining the precursors for the occurrence/absence of scintillations on night-by-night basis during the high and low sunspot years using the VHF (244 MHz) and L-band scintillation data.

2 DATA AND METHOD OF ANALYSIS:

In the present study the amplitude scintillation (S4 index) data at 1.575 GHz recorded by the dual frequency GPS receivers installed at the 18 different locations in the Indian region under the Indian GAGAN programme during an eighteen-month period from January 2004 to July 2005 are used. The chain of receivers are installed to cover the Indian region from the magnetic equator to the equatorial anomaly crest and beyond, at a grid spacing of about 5^o x 5^o in latitude and longitude as depicted in Fig. 1. Here the longitudinal coverage of these stations vary from 72^o E to 92^o E, and the geographic latitudes vary from 8^o to 32^o N covering a range of 1^o S to 23^o N magnetic latitudes.

The scintillation index (S4) and TEC data thus recorded are processed for each of the satellite passes with an elevation mask angle greater than 40^o so that the effects of low elevation angles such as tropospheric, water vapour scattering and multipath effects are avoided. The 40^o mask angle may reduce the number of satellites available for actual Satellite Based Augmentation Systems operation, but allows studying the effects of ionospheric irregularities alone on the GPS navigation limiting the tropospheric and multipath effects at the low elevation angles.

Further, two digital ionospheric sounders have been operated simultaneously, one at an equatorial station Trivandrum (8.47°N, 76.91°E, 0.9°N dip) and the another at an off equatorial station Waltair (17.7°N, 83.3°E, 20°N dip) and the ionograms are recorded at 15 minute intervals during the relatively high and low sunspot years, 2001 and 2004 respectively. During the same periods, amplitude scintillations at VHF (244 MHz) have also been recorded from a geostationary satellite FLEETSAT (73°E) at Waltair.

The pre-reversal enhancement (PRE) in the upward ExB drift is derived by measuring the height of the 4 MHz return signal and measuring the height rise in a given time interval at the magnetic equator (Anderson et al., 2004). In the present study, the height of the 4 MHz return signal is taken as the true height (since the difference between true height and virtual height is very small at this low frequency), which corresponds to the altitudes where the electron density is approximately 2 x 10^5 el/cm^3. The virtual height of the 4 MHz return signal (h'F) on the ionograms of the equatorial station Trivandrum is scaled at 15 minute intervals, and the computed dh'F/dt during the post sunset hours is taken as the pre-reversal enhancement in upward ExB drift (herein after is called as PRE ExB drift).

The principal causes for the F-layer height rise after sunset are: (i) the rapid post sunset enhancement of zonal electric field that give rise to large vertical plasma drift (ExB) velocities, thereby lifting the F-layer to a higher altitudes, (ii) the decay of the bottom side ionization due to chemical recombination in the absence of production by solar ionizing radiations after sunset and (iii) the presence of equator ward meridional neutral wind that transports the ionization along the field lines, thereby lifting the F-layer to higher altitudes. At the magnetic equator, the effect of meridional wind is unimportant because the geo-magnetic field lines are horizontal. The height rise due to chemical losses is of the order of 5 m/s, and is negligible when compared to large vertical drift velocities due to the pre-reversal enhancement (PRE) in the zonal electric field (Krishna Murthy et al., 1990; Basu et al., 1996; Anderson et al., 2004). Hence, the method adopted in computing the PRE ExB drift used in the present study is justified.

3. RESULTS

In this section, first, we present the morphological characteristics of the L-band scintillations observed from a network 18 GPS Receivers installed at different locations in India under Indian GAGAN program and their impact on GPS Signals. Later, we present the results of a systematic study carried out in predicting the VHF and L-band scintillations that quantitatively describes the pre cursors for the onset of scintillations on a day-to-day basis during high and low sunspot years.

3.1 MORPHOLOGICAL CHARACTERISTICS OF L-BAND SCINTILLATIONS AND THEIR IMPACT ON GPS SIGNALS

3.1.1 L-band scintillations in Indian region:

In the recent years, with the increasing demand for the trans-ionospheric communications in the navigation of space borne vehicles such as satellites, aircrafts and surface transportation systems, the study of ionospheric scintillations, particularly at the L-band frequencies (which is commonly used in these systems), has gained importance. It is well known that the scintillations are severe at the low latitude and equatorial regions during the equinox months and during high sunspot activity (HSSA) periods (Aarons, 1982; Basu et al., 1988; Aarons, 1993). The Indian region includes the magnetic equator, the northern ionization anomaly crest region and beyond up to 27° N geomagnetic latitudes. Therefore, the scintillation activity is severe for more than half of the area (EIA region) in the Indian Flight Information Region (FIR) as may be seen from Fig. 1.

Therefore, with a view to examine the nature of occurrence of scintillations over the entire Indian region at any give point of time, plots of S4 index as a function of local time (from 18 to 06 hrs LT) are made for all the 18 stations for each day from all the available satellite passes. In Fig. 2, are presented the day to day occurrence of scintillations during the month of March 2004 for four typical stations, namely, Trivandrum

(8.4° N geographic latitude, 0.47° S geomagnetic latitude), Waltair (17.7° N G., 8.22° N G.M), Raipur (21.1° N G., 12.78° N G.M) and Jodhpur (26.2° N G., 17.6° N G.M) representing the four different latitude zones in the Indian sector. Trivandrum is an equatorial station, Waltair is a sub-tropical station situated at the inner edge of the equatorial ionization anomaly (EIA), Raipur is a station situated in the crest region of the anomaly, whereas Jodhpur is situated beyond the anomaly crest region. The power levels of the scintillation recorded (S4 index) presented in Fig. 2 are divided into three categories, namely weak (3 to 6 dB, i.e., S4 = 0.17 to S4 = 0.3), moderate (6 to 10 dB, i.e., S4 = 0.3 to S4 = 0.45) and strong (>10 dB) scintillations respectively.

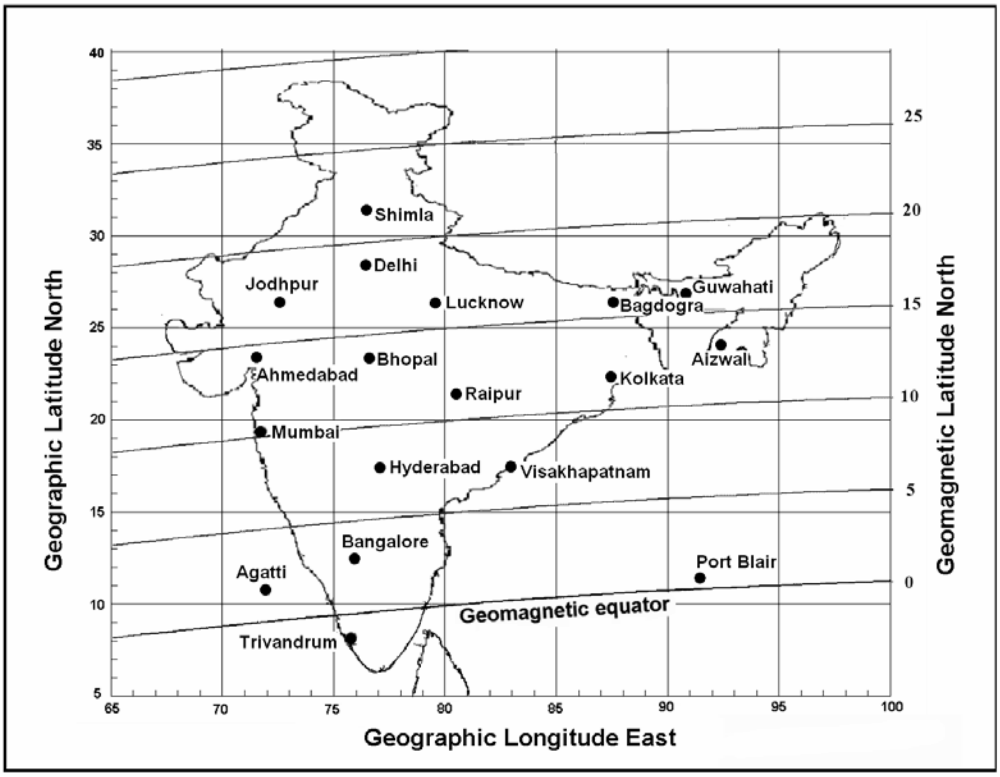

Figure 1. Location of the GPS receiver installations in the Indian region.

It may be seen from Fig. 2(a), which shows the scintillation occurrence at the equatorial station, Trivandrum, the occurrence of weak scintillations (3 to 6 dB) are more with practically no occurrence of strong (>10 dB) scintillations. Whereas at Waltair a station situated at the inner edge of the equatorial anomaly crest (Fig. 2b), the occurrence of scintillations at all the three power levels is high. At Raipur (Fig. 2c), a station situated at the crest of the anomaly, the occurrence of strong scintillation is highest. At Jodhpur (Fig. 2d), a station situated beyond the anomaly crest region, the scintillation activity has considerably decreased to a minimum. The set of these four figures clearly indicates that strong (>10 dB) scintillations occur at and around the EIA region owing to the presence of short scale length (~ few hundred metres) irregularities and high ambient electron densities accompanied by large electron density gradients even during the low sunspot activity (LSSA) period of March 2004. On the other hand, it may be noticed that the occurrence of weak scintillations over the magnetic equator, Trivandrum is maximum compared to the occurrence of weak scintillations at the crest region. Here it may be mentioned that due to the geographic shape of India, the number of GPS receiver stations are less limiting the spatial coverage (added to that lack of data from 13th to 17th March 2004) around the equatorial region compared to the crest region; hence the weak scintillation activity is not prominently visible to the extent expected in Fig 2(a). The occurrence of weak scintillations is due to the presence of large scale size irregularities, low ambient electron densities and low electron density gradients at the equator during the LSSA periods.

Whereas at the anomaly crest regions, the accumulated ionization transported from the equator is high, resulting in high electron density gradients and small scale irregularities giving rise to the generation of strong scintillations at the L-band frequency of 1.5 GHz.

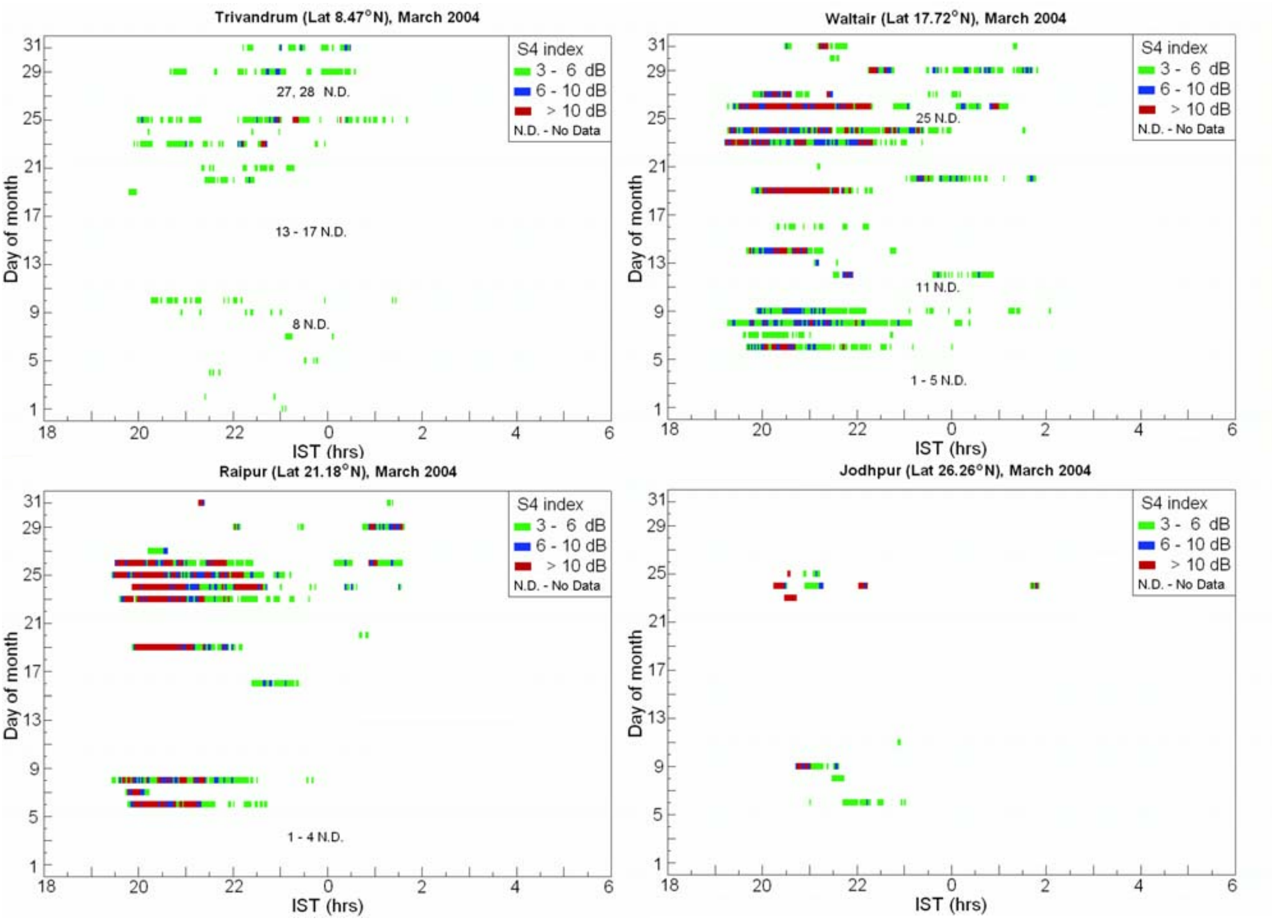

Figure 2. Day to Day occurrence of scintillations with different power levels for the month of March 2004 for four typical Indian latitudes representing (a) Equatorial station (Trivandrum), (b) low latitude station (Waltair), (c) anomaly crest station (Raipur), (d) station beyond the anomaly crest (Jodhpur)

3.1.2. Temporal and Spatial variation of L-band Scintillations

The monthly mean percentage occurrences of strong scintillations of power levels greater than 10dB (S4 ≥ 0.45) for the 18 month period (from January 2004 to July 2005) are computed, and their temporal (month to month) and spatial (latitudinal) variations are presented in Fig. 3. It is strikingly observed from this figure that the percentage occurrence of scintillations greater than 10 dB (Fig.3), which are of serious concern in trans-ionospheric communication at the L-band frequencies, are maximum during the equinox months of March, April, September and October and are mostly confined to a latitudinal belt around 20^o N during the vernal equinox and to around 18^o N in the autumnal equinox. There is practically no scintillation activity during the winter and summer months of the low sunspot years of 2004 and 2005 at the L-band frequency of 1.575 GHz. The equinoxial maxima are explained on the basis of the alignment of the solar terminator with the magnetic meridian in both the hemispheres. Over the sunlit hemisphere, the E-region ionization short circuits the polarization electric fields, developed in the F-region during the evolution phase of the ESF irregularities (Tsunoda, 1985). During the equinox, the solar terminator aligns closely with magnetic meridian and thereby simultaneously decreasing the conductivity of the E-regions that are magnetically conjugate to the F layer (which acts as a short circuit over sunlit hemisphere) during sunset hours. This simultaneous decrease in E-region conductivity, opens or releases the F region dynamo electric field that then produces ***E*** x ***B*** upward drift of the equatorial F layer, creating favourable conditions for the generation of plasma irregularities during the equinox months as seen above. Thus, it may be concluded that strong (>10 dB) scintillations do occur, particularly during the equinox months in the low latitude sectors such as in India even during the LSSA period.

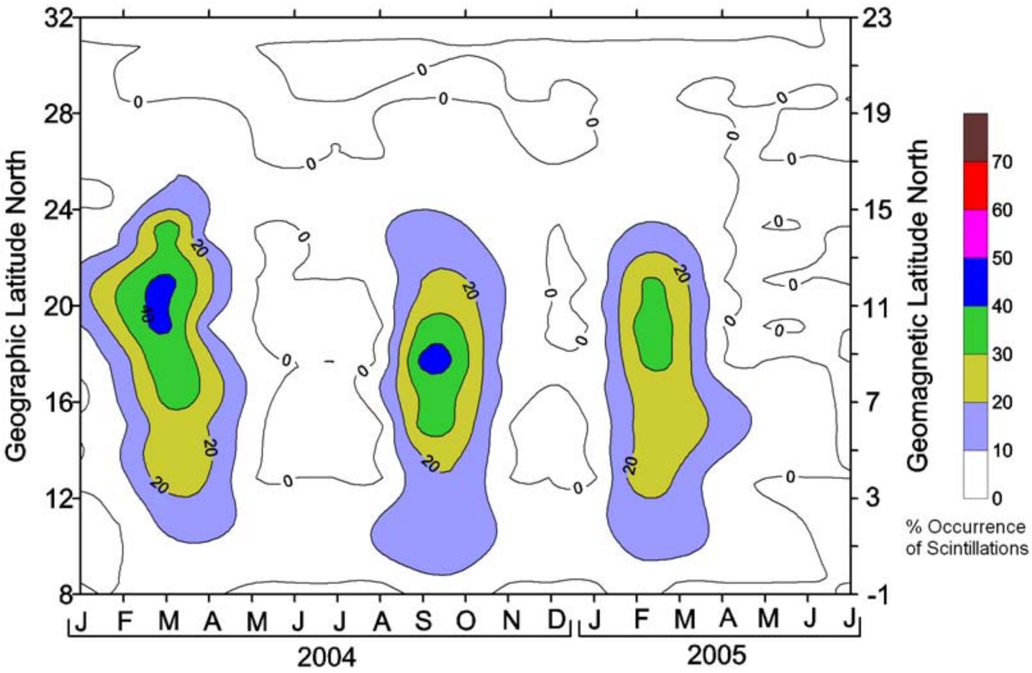

Figure 3. Temporal & Spatial variation in the Occurrence of scintillations > 10 dB power levels during the low sunspot activity years of 2004 and 2005.

Characteristics of TEC depletions/bubbles:

It is known that the amplitude scintillations of high intensity and high fading rates are often accompanied by the TEC-depletions, which are the signatures of the plasma bubbles, particularly, during the pre-midnight period where there may be a series of bubbles occurring within a single scintillation patch (Yeh et al., 1979; Dasgupta et al.,1983; Rama Rao et al., 2006).

When the depleted ionospheric plasma (plasma bubble) comes into the line-of-sight between the GPS satellite and the receiver, the TEC decreases and is seen as depletion in the diurnal variation of TEC. Plasma depletions are of particular importance when they extend to the latitudes of the anomaly crest region; where these bubbles intersect the highest levels of electron density, so that trans-ionospheric radio frequency propagation through this intersection undergoes the highest disruptive levels of scintillation, both in amplitude and in phase levels which are the highest during solar maximum (Klobuchar et al., 1991).

In the present study, the scintillations observed with the GPS L-band frequency of 1.575 GHz, at and near the anomaly crest region are often found to be associated with the plasma bubbles, which are detected as TEC depletions in the GPS TEC data. In Fig. 4 is shown four typical examples of depletions in TEC and their associations with scintillations (S4-Index). It is observed that when the plasma depletion is detected in the vertical TEC data derived from the satellite pass, the spatial gradients of TEC (ΔTEC/ΔLatitude, ratio of change in TEC to the change in latitude) at the edge of the bubbles are found to vary from 10 to 40. These density gradients give rise to favorable conditions for the generation of small scale irregularities that effect the L-band frequencies. However, in the present study, strong scintillations ($S4 \geq 0.45 \approx 10$ dB) are found to occur at and around the equatorial ionization anomaly region if the gradients are greater than 15. Further, these gradients are found to vary from ~ 25 to 40 closer (± 5°) to the anomaly crest region. As the plasma depletions extend in latitude to the crest regions, the strong scintillations which are associated with small scale irregularities contribute for degradation of the positional accuracies in the Satellite Navigational systems such as GPS.

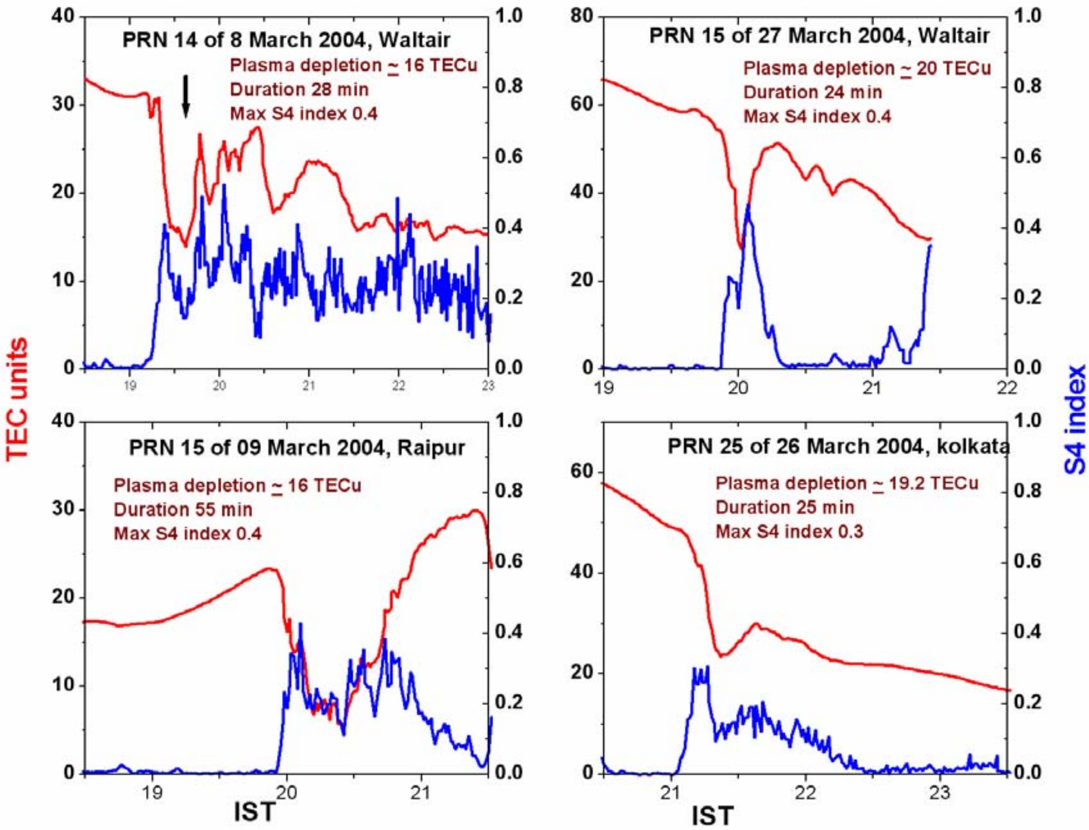

Figure 4. Typical examples of scintillations (S4 index) associated with TEC depletions observed in the GPS data from four typical Indian stations.

In Figs. 5 a & b, are shown typical example, in the nocturnal occurrence pattern of depletions and associated scintillations (S4 index), respectively for the month of March 2004, as a function of latitude in the Indian region. The S4 index and the TEC depletions detected from the GPS signals are plotted in these figures spatially where the blue circles in Fig. 5(a) indicate the plasma depletions, and the red circles show loss of locks of the phase of the receiver that are discussed in the later section of this paper.

It may also be seen from Fig 5(a) that most of the depletions seen are confined to the anomaly crest region of geomagnetic latitudes ranging from 5° to 15° N (viz., 15° to 25° N geographic latitudes). The same belt of latitudes also show the presence of intense (S4 index >0.45) scintillation activity as may be seen from Fig. 5b. The scintillations are moderate to weak at latitudes closer to the equator because of the presence of low electron density and absence of the short scale length irregularities, which do not significantly affect the radio signals at L-band frequencies. Whereas at the anomaly crest region, because of increased electron densities and the presence of large gradients, the generation of small scale irregularities is relatively high which contribute to the occurrence of strong scintillations that severely effect the L-band signals.

It is also interesting to note that the TEC depletions and the strong scintillation events are aligned more to the geomagnetic latitudes showing the geomagnetic field control on these events. The population (occurrence) of high S4 index (intense scintillation activity) is more in the inner edge of the anomaly crest compared to that at the outer edge where the TEC falls of sharply towards the mid latitudes than towards the equator.

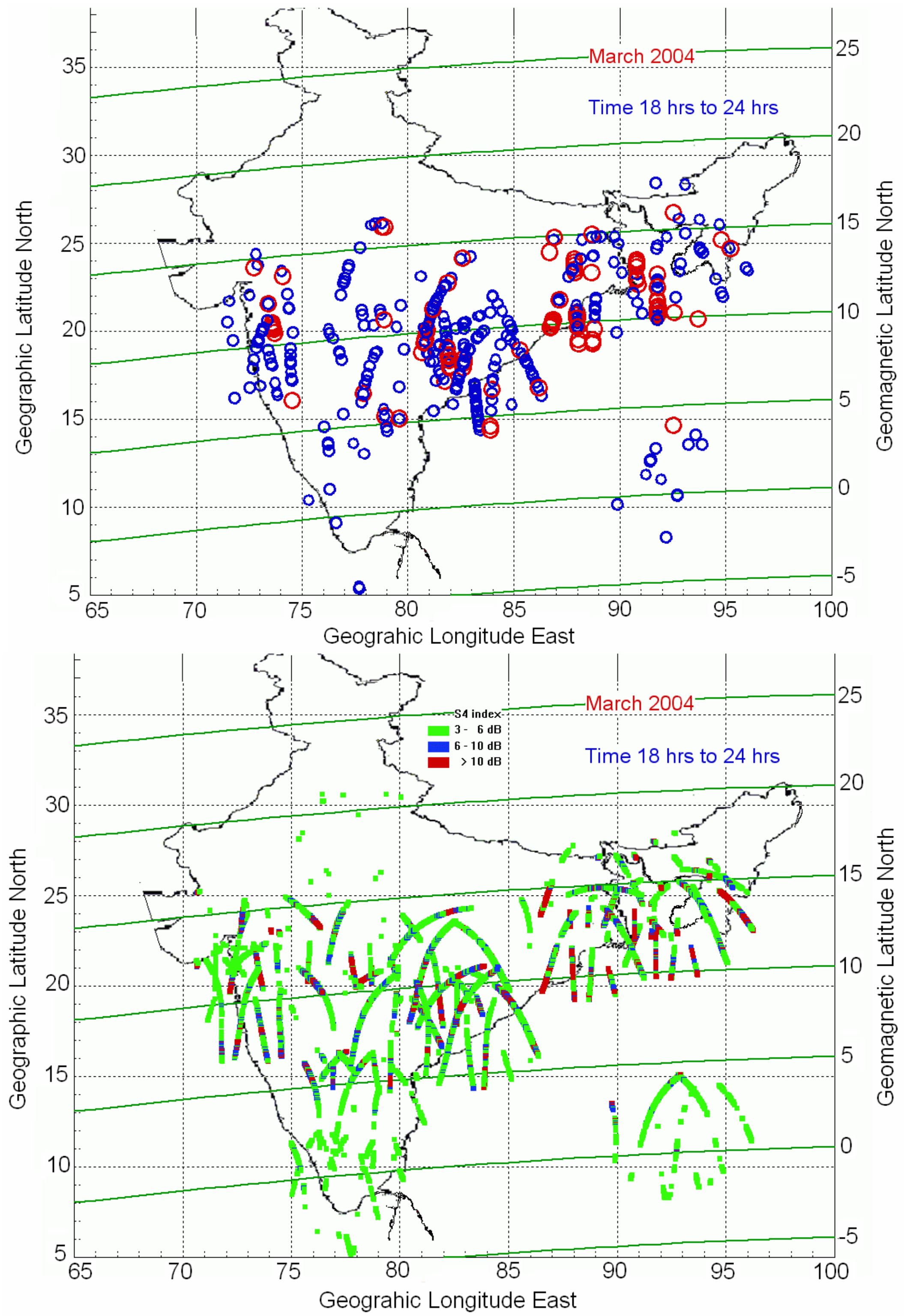

Figure 5. Occurrence of L-band scintillations associated with TEC depletions (bubbles) and loss of lock events during the month of March 2004. (a) Bubbles (blue circles) and loss of locks of the GPS receivers (red circles) and (b) The scintillations at three different power ranges of 3 to 6 dB (Green), 6 to 10 dB (Blue) and > 10 dB (Red).

The length of durations of the plasma depletions and the depth of their amplitudes determine the effect on the GPS based navigation systems. In the equinox month of March 2004 alone, a maximum number (297) of depletions are detected from all the Indian stations. The TEC depletions observed during this month are categorized into different ranges of durations and amplitudes in TEC units and presented as histograms in Figs. 6(a) & (b) respectively. It is observed from these histograms that the most probable durations vary from 5 to 25 minutes (Fig 6a), and the most probable depth of depletions vary from 5 to 15 TEC units (Fig. 6b). It is known that the ionosphere causes a group delay of 0.162 meters per one TEC unit (10^{16} ele/m^2) at the GPS L1 frequency of 1.575 GHz (Warnant, 1997; Klobuchar et al., 1993), and thus in the present case the depletion amplitudes of 5 to 15 TEC units introduce range errors of about 1 to 3 metres.

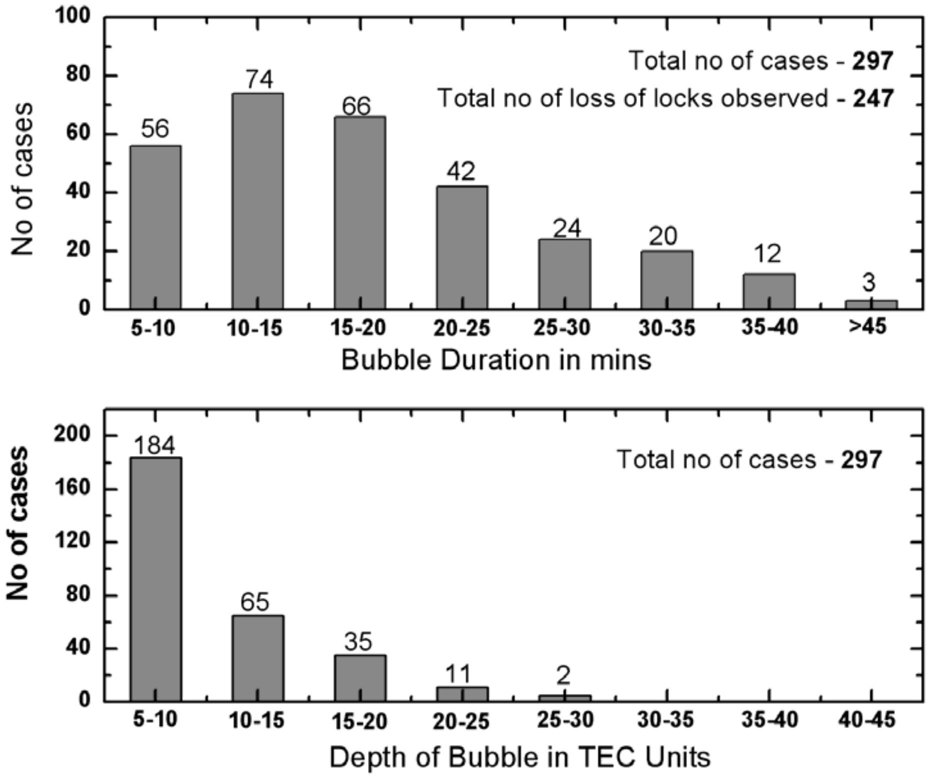

Figure 6. Statistics showing the duration (a) and intensity (b) of the TEC depletions observed over Indian region for the month of March 2004.

Thus, at the anomaly crest region, during the post sunset hours when strong scintillation (S4 > 0.45) activity is present, the duration and depth of amplitude in TEC depletion play an important role in introducing errors in the range correction to be made in SBAS signals derived from the reference stations. Therefore, the region of geographic latitude range of 15^o to 25^o N in the Indian sector, which is almost 50% of the SBAS area in India is expected to be frequently affected by strong scintillations and depletions, particularly during equinox months even during the LSSA periods (2004-2005). The range of latitudes or the FIR region that is likely to be affected by the scintillations could be expected to increase significantly with the increase of the solar activity.

3.1.4 Loss of lock of the GPS receivers:

GPS receiver tracking performance gets degraded in the presence of scintillation effects. Rapid phase variations cause a doppler shift in the GPS signal, which may exceed the bandwidth of the phase lock loop (PLL), resulting in a loss of phase lock (Leick, 1995). Additionally, amplitude fades can cause the signal-to-noise-ratio (SNR) to drop below the receiver threshold level, resulting in loss of code lock. These effects have a larger impact on tracking loops employing codeless and semicodeless technologies, versus full code correlation. In particular, codeless and semicodeless tracking loops experience losses of 27–30 dB and 14–17 dB respectively, with respect to full code correlation, and are therefore more susceptible to the effects of amplitude fading (Leick, 1995). The L2 phase locked loop (PLL) also employs a narrower bandwidth (≈1 Hz, compared to ≈15 Hz for L1) to eliminate excess noise, and is more susceptible to loss of lock due to phase scintillations. These effects therefore are of significant concern for users who require dual frequency data for estimation of ionospheric effects, or resolution of widelane ambiguities. Investigations of GPS receiver performance recently conducted by Knight et al. (1999) using an array of eight GPS receivers in the equatorial region have shown that on some occasions during which L2 phase observations were corrupted up to 27% of the time, and loss of L2 code lock was often observed. L1 tracking performance was degraded to a lesser extent. The results of such studies depend not only on the magnitude of scintillation activity, but also on the receiver tracking capabilities that can vary widely between different manufacturers and models.

In Fig. 7 is shown some typical samples of loss of locks detected in the GPS receiver TEC data during times of severe scintillations in the Indian sector. It can be noticed from this figure that loss of locks are observed when ever the S4 index exceeds 10 dB (S4 > 0.45) power levels. The receiver PLL recovers from the loss of lock within a short duration of about 1 to 4 minutes. It was also observed that the receiver looses its lock more than once when the scintillation activity is severe particularly at the anomaly crest regions, and also if the satellite is at a low elevation angle.

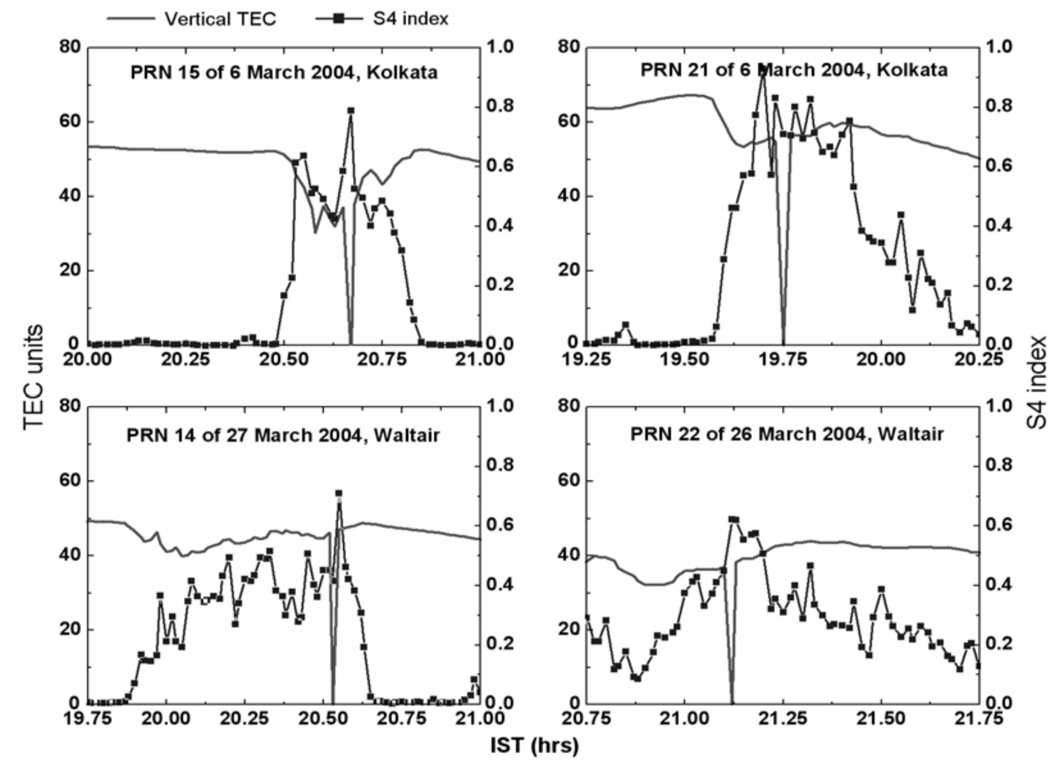

Figure 7. Typical examples of scintillation activity showing the values of S4 index exceeding 0.45 causing loss of lock of the GPS receivers.

It may be revealed that in Fig. 5(a), the spatial distribution in the occurrence of depletions/bubbles, where the loss of lock events (red circles) of the receivers are also plotted for studying the spatial distribution of these events during the typical month of March 2004. It can be seen from that figure that the loss of locks also occur in the same geographic latitude range of 15^{o} to 25^{o} N as those of bubbles and strong scintillations. Also as shown in Fig. 5(b), the corresponding S4 index data for the month of March 2004 shown as colour coded dots (red) for S4 index > 0.45, it is observed that there is a good correspondence between the occurrence of S4 index greater than 0.45 and the loss of lock events. From a close examination of the GPS data with the help of an in house developed software, it is noticed that whenever the L-band scintillation activity (S4) exceeds 0.45 or 10 dB power levels, the receiver looses its lock for a duration of about 1 to 4 minutes. Also, it is observed that the GPS receivers are subjected to loss of locks mostly during the equinox months of March, April, September and October of 2004, and February and March of 2005 where the S4 index often exceeded 0.45 (10 dB) in the regions of strong scintillation occurrences shown in Fig. 3. As many as 247 loss of lock events are observed during the month of March 2004 (Fig. 6) alone from all the GPS receivers located in the Indian region. The geographic latitude zone of 15^{o} to 25^{o} N is identified to be the most affected region in the equinox months during this period. There is practically no loss of lock events in the post midnight hours and during summer & winter months. The latitude range as well as the number of loss of locks may increase significantly during the ascending phase of the sunspot number.

The plasma depletions that might have been detected simultaneously by two or three GPS satellite signals that have the line of sight through the same depletion region are not separately accounted for in this preliminary study, as the emphasis is on the number of available satellite PRNs that are effected by these plasma depletions for SBAS operation. Therefore, the number of TEC depletions detected here may give rise to a larger number than the actual number of plasma bubbles that existed in that region at that point of time, and each of the detected bubble may have different durations and magnitudes depending on their intersection direction and duration with that particular plasma depletion. This may be one of the reasons for the number of TEC depletions observed are much greater than the number of loss of lock events detected as shown in Fig. 6. Further all the plasma depletions may not intersect high density TEC regions to have enough gradients on the edges of the depleted regions that can generate the small scale length irregularities to produce intense scintillations (> 10 dB), which can lower the GPS signal power below the threshold level (due to strong amplitude scintillation) or can cause rapid phase changes in the received signal that result in loss of lock of the receiver. Further, no loss of lock events are detected without the presence of TEC depletion and intense scintillation activity (S4 >0.45).

3.2 PRECURSORS FOR THE OCCURRENCE OF SCINTILLATOINS

3.2.1 PRE ExB drifts and the occurrence of VHF Scintillations

With a view to examine the role of post sunset vertical drift of the equatorial F-region and its control over the occurrence of VHF scintillations, the PRE ExB drift velocities are derived from the ionosonde data recorded at Trivandrum (0.9^{o}N dip). The monthly mean peak drift velocity is computed by taking the maximum dh'F/dt between local sunset (1800 hrs local time) and the onset time of the Spread-F on each day, and is averaged for a month. The percentage occurrence of VHF scintillations at Waltair (20^{o}N dip) is computed as the ratio of the number of days on which post sunset (1800 – 2200 hrs local time) scintillations occurred to the total number of days for which data is available. In Fig. 8, is shown the monthly mean PRE peak ExB drift (solid line with error bars) and the percentage occurrence of VHF scintillations (vertical bars) at Waltair for each month during a high sunspot year, 2001. During this year, the monthly mean sunspot number (Rz) varies from a minimum of 80.6 during February 2001 to a maximum of 150.7 during September 2001. The peak drift velocities are shown on the left hand side of the y-axis and the percentage occurrence of scintillations is shown on the right hand side of the y-axis.

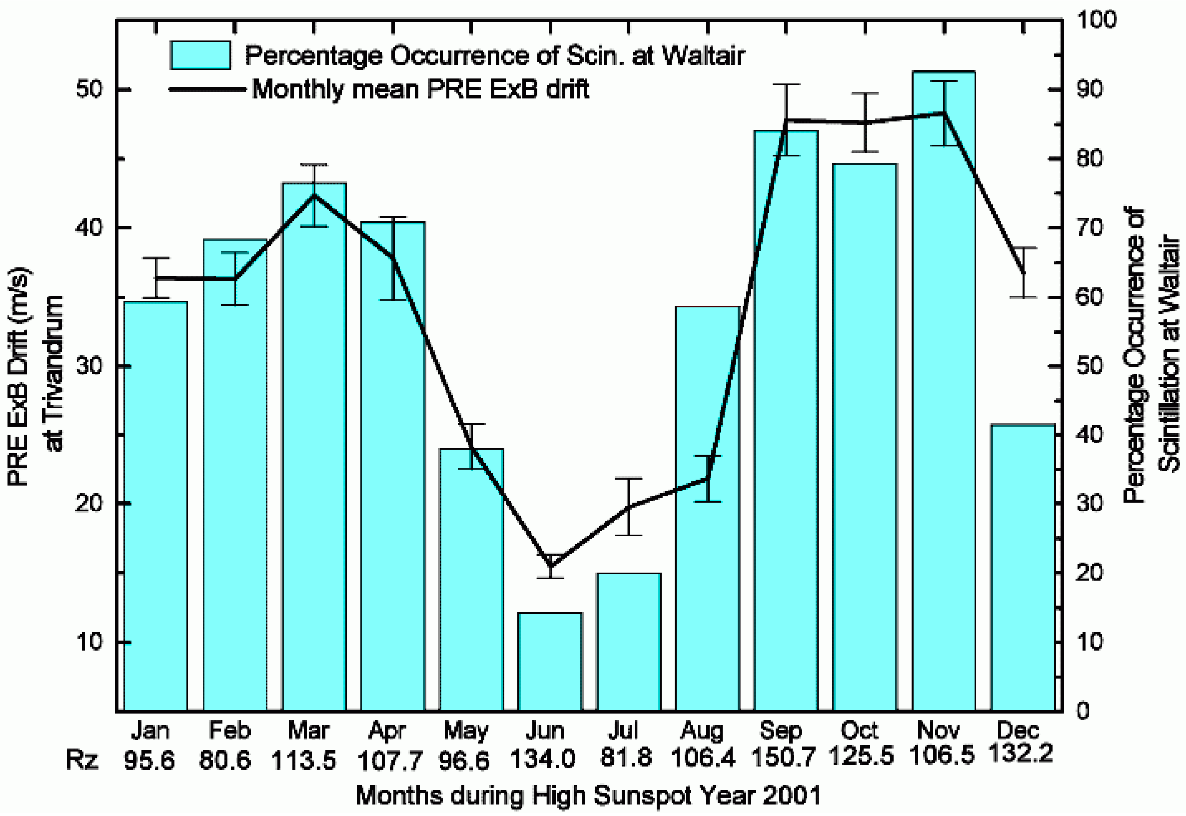

Fig 8. The correspondence between the monthly mean PRE ExB peak drift velocities (solid line) and percentage occurrence of VHF scintillations (vertical bars) during a high sunspot year 2001.

From the figure, it is seen that the percentage occurrence of VHF scintillations shows a good correspondence with the monthly mean PRE peak ExB drift velocity and also exhibits a clear seasonal variation with prominent equinoctial maxima followed by winter and with a minimum in summer. The mean vertical drift velocity exhibits peak values during equinoctial months (March, April, September and October) and also during the month of November 2001. During the month of November 2001, the percentage occurrence of scintillations (93 %) as well as the corresponding mean PRE ExB peak drift velocity is maximum (48.27 m/s). On the other hand, both the mean peak vertical drift and the percentage occurrence of scintillations are much reduced during the month of May and the summer months June, July and August with minimum values of 15.47 m/s and 13 % respectively during June 2001. These results are consistent with the results of Fejer et al. (1999), who reported that the largest and smallest vertical drift velocities do occur during equinoxes and June solstices, respectively.

Fig. 9 shows the association of the mean PRE peak ExB drift velocity with the percentage occurrence of VHF scintillations during a low sunspot year, 2004. During this period, the monthly mean sunspot number (Rz) varies between a minimum of 17.3 during December 2004 and a maximum of 51.1 during July 2004. It is seen from this figure that both the mean vertical peak drift velocities as well as the percentage occurrences of scintillations are reduced significantly as the sunspot number decreased from the years 2001 to 2004. However, the seasonal variation in both the vertical drifts and the percentage occurrences still show maxima during the equinoxes, less in winter and a minimum in summer months. The percentage occurrence of VHF scintillations observed at Waltair also shows a good correspondence with the monthly mean PRE ExB peak drift measured at Trivandrum. Thus, Figs. 8 and 9 suggest that the PRE ExB peak drift at the equator is one of the most important parameters that control the scintillation activity at off equatorial stations like Waltair (20^{o}N dip) during both the solar cycle epochs.

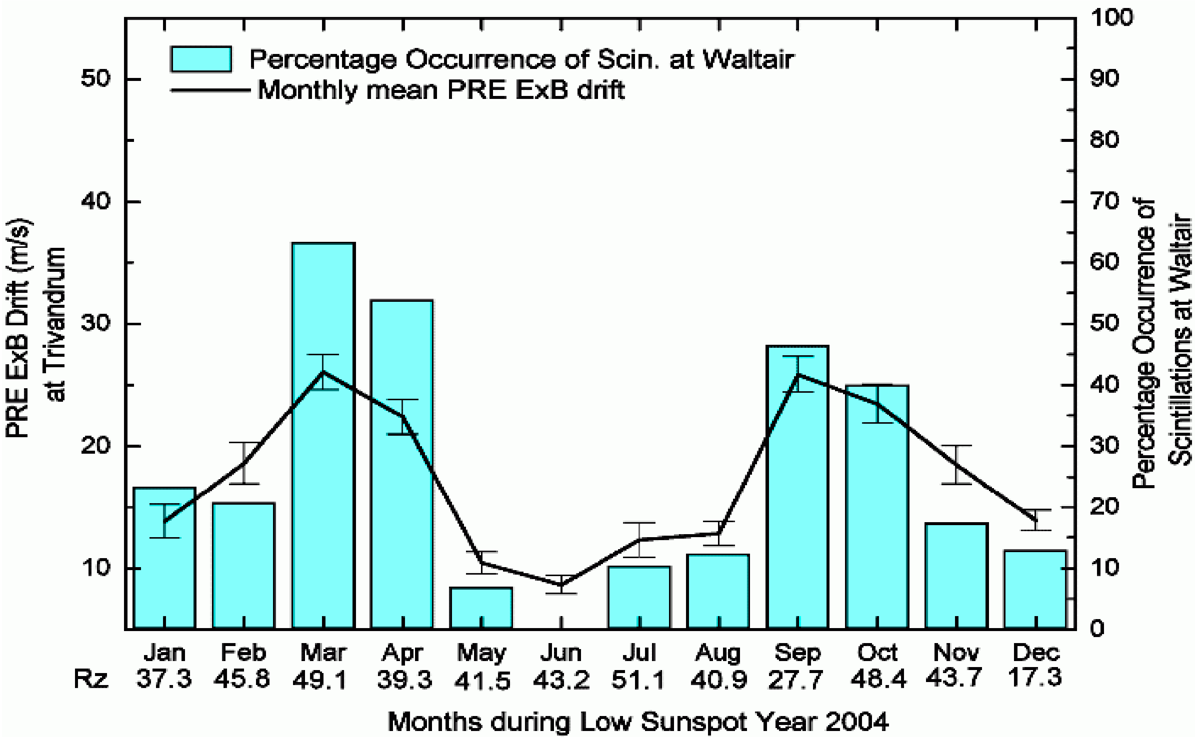

Fig. 9: The correspondence between the monthly mean PRE ExB peak drift velocities (solid line) and percentage occurrence of VHF scintillations (vertical bars) during a low sunspot year 2004.

3.2.2 The PRE ExB drift and the Equatorial Ionization Anomaly gradient

To examine the effect of post sunset vertical (ExB) drift on the strength of the Equatorial Ionization Anomaly (EIA) and its impact on the occurrence and the intensity of scintillations, we have measured the anomaly gradient (dN/dL) from the ionosonde data of Trivandrum (TVM) and Waltair (WLT). The peak electron density of the F-layer (NmF_2) at 15 minute intervals has been computed from the foF_2 data of both stations and the gradient (dN/dL), which is defined as (NmF_2 at WLT - NmF2 at TVM) / (Geog.lat of WLT – Geog.lat of TVM), is evaluated for each 15-minute interval. While computing the dN/dL, the local time difference due to the longitudinal difference in the locations of the two stations is corrected to Indian Standard Time (IST).

Fig. 10 presents the diurnal variation of the anomaly gradient for the days on which strong (≥ 10 dB) scintillations have occurred. Figs. 10(a) and 10(b) correspond to March and November months of the high sunspot year (2001), and Figs. 10(c) and 10(d) correspond to March and November months of the low sunspot year (2004), respectively. The gray points represent the actual data and the black line with dots indicates the average curve. It can be clearly seen from the figure that the anomaly gradients (dN/dL) show significant enhancements that starts around post sunset hours (1800 hrs IST) and increases rapidly from 18 to 21 hrs IST. The rate of change of dN/dL as well as the magnitudes of the anomaly gradients is significantly higher during the high sunspot periods than during the low sunspot periods. This is due to the larger post sunset vertical drifts observed during the high sunspot year 2001 than during the low sunspot year 2004 as may be seen from Figs.8 and 9. Also, it is noticed from Fig. 10 that the post sunset enhancement in the anomaly gradient (dN/dL) is higher in November 2001 (Fig. 10(b)) than during March 2001 (Fig. 10(a)), which is evidently due to larger PRE ExB drift velocities observed during November than during March (Fig. 10). The rapid enhancements in the anomaly gradients during the period 18-21 hrs IST suggests that the large PRE ExB drifts at the equator causes rapid uplifting of equatorial F-region thereby resurging the equatorial fountain effect.

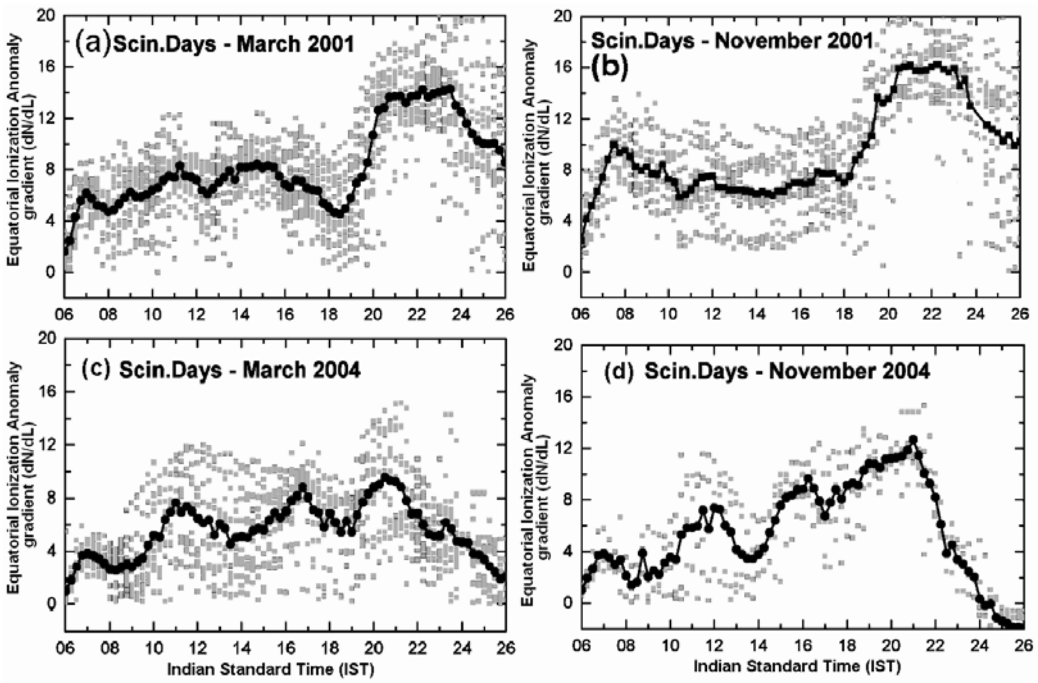

Fig. 10: The diurnal variations of the Equatorial Ionization Anomaly gradients (dN/dL) for the days on which strong (≥ 10 dB) scintillations have occurred during (a) March 2001, (b) November 2001, (c) March 2004 and (d) November 2004.

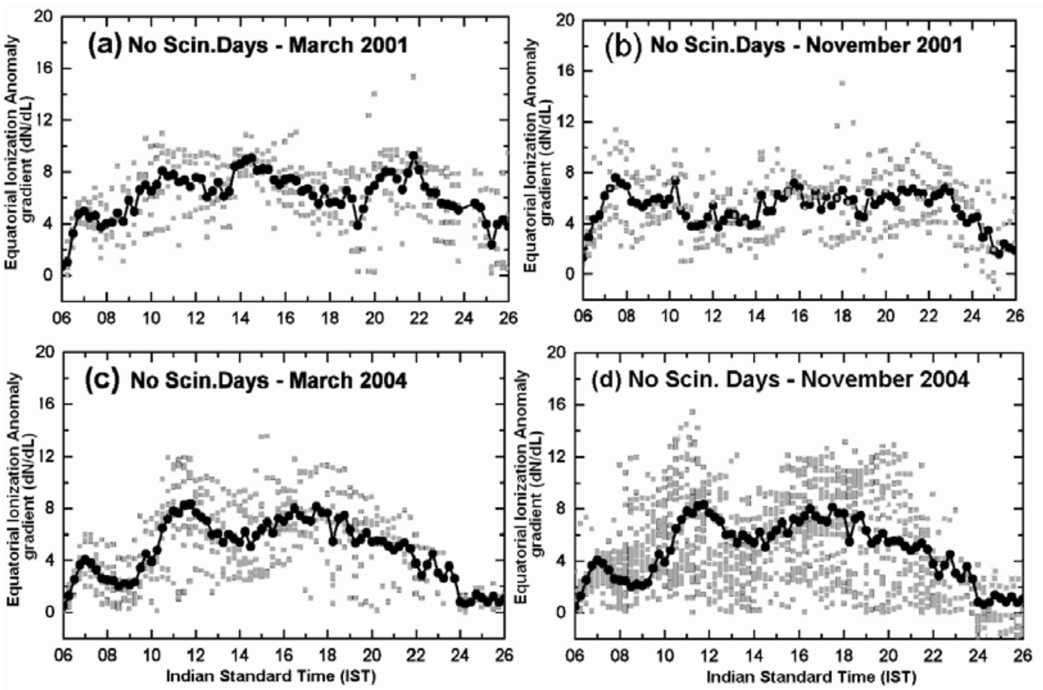

Fig. 11: The diurnal variations of the Equatorial Ionization Anomaly gradients (dN/dL) for the days on which scintillations are weak (< 10 dB) or absent during (a) March 2001, (b) November 2001, (c) March 2004 and (d) November 2004.

Fig. 11 shows the diurnal variation of the anomaly gradient (dN/dL) for the days on which scintillations are weak (< 10 dB) or absent. Figs. 11(a) and 11(b) correspond to March and November months of high sunspot year (2001), and Figs. 11(c) and 11(d) correspond to March and November months of low sunspot year (2004), respectively. The post sunset enhancements in the anomaly gradient are not seen in this figure, indicating that the PRE ExB drift velocities are not high enough to lift the equatorial F-layer to higher altitudes, depriving the equatorial fountain to energize. Thus, Figs. 10 and 11 clearly show the control of the PRE ExB drift velocities over the equator on the Equatorial Ionization Anomaly and the subsequent occurrence of VHF scintillations at the off equatorial station.

3.2.3 PRE ExB drift velocity, Geo-magnetic index (Kp) and the occurrence of VHF Scintillations

The results shown in Figs. 8 to 11 clearly indicate that the PRE ExB drift is the most important parameter that controls the scintillation activity. To examine the day-to-day randomness in the occurrence of scintillations, a quantitative study is made in describing the role of PRE ExB drift and the geo-magnetic activity index (Kp) on the occurrence or inhibition of scintillations. Fig. 12 presents the PRE ExB peak drift velocities measured over the equator on each day during the high sunspot year, 2001 as a function of the corresponding geomagnetic activity index (Kp). Fig. 12(a) corresponds to equinoctial months (March, April, September and October), Fig. 12(b) corresponds to November and winter months (January, February and December) and Fig.12(c) corresponds to May and summer months (June, July and August). The Kp-index shown on the x-axis is the 6-hour mean Kp-index value prior to the local sunset (0600 – 1200 hrs UT which corresponds to 1230 – 1730 hrs IST). The triangles indicate the PRE ExB peak drift velocities for the days on which strong ($\geq$ 10 dB) post sunset scintillations have occurred. The circles represent the weak (< 10 dB) scintillation days and the squares represent the days on which there is no scintillation occurrence. From these plots, it can be seen that, for the magnetically quiet days (average $Kp \leq 2$), strong post sunset scintillations are found to occur whenever the PRE ExB peak drift is $\geq$ 30 m/s. Also, during the days on which the PRE ExB drift is greater than 30 m/s but the average Kp lies between 2 and 4, there is an equal probability in the occurrence of strong, weak or no scintillation events to occur even when the vertical drift velocity exceeds the threshold value of 30 m/s. However, when the PRE ExB drift is less than 30 m/s and/or the average Kp is greater than 4, scintillation is very rarely observed.

In Figs. 12(a) and 12(b), during equinoctial and winter months respectively, it is also observed that the vertical ExB drift velocities decrease with increasing Kp and this feature is more pronounced during equinoctial months (Fig. 12(a)). However, this decrease in drift with increasing Kp is not seen during summer months (Fig. 12(c)).

Similarly, Fig. 13 shows the drift velocities for each of the days as a function of average Kp-index during the low sunspot year 2004. From the plots of this figure (a, b and c), it is noticed that there also exists a threshold value of 20 m/s of the PRE ExB peak drift velocity to cause strong ($\geq$ 10 dB) scintillations during the magnetically quiet days (average $Kp \leq 2$). But, for the days on which the average Kp between 2 and 4, the strong, weak and no scintillation events are distributed with nearly equal probability even though the PRE ExB peak drift velocity exceeds the threshold value of 20 m/s. It is interesting to note here that the threshold PRE ExB drift for the generation of irregularities decreases from 30 m/s during the high sunspot activity year 2001 to 20 m/s during the low sunspot year 2004.

Also during the low sunspot year, it is seen that the post sunset upward drift velocities decrease with increasing magnetic activity (Kp-index), more significantly during equinoxes (Fig. 13(a)) followed by winter months (Fig. 13(b)). However, during summer months, this decrease of drift velocities with increasing Kp-index is not visible.

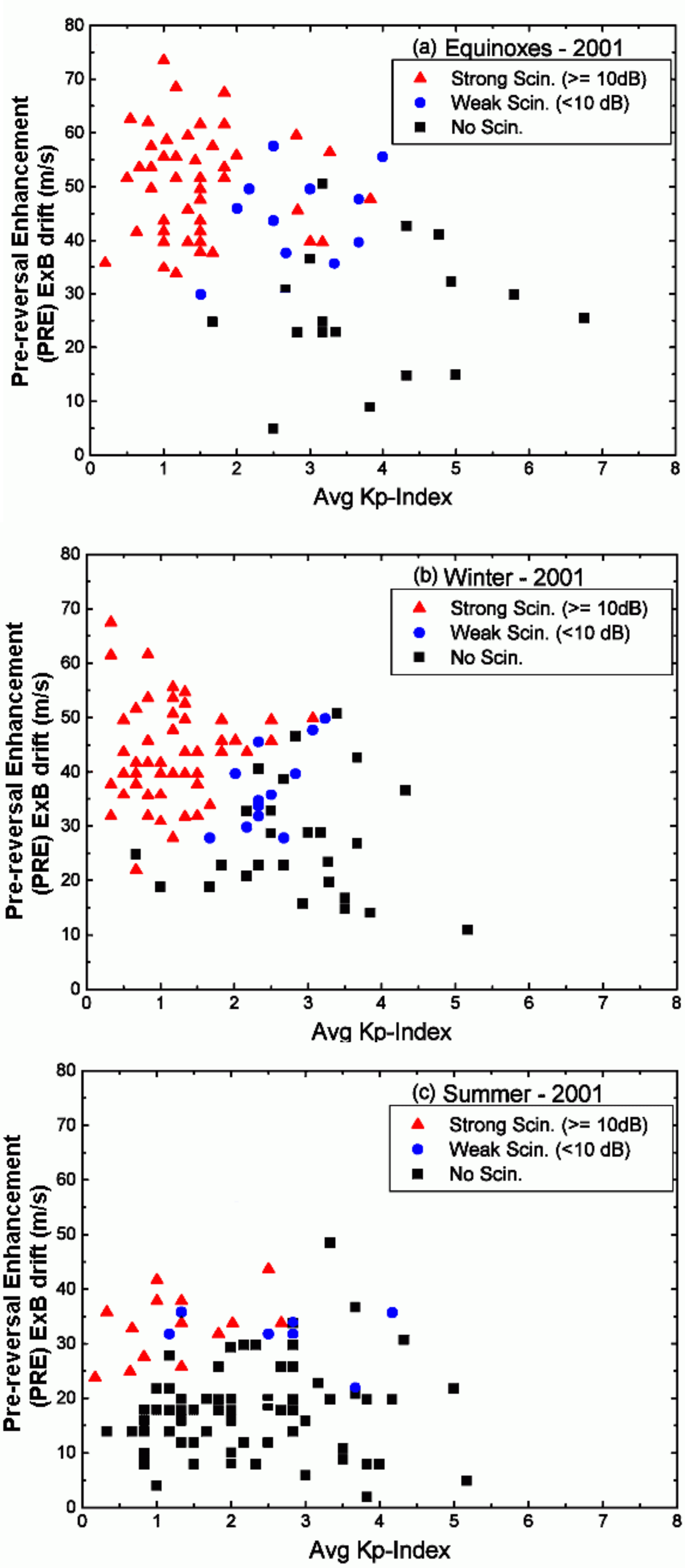

Fig. 12 : The Pre-reversal enhancement (PRE) ExB drift velocities as a function of the 6-hour average Kp, observed for each day during (a) equinoxes, (b) winter and (c) summer months of high sunspot activity year, 2001.

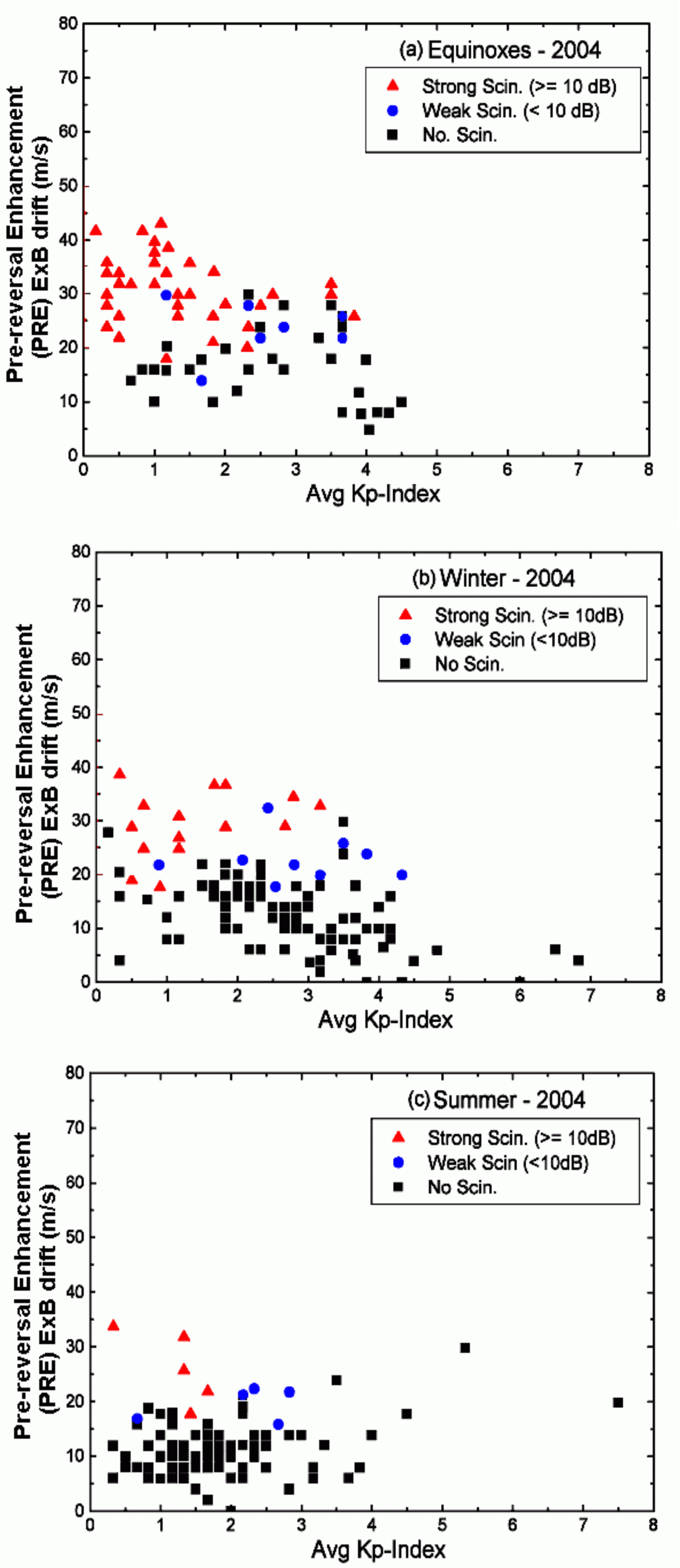

Fig. 13 : The Pre-reversal enhancement (PRE) ExB drift velocities as a function of the 6-hour average Kp, observed for each day during (a) equinoxes, (b) winter and (c) summer months of low sunspot activity year, 2004.

In this study a total of 259 days with simultaneous data of PRE ExB drift measured from Trivandrum and VHF scintillations recorded at Waltair was considered during the high sunspot year, 2001. Out of these 259 days, on 114 nights (53 during equinoxes, 47 during winter and 14 during summer months) strong (≥ 10 dB) post sunset scintillations were observed. During the equinoctial months (Fig. 12(a)), all the 53 strong scintillations events occurred only when the PRE ExB peak drift velocity exceeded 30 m/s. However, 2 scintillation events (out of 47 nights) during winter (Fig. 12(b)) and 4 scintillation events (out of 14 nights) during summer (Fig. 12(c)) occurred even though the PRE ExB peak drift velocity was less than 30 m/s. Thus, these results indicate that the necessary condition for the onset of strong post sunset scintillations during the high sunspot year 2001 is well defined during equinoxes, less in winter and least in summer months.

During the low sunspot year of 2004, only on 57 nights (37 in equinoxes, 15 in winter and 5 in summer), strong (≥ 10 dB) post sunset scintillations occurred out of the available 268 days of observations. Out of the 37 nights of strong scintillation activity during the equinoctial months (Fig. 13(a)), 36 scintillation events occurred when the PRE ExB peak drift velocity exceeded 20 m/s, and only on one night strong scintillation activity was observed even though the PRE ExB drift was less than 20 m/s. During the winter months (Fig. 13(b)), 2 scintillation events (out of 15 nights) occurred even though the PRE ExB peak drift velocity was less than 20 m/s. These numbers indicate that the necessary condition for the occurrence of intense post sunset scintillations during the low sunspot year 2004 is also better defined during equinoctial months than during the winter months.

3.2.4. EIA gradient, PRE ExB Drift and the Occurrence of L-band scintillations observed from GPS

The GPS receivers installed at the stations Trivandrum, Bangalore, Hyderabad, Raipur, Bhopal, Delhi and Shimla span from the magnetic equator to the anomaly crest and beyond along the common meridian, give an unique opportunity to make a systematic study on the Equatorial Ionization Anomaly (EIA) over the Indian sector. The vertical TEC values derived from these seven stations around the local time of 1400hrs to 1700hrs are plotted against the latitude. From these plots the trough (Trivandrum) to crest (Raipur/Bhopal) gradients in TEC (dTEC/dLat) are calculated for every 15 minutes interval. The maximum value of the gradient in TEC between 1400 hrs to 1700 hrs local time of each day is considered as the EIA gradient for that day. Fig. 14 shows the PRE ExB drift velocities as a function of Equatorial Ionization Anomaly (EIA) gradient in TEC observed from the chain of seven GPS receivers chosen along the meridian. The red triangles indicate the strong scintillation (≥ 10 dB) days, blue circles indicate weak scintillation (< 10 dB) days and black squares indicate the days on which no scintillations were observed at GPS L1 frequency.

It can be observed from this figure, which corresponds to low sunspot activity year of 2004, strong (≥ 10 dB) L-band scintillations were observed for the days on which afternoon anomaly gradient exceeds 1.25 and PRE ExB drift exceeds 20 m/s. Also, it may be seen from this figure that the post sunset vertical drifts increase linearly with the increase in the anomaly gradients. These results suggest that a well-developed anomaly (trough to crest gradient in TEC) around the afternoon to evening hours is a precursor for large post sunset vertical drifts at the equator and a subsequent occurrence of scintillations. Sridharan et al (1994) from OI 630.0 nm dayglow photometer observations over Waltair have shown that there exists a precursor of EIA strength, which enables the prediction of ESF at least 3 hours prior to the actual occurrence. Rama Rao et al (1997) using similar ionosondes from four locations in India covering the regions from the equator to the northern crest of the EIA, have shown that a well-developed anomaly around 1500 hrs to 1600 hrs LT is one of the base-level conditions for the generation of Spread-F. Hence, the results obtained in the present study are consistent with the results reported earlier.

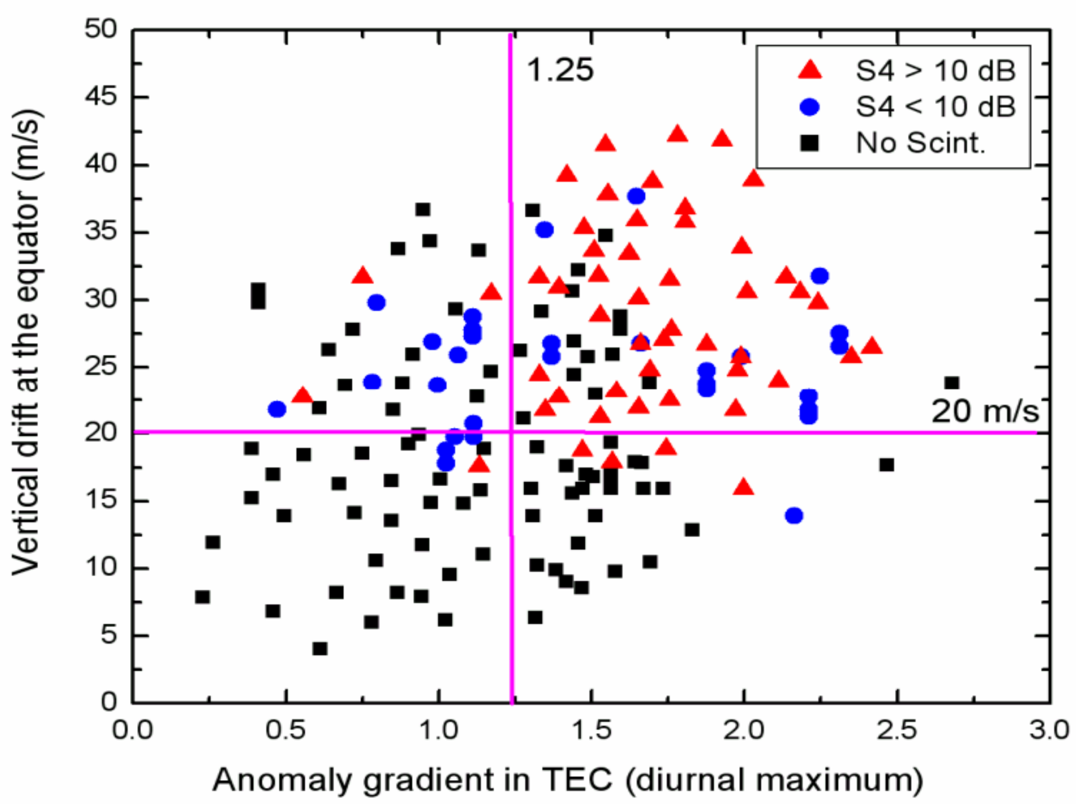

Fig. 14: Post sunset vertical drifts at the equator as a function of peak anomaly gradient in TEC (diurnal maximum) for each day during 2004. The red triangles indicate the strong scintillation (≥ 10 dB) days, blue circles indicate weak scintillation (< 10 dB) days and black squares indicate the days on which no significant scintillations were observed at GPS L1 frequency.

4. DISCUSSION

During the early evening hours, the E-region ionization is quickly eroded due to the recombination of electrons and ions in the absence of production by solar ionizing radiations from the sun. Therefore, soon after the local sunset the F-region ambient ionization is relatively high with sharp gradients at the bottom side of the F-layer which become anti-parallel to the gravity (Kelley, 1989). Further, the rapid post sunset enhancement in the zonal electric field leads to large vertical ExB drifts, thereby lifting the F-layer to greater altitudes where the recombination effects are negligible and collisions are rare resulting in a condition conducive for the development of plasma irregularities. Through the Generalized Rayleigh-Taylor Instability (GRT) mechanism, the bubbles with depleted plasma density are uplifted to higher altitudes and at this time small scale irregularities grow on large scale gradients in plasma bubbles through secondary instabilities. As the plasma-depleted bubble rises from the bottom side of the F-layer, they are elongated along the field lines to off equatorial latitudes and extend up to a north-south dimension of the order of 2000 km (Aarons et al., 1980).

Further, the large post sunset vertical drifts resurges the equatorial fountain effect by depleting the ionization near the magnetic equator, and simultaneously increasing the ionization at off equatorial latitudes. Thus, the ambient ionization near off equatorial stations like Waltair (20^{o}N dip) becomes higher than that at the equatorial stations like Trivandrum, giving rise to large ionization anomaly gradients (dN/dL) during the post sunset hours, as may be seen from Figs. 10 and 11. Since the irregularity amplitude dN/N is preserved along flux tubes, and the magnitude of scintillation at the stations near to the crest of the equatorial ionization anomaly is increased because the ionization density N is high. This is because, the magnitude of scintillation is proportional to the product (dN/N) x N integrated through the ionosphere. Figs. 10 and 11 confirm that the significant enhancement in the anomaly gradient is accompanied by the intense (≥ 10 dB) scintillation activity observed over Waltair. Valladares et al. (2004), from a chain of GPS receiver network in the American sector, have also reported that the anomaly peak-to-trough ratios show larger values around post sunset hours during the days of intense scintillation activity.

Our study further confirms the existence of a threshold value of PRE ExB upward peak drift velocity of 30 m/s (Fig. 12) during a high sunspot year, 2001 for the strong scintillations to occur as reported by earlier studies from western sector (Fejer et al.,1999; Anderson et al.,2004). Also, it is observed that this threshold value decreases to 20 m/s (Fig. 13) during the low sunspot year, 2004. Fejer et al.(1999), from Jicamarca radar observation of a total of 200 events during evening and nighttime periods from April 1968 to March 1992, have reported that the threshold drift velocity for the generation of strong early night irregularities varies linearly with solar flux. Basu et al. (1996) from their campaign observations during September 25 to October 7 of 1994 in the South American sector that the pre-reversal enhancement in upward drift, even though of only 20 m/s during solar minimum period, is a necessary condition for the development of scintillation activity. Hence, the results obtained from the present study are consistent with most of the results reported earlier.

Fejer et al.(1999) have also shown that the extended magnetic activity during equinox solar maximum conditions generally causes large reductions in the amplitude of the pre-reversal enhancements, which inhibit the occurrence of Spread-F. Whalen, (2002) has shown that each level of Spread-F decreases as a linear function of Kp averaged in the 6 hours preceding the observations during March, April, September, and October, and November-February; however, during May-August the Spread-F levels are small and are independent of Kp. The disturbance dynamo electric fields which are driven by the enhanced energy deposition into the high-latitude ionosphere during the magnetically disturbed periods causes large reduction of the evening upward drifts at the equator, thereby inhibiting the generation of ESF irregularities. Fejer et al. (1999) have also shown that this decrease of the evening upward drifts during the magnetically disturbed days is more pronounced during equinoctial solar maximum periods. Whalen (2002) have also reported that the suppression of irregularities resulting from the decrease of maximum pre-reversal eastward electric fields by the geomagnetic activity represented by Kp averaged over 6 hours is greatest in the equinoctial months, less in the December solstice months, and nil in the June solstice months during the solar maximum periods. Hence, the results obtained from our studies presented in Figs. 12 and 13 are in good agreement with the results reported earlier by Fejer et al.(1999) and Whalen (2002). Further, the present results also show that the influence of the 6-hour average Kp-index preceding the sunset on the maximum PRE ExB drift velocity and thereby on the suppression of ESF irregularities is significant even during the relatively low sunspot year 2004.

5 SUMMARY

The scintillation index (S4) data at the L-band frequency of 1.575 GHz recorded from the GPS receivers installed at 18 different locations (nearly at a spacing of 5^o x 5^o grid) under ISRO-GAGAN programme in the Indian region has given an unique opportunity, for the first time, to study the spatio-temporal and intensity characteristics of the ionospheric scintillations during the 18 month period from January 2004 to July 2005.

The results of the study reveal the following characteristic features in the occurrence of the L-band scintillations in the Indian equatorial and low latitude region.

I L-band scintillation characteristics:

(1) The percentage occurrence of L-band scintillations is maximum during the post sunset to midnight hours with very little activity during the post midnight hours during the current LSSA period of 2004-2005.

(2) Scintillations are found to occur mostly during the equinox months with practically no activity during summer and winter months of the LSSA period of 2004-2005.

(3) The occurrence of strong scintillations (>10 dB) is maximum around the equatorial ionization anomaly crest region of to 15^o to 25^{o}N geographic latitude i.e., 5^o to 15^o N geomagnetic latitude in the Indian sector. The presence of high ambient electron densities and large electron density gradients associated with small scale irregularities in the EIA region are the causes for the occurrence of strong scintillation.

II Characteristics of electron density depletions/bubbles observed in the TEC data:

(1) Significant number of TEC depletions are found to occur during the post sunset hours, often accompanied by the occurrence of scintillations at the L-band frequency of 1.575 GHz of the GPS L1 signal.

(2) The occurrence of these bubbles is also found to be maximum during the equinox months peaking around the equatorial ionization anomaly region of 15^o to 25^o geographic latitudes.

(3) The most probable durations of these bubbles vary from 5 to 25 minutes and their amplitudes vary from 5 to 15 TEC units, which correspond to a range error of about 1 to 3 metres in the GPS navigation.

III Loss of lock of GPS receivers:

(1) During the equinox months when the occurrence of strong scintillation is maximum (i.e. S4 $\geq$ 0.45) around the EIA crest region, it is often found that the GPS receiver losses its lock for a short duration of 1 to 4 minutes in the phase channel (L1).

(2) Multiple number of loss of locks are also observed during times of some strong scintillation events.

(3) During the entire period of 18 months of data considered, a total of 395 loss of lock events are detected in the Indian sector which are of serious concern in the GPS aided navigation.

(4) The bubble events, as well as the loss of lock events are likely to increase significantly during the high sunspot activity periods resulting in severe degradation in the trans-ionospheric communications and GPS navigation systems.

IV Precursors for the occurrence of Scintillations

(1) The percentage occurrences of VHF scintillations show a good correspondence with the monthly mean PRE ExB vertical drift velocities at the equator and these two parameters show a clear seasonal behavior with a maximum during equinoxes followed by winter and a summer minimum during both high and low sunspot activity years.

(2) The ionization anomaly gradient (dN/dL) measured between the equatorial station, Trivandrum (0.9^{o}N dip) and an off equatorial station, Waltair (20^o N dip) shows a significant enhancement during post sunset hours for the days on which intense scintillation activity is present.

(3) The PRE ExB peak drift velocities are found to decrease with increasing geomagnetic activity as measured by the 6-hour average Kp-index, preceding the local sunset, during both high (2001) and low (2004) sunspot years. Also, this decrease is more prominent in equinox, less in winter and insignificant in summer months.

(4) There exists a threshold value of PRE ExB drift of about 30 m/s for the subsequent occurrence of intense ($\geq$ 10 dB) scintillations on magnetically quiet days (avg Kp < 2) during 2001. However, this threshold value of the drift reduces to 20 m/s during the low sunspot year 2004.

(5) The PRE ExB drift velocities are found to increase linearly with the increase in the afternoon (1400 to 1700 hrs LT) EIA gradient in TEC. Strong ($\geq$ 10 dB) L-band scintillations are observed

for the days on which the afternoon anomaly gradient exceeds a thereshold value of 1.25 and the PRE ExB drift exceeds 20 m/s. This suggests that a well-developed anomaly (trough to crest gradient in TEC) around the afternoon to evening hours is a precursor for increase in the post sunset vertical drifts at the equator and a subsequent occurrence of scintillations.

REFERENCES :

[1] Aarons, J., J.P.Mullen., H.E.Whitney., and E.M.Mackenzie., The dynamics of Equatorial Irregularity Patch Formation, Motion and Decay, J. Geophys. Res., 85, 139-149, 1980.

[2] Aarons, J.: Global morphology of ionospheric scintillation, Proc. IEEE, 70, 360-378, 1982.

[3] Aarons, J.: The longitudinal morphology of equatorial F-layer irregularities relevant to their occurrence, Space Sci. Rev., 63, 209-243, 1993.

[4] Anderson, D.N., B. Reinisch, C. Valladares, J. Chau, O. Veliz., Forecasting the occurrence of ionospheric scintillation activity in the equatorial ionosphere on a day-to-day basis, J. Atmos. Terr. Phys, 66, 1567-1572, 2004.

[5] Basu, S., Kudeki, E., Basu, Su., et al.: Scintillations, plasma drifts, and neutral winds in the equatorial ionosphere after sunset, J. Geophys. Res., 101, 26 795-26 809, 1996.

[6] Basu, S., MacKenzie, E., and Basu, Su.: Ionospheric Constraints on VHF/UHF Communications Links During Solar Maximum and Minimum Periods, Radio Science, 23, 363 - 378, 1988.

[7] Basu, Su., and S. Basu., Equatorial scintillations : advances since ISEA-6, J. Atmos. Terr. Phys., 47(8), 753-768, 1985

[8] Calvert, W., and R. Cohen., The interpretation and synthesis of certain Spread-F configurations appearing on equatorial ionograms, J. Geophys. Res., 66, 3125,1961

[9] DasGupta, A., Aarons, Basu, S., J., Klobuchar, J. A., Basu, Su., and Bushby, A.: VHF amplitude scintillations and associated electron content depletions as observed at Arequipa, Peru, J. Atmos. Terr. Phys., 45, 15 - 26, 1983.

[10] Farley, D.T., B.B. Balsley., R.F. Woodman., and J.P. McClure., Equatorial Spread F : Implications of VHF radar observations, J. Geophys. Res., 75,7199-7216,1970.

[11] Fejer, B.G., L.Scherliess, and E.R.de Paula, Effects of the vertical plasma drift velocity on the generation and evolution of equatorial Spread-F, J. Geophys. Res., 104(A9), 19,859-19,869, 1999.

[12] Kelley, M. C., The Earth's Ionosphere, Academic Press, Inc., San Diego, 121-125,1989.

[13] Klobuchar, J. A., Anderson, D. N., and Doherty, P. H.: Model studies of the latitudinal extent of the equatorial anomaly during equinoctial conditions, Radio Science, 26, 1 025 - 1 047, 1991.

[14] Klobuchar, J.A., Basu, S. and Doherty, P.: Potential limitations in making absolute ionospheric measurements using dual frequency radio waves from GPS satellites, Proc. of Ionospheric Effects Symposium, IES-93, May, 187 - 194, 1993.

[15] Knight, M., Cervera, M., and Finn, A.: A comparison of predicted and measured GPS performance in an ionospheric scintillation environment, Proceedings of the ION GPS - 99, Nashville, Tennessee, September, 1999.

[16] Krishna Murthy, B.V., S.S. Hari., and V.V. Somayajulu., Nighttime equatorial thermospheric meridional winds from ionospheric h'F data, J. Geophys. Res.,95(A4), 4307-4310, 1990

[17] Leick, A.: GPS Satellite Surveying, second edition, JohnWiley & Sons, U.S.A., 1995.

[18] Ossakow, S. L., S.T. Zalesak, B.E. McDonald, and P.K. Chaturvedi, Nonlinear equatorial spread F: Dependence on altitude of the F peak and bottomside background electron density gradient length, J. Geophys. Res., 84, 17-29, 1979.

[19] Rama Rao P.V.S., P.T. Jayachandran, and P. Sri Ram. : Ionospheric irregularities: The role of the equatorial ionization anomaly, Radio Sci., 32(4), 1551-1557, 1997.

[20] Rama Rao, P.V.S., S. Tulasi Ram, S. Gopi Krishna, K. Niranjan, and D.S.S.V.D. Prasad Morphological and Spectral Characteristics of L-band and VHF scintillations and their impact on trans-ionospheric communications, Journal of Earth Planets and Science, (in press), 2006.

[21] Rastogi, R.G., and J. Aarons, Nighttime ionospheric radio scintillations and vertical drifts at the magnetic equator, J. Atmos. Terr. Phys., 42, 583-591,1980

[22] Sridharan, R., D.Pallam Raju, and R. Raghavarao. : Precursor to equatorial spread-F in OI 630.0 nm dayglow, Geophy. Res. Lett., 21(25), 2797-2800,1994

[23] Tsunoda, R.T., Control of the seasonal and longitudinal occurrence of equatorial scintillations by the longitudinal gradient in integrated F region Pedersen conductivity, J. Geophys. Res., 90, 447-456,1985.

[24] Valladares C.E., R. Sheehan and J. Villalobos, A latitudinal network of GPS receivers dedicated to studies of equatorial spread F, Radio Sci.,39, RS1S23, doi:10.1029/2002RS002853, 2004.

[25] Warnant, R.: Reliability of the TEC computed using the GPS measurements: the problem of hardware biases, Acta Geodaetica et Geophysica Hungarica, 32(3-4), 451 - 459, 1997.

[26] Whalen, J. A., Dependence of equatorial bubbles and bottomside Spread F on season, magnetic activity, and ExB drift velocity during solar maximum, J. Geophys. Res., 107 (A2), 1024, doi:10.1029/2001JA000039, 2002.

[27] Woodman, R. F. and LaHoz, C.: Radar observations of F region equatorial irregularities, J. Geophys. Res., 81, 5 447 - 5 466, 1976.

[28] Yeh, K. C., Liu, C. H., Soicher, H., and Bonelli, E.: Ionospheric bubbles observed by the Faraday rotation method at Natal, Brazil, Geophysical Research Letters, 6, 473 - 475, 1979.

[29] Yeh, K.C., and C.H.Liu., Radio wave scintillations in the ionosphere, Proc. IEEE, 70, 324-360, 1982.