HF Doppler radar observations on the relationship between electrostatic turbulence and equatorial spread-F

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The HF Doppler radar observations of the vertical drift velocity on a few equatorial spread-F (ESF) days are presented. The correlation lifetime, spectral width and vertical electromagnetic drift velocity of spread-F irregularities have been investigated using the high temporal resolution HF Doppler radar data. The value of correlation lifetime is found to vary between 0.1 and 6s and it is also observed that regions of high echo power are associated with low correlation lifetime and vice versa. The vertical plasma drift velocity during spread-F shows a complicated pattern, changing sign every few minutes with magnitude, sometimes increasing 3-4 times the normal value. The existence of these unexpectedly large drift velocity implies that spread-F is associated with a mechanism capable of producing turbulent electric field having r.m.s. value several times higher than the normal dynamo electric field.

1 Introduction
The F-region ionosphere becomes extremely turbulent after sunset and is found to be a region of plasma irregularities and discontinuities. The understanding of the generation of irregularities in electron densities in the equatorial F-region has been improved in recent years through a variety of observational techniques as well as theoretical and computer simulation studies along with ground-based and satellite-borne probes1-5. Satellite observations of electric fields in the ionosphere have indicated a statistical link between electrostatic turbulence and spread-F6-8. A direct link between electrostatic turbulence and certain types of well developed spread-F irregularities have been established earlier via radar observations of spread-F made at Jicamarca, Peru9. Jicamarca observations have shown that there are two types of spread-F—one, the ‘weak’ type in which the irregularities move with the same electromagnetic drift velocity as that of the undisturbed ionosphere, and the other ‘strong’ type in which irregularities are much more intense and move in a highly structured pattern entirely different from that of the undisturbed ionosphere10.

The HF Doppler radar at Trivandrum (dip 0.5° N) provides a facility for the high resolution measurement of plasma motion at equatorial F-region. In this paper, vertical plasma drift velocity, correlation lifetime, spectral width and echo power have been studied during a few equatorial spread-F events. The days selected are those in which the vertical drift pattern is entirely different from that of the undisturbed ionosphere.

2 Observations and data analysis
The simple phase coherent HF Doppler radar used for the present study has been described by Joymon et al.11. The system comprises a pulsed HF transmitter and three spaced phase coherent receivers, which allows the measurement of vector plasma drifts. The system was operated at a frequency of 5.5 MHz with a pulse width of 100 μs and pulse repetition frequency of 50 Hz to probe the bottomside of the F-region. Depending upon the ionospheric conditions, the receiver input signal strength may vary from a few hundred μV to few mV which is compensated using attenuators. The signal is collected through three dipole antennas located at the corners of a right angled isosceles triangle of sides 100 m. The received complex signal from one of the three spaced receivers was continuously sampled at the rate of 1024 samples per minute using an A/D converter and stored in magnetic cartridges for further processing. The data were recorded during the evening hours till the disappearance of the return echo from the ionospheric F-region. The Doppler data are Fourier-analysed using an FFT technique to extract the direction and magnitude of Doppler frequency shift every 1 min interval. It is found that, during non-spread-F period, the power spec-
trum is highly monochromatic with a significant peak [Fig. 1(a)]. So, during this period the frequency corresponding to peak power and its sign are easily identified. But, during spread-F period as shown in Fig. 1(b), the power spectrum usually contains more than one significant peak. Hence, during spread-F it is required to evaluate the mean frequency shift from which the drift velocity pattern could be evaluated. During spread-F period, data are Fourier-analysed and are subjected to spectral moment estimation to obtain the mean Doppler shift, spectral width and echo power. The correlation lifetime, defined as the time taken by the auto-correlation function to fall to half the peak value, is evaluated during spread-F for each minute.

3 Results and discussion

Among the four parameters investigated, the spectral width is a measure of the intensity of spread-F. Figure 2 shows the time variation of spectral width during a few equatorial spread-F (ESF) events. It is found that during non-spread-F period the Fourier spectrum of Doppler data is highly monochromatic with spectral width less than 0.2 Hz, but during spread-F the spectral width increases and varies between 0.2 and 1.8 Hz. Among the 6 spread-F events selected for the present study the spectral width is largest on 26 Sep. 1995 and is smallest on 24 Feb. 1995, which implies that the spread-F of 26 Sep. 1995 is more intense than that on other days. Moreover, the duration of spread-F is also found to be different for different days. The time variations of echo power shown in Fig. 3 is a measure of electron density fluctuations, as the received echo during spread-F is due to both reflection and scattering. It is also clear from Figs 2 and 3 that the echo power directly resembles the spectral width, which implies that equatorial spread-F is related to irregularities of electron density aligned with earth's magnetic field present in the ionosphere. The direct resemblance between echo power and spectral width can be seen from their scatter plots as shown in Fig. 4. The straight line with positive slope shown in Fig. 4 is the regression line drawn by the method of least squares fit.

The time variation of correlation lifetime is depicted in Fig. 5. The correlation lifetime is found to vary with local time in the range 0.1-6s. This correlation lifetime can be taken as a measure of

Fig. 1—Sample Doppler spectrum of 1 min duration Doppler data during (a) non-spread-F and (b) spread-F

Fig. 2—Time variation of spectral width during spread-F
the random changes associated with the irregularities. Figure 6 shows the time variation of the vertical plasma drift velocity and group height for a typical non-spread-F day. The vertical plasma drift velocity shown in Fig. 7 is one of the most important parameters of the spread-F echoes, because this parameter is directly related to the quasi-vertical component of electromagnetic drift that the irregularities must share with the background plasma in the F-region. The most striking feature of this observation is the complicated pattern of vertical drift velocity shown in Fig. 7. Often during spread-F the magnitude of vertical drift velocity is larger than the usual velocity during non-spread-F. From Fig. 7, it is noticed that there are occasions when the vertical drift velocities are 3 to 4 times larger than the normal value.

It is clear from these observations that, in general, there exists an inverse relationship between the intensity of spread-F (spectral width) and lifetime of the spread-F irregularities as seen by the radar. This result is in agreement with the earlier findings of McClure and Woodman. For the weakest irregularities discussed by Farley the correlation lifetime was 1-3s and for the strong irregularities as discussed by McClure and Woodman, the correlation lifetime was often less than 1s. However, for the spread-F irregularities under this study, the correlation lifetime varies between 0.1 and 6s. For periods of intense spread-F the correlation lifetime is very small as seen from Fig. 5. In order to quantify the direct relationship between spectral width (intensity of spread-F) and
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Fig. 7—Time variation of vertical plasma drift velocity during spread-F (The horizontal bar shows the duration of spread-F)

Fig. 5—Time variation of correlation lifetime during spread-F

Fig. 6—Time variation of (a) vertical plasma drift velocity and (b) group height of a typical non-spread-F day

echo power (electron density fluctuations) and the inverse relation between the spectral width and correlation lifetime, cross-correlation analysis is performed and the results obtained are shown in Table 1. The positive correlation between spectral width and echo power substantiates the direct relationship between them, while the comparatively low negative correlation between spectral width and correlation lifetime suggests that the inverse relationship is only general. These observations also show that often the velocity was large and changed sign every few minutes or even every minute in some cases. This structure in velocity pattern is believed to be another manifestation of electrostatic turbulence reported by Kelly. The existence of these unexpectedly large drift velocities implies that spread-F is associated with a me-
Table 1—Correlation coefficient between echo power and spectral width ($R_e$), spectral width and correlation lifetime ($\lambda_e$) and $\lambda_p$ values

<table>
<thead>
<tr>
<th>Date</th>
<th>$R_e$</th>
<th>$R_\lambda$</th>
<th>$\lambda_p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>18 Oct. 1994</td>
<td>0.67</td>
<td>-0.54</td>
<td>5</td>
</tr>
<tr>
<td>19 Oct. 1994</td>
<td>0.72</td>
<td>-0.67</td>
<td>8</td>
</tr>
<tr>
<td>24 Feb. 1995</td>
<td>0.77</td>
<td>-0.51</td>
<td>3</td>
</tr>
<tr>
<td>27 Feb. 1995</td>
<td>0.67</td>
<td>-0.48</td>
<td>25</td>
</tr>
<tr>
<td>21 Mar. 1995</td>
<td>0.64</td>
<td>-0.47</td>
<td>2</td>
</tr>
<tr>
<td>26 Sep. 1995</td>
<td>0.88</td>
<td>-0.56</td>
<td>5</td>
</tr>
</tbody>
</table>

Mechanism capable of producing a turbulent electric field having an r.m.s. value several times the magnitude of the normal dynamo electric field of the undisturbed ionosphere. A necessary condition for the operation of the mechanism is probably the relatively low electron concentration in lower ionosphere near the equator at night and in the early part of the sunrise period (these are the hours when equatorial spread-F occurs), which, in turn, leads to enhanced polarization fields in the F-region.

4 Summary

The following conclusions can be drawn from the present study:

(i) During non-spread-F period, the power spectrum of the Doppler data is highly monochromatic with spectral width 0.2 Hz or even less, and during spread-F the spectral width varies between 0.2 and 1.8 Hz and the spectrum usually contains more than one significant peak.

(ii) The direct resemblance of echo power (electron density fluctuations) to spectral width (intensity of spread-F) shows that the generation of equatorial spread-F is related to the irregularities in electron densities.

(iii) During spread-F the irregularities move in a random fashion, as reflected by the lifetime. Moreover, it seems that the irregularities causing strongest spreading have lowest lifetime.

(iv) The vertical plasma drift velocity during spread-F shows a complicated pattern, changing sign every few minutes with magnitude sometimes increasing 3-4 times the normal value.

(v) Equatorial spread-F (at least for the irregularities discussed here) is associated with a mechanism capable of producing a turbulent electric field.

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