A fading record may be considered to be the sum of a number of sinusoids of different frequency with some phases difference relative to each other. A Fourier analysis of such a curve would resolve it into the sine waves, of which it is composed of, giving the amplitude and phase of each component present. One can therefore find out the amplitudes and relative phases of the various Fourier components present in a fading records at the three receivers. From the phase lags between any pair of the records for each of these frequencies, the drift speed and direction at that particular fading frequency can be estimated knowing the relative separations of the receivers. If the irregularities in the ionosphere are moving under the influence of a steady wind, and there are no turbulent movements, the diffraction pattern on the ground would move steadily and all the Fourier components derived by the above analysis would have same speed and direction. Any dispersion in the values of drift speed and direction is therefore an indicator of the randomness in the diffraction pattern. The random variations of signal strength or noise might also occur and it is a limitation of a single Fourier
analysis as described above, as it would not distinguish between the required signal and unwanted noise.

If such an analysis is attempted in practice, it is found that the spectrum is not smooth. The technique of Fourier analysis has however been considerably developed to avoid this difficulty. Much improvement in the spectrum analysis have been made to obtain the genuine power of the waves within the desired limits namely the hamming, hanning and other techniques. JONES and MAUDA (1968) have given a working scheme for the cross-spectral analysis of the three receiver fading records.

The ionosphere can be compared to an amplifier of unit amplification, one fading curve being the input and the second as the output. If this amplifier has the linear characteristic the whole operation is known if the phase change and amplification are known for all the frequencies.

Thus if the input is \( x(t) = a \sin(2\pi ft + \phi) \) ....(1)

The output will be \( y(t) = a G(f) \sin(2\pi ft + \phi + \Phi(f)) \) and the operation is defined by the functions \( G(f) \) and \( \Phi(f) \), which are related by the following equation:

\[ H(f) = G(f) \exp(2\Phi(f)) \] ....(2)
The difficulties arise if the relationship of $Y$ and $X$ is contaminated by noise $n$. The measured response then must be subjected to a filtering procedure in order to find estimates of gain and phase i.e. $G(f)$ and $\phi(f)$. GOODMAN (1957) examined such a system on the assumption that $X$, $Y$ and $n$ are stationary Gaussian noises, with $X$ and $n$ statistically uncorrelated with each other. His analysis showed that from the input spectrum $S_X(f)$ and input-output cross-spectrum $S_{XY}(f)$, with suitable smoothing, one can recover the frequency response function in the form.

$$H(f) = \frac{S_{XY}(f)}{S_X(f)}$$

as though there was no noise $n$.

Following TUKLY (1949), Goodman established a method of estimating spectra $S_X$, $S_Y$ and $S_{XY}$ from finite sample records of $x$ and $y$ and estimating the frequency response function $H(f)$. In case of ionospheric drift there are three fading records. Three independent estimates of phase differences $P_{12}$, $P_{13}$ and $P_{23}$ can therefore be obtained for each pair of records, unlike the simple Fourier analysis, which will give only two independent phase differences.

(a) Method of analysis

Given amplitudes $x(t)$, $y(t)$ and $z(t)$ for the three fading records obtained at closely spaced receivers
of the $D_1$ method, the cross-spectral analysis involves the following steps:

1. Calculation of co-variance functions.
2. Correlation of co-variance functions for means and trends.
3. Calculation of 'raw' spectral estimates.
4. Smoothing to give the final spectral estimates.
5. Computation of the estimated gain $G(f)$ and phase $\phi(f)$ of the frequency response function.
6. Calculation of velocity and direction from the phase differences, e.g., $\gamma_{xy} = \gamma_{12}/2_{12}$, etc.
7. Rejection of those values in which 'noise' has obscured the true values (significance of the results).

The three fading records are read at a particular sampling interval of time $\Delta t = h$ (say) for amplitudes. Then following Blackman and Tukey (1958), the 'Nyquist frequency' is given by $f_0 = h/2$.

Goolahab et al. (1961) has shown that $\Delta t$ should not be chosen so small that the whole spectral weight is crowded down to the bottom one or two points. Further, to minimize the distortion due to aliasing, $\Delta t$ must be small enough to ensure that the continuous data have no appreciable power above $f_0$. A value of $\Delta t$ between 0.1 - 0.2 secs was found suitable for the drift records taken at Thumba (0.6°S dip).
She cross-spectral estimates at a given frequency 'f' is given by
\[ S_{jk}(f) = C_{jk}(f) - Q_{jk}(f) \] ....(1)
and the phase \( P(f) = -\frac{Q_{jk}(f)}{C_{jk}(f)} \) ....(2)

From the values of \( P(f) \), we can calculate the velocity and direction of each Fourier component as follows:

The phase differences can be converted to time shifts as:
\[ \tau_{jk}(f) = \frac{P_{jk}(f)}{2\pi f} \] ....(3)

Any pair of time lags for one frequency 'f' can be converted into the velocity and direction of drift in the same way as in similar fades method (MITRA, 1949). However as the present treatment is concerned with the oscillations and waves, it is easier to consider wave fronts rather than the line of maxima. In a plane wave, the wave numbers add vectorially, so that the wave number along the line between the aerials \( j \) and \( R \) separated by a distance \( c_{jk} \) will be \( \mathbf{E}_{jk} = \mathbf{E}_{jk}/x_{jk} \) and the vector addition of two such values will give the vector wave number \( K \) in the direction of motion, which has a velocity \( V = 2\pi f / |\mathbf{K}| \)

Hence if \( x_{12} \) and \( x_{13} \) are at right angles to each other \( V = 2\pi f / \left( \frac{P_{12}}{X_{12}} \right)^2 + \left( \frac{P_{13}}{X_{13}} \right)^2 \) \[ \frac{1}{2} \]

and angle \( \theta \) with respect to \( x_{12} \) is given by:
\[ \theta = \tan^{-1} \left( \frac{P_{12}}{X_{12}} \cdot \frac{X_{13}}{P_{13}} \right) \]
should be divided by a factor of 2 in order to get the velocity in the ionosphere.

**Significance criteria**

In order to reject the values of \( V \) and \( \phi \) for which the power is negligible, the following criteria is found to work satisfactorily:

Values of \( V \) and \( \phi \) are not reliable when

\[
\alpha' = \tan^{-1} \left( \frac{X_{23}}{X_{12} (P_{12} - P_{23})} \right)
\]

and

\[
\alpha^{15} = 0.17 \text{ radians or } 10^\circ
\]

Coherence \((\gamma)\) of cross-spectra criteria given by GOODMAN et al. (1961) is found to fail in this case as when \( \gamma \) is low, its estimates are not accurate. Other criteria which may be tried are the extent to which \( G(f) \) differs from the value of \( G \) averaged over all frequencies.

Also those records for which the equality \( P_{12}(f) + P_{13}(f) = P_{23}(f) \) does not hold good, are rejected.

**(b) Application to Thumba drift records**

Yearly one hundred drift records of Thumba for E and F regions were subjected to the cross-spectral analysis. The amplitudes at each of the three aerials were read at suitable intervals, depending on the fading frequency (see Chapter III for the criterion) and two hundred or more values were used. Nearly 10% legs of the total number of values were given. All the computations were done with the help of IBM 1625 machine.
The cross-power spectrum $P(f)$ for each pair of aerials consists of one broad peak around the most predominant frequency of fading. Secondary peaks whenever present correspond to the higher frequencies, superimposed over the main fading frequency. The cross-power $P(f)$ spectra for a few typical day and night-time drift records of Thumba for both $E$ and $F$ regions are drawn in Fig.7.1, 7.2, 7.3, 7.4 and 7.5. The shape of the cross-power is essentially the same between any pair of the three receiving aerials.

The corresponding drift speed $V(f)$ as a function of Fourier frequency is also shown on the same diagrams. The drift direction $\theta(f)$ remains unchanged within a few degrees over the entire frequency range in all the cases studied and hence not shown in figures. The significance of the drift speed and direction over spectral range is ascertained by applying the criteria mentioned in the last section.

The cross-power spectrum for Thumba drift records can be broadly classified into three groups. Firstly, where the peak power occurring at low frequency (upto 30 fades/min) and a slowly decaying tail. Secondly, those showing peak power at medium frequency (30-60 fades/min) and thirdly those with a double distribution. The first one is common in
the daytime records while the last one in the night-time records. The normal distribution seems to be frequent for both the regions as well as day and night hours. The double peak of $P(f)$ in $F$-region night-time corresponds to the drift records taken during the onset of spread-$F$ where a fast fading is superimposed over a normal slow fading in the night.

The drift speed is found to increase slightly with the fading frequency in most of the cases studied. The drift direction showed no significant change with the fading frequency. The total range of variation of $V(f)$ was higher during day and smaller during night. The values of $V(f)$ varied systematically over the significant power range after which there was found to be a sudden increase in $V(f)$. These values were not used.

The magnitudes of $V_a$ (apparent drift speed from the shift of the peak of cross-correlogram) and the characteristic drift speed $V_c$ (as derived by full-correlation method of BRIGGS et al. 1950) are also mentioned in the corresponding blocks. The horizontal and vertical arrows represent the magnitudes of $V_a$ and $V_c$ respectively on the same scale as $V(f)$. It is noticed that $V_a$ represents in most of the cases the value of $V(f)$ at the highest significant fading frequency and $V_a$ is nearly equal to total frequency spread of $V(f)$.
THUMBA DRIFTS

F REGION (DAY TIME)
CROSS-SPECTRAL ANALYSIS RESULTS

Vc in m/s and Hz in arbitrary units.

FIGURE 7.5

THUMBA DRIFT 1967-68
COMPARISON OF CROSS-SPECTRAL RESULTS WITH CORRELATION RESULTS

Vc by full correlation vs Vg by cross correlation.

FIGURE 7.6

E REGION 2.2 MC/S 1964.
F REGION 4-7 MC/S 1964.

OPTIMUM CORRELATION METHOD (M/S)

FIGURE 7.7
The Fig. 7.6 gives the plot of the $v_c$ against the frequency spread in $V(f)$ as well as the plot of $\bar{v}_a$ against the highest frequency value of $V(f)$. Both the plots show a linear relationship.

The results for Thumba also show that the drift speed ($V$) determined by the similar fades method agree very well with the drift speed of the major wave component determined from the power spectrum analysis, showing that in most of the cases, except those during spread-$F$, the similar fades method (MITRA, 1949) yields reliable results.

The present method of analysis yields full information in regard to the dispersive movement of the ionospheric irregularities. Whenever there is a consistent variation of speed with frequency, even after rejecting those values for which power is not significant implies that none of the traditional methods of analysis described in the Chapter II, III and V, yield a meaningful result for $V$ and $\phi$. The results for Thumba show a positive dispersion of apparent drift speed for both $E$ and $F$ regions. The total extent of this dispersion is more in the day than the night. One explanation of such a result would therefore be that a system of waves exists in the ionosphere, each of these moving with different velocity. This has been shown mathematically by JONES and MAUDE (1965). This
involves an assumption concerning the shallowness of the disturbances and other interpretations are also possible.

7.2 Power spectrum results for drifts at other stations

Dispersion analysis has been applied to a number of different types of drift records from the ionosphere and the interplanetary medium. Yerg (1956), Jones and Maude (1965), Mcgee (1966), Gossard (1967), Jones and Maude (1968), Golley and Rossiter (1970), Pfister (1970) and Haug and Patterson (1970) analysed records of ionospherically reflected waves. The analysis has also been applied to records of ionospheric scintillations of radio stars and satellites, by Briggs and Golley (1968), Papagiannis and Elkins (1970) and to the records of interplanetary scintillations of small diameter radio sources by Golley and Dennison (1970). The results of some of these workers are discussed below.

Gossard (1967) has analysed fading records for 90 km height by cross-spectral method after removing the Doppler spectral components resulting from the interference of the off-vertical reflections. Significant variations are observed both in \( V(f) \) and \( \sigma'(f) \).
JONES and MAUDE (1968) have applied the above method to a few E-region records for Aberystwyth (51°N) and found that the drift speed increases steadily with the fading frequency while the direction is not affected much. BRIGGS and GOLLEY (1968) have also noticed the presence of a positive dispersion of drift speed in the E-region, by the cross-spectral analysis of the scintillation records taken at three spaced interferometers (38 MHz) at Cambridge (52°N). The drift direction however remained more or less unaffected by the fading frequency. They also compared the values of $V(f)$ and $\phi(f)$ with those of $\varpi_a$ and $\theta_a$ as well as $\varpi_c$, determined from the cross-correlograms, (BRIGGS, PHILLIPS and SHANN, 1950). They found that $\varpi_a$ is nearly equal to the $V(f)$ at the highest significant frequency of the fading in the record and $\theta_a$ agreed closely with $\phi(f)$, which did not change much. It was also found by them that $\varpi_c$ is nearly equal to the total range of variation of $V(f)$. 


SPRENGER and SCHMIDTER (1969) have shown using the high pass mathematical filters of variable cut off frequency $f_c$ for low frequency drift records taken in central Europe, that $V_a$ is independent of fading frequency. They concluded from this that in the lower ionosphere, the drift of the ionization results from a bodily movement of the irregularities, blown by the wind.

GOLLEY and ROSSITER (1970) have studied the frequency dependence of the drift velocity at Adelaide for the E-region and found that a significant number of drift records showed a positive dispersion in the drift. It occurred more frequently for the partially reflected echoes than for the total reflection from the E-region. On comparison with $V_a$ and $\phi_a$ as well as $V_c$, similar results were obtained as BRIGGS and GOLLEY (1968) have obtained for Cambridge.

An independent confirmation of these findings has been recently reported by PFISTER (1970), using modified experiment with three or more receivers, where phase and amplitude variations are measured, simultaneously in order to dispense with long array of aerials as used by BRIGGS et al. at Adelaide. Pfister has shown that for E-region at Billerica, Massachusetts, $V(f)$ increases with fading velocity and $\phi (\gamma)$ agrees with in $30^\circ$ to the $\phi_a$ values.
HAUG and PATTERSEN (1970) have observed a positive dispersion of drift velocity at Tromso (Norway).

7.3 Interpretation of results

Little variation of $\varphi(f)$ and its close agreement with $\varphi_a$ is expected as the cross-spectral analysis makes no correction for anisotropy and the direction must therefore be very nearly perpendicular to the axis of elongation of the pattern. The same is true for $\varphi_a$, which is the apparent direction from the cross-correlogram. The value of $V_a$ determined from the shift of the peak of cross-correlogram takes into account mainly the highest frequency component of the record and hence agrees with the high frequency end of $V(f)$. The low frequency components will contribute to the shapes of the functions at large time shifts (SPRENGER and SCHMINDNER 1969) but will be relatively unimportant in influencing the positions of the maxima.

JAMES (1962) has shown that if a number of patterns moving with different speeds are superimposed, the value of $V_c$ will be of the same order as the range of velocities involved. The present result for Thumba as well as other stations is not unexpected due to the dispersion effects. MCGEE (1966) has shown that the dispersion is associated with the showness of the cross-correlation functions. This aspect is discussed in details for Thumba in the next section of this chapter.
Origin of dispersion in the ionosphere

The most direct explanation could be the propagation of some kind of dispersive waves through the E and F regions of ionosphere. However this interpretation involves serious difficulties as the dispersion observed is very variable in magnitude and even reverses its sign occasionally (as can be seen from some of the results for Thumba). Also the dispersion is most often positive whereas internal gravity waves can give rise to only negative dispersion.

It therefore confirms that the movements observed in splaced receiver experiment are a type of plasma drift produced by the combined action of $\mathbf{E}$ and $\mathbf{B}$ fields (MARTYN, 1959). On this theory, the variability and the effect of magnetic disturbances on the drift is readily expressed by the changes in the electric field strength. If an electric field $\mathbf{E}$ exists in the ionosphere, this will produce a bodily drift of ionization with a velocity $\mathbf{E} \times \frac{\mathbf{B}}{B^2}$, where $B$ is the strength of earth's magneticfield. CLEMOW and JOHNSON (1959) have shown that weak cylindrical irregularities, aligned in the direction of $\mathbf{B}$ will also drift with the same velocity. The same authors have also derived the dispersion equation using a perturbation treatment, which gives the relation between frequency and wave number of a particular Fourier component of electron density.
perturbation. The dispersion of velocity derived from this
is more or negligible to account for the observed
dispersion in the drift.

Other possible causes of the dispersion in the
ionosphere which can be significant are discussed below:

(i) **Height gradient of the horizontal drift in the
ionosphere**

Height variation of the horizontal drift both on
E and F regions at Thumba has been earlier indicated (MINNA
and RASTOGI 1970). BEDILGER et al. (1968) have also shown
by the rocket experiments that there are sharp gradients
of drift speed around 100 km within a range of 5 Kms. Simi­
lar results have been obtained by RAO and RAO (1964) for
F-regions at Waltair. As the electronic gate used for the
selection of a particular echo for drift recordings has a
finite width (0-5 Kms), the record thus obtained is contami­
minated with the echoes from the very close range with­
this height interval and the dispersion nature of drift
velocity is revealed in the cross-spectral analysis
according to the relation $f = V/\lambda$. The fading indefi­
ited at different points will be of different frequencies.

Another possibility could be that apart from the
vertical dispersion of the velocities, at any given height
there exists a spectrum of velocities (RAO and RAO
1967). Therefore, at any height it is definite, but due to
varying \( \lambda \), we shall see according to the equator \( f = v/\lambda \).

different fading frequencies from different slant heights
from the same level of reflection. Each reflecting height
would produce one frequency spectrum shifted to the right
or left depending on the velocity. The results of observed
amplitude at frequency \( f_1 \), say, would now arise from super-
position of the components coming from different heights
each having a different velocity and wavelength but all
satisfying the relation \( f_1 = v/\lambda \). The velocity at \( f \),
will therefore be an integrated mean of the velocities
of all these components. Similarly for other frequencies.

(ii) \textbf{Independently moving reflecting screens}

HAUG and PATTERSON (1970) has generated mathemati-
cally the observed dispersion of drift velocities at
Tromso (Norway) in terms of the velocities \((v_1, \phi_1)\),
\((v_2, \phi_2)\) etc of a number of independently moving reflect-
ing screens at the same height. Such an analysis was
possible from the skewness of the cross-correlograms.

(iii) \textbf{Dispersive nature of the vertical drift velocity}

The component of non-horizontal drifts in the ion-
osphere is also measured by the closely spaced receiver
method, alongwith the actual horizontal drift of the ioni-
ization. It is, therefore, possible that the dispersive
nature of this oblique movement of the ionospheric irregularities could give rise to the dispersion of the horizontal drift determined by the cross-spectral analysis. RASTOGI (1971) has shown evidence of the height variation of the vertical drifts from the upward moving kinks on the ionograms.

This effect will however be significant only when the magnitude of vertical drifts is comparable with that of the horizontal drift. For an equatorial station such as Thumba, this possibility is very rare as the horizontal drifts are of the order of 100-200 m/s whereas the vertical drift in F-region is nearly 16-20 m/s (see section 2.5 of Chapter VI). However, the vertical drift increases with height in F-region and reaches a magnitude of nearly 50 m/s near the peak $F_2$-region (at about 400 Km). Near the Sq focus, $V_x$ and $V_z$ are of comparable magnitudes. For higher latitude $V_z$ is low and should not be taken as the contributing factor \( V_z = \frac{E_y}{B \cos I} \).

(iv) **Height gradient of scale size of irregularities**

To account for the occasional observations in which the sign of dispersion is reversed, it is necessary to postulate that on these occasions the scale size of the irregularities also varies with height. Suppose, for example, that the irregularities have a larger scale size in the
regions where the drift velocity is large than in the regions where it is small. Then if the variation of scale size is sufficiently great, it will be found that the low frequency components give the higher velocities. In general, the variations of scale size with height will introduce an additional cause of dispersion which may either add to or subtract from that produced by a vertical gradient of horizontal velocity. The above theory will still hold when the transmission is oblique instead of vertical with the only difference that the variation of $V$ and scale size with height will be replaced by the variation along the line of sight.

(v) Gravity waves

Gravity waves are generated by the lower atmospheric disturbances such as thunderstorms, nuclear explosions and other man made disturbances. A considerable part of the energy of these oscillations is able to penetrate through the troposphere and effect the $E$ and $F$-regions of the ionosphere. These waves have a period of 10 mins to 2 hrs and are amplified as they move upward due to decreasing density. There are two types of gravity waves, namely internal and external or surface gravity wave. A gravity wave is called internal when the wave number $K$ is real and surface wave when it is imaginary. Hines (1960) and
SCORDER (1953) have respectively discussed the properties of these two types of waves. HINES and RAO (1968) have discussed the possible effects of the gravity waves on the ionosphere in producing wavemotions. The velocity for the internal gravity waves decreases with the increasing frequency and hence these are either not present in Thumba ionosphere or they are not detectable by the closely spaced receiver method as there is always a positive dispersion observed at Thumba. Surface gravity waves however have a positive dispersion and are produced by wind shears in the atmosphere. The Thumba results of cross-spectral analysis, similar to those for Adelaide, Cambridge and Abersweth, show the presence of positive dispersion and hence the surface gravity waves.

(vi) Variability of ionfit speed during the course of a record

BRIGGS (1967) and FELGATE and GOLLEY (1971) have shown that the positive dispersion will result if the record length analysed is larger than the period over which the drift is likely to remain constant. Experience shows that the drift at Thumba is fairly fixed in both magnitude and direction except around the reversal timings for a period of nearly one to two hours where as the length of the records used for analysis are only half to one magnitude long.
It has however been shown by FALCO, E and GOLLEY (1971) that artificially introduced variations in the velocity of ionospheric drifts records also produce a positive dispersion, similar to the drift records with naturally occurring velocity variations. Three receiver dispersion analysis (cross-spectral analysis) must therefore be treated with some caution unless it can be shown that the records are statistically stationary. A two dimensional spatial dispersion analysis given by BRIGGS (1968) is not affected by these spurious velocity variations. However, a very large array of receiving aerials is required for this method such as used by GOLLEY and ROSSITER (1970) at Buckland Park, Adelaide which consists of 89 receiving dipoles.

The wavelike character of the diffraction pattern on the ground is therefore confirmed from four independent measurements at different stations namely Adelaide, Thumba, Cambridge, and Billerica, Mass. Little can be said about the horizontal wavelength or period of atmospheric waves or their vertical excursion. Obviously a single smooth and well defined wave does not fit the observations. It could be a combination of a large internal gravity wave and a superposition of relatively short lived ripples moving essentially with the wave. The fact that the measurements of the receiver are limited practically to short distance, the picture of the reflection surface is incomplete.
This deficiency can be corrected with a relatively simple improvement in the data recording system by scanning the height gate in discrete steps as described by EIN and GORMAN (1970). It then will be possible to determine slant range, dippler shift, and the direction of all the reflecting areas of a single frequency at a given instance and their variation with time. This should lead to a realistic description of the motions and fine structures in the ionosphere.

Some other tests for the dispersion in the ionospheric drifts

Though the full cross-spectral analysis is the best method to study the dispersion in the drift velocity, it requires very tedious and time-taking mathematical computation. The idea of the dispersion in the drift can be had by studying the following three properties of the cross-correlograms, which are obtained while analysing the drift record by Phillips and Spencer's method. These are described in the following:

7.4 Comparison of apparent drift speed as determined by similar fades method and from the shift of the maxima of cross-correlogram

JONES and MAUDE (1968) have shown that the difference between \( V' \) and \( V_a \) would be one of the indications of the presence of dispersion in the ionosphere. This is shown by
the analysis of artificially constructed fading records. On account of the presence of dispersion or the randomness, the fading records at any two aerials are similar but not identical in details. In the simple Mitra's method of similar fades which consists of the optical comparison of the similar features of the two records, the eye would unconsciously pick out the sharp defined features for comparison so that the velocity thus obtained would correspond to the highest frequencies present in the record. The numerical correlation would on the other hand give an equal weighting to all the frequencies present. If the \( V' \) values are consistently higher than \( V_a \) the positive dispersion is present and if \( V'<V_a \) then the dispersion is negative.

This method was applied to the drift data for Thumba as shown in the Fig. 7.7. It is seen that for both I and F-regions the deviation between two values is not much for smaller values but slightly more for the higher values of velocity.

As the points are distributed more or less equally on both sides of the 45° line, and as the spread is very small it can be concluded that in general there is very little dispersion at Thumba.
7.5 Skewness of the cross-correlograms

Moggridge (1965) has shown that the asymmetry of the cross-correlation curves is associated with the dispersion in the drift velocity along that direction. He defined an skewness parameter for the asymmetrical cross-correlation as follows:

If M is the point of maximum cross-correlation and P is the foot of the perpendicular from M on the line AC drawn at half the height of maximum and B is the middle point of this line, then the Skewness of this curve is given by \( S = \frac{PB}{BC} \).

The skewness is positive if B is further away from origin than the point P. In the given figure, the skewness would be negative. Some convention will hold if the asymmetry is in the other direction. The advantage of this technique has in the fact that it can be quickly applied to the existing cross-correlogram used for full correlation method, to determine the nature of ionospheric movements (i.e. whether it is a mass movement or the wave motion).

If the random drift parameter is caused by the dispersion or the spread of \( V \) with frequency, as shown by the results discussed in the section 7.4 of this chapter, then the skewness \( (S) \) should be related directly to the ratio of random to steady drift \( (i.e. \frac{Ve}{V}) \) as determined from
the full-correlation analysis.

The skewness parameters for Thumba were studied in the light of above discussion. Only ten percent of the records studied, showed the skewness in the E-W cross-correlograms. The N-S cross-correlograms were mostly symmetrical. These were grouped in the day and night hours and the histograms for the percentage occurrence were made as shown in the Fig. 7.8. The skewness was found to be predominantly positive during the day and negative during the night with the most probable values as +0.12 and -0.15 respectively.

This effect has been investigated by a few other workers for different stations. BRIGGS and GOLLEY (1968) have studied the distribution of skewness parameters for Cambridge, using the spaced scintillation records of the source casiopea-A. They found a most probable value of this parameter to be +0.03, though it was present in almost all their records. Kaushik studied the distribution of S for Ahmedabad and Halleybay.

The interrelation of S and Vc/N is shown in the Fig. 7.9 for Thumba. There is a fairly linear relationship showing that the dispersion of the drift in ionosphere contributes directly to the randomness parameter Vc.
THUMBA DRIFT 1968-69.

THUMBA DRIFT 1960-69.

PERCENTAGE OCCURRENCE

Figure 7.8

Figure 7.9

THUMBA E-REGION

VARIATION OF E-W CROSS-CORRELATION FOR THE FREQUENCY FILTERED RECORDS OF DRIFT

Figure 7.10
HAUG and PATTERSON (1970) have explained the asymmetry of the cross-correlograms in terms of the individual reflecting screens moving with different velocities. They have calculated these velocities for a few observed asymmetric correlograms.

Cross-correlation functions for satellite scintillations at spaced receivers show a systematic skewness indicative of the dispersive motions (PIAGIANNIS and ELKINS, 1970).

7.6 Analysis of frequency filtered drift records

From the investigation of the power spectrum of the reflected signals by theory of the auto-correlation functions, it is seen that there is always a considerable power in the fading components with periods shorter than the mean fading period. In order to study the behaviour of these short period fading components separately, SPRINGER and SCHIMINDER (1969) suppressed the long period fading components before subjecting the records to correlation analysis. This has been achieved by transforming the original fading functions $X(t)$, $Y(t)$ and $Z(t)$ according to:

$$X(t)' = \frac{1}{T_f} \int_{t-T_f/2}^{t+T_f/2} X(t) \, dt$$

and similarly for $Y(t)'$ and $Z(t)'$. 

The deviations from a running mean are calculated over a given time interval $T^*$ which is centered on the time $t$ of the respective amplitude value. The new functions $X(t)'$, $Y(t)'$, and $Z(t)'$ are then used for the computation of the correlation functions. This procedure acts as a high pass filter with a cut-off frequency $f^* = 1/T^*$ and suppresses fading components with frequencies $f < f^*$.

Sprenger and Schminder (1969) compared the cross-correlationograms for these five filtered series of amplitudes. It was found that the width of the correlation functions decreases systematically with the increasing cut-off frequency but the time shifts of the maxima of cross-correlation function remained nearly unchanged (in contrast to the results of Jones and Maude (1965). Thus the apparent drift speed $V_\text{app}$ calculated from these time lags did not change with fading frequency. Sprenger and Schminder (1969) also calculated the steady drift speed $V$ and the characteristic drift speed $V_c$, using the relations given by Briggs et al. (1950). The steady drift $V$ showed a distinct increase with the increasing frequency of the fading components, whereas the random drift $V_c$ showed only a slight decrease. The increase of $V$ with frequency is interpreted by the short period fades originating from a reflection level slightly higher than the long period fades. The observed velocity increase may
therefore indicate a real velocity gradient with height. A gradient of nearly 1-2 m/s/km has thus been derived. Normal vertical wind gradients of this order of magnitude have been found from the radar meteor wind measurements (GREENHOW and NEWFIELD, 1961). The slight decrease of $V_c$ with fading frequency can also be explained in terms of this concept of different reflecting levels for the components of different fading frequency, since the upper part of the reflecting region is near the turbo-pause level where turbulence vanishes.

A number of drift records for $E$ and $F$ region for Thumba were filtered mathematically using the cut off frequencies $F_f = 0.2, 0.3, 0.5, 0.6$ and 2.0 c/s. The resulting series of amplitudes $x(t)$, $y(t)$, and $z(t)$ were used to compute the cross-correlograms in E-W and N-S directions. A set of E-W cross-correlograms for $F$-region for some of these records are shown in the Fig. 7.10. The N-S correlograms showed no significant change with the variation of $F_f$ due to extremely high correlation in that direction at Thumba and hence are not shown here.

Two types of cases were observed. Firstly those in which the peak of the cross-correlogram did not shift with the increase in $F_f$, such as on 15th Nov, 2000 hr and 27th Nov 2200 hr. These were the cases when the ionization
moved as a whole as far as the apparent drift is concerned. In the second type of cases, the peak of the cross-correlogram shifted more and more away from the zero, as $\Delta f$ increases. This indicated a positive dispersion in the apparent drift speed. Sometimes $\nu_c$ showed an irregular variation with the $\Delta f$ when both positive and negative dispersions were present. The steady and random drift speeds $V$ and $\nu_c$ were also derived by using these correlograms (BRIGGS et al. 1950) and a slight increase in $V$ with $\Delta f$ was noticed in a number of cases. $\nu_c$ however did not show a definite dependence on $\Delta f$.

7.7 Variation in the shape of the cross-correlation curves with the receiver separation

The auto-correlation and the power spectrum of the fading signal are Fourier transforms of each other. If the pattern on the ground is considered to behave as a number of sine waves moving with possibly different velocities, the signal recorded at a second nearby receiver will be the same as that at the first receiver except for a phase change for each sine wave. The cross-correlation curve will therefore be the same as the auto-correlation curve except for a phase change of the various frequencies of which the pattern is composed of.
It is possible to make use of a mathematical analogy to predict qualitatively how the cross-correlation curve will change if the separation of the two receivers is increased. DOWN and ALUDE (1968) derived mathematically the shape of this curve, at various separations in terms of the wave packet at various times. A wave packet too may be considered as being made up of a number of sine waves and its shape sometimes later may be found by imposing a phase change on each of these waves. If the wave packet is travelling through a non-dispersive medium, the phase change will be inversely proportional to the wavelength and the wave packet will move, undistorted to a new position. In the same way, if the phase change of the cosine functions which make up the auto-correlation curve is inversely proportional to their period, the cross-correlation curve will have the same shape as the auto-correlation curve but will be displaced sideways. This will be the case if the pattern moves as a whole over the ground.

If the wave packet travels through a dispersive medium, the phase and group velocity will differ and wave-packet will distort as it moves. In particular if the spectrum of the wave packet is sufficiently narrow for the packet itself to show oscillations around the principal wavelength, the individual peaks will travel through the
packet, growing as they enter from one side and dying away again as they leave from the other-side.

If the pattern of signal strength on the ground moves in a dispersive manner, the phase change which is imposed on each frequency in transforming the auto-correlation into cross-correlation function will not be inversely proportional to the frequency and some kind of distortion which occurs to the wave packet will occur to the shape of the correlogram too (see Fig. 7.11 a).

Of particular importance is the case where the phase change imposed is independent of frequency as this is approximately the condition in the case described by McILW and JONES (1965). In this case the group velocity is zero and the individual peaks will pass through a stationary packet.

The above reason is general and does not depend on the power spectrum. Fig. 7.11(b) shows a set of cross-correlation curves resulting for varying receiver separation, when the drift velocity is assumed to be proportional to the fading frequency. The theoretical variation of the delay of a maximum of cross-correlation curve with the increasing receiver separation will look-like the parallel line of Fig. 7.11(c). This line will pass through the origin only if the ground diffraction pattern moves
as a whole. A few sets of multi-antenna records for E-region were taken for the investigation of this effect. Out of nearly thirty records studied for the cross-correlation curves with the increasing aerial separation in eastwest or north-south direction, most of them showed no distortion in their shape with increasing separation. Only a few showed the distortions similar to what is discussed above. Some of the F-region cross-correlograms for different aerial separations in the east-west direction are shown in the Fig.7.12. A few actual records are reproduced in the accompanying plate. As the pattern is highly elongated along the north-south direction at Thumba, it was not possible to detect the presence of wave motion in this direction as the correlation value charged very little even with the large change in the receiver separation.

The plot of the time lag of maxima with increasing receiver separation is given in the Fig.7.13. Only two of these lines pass through origin indicating the mass movement of the ionization. The other two cases indicate a dispersive drift of ionization in accordance with the theoretical prediction of DOWN and MAUDIE (1968).

KELLEHER (1966) has also studied the cross-correlation curves for F-region and JONES (1968) has studied the dispersion of E-region by this method. KELLEHER found
THUMBA DRIFTS

SHAPE OF EAST-WEST CROSS-CORRELATION WITH E-W DEVIATIONS.
(PRESENT OF WAVY MOTION)

TIME LAG IN SECS

THUMBA E-REGION

MULTI FREQUENCY CORRELATION

FIGURE 7.11

FIGURE 7.12

FIGURE 7.13

FIGURE 7.14
that only a quarter of the 66 records studied gave a straight line passing through the origin. In other cases these lines did not pass the origin, but were parallel to this. Jones too obtained similar results for E-region. Thumba results are of two types, one in which the plot of $T_{\text{max}}$ vs $\frac{2}{f}$ passes through origin and another in which it does not. ELKINS and P.A. BIANNIS (1970) have studied the multi-frequency cross-correlation curves instead of the multi-antenna curves, which show a similar variations of the shape as would be expected in the case of dispersion. The frequency separation instead of receiver separation also causes the variation of total path length traversed by the wave-packet as the height of the reflection changes and hence is the manifestation of a similar phenomenon. Frequency separated cross-correlograms were studied for Thumba also for F-region in a limited number of cases. The E-region results are shown in the Fig. 7.14. The maximum correlation is not significant, probably due to large height change by a change of only 0.1 MHz. Still the shape of the cross correlograms is very much variable with the increasing difference of frequency, in the case of E-region. Due to low values of correlations involved, it is not possible to say definitely by this result, that the dispersion is present in the drift speed.
Figure 7.15

MULTI ANTENNA FADING RECORDS AT THUMBA
IN THE EAST-WEST DIRECTION

IN THE NORTH-SOUTH DIRECTION
7.8 Conclusions

It can be concluded from these results that the horizontal drifts at Thumba exhibit slight positive dispersion during day and slight negative dispersion during the night. The results of the similar fades analysis as discussed in Chapter II are reliable measurements of the drift speed and direction of the major wave component present in the fading of the signal. The height gradient of horizontal drift and presence of gravity waves may be the possible causes of slight dispersion in the drift speeds in E and F regions at Thumba.