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SHORT COMMUNICATION

Dependence of Coherence Scales of Ionospheric Scintillation Patterns on Magnetic Activity

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Abstract: The amplitude scintillation data, recorded at 251 MHz by two spaced receivers at low latitude station Kolhapur [16.42°N, 74.2°E] are used. We have considered data of magnetically disturbed days (Ap > 20) to investigate the effect of magnetic activity on the ionospheric irregularities by observing the coherence scales of the scintillation pattern produced by the irregularities. The coherence scales are calculated using the method introduced by Bhattacharyya et al. (2003). Coherence scale lengths on magnetically disturbed days are higher than that of on quiet days. During magnetically disturbed period the coherence scales in the post midnight period are greater than that of in the pre midnight period. This suggests that magnetospheric electric field generated in storm time causes increase in coherence scales but shows large increase after midnight.

Keywords: Ionospheric irregularity; Magnetic activity; Coherence scale length; Amplitude scintillation

1. Introduction

The ionospheric irregularities aligned with magnetic field lines have spatial scales from few meters to tens of kilometers [1, 2] at low latitudes. These irregularities cause fluctuations in phase and frequency of the radio signals in the range of very high frequency VHF and UHF in near equatorial crest region. The evolution of irregularities is season, magnetic activity, and local time dependent phenomena. So it is important to study the spatial evolution of the ionospheric irregularities with respect to time in this region. Seasonal variation of F region irregularities and its dependence on magnetic activity has been studied in low latitude region [3]. Vertical plasma drift, which plays a key role in the generation and evolution of the irregularities, shows variation with solar flux [4]. Longitudinal asymmetries in the occurrence of irregularities are explained by Kil et al. 1998 [5]. The variation of critical frequency of ionosphere (*foF2*) [6] is dependent on the disturbances in magnetospheric electric field and also on the Earth's surface, such as earthquakes [7]. Effect of magnetic field on the ionosphere is a well known phenomenon and has been extensively studied by the scientific community using variety of ground and space based techniques [8–10]. The drift of the ground scintillation pattern obtained by spaced receivers is affected by magnetic activity [11]. At post sunset period height of the F layer, which is variable, is known to be very important parameter in the evolution of irregularities. This variation is also dependent on the geomagnetic activity in low latitude region [12].

Spatial scales of the irregularities show increasing trend with the solar flux in pre-midnight period studied at low latitude region Tirunelveli [13]. The velocity dependence of the spatial scale of the irregularities has been studied by Singh et al. 2006 [14] in equatorial crest region using power spectral analysis. The drift of the ground scintillation pattern, resulting from the vertical and zonal drifts of the irregularities estimated from spaced receiver scintillation

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observations is used in a study of the effect of magnetic activity on the dynamics of equatorial F region irregularities by Bhattacharyya et al. (2002) [11]. Three dimensional simulation shows difference in irregularity evolution on magnetically disturbed nights as compared with the quiet nights [15]. If the virtual height ($h'F2$) [6] is higher than 300 km, the large scale irregularities like EPBs are observed in the equatorial region [16]. Similar to these studies of spatial scale variations of irregularities with solar flux, magnetic disturbances and drift velocity, it will be useful to study their variations with local time on magnetically disturbed and quiet nights at low latitude station Kolhapur.

Bhattacharyya et al. (2003) have introduced a method to determine the spatial scales of irregularities using the amplitude scintillation patterns which is applicable to strong and weak scintillations. This method was carried out at Ancon near the dip magnetic equator and Ascension Island near the crest of equatorial anomaly using scintillations of L-band and UHF signal. In present work we have also used the same method to determine variations in spatial scales of ionospheric irregularities with magnetic disturbed and quiet nights as well as local time. The effect of magnetic activity on the spatial scales and its nocturnal variation has also been studied in the present paper.

2. Data Analysis

Observations of amplitude scintillation of 251 MHz signal transmitted by UFO2 geostationary satellite (positioned at 71.2°E) were made. Two identical receivers with eleven element Yagi-Uda antennae spaced ∼300 m apart in magnetic east–west direction are installed in Shivaji University, Kolhapur (SUK) by Indian Institute of Geomagnetism (IIG), Navi Mumbai, under the scientific collaborative program between SUK and IIG. The ionospheric scintillations are digitally recorded at sampling rate 20 Hz.

Scintillation in the signal is calculated using a parameter S_4-index (S_4), which is the root mean squared standard deviation of intensity of the signal. Generally, it indicates the strength of amplitude scintillation (Wernik et al. 2004) [17].

$$S_4^2 = \frac{\langle I\rangle^2 - \langle I\rangle^2}{\langle I\rangle^2} \tag{1}$$

where, I is the intensity of the signal. To minimize the effect of noise in the signal, we have used data intervals with $S_4 > 0.15$.

The temporal variations of VHF signal are useful in the investigation of coherence scale length. Knowing the form of space-time correlation function of the intensity scintillations, the coherence scale, d_I can be determined. The coherence scale length for spatial variations of intensity in the ground scintillation pattern, is linked with the spectrum of the intermediate scale irregularities and their evolution near the peak of the equatorial F region contribute mostly to the observed scintillations [18]. Spatial scales present in the ground scintillation pattern carry information about the spatial structures of (Equatorial Spread F) ESF irregularities, which produce the observed scintillations on incoming radio signal. Temporal and solar flux dependence of coherence scale, d_I have been investigated with help of spaced VHF receiver [13]. It is interesting to investigate the variation of d_I in magnetically disturbed (Ap > 20) and quiet nights. Data of six disturbed and quiet nights have been considered for analysis. Scintillation events in disturbed period are lower than in quiet period therefore useful data points in disturbed period are low.

The spatial scales present in the scintillation patterns of two spaced receivers can be determined using method given by Bhattacharyya et al. 2003 [19]. The weak as well as strong scintillation events having maximum correlation coefficient, $C_I(x_0, t_m) \geq 0.5$ are used for further investigation.

According to cross correlation technique, the space time correlation function of the intensity scintillation pattern received by two spaced receivers on ground is of the form (Briggs, 1984) [20],

$$C_I(x,t) = f\left[(x_o - V_o t)^2 + V_c^2 t^2\right] \tag{2}$$

Here, x_o is the distance between two receivers, V_o is zonal drift of the irregularity patterns across the propagation of VHF signal and V_c is the measure of spatial and temporal changes in the irregularity which is evolving randomly [19]. f is monotonically decreasing function of space and time with $f(0) = 1$. To investigate the spatial scales present in the ground scintillation pattern, it is necessary to find the parameter, coherence scale d_I and to know the form of the function f, such that

$C_I(x = d_I, t = 0) = 0.5$.

The maximum value of cross correlation function $C_I(x, t)$ obtained at time t_m for the two spaced receivers having separation x_o is given as,

$$C_I(x_o, t_m) = f\left[\frac{x_o^2 V_c^2}{V_o^2 + V_c^2}\right] \tag{3}$$

From mass plot of the $C_I(x_o, t_m)$ versus $\left[\frac{x_o^2 V_c^2}{V_o^2 + V_c^2}\right]$ one can get the plot of $C_I(x, 0)$ versus x. If it is fitted with Gaussian, $C_I(x,0) = e^{-\left[\frac{(0.832)x}{d_I}\right]^2}$ it gives d_I (coherence scale).

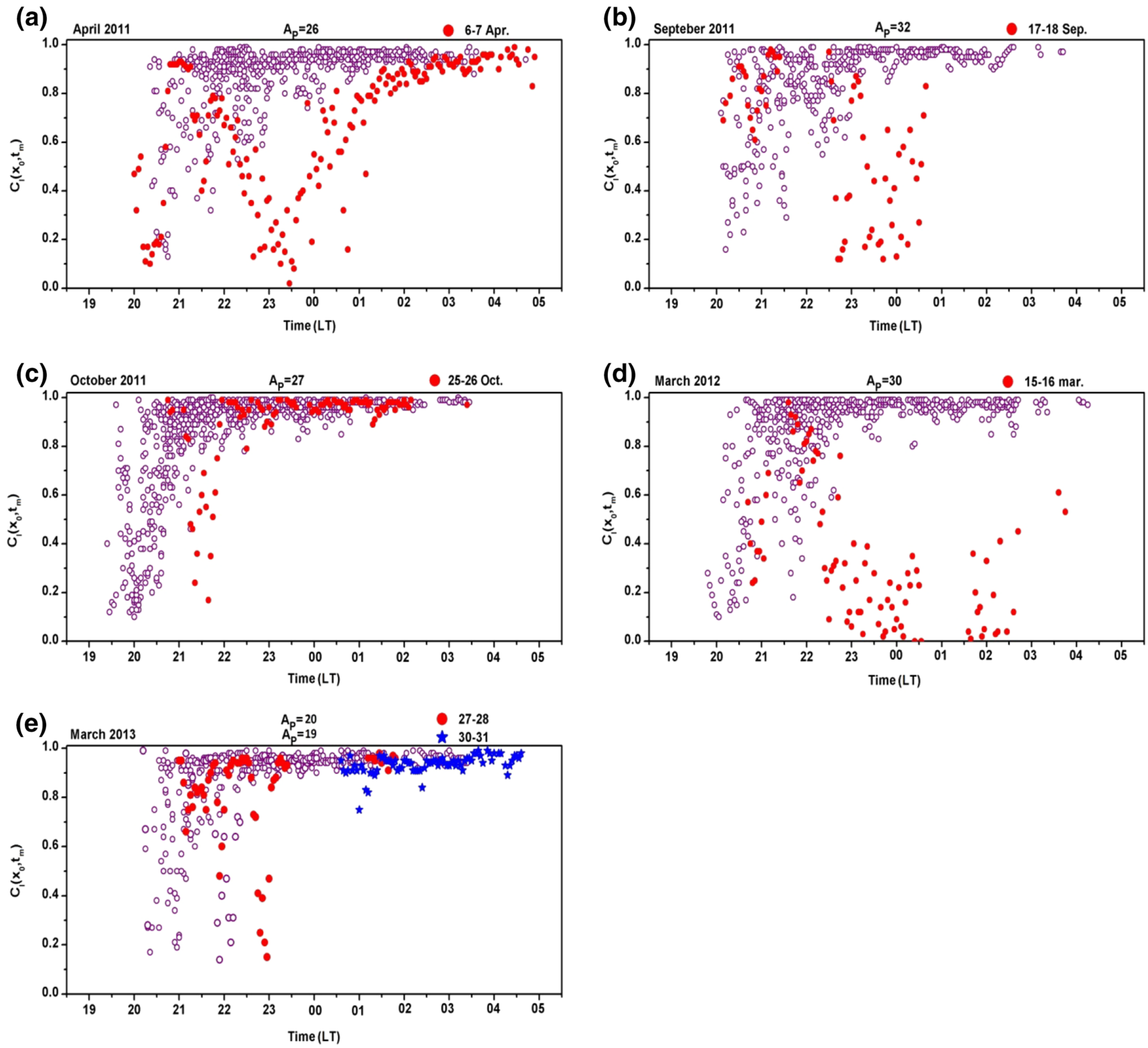

Fig. 1 Each *panel* indicates the plot of $C_I(x_o, t_m)$ with time Local Time (LT) for each disturbed day with available quiet days of corresponding month

3. Results and Discussion

To study the coherence scale of the irregularities, at first, it is necessary to identify the irregularities generated in ionosphere. The maximum correlation coefficient, $C_I(x_o, t_m)$ of intensities of two signals received by VHF receivers has been used for the identification of the freshly generated irregularities by Kakad et al. 2007 and Kakad et al. 2012 [21, 22]. Similarly, in present work in the initial phase of the generation of the irregularities during quiet period $C_I(x_o, t_m)$ shows high variability due to the electric field at the generation phase, this field dies down after Local Time (LT) 2200, so $C_I(x_o, t_m)$ have higher values and are maintained afterwards during remaining night. But, in the disturbed period the $C_I(x_o, t_m)$ values decreases again after 2200 LT, this may be the effect of disturbance dynamo, prompt penetration of electric field or combination of both. The $C_I(x_o, t_m)$, for six disturbed days and six quietest days in each corresponding month, is plotted in Fig. 1. This figure shows all values of $C_I(x_o, t_m)$ from 0 to 1 to study the effect of magnetic disturbance, but for the calculations of coherence scales, only the time intervals for which $C_I(x_o, t_m) > 0.5$ have been used. The variation of $C_I(x_o, t_m)$ for the disturbed days is shown in Fig. 1 indicates the maximum disturbance about 2300 LT to 0100 LT, which shows generation phase of irregularities in this period because of combination of disturbance dynamo and prompt penetration electric field. Figure 1e shows lower values of $C_I(x_o, t_m)$ about 2300 LT on 27–28 March 2013 and about 0100 LT on 30–31 March 2013.

The evolution of the ionospheric irregularities, responsible for scintillations, may be caused due to the enhancement in magnetospheric electric field during storm time [11, 23]. Since irregularities continuously evolve with time and magnetic disturbance, the coherence scale obtained for each scintillation event will be changing with time and will give variation according to magnetic disturbance. The mass plot of coherence scale with maximum space-time correlation is shown in Fig. 2a for quiet nights. Using Gaussian least square fitting explained in above Sect. 2, the coherence scale for quiet period is obtained to be 85 m; similar mass plot for magnetically disturbed days is shown in Fig. 2b which gives the coherence scale 115 m. This increase in the coherence scale at magnetically disturbed days have scale size of the order of Fresnel scale, $d_I = (2\lambda z)^{1/2}$ where, λ is the wavelength of the signal and z is average distance of the irregularity layer from receiver. The F region height variation at the time of magnetic

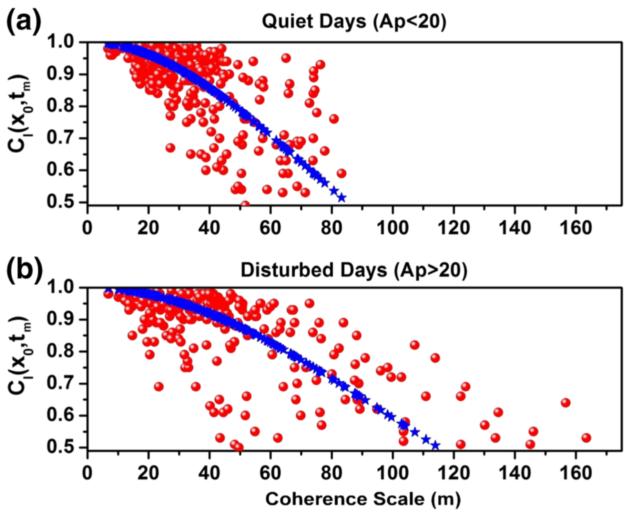

Fig. 2 The mass plot of $C_I(x_o, t_m)$ and coherence scale (m) for quiet (*upper panel*) and disturbed days (*lower panel*) with gaussian fit curve

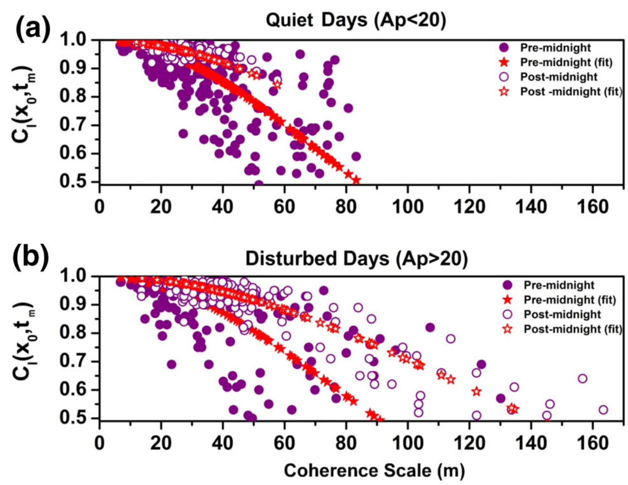

Fig. 4 *Upper panel* The mass plot of $C_I(x_o, t_m)$ and coherence scale for quiet days with gaussian fit curve for pre and post-midnight period, *Lower panel* The mass plot of $C_I(x_o, t_m)$ and coherence scale for all disturbed days with gaussian fit curve for pre and post-midnight period

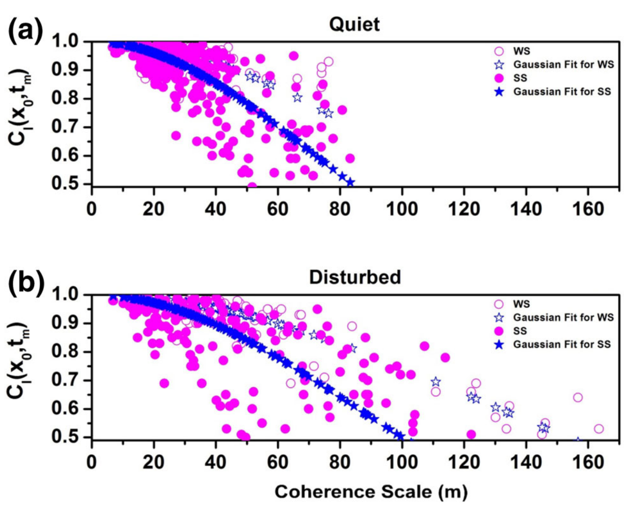

Fig. 3 *Upper panel* The mass plot of $C_I(x_o, t_m)$ and coherence scale (m) for quiet days with gaussian fit curve for weak and strong scintillations, *Lower panel* The mass plot of $C_I(x_o, t_m)$ and coherence scale (m) for all disturbed days with gaussian fit curve for weak and strong scintillations

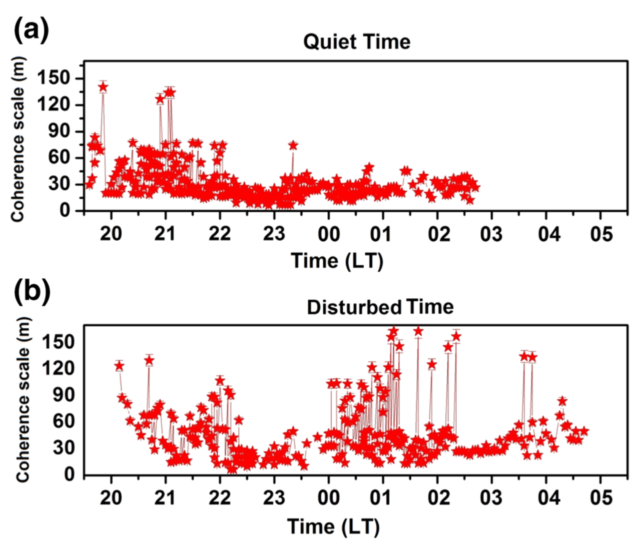

Fig. 5 Variation of coherence scale with Local Time (LT) for quiet days (*upper panel*) and disturbed days (*lower panel*)

Table 1 Coherence scales for quiet days, disturbed days, $S_4 \leq 0.5$ and $S_4 > 0.5$

	Coherence scale (m)			
	Pre-midnight	Post-midnight	$S_4 \leq 0.5$	$S_4 > 0.5$
Quiet period	84	116	118	84
Disturbed period	90	141	153	100
Quiet and disturbed period	82	130	142	90

disturbance may be responsible for the increase in coherence scale. Fejer et al. (1999) and Jyoti et al. (2004) show that ESF irregularities form at higher altitude during increasing solar cycle.

Irregularities, having angular sizes of the order of Fresnel scale, cause weak scintillations. These are responsible for higher coherence scale as shown in Fig. 3. The mass plot of $C_I(x_o, t_m)$ versus $\left[\frac{x_o^2 V_c^2}{V_o^2+V_c^2}\right]$ for weak and strong scintillations in quiet period is shown in Fig. 3a. Similar mass plot for disturbed period is shown in Fig. 3b. For both quiet and disturbed periods it is seen that strong scintillations caused by smaller coherence scale and weak scintillations caused by larger coherence scales of the irregularities. Bhattacharyya et al. (2003) have also observed that weak and strong scintillations are associated with large and smaller coherence scales respectively. Comparison of coherence scales for weak and strong scintillations in quiet time with that of the disturbed time are given Fig. 3a and b respectively. It is clear that the coherence scales for both weak and strong scintillations in the disturbed time are larger than that of in quiet time.

Scale size of irregularities in pre-midnight period of quiet days is 84 m which increases to 116 m in post-midnight. For the disturbed days these values are 90 m and 141 m. This shows the evolution in size of irregularities with respect to time from lower to higher scales in both quiet and disturbed days. But increase in the size of the irregularities is more during disturbed days (Fig. 4a, b). This could be due to the fact that the irregularities start to evolve in pre-midnight and is sustained to smaller scales up to post-midnight period of quiet days but in disturbed days the irregularities evolve from pre to post-midnight with greater scales because of the magnetospheric electric field during storm time. Study of coherence scale variations during pre and post midnight period were carried by Engavale et al. (2005). They found increase in coherence scale in pre midnight period with solar flux.

It is also seen that during disturbed time period, the fluctuations in values of coherence scale are higher than in quiet time as shown in Fig. 5, this shows the random changes in scales of the irregularities in disturbed period. One more thing can be noted from Fig. 5a and b is that during quiet period, fluctuation of coherence scale in pre-midnight is larger than that in post-midnight. This may be

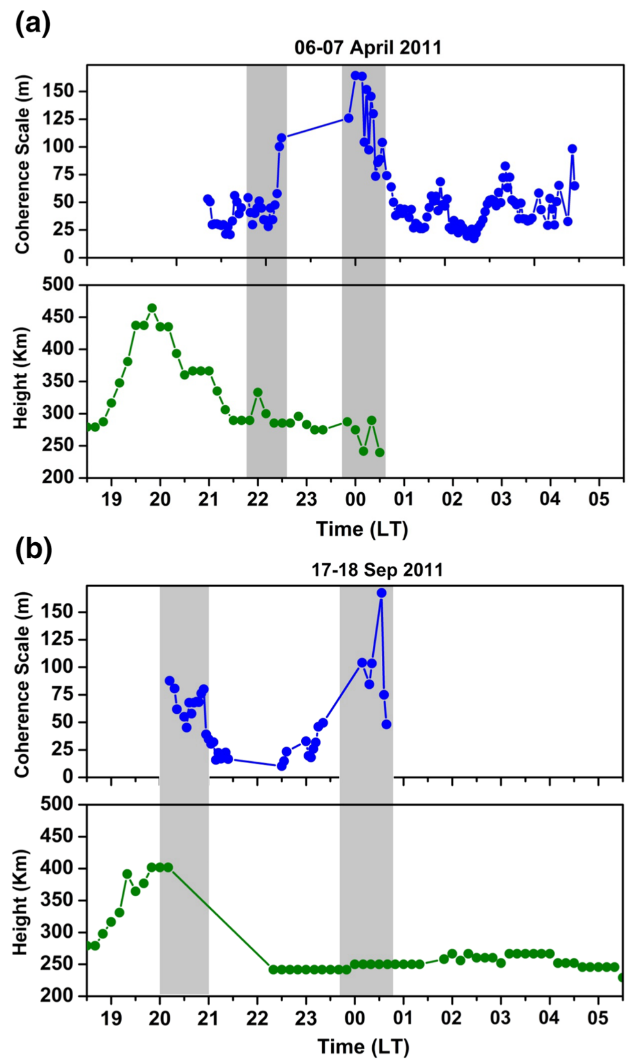

Fig. 6 Comparison of coherence scale (*upper panel*) with critical height ($h'f$) of th F region (*lower pannel*)

due to the generation phase of the ionospheric irregularities during the pre midnight period and the decay phase of the irregularity in post midnight period. Whereas in disturbed period, fluctuation of coherence scale in post-midnight is larger than that in pre-midnight. It leads to the conclusion that there is enhancement of the eastward electric field in post mid night period. Coherence scales for pre and post midnight period and for weak ($S_4 \leq 0.5$) and strong ($S_4 >$

0.5) scintillations of quiet and disturbed days is summarized in Table 1.

Scintillations observed are generated at magnetic equator and, maps down to low latitude station Kolhapur. Therefore, it is useful to see the effect of magnetic activity on height of F layer. The F region height varies with magnetic activity because of magnetospheric electric field which may be responsible for variations in coherence scales. During the quiet nights average coherence scale is 30 m, but during the disturbed nights it is 46 m. Coherence scale has very high values such as from 104 to 164 m within time from 0000 to 0040 LT on 06–07 April 2011 and 74 to 167 m within time 0000–0030 LT on 17–18 September 2011 as shown in upper panels of Fig. 6a and b respectively. These large values of coherence scale at mid night and in post midnight period shown in upper panel of Fig. 6a and b are compared with the virtual height $h'F2$ of the F layer in lower panel of Fig. 6a and b. On 06–07 April 2011, $h'F2$ shows fluctuation from 285 to 335 km within time 2150–2235 LT and 240 to 280 km within time 2350–0035 LT as shown in Fig. 6a. On 17–18 September 2011 d_I shows almost all values above 50 m within 2000–2100 LT and $h'F2$ at this time is not available but for small increase of $h\prime F2$ about 0000 LT shows large increase in d_I. The higher d_I is shaded by gray color in both figures. The small increase in $h'F2$ may be due to generation of eastward electric filed in this period. The increase in d_I in pre midnight period for both the cases is agreement with Engavale et al. (2005) and d_I in post midnight period increases with increase in critical height of equatorial F layer. The F region height increases at the time of solar maxima [4, 24]. It should also be noted that the deviation of d_I from average, is very high in post midnight period.

4. Summary

We have used the data of six quiet and disturbed nights. Study has been focused on dependence of coherence scale d_I, on magnetic disturbance. We observed that coherence scale is 115 m for magnetically disturbed days which is larger than that of quiet days (85 m). If we separate out the pre and post midnight scales which are 90 m and 141 m respectively indicates the evolution of irregularities because of perturbation in magnetospheric electric field. Strong scintillations are due to the small coherence scales and weak scintillations are due larger coherence scales. From comparative study of the virtual height $h\prime F2$ and coherence scale, it is observed that at the time of increase in $h\prime F2$ coherence scale increases. So, it may be concluded that the eastward electric field generated on magnetically disturbed night which is responsible to increase $h\prime F2$ also causes to increase the coherence scale. Also, temporal changes in scale length show large variation in post-midnight period than pre-midnight for disturbed period.

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