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HF Doppler radar observations of sporadic E at an Indian low latitude station, Visakhapatnam

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Abstract. 5.5 MHz HF Doppler radar observations of Sporadic E over an Indian low latitude station, Visakhapatnam (17.7° N, 83.3° E and Dip 20°) with 10 s resolution showed quasi-periodic variations of the echo strength and Doppler velocity variations with periods of a few minutes to a few tens of minutes. The echo strength and Doppler velocity variations with time in different range bins of the E_S echo showed variations which are some times similar and some times significantly different in successive range bins at intervals of 7.5 km. The E_S echo occurs with the height of maximum echo strength in the range of 100 km to 120 km and some times at 130 km. The altitude variation of the average Doppler velocity is highly variable and the height of maximum echo strength is not the same as the height of maximum Doppler velocity. Observations of E_S echoes at different times of the day are presented to bring out the differences between the day and night time E_S echoes. The relationship between Radar and E_S parameters derived from Ionograms is poorer than that of mid latitudes which is quite consistent with the expectations based on gradient drift instability.

Keywords. Ionosphere (Equatorial ionosphere; Ionization mechanisms; Ionospheric irregularities)

1 Introduction

Sporadic-E or E_S has been a topic of active research for more than four decades and the occurrence characteristics of E_S in different latitude and longitude regions obtained from analysis of the huge wealth of HF sounders data was well documented. The formation of E_S layers at E region heights was explained by the wind shear theory (Dungey, 1956, 1959; Axford, 1961; Whitehead, 1961). Field-aligned irregularities (FAI) in the equatorial and auroral E region have been reported by Fejer and Kelley (1980); and Haldoupis (1989). With the advent of high power VHF radars, there have been some reports on E region FAI in the mid-latitudes (Keys and Andrews, 1984; Ecklund et al., 1981; Riggin et al., 1986; Yamamoto et al., 1991) and these were reported to be closely associated with E_S layers. Tanaka and Venkateswaran (1982a, b) analyzing 25 MHz radar data, reported similar observations from Iioka, Japan (35.7° N, 140.8° E). These meter scale irregularities producing coherent (Bragg's) scatter for radar beam incidence orthogonal to the geomagnetic field, appear to be generated by gradient drift instability mechanism (Simon, 1963; Kato, 1972).

Yamamoto et al. (1991) using MU radar observations in five antenna beam directions, all orthogonal to the geomagnetic field at 100 km altitude, reported that two types of FAI echoes, one appearing continuously after sunrise, and another after sunset with quasi-periodic variations. The continuous echoes are from 90 to 100 km altitude and the quasi-periodic (QP) echoes were intermittent with periods 5 to 10 min and were from altitudes above 100 km. The QP echoes were reported from many radars locations (Yamamoto et al., 1991, 1992, 1994; Woodman et al., 1991; Tsunoda et al., 1994, 1995), which were reported to be usually located in the valley region between the E- and F-regions and extend from 177 km to 215 km (Tsunoda et al., 1995) and the slope of the range rate was about −100 m/s and always negative. The QP echoes first reported by Balsley (1964) as 150 km echoes were studied close to the magnetic equator in great detail (Royrvik and Miller, 1981; Royrvik, 1982; Kudeki and Fawcett, 1993; Hysell et al., 1997; Chau and Woodman, 2004; Chau, 2004; Kudeki et al., 1998; Tsunoda and Euklund, 2000, 2004; Blank et al., 1996; de Paula and Hysell, 2004). There were reports from the Indian MST radar at Gadanki outside the equatorial electrojet (Geomag. Lat. 6.3° N) in India (Choudhary et al., 2004; Patra and

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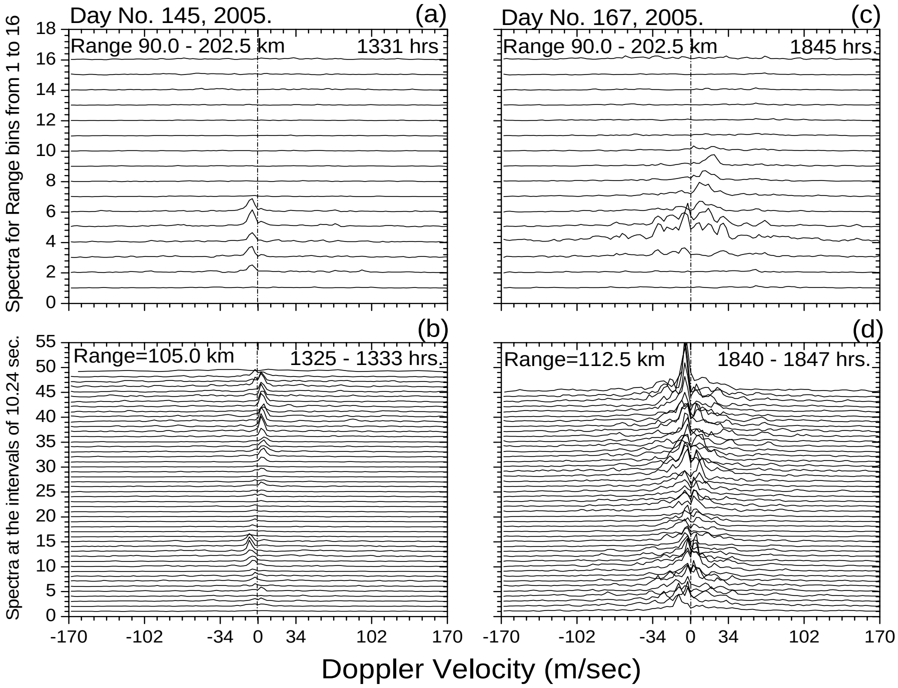

Fig. 1. **(a)** Spectra of the signals received in the 16 range bins for day no. 145, 2005 (25 May 2005), **(b)** Doppler spectra of E_S echo in range bin 3 (range 105 km) at successive intervals of 10.24 s, **(c)** is similar to (a) except for day no. 167, 2005 (14 June 2005)and **(d)** is similar to (b) except for day no. 167, 2005 and range bin 4 (range 112.5 km). Positive velocities indicate upward motion and negative velocities indicate downward motion.

Venkateswara Rao, 2006) on the daytime 150 km echoes having characteristics similar to those reported from near the magnetic equator.

Almost all HF radars built and operated in different geographical locations did not have the Doppler spectrum capability and hence the characteristics of E_S from them were limited to occurrence characteristics and relationship with geophysical phenomena. In this study the characteristics of E_S echoes observed over a low latitude Indian station Visakhapatnam (17.7° N, 83.3° E), at different local times using 5.5 MHz Doppler radar with spectral capability are presented. The characteristics of E_S echoes at different altitudes are studied for each occurrence of E_S using the plots of Range Time SNR (RTS), phase height variation with time at the range where the echo intensity is high and Doppler velocity at all range bins. This study is essentially concerned with the detailed structure of E_S echo signal strength and Doppler velocity at different altitudes at different times of the day as observed by HFD radar.

2 Observational description

At the low latitude station Visakhapatnam the critical frequency of normal E-region never exceeds 4 MHz and any 5.5 MHz radar echoes from 95 km to 140 km altitudes were taken to be from E_S layer. Nearly forty events of E_S were recorded during the year 2005. The occurrences were more frequent during the day time than at the night. We present five typical cases of AUHFD radar observations of E_S at different times of the day and in all the cases the 15 min ionograms recorded at Visakhapatnam showed E_S.

The data recorded in successive files were arranged sequentially to form a continuous time series of I & Q values for each range bin and were analyzed by 512 point FFT routine to compute the complex Doppler spectra at intervals of 10.24 s. For each Doppler spectrum, the signal to noise ratio (S/N), line of sight velocity (V) and the spectral width (SW) were computed from the three lower, 0th, 1st and 2nd, order moments (denoted as M_0, M_1 and M_2 respectively) representing the echo power (P_S), weighted mean Doppler shift ($\overline{f_d}$) and variance (f_w^2) which is a measure of the dispersion from the mean Doppler frequency ($\overline{f_d}$), respectively, using the expressions given by Woodman (1985).

The echoes in different range bins, in principle, could be from echoing regions displaced horizontally or vertically or both. For horizontally displaced echoing regions, the echoes in each range bin would be from a constant zenith angle but from various azimuth directions and for larger range the zenith angle would be larger. In such a case the spectra for each range bin would be symmetrical with both positive and negative Doppler velocities that were never observed and therefore it can be concluded that the echoes of larger range are essentially from higher heights.

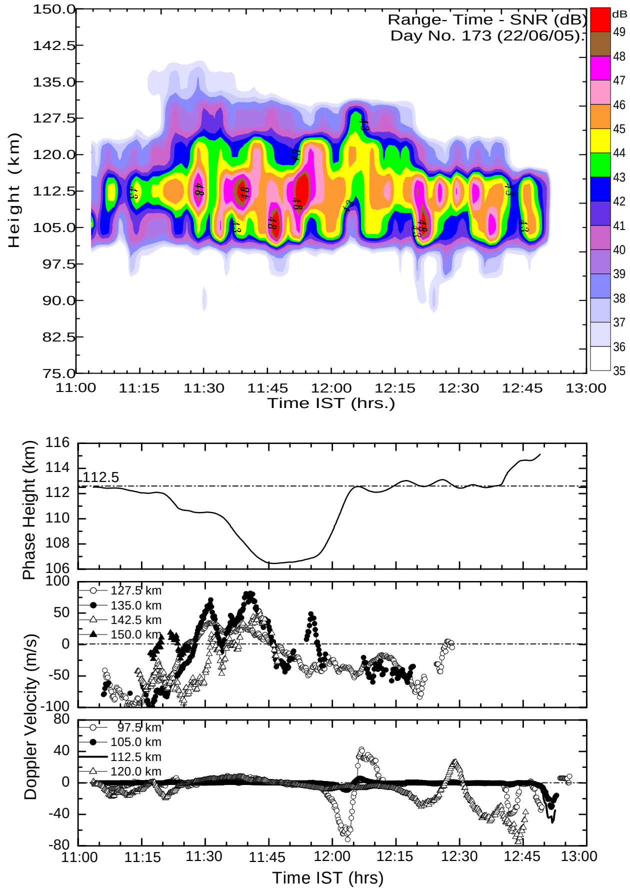

Fig. 2. Top panel shows Range Time Intensity maps for Day no. 173 (22 June 2005). Second panel shows phase height variation of the echo at the range bin where echo intensity is highest. And bottom two panels show the time variations of line of sight Doppler velocity in each range bin.

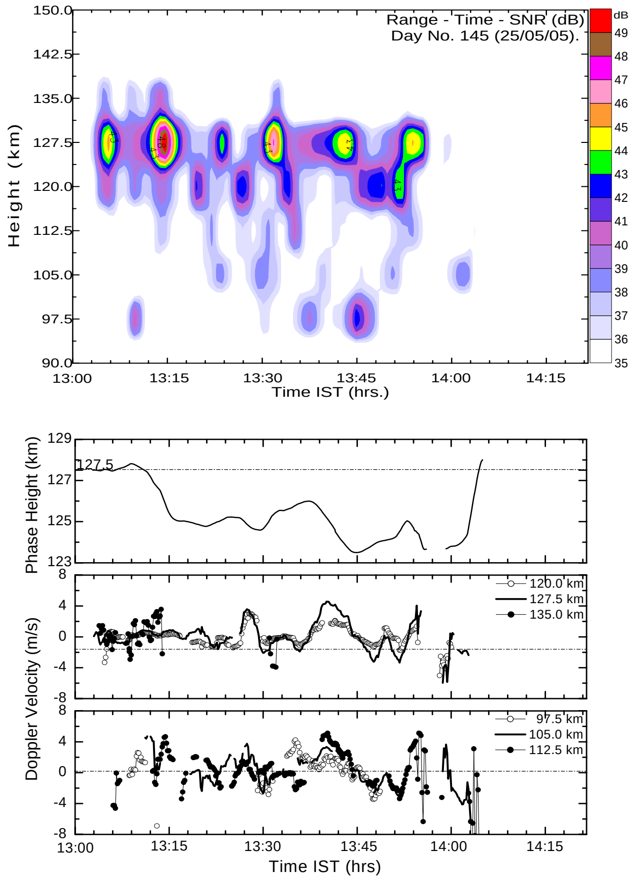

Fig. 3. Same as Fig. 2 except for the Day no. 145, 2005 (25 May 2005).

3 Doppler spectra of E_S echoes

Figure 1a shows the spectra of Radar echoes in all the 16 range bins. E_S echo peaks are seen in range bins 1 to 6 (heights 97.5 km to 135 km in steps of 7.5 km) with −5.326 m/s Doppler velocity. Normally, the Doppler velocity in sets of three successive range bins is the same because of the 100 μs transmitter pulse width while the range bins are at 50 μs intervals and that the echoes are from two discrete reflecting layers producing the same Doppler velocities. Figure 1b shows time series of successive spectra for range bin 3 (105 km) at intervals of 10.24 s from 13:25 to 13:33 IST. The echo intensity (I) and Doppler velocity can be seen to vary with time. Figure 1c shows two discrete reflecting layers with different velocities. In the lower range bins (i.e. from 105 km to 127.5 km) the echoes are diffused whereas specular echoes were observed in the higher range bins. The weighted mean Doppler velocities differ by less than a meter/s in successive range bins. Figure 1d shows time variations of the spectra of the same event shown in Fig. 1c, in range bin 4 (112.5 km). The multiple peaks in each spectrum indicate the presence of echoes not resolved in range, unlike in the event shown in Fig. 1b.

4 The Range-Time-S/N (RTS) variations during E_S at different times of the day

Figures 2, 3, 4, 5 and 6 show the temporal variations of SNR (top panel of each figure), phase height (middle panel) and Doppler velocity (bottom two panels for different heights) of E_S during the different times of the day, viz., forenoon, afternoon, pre sunset, post sunset and post mid night hours. The Range Time Signal to noise ratio (RTS) variation shown in top panels is equivalent to Range Time Intensity (RTI) maps since the noise power per frequency bin is fairly constant for all ranges of E_S echoes. The signal intensity “I” for each range bin is sum of the squares of the signal amplitudes of all Doppler frequency bins from −6.5 Hz to +6.5 Hz and S/N was calculated for the same Doppler bins. The echoes started appearing about five minutes earlier than the starting times shown in the plots, which is time taken for setting the

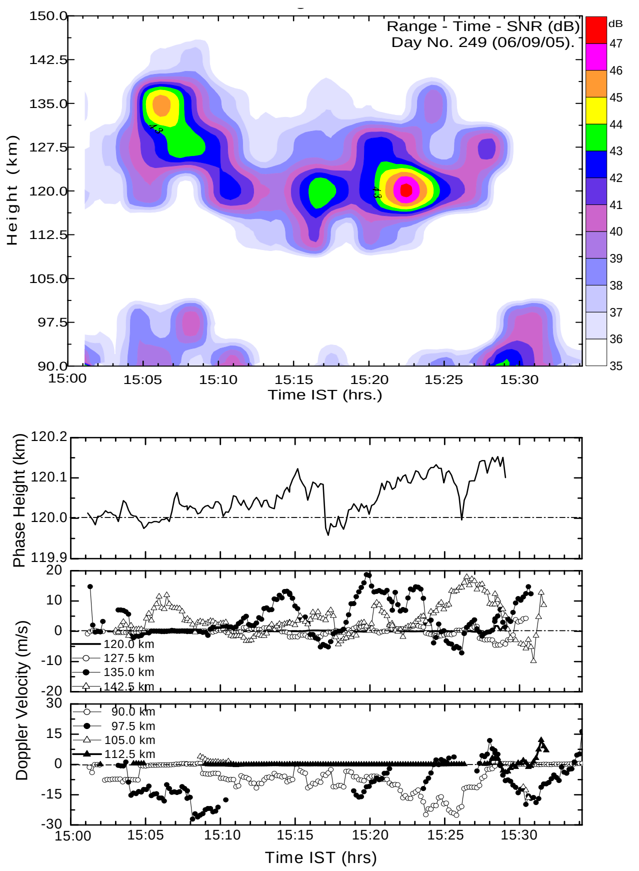

Fig. 4. Same as Fig. 2 except for the Day no. 249, 2005 (6 September 2005).

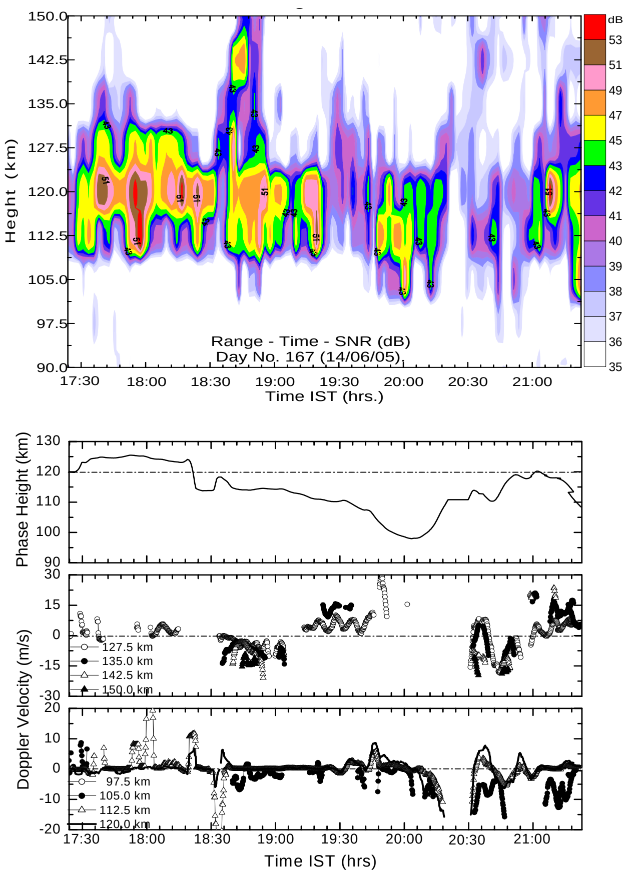

Fig. 5. Same as Fig. 2 except for the Day no. 167, 2005 (14 June 2005).

range bins to echo heights. The echoes with S/N exceeding 35 db only are plotted. However, the plots were drawn for the echoes with 10 dB SNR at the receiver output, since the process gain improves (nearly 25 dB) with 512 point FFT. The RTS map plotted for 22 June 2005 (day no. 173), in Fig. 2, shows E_S echo recorded during 1106 h to 1251 h. The intense part of the echo is one transmitter pulse (15 km) wide centered around 112.5 km and the echo range some times is spread from 97 km to 142 km. The bottom height of the E_S is about 100 km and remained constant with time where as the top height showed small changes with time. The S/N variations at each height are quasi-sinusoidal with 5 min to 12 min period. The bottom and top heights of the E_S echoes do not show any variations with time. The occurrence of S/N maxima successively at lower altitudes at intervals of about 7 km with a delay of about 5 min is very significant.

In contrast during noon hours (Fig. 3 for 25 May 2005), large variation was observed in the bottom height through out the duration for which the echo is seen. The S/N variations at each height are quasi-sinusoidal at intervals of 5 min to 10 min. From the figure, we have observed echoes at 97.5 km altitude that most of the time are delayed by 3 to 6 min from those observed at higher altitude of 127.5 km, though not very consistently, which seem to reflect the characteristics of QP echoes in those cases.

During post noon hours (day no. 249 for 6 September 2005, shown in Fig. 4), the bottom height of E_S echoes is below 90 km. For this episode E_S of two heights of S/N maxima, with no echo regions in between was observed. We could not probe altitudes below 90 km because of the limitation on the number of range bins to 16. The quasi-periods of the echo intensity variations are in the range of 4 to 8 min and the altitude of maximum intensity is at 120 km with S/N variations are similar to the variations during noon hours, but with a time delay of about 5 min between the S/N maxima at lower heights.

During the post sunset hours (on day 167, i.e., 14 June 2005, Fig. 5) height occasionally crossed 150 km on the top side with periods in the range 10 min to 15 min. The delayed occurrence of S/N maxima at successive lower heights is not clear during the post sunset event as observed clearly for the other episodes. These variations imply partially range resolved echoes from discrete stratifications in the E_S layer. For post mid night hours, (day no. 256: 13 September 2005 – Fig. 6) the E_S echoes were observed from 90 to 127 km range with 7–10 min periodicity and with S/N maximum at

112.5 km. The delayed occurrence of S/N maxima at successive lower heights was also seen not like post sunset event.

The overview of the RTS maps shows that the height of occurrence of E_S is not constant with time. There are quasi-periodic variations of S/N at each height and also the time of maximum S/N at lower altitudes is delayed by about 5 min where as the S/N maxima at each height are at intervals of 5 to 12 min. The negative phase of the maximum intensity observed for successive lower altitudes shows the gravity wave influence on E-region heights. The contours of constant S/N are rather vertical but the maxima of S/N at lower height only are delayed. The height of maximum intensity is higher for afternoon hours. The post sunset E_S events appear to be of different characteristics compared to E_S at other times of the day as the negative phase of the maximum intensity contour in the vertical plane is absent for post sunset hours.

5 Phase height variations E_S echo

The phase height variations at the range bins where the echo intensity is highest for different times of the day corresponding to the RTS map shown in the top panel of each day are shown by dotted line in second panels of Figs. 2 to 6. The phase height varies between 0.2 to 25 km with larger variation during post sunset hours compared to noon hours. For all days, these variations are less at the maximum intensity range than at the other ranges. The phase height variations with quasi periods of 10 min to 15 min are clearly observed for the noon time E_S event shown in Fig. 3. During post noon hours when small phase height variations were observed, very small scale oscillations were overlapped on large scale variations. Continuous upward movement (i.e. +ve velocity) is observed for post midnight hours as shown in Fig. 6 for 13 September 2005.

6 Doppler velocity variations of E_S echoes at different times of the day

The bottom two panels in Figs. 2 to 6 show the Doppler velocity maps of E_S echoes corresponding to the RTS maps shown in top panels. Except for the range where the echo intensity is high, the velocities are plotted by line with different symbols. Velocity values for S/N greater than 35 dB are only plotted resulting in discontinuous plots at each height when the S/N was less than 35 dB.

The lack of similarities in time variations of Doppler velocities even for adjacent heights is the most striking feature observed for almost all E_S episodes under study. During pre-noon hours (Fig. 2), velocity is close to zero at heights 105 km through 112.5 km most of the time. At 97.5 km also the velocity was close to zero during 1100 h to 1155 h, but during 1200 h to 1215 h the velocity decreased first and then increased to as much as 40 m/s. At 120 km to 150 km the velocity varied quasi-sinusiodally, some times with large magnitude, and the quasi-periods are even more than 20 min, in contrast to 5–12 min periods observed in the RTS plots shown in the top panels. The velocity variations at higher range bins are with large magnitudes than at the lower range bins which show the diffusive character of the echoes from higher range bins. During post noon (Fig. 3), the velocity variations show quasi periodicity with periods ranging from 5 to 15 min ending with random variations. The velocity variations are similar for the upper ranges whereas random variations were observed for the lower ranges. During pre-sunset hours (Fig. 4) the magnitude of velocity variations is larger for lower and higher range bins than at the range bins where echo intensity is highest. Also, there are high frequency variations of small magnitudes superposed on the large scale variations corresponding to very small scale variations observed in phase height. The quasi periods are ranging from 5 to 8 min for this event. The line of sight Doppler velocity variations bear no similarity with the echo intensity variations and in fact the velocity variations are small when the echo intensity variations are large and vice versa.

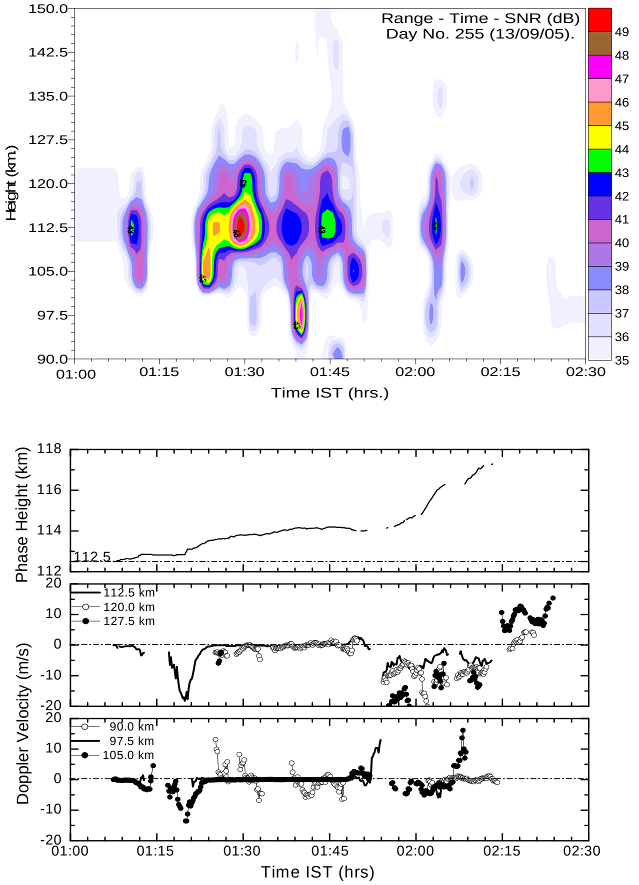

Fig. 6. Same as Fig. 2 except for the Day no. 256, 2005 (13 September 2005).

In general, the RTS and Doppler velocity variations of E_S show quasi-periodic increases and decreases with periods

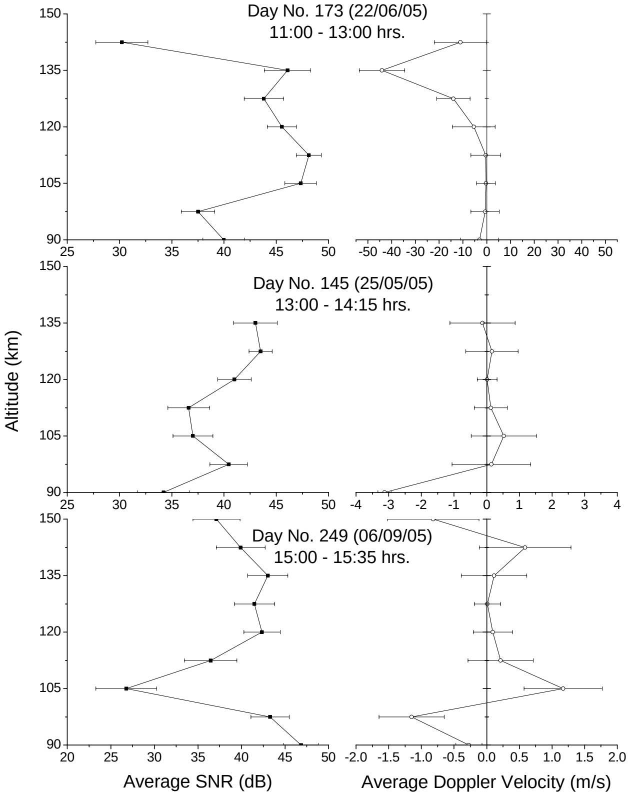

Fig. 7a. Altitude versus average SNR (left panels) and Doppler velocity (DV) (right panels) of individual E_S occurrences on 173, 145 and 249.

varying from a few minutes to as large as 20 min implying the influence of medium scale TIDs at E-region heights over this low latitude. The lack of similarity in velocity variations for successive ranges (even though the transmitter pulse (100 μs) is over-sampled at 50 μs interval) indicates strong discrete reflecting layers within the altitude structure of the E_S layer. In general, the velocity of the E_S echoes is in between ±20 to ±30 m/s except for pre-noon hours when the velocities are as high as 70 m/s. The smaller velocities observed at the ranges where the echo intensity is highest can be interpreted as the accumulation ions because of the shear explained by the "Wind Shear Theory" (Whitehead, 1961).

7 Profiles of range versus average echo intensity and average line of sight velocity

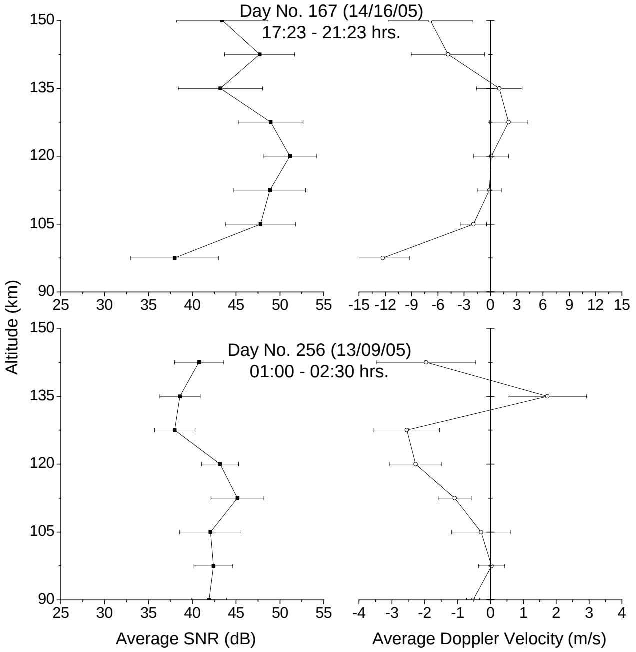

Fig. 7b. Same as Fig. 7a except for events occurred on 167 and 256.

Figure 7a and b shows the profiles of Average SNR (AS) and Average Doppler Velocity (ADV) of E_S layers observed during different times of the events reported in Figs. 2 to 6. The ADV for each range bin was computed only for echo intensity magnitudes more than 0.75 (arbitrary units). On all the days, except for the post midnight event, the average SNR shows two peaks indicating the discrete layer structure within the E_S. The AS shows a prominent peak at 112.5 km during the pre noon hours. During pre sunset and post sunset hours the peak is at 120 km while it is at 112.5 km for the post midnight event. During post noon hours there are two peaks, the lower one at 97.5 km and the upper one at 127.5 km. There is no similarity between the ADV velocity profiles and the AS profiles. The maximum ADV velocity varied with time and is below 5 m/s except during pre noon and post sunset hours. For the post sunset E_S occurrence, the maximum ADV was 15 m/s upwards at 90 km. It decreased to zero at 120 km and then increased to 12 m/s upwards. The ADV is mostly upwards during other times with very small increases or decreases at a rate of less than 0.1 m/s. The average Doppler velocity attains high negative value at higher ranges implying upward movement of the E_S echo. By and large, it can be observed that the range of maximum AS is not coinciding with the maximum ADV.

8 Summary and discussion

This paper reports the first observations on low latitude ionospheric E-region irregularities using a HF Doppler Radar with spectral capability. The major difference between those reported earlier and the present observations is that since this is a 5.5 MHz Radar, the observations reflect the mean background dynamics when the irregularities are present and the salient observations are:

1. The density fluctuations as represented by the Range-Time-Signal to noise ratio (RTS) plots indicate quasi

periodic variations with periods in the range 5–20 min.

2. Lower velocities at the height of maximum density and relatively higher velocities at the top and bottom heights indicate the diffusive nature of the echoes.

3. The irregularity structure sometimes show the descending nature of the quasi periodic echoes indicating that the E-region irregularities as recorded by the HF Doppler Radar could be a mix of Sporadic E as well as the QP echoes.

4. The lack of similarity in the Doppler velocities even for adjacent heights indicates the background shear in the irregularity structure.

5. Echoes observed at E-region heights during post sunset and mid night hours show different characteristics with discrete stratifications and absence of delayed echoes at lower altitudes.

With spectrum capability, HF Doppler radar observations of E_S echoes sampled in different range bins can provide an insight into the time variations of the layer structure and dynamics. The echo intensity variations with time obtained from HF Doppler radar spectra show 5 to 12 min quasi periodic increases and decreases, similar to the 150 km echoes reported extensively from VHF coherent back scatter radars (Yamamoto et al., 1991, 1992, 1994; Woodman et al., 1991; Tsunoda et al., 1994, 1995). It is well established that the 150 km echoes are produced by meter scale FAI for radar signals incident perpendicular to the magnetic field lines. It is, however, not clearly known whether the E_S echoes in HF radars are also produced by coherent scatter from 27 m scale irregularities only or by reflection at the appropriate electron density level and diffraction effects and/or focusing of signal due to the phase variations across the reflected wave front due to the electron density irregularities close to the reflection level. It is important to note that the line of sight velocity of the 150 km echoes, also referred as QP echoes and valley region echoes, reported from VHF radars observations is between -150 m/s to 250 m/s and further the velocity variations are random (Patra and Rao, 2006). The Doppler velocities observed in the present investigation at 5.5 MHz are lower (<30 m/s) than those reported from VHF radar observations. The E_S echoing process, whether reflection and/or by coherent scattering from decameter scale FAI, can be resolved by measuring the directions of arrival of the echoes. Recently, Patra and Rao (2006) reported a necklace shaped local time variation, between 145 km to 155 km, of the height of the 150 km echoes. We find that the altitude of maximum echo intensity varies from 105 km to 135 km, but it is too premature to conclude a local time variation from the limited data presented in this study. It is interesting to note that during this study E_S was not observed at 5.5 MHz before 10:00 IST and the occurrence possibility is high in the noon time, thus suggesting the asymmetry of the instability mechanism causing E_S with respect to the noon. It is also possible that the present observations using the HF Doppler Radar could be a mix of Sporadic E layer as well as the QP echoes.

The earliest HF radar observation of E_S layers was explained by the wind shear theory (Dungey, 1956, 1959; Axford, 1961; Whitehead, 1961). Kherani et al. (2004) explained the presence of night time valley region echoes in VHF radars to be from irregularities produced by Rayleigh-Taylor instability due to fringe (polarization) fields from the highly extended Spread F plumes. Cosgrove and Tsunoda (2001, 2002), described a direction-dependent instability, similar to Perkins instability (Perkins, 1973), of E_S layers in the night time mid latitude ionosphere. He showed that the accumulation of E_S ionization at the zonal wind shear node is unstable at night. During night time the F layer and E_S layers in mid latitudes are a coupled system and that the kilometer scale Hall electric fields in E_S map efficiently between E_S and F layers. Cosgrove and Tsunoda (2002) described a fragmentation process of E_S layer involving a closed current system between the two dynamos on either side of the wind shear node producing electric fields larger than the $U \times B$ by a factor equal to or even larger than the ratio of the field line integrated Hall and Pedersen conductivities. E_S layer modulation by gravity waves or KH instability billows were proposed to produce the large electric fields. It is, however known, that gravity waves exist almost always in the E-region and the fact that E_S layers are not observed very frequently is probably due to the directional dependence of the instability during the night time (Casagrove and Tsunoda, 2002b). Our observation that the E_S layer echo intensity in different range bins is modulated by 5 to 20 min quasi periods both during day time and night time, and the QP echoes at 150 km are also observed during day time in low latitudes (Patra and Rao, 2006) is to be investigated in terms of the gravity wave modulation of the irregularities during different times of the day.

Maruyama et al. (2006) found a close relationship between the appearance of QP echoes in the RTI plot and the level of in-homogeneity in Sporadic E plasma, signified by the difference between $f_b E_S$ and $f_o E_S$. During QP echo events, $f_o E_S$ increased while $f_b E_S$ decreased so that the difference between these two enhanced indicating the development of strong spatial structuring in electron density within the sporadic E layer. To investigate this feature, we have shown in Fig. 8 (top panel) the time variation of $f_b E_S$ and $f_o E_S$ for noon time on day 173 (22 June 2005) when Es was observed at 5.5 MHz on the HF Doppler Radar. As reported by Maruyama et al. (2006), we also have observed an increase in the difference between the two supporting the above arguments. But on the other hand, we have observed cases of QP echoes on HF Doppler Radar with no increase in the difference between the $f_b E_S$ and $f_o E_S$ (bottom panel of Fig. 8 for day 249, 6 September 2005) and hence the correlation is not perfect. Patra et al. (2005) also found rather a

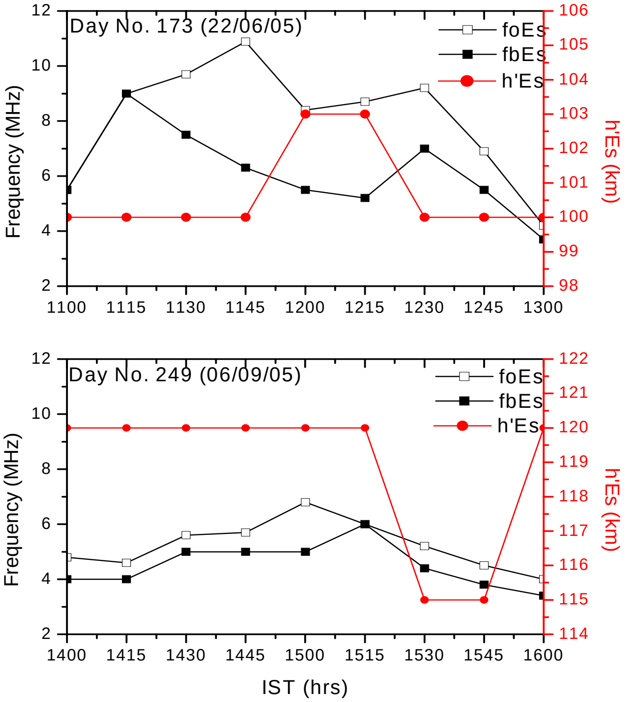

Fig. 8. Time variations of $f_o E_S$, $f_b E_S$ and $h' E_S$ for pre noon (top panel) and post noon (bottom panel) hours.

poor correlation between coherent back scatter obtained with Gadanki MST Radar and $f_T E_S – f_b E_S$ from SHAR during night. The development of spatial in-homogeneity as evidenced by the difference in $f_o E_S$ and $f_b E_S$ is necessary for the onset of QP echoes which confirmed the results of Ogawa et al. (2002) at mid latitudes, but did not agree well with the recent findings of Patra et al. (2005) and the present observations at low latitudes. Patra et al. (2005) reported that the most intense echo is below the virtual height of E_S layer during daytime while it is either above or below during night. The strength of the FAI is better correlated with the top penetration frequency $f_t E_S$ and $f_b E_S$ during night than during day. The relationship between Radar and Es parameters derived from Ionograms is poorer than that of mid latitudes which is quite consistent with the expectations based on gradient drift instability.

QP structures are often embedded in descending echoing region which are reminiscent of tidal ion layers (Chau and Woodman, 1999; Mathews, 1998) and thus indicate the role of tidal and gravity waves in the observed features. Yamamato et al. (1991) have shown that QP striations in which SNR peaks at two different altitudes as was observed in some of the cases shown in Fig. 7a and b. Further, QP echoes at higher altitudes with undulations at lower altitudes can be understood in terms of altitude variation of the efficiency of gravity waves in modifying the underlying plasma (Choudary and Mahajan, 1999). Occurrence of QP echoes at higher altitudes during night time hours may be associated with descending intermediate ion layers which descend down to upper E-region altitudes (Mathews, 1998) as reported by Rao et al. (2008). Kherani et al. (2004) reported that the night time valley region echoes could also be because of the downward extension of the Spread F irregularities from F-region altitudes and hence the observed night time echoes show different structures.

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