GLOBAL IONOSPHERIC IRREGULARITIES MEASURED USING GPS RADIO OCCULTATION (GPS RO) TECHNIQUE PERFORMED ON COSMIC SATELLITES

6.1 INTRODUCTION

The well-known effect of space weather was variations in the amplitude and phase of radio wave signals that passed through the ionosphere (Hey et al., 1946). These variations are known as scintillations. These scintillations are strong enough; they degrade the quality of signal, reduce its content of information, or cause failure in receiving the signal. It is a known fact that the frequency of signal and strength of irregularities determines the strength of ionospheric irregularities which produce scintillations. Generally the ionospheric scintillation affects the radio wave signals which maintain the frequency varies between 100 MHz to 4 GHz, (Basu et al., 1988; Aarons, 1993; Aarons and Basu, 1994). The scintillations of ionosphere can rigorously affect numerous applications including positioning and navigation in Global Positioning System (GPS), communication and remote sensing, etc. (for example, Aarons, 1982, 1993; Basu et al., 1985, 1996; Bishop et al., 1996; Knight and Finn, 1996; Aarons et al., 1997).

The study of ionospheric scintillations is one of the most significant aspects of ionospheric investigations as the phenomena of scintillation is the manifestation of irregular structure of ionospheric plasma, and owing to its implications on the design of communication systems. At higher frequencies, denser plasmas can generate scintillations and further stronger scintillations of amplitude are produced by irregular plasmas. The time-based performance of diffractive scintillations will be influenced by the drift speed of the ionosphere, the Fresnel length of the scintillations and the relative velocities of the satellites and receivers (Kintner et al., 2003). The initial studies of scintillations were essentially in the VHF and UHF radio bands and paying attention to the scintillation effects on communication signals (Whitney and Basu, 1977).

By the introduction of L-band radio communication links on satellites, the scintillations of the ionosphere were studied at higher frequencies are used by the GPS satellites (Basu et al., 1980; Aarons and Basu, 1994). These studies helped to use the GPS in civilian applications. In meticulous, to new applications which are life-
critical such as GPS aided aviation (Conker et al., 2003; Dehel et al., 2004). In such a way scintillations are concerned for both engineering and science. These scintillations are used to explore the irregularities of medium that generate them.

The Global Positioning System is a space-based satellite navigation system that provides an exact position, velocity and information on time information worldwide and continuously in all conditions of weather, providing a clear line of sight (LoS) to four or more Global Positioning System satellites. GPS is maintained by the Government of United States and is freely available to every individual having a mere GPS receiver. Due to the intense fluctuations signal effect GPS receivers to stop signal tracking of GPS satellites in a process called as ‘‘loss of lock.’’ This may cause errors in navigation and causes failure in navigation. Acquiring or re-acquiring signals of satellite become problematic during scintillations. To investigate the behavior of ionosphere, these fluctuations are used. The irregularities producing scintillations are situated in the F-layer at an altitude ranging from 200 to 1000 km. The ionospheric scintillations are more intense in the equatorial and polar regions, occurring only at night in the former region. Wild and Roberts (1956) suggested that nighttime scintillations are associated with the Spread-F, while the daytime scintillations are correlated with the Sporadic-E.

Aarons (1982) could be considered the first one to present the climatology of scintillations at the equatorial and polar regions through the organizing of the amplitude and phase scintillations in radio beacons of 40 to 3000 MHz. In the initial stages, the studies focused on VHF and UHF radio bands and after words the attention was on L-band (GHZ), because of the societal completely dependent on GPS and satellite based communication/navigation systems. Around the world, varied VHF and L- band scintillations measurement campaigns have been conducted both at regional and individual levels. For instance, De Paula et al., (2003) made use of GPS L1 (1.575GHz) frequency signal in measuring the amplitude scintillations in Brazil, Otsuka et al., (2006) from GPS L1 (1.57542 GHz) frequency receivers which were installed at the Equatorial Atmospheric Radar (EAR) site at Kototabang, Indonesia brought out the reports on amplitude scintillations and Chandra et al., (2007) made use of 244MHz (from a radio beacon on-board FLEETSAT satellite) signal in measuring the amplitude scintillations in Indian low-latitude stations. In order to maintain a prolonged observation, a network consisting of 7 ground-based receivers
of geostationary satellite, VHF (250 MHz) and L-band (GPS frequencies) transmissions named Scintillation Network Decision Aid (SCINDA) has been operated (Groves et al., 1997). Further, SCINDA is further to comply with the Communication/Navigation Outage Forecasting System (C/NOFS) mission, which is the first satellite (inclination 13°) equipped with a rich set of sensor suite that can measure ionospheric scintillations, ambient and fluctuating electron densities, ion and electron temperatures, magnetic fields and neutral winds and provide short-term forecasts of scintillation activity at equatorial and low latitude in real-time [O. de La Beaujardière et al., 2004]. Although, global observations of equatorial ionospheric irregularities and/or the related processes by using satellite in-situ and topside soundings have long been studied [for example, Hanson and Sanatani, 1971; Hanson et al., 1973; Basu et al., 1976, Maruyama and Matuura, 1980, 1984; Burke et al., 2004a, b; Nishioka et al., 2008; Su et al., 2008; Kil et al., 2009], they are primarily limited to two dimensional perspective.

In addition to this, by the utilization of Low Earth Orbit (LEO) satellites which can perform GPS RO observations, it is amicably possible to get the global soundings of the atmospheric profiles in three-dimensional perspective, starting from the Earth’s surface to the topside of the satellite altitude with a higher vertical resolution (Schreiner et al., 2007). In order to achieve three-dimensional seasonal global maps of scintillation index and to understand the global phenomena of irregularities of ionosphere, it is essential that an RO technique with multiple satellites that can yield spatial coverage of the world such as COSMIC is essential. COSMIC is a joint collaborated US/Taiwan mission containing of six similar micro-satellites were launched into a circular, 72° orbit inclination at an altitude of 512 km from Vandenberg Air Force Base, California on April 15, 2006 (Cheng et al., 2006). At the time of the first 17 months of launch, the satellites were gradually detached into the final orbits at ~800 km. Since the COSMIC mission six satellites were launched into circular orbits with a separation angle between neighboring orbital planes of 30° longitudes, relatively higher spatial coverage in 24 hours can be achieved through this technique which further passed the path enabling us to concentrate on the global morphology of ionospheric irregularities causing the scintillation effect (in terms of S4 index) to the amplitude of the GPS RO signal. COSMIC orbital configuration (with a separation angle between neighboring orbital planes of 30° longitudes) would
provide global coverage of approximately 2000 soundings per day and most of these soundings are distributed nearly uniformly in local solar time. An occultation occurs when a GPS sets or rises behind the Earth’s atmosphere as noticed by the Low-Earth-Orbit (LEO) satellite. The receiver on LEO satellite receives the GPS radio signals and that kind of occultation last for a few minutes. After receiving the GPS signal at LEO in the procedure of occultation and the on-board algorithm, that was implemented into the GPS RO receiver software by the Jet Propulsion Laboratory (JPL)(Syndergaard., 2006.), http://cosmicio.cosmic.ucar.edu/cdaac/doc/documents/s4_description.pdf). It provides SNR intensity variations from the raw 50-Hz L1 amplitude observations are recorded in the data stream at a 1-Hz rate at the ground receiver so as to minimize the size of the recorded data. Therefore, the raw measurements of scintillation from the receiver is the RMS of the intensity fading over 1 sec ($\sigma_i$) which can be given as, $\sigma_i = \sqrt{\langle (I-\langle I \rangle)^2 \rangle}$ where I is the square of the L1 CA SNR, and the brackets $\langle \rangle$ represents the mean taken over one second. From the one-second L1 C/A SNR (denoted by $\langle SNR \rangle$ and $\sigma_i$, an estimated value of $\langle I \rangle$ can be calculated on the ground. The S4 index values are reconstructed by the COSMIC Data Analysis and Archive Center (CDAAC) through ground processing. From CDAAC center the $\sigma_i$ data are downloaded. Even though deriving S4 index value from the two parameters $\sigma_i$ and 1 Sec average $\langle SNR \rangle$ an extra two steps are incorporated in the ground processing. The first one is a Gaussian distribution is due to scintillations. The second one is a new average of the intensity $\langle I \rangle_{new}$ at each second, by applying a low pass filter to the time series of $\langle I \rangle$ for obtaining $\langle I \rangle_{new}$ to replace $\langle I \rangle$ in the calculation of S4 index values. The output of this being a long-term detrended S4 scintillation index, which can be reconstructed on the ground. The computed detrended S4 scintillation index values are available to the scientific community on the CDAAC website from 28th December 2006 onwards. Therefore, it becomes possible to reconstruct a long-term detrended S4 index on the ground basing on the two parameters which are provided by the GPS receiver every second viz., $\langle SNR \rangle$ and $\sigma_i$. From 28th December 2006 onwards, the computed S4 index values are available for COSMIC Data Analysis and Archival Center (CDAAC, UCAR,
USA) continuously. Apart from COSMIC-GPS amplitude S4 scintillation index, CDACC provides essential ionospheric altitudinal profiles of the height of the density peak (Hmax), electron density (Ne), the maximum density of each of the density profiles (Nmax). To understand the global characteristics of lower and upper ionosphere numerous researchers have successfully used the ionospheric parameters and link with lower atmosphere (Lin et al., 2007; Liu et al., 2008; Chu et al., 2009; Potula et al., 2011; Brahmanandam et al., 2011). For instance the S4 index data is concerned, there are two types of Level-1 scintillation data are available including profile and global data. Even though profile data be responsible for 1 Hz parameters of S4 index values, signal to noise ratio on the L1 (1.5 GHz) channel CA code (caL1_SNR), elevation angle of LEO-GPS link, square root of mean intensity on L1 CA (sqrtI) and also throughout an occultation, the position of the LEO (GPS) at the time of signal reception (transmission) the global profiles, provide the extreme value of S4 (S4max) index, the mean S4 index over the 9s around the maximum S4 index (S4 max 9sec), and the minimum value of S4 index (S4min) during the occultation period that lasts from 1 to as long as 16 minutes, depending on the geometry of occultation. In the present research, we have used S4max (after the application of grid smoothing of S4max data, which is equal to 5sec running mean) available in global profile data as it represents the spatially correlated density depletions and strong scintillations.

Figure 6.1 depicts the temporal profile of 9s running mean of S4 maximum S4max 9sec (second panel) along with some relevant parameters including elevation angles (top panel), SNR (third panel) and sqrt I during an occultation that starts at 00:00:01UT on 02 January 2008 and lasts for very near to 6 minutes. It is clear from Figure 6.1 that it is a setting occultation (elevation angle from less negative toward higher negative) and S4 (continuous blue line in the second panel, whereas individual dots represent maximum S4 values- S4max) is associated with relatively low values in between ~0.1 and ~0.2 at a tangent altitude of 120.32 km for about 15sec only. However, though SNR (third panel) did not show any fluctuations, SQRT (I) (bottom panel) values have associated with similar fluctuations in the same lines with S4 values that presented in the second panel.
6.2 MOTIVE BEHIND THE PRESENT RESEARCH

The objective of the present research is that to present three-dimensional seasonal global maps of S4 index, which have not yet possible with any experimental data as well as theoretical models. By this, we expect to contribute to the development of global morphology of S4 index and to investigate the onset conditions of ionospheric irregularities that cause scintillation effects to the satellite signals. One of important features of this study is that a weak or almost no scintillation activity found at higher latitudes and further no prominent scintillation activity is observed beyond 300-350 km altitude bin.

6.3 OBSERVATIONAL RESULTS AND INTERPRETATIONS

6.3.1 Seasonal variations of S4 index maps

At the outset, we present in this study three-dimensional global maps of the S4 index for four seasons, including M-months (March 21 ± 1.5 month), S-months (September 21 ± 1.5 months), D-months (December 21 ± 1.5 months) and J-months (June 21 ± 1.5 month) (hereafter M, S, D, and J-months respectively). In figure 6.2, it
is clearly shown that the global variation of the maximum S4 index from noon to noon in Magnetic Local Time (MLT) for altitude range, which starts from 0 to 800 km during M-months in the year 2008 and each one of the panels shows the integrated maximum S4 index data for each 50 km altitude interval starting from 0 to 800 km. From this figure, it is crystal clear to understand that the equatorial scintillations are prominent and started from post-sunset hours and often remained till post-midnight hours (i.e., from 1900 to 0300 MLT) at the F-region altitudes. Though there is an increase in the S4 index intensity by the increasing altitude up to 300 – 350 km altitude bin, latitudinal extent, however, showed a decrease and got fixed to the magnetic equatorial regions particularly between 150-350 km and finally disappeared beyond 350 km altitude. Quite interestingly, yet another observation has been made that the latitudinal extent of S4 index has slowly moved towards the northern hemisphere from the equator at altitudes from 150-350 km. And moreover, the scintillation activity at the 100-150 km altitude bin becomes very prominent although the day and night and takes an extension up to mid latitudes on both sides of the magnetic equator though less activity is present in and around the magnetic equatorial regions.

However, a special emphasis will be given to some important observations of the global S4 index at E-region altitudes (75 to 125 km) during different seasons of 2008 in the ensuing sections of this paper. The S4 index data for S-months as seen in Figure 6.3 depicts that the intense scintillation activity appears near the equator and low latitudes at F-region altitudes similar to M-months. Further, the scintillation activity is extended to post-midnight hours in the same lines with M-months. It is obvious from the scintillation activity during the D-months as shown in Figure 6.4 that S4 index is confined to the southern hemisphere till 100-150 km altitude bin and beyond this the S4 index is maintained symmetry with equator till 300-350 km altitude bin. The interesting observation during this season is that the S4 index is characterized by relatively higher values at F-region altitudes, particularly at 200-250 km and 250-350 km altitude bins. S4 index during J- months, as shown in Figure 6.5, is confined to the northern hemisphere particularly in between 100 and 150 km. On the other hand, the intensity of scintillation activity is very less when compared with other seasons at F-region altitudes and it is almost disappeared beyond the 250-300 km altitude bin.
In spite of the post-sunset scintillation activity and the time span during this study is very similar to Basu et al., (1988) study; the post-midnight L-band scintillation activity during a solar minimum year is the unique result. In the equatorial region, during the sunset, the F-region zonal neutral wind and conductivity gradient which is occurring because of the sunset terminator interact to develop an enhanced eastward electric field towards the day side of the terminator and a westward electric field towards the night side (Rishbeth, 1981; Farley et al., 1986). The eastward electric field (E) which is enhanced, named the Pre-Reversal Enhancement (PRE), can make the F-region to move upward en route $E\times B$ drift velocity. If this PRE maintains the sufficient amount of magnitude, the bottomside of the F-region steepens and the threshold for rapid development of the Rayleigh Taylor (R-T) instability can be crossed. As an outcome of the above, plasma bubbles are generated (Ossakow, 1981) and the irregularities that are ranging from hundreds of kilometers to tens of centimeters are formed. It is a known fact that the smaller scale irregularities can effectively produce scintillations at L-band while the kilometer-scale irregularities produced UHF and VHF band. Once, after the forming, they can scatter the electromagnetic waves which further lead to diffractive scintillations at the receiver in L-band, UHF and VHF bands. With the progress of time, the strength of smaller scale irregularities will be corroded, possibly because of the plasma diffusion in the direction which is perpendicular to the geomagnetic field lines (Kelley, 1989), that results in the absence of L-band scintillations during post-midnight times, whereas scintillations at UHF and VHF bands do linger even during post-midnight hours. A vast number of observational results in favor of the above mentioned observations have appeared in the literature (for eg. Basu et al., 1978; Das Gupta et al., 1982; and Otsuka et al., 2006 to name a few). The prevalence of L band scintillations noted in this study in different seasons during post-midnight is perhaps because of either the longer lifetime of smaller scale irregularities or even the different instability mechanisms might have been operated in order to produce ionospheric irregularities which have the capacity to scatter L-band radio waves. Moreover, the weak and complete absence of scintillation activity is present at mid and higher latitudes, observational evidence which stands contrary to the Basu et al., (1988) observation.

Basu et al. (1988) reported no activity at mid-latitudes and less activity at high and Polar Regions during LSA year and summarised that the reduced background
ionospheric densities during LSA periods could be one of possible conditions for such observations. It was reported by Heelis et al., (2009) that the latter half of the year 2008 was characterized with extremely LSA (F10. 7~ 69). Further, they reported with the help of Coupled Ion Neutral Dynamics Investigation (CINDI) onboard C/NOFS satellite that the ion concentrations were decreased by a factor of 10 during nighttime in the year 2008. Thus, it is conceivable to expect completely absent S4 index during an extremely LSA year. In addition, our observational results are in general agreement with Béniguel et al (2009) study that reported on scintillation characteristics at high latitudes in 2006 and 2007, two solar minimum years.

The investigations carried out recently were focused on to ascertain whether the pre-reversal enhancement in $\bar{E}X\bar{B}$ drift is necessary and sufficient or merely necessary to create the ambient conditions conducive to scintillation activity (for example Fejer et al., 1999; Fagundes et al., 1999; Anderson et al., 2004; Stolle et al., 2006; and Kil et al., 2009). More importantly, Fejer et al., (1999) have studied the effect of F-region vertical plasma drift on the generation and evolution of ionospheric irregularities by making use of Jicamarca incoherent scatter radar observations from 1968 to 1992 and came to the conclusion that if the drift velocities were large enough, the necessary seeding mechanisms for the generation of strong irregularities would always appear to present. Kil et al., (2009) arrived at a good agreement between the global equatorial plasma bubbles (EPBs) distribution which was calculated from the first Republic of China Satellite (ROCSAT-1) during 1999-2004 and the global morphology of the evening PRE of the vertical ion velocity and hypothesized that the PRE is of paramount important factor to generate EPBs. The findings of the above research works demonstrate that the scientific fraternity needs to further investigate the relation between the occurrences of ionospheric irregularities and enhanced vertical $\bar{E}X\bar{B}$ drift using an ample database. Keeping the above mentioned in mind seasonal dependencies of S4 index was evaluated in terms of the seasonal variation of PRE of the eastward electric field. It has been recorded that the evening PRE amplitude characterized by higher values, excepting for a few months from May to August, during an HSA year (Fejer et al., 1979). On the other side, during the time of LSA year, PRE amplitude is very much less than that of solar maximum years, which in turn causes the F-region to get situated at lower altitudes, where the rate of recombination between ions and neutrals appear relatively higher that opposes the
formation of ionospheric irregularities that results in the sparse scintillation occurrence. However, as per the seasonal variation of PRE during LSA years that the equinox seasons are characterized by the moderate amplitudes and December solstice with lower values while during June solstice PRE is characterized by even lower values. Despite the scintillation activity at F-region altitudes observed in the present study shows closely equal trend, particularly in the onset time of this activity, in both equinox seasons (Figure 6.2 and 6.3), during December solstice season (Figure 6.4) however, relatively higher values are observed while a weak or completely absent scintillation activity is noticed during the June solstice season (Figure 6.5). Overall, S4 index during LSA year 2008 seems to be following the seasonal variation of PRE, though some discrepancies observed in the December solstice season.

Fig.6.2 Global S4 index from noon to noon at various altitudes measured by COSMIC satellites during M-months in 2008
Fig. 6.3 Global S4 index from noon to noon at various altitudes measured by COSMIC satellites during S-months in 2008

Fig. 6.4 Global S4 index from noon to noon at various altitudes measured by COSMIC satellites during the D-months in 2008
6.3.2 Monthly variations of S4 index maps at lower and upper F-region altitudes

With a view to verifying exclusively, the global S4 index behavior within and beyond the F-region altitudes in the year 2008, it is also presented maps from 150-350 km and 350-800 km and such trends are highlighted in figures 6.6 and 6.7 respectively. As shown in figure 6.6, though the global S4 index at F-region altitudes, from January to December is characterized by a common property that it maintains more or less symmetric condition with the Geo magnetic equator, the associated intensity and latitudinal extension are considerably differed among the various months. For example, November - February months are characterized as a higher S4 index activity and latitudinal extension appears to be widened as the months progressed. The S4 index has witnessed nearly equal trends during both equinox seasons (March-April, and September-October) seemed to characterize by merely equal properties. As far as global S4 index during May - August months is concerned, one can observe minimum activity and it seems to get decreased as the months progressed in contrast to the November-February trend. A close observation of figure 6.7 tells that the S4 index during January-December months does not exhibit any proper shape; how be it, the dominance of S4 index particularly during January - February, March - April and September months is clear.
Fig. 6.6 Monthly occurrence of global S4 index at F-region altitudes from January to June (top six panels) and July to December (bottom six panels) in 2008

Fig. 6.7 Monthly occurrence of global S4 index beyond F-region altitudes from January to June (top six panels) and July to December (bottom six panels) in 2008
6.3.3 Altitudinal S4 index maps during different seasons

In order to examine at which altitude the maximum S4 index in the F - region is observed conspicuously, the peak height of F2 (hmF2) layer that was retrieved from the COSMIC RO measurement technique was used for comparing with the equatorial S4 index maps during varied seasons and magnetically quiet and active epochs. Figure 6.8-6.11 show MLT vs. altitude S4 index map for ± 50 magnetic latitudes in different seasons inclusive of M-months (6.8), S-months (6.19), D-months (6.10), and J-months (6.11) with average hmF2 value (black line with diamond symbol) superimposed onto them. As already observed, during most of the seasons the maximum S4 index appears below the hmF2. However, in pursuit of assessing quantitatively the dominance of individual parameters from 1800 to 0400MLT, a statistical study has been carried out where the altitudes of maximum S4 index with hmF2 for different seasons and also during magnetically quiet and disturbed days are compared. Since S4 index has been computed for every single minute one to one comparison between the altitude of the maximum S4 index and hmF2 is not possible. Thus we get to compute the mean value of an S4 index in an interval of 6 minutes, the minimum time span during which at least one hmF2 value has been possible for sure, in carrying out the comparisons. By performing the above mentioned calculation, it became possible to go for an evaluation of the dominance of a particular parameter over the other and the range of dominance from time to time interval sequentially. For example, it has been observed that during the M - and D- months the dominance of hmF2 over a maximum altitude of S4 index is crystal clear in 71% and 84% of the cases with maximum dominance around 2200 and 0400MLT and the range of dominance is identified to be between 0 and 80 km in most of the cases. Whereas, on one side, though the dominance of hmF2 over a maximum altitude of S4 index is present during S- and J- months, it has been restricted to only 51% and 54% of the cases to a maximum around 2200 and 0400 MLT and the range of dominance oscillate between 0 and 80 km in harmony with which that are identified during the M - and D- months. In addition to this, the dominance of hmF2 over S4 index has been continued during magnetically quiet and disturbed days with maximum number of cases (70 and 68%) between 2000 and 0400 MLT and the range of dominance is identified between 0 and 80 km. Further, the total duration and the time of maximum S4 index at F-region altitudes considerably varies among different seasons i.e., around
1900 to 0300 MLT and 2230 MLT for M-months and 1900 to 0200 MLT and 2300 MLT for S-months respectively. Till now there is no remarkable S4 index noticed during J-months at F-region altitudes and it stands as the reason to mention here that this feature has been already documented when discussing the global S4 index maximum maps that were presented in figure 6.5. As far as the equatorial S4 index intensities at F-region altitudes during different seasons are concerned, M-months were characterized by relatively higher intensities followed by S, D, and J months. Figure 6.12 depicts the S4 index maps for magnetically quiet days with superimposed hmF2 values. In spite of the maximum S4 index appearing below the F2 peak during magnetically active conditions, and during the quiet conditions, however it appears as if it starts below the F2 peak and gets extended to further several kilometers above the F2 peak. Moreover, it has to be made a note that the quiet days are associated with relatively higher values of S4 index while compared to the disturbed days.

![Figure 6.8](image)

**Fig.6.8** Magnetic local time and altitude profile of S4 index with superimposed average hmF2 value during M-months in 2008
Vertical profiles of S4-index for S-months

Fig. 6.9 Magnetic local time and altitude profile of S4 index with superimposed average hmF2 value during S-months in 2008

2008 S4-index at F-layer altitudes

Fig. 6.10 Magnetic local time and altitude profile of S4 index with superimposed average hmF2 value during the D-months in 2008
Vertical profiles of S4-index for J-months

Fig.6.11 Magnetic local time and altitude profile of S4 index with superimposed average hmF2 value during J-months in 2008

Vertical profiles of S4-index for Quiet days (Kp = 0-3)

Fig.6.12 Magnetic local time and altitude profile of S4 index with superimposed average hmF2 value during magnetically quiet times in 2008
6.3.4 Monthly and seasonal variations of S4 index maps at E-region altitudes

Sporadic E-layer, as the name itself suggests appear as sporadically in the altitude range from 90 – 120 km is always known as layered structures of enhanced electron density. The observations which were carried out earlier by Es layers concentrated mostly on the ground based ionosonde and incoherent scatter radar (for example, Whitehead, 1989; Mathew, 1988) which suffer at length from global coverage. On the other side, by the virtue of the GPS RO technique significantly paved the path for the betterment of spatial and temporal resolution of global coverage of irregularities on a small scale process (in terms of S4 index) such as Es which is possible (Wickert et al., 2004; Wu et al., 2005). In this vast study, we represent the global maps of small scale ionospheric irregularities in terms of S4 index which was observed through F3/C RO technique. As Es layers are embedded in the E-region of the ionosphere, S4 index between 75 and 125 km altitude has been taken into consideration to derive the global climatology of small-scale irregularities and also in studying the altitudinal variations of Es layer during different seasons in the year 2008. The similar findings at E-region altitudes is that S4 index is quite often related to sharp intense values, which may be because of diffraction and/or defocusing/focusing effects on occulting rays of the E-layer (Wu et al, 2004; Ko and Yeh, 2010; Zeng and Sokolovskiy, 2010). The monthly occurrence of an S4 index at global level in year 2008 is presented in figure 6.13, in which the top six panels represent the months between January and June where as the bottom panels from July-December. From this figure, it is very clear that the S4 index during March - April and September - October is characterized by the lower values and seems as if it has been maintained symmetry with geomagnetic equator with relatively lower values at and around the magnetic equator. On the other hand, S4 index starting from May-August seems not only associated with higher values, but also restricted to the northern middle latitudes between ~25°N and ~55°N. In contrast to the above mention, S4 index between November and February is confined to southern middle latitudes between ~25°S and ~50°S and the intensity of the S4 index has been identified to be lower than that which was observed during May - August months. As it is already ascertained that the global S4 index at E-region altitudes is showing a strong seasonal variation, we stand to present the seasonal variation of S4 index in latitude – altitude cross section in figure 6.14. From this figure, the noteworthy feature
is that during J- months, S4 index goes to the extent of dominating at altitudes of ~98-120 km between around 20°N and 55°N geomagnetic latitudes. S4 index is confined during the D- months in a narrow altitude (104-118 km) and latitude (25°N- 45°N) ranges. On the other side apart from getting characterized by relatively lower values during M and S months, the S4 index stands as if it is confined to a meager altitude that is ranging from around 108-112 km and 105-114 km.

The global S4 index maps which were constructed in the E-region (from 75 to 120 km) of the ionosphere revealed a variety of quite interesting features which includes strong seasonal variations with a conspicuous summer showing maximum in the middle latitudes while the equinox months are characterized by a moderate S4 index on both the sides of the magnetic equator. As the S4 index has appeared because of the presence of Es at those altitudes, the seasonal variations which we observe can be further explained by understanding the basic formation of the mechanism of the Es layer. The process of the formation mechanism of Es layer is the contrast to between equatorial, low and middle latitudes and it is well known that the famous Windshear theory (Whitehead, 1971) has now been accepted widely for the responsible mechanism in the formation of Es at middle latitudes. According to this, vertical wind shears in horizontal winds with an appropriate polarity can be a reason, by the combined action of ion-neutral collisional coupling and the Geo-magnetic Lorentz is forcing the long- lived metallic ions move vertically and coverage into dense plasma layers. By and large, this theory completely dependent on the steady state ion momentum equation and, accordingly the vertical velocity of ions (Mathews and Bekeney, 1979) can be written in the following manner:

\[
W_z = \frac{\cos I \sin I}{1 + \left( \frac{V_i}{w_i} \right)} U + \frac{\left( \frac{V_i}{w_i} \right) \cos I}{1 + \left( \frac{V_i}{w_i} \right)} V
\]  

(6.1)

where \(U\) and \(V\) are the geomagnetic southward and eastward components of the neutral wind (which approximately represent meridional and zonal wind components), \(I\) is the magnetic dip angle, and \(\frac{V_i}{w_i} = r\) is the ratio of ion-neutral collision frequency to ion gyro-frequency.
The reason being dip angle (magnetic inclination) at magnetic equator is zero (i.e., no vertical component of the magnetic field), Eq. 6.1 becomes null and hence no vertical moment for ions that are resulting in the absence of formations of Es layer along the equator. Nevertheless, away from the equator the windshear in meridional zonal wind components would contribute in the formation of the Es layer as it has been confirmed in the present and as well as in the previous studies (Leighton et al., 1962; Wu et al., 2005; Arras et al., 2008). In addition to this, the marked presence of Es layer during summer season, as under the debate for a long time and even the windshear theory cannot stand to explain this comprehensively. This could be because of the annual variation of sporadic meteor deposition in the upper atmosphere as per the suggestions given by Haldoupis et al., (2007).

Fig.6.13 Monthly occurrence of global S4 index at E-region altitudes from January to June (top six panels) and July to December (bottom six panels) in 2008
6.4 SUMMARY

The present research has provided for the first time the three-dimensional seasonal variations of the scintillation index (S4 index) measured from the signal-to-noise ratio (SNR) fluctuations of intensity of the L1 channel of GPS Radio Occultation (RO) signals by making use of COSMIC satellites for a Low Solar Activity year 2008, which reveals some of the interesting features which are presented in the following lines:

1. The S4 index, which got confined around ± 30° magnetic latitudes, has been identified to take a start around post-sunset hours (1900 MLT), and quite often persists till post-midnight hours (0300 MLT) between 150 and 350 km altitude during the equinox in northern winter seasons.

2. On the other hand, no such related features have been observed during the southern winter season of the year 2008.

3. High latitudes are observed to be characterized by no scintillation activity beyond 150 km during any season, whatsoever which implies that in the solar minimum period, the instability drives in the auroral, cusp and polar cap regions, namely the gradient drift and velocity shear, are found to be absent.
4. The S4 index at F-region altitudes during magnetically quiet times has been observed to be more intense and gets extended to higher latitudes.

5. The equatorial S4 index appears below the peak of F2 layer (hmF2) during most of the season in spite of being associated intensities and the time of maximum occurrences is relatively higher and earlier during vernal equinox that was followed by autumn equinox.

6. At E-region altitudes (between 75 and 125 km) the global maps of S4 index show strong seasonal variations with maximum activity during northern and southern summer solstice months in the middle latitudes as it appears on the both sides of the magnetic equator with no or less activity at and around the equator in equinox seasons.

7. It can be understood that in terms of vanishing vertical component of the magnetic field lines the absence of S4 index throughout the equator that can slow down the vertical movement and Es-layer which is layered deposition of ionized particles of thin irregular electron density.