PART II

Studies on Equatorial F region
CHAPTER I

INTRODUCTION

The E-region is the region of the ionosphere starting from about 150 Km altitude. The upper boundary of the region may be taken as the level where the lighter ions (Hydrogen, Helium) predominate over heavier ions (atomic oxygen). This level varies in the range between 600 Km to 1000 Km depending upon the time of the day, season, solar activity and latitude of the location.

The principal neutral constituents in the F-region are atomic oxygen and molecular nitrogen. Molecular oxygen is easily dissociated by ultraviolet radiation and exists mainly in atomic form in the F-region, but nitrogen is mainly in the molecular form. The minor constituents include molecular oxygen, atomic nitrogen and the inert gases. With increasing altitude, the dominant constituent changes from nitrogen to atomic oxygen, to helium and finally to atomic hydrogen.

Solar ultraviolet radiation is the principal source of energy for the ionization in the F-region with the wavelength ranging from 165 to 911 Å. The low energy end of the range is set by the ionization potential of atomic oxygen at...
911 Å. The ionization threshold for molecular nitrogen, 796 Å falls within this wavelength range. The radiations produce a peak in the production rate of ionization around 120 Km. Combination of ionization production and losses due to chemical processes, produces a minor peak in the electron density, called as $F_1$ region peak. The $F_1$-region extends approximately from 140 to 200 Km. It was found that the $F_1$ layer critical frequency $f_0F_1$, though detectable on ionograms only at times, shows a dependence on solar zenith angle fairly similar to the well-known Chapman formula,

$$f_0F_1 \propto (\cos \chi)^{0.25}$$

$f_0F_1$ also varies with the sunspot cycle. The published data of $f_0F_1$ confirm quite well to the equation, (Rishbeth 1967)

$$f_0F_1^4 \propto (N_mF_1)^2 1 + 0.016 R,$$

where $R$ is monthly mean Zurich sunspot number. On the other hand, the $F_2$ critical frequency varies quite irregularly with solar zenith angle. Ratcliffe and Weekes (1960) showed that at any one station at noon, at a given season, $N_mF_2$ ($F$-region peak electron density) depends on solar activity and has the form

$$(f_0F_2)^2 \propto N_mF_2 1 + 0.02 R.$$
Transport of ionization plays an important role in determining the $F_2$-region behaviour apart from the ionization production and chemical loss. The electron density continuity equation for $F_2$-region is written as

$$\frac{dN}{dt} = q - L - \text{div} (NV)$$

Where $N$ is the electron density
$q$ is the production rate
$L$ is the chemical loss rate
and $V$ is the velocity of the plasma.

The velocity $V$ may arise due to,

1) gravity and partial pressure gradients which cause the plasma to diffuse;

2) electric fields, which interact with geomagnetic field producing electromagnetic drifts;

3) neutral winds

Taking into account the divergence term in the continuity equation, solutions of the continuity equation have been obtained to explain the $F_2$ region behaviour (Martyn 1955, Yonesawa 1956, Rishbeth and Barron 1960).
Equatorial anomaly:

Appleton (1946) was the first to show that for noon equinox conditions the peak electron densities $N_m F_2$ show a smooth variation when plotted against magnetic latitude, and that the values at the magnetic equator are some 20 to 50 percent less than at 15° or 20° away from it. This feature is commonly called as 'equatorial anomaly.'

Later it was found that for 0900 hours, $f_0 F_2$ ($F_2$ region critical frequency) has a single maximum around the magnetic equator, for 1200 hours there were two maxima on both sides of the equator, and at 2100 hours again a single maximum around the equator (Appleton 1954). Rastogi (1959) from the study of the anomaly during the different hours of the day in the sunspot minimum period found that subtropic maximum first develops in the morning at low latitudes and later shifts towards higher latitudes with the progress of the day, the course being reversed in the evening hours.

The width of the equatorial trough in $N_m F_2$ not only has diurnal variation but depends also on the season of the year. The position of the $N_m F_2$ maximum is shifted towards the pole in the summer hemisphere (Burkard 1954). Rastogi (1960) studying the variations in the Indian zone found that
the $f_0F_2$ peak occurs at about 35° dip during equinoxes and at about 25°-30° dip during solstices. For sunspot minimum, Rastogi (1959) has shown that at noon equinoctial conditions the ratio of the maximum $N_mF_2$ to $N_mF_2$ at the equator is about 2.3, with $(N_mF_2)_{\text{max}}$ occurring at a magnetic latitude of about 17°. From the Alouette results King et al. (1964) arrived at the same conclusion. The equatorial anomaly during sunspot maximum years has been studied by various investigators (Lyon and Thomas 1963, Rao and Malhotra 1964, Thomas 1968) and it has been found that the equatorial anomaly during high sunspot years continues till even after sunset.

Mitra (1946) first gave a qualitative explanation to the two subequatorial latitude $N_mF_2$ maxima. He suggested that ionization produced at great heights over the equator diffuses down the lines of magnetic field under the influence of gravity giving rise to the $N_mF_2$ maxima observed at higher latitudes. Rishbeth et al. (1963) and Kendall (1963), including diffusion along the geomagnetic field lines and production and loss processes, solved the continuity equation. They obtained electron density as a function of latitude and height and found a small equatorial trough in the peak electron density. This showed that diffusion along the field lines alone is not sufficient to explain the equatorial anomaly.
Martyn (1955) proposed another kind of ionization movement, which was later developed by Duncan (1960), to explain the equatorial anomaly. Martyn suggested that the presence of electrostatic field in the F-region can cause the ionization to drift in a direction perpendicular to both the magnetic field lines and the electric field direction (EXB drift). Martyn (1955) further suggested a 'fountain effect' in which the ionization is lifted upward (by E x B drift) at low latitudes and then deposited at higher latitudes by diffusion along the field lines. Bramley and Peart (1964, 1965) including electromagnetic drift of arbitrary magnitudes, along-with photoionization, loss and diffusion along the magnetic field lines in the electron continuity equation found that under the representative daytime ionospheric conditions, an upward drift of a few meters per second is sufficient to produce observed equatorial anomaly. Hanson and Moffett (1966) solved the continuity equation for electrons for the region near the magnetic equator under noon conditions, taking photoionization, recombination, diffusion, neutral winds, and electromagnetic drift terms explicitly into account. They found that drift velocity of about 10 meters per second is sufficient to cause equatorial anomaly. It is also shown that a 15 percent interhemisphere asymmetry in the
electron concentration at the $N_{m}F_2$ peaks can be caused by a 60 meter per second neutral wind blowing from north to south. Abbur-Robb (1969) has also shown, solving the continuity equation, that EXB drift alone can explain the equatorial anomaly.

Dunford (1967) has shown that the product between the latitudinal extent and the magnitude of the anomaly is proportional to the daily range of the magnetic field near the magnetic equator. Patel and Kotadia (1971) reported that $f_0F_2$ is correlated to daily range of the magnetic field in the equatorial region. Balsley (1969), Balsley and Woodman (1969) from incoherent radar observations showed that $h_{max}$, height of the maximum electron concentration of the $F_2$ layer, and $F$-region vertical plasma drift follow the variation of $E$-region horizontal electron drift.

The association between the $F$-region parameters and the east-west electric field at magnetic equator is investigated in the present work and the results are presented in the next chapter.
CHAPTER II

EFFECTS OF E REGION ELECTRIC FIELD ON
F REGION PARAMETERS

Vertical ionization density motions in the F region are generally attributed to the electrodynamic drifts. The F region electrodynamic drifts are in turn due to the E region east-west electric field communicated to the F region along the highly conducting magnetic field lines. An eastward electric field will give rise to an upward movement in the F region and a westward field a downward movement. It is expected on theoretical considerations (Bramley and Young, 1968) that a large eastward field will give rise to a small peak electron density $N_m$ at a large height $h_m$. Balsley and Woodman (1969) using back scatter radar observations compared the E region irregularity motion (which corresponds to the E region east-west electric field) with the F region vertical drift velocity over Jicamarca and found a close correspondence between the two. Dunford (1970) compared E region electric fields estimated from the magnetic field variations with F region ionization parameters and found that changes in the peak electron density and height are closely correlated with the electric field.
It would be interesting to study the changes in the F region parameters during the SDE$_s$ event, as considerable changes in the electric field are found to be associated with it. In the present chapter, the changes in the F-region electron density parameters at Trivandrum are investigated in relation to the estimated electric fields from the ground magnetic field variations on SDE$_s$ event days as well as on other quiet days. In Chapter III, it has been shown that the sudden disappearance of equatorial sporadic E (SDE$_s$ event) during day time, is associated with a decrease in horizontal magnetic field (H). This decrease in H was attributed to a decrease in the eastwest electric field at E-region levels. It has also been noted that the SDE$_s$ event is not a localized one confined to a single location. It was found to occur simultaneously at two stations separated 3° in geomagnetic latitude (Trivandrum and Kodaikanal).

**Analysis and Results:**

With a view to see the effect of sudden changes in day time eastward electric field in the E-region levels during SDE$_s$ events in the F-region, electron density true height profiles have been analysed.
All the day time ionograms from 0630 to 1730 Local
time for the days of SDE$_g$ events ($\Sigma K_p \geq 18$), of the year 1970,
as mentioned in Chapter II, have been reduced to electron
density true height (N-h) profiles. N-h profiles for the
international quiet days without SDE$_g$ event in each month are
also obtained from the ionograms with a view to compare the
F region parameters during SDE$_g$ event days with those during
quiet days. The ionograms have been reduced to electron density
true height profiles following the method given by Budden
(1955). For the reduction of ionograms to N-h profiles,
virtual heights at every .2MHz have been noted, starting from
1 MHz. The ionogram reduction has been performed with the
help of IBM 360 computer. During the period of SDE$_g$ event,
ionograms at every 15 minute interval have been reduced to
N-h profile where as for the rest of the day hourly N-h pro-
files are obtained. International quiet day N-h profiles have
been obtained for each hour starting from 0630 LT to 1130 hours
and for every quarter hour during afternoon periods as on
SDE$_g$ event days.

Constant electron density height contours have been
obtained from the electron density-true height profiles, for
the SDE$_g$ event days as well as on quiet days without SDE$_g$
events. Constant electron density height contours corresponding to
electron densities $4 \times 10^{11}$, $6 \times 10^{11}$, $7.5 \times 10^{11}$, $9 \times 10^{11}$, $1.0 \times 10^{12}$, $1.1 \times 10^{12}$, $1.2 \times 10^{12}$ and $1.3 \times 10^{12}$ electrons/meter$^3$ are obtained.

In Figure 1, plots of constant electron density height contours with time are shown for two quiet days without SDEs event in January 1970 (from 0530 LT to 1730 LT). The height contours are plotted for electron densities $6 \times 10^{11}$, $7.5 \times 10^{11}$, $9 \times 10^{11}$, $1 \times 10^{12}$, $1.1 \times 10^{12}$, $1.2 \times 10^{12}$ and $1.3 \times 10^{12}$ N/m$^3$ whenever the data are available.

On January 4, 1970, the height contours corresponding to $N = 6 \times 10^{11}$ and $7 \times 10^{11}$/m$^3$ indicate a gradual decrease in the height from 0730 to 1130 LT. Before 0930 LT the contours corresponding to higher values of $N$ could not be obtained as the ionograms are not very clear at the high frequency end. A clear minimum in the height is shown at higher values of $N$ around 1130 LT. There is a sharp rise in the contours after 1130 and a broad peak is shown around 1400 LT. An increase in the height contours is shown after about 1530 LT.

The height contours on January 19, 1970 show the morning peak occurring around 030 LT. The afternoon peak is small. A very clear on this day. An interesting feature of the behaviour of the true height contours on this is almost a steady increase of the height in the afternoon period.
Fig. 1  Quiet-day constant electron density contours without SDEs event

1  $\rightarrow 6 \times 10^{10} \text{ N/m}^2$
2  $\rightarrow 7.5$
3  $\rightarrow 9.0$
4  $\rightarrow 1.0 \times 10^{10} \text{ N/m}^2$
5  $\rightarrow 1.1$
6  $\rightarrow 1.2$
7  $\rightarrow 1.3$
The constant electron density contours on two SDE$_g$ days in the month of January are shown in Figure 2. The duration of the SDE$_g$ event is indicated by the arrow marks on the time axis. On January 8, 1970, it can be seen from the figure, the heights are lower during the SDE$_g$ event. Same feature is evident from the contours on January 9, 1970, (Figure 2) another SDE$_g$ event day. From comparison of figures 1 and 2, it appears that the contours are compressed during the SDE$_g$ event compared to the contours at the same time on quiet days without SDE$_g$ event. This indicates a reduction in the layer thickness during the SDE$_g$ event.

It has already been shown that the SDE$_g$ events are associated with the magnetic field depressions, or equivalently a reduction in the east-west electric field ($E_y$) at E region levels. With a view to study the relation between $E_y$ and F region parameters, the estimated values of $E_y$ (Chapter III, part I) are plotted against time in Figures 3, 4 and 5 along with the electron density height contour for $N = 7.5 \times 10^{11}/m^3$, represented as $h_{7.5}$. A layer thickness parameter $T$ which is equal to the height difference between $N = 6 \times 10^{11}/m^3$ and $1.0 \times 10^{12}/m^3$ levels, is also plotted in Figures 3, 4 and 5. $T$ can be taken to represent the semithickness of the layer. Thickness up to the level where $N = 1.0 \times 10^{12}/m^3$ only is
Figure 2: Constant electron density contours on SLE* event days.

1 → \(6 \times 10^9 \text{ N/m}^3\)
2 → 7.5 
3 → 9.0 
4 → \(1.0 \times 10^{11} \text{ N/m}^3\)
5 → H1 
6 → H2
considered in estimating $T$, because for some ionograms it was not possible to carry out the $N$-$h$ profile reduction up to the critical frequency. Also plotted in Figures 3, 4 and 5, is the electron density at 270 km altitude ($N_{270}$).

Figures 3, 4 and 5 show the variations of $E_y$, $h_{7.5}$, $T$ and $N_{270}$ for different days of the year 1970, including both SDE$_s$ days and quiet days without SDE$_s$ event. Days marked in the figure with an asterisk are SDE$_s$ days. The duration of the SDE$_s$ event is marked by vertical arrows on the time axis. When $E_{sq}$ did not reappear after SDE$_s$ event, only one arrow mark is shown at the time of the event. On December 5, 1970, $E_{sq}$ disappeared in only one ionogram around 1000 hours LT and this is indicated by an arrow mark. For some days, values of $T$ in the prenoon period could not be obtained though $h_{7.5}$ values are available, because of critical frequency being lower or the ionogram could not be reduced to $N$-h profiles up to the $f_oF_2$ level.

It is interesting to note from Figures 3, 4 and 5, that in the prenoon period, $T$ and $h_{7.5}$ follow in general, the $E_y$ variations quite well for both SDE$_s$ and non-SDE$_s$ days. In general, $E_y$, $h_{7.5}$ and $T$ show an increase in the prenoon period. Examining the figures 3, 4 and 5, for non-SDE$_s$ days in the
Fig. 3.
Fig 4.
Fig 5.
afternoon period, it can be noted that $E_y$ and $T$ show in general a decrease initially and an increase in the late afternoon in some cases. On the other hand, $h_{7.5}$ does not, on all non-SDE days follow $E_y$ variations. On some non-SDE days, opposite variations are shown by $E_y$ and $h_{7.5}$ in the afternoon period. For example on January 12, 23, 1970, June 22, 23, August 24 and December 11, 1970, $E_y$ and $h_{7.5}$ did not show similar variations in the afternoon, whereas on the other four non-SDE days (January 4, February 8, 22, December 5, 1970), they exhibit similar variations.

On SDE days, during the afternoon period, $h_{7.5}$ and $T$ show similar variations as $E_y$. All the three parameters show a general decrease in the afternoon period. On December 5, 1970, $E_{sq}$ disappearance was shown in one ionogram in the morning at about 0930 hours and reappeared again. $E_{sq}$ disappeared again around 1030 hours for a period of about half an hour. It is interesting to note that on this day, $T$ and $h_{7.5}$ followed the same variations as $E_y$.

A close examination of Figures 3, 4 and 5 reveals that on SDE event days, there is a larger variation in $E_y$ during the afternoon compared to its variation on non-SDE days during afternoon. The decrease in $E_y$ in the afternoon on
SDG event days is more in comparison with non-SDE days. So, it appears from the present analysis, that in the afternoon whenever $E_y$ shows large variation (decreases) in the afternoon, the true height of a constant electron density follows its variation. When the $E_y$ decrease is small in the afternoon, $h_{7.5}$ does not show similar variation as $E_y$; in fact on some days it shows an increase when $E_y$ is decreasing.

Examining the variations of the parameters $N_{270}$, from figures 3, 4 and 5, it can be noted that it exhibits in general, variations opposite to $h_{7.5}$ as expected. It may also be noted that $E_y$ and $N_{270}$ show, in general opposite variations both on SDE and non-SDE days. The noon bite-out phenomenon is not evident on all the days in figures 3, 4 and 5. This phenomenon is exhibited only on January 4, 5, 9, February 25 and December 5, 1970.

The parameters $h_{7.5}$, $T$ and $N_{270}$ show a clear time lag of about 1 - 2 hours behind $E_y$ on January 4, 1970 (Figure 3) and December 5, 1970 (Figure 5). On both these days, variation in $E_y$ occur earlier than the corresponding variations in $h_{7.5}$, $T$ and $N_{270}$. On other days shown in the figures, no clear time lag is evident between these parameters. Analysis based on a larger amount of data is necessary to establish this time lag between the parameters studied.
With a view to see whether the day to day variations in constant electron density contours follow $E_y$, the contours height corresponding to $N = 6.0 \times 10^{11}/m^3 \ (h_{6.0})$ and $N = 7.5 \times 10^{11}/m^3 \ (h_{7.5})$ are plotted as a scatter plot for hours between 0930 and 1630 against the corresponding $E_y$ for January 1970 and the plots are shown in Figures 6 and 7. Both SDE and non-SDE days are included in these plots. It can be seen from Figures 6 and 7 that for hours 0930, 1030, 1130 and 1230, the parameters $h_{6.0}$ and $h_{7.5}$ show good linear relationship with $E_y$. For the afternoon hours namely, 1330, 1430, 1530 and 1630, no clear relationship is evident from the figures (8a and 8b) between the height parameters $h_{6.0}$ and $h_{7.5}$ and $E_y$. There is considerable scatter for these hours. It may be noted that data on both SDE and non-SDE days in January 1970 are included in these plots.

Mean straight lines are drawn for the morning hours as shown in the figures. The gradients are found out from the mean straight lines and are tabulated as shown in Table 1. The height corresponding to $E_y = C$ is also obtained from the figures 6 and 7 and is shown in Table 1.
Fig. 6: E-Region Electric Field Against True Height Corresponding to $6 \times 10^8$ N/m$^2$
Fig. 7: Electric field against true height corresponding to $7.5 \times 10^6$ N/m$^3$. 
Fig: 8a. E-Region Electric Field Against True Height Corresponding to $6 \times 10^4$ N/m$^2$. 
Fig 8b. E-Region Electric Field Against True Height Corresponding To $7.5 \times 10^5$ N/m$^3$. 
Table 1

<table>
<thead>
<tr>
<th>TIME</th>
<th>$\Delta h_{6.0}$</th>
<th>$\Delta h_{7.5}$</th>
<th>$h_{6.0}$ for $E_y=0$</th>
<th>$h_{7.5}$ for $E_y=0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0930</td>
<td>$0.7 \times 10^5$</td>
<td>$1.0 \times 10^5$</td>
<td>213</td>
<td>233</td>
</tr>
<tr>
<td>1030</td>
<td>$0.47 \times 10^5$</td>
<td>$0.71 \times 10^5$</td>
<td>222</td>
<td>242</td>
</tr>
<tr>
<td>1130</td>
<td>$0.55 \times 10^5$</td>
<td>$0.87 \times 10^5$</td>
<td>217</td>
<td>230</td>
</tr>
<tr>
<td>1230</td>
<td>$0.44 \times 10^5$</td>
<td>$0.81 \times 10^5$</td>
<td>225</td>
<td>238</td>
</tr>
</tbody>
</table>

It can be seen from Table 1 that the gradient is positive and is greater for $h_{7.5}$ than that for $h_{6.0}$ for all the four hours considered. This indicates that a change in the electric field produces greater change at higher levels than at lower levels. The height corresponding to $E_y = 0$, shows a minimum at 1130 hours both for $N = 6 \times 10^{11}/m^3$ and $N = 7.5 \times 10^{11}/m^3$. It may be noted that only data extended over one month is considered in Figures 6, 7, 8a and 8b. For other months similar plots could not be obtained because of insufficient data.
Summarising the results the following points may be noted.

1. The constant electron density contours and thickness parameter follow $E_y$ variations in the pre-noon period.

2. In the afternoon period, on SDE$_g$ days when $E_y$ shows large decrease, constant electron density contours and $T$ show similar variations as $E_y$. Both show decreases corresponding to decrease in $E_y$.

3. Electron density at a fixed height (270 Km) shows, in general, variations opposite to those shown by $E_y$, $T$ and $h_{7.5}$.

4. Day to day variations in constant electron density contours show linear relationship with $E_y$ in the pre-noon period. In the afternoon no such clear linear relationship is evident between the two.

Discussion:

An eastward electric field at E region levels when communicated to F region through magnetic field lines produces an upward motion in the F region. Bramley and Young (1968) have shown from theoretical considerations, that a large eastward electric field will give rise to small peak electron
density at a large height in the F region. Assuming that this prediction holds good below the F region peak also, the results of the present investigation are in accordance with this prediction. Dunford (1970) analysing Jicamarca (dip ~2°N) F region data found that the changes in \( E_y \) are well correlated with the changes in the peak electron density and changes in the height of the peak density. In his analysis, he has combined the data for all the daytime hours and found the correlation. In the present analysis, it is shown that \( E_y \) and F region parameters follow each other, in general, especially in the morning hours and on days when there are large changes in \( E_y \) (SDE\(_s\) days). Also, on a day to day basis, it is shown that in the morning hours, the height corresponding to a constant electron density varies linearly with \( E_y \). In the afternoon hours the relationship between the two is not very clear. It may be noted that there are other factors like neutral wind which affect the equatorial F region apart from the electrodynamic drift (Hanson and Moffett 1966, Bramley and Young 1968). It is likely that in the afternoon hours other factors like neutral wind may be important in determining the F region behaviour. It may be noted that on days when there are large changes in \( E_y \) (SDE\(_s\)) days in the afternoon, \( h_{7.5} \) follows the \( E_y \) variations. Patel and Kotadia (1971) reported from an
analysis of Kodaikanal (dip ~ 3.5°N) data that on days of strong electrojet, $F_2$ region electron density remains below normal.

It may be noted that $F$ region situated at Trivandrum (dip ~ 0.6°S) would be linked to the dynamo region at magnetic latitude of about 10°. The fact that a close association has been found between $F$ region parameters at Trivandrum and $E_y$ estimated from Trivandrum magnetograms, indicates that the scale of the electric field, producing the changes, must be at least 10° in latitude.

The $E_y$ values used in the present investigation have been estimated using ground horizontal magnetic field changes. The fact that the $E_y$ so estimated, shows good correlation with $F$ region parameters, indicates that magnetic field changes are mainly due to changes in $E_y$ and not due to conductivity changes in the $E$ region. This supports the earlier contention in Chapter III, part I.
CHAPTER III

STUDY OF NIGHTTIME F-REGION VERTICAL VELOCITIES FROM N-h PROFILES

It is well known that the F-region of the ionosphere differs greatly from the behaviour predicted by the theory of Chapman in which ionization is produced by solar radiation and is removed only by recombination or attachment. Transport phenomena plays a very important part in the F region behaviour. Taking into account the transport term, the basic continuity equation for electron density can be written as

$$\frac{dN}{dt} = q - L - \text{div}(NV) \quad (1)$$

where $N$ is the electron density; $q$ the rate of electron production; $L$ the electron loss term; $V$ is the transport velocity of the electrons. The divergence term contains derivatives of $N$ and $V$ in horizontal directions and vertical direction. The horizontal gradients of $N$ and $V$ are usually much smaller than the vertical gradients and as such their contribution to the divergence term can be neglected. The equation (1) can be written as

$$\frac{dN}{dt} = q - L - \frac{d}{dh}(NV)$$

where $h$ is the height.
The velocity $V$ contains contributions due to electrodynamic drift, neutral winds and plasma diffusion. At and near the magnetic equator, the contributions to vertical velocity due to neutral winds and plasma diffusion are usually small as these contribute to motion along the magnetic field lines. As such the vertical velocity at the equator is mainly due to the electrodynamic drift which is approximately equal to $\frac{E \times B}{B^2}$ where $E$ is the electric field in the east-west direction and $B$ is the ambient magnetic field.

Many attempts have been made to estimate the vertical drift velocity from the electron density continuity equation using the electron density – true height (N-h) profiles. Chandra et al (1960) calculated the E-region vertical velocity $V$ from N-h profiles, by assuming reasonable values of $V$ at some reference height. By integrating the continuity equation, an expression for vertical drift velocity $V$ can be obtained, which can be written as

$$V_h = \frac{N_o V_o}{N_h} + \int_{h_o}^{h} (q - L - \frac{dN}{dt}) \, dh$$

where $N_o$ and $V_o$ are the electron density and vertical velocity respectively at a reference height $h_o$ and $N_h$ and $V_h$ at height $h$. Assuming reasonable values of $V_o$, i.e. the reference level
vertical velocity, Chandra et al. computed velocity height profiles for different hours. By taking the reference level velocities ($V_o$) between $+20$ and $-20$ meters/sec, the velocity profiles obtained by them were found to decrease with increasing height, as $\frac{N_0 V_o}{N}$ becomes smaller at greater heights. This feature enabled them to estimate the velocity with less uncertainty at greater heights. Using this method they estimated transport velocities both during day and night at four stations (Huancayo, dip 2°N; Talara, dip 13.1°N; Panama, dip 37.9°N; Washington, dip 71.5°N.) for magnetically quiet days. They found a predominantly downward velocity during the night and predominantly upward velocity during the day, both in summer and winter at the stations close to the equator.

Garriott and Thomas (1962) presented a method of estimation of the nighttime vertical electrodynamic drift velocity by numerically solving the continuity equation based on a large number of observed electron density profiles corresponding to Puerto Rico (dip 51.3°N). They estimated contribution due to plasma diffusion to vertical velocity by using the expression for the diffusion velocity. They assumed that the electrodynamic drift velocity is independent of height in the F-region. They found that the electrodynamic component of vertical drift velocity at nighttime during the period of high magnetic activity to be higher than the quiet night values.
Mitra et al (1964, 1967) estimated the vertical velocity and also the loss coefficient for the period around midnight by assuming height profiles of $V$ and $\mathbf{B}$ and that $V$ and $\mathbf{B}$ do not change for a considerable length of time around midnight and $\frac{dN}{dt} = 0$. They applied this method for determining vertical velocity and loss coefficient over Delhi (42.5°N dip) and Huancayo (2°N dip) for some of the quiet days in the year 1958. They found that the transport velocity is downwards during 00-03 hours and varies from 12 to 16 meters/sec at Huancayo and is about 6-7 meters/sec at Delhi.

Using N-h profiles, obtained by incoherent scatter radar at Arecibo, and assuming a height distribution of vertical drift, Prasad (1967) estimated the night vertical drifts. Prasad (1967) assumed that $V$ is of the form

$$V = V_0 + ah + bh^2$$

and made use of the fact that the electron density is same at two heights, one below and other above the F-region peak.

Shimazaki (1966) developed a least squares method to determine simultaneously the temporal variations in temperature and drift velocity in the ionosphere from the observed temporal variations in the electron density profiles. For computing $\frac{dN}{dt}$ from continuity equation, Shimazaki (1966) calculated contribution of ambipolar diffusion velocity ($U_D$),

$$U_D = \frac{1}{n_e} \frac{dN}{dt}$$

where $n_e$ is the electron density.

Using these methods, they were able to determine the spatial and temporal variations in the ionosphere.
velocity ($\mathcal{V}_T$) of thermal expansion and contraction and the electrodynamic drift velocity ($\omega$) separately in the total transport term. Using these and the attachment coefficient, $\frac{\partial N}{\partial t}$ is calculated. Then the residual of $\frac{\partial N}{\partial t}$ calculated, and $\frac{\partial N}{\partial t}$ observed, is estimated. Average of square of the residuals over a particular height range, for which the N-h data is available, is calculated. The values of $\mathcal{V}_T$ and $\omega$ are adjusted such that the mean of the squares of the residuals is minimum for the height range considered. These adjusted values of $\mathcal{V}_T$ and $\omega$ are taken to be the velocities corresponding to that height range. One of the assumptions made in this method is that the $\omega$ is independent of height ($\frac{d\omega}{dh} = 0$).

The above method was applied to observed monthly mean electron density profiles from March 1959 to February 1962 at Puerto Rico (dip 51.3°N) (Shinazaki and Laird 1968). Shimazaki and Laird (1968) found that there is no systematic seasonal and solar cycle variation in the prevailing and semidiurnal component in the vertical drift velocity except that the downward prevailing component is appreciably larger in winter than in summer in the year of high sunspot activity. He also observed that the nighttime drift velocity is generably downwards and has a marked semidiurnal component with a minimum around 2200 - 2300 hours.
As seen above, estimation of F-region vertical velocities from electron density-true height (N-h') profile involves solving the electron density continuity equation numerically. For nighttime conditions, as production term q=0, continuity equation (1) can be written as

\[ \frac{dN}{dt} = -L - \text{div}(NV) \]  

(2)

When the horizontal gradients of N and V are small and can be neglected in comparison with the corresponding vertical gradients, equation (2) can be written as

\[ \text{div}(NV) = N \frac{dV}{dZ} + V \frac{dN}{dZ} \]

\[ = (-L - \frac{dN}{dt}) \]

\[ = P \text{ (say)} \]  

(3)

where \( Z = h - h_0 \), \( h_0 \) being the reference height.

Integrating (3)

\[ V = \frac{N_0 V_0}{N} + \frac{1}{N} \int_0^Z P \, dZ \]  

(4)

where \( N_0 \) and \( V_0 \) are the electron density and velocity respectively at some reference height \( h_0 \). \( V \) at other heights can be estimated if the velocity-height distribution (Prasad 1967) or the velocity at some reference height (Chandra et al 1960) is assumed.
In the following, it is shown that the velocity at some reference height can be estimated under some conditions from equation (3) (Krishna Murthy and Sen Gupta 1972). Using this method, the nighttime velocity height profiles are estimated for both magnetically quiet and disturbed days of the year 1970 and are presented here.

**METHOD OF ESTIMATION OF V.**

In a height interval \( h_2 < h < h_1 \) (in the lower F-region) if \( N \), the electron density and \( P \), \((-L-\frac{dN}{dt})\) are linear, then they can be expressed as

\[
N = m_1 Z + N_0
\]
\[
P = m_2 Z + P_0
\]

Substituting these in equation (3), and rearranging the terms, we get

\[
\frac{dV}{dz} + \frac{V m_1}{m_1 Z + N_0} = \frac{m_2 Z + P_0}{m_1 Z + N_0}
\]  \( (5) \)

Solving this differential equation for \( V \),

\[
V = \frac{m_2 Z^2 + P_0 Z + C}{m_1 Z + N_0}
\]

where \( C \) is the integration constant. At \( Z = 0 \) (\( h = h_0 \)) let \( V = V'_0 \); then \( C = N_0 V'_0 \).
Equation (6) shows that if

$$V_i = \frac{m_2 Z^2}{2} + P_0 Z + N_0 V_o'$$

or

$$V_i = \frac{m_2}{2m_1} \cdot Z + \frac{1}{m_1} \left( \varphi_0 - \frac{m_2}{2m_1} \cdot N_0 \right) + \frac{N_0}{N} \left[ v_o' - \frac{1}{m_1} \left( \varphi_0 - \frac{m_2}{2m_1} \cdot N_0 \right) \right]$$

Equation (6) shows that if

$$V_o' = \frac{1}{m_1} \cdot (P_0 - \frac{m_2}{2m_1} \cdot N_0),$$

$$V$$ is linear in the height interval $h_0 < h < h_1$

It can be seen that if $N$ and $P$ are linear at least down to a height where $N$ and $P$ are small, then equation (7) will approximately hold good. During nighttime conditions when the low lying ionization is small, the above conditions can be met. Under these conditions,

$$V = \frac{m_2 Z^2}{2m_1} + \frac{1}{m_1} \cdot (P_0 - \frac{m_2}{2m_1} \cdot N_0)$$

or

$$V = \frac{2P dN}{dZ} - N \frac{dP}{dZ}$$

$$2 \left( \frac{dN}{dZ} \right)^2$$
This expression for $V$ holds good in the height region where $N$ and $P$ vary linearly with height. In practice, the $N$-$h$ profiles would not be linear in the entire height range. To estimate $V$ for the entire height range, the following procedure is adopted. From nighttime $N$-$h$ profiles, only those profiles satisfying the condition that $N$ and $P$ vary linearly in a small height range in the lower region, are chosen. In this height range, $V$ is estimated using equation (8). $V$, thus estimated, is taken as $V_0$ corresponding to a height $h_0$ in the interval $h_0 < h < h_1$, and velocity at any other height is estimated numerically using equation (4). Thus the condition that $\frac{dP}{dz}$ and $\frac{dN}{dz}$ remain constant with height need not be satisfied in the entire height range for which data exists. It is sufficient if it is satisfied in a small height range to estimate $V_0$ by the present method. In practice, the height interval $h_0 < h < h_1$ has been taken to be 40 Km in the lower height region.

It needs to be pointed out here that as the $N$-$h$ data would be available only for a limited range of heights, the numerical solution of $V$ obtained, would be consistent with the data in this height range only. In fact all methods for estimation of $V$ using $N$-$h$ profiles suffer from this limitation. If the $P$-$h$ and $N$-$h$ distributions are linear below the reference height or at least to a height where $N$ and $P$ become small.
the errors in the $V_\text{o}$ values obtained will be very small as equation (7) will hold good almost exactly. Thus, to minimise the uncertainty in $V_\text{o}$ obtained from equation (8), it is necessary to choose the lowest height region for which data exists, satisfying the condition that $dN/dZ$ and $dP/dZ$ do not vary with height in that region. In practice, it would be possible to get $N$ and $P$ profiles approximately linear in the lower height range in most of the cases for nighttime conditions. At any rate, the inaccuracies in the estimated velocities arising from uncertainty in $V_\text{o}$ will be much less at greater heights as can be seen from the equation (4).

**ESTIMATION OF VERTICAL VELOCITY:**

The above described method has been used to estimate vertical velocity from nighttime $N$-$h$ profiles obtained at Thumba (dip 0.6°S). The vertical velocities have been estimated for all the five international quiet days of the year 1970 and also, for some of the disturbed days of the year 1970.

The nighttime ionograms from 1900 hours to 0400 hours local time, for all the five international quiet days of each month of the year 1970 and for some of the magnetically disturbed days of the year 1970 have been reduced to true height profiles. The ionograms have been obtained from $C_4$ ionospheric recorder,
stationed at Thumba (same as Trivandrum, dip 0.6°S) as described in Chapter II of Part I. The ionograms have been reduced to electron density true height profiles following the method, given by Budden (1955). Virtual heights at every 0.2 Mc/s intervals have been read, starting from 1 Mc/s, for the reduction of ionograms to true height-electron density profiles.

In order to estimate the quantity $\frac{dN}{dt}$ and the loss factor $L$ need to be evaluated.

Close interval (~15 minutes) electron density–true height profiles have been used to determine $\frac{dN}{dt}$ at each hour of the night between 1900 and 0400 hours local time. $\frac{dN}{dt}$ has been obtained at every 10 km height interval.

**LOSS FACTOR:**

In the F-region the positive ions are mainly $O^+$. The main processes of electron loss in the F-region are composed of a two-stage reaction. By the ion-atom interchange reaction, the atomic ions ($O^+$) first form molecular ions.

\[
O^+ + O_2 \rightarrow O_2^+ + O, \quad (\lambda_1)
\]

and

\[
O^+ + N_2 \rightarrow NO^+ + N, \quad (\lambda_2)
\]
Where paranthesized letters indicate the rate coefficients. The second stage of the loss process is the dissociative recombination process, which recombines the molecular ions ($O_2^+, NO^+$) with electrons and produce excited neutral atoms. These processes can be written as

$$O_2^+ + e \rightarrow O' + O'' \quad (\lambda_1)$$
and
$$NO^+ + e \rightarrow N' + O' \quad (\lambda_2)$$

Shimazaki (1965) arrived at the loss term as

$$L = \frac{\lambda_1 [O_2] + \lambda_2 [N_2]}{\lambda_1 [O_2] + \lambda_2 [N_2]} \cdot N^2 \quad (9)$$

where $\lambda_1, \lambda_2, \lambda_1, \lambda_2$ are the rate coefficients of the reactions given above, and $[O_2]$ and $[N_2]$ are the number densities of $O_2$ and $N_2$ respectively. At F-region heights, i.e., above about 250 km since $\lambda_1 \& \lambda_2 \gg \lambda_1 \& \lambda_2$ the ion-atom interchange reactions control the electron loss term. Then $L$ can be approximated as

$$L = \left\{ \frac{\lambda_1 [O_2] + \lambda_2 [N_2]}{\lambda_1 [O_2] + \lambda_2 [N_2]} \right\} \cdot N \quad (10)$$

where $B$ is loss coefficient.
The reaction rate coefficients which have been used for computing loss term are given below (Mitra, 1970)

\[ \lambda_1 = 2 \times 10^{-11} \left( \frac{T}{300} \right)^{-0.5} \text{cm}^3/\text{sec.} \]

\[ \lambda_2 = 1.2 \times 10^{-12} \text{cm}^3/\text{sec.} \]

\[ \lambda_1 = 2.2 \times 10^{-7} \left( \frac{T}{300} \right)^{-1} \text{cm}^3/\text{sec.} \]

\[ \lambda_2 = 5 \times 10^{-7} \left( \frac{T}{300} \right)^{-1} \text{cm}^3/\text{sec.} \]

where \( T \) is the neutral temperature.

The loss coefficient \( \beta \) has been computed for each hour at every 10 Km height. Appropriate neutral densities and neutral temperature corresponding to 10.7 cm solar flux of the particular day are taken from CIRA 1965, for calculating the rate coefficients and the loss coefficient. In Figures 9 and 10 nighttime \( \beta \) values for 0000 hours and 0200 hours are shown corresponding to two different nighttime minimum exospheric temperatures \( T_{04} \) values, 1000°K and 1400°K.

From the estimated values of \( \beta \) and \( \frac{dN}{dt} \), the parameter \( P \), ie \( -\frac{dN}{dt} \), can be evaluated.

To illustrate the method of evaluation of \( V \), typical plots of \( P \) and \( N \) with height, corresponding to different times
of the night are shown in Figure 11. These data correspond to 2000 hours on 9.4.70, 1900 hours on 25.5.70 and 2300 hours on 30.12.70. It can be seen that P and N for the above mentioned hours are fairly linear in the height range 300 to 330 Km, 340 to 370 Km and 260 to 280 Km respectively. These regions satisfy the condition for estimating \( V_0 \) by the above described method. \( V_0 \) is calculated at 310 Km for 9.4.70, 350 Km for 25.5.70 and 270 for 30.12.70, using equation (8). Using the computed \( V_0 \), \( V \) is estimated numerically for other heights using equation (4). The resulting velocity height profile is shown in the same figure. It can be seen that the velocity height-profiles are also fairly linear in the height range where P and N are linear. This indicates that the condition on which the expression (8) was arrived at, is satisfied.

Results:

Following the above described procedure, the vertical velocity profiles for the night period for each hour from 1900 to 0400 hour local time, have been obtained for magnetically quiet and disturbed days. Whenever spread F is present on the ionograms, those ionograms have not been considered for the estimation of vertical velocities. In Figure 12 some typical magnetically quiet day nocturnal vertical velocity profiles are shown. It may be mentioned here, that for the
Fig. 11

True height in km.

V, m/Sec

9 April 1970, 2000 hr. LT

25 May 1970, 1900 hr. LT

30 Dec. 1970, 2300 hr. LT

Fig. 11
hours for which the vertical velocities are not shown on the Figure 12, could not be estimated either due to the presence of spread F or P and N not being linear with height at the lower height region. It can be seen from the figure that the vertical velocities during nighttime are negative i.e., downward. On 25th May 1970 at 1900 hours the velocity is positive i.e., upward and is of the order of 15 meters/sec. The reversal of velocity from upwards to downwards occurred on this day between 1900 and 2000 hours local time as can be noted from the figure. After 2000 hours local time, velocities continue to remain negative. It can be seen that the downward velocities reach values as high as 70 meters/sec after midnight. It is interesting to note that the vertical velocity above about 280 Km, in general, does not show any significant change with height. Velocities obtained in the height range 220 to 280 Km show, in general, variation with height. This behaviour has been observed, in general, for all the magnetically quiet nighttime vertical velocity profiles obtained in the present investigation.

Figure 13 shows the vertical velocity plotted against height for some of the magnetically disturbed days analysed. It can be seen that the velocity variation with height is not significant at greater heights where as at lower heights
FIG. 12 TYPICAL QUIET DAY NOCTURNAL VERTICAL VELOCITY PROFILES OVER TRIVANDRUM.
FIG 13. TYPICAL DISTURBED DAY NOCTURNAL VERTICAL VELOCITY PROFILES OVER THE ARCTIC.
there is considerable variation with height. This feature is the same as that shown by quiet time velocity-height-profiles.

Figure 14 shows velocity at the height of F-region maximum (or close to it) plotted against the corresponding height for three hours of the night, 1900, 2200 and 0200 hours for the year 1970. Velocities at or close to the height of the maximum are plotted as contribution of any uncertainty in the reference height velocity would be small at greater heights. Disturbed time points are shown by crosses and quiet time points by circles. It can be seen from this figure that at all the three hours, velocity is negative (downwards) at lower heights. Downward velocity decreases with increasing height and at 1900 and 0200 hours velocities are positive (upwards) at greater heights. This is as may be expected because if the vertical velocity is downwards the F-region maximum would be situated at a lower height and vice versa. This indicates in qualitative way the general consistency of the velocities deduced by the present method.

With a view to investigate the quiet time seasonal behaviour, the velocities are grouped according to the four seasons, namely, vernal equinox (February, March and April), North solstice (May, June, July), Autumnal equinox (August, September and October) and South solstice (November, December and January). The velocities at or close to the height of
Fig. 14 VERTICAL VELOCITY AT THE HEIGHT OF F-REGION MAX. AGAINST CORRESPONDING HEIGHT
F-region maximum ($N_m \, F_2$) are plotted against local time for all the four seasons and shown in Figure 15. Number of points are not many for each season in these plots, as many ionograms have been discarded, either due to the presence of Spread F or due to the non-linearity of $N$ and/or $P$ in the lower height region. Mean curves are drawn through the points showing the nocturnal variation of the velocity (Figure 15).

The velocities are found to be downwards after 2000 hours in all the four seasons. As the daytime velocities are known to be generally upwards, Figure 15 indicate that the reversal of velocity direction from upwards to downwards occurs in general earlier in South Solstice compared to the other three seasons. The velocities in all the four seasons show very wide variations at each hour. The downward velocities during the post midnight period are in general, greater than those during pre-midnight period. The downward velocities reach high values like 60-80 m/sec in the early morning hours (0300 - 0400 hours). From the mean curves drawn, in Figure 15, it can be seen that there is a seasonal variation in the nighttime velocities. These figures indicate that nighttime downward velocities are higher in the equinoxes compared to the velocities in the solstices.
FIG. 15: QUIET DAY NOCTURNAL VERTICAL VELOCITY OVER TRIVANDRUM.
FIG. 15. (CONT'D)
The magnetically disturbed time velocities are also grouped according to the season and shown in Figure 16. In the Autumnal equinox season velocities could not be deduced on disturbed days. It may be noted that there are wide variations of the velocity at each hour in the three seasons considered. Some upward velocities are shown in the postmidnight period in North solstice and South solstice seasons. No clear distinction is evident from these figures between the disturbed and quiet time velocities. This may be partly due to the less number of data points available.

Summary of results and Discussion.

Results obtained in the present investigation can be summarised as follows.

1. Vertical velocities are predominantly negative (downwards) between 2000 and 0400 hours local time on quiet days. At 1900 hours both positive and negative velocities are observed.

2. Reversal of the velocity direction from upwards to downwards appears to occur earlier in South solstice compared to other seasons.

3. The spread of velocities at any one time for different days is as large as the velocities themselves.
FIG. 16 - DISTURBED DAY NOCTURNAL VERTICAL VELOCITY OVER TRIVANDRUM.
4. Velocity shows no significant change with height at greater heights say above around 280 km. Velocity varies with height at the lower heights.

5. Velocities show seasonal variation. Downward velocity is less during solstices than the velocities in the equinoxes.

6. The downward velocities during the postmidnight period are, in general, greater than those during premidnight period.

7. Magnetically disturbed time velocities also show wide variation at each hour. Some upward velocities are also observed in the post-midnight period during solstices.

The results obtained from the estimation of nighttime vertical velocities over Thumba (dip ~ 0.6°S) which have been presented here can be compared with the results arrived by other investigators.

The dynamo region electric field is westwards during nighttime. This field communicated to F-region levels by the highly conducting magnetic field lines produces downward drift (Martyn 1947). The downward velocities during night, obtained in the present investigation, agrees with this.
Woodman (1970) from incoherent scatter observations showed that at Jicamarca (dip 2°N) the nighttime F-region vertical velocities are downwards.

In the present investigation it has been seen that at greater heights (ie above 280 Km) vertical velocity is nearly constant as a function of height. Same conclusion has been drawn by Woodman (1970) from incoherent scatter observations of vertical velocities taken at Jicamarca (2° dip)

Woodman (1970) observed reversal of vertical velocity direction around one to two hours after sunset. The results in the present investigation also indicate the same. He has also observed that there is a wide variability in the vertical velocities at any one time for different days. This result agrees well with the present findings.

Shimazaki (1968) from N-h profile estimated vertical velocity over Puerto Rico which is a higher latitude station (dip ~ 51.3°N), arrived at the result that the downward velocity is more during South solstice period than the North solstice period. Results for Trivandrum obtained in the present investigation indicate equinoctial maxima and solsticial minima in the downward nighttime velocities.