Effect of solar variability on transionospheric radio wave propagation in the equatorial region

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Abstract. Growth of plasma instabilities in the post-sunset equatorial ionospheric F region gives rise to irregularities known by the generic name: equatorial spread F (ESF), which scatter incident VHF or higher frequency radio waves to produce scintillations on trans-ionospheric radio waves. Changes in large scale (> 10 km) electron density distribution in the equatorial and low latitude ionosphere due to electrodynamic effects associated with magnetic storms, influence the generation of ESF irregularities as seen in the pattern of occurrence of nighttime equatorial scintillations that may be specifically linked with magnetic activity. Besides such effects due to transient solar events, it is well known that the probability of occurrence of ionospheric scintillations caused by ESF irregularities as well as the strength of these scintillations during different phases of the solar cycle show a significant modulation of the generation and evolution of these irregularities by solar cycle related changes in the ionosphere and thermosphere. Evolution of spatial structure in the ESF irregularities determines the spatial scales that occur in the ground scintillation pattern during different phases of a scintillation event, and these spatial scales together with the dynamics of the irregularities determine the extent of degradation of transionospheric radio signals. Solar cycle effects on the structure and dynamics of ESF irregularities and hence on degradation of transionospheic radio signals during magnetically quiet periods, as also the effect of magnetic activity on the generation of ESF irregularities are discussed here on the basis of long term spaced receiver scintillation observations at an equatorial location.

Index Terms. Equatorial plasma bubbles, ionospheric scintillations, magnetic activity, solar variability.

1. Introduction

An important consequence of physical changes in the near Earth space environment in response to variations in solar radiation, solar plasma ejection, and the electromagnetic status of the interplanetary medium, is the effect on the distribution of plasma in the ionosphere and plasmasphere through which radio waves used for communication and navigation propagate. Changes in the electron density distribution in the path of a signal due to production or loss processes, electrodynamics of the intervening plasma, and variations in the neutral component that affect the ionospheric plasma, alter the propagation medium and hence its dispersive and scattering effects on radio wave signals (Bhattacharyya and Basu, 2002).

For an undisturbed ionosphere, electron density does not vary significantly over scale lengths shorter than or comparable to the Fresnel scale for VHF and higher frequency signals, since the Fresnel scale length for these signals, determined by the signal frequency and average height of the ionospheric layer under consideration, is expected to be about 1 km or less. In this situation, changes in the total electron content along the signal path only alter the time delay introduced by the ionosphere in the travel time of the signal. However, the ionosphere in the equatorial and polar-cap/auroral regions often exhibit significant departure from an undisturbed, smooth state when growth of plasma instabilities gives rise to irregularities.

Growth of a generalized Rayleigh-Taylor (GRT) instability in the post-sunset equatorial ionospheric F region may produce geomagnetic field-aligned equatorial plasma bubbles (EPBs) and intermediate scale length (tens of km to ~ 100m) irregularities in the equatorial and low-latitude ionospheres. These irregularities, which are included in the so-called equatorial spread F (ESF) irregularities, are capable of scattering incident VHF and higher frequency radio waves to cause scintillations on these signals. Ostensibly, basic condition for the growth of the GRT instability is present every day shortly after sunset. However, in reality, occurrence of ESF is not a daily phenomenon, and understanding the occurrence pattern and characteristics of these irregularities continues to be a challenge. Height of the post-sunset peak of the equatorial F region has been identified as one of the key parameters in the occurrence of ESF irregularities (Jayachandran et al., 1993; Fejer et al., 1999). Hence any change in this parameter caused by solar variability is expected to affect the generation of EPBs and evolution of spatial structure in them. The ambient zonal electric field thus plays an important role in the growth and evolution of these irregularities as it controls the height of the nighttime equatorial F layer. For magnetically undisturbed post-sunset periods, a pre-reversal enhancement of the ambient eastward electric field, before it turns westward, is expected to enhance the growth rate of the GRT instability. In the equatorial and low-latitude regions, the ambient electric field may be modified due to solar variability and resultant changes in large-scale plasma distribution may on some occasions create the right condition for generation of ESF irregularities, which affect transionospheric radio wave propagation, while at other times the zonal electric field is modified in such a manner as to suppress the growth of the GRT instability during the post-sunset hours. Two aspects of solar variability, which influence the generation of EPBs and evolution of spatial structure in them, are considered in this paper: (a) solar cycle variations; (b) transient solar events that result in geomagnetic activity.

Effects of long-term solar variability on the equatorial ionosphere as seen in solar cycle related changes in parameters derived from ionosonde observations have been studied extensively in the past. These are changes in large-scale characteristics of equatorial ionospheric plasma. As far as irregularities are concerned, dependence of the pattern of occurrence of ESF irregularities on solar cycle have been studied using long term VHF scintillation data recorded near the crest of the equatorial anomaly region in India (Chakraborty et al., 1999), and also data obtained with the JULIA radar at Jicamarca (Hysell and Burcham, 2001). The present paper focuses on the effect of solar cycle variations on the structural evolution of plasma bubbles.

Modification of the electric field in the equatorial and low-latitude ionosphere, as a result of magnetic activity, takes place through one or both of the following processes: (a) prompt penetration of magnetospheric electric fields to lower latitudes either when the shielding is not adequate or due to 'overshielding' (Kelley, 1989); (b) ionospheric disturbance dynamo set up by wind patterns created due to enhanced Joule heating in the high latitudes (Blanc and Richmond, 1980; Fejer et al., 1991; Fejer and Scherliess, 1995, 1997; Fuller-Rowell et al., 2002; Huang et al., 2005). EPBs are not generated in the nighttime equatorial ionosphere once the height of the equatorial F region peak goes below a threshold, due to reversal of the zonal electric field to westward. After this time, EPBs may be freshly generated due to eastward turning of the zonal electric field brought about as a result of magnetic activity. In order to identify such EPBs, spaced receiver scintillation data has been used and statistics of their occurrence has been derived for different seasons. Section 3 describes this aspect of generation of EPBs due to solar transient events that are geo-effective.

2. Solar cycle variations

The level of degradation of transionospheric VHF and higher frequency radio wave signals due to ionospheric scintillations is determined by: (1) depth of fading of the signal, which depends on the strength and spatial structure of the ionospheric irregularities; (2) fading rate of the signal, which depends on (a) the strength and spatial structure of the irregularities that determine the spatial variation of intensity in the ground scintillation pattern; and (b) the drift speed of the irregularities transverse to the signal path. Spatial scales in the ground scintillation pattern produced due to scattering of incoming radio waves by ESF irregularities, are determined both by the strength of the irregularities as well as the characteristics of their power spectrum. As the ground scintillation pattern drifts past a receiver due to the movement of irregularities across the signal path, these spatial scales are converted into temporal scales in the scintillations recorded by the receiver. An example of scintillations on a VHF signal transmitted from a geostationary satellite and recorded by spaced receivers located close to the dip equator is shown in Fig. 1.

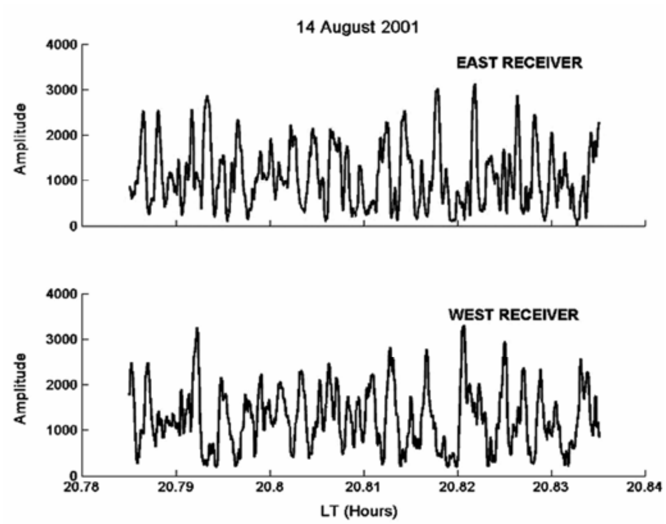

Fig. 1. Amplitude scintillations on a 251 MHz signal transmitted from a geostationary satellite and recorded by two receivers spaced along a magnetic east-west baseline at Tirunelveli near the dip equator.

The average drift speed of the irregularities transverse to the signal path varies throughout a scintillation event, its variability being largest during the initial development phase of the EPB's. Other characteristics of the irregularities, which produce the observed scintillations, also vary throughout a scintillation event. Hence extraction of information about spatial scales in the ground scintillation pattern from the data is not straightforward. However, since these spatial scales are related to the spatial structure of irregularities, a method was developed to derive this information from spaced receiver scintillation data (Bhattacharyya et al., 2003), which has been used to study changes in the spatial correlation function of intensity variations in the ground scintillation pattern due to evolution of the ionospheric irregularities.

Simulations of nonlinear evolution of EPBs, based on an inhomogeneous, magnetic-flux-tube-integrated electrostatic model, have shown that structure generation in the EPBs which occurs at high altitudes, depends on the background Pedersen conductivity as well as ion polarization current profile (Keskinen et al., 1998). Since some of these factors vary with solar flux, the evolution of structure in EPBs is also expected to show some dependence on solar flux. Use of a 3-mode system to describe the non-linear evolution of EPBs through the growth of an electromagnetic R-T instability led to the following condition for chaotic evolution of the EPBs, which would produce small scale structures (Bhattacharyya, 2004) :

$$\nu_i + \frac{\mu_0 V_A^2 \Sigma_P^E}{l} < \sqrt{\frac{g}{2L}}$$

Here ν_i is the ion-neutral collision frequency, Σ_P^E is the field line integrated Pedersen conductivity of the conjugate E region in either hemisphere at the foot of the geomagnetic field line, which connects this E region with the equatorial F region (hemispheric symmetry, which implies alignment of the sunset terminator with the magnetic meridian, emerges as a necessary condition for the growth of the EPBs in this theory), l is the length of the geomagnetic field line that connects the equatorial F region with the E-region in either hemisphere; g is the acceleration due to gravity, V_A is the Alfvén speed and L is the density gradient scale length on the bottom-side of the equatorial F region. This condition introduces a new time scale – that for discharge of the EPB and hence decay of the perturbation electric field associated with the R-T instability, which plays an important role in the evolution of spatial structure in EPBs, by currents flowing through the conjugate E regions. According to this theory, when the bottom-side of the equatorial F region is at such a low height that the above condition is not met, the R-T instability evolves into the bottom-side sinusoidal structures, which, as the nomenclature suggests, are predominantly sinusoidal. Such structures, with scale lengths of about 1 km, have been observed by satellite measurements (Valladares, 1983), and are characterized by steep irregularity power spectra. Thus, it is surmised on the basis of the above theory that small-scale irregularities are more likely to occur for higher heights of the post-sunset equatorial F region.

For weak scintillations, the dominant scale size in the ground scintillation pattern is largely determined by the Fresnel scale and to a smaller extent by details of the irregularity power spectrum such as the spectral index of a power-law type of spectrum. However, for strong scintillations, there does not exist a simple relationship between the spatial structure of the irregularities and the spatial scales seen in the ground scintillation pattern. In this case, a theoretical model of the irregularities has to be used in a numerical calculation of the spatial correlation function of the intensity variations in the ground scintillation pattern. Results of such a calculation (Engavale and Bhattacharyya, 2005) are displayed in Fig. 2, which shows how the spatial scale for 50% decorrelation, referred to as the coherence scale, decreases as the strength of the irregularities, measured by the standard deviation of electron density fluctuations, increases. In this figure, m is the power-law index for a 2-dimensional irregularity spectrum, R_0 refers to the outer-scale of the power-law spectrum, and H_{AVG} is the average height of the irregularity layer. These theoretical results are used to make inferences regarding the evolution of ESF irregularities from scintillation data.

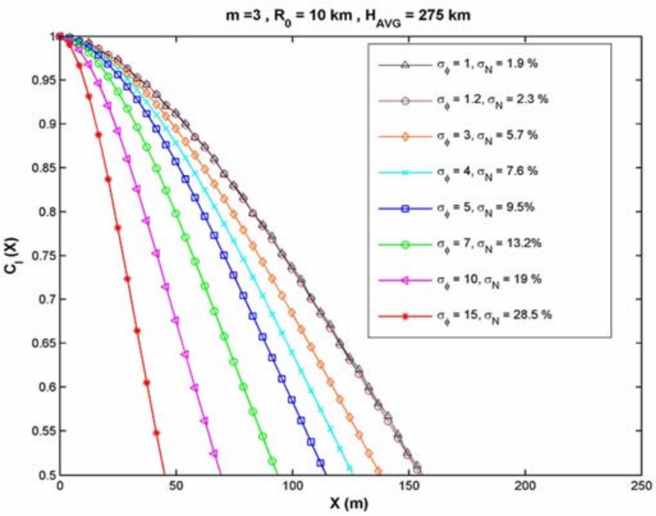

Fig. 2. Theoretical spatial correlation functions of intensity variations in the ground scintillation pattern for different irregularity strengths. σ_N is the standard deviation of normalized electron density fluctuation in the irregularity layer, and σ_ϕ is the standard deviation of phase perturbations (in radians) imposed on the incident radio wave by the irregularity layer.

Spaced receiver observations are generally used to calculate the average zonal drift speed V_0 of the ground scintillation pattern along the receivers' baseline. For a signal path elevation angle that deviates from 90º, V_0 has contributions from both the zonal and vertical drifts of the irregularities, which produce the observed scintillations. The irregularities evolve with time and therefore characteristics of the ground scintillation pattern may vary randomly within the time interval used for calculating V_0, and these random variations cause decorrelation of the signals recorded by spaced receivers. Hence, the full correlation technique introduced by Briggs (1984), which takes into account the decorrelation of the spaced receiver signals, is used to determine V_0. This technique also provides an estimate for a parameter V_C designated the 'random velocity', which is a measure of random changes in the ground scintillation pattern as the irregularities drift across the signal path (Bhattacharyya et al., 1989). The full correlation technique is based on certain assumptions which are most likely to be valid when the maximum cross correlation of the spaced receiver signal intensities, $C_I(x_0, t_m)$, where x_0 is the distance between the two receivers, and t_m is the time lag for maximum cross correlation, is not less than 0.5. Spaced receiver scintillation observations at Tirunelveli (77.7ºE, 8.7ºN, dip latitude 0.6ºN), on a 251 MHz radio wave signal transmitted from geostationary satellites FLEETSAT and UFO2 located at 73ºE and 71.2ºE respectively, have been used to study the characteristics of intermediate scale ESF irregularities during different stages of their evolution. For each 3-minute interval during a scintillation event, strength of the intensity scintillations is provided by the S_4 -index, which is the standard deviation of normalized intensity of the radio signal recorded during this interval. For all such intervals with S_4 > 0.15 and $C_I\left(x_0, t_m\right) \geq$ 0.5, V_0 and V_C are calculated using full correlation analysis. The computed $C_I\left(x_0, t_m\right), V_0$, and V_C yield one point in the $C_I\left(x, 0\right)$ vs x plot for every 3 min interval, in the technique developed by Bhattacharyya et al. (2003). This is sufficient to estimate the coherence scale, d_I, of the ground scintillation pattern for each 3 min interval, on the assumption that the spatial correlation function for intensity variations during each interval has an exponential form: $C_I\left(x,0\right) = \exp\left[-0.693\left(x/d_I\right)^2\right]$. Fig. 3 shows the evolution with local time (LT) of the spatial correlation functions of ground scintillation patterns for a given month, derived from spaced receiver scintillation observations at Tirunelveli. Before 20 LT, scintillations are often weak yielding large coherence scales d_I. After 20 LT the coherence scales tend to become shorter, but after 02 LT they increase again due to steepening of the irregularity spectrum as shown theoretically by Engavale and Bhattacharyya (2005). This is expected due to earlier decay of shorter scale length irregularities through diffusion.

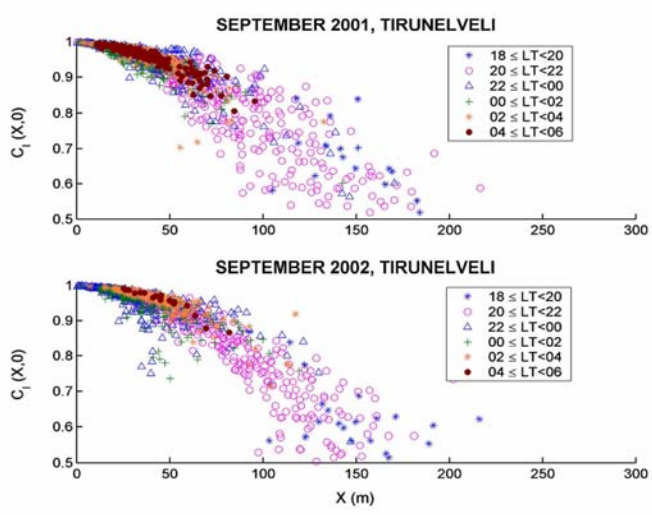

Fig. 3. Plots of points on the spatial correlation function of intensity variations in the ground scintillation pattern versus the spatial lag X show how the dominant spatial scale in the ground scintillation pattern varies as ESF irregularities evolve with time.

In the initial phase of development of EPBs, when small scale structures evolve in them, zonal and vertical drift of the irregularities and hence V_0 is highly variable due to the $\mathbf{E}\times\mathbf{B}$ drifts arising from perturbation electric fields associated with the R-T instability. For magnetically quiet periods this generally occurs before 22 LT, so that the irregularities tend to drift with the background plasma after 22 LT. During the period 22-24 LT, when short spatial scales are found in the ground scintillation pattern, the average zonal drift, $\left\langle V_0\right\rangle$, of the ground scintillation pattern shows an increase with increasing 10.7 cm solar flux, both during solstice and equinoctial months as shown in Fig. 4. Such an increase has also been reported for the zonal drift of the equatorial F region plasma obtained from Jicamarca radar observations (Fejer et al., 2005).

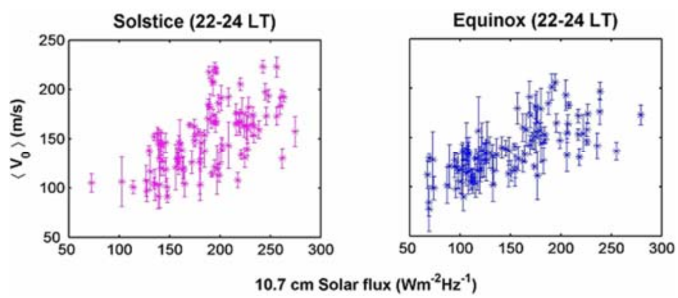

Fig. 4. Variation of average zonal drift of the ground scintillation pattern during 22-24 LT, with 10.7 cm solar flux.

For a given scintillation event, $\left\langle d_{I\max}\right\rangle$, the average of 5 largest values of d_I, obtained when the scintillations are weak, show a clear increase with solar flux as seen in Fig. 5. This may be attributed to an increase in the Fresnel scale length due to a higher threshold height of the equatorial F layer for generation of ESF irregularities, with increasing solar flux (Fejer et al; 1999; Hysell and Burcham, 2002; Engavale et al., 2005). However, as far as degradation of transionospheric radio wave signals is concerned, it is the shortest spatial scale length, taken as the average, $\left\langle d_{I\min}\right\rangle$, of the five smallest values of d_I generally found in the ground scintillation pattern during the pre-midnight period of a given scintillation event, which is important.

Fig. 5 shows that $\left\langle d_{I\min}\right\rangle$ also tends to increase with solar flux. This indicates that during pre-midnight hours when the smallest spatial structures are generally found in ESF irregularities for magnetically quiet conditions, the irregularity power spectrum is steeper for higher $F_{10.7}$, which implies more rapid decay of short wavelength (< 500 m) irregularities with increasing solar flux. This may be attributed to larger post-reversal westward electric field for higher solar flux, which would cause the irregularities to descend more rapidly to lower heights where the decay is faster due to better coupling with the conjugate E regions. As a result of this increase in $\langle d_{I\min} \rangle$ with solar flux, $\langle \tau_{\min} \rangle = \langle d_{I\min} \rangle \Big/ \left(\sqrt{\langle V_0 \rangle^2 + \langle V_C \rangle^2} \right)$, which represents the shortest correlation interval, shows a tendency to level off for $F_{10.7}$ values exceeding 150, after an initial rapid decrease with increasing $F_{10.7}$ up to around 150, during equinoctial periods. For solstices, there is no well-defined pattern in the variation of $\langle \tau_{\min} \rangle$ with $F_{10.7}$ for reasons discussed in the summary

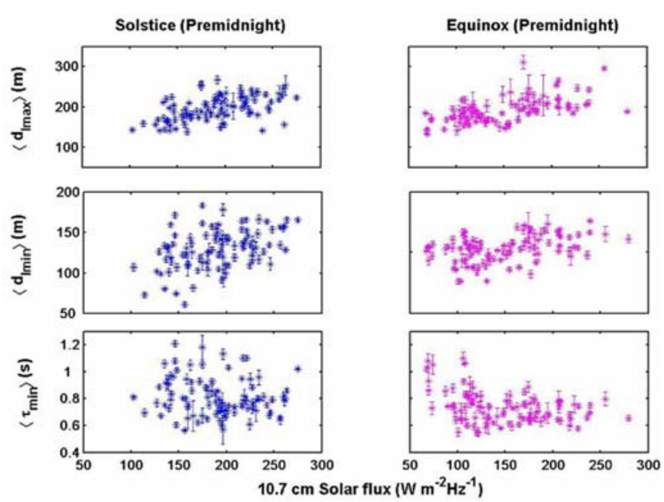

Fig. 5. Variation with 10.7 cm solar flux of the largest (top) and smallest (middle) spatial scale lengths found in the ground scintillation pattern, and the shortest intensity correlation interval (bottom) for each scintillation event.

3. Effect of geomagnetic activity

One of the requirements for establishing a cause effect relationship between geomagnetic activity and generation of ESF irregularities is to identify EPBs that are freshly generated as a result of magnetic activity. In techniques such as ionospheric scintillations, it is not possible to determine on the basis of data from a single receiver, whether the observed scintillations are caused by freshly generated irregularities, or by irregularities, which have been produced a few hours earlier, and later drifted on to the signal path. However, it is seen from spaced receiver scintillation observations that the maximum cross correlation between the signals recorded by two receivers spaced along a magnetic east-west base line, with a separation less than the Fresnel scale, falls well below the value of 1 in the early phase of development of the EPBs. This has been attributed to the presence of perturbation electric fields associated with the R-T instability, which cause the irregularity drift to be highly variable during this phase (Bhattacharyya et al., 2001). For magnetically quiet days, V_C attains high values in the initial phase of development of the EPBs, which lasts up to around 22 LT, and after that time, V_C generally has a small value ($\leq$ 15 m/s). Resurgence in the value of V_C after 22 LT has been observed to be always associated with magnetic activity (Bhattacharyya et al., 2002). However, since $C_I(x_0, t_m)$ is often found to fall below 0.5 in the initial phase of development of EPBs and V_C is not estimated in such a situation, more information about fresh generation of EPBs is obtained by considering $C_I(x_0, t_m)$ itself.

This idea is supported by simultaneous observations made with a 18 MHz radar at Trivandrum (77°E, 8.5°N, dip lat 0.5°N) while scintillations on a 251 MHz radio signal transmitted from a geostationary satellite were recorded by the two spaced receivers located at Tirunelveli (Tiwari et al., 2006). It is seen in Fig. 5 of Tiwari et al. (2006) that in the absence of magnetic activity related effects, the rapid increase in C_I ($= C_I(x_0, t_m)$) to a value close to unity after the initial phase of development of an EPB is over, has a counterpart in the rapid decline of the maximum height of radar echoes, and of the maximum spectral width derived from radar echoes. This decrease in the height of 8.3 m scale ESF irregularities, which are responsible for 18 MHz radar backscattered signal, in conjunction with increasing C_I is also supported by a comparison of the lowest value of C_I seen on a particular night with the maximum strength and latitudinal extent of observed GPS L-band scintillations on that night. Low values of C_I are associated with greater occurrence of moderate to strong GPS L-band scintillations ($S_4 > 0.5$) over a wider latitudinal belt, implying a greater height of the corresponding magnetic field-aligned EPBs.

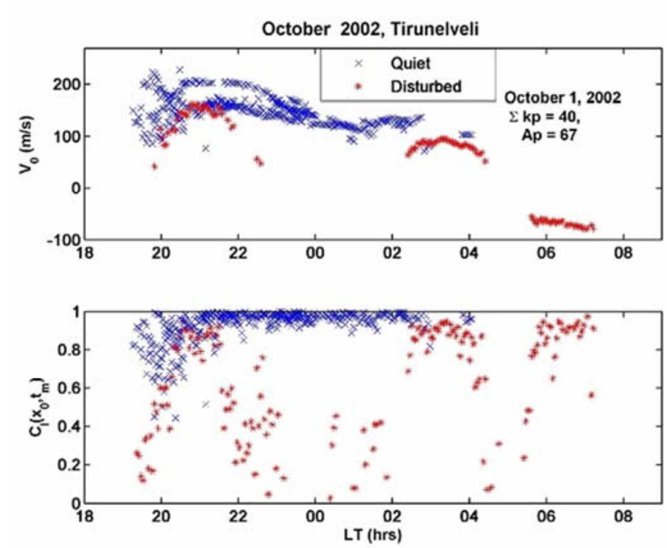

Fig. 6. Eastward drift of the ground scintillation pattern estimated from spaced receiver observations (top) and maximum cross-correlation of the two spaced receiver signals (bottom), as a function of local time for all the magnetically quiet days with scintillations during October 2002, and for the magnetically disturbed day: October 1, 2002.

Use of $C_I(x_0, t_m)$ to identify nascent EPBs, as demonstrated in Fig. 6, makes it possible to compare the statistics of generation of EPBs during different LT intervals for magnetically quiet and disturbed periods. In deriving these statistics, the various criteria used to define a magnetically disturbed day are: (a) $Ap \geq 20$ for the day; or (b) $ap \geq 20$ for $12 - 15, 15 - 18$ or $18 - 21$ UT (LT = UT + 5.5 Hrs); or (c) long-term effects (time lag = 20 - 30 Hours); or (d) AE > 200 nT. Fig. 7 shows that the patterns for magnetically quiet and disturbed periods are distinctly different. On magnetically quiet days, there is generally no fresh EPB produced as a result of the growth of the GRT instability after 22 LT. The distribution in LT of fresh generation of EPBs, due to magnetic activity, is also found to have a dependence on season.

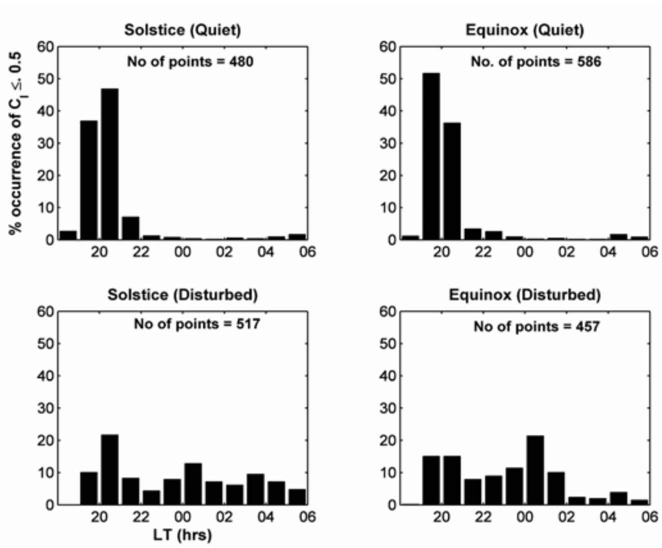

Fig. 7. Distribution of intervals for which observed scintillations are produced by nascent EPBs as identified using the decorrelation of signals recorded by the two spaced receivers.

4. Summary

Influence of solar variability on space-based communication and navigation systems is an area of major concern, given the increasing dependence of humanity on such systems. It has been observed that during a solar cycle, with increasing solar activity the outage of such systems increases. Transient solar events of coronal mass ejections, on the other hand, have to be first of all geoeffective, to have any effect on Earth's magnetosphere-ionosphere-thermosphere coupled system. Further, the resultant changes in the post-sunset electric field in the equatorial ionosphere show considerable variability depending on the history of the geomagnetic disturbance (Scherliess and Fejer, 1997). It is well known that electrodynamics of the equatorial ionospheric plasma and F region meridional winds determine the occurrence pattern of ESF irregularities (Jayachandran et al., 1993; Fejer et al., 1999; Jyoti et al., 2004) and these factors are influenced by solar variability. However, effects of solar variability on the evolution of spatial structure in EPBs, which is the crucial question as far as degradation of satellite radio wave signals due to ionospheric scintillations is concerned, has not been addressed so far. Here, this aspect and the issue of identifying nascent EPBs, which is critical for establishing a cause-effect relationship between magnetic activity and generation of EPBs, have been discussed, on the basis of results derived from spaced receiver scintillation observations.

As far as solar cycle variations are concerned, it is found that there is more rapid decay of small-scale length (< 500 m) irregularities with increasing $F_{10.7}$, which results in an increase in the smallest spatial scales seen in the ground scintillation pattern during the course of a scintillation event. However, zonal drift speed of the scintillation pattern past a receiver increases with increasing solar flux, with the net result that during equinoxes there is a rapid decline in the shortest correlation interval of the signal for a given scintillation event as $F_{10.7}$ increases up to 150, beyond which there is little variation in the correlation interval with increasing $F_{10.7}$. There is no such clear pattern for solstices, which demonstrates that the evolution of spatial structure in ESF irregularities during solstices differs from that during equinoxes. In the Indian region scintillations are generally a much more common occurrence during equinoxes than during solstices. The correlation interval determines the fading rate of the signal, and hence during the important equinoctial period, it is expected that signal degradation would increase rapidly as $F_{10.7}$ increases up to 150, beyond which there should not be any further degradation. In the past a saturation effect has been reported in the dependence of percentage occurrence of $S_4 > 0.5$ on sunspot numbers from scintillation data recorded at Ascension Island (L-band), Manila (VHF) and Huancayo (VHF) (Secan et al., 1995).

In order to establish a cause-effect relationship between magnetic activity and occurrence of EPBs, it is necessary to address the question of the 'age' of the irregularities that are observed using techniques such as scintillations, which may also be caused by EPBs generated a few hours earlier at another location and later drifting on to the path of the radio wave signal. Use of the decorrelation of spaced receiver signals to settle this issue has yielded a statistical picture of the effect of magnetic activity on the generation of EPBs. In this area further work needs to be done to quantify such effects, and also to evaluate solar cycle dependence of EPB generation due to geomagnetic activity because the ambient ionospheric plasma distribution plays a role in determining the effect of a disturbance dynamo in the post-sunset equatorial ionosphere.

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