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Refinement of the background ionospheric conditions and plausible explanation based on neutral dynamics for the occurrence/non-occurrence of L-band scintillation patches against forecast.

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ABSTRACT

The recently evolved L-band scintillation forecast mechanism based on the characteristic features of the daytime F-region electron density fluctuations and also on the basic ionospheric conditions had been successful to a reasonable extent in forecasting the spatio-temporal map of scintillation patches. There had been a few non-compliances in the expected pattern within/outside the forecast windows. The present paper attempts to address such non-compliances and offers a plausible explanation based on neutral dynamics, especially the local time variation of vertical winds over the magnetic equator, while at the same time refining the earlier stipulated background ionospheric conditions. With the above refinements, it is anticipated that the forecast mechanism would become very robust. The present results highlight the importance of the neutral dynamical parameters and the urgent need to concentrate on the efforts to make systematic measurements of the same in order to characterize their variability.

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1. Introduction

The L-band scintillations, one of the manifestations of the medium scale plasma density irregularities in the post sunset equatorial F-region, has a unique place in the over all scenario of the phenomenon of Equatorial Spread-F, mainly because of its significant effect on the ground-satellite-ground communication links. The positional inaccuracies introduced by these scintillations have the potential to become critical in satellite based navigation which incidentally is becoming the order of the day.

Many times, the ground and/or, air/space borne receivers may even lose the synchronization/lock during the presence of intense scintillations, making the satellite-based navigation totally ineffective. Therefore, understanding the spatial and temporal morphology of this phenomenon is extremely important not only from the point of view of the basic physical processes involved, but also from the practical applications as well. Ideally, one should be able to forecast the impending spatial/temporal occurrence pattern of scintillations so as to issue necessary warning to any potential user with details of the actual occurrence pattern typically with a time resolution of ~10 min, at least few hours before the actual occurrence of the phenomenon. The forecast should include information like, 'whether they would occur over any given location' and in case affirmative, it should be able to specify 'the actual time of its occurrence along with its duration'. It should also indicate its 'probable intensity'. Though the morphology and the various manifestations of the phenomenon have been understood reasonably well including the primary and secondary driving forces, certain enigmatic aspects like the day to day variability had been posing a challenge. Under near identical background ionospheric conditions, the phenomenon might be present on one day and may be totally absent on another, leave alone its temporal evolution during a night.

In general, the variability is believed to be due to the modulation of additional external forcings on the primary plasma instability process, in this case the collisional Rayleigh–Taylor instability, the growth rate for which in its simplest form is given as Haerendel (1973)

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$$\gamma = (1/L)(g/\nu_{in}) \tag{1}$$

where γ represents the growth rate, L the plasma scale length, g the acceleration due to gravity and ν_{in} the ion-neutral collision frequency. As could be seen, the growth rate is inversely proportional to the density gradient length in the electron density and the ion-neutral collision frequency.

When it comes to the variability exhibited by the phenomenon, (i) the solar activity dependence is brought about through the changes in both the ionosphere and the neutral thermospheric densities and their overall energetics (e.g. Aarons, 1993, Tulasi Ram et al., 2006), while (ii) the seasonal and longitudinal variations are broadly understood to be due to the magnetic declination and the resultant asynchronous conjugate E-region sunset, affecting the overall electro-dynamical conditions of the equatorial ionosphere (Abdu et al., 1981, 1992; Maruyama and Matuura, 1984; Tsunoda 1985). The day to day variation has been identified as an enigma (Tsunoda, 2005) and it has been conjectured in the literature to be due to the variations encountered in the equatorial electro-dynamical forcing and the consequent development of the Equatorial Ionization Anomaly (EIA) (Raghavarao et al., 1988; Sridharan et al., 1994; Jayachandran et al., 1997; Valladares et al., 2001; Fejer et al., 2014) – the further consequential development of the Equatorial Temperature and Wind Anomaly (ETWA) and in addition, to the subsequent changes in the neutral dynamics in the form of establishment of a meridional circulation cell (Raghavarao et al., 1993; Devasia et al., 2002). There had been a few attempts to forecast the day to day variation of the occurrence of scintillations in a broader sense by some of the earlier workers (Anderson et al., 2004; Redmon et al., 2010).

The primary R–T instability is generally followed by a hierarchy of secondary instabilities which finally culminate in the wide spectrum of irregularities that typically span ~ 7 orders of magnitude in the scale sizes from 100 s of kilo-meters to centimetres Haerendel (1973). It is well understood that, in the post sunset equatorial F-region, the background conditions are favourable for the R–T instability to operate. In most of the earlier treatments, the background conditions had been given all the importance and the perturbations that initiate the instability had been taken for granted and assumed to be omnipresent. Till recently, only very few studies had been concentrated on the possible, critical role of the perturbations (Huang and Kelley, 1996; Sreeja et al., 2009; Tsunoda, 2005; Abdu et al., 2009). In the recent times, the importance of perturbations in controlling the occurrence pattern of L-band scintillation patches had been demonstrated through a series of systematic studies which enabled the formulation of a forecast mechanism for their occurrence pattern (Bagiya and Sridharan 2011; Bagiya et al., 2014; Sridharan et al., 2012, 2014 and the references cited therein).

Based on the observed similarity in the negative phase of the fluctuating component of the F-region electron densities and the occurrence of L-band scintillations, the close linkage and their one to one correspondence was established through case studies (Bagiya and Sridharan, 2011). This paved the way for concentrating on the nature of the perturbations. After confirming through spectral analysis that the nature of the electron density perturbations, as seen either in TEC (Sridharan et al., 2012) or in the square of the F region critical frequency $[f_oF_2]^2$, retains its daytime characteristic features during night time as well Bagiya et al. (2014), a novel method was formulated to forecast the evening and night time perturbations based on their day time values. On most of the occasions, the scintillation patches were found to occur in the forecast time window. Additional constraints on the background ionospheric conditions were stipulated based on ground based ionosonde data, like (i) the base height of the F-region should be >225 km and the plasma scale length 'L' centred around 3.5–4.5 MHz to be <20 km Bagiya et al. (2014), for the irregularity generation. After establishing a possible relation between the base height of the F-region at 1930 LT $[h'F]_{1930}$ and, the maximum altitudinal extent of the irregularities over the night (Bagiya et al., 2013) and also to the total duration of the scintillations, the forecast exercise was extended to generate the first of its kind spatio-temporal maps of the likelihood of scintillation occurrence (Sridharan et al., 2014). There had been a simplistic assumption that the eastward velocities of the perturbations remained uniform all through. Though the success rate of the forecast had been impressive, there had been a few slips which were ascribed by them to be possibly due to the velocity not remaining uniform all through the night.

In all the above studies, the scintillation patches did occur favourably in the forecast time windows which were specified as early as 1930 LT. There were a few exceptions in the form of scintillation patches when not expected, and absence of scintillations when expected, purely based on the nature of the phase of the perturbations and the stipulated ionospheric background conditions. Though from the navigational application point of view, the latter situation may be inconsequential, as it just makes one to be prepared, the former situations are considered serious as it may take-on the user completely unaware. However, as a scientific problem, a complete understanding of both the above non-compliances is important. The present short note addresses this aspect.

Sridharan et al. (2014), in the context of generating the spatio-temporal map, have estimated the total time duration of the anticipated scintillations based on the $h'F$ at 1930 LT. Their interesting observations based on a few days of campaign data revealed that the scintillations lasted for the shortest duration when $h'F$ at 1930 LT was centred around 310 km. When the $h'F$ was more, or less than this value, the favourable duration turned out to be longer. It was suggested by them that, when the base height ($h'F_{1930}$) was higher than ~310 km, depending on how much higher it had reached, the total duration susceptible for the scintillations turned out to be larger. In other words, with the reduction of base height $[h'F]_{1930}$, from >310 km, up to ~310 km, the total duration susceptible for scintillation decreased. This is due to the exponential increase of the ion-neutral collision frequency, which is dictated by the dominant neutral species, in this case atomic oxygen [O]. On the other hand, for $[h'F]_{1930} < \sim 300$ km, though the ν_{in} continued to increase nearly at the same rate, it could get overcompensated by the steep decrease in the plasma scale length L. Sridharan et al. (2014) hypothesised that the competing role between the changes in the ν_{in} and L could be responsible for the increase in scintillation-prone duration, for altitudes <300 km and up to ~250 km. Below 250 km however, the duration was expected to steeply decrease due to the combined effect of the steep increase in L and also the exponential increase of $\nu_{in.}$ With this background, the data from an exclusive campaign from Trivandrum (8.5N, 76.9 E, 0.5N dip lat) during April 2012 for studying the scintillation pattern had been looked into critically. Good quality, uninterrupted data on ionospheric scintillations with a time resolution of 1 min from the ground based receiver (GSV 4004) and the ionospheric parameters from the Digisonde (DPS 4D – University of Massachusetts Lowell, Centre for Atmospheric Research,) with a sounding at 7.5 min. interval, were collected for ~7 days. As discussed by Sridharan et al (2014), the $[f_oF_2]^2$ data during day time (till 1800 h) had been detrended and the difference between the detrended values and the actual values were taken to represent the fluctuating components of the electron densities. These fluctuating components had been subjected to wavelet analysis to decipher the prominent frequency components. We concentrate ourselves to periods <4 h so as to concentrate on the gravity wave periods which are believed to play the role of perturbations. The multiple frequency components had different amplitudes and phases at any given instant. The individual frequency components had been extended in time, deep into the night and while doing so, their relative phase and amplitude had been maintained all through. These extended fundamental frequency components were added at every second, to arrive at the composite/synthetic perturbation. Emphasis is given to the negative phase of the perturbation for the scintillation forecast. Further details of the analysis strategy have been discussed elsewhere (Sridharan et al., 2012, 2014). In the present context, only the occurrence of scintillations during the campaign period is emphasised with reference to the background ionospheric conditions.

The growth rate (γ) of the R–T instability is inversely proportional to the plasma scale length (L) and also the ion-neutral collision (ν_{in}) frequency (equation (1)). In their earlier studies Mala Bagiya Mala et al., (2014) had taken $h'F$ to represent ν_{in} and made use of measured L while working out the necessary back ground conditions ($L < 20$ km and $h'F > 225$ km) for the initiation of the instability that finally culminated in to medium scale size irregularities that are responsible for the L-band scintillation. In order to check the validity of the above background conditions, for an atmosphere which is in hydrostatic equilibrium, the instantaneous values of $h'F$ and L as revealed by the ground based ionograms from Trivandrum along with information on the presence/absence of medium scale irregularities from the GPS receivers during the campaign period, have been looked into. Fig. 1 represents a scatter plot of $h'F$ and the observed 'L', estimated at 3.5–5 MHz frequencies which is considered as a fair representation of the base of the F-region. The filled circles correspond to the presence of L-band scintillations ($S_4 > 0.1$) at that instant and the open circles to the absence of scintillations, when the phase of the perturbation was favourable (−ve) but without any further restraints on the L and $h'F$. The crossed circles correspond to the presence of scintillations though not favoured by the phase of the perturbations. In other words, the crossed circles represent more serious failure of the forecast mechanism formulated by Sridharan et al. (2014). The horizontal line at 20 km and the vertical line at 225 km represent the stipulated background conditions by Bagiya et al. (2014), for the plasma instability to grow, for the solar epoch under consideration. Attention is drawn, to the many open circles within the stipulated favourable conditions which includes the phase of the perturbation and also to a few filled circles that could be seen out of the favourable bounds. The above observation suggests a refinement of the background conditions.

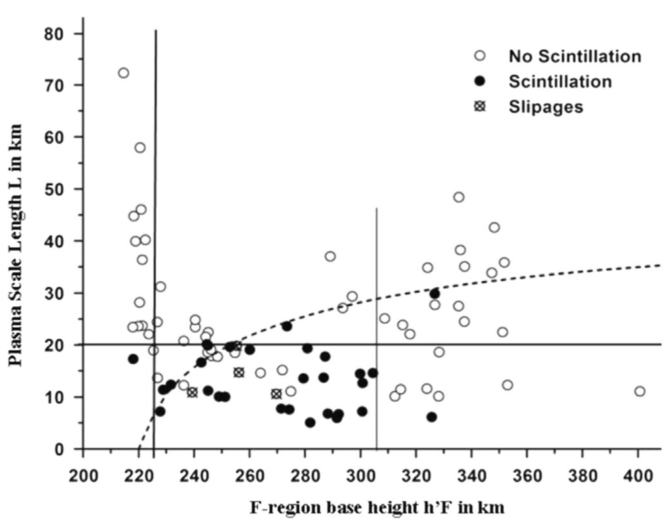

Fig. 1. Scatter plot between the instantaneous $h'F$ and the corresponding scale length (L) along with indications for the presence/absence of L-band scintillations at that instant during the negative phase of the perturbation. The crossed circles referred to as 'slippages' represent scintillations when not expected based on the phase of the perturbations. The vertical line at 225 km and the horizontal line at 20 km represent the favourable back ground conditions stipulated earlier by Bagiya et al. (2013) and the dashed line is the nonlinearly varying L encompassing all the scintillation events. The intersection of the dashed line with the vertical line at $h'F$ 225 km represents the least possible L value. The steep rise of L with further decrease of $h'F$ results in a stable F-region.

The stipulated conditions of a plasma scale length of < 20 km for scintillation to occur, though had been based on observations, is still somewhat arbitrary. In the upper atmosphere, the parameters like neutral density vary exponentially with height. Since L is dictated by the recombination process, it would decrease/increase exponentially according to the scale heights of the molecular [O_2, N_2] species, as the base height of the F-region moved down/up in altitude. It is also well established that the post sunset $h'F$ over the magnetic equator is controlled by the electrodynamical processes manifesting as F-region vertical plasma drift which is known to decrease with altitude in the bottom side F-region (Fejer et al., 2014). Therefore the plasma scale length L and the growth rate which is inversely dependent on L would vary nonlinearly with $h'F$. Under these circumstances, a discrete threshold value of 20 km may not be proper. Taking a cue from the scatter plot, a nonlinearly varying threshold for 'L' encompassing almost all the scintillating events could be inferred and the same is represented in Fig. 1 by means of a dashed curve. The intersection of the dashed line with the $h'F$ (225 km) vertical line, corresponding to $L \sim 10$ km could be taken as the lowest L value. Below 225 km, the L value is observed to increase steeply, contributing to the stability already arising from the decreasing g/ν_{in}. This logical argument brings a couple of non-complying instances within the acceptable limits. Nevertheless, the suggested changes in the prerequisite for the scintillation to occur leaves several open circles that represent occasions when the perturbation phase and the background ionospheric conditions had been favourable but with no trace of scintillation, still to be explained. It is worth noticing that most of the open circles are typically seen when $h'F > 310$ km.

2. Plausible explanation based on neutral dynamics

So far, only the simplest of the growth rate expression had been considered. Even in this expression it would appear that when the base height is larger, conditions would be conducive for the instability due to the steep reduction in the collision frequency ν_{in}. On the other hand, during the campaign period, it is seen (Fig. 1-filled circles) that lower heights ($h'F < 300$ km) where ν_{in} is significantly larger turn out to be more favourable for scintillation. This gives us a clue that there should be other forcings that have not been accounted for in the above simplistic picture. Neutral wind components are known to have the potential to tilt the balance. In the growth rate expression (Sekar and Raghavarao, 1987) for the R–T instability including the effects of neutral winds,

$$\gamma = 1/L\{g/\nu_{in} + W_x(\nu_{in}/\Omega_i) - W_z\} \quad (2)$$

L – Plasma scale length.
ν_{in} – ion-neutral collision frequency.
W_x – zonal (positive east) wind component.
W_z – vertical (positive upward) wind component.
Ω_i – ion gyrofrequency.

We find that the eastward winds in the presence of westward gradients and vertical winds in the presence of upward gradients could also modulate the instability and hence the occurrence of scintillations. Out of these two, the role of vertical winds and its local time variation is more significant as it directly enters in to the expression. We explore below to what extent it could be possible in our examples.

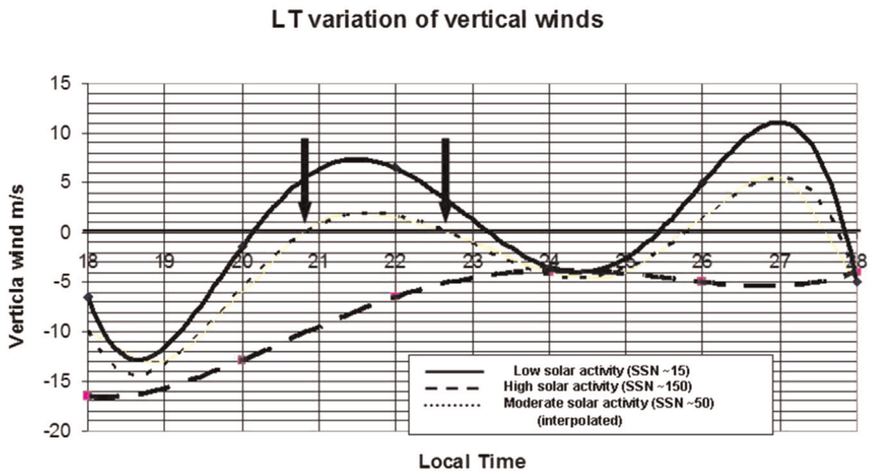

Fig. 2. The local time variation of vertical winds over the equator as derived from the published results (Raghavarao et al., 1998; Suhasini et al., 2001) on low and high solar activity pattern of the Equatorial Temperature Anomaly (ETA) and the Equatorial Temperature and Wind Anomaly (ETWA).

After having assessed the possible role the vertical winds might play, the available results on this parameter are examined. Unfortunately, due to the practical difficulties encountered in the past in the measurement techniques like vapour releases, ground based spectroscopic techniques and insitu measurements, there had been only very limited success in its measurements.The model estimates and the actual measurements differ significantly when it comes to the magnitudes.The models like Thermosphere–Ionosphere-Electrodynamics General Circulation Model (TIEGCM) generally expect an upward trend during daytime conditions and downward winds during night time over the equatorial region (Richmond et al., 1992). When it comes to the actual measurements, only a few cases of DE-2 satellite data are available apart from a few sporadic in-situ measurements using vapour release experiments. We attempt to establish an empirical relation between the simultaneously measured parameters viz., neutral temperatures and the vertical winds. This relationship is used in deriving the LT variation of the latter using the larger data base available for the independently measured neutral temperature. This is the best that could be done in the absence of any direct measurements. In spite of the several assumptions and also the very few measurements, the results still show some consistency. These are presented and discussed below.

Raghavarao et al. (1991, 1999) and Raghavarao and Suhasini (2002), in the context of their discovery of Equatorial Temperature and Wind Anomaly (ETWA) studied the local time variation of ETWA and also the nature of the vertical winds using the DE-2 data (Raghavarao et al., 1998). They had reported vertically upward winds over the ionization crest region with simultaneous downward winds of comparable magnitude over the magnetic equator. This led them to hypothesise the setting up of a meridional circulation cell with the return flow in the lower thermosphere (Raghavarao et al., 1993, 1999). Their measurements were representative of high solar activity period and mostly pertained to post sunset hours. Nevertheless, the presence of the ionization anomaly and the above mentioned vertical wind polarities were unambiguous in their analysis. Taking a cue from their results and assuming that the vertical winds, are purely due to the temperature enhancements and the consequent pressure ridges, bear a linear relation amongst them, it is estimated that ~60 K enhancement in the crest temperature might be responsible for a downward wind of ~10 ms^{-1} over the trough region centred over the magnetic equator. The occurrence of the neutral temperature anomaly over the ionization crest region itself had been a topic of intense studies in the literature. Raghavarao et al. (1991) suggested it to be due to ion drag experienced by the daytime zonal winds, while Fuller-Rowell et al. (1997) suggested that the temperature enhancement could be due to the exothermic chemical recombination reaction and the resultant heating. On the other hand, Pant and Sridharan (2001) were of the opinion that both the ion drag and chemical heating have comparable effects. More recently, Lei et al. (2012) while emphasising the latitudinal differences in the ionization and the temperature crests have shown that the drag experienced by the meridional wind is also capable of causing such temperature anomaly. In the present study we take the temperature enhancement in the crest region as an observed fact and restrict ourselves to the possible effects such temperature enhancements could have in the thermosphere–ionosphere system irrespective of what might have caused these enhancements. The LT variation of the differences in temperature (ΔT) at the crest and the trough as reported by Raghavarao et al. (1998) corresponding to high solar activity periods and by Suhasini et al. (2001) based on the AE satellite data for low solar activity periods have been made use of, in relating the temperature enhancement and the vertical winds using our proposed linear relation. This ultimately gives a clue to the possible LT variation of vertical winds. It should be kept in mind that this behaviour is purely due to the EIA/ETWA associated circulation pattern which would be over and above the variation due to the overall wind circulation pattern, if any.

Fig. 2 depicts the evaluated local time variation of vertical winds during low (continuous line) and high (dashed line) solar activity years. The interesting feature in the figure is that the vertical wind during low solar activity years (SSN~15) tends to become upward for some time in the post sunset hours showing a wavy structure. On the other hand, the wind remains downward all through, during high solar activity periods (SSN 150). It now becomes possible to explain the slippages in the forecast of L-band scintillations based on the above information on the vertical winds and their temporal variability, during the moderate activity levels, similar to what had been experienced during 2012 April– May period.

3. Discussion and conclusion

One of the important aspects in our studies pertains to the assumption that daytime gravity wave signatures are retained through out night time. Going by the success rate of the forecast ($>85\%$) of the scintillation patches occurring within the forecast window, the above assumption seems to be holding good at least for normal circumstances, that prevailed during the campaign period. Understandably, any deviation from this assumption would cause slippages in the forecast pattern. This would then limit the accuracy of the forecasts and hence is not discussed any further. On the other hand, the neutral dynamics, as indicated above, could even be more deterministic as discussed below. Going by the first indicative theoretical results of Sekar and Raghavarao (1987) followed by their detailed non-linear numerical simulation (Raghavarao et al., 1992; Sekar et al., 1994) that included the effects of vertical winds, it had been shown that vertically downward winds effectively enhance the growth rate by assisting the principal driving force viz., the gravity, in sustaining the primary R–T instability.On the other hand, vertically upward winds are expected to reduce the growth rate and, depending on their magnitude, could even impede the instability. During low solar activity periods (monthly smoothed sunspots of ~15), similar to what had been experienced during the AE satellite time frame, the inferred vertical wind tends to turn upwards during post sunset hours (2000–2200 LT) and also in the post mid night hours of 0130–0400 LT (Fig. 2). Since solar activity level was moderate (SSN~50) during the period of our observations, one would expect the nature of the vertical winds to be different, tending towards reduction in the duration of the upward winds both in the pre and post midnight hours. If we assume that the trend changes somewhat linearly from low to high solar activity periods, we could infer the trend for the moderate activities through interpolation. The interpolated values, which could be treated as an average representative picture, are also plotted in Fig. 2. According to this curve, the vertical wind would be positive (upward) for a shorter duration of ~90 min. It tends to become positive around 2100 LT and remains so till 2230 LT. This trend of ETWA associated wind would add up to the prevailing general circulation if any.

At this juncture, a brief discussion on the possible behaviour of EIA, ETWA and the associated neutral dynamics during different solar epochs is in order. During low solar activity periods it is well known that the waning and waxing of the EIA crest formation is significantly faster as compared to high solar activity periods (Raghavarao et al., 1988). The latitudinal extent of the crests is also smaller. For all practical purposes**,** the EIA crests would have retreated back to the equator in the form of a reverse fountain much earlier than the sunset hours. However, with the dormant F-region dynamo becoming active after sunset, the F-region would experience a sudden uplift and there would be a rejuvenation of the EIA. This rejuvenation and the consequent setting up of a circulation cell in the form of (i) an upward wind over the crests, (ii) upper thermospheric equatorward winds, (iii) downward winds over the magnetic equator followed by (iv) poleward flow in the lower thermosphere is likely to take a couple of hours. In this context, one could anticipate favourable wind polarity that would assist the instability only a couple of hours after sunset. The observation of scintillations, only after 2030 LT, fits in with the above expectation. However, the uplifting of the F-region due to the F-region dynamo immediately after sunset, known as Pre-Reversal Enhancement (PRE), is also expected to provide a favourable condition for the instability to occur. Normally, whenever the F-layer reached beyond the threshold height, dictated by the ion-neutral collision frequency, the irregularity generation and the consequent scintillation would have occurred within 30–45 min after the sunset. This is typically the case during high solar activity periods when the zonal electric field is quite strong. During low to moderate activity, similar to the campaign period, not on all days the F-layer crosses the threshold height, leaving the F-region irregularity-free and letting the other factors like the neutral winds to take control. Even though the vertical wind amplitude may appear to be very small, as shown in expression (2), its effect is directly equivalent to what gravity does for the R–T instability. As mentioned earlier, Sekar and Raghavarao (1987) had shown that a vertical wind of 20 $\mathrm{ms^{-1}}$ at 300 km altitude has a comparable effect due to gravity itself. Therefore, even wind magnitudes of 2 $\mathrm{ms^{-1}}$ would form ~10% of the effect of gravity (at ~300 km) which is considered significant. The above discussion indicates that, for the low–moderate activity levels, the neutral dynamical forcing either could be in phase/out of phase with the electrodynamical forcing. This would depend upon their relative intensities and their respective local time variation. On the other hand, during high solar activity periods, by virture of the EIA extending well into the night, the polarity of the vertical winds would always be downward and hence would always assist gravity in making the F-region unstable, even at relatively lower *h′F*. Further, it should be borne in mind that we are currently conjecturing in the absence of any direct measurements and the duration and cross over to either of the polarities could vary on a day to day basis. The message we intend to convey through the above discussion is that there is a parameter which could bring about variations on the occurrence pattern of the L-band scintillations through its relationship on the background ionospheric–thermospheric conditions and currently, there is very little information available about it. The first occurrence of scintillations ($S4 > 0.1$) during the campaign reveals that they were hardly encountered before 2030 LT and were seen more favourably after 2130 LT. One would require a wind amplitude that forms a significant percentage of the other driving forces put together, in order to have a control on the instability. As conjectured, if the upward winds were responsible for the observed slippages in the forecast, then it is expected that these slippages should be favourably seen in the late evening hours i.e., beyond ~ 2030 LT. Typically, the F-layer base would have reached higher altitudes in the post sunset hours due to the effect of the pre-reversal enhancement (PRE) of the zonal electric fields at about 1900 LT and, later, the F-layer would slowly descend to altitudes as low as 220 km beyond mid night. Therefore, one could state that almost all the higher altitude points in the scatter plot (Fig. 1) have to necessarily correspond to pre midnight hours which incidentally coincides with the time window for the upward vertical winds in the solar epoch under consideration. There is a similar surge of upward winds around 0300 LT (2700 h). However, since the base of the F-region typically would have reached ~220 km, even without the assistance of the vertical winds, the region would remain stable. Based on the circumstantial evidence, it is conjectured that the day to day variation in the vertical wind pattern could be responsible for the F-region to remain stable. The F-region would be void of any irregularities, in the time windows identified to be likely time zones for irregularities, based on the background ionospheric state and the phase of the perturbations. As mentioned earlier, there are no reliable and continuous measurements of vertical wind component covering different seasons, solar activity levels and other geophysical conditions. The inferred variation of this important parameter from the limited published data is only an average, representative variation and intended to show that its variabilites have the potential to modulate the occurrence pattern of scintillation.

Though very few, the converse, namely the occasions when strong scintillating patches were seen when not expected, could also be due to the unusual wind patterns at that time. However, these conjectures need experimental confirmation. Till then, they will only remain speculative and are valuable to the extent that they indicate the direction for future studies. Out of the limited options available, the ground based optical interferometric measurements of natural airglow emissions face severe constraints in the form of reduced and largely varying airglow intensities due to the uplifting of the F-region to higher altitudes over the equator. It leaves only the other option of trying out a WATS (Wind And Temperature Spectrometer) type of instrument in a polar orbiting satellite platform similar to the Dynamic Explorer-2 satellite. In the absence of such a facility one may have to indirectly infer on the neutral dynamical variables.

In this context, some of the earlier results from the Indian zone reported by Devasia et al. (2002) are relevant as they attempted to link the ESF as seen in the ionograms to the vertical winds. They had made use of Ionosonde data from two nearby locations in the equatorial zone and had inferred meridional winds in the evening hours. They have shown that, whenever the base of the F-region was below a critical level around 300 km, ESF occurred only on occasions when the meridional wind was equatorward. The threshold height was shown to have significant solar activity dependence by Jyoti et al. (2004). When the base height had been above the threshold value, irrespective of the polarity of the meridional winds ESF had occurred. Devasia et al. (2002) had concluded that when the F-layer base height was lower, then the quenching effect due to the increased ion-neutral collision frequency had to be compensated by an additional forcing that assisted the primary mover viz., gravity. Vertically downward winds, as a consequence of equatorially converging meridional winds associated with ETWA, were suggested to effectively play this role. All the above studies were concentrated on the occurrence or non-occurrence of ESF during a night and more emphasis was given to the evening hours when initially the ionospheric conditions were favourable, with a presumption that the perturbations were omnipresent to provide the necessary trigger. The awareness that ESF and its various manifestations are not the outcome of a free running system and are closely linked to the characteristics of the perturbations (Bagiya and Sridharan, 2011) is rather new and has been effectively used in forecasting the spatio-temporal occurrence pattern of L-band scintillations (Sridharan et al., 2014). In the present paper, we proceed to conclude that along with the base height ($h'F$) and the plasma scale length (L), the nature of the vertical component of the neutral winds, especially its polarity, would decide the back ground ionospheric/thermospheric condition. In the absence of any direct measurement of the vertical winds, either by ground based or by space borne methods, one could attempt to get the real strength of the EIA crest with respect to the equatorial trough in the evening hours as an index for the vertical winds, since the latter is expected to be directly related to the former. The strength of the anomaly could be added as one more independent parameter in the forecast method of Sridharan et al. (2014) in addition to $h'F$ and L. More systematic studies in these directions are underway.

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References

Aarons, J., 1993. The longitudina1 morphology of equatorial F-layer irregularities relevant to their occurrence. Space Sci. Rev. 63, 209–243 1993.

Abdu, M.A., Bittencourt, J.A., Batista, I.S., 1981. Magentic declination control of the equatorial F region dynamo field development and Spread-F. J. Geophys. Res. 86, 11443–11446.

Abdu, M.A., Batista, I.S., Sobral, J.H.A., 1992. A new aspect of magnetic declination control of equatorial spread-F and F-region dynamo. J. Geophys. Res. 97, 14,987–15,904.

Abdu, M.A., Alam Kherani, E., Batista, I.S., de Paula, E.R., Fritts, D.C., Sobral, J.H.A., 2009. Gravity wave initiation of equatorial spread F/plasma bubble irregularities based on observational data from the Spread F-Ex campaign. Ann. Geophys. 27, 2,607–2,622.

Anderson, D., Reinisch, N.B., Valladares, C., Chau, J., Veliz, O., 2004. Forecasting the occurrence of ionospheric scintillation activity in the equatorial ionosphere on a day-to-day basis. J. Atmos. Sol. Terr. Phys. 66, 1,567–1,572.

Bagiya, Mala S., Sridharan, R., 2011. Evolutionary phases of equatorial spread-F including L-band scintillation and plumes in the context of GPS total electron content variability: a case study. J. Geophys. Res. . http://dx.doi.org/10.1029/2011JA016893

Bagiya, Mala S., Sridharan, R., Sunda, S., 2013. Pre-assessment of the "strength" and "latitudinal extent" of L-band scintillation: a case study. J. Geophys. Res. 118, 1–8.

Bagiya, Mala S., Sridharan, R., Sunda, S., Jose, L., Pant, T.K., Choudhary, R.K., 2014. Critical assessment of the forecasting capability of L-band scintillation over the magnetic equatorial region – campaign results. J. Atmos. Sol. Terr. Phys. 110–111, 15–22.

Devasia, C.V., Jyoti, N., Subbarao, K.S.V., Viswanathan, K.S., Tiwari, Diwakar, Sridharan, R., 2002. On the plausible linkage of thermospheric meridional winds with the equatorial spread F. J. Atmos. Sol.-Terr. Phys. 64, 1–12.

Fejer, B.G., Hui, D., Chau, J.L., Kudeki, E., 2014. Altitudinal dependence of evening equatorial F region vertical plasma drifts. J. Geophys. Res. 119, 5877–5890.

Fuller-Rowell, T.J., Codrescue, M.V., Fejer, B.G., Barer, W., Marcos, F., Anderson, D.N., 1997. Dynamics of the low latitude thermosphere: quiet and disturbed conditions. J. Atmos. Terr. Phys. 59, 1,533–1,540.

Haerendel, G., 1973. Theory of Equatorial Spread F. Report. Max-Planck Inst. Phys. Astrophys., Munich, Germany, pp. 200–202.

Huang, C., Kelley, M.C., 1996. Non-linear evolution of equatorial spread F-2. Gravity wave seeding of Rayleigh–Taylor. J. Geophys. Res 101 (A1), 293–302.

Jayachandran, T., Sri Ram, P., Somayajulu, V.V., Ramarao, P.V.S., 1997. Effect of equatorial ionization anomaly on the occurrence of spread-F. Ann. Geophys. 15, 255–262.

Jyoti, N., Devasia, C.V., Sridharan, R., Tiwari, Diwakar, 2004. Threshold height (h'F)c for the meridional wind to play a deterministic role in the bottom side equatorial spread-F and its dependence on solar activity. 2004. Geophys. Res. Lett. 31. http://dx.doi.org/10.1029/2004GL019455.

Lei, J., Thayer, J.P., Wang, W., Richmond, A.D., Roble, R., Luan, X., Dou, X., Xue, X., Li., T., 2012. Simulations of the equatorial thermosphere anomaly: Field aligned ion drag effect. J. Geophys. Res. 117. http://dx.doi.org/10.1029/2011JA017114.

Maruyama, T., Matuura, N., 1984. Longitudinal variability of annual changes in activity of equatorial spread F and plasma bubbles. J. Geophys. Res. 89, 10,903–10,912.

Pant, T.K., Sridharan, R., 2001. Plausible explanation for the equatorial temperature and wind anomaly (ETWA) based on chemical and dynamical process. J. Atmos. Sol.-Terr. Phys., 63885–63891.

Raghavarao, R., Nageswararao, M., Sastri, J.H., Vyas, G.D., Rao, S.M., 1988. Role of equatorial ionization anomaly in the initiation of equatorial spread-F. J. Geophys. Res. 93, 5959–5964.

Raghavarao, R., Sridharan, R., Sastri, J.H., Agashe, V.V., Rao, B.C.N., Rao, P.B., Somayajulu, V.V., 1988. The equatorial Ionosphere. WITS Handbook. vol. I; , pp. 48–93.

Raghavarao, R., Wharton, L.E., Spencer, N.W., Mayr, H.G., Brace, L.H., 1991. An equatorial temperature and wind anomaly (ETWA). Geophys. Res. Lett. 18, 1,193–1,196.

Raghavarao, R., Sekar, R., Suhasini, R., 1992. Non-linear numerical simulation of equatorial spread-F: effects of winds and electric fields. Adv. Space Res. 12 (6), 227–230.

Raghavarao, R., Hoegy, W.R., Spencer, N.W., Wharton, L.E., 1993. Neutral temperature anomaly in the equatorial thermosphere – a source of vertical winds. Geophys. Res. Lett. 20, 1,023–1,026.

Raghavarao, R., Suhasini, R., Hoegy, W.R., Mayr, H.G., Wharton, L.E., 1998. Local time variation of equatorial temperature and zonal wind anomaly (ETWA). J. Atmos. Sol.-Terr. Phys. 60, 631–642.

Raghavarao, R., Suhasini, R., Mayr, H.G., Hoegy, W.R., Wharton, L.E., 1999. Equatorial spread-F (ESF) and vertical winds. J. Atmos. Sol.-Terr. Phys. 61, 607–617.

Raghavarao, R., Suhasini., R., 2002. Equatorial temperature and wind anomaly (ETWA) – a review. J. Atmos. Sol.-Terr. Phys. 64, 1,371–1,381.

Redmon, R.J., Anderson, D., Caton, R., Bullett, T., 2010. A forecasting Ionospheric real-time scintillation tool (FIRST). Space Weather 8. http://dx.doi.org/10.1029/2010SW00582.

Richmond, A.D., Ridley, E.C., Roble, R.G., 1992. A thermosphere/ionosphere general circulation model with coupled electrodynamics. Geophys. Res. Lett., 19, 601–19,604.

Sekar, R., Raghavarao, R., 1987. Role of vertical winds on the Rayleigh Taylor mode instabilities of the night time equatorial ionosphere. J. Atmos. Terr. Phys., 49,981–49,985.

Sekar, R., Suhasini, R., Raghavarao, R., 1994. Effects of vertical winds and electric fields in the non-linear evolution of equatorial spread-F. J. Geophys. Res. 99, 2,205–2,213.

Sreeja, V., Vineeth, C., Pant, Tarun Kumar, Ravindran, Sudha, Sridharan, R., 2009. Role of gravity wavelike seed perturbations on the triggering of ESF – a case study from unique dayglow observations. Ann. Geophys. 27, 313–318.
Sridharan, R., Pallam Raju, D., Raghavarao, R., Rama Rao, P.V.S., 1994. Precursor to the post sunset equatorial spread-F in OI 630.0 nm dayglow. Geophys. Res. Lett. 25, 2,797–2,800.
Sridharan, R., Bagiya Mala, S., Sunda, S., 2012. A novel method based on GPS/TEC to forecast L band scintillations over the equatorial region through a case study. J. Atmos. Sol.-Terr. Phys. 80, 230–238.
Sridharan, R., Bagiya, Mala S., Sunda, S., Choudhary, R., Pant, T.K., Jose, L., 2014. First results on forecasting the spatial occurrence pattern of L-band scintillation and its temporal evolution. J. Atmos. Sol.-Terr Phys. 19, 53–62.
Suhasini, R., Raghavarao, R., Mayr, H.G., Hoegy, W.R., Wharton, L.E., 2001. Equatorial temperature anomaly (ETA) during solar minimum. J. Geophys. Res. 106, 24,777–24,783.
Tsunoda, R.T., 1985. Control of the seasonal and longitudinanl occurrence of equatorial scintillations by longitudinal gradient in integrated E-region Pedersen conductivity. J. Geophys. Res. 90, 447–456.
Tsunoda, R.T., 2005. On the enigma of day to day variability in equatorial spread-F. Geophys. Res. Lett. 32, 0094–8276. http://dx.doi.org/10.1029/2005GL022512, issn.
Tulasi Ram, S., Ramarao, P.V.S., Niranjan, K., Prasad, D.S.V.V.D., Sridharan, R., Devasia, C.V., Ravindran, Sudha, 2006. The role of post sunset vertical drifts at the equator in predicting the onset of VHF scintillation during high and low sunspot activity years. Ann. Geophys. 24, 1–8.
Valladares, C.E., Basu, S., Groves, K., Hagan, M.P., Hysell, D., MazellaJr., D., Sheehan, R.E., 2001. Measurement of the latitudinal variation of TEC during ESF events. J. Geophys. Res. 106, 29133–29152.