DAYTIME SCINTILLATIONS AND IRREGULARITIES IN EQUATORIAL ELECTROJET

Scintillations occurred regularly at 40 MHz and 140 MHz during daytime also. ATS-6 to Trivandrum ray-path (Fig. 3.12) passes the E region of the ionosphere through the equatorial electrojet (EEJ). The EEJ is known to be a seat of strong electron density irregularities (e.g., Reid, 1968), the manifestations of which include the equatorial sporadic E (Es) observed in bottomside ionograms and the back-scattering of VHF radio signals. Thus the daytime scintillation occurrences also could be associated with E region irregularities, rather than the F region irregularities which are generally smoothed out by daytime at equatorial latitudes. Such an association has also been reported recently at other stations (e.g., Basu et al., 1977).

The features of daytime scintillations observed at Trivandrum are studied separately from those of the nighttime ones. The details of the analyses carried out by the
occur and the results obtained are described in the following sections and their relation to other manifestations of the EEJ irregularities are discussed.

5.1. OCCURRENCE FEATURES

Visual examination of the chart records revealed that daytime scintillations occurred almost regularly on all days at both 40 MHz and 140 MHz. However, these are found to be generally weaker compared to the nighttime ones and are generally absent at 360 MHz. In general, daytime scintillations are found to occur separated from the nighttime ones by a significant time gap in the morning and are quite independent of the scintillation conditions in the preceding night.

5.2. DIURNAL AND SEASONAL FEATURES

Following the steps described earlier in Section 3.1, the monthly mean quarter-hourly percentage occurrence \( P_{t,1} \) for the \( ith \) quarter-hour interval centred about 0615, 0630...1745 hrs of every month and the monthly mean percentage occurrence \( P_{m} \), for every month, from November 1975 to July 1976 are determined separately for 40 MHz and 140 MHz. As observable levels of scintillations (fluctuations exceeding \( \pm 5\% \) of mean) occurred on 360 MHz only very rarely, 360 MHz data has not been used in the present study. Because daytime scintillations
Fig. 5.2: Temporal variations of monthly mean quarter hourly percentage occurrences of scintillations and Esq: Equinoxial months.
Fig. 5.3: Temporal variations of monthly mean quarter hourly percentage occurrences of scintillations and Esq: Summer months.
could be associated with the EEJ irregularities, the manifestations of which include the regularly appearing sporadic E, E\textsubscript{sq}, in ionograms, the monthly mean percentage occurrences \(P_t\) and \(P_m\) of E\textsubscript{sq} are also obtained for all the months from 0615 to 1745 IST, for comparing with the morphology of scintillations. Here the ionogram times are suitably corrected for the longitude difference (of 1° in this case, for irregularities situated at E region heights) arising from the ray path geometry as described earlier in Section 3.3.1.

5.2.1. Diurnal Variation

To study the diurnal features, \(P_t\) is plotted against time and are shown in Figs. 5.1, 5.2 and 5.3 for winter (Nov-Jan), equinoxial (Feb-Apr) and summer (May-Jul) months respectively. The figures show the following general similarities, irrespective of season.

i) Percentage occurrence of scintillations at 40 MHz and 140 MHz and E\textsubscript{sq} show a rapid increase to the peak, occurring around 0900 hrs IST. During this period the percentage occurrence is generally high for E\textsubscript{sq} and low for scintillations at 140 MHz.

ii) A broad peak occurs during 0900-1300 hrs for both E\textsubscript{sq} and scintillations (40 MHz), except for scintillations in December.

iii) In the afternoon, the percentage occurrences de-
Fig. 5.1: Temporal variations of monthly mean quarter hourly percentage occurrences of scintillations and Esq: winter months.
crease gradually for both scintillations and $E_{sq}$ becoming insignificant by about 1800 hrs.

Over and above these similarities, the following distinctive differences are also noted.

i) Percentage occurrence of $E_{sq}$ generally shows little variation during 0830 to 1400 hrs, but stays around the maximum value. But scintillations show significant fluctuations during this period. The diurnal peak of scintillations is sharp during December, May and July (Figs. 5.1 and 5.3) while that of $E_{sq}$ is broad.

ii) The occurrence peaks of scintillations are generally narrower in winter and summer, than in equinoctial months.

iii) Percentage occurrence of scintillations generally show a secondary peak during 1600-1800 hrs, except perhaps during January and July; but $E_{sq}$ shows the peak only in equinoxes and perhaps also in November.

iv) Occasional occurrences of scintillations are observed in the absence of $E_{sq}$.

5.2.2. Seasonal Variations

Seasonal variations of monthly mean percentage occurrence $P_m$ of scintillations and $E_{sq}$ are shown in Fig. 5.4.
Fig. 5.4: Seasonal variations of monthly mean percentage occurrence of daytime scintillations in comparison with that of Esq.
It can be seen that, the variations are quite similar generally, both depicting an equinoxial peak. However, the following features are distinctively seen.

i) Seasonal variations are more pronounced for scintillations than for $E_{sq}$.

ii) For $E_{sq}$, the summer peak occurs in May, while for scintillations it is in June. Similarly, the winter peak occurs in December for $E_{sq}$, while it occurs in November for scintillations.

iii) Percentage occurrence of $E_{sq}$ shows a decreasing trend from November to July, which is not shown by scintillations.

The above studies have revealed that morphological features of scintillations are generally much similar to those of $E_{sq}$, except perhaps during summer months and during evening periods (1600-1800 hrs.) It is well known that in the E region, in general, two types of $E_s$ are found in ionograms, namely $E_{sq}$ (equatorial sporadic E) and $E_{sb}$ (Blanketing sporadic E). $E_{sq}$ occurs regularly and frequently at equatorial latitudes while $E_{sb}$ occurrences are more frequent and strong at latitudes away from the equator (Reddy and Devasia, 1977). Earlier studies on the occurrence of $E_{sb}$ layers at Trivandrum during solar minimum conditions, have revealed them to be a late afternoon phenomena with relatively frequent occurrence during summer months (Reddy and
Devasia, 1973; Devasia, 1976). In the light of the above, the occurrence features of $E_{sb}$ are also investigated in association with scintillations. Fig. 5.5 gives the monthly mean percentage occurrence of $E_{sb}$ (obtained using occurrence charts prepared similar to those of scintillations and $E_s$) as a function of time and season, as contours of equal percentage occurrence. It can be noticed from the figure that $E_{sb}$ is mainly an afternoon phenomenon, with peak occurrence during 1600-1800 hrs of summer months. During winter and equinox months of November to March, the activity is quite insignificant. As $E_{sb}$ layers are characterised by thin layers of steep ionisation gradients, these also can act as seats of electron density irregularities and cause scintillations.

5.3. ASSOCIATION BETWEEN SCINTILLATIONS AND $E_{sb}$

Using the daily occurrence charts of scintillations and $E_{sb}$, the number of 15 minute intervals in each day when scintillations were present simultaneous with the $E_{sb}$ occurrences in ionograms are counted and summed up for each month. The total number of such intervals of $E_{sb}$ occurrences are also determined for every month. These are compared in the histogram plots in Fig. 5.6, with the shaded ones corresponding to scintillations at 40 MHz (associated with $E_{sb}$) and the unshaded ones to total $E_{sb}$ occurrences, for each month. It can be noticed that $E_{sb}$ associated scintillations have significant occurrences during November, April,
FIG-5:  PERCENTAGE OCCURRENCE . CONTOURS OF BLANKETING Es.
Fig. 5.6: Histogram representation of the total number of 15 min intervals of occurrence of Esb *unshaded histograms* and that of associated 40 MHz scintillation occurrence *shaded histograms* for individual months.
May and June. Referring back to Fig. 5.5, it is seen that during these months, $E_{sb}$ activity is maximum during 1600-1800 hrs. Again referring to Figs. 5.1 and 5.3, it is seen that during these months scintillations show a secondary peak in percentage occurrence, which is absent in $E_{sq}$. Thus it can be concluded that $E_{sb}$ produces significant scintillation activity during the evening periods of November, April, May and June.

Another important point emerging from Fig. 5.6 is that, there are several occurrences of $E_{sb}$ during which scintillations did not occur (the unshaded portion of the histogram). Again referring back to Fig. 5.5, it is seen that significant occurrence of $E_{sb}$ is present even at 1900 hrs especially in summer and November, while scintillations generally disappear by 1800 hrs, as far as daytime is concerned. Thus many $E_{sb}$ occurrences are not associated with simultaneous scintillation occurrences.

Blanketting $E_s$ layers are thin sheets of enhanced ionization with a rather short horizontal extent (Reddy and Devasia, 1977). These are known to occur in the EJ region around times when the normal eastward electric field reverses to westward, as in the counter electrojet events (Sengupta and Krishna Murthy, 1975). Weak horizontal electric fields are conducive to the formation of $E_{sb}$ layers (Reddy and Devasia, 1977). As the electron
density-height gradient in $E_{sb}$ layers is quite high, even the weak ambient electric field can produce strong electron density irregularities by the cross-field plasma instability mechanism (Reid, 1968). Such irregularities have generally their sizes ranging from few kilometres to few metres (Reid, 1968; Balsley et al., 1976) and can produce scintillations at VHF, if they are sufficiently strong. Thus $E_{sb}$ layers can cause simultaneous scintillations. However, the strength of $E_{sb}$ irregularities depends on the magnitude of the electron density gradient and also on the ambient electric field.

During late evenings the ambient electron density and the electric field may be very small and hence all $E_{sb}$ events may not generate irregularities strong enough to cause scintillations. Also as $E_{sb}$ layers have short horizontal extent, the $E_{sb}$ layer observed by the Trivandrum ionosonde need not be intercepted by the satellite ray path which crosses the $E$ region at about 110 km west of Trivandrum. This explains, at least qualitatively, the fact that at $E_{sb}$ events are not always accompanied by scintillations.

5.4. FADING FEATURES

5.4.1. Strength Of Scintillations

Daytime scintillations are generally weaker compared to the nighttime ones, even though they occur almost regularly. It is found that $S_4$ index rarely exceeded 0.5 at 40 MHz and 0.2 at 140 MHz. Daytime scintillations are found to be
almost indistinguishable from noise at 360 MHz. To evolve a quantitative picture, the monthly mean quarter hourly SI, $S_{1t}$ centred at every quarter hour 0615 to 1745 and the monthly mean SI indices $S_{1m}$ have been determined for each month separately for 40 MHz and 140 MHz, following the steps described for nighttime scintillations in Chapter 3. The diurnal variations of the average scintillation activity are given in Fig. 5.7, 5.8 and 5.9, respectively for the winter, equinox and summer months. The average, $S_{1m}$, increases gradually from a low morning value to reach a rather broad diurnal peak by $\sim$1000 hrs. The peak activity generally continue until $\sim$1300 hrs. Then the strength decreases gradually and becomes almost insignificant by 1800 hrs .. In all the months, the peak strength attained is around 0.5 for 40 MHz and around 0.25 for 140 MHz, even though the peak percentage occurrence generally goes to 90% to 100% for 40 MHz and upto 75% to 80% for 140 MHz (Figs. 5.1 to 5.3). Like the percentage occurrence, $S_{1m}$ also shows a broad diurnal peak. In the summer months, and also during November and December, there is an increase in $S_{1m}$ around 1700 hrs , which is associated with the increase in percentage occurrence associated with $E_s$ activity. By around 1800 hrs, the monthly mean SI becomes less than 0.1 during all months, except perhaps in February. Another important feature is the observation of a rather high level of scintillations in the morning ($\sim$0615) in summer months, which is not seen in other months,
Fig. 5.7: Temporal variations of monthly mean quarter hourly SI: Winter months.
Fig. 5.8: Temporal variations of monthly mean quarter hourly SI: Equinoctial months.
Fig. 5.9: Temporal variations of monthly mean quarter hourly SI: Summer months
except perhaps November. This is attributed to the nighttime C-II scintillations (which are dominant in November and summer months) continuing even after 0600 hrs and merging into the daytime ones.

The seasonal variation of the scintillation strength, shown in Fig. 5.10 is obtained by plotting the monthly mean SI against the respective months. The seasonal variations consist of a weak equinoctial peak with solstitial minima; the one during winter is more deep.

5.4.2. Fading Periods

Since nighttime scintillations have been classified according to the fading periods, as determined by the $e^{-1}$ width of the auto correlogram, it is interesting to examine the fading periods of daytime scintillations as well. Visual examination of the data revealed fast fading similar to that of C-I. To get a quantitative picture the $e^{-1}$ width for about 50 samples of statistically stationary scintillation data at 40 MHz and 140 MHz and spread over the recording period is determined following the procedure outlined for nighttime scintillations.

The histogram in Fig. 5.11 gives the distribution of the fading periods. From the figure it can be seen that in more than 90% of the cases, the fading period is less than 6 s and only on one instance does it exceed 10 s.
Fig. 5.10: Seasonal variations of monthly mean SI.
Fig. 5.11: Histogram representation of the fading periods.
Those results show that daytime scintillations are generally fast in nature. The data analysed includes those associated with $E_{sq}$ and $E_{sb}$. No preferential dependence of $E_s$ type is seen on fading period. The above fading feature of daytime scintillation shows that the typical fading periods fall in the range of the values observed for nighttime C-I scintillations. It is also interesting to see that daytime scintillations did not show any distinctive separation in fading periods, like in the case with nighttime ones, where two distinctive fading features have been one of the important criterion for evolving the classification.

2.4.3. Variation Of Fading Period With $S_4$

To study the dependence of the fading period on the $S_4$ values, $S_4$ index is calculated for all the above 50 samples of scintillation data for which the fading periods have been estimated. The range of $S_4$ values is grouped in steps of 0.1 and the average value of $\tau$ width relevant to each group has been determined separately for 40 MHz and 140 MHz ($T_1$ and $T_2$ respectively). The number of events analysed ($N$) in each case is also noted. The results are given in Table 5.1.
It can readily be seen from Table 5.1 that there is a consistent decrease in the average width of the correlogram with increase in $S_4$, for both 40 and 140 MHz. In this case of daytime scintillations, the decrease in the fading period cannot be attributed to presence of strong scintillations (multiple scatter conditions) because $S_4$ is generally low. It may be noted that the daytime scintillations are very well associated with $E_{sq}$ and hence are attributed to irregularities in the equatorial electrojet region. As discussed in a later section, irregularities in the electrojet region are generated due to east-west electric field in the region. As the electric field becomes stronger by noon, the irregularities become stronger and also drift with higher speeds. Irregularities with higher drift speeds would cause faster temporal fluctuations for the same spatial
scale (Equation 4.23). Also, as the large irregularities grow stronger with increasing electric field, smaller scale irregularities become significant. This again would lead to faster scintillations. These considerations explain, on a qualitative basis, the association of faster scintillations (daytime) with high $S_4$ values.

5.5. FREQUENCY INDEX

5.5.1. Variation With $S_4$

As described earlier for nighttime scintillations in Chapter 4, the frequency index $\eta$ has been estimated for about 20 samples of daytime scintillations using simultaneous $S_4$ values at 40 MHz and 140 MHz. The estimated values of $\eta$ are found to be in the range of 0.4 to 1.6 with a median value of 1.0. As has been done for nighttime scintillations, the values of $\eta$ are grouped into regular class intervals of width 0.2, (0.4-0.6, 0.6-0.8, 1.4 to 1.6) and the average $S_4$ at the higher frequency (140 MHz) relevant to each class interval has been determined. These are then plotted against $\eta$, and are shown as filled circles in Fig. 5.12. It is seen that $S_4$ at 140 MHz shows very little variation, as shown by line (1) in the figure. As such, the average $S_4$ at 40 MHz has been determined for each of the class intervals as representative of the prevailing scintillation conditions.
Fig. 5.12: Variation of frequency index $\eta$ with strength ($S_4$) of scintillations. Filled circles correspond to $S_4$ of 140 MHz and unfilled circles represent that of 40 MHz.
These are shown by open circles in Fig. 5.12. The best fit straight line (line 2) drawn through these points indicates that, in general, $\gamma$ increases linearly with increase in $S_4$ at 40 MHz.

5.5.2. Irregularity Spectral Features

It is known that irregularities with scale sizes of a few kilometers exist in the E-region (Reid, 1968). It is reasonable to consider that the scintillation observations at 40 MHz and 140 MHz are made, generally, in the near zone. As such the information concerning frequency index can be transferred to the spectral features of the E-region irregularities following the Equations (4.7 to 4.9). The above results then suggest that the three dimensional spatial spectra of these large scale irregularities in the E-region become steeper as they grow in amplitude (i.e., as strength of scintillations increases). It has been observed that the strength of scintillations, on an average, has a diurnal variation as revealed by Figs. (5.7-5.9). It is interesting to see how the spectral features of the E-region irregularities change with time of the day.

To accomplish this, using simultaneous data on 40 MHz and 140 MHz, the values of $\gamma$ are determined at every 15 minute intervals (during 0615-1800 Hrs) for all the days of the recording period. Here, as large volumes of data
are to be handled, the SI index has been used rather than the $S_4$ and $\bar{\eta}$ has been estimated using Equation (4.5) as in the case with nighttime scintillations. These 15 minutes values of $\bar{\eta}$ are then averaged over the entire period of recording and over hourly intervals to obtain the yearly average ($\bar{\eta}$). Similarly the yearly average values (SI) of SI have also been determined at hourly intervals for both 40 MHz and 140 MHz. The diurnal variation of $\bar{\eta}$ and $\bar{SI}$'s are compared in Fig. 5.13, with $\bar{\eta}$ in the bottom panel and $\bar{SI}$'s in the top panel. It can be seen that the curves are, in general, consistent with the earlier findings. From a low value in the morning, $\bar{\eta}$ gradually increases, reaching the peak by 1100 - 1200 hrs IST, and drops to low values in the afternoon hours. $\bar{SI}$ also shows a similar variation at 40 MHz, while at 140 MHz the variations are rather small and present only during 0800 to 1100 hrs and 1400 to 1800 hrs. It is interesting to note that during periods of blanketing $E_b$ (shown by dotted lines in Fig. 5.13) when rather strong scintillation activity occurs, (evidenced by a small peak in $\bar{SI}$ at both the frequencies) $\bar{\eta}$ also shows a similar peak. All these indicate that the spectrum of E-region irregularities changes with time, becoming steeper by midday and flatter by evening. During $E_{sb}$ periods the spectra are more steep than at $E_x$ periods.
Fig. 5.13: Temporal variation of yearly average frequency index (\( \bar{\eta} \)) bottom panel and SI top panel of scintillations. The dashed portions of the curves correspond to values during blanketing Es periods.
5.6. POWER SPECTRA OF DAYTIME SCINTILLATIONS

Power spectral estimates have been made for a number of daytime scintillations data samples, following the methods employed for nighttime scintillations as discussed in Section 4.5.2 earlier. Typical power spectra thus obtained are shown in Fig. (5.14) for both 40 MHz and 140 MHz on a log-log scale, the spectra being consistent with the general inverse-power law form as discussed in case of nighttime ones. The slope of the mean straight line (dashed one in the figures) drawn in the roll off portion gives the scintillation spectral index $\alpha_2$. For the cases shown in figure the value of $\alpha_2$ are 2.0 and 1.8 at 40 MHz and 1.0 and 1.5 at 140 MHz respectively, indicating again a change in scintillations spectral index with frequency as has been the case with nighttime scintillations. This means that the irregularity power spectral index changes with spatial scale size for E region irregularities too. To investigate this further $\alpha_2$ values are determined from the ground scintillation spectra for a number of simultaneous scintillation data at 40 MHz and 140 MHz. The values are given in Table 5.2.
Fig. 5.14: Typical daytime scintillation power spectra at 40 MHz and 140 MHz. The ordinate scale for 140 MHz is shown shifted away to left of the ordinate, while for 40 MHz, the scale is closer to the ordinate.
<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>$\alpha_2$ (40 MHz)</th>
<th>$\alpha_2$ (140 MHz)</th>
<th>Sl. No.</th>
<th>$\alpha_2$ (40 MHz)</th>
<th>$\alpha_2$ (140 MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>1.3</td>
<td>9</td>
<td>2.6</td>
<td>1.8</td>
</tr>
<tr>
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<td>1.2</td>
<td>10</td>
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<td>1.4</td>
</tr>
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<td>1.9</td>
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<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
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<td>1.2</td>
<td>1.9</td>
<td>12</td>
<td>2.4</td>
<td>2.8</td>
</tr>
<tr>
<td>5</td>
<td>1.8</td>
<td>1.0</td>
<td>13</td>
<td>2.1</td>
<td>1.4</td>
</tr>
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<td>1.9</td>
<td>1.3</td>
<td>14</td>
<td>2.4</td>
<td>2.2</td>
</tr>
<tr>
<td>7</td>
<td>1.7</td>
<td>1.0</td>
<td>15</td>
<td>2.4</td>
<td>1.8</td>
</tr>
<tr>
<td>8</td>
<td>1.3</td>
<td>0.5</td>
<td>mean</td>
<td>2.2</td>
<td>1.6</td>
</tr>
</tbody>
</table>

The table shows clearly that $\alpha_2$ values at 140 MHz are lower than the corresponding values at 40 MHz. In the last column of Table 5.2, are shown the average value of $\alpha_2$ at these two frequencies. Expressing in terms of the three dimensional spectrum of the E-region irregularities, the results in Table 5.2 indicate a significant decrease in the irregularity power-law exponent as the scale size decreases from about 2 km to ~ 1 km (1st Fresnel size corresponding to 40 MHz and 140 MHz for 100 km altitude and taking into account the ray-path geometry). To state in other words, the irregularity power decreases (with decrease in scale size) faster at larger scale sizes.
Fig. (5.15) is a histogram representation of the distribution of scintillation spectral indices $a_z$ at 40 MHz. Above each vertical block is given, the average value of $S_4$ at 40 MHz calculated from the data samples that have been used to obtain the values of $a_z$ in that range. It could be seen that,

i) the $a_z$ values are generally spread in the range 1.4 to 3 with values in the range 1.6 to 2.0 occurring more frequently.

ii) Higher values $a_z$ are in general associated with higher values of $S_4$ i.e., the scintillation spectra become steeper with increase in strength of scintillation. This is in line with the features of irregularity spectra, deduced earlier from frequency index studies.

At this juncture it is interesting to compare the spectral features of E-region irregularities, as revealed by the different estimates. This has been done for two typical days, and shown in Fig. 5.16 (a and b) where the diurnal variations of the different scintillation parameters are plotted. The ordinate on the r.h.s. gives $n$ estimated from $S_4$ values and the three dimensional irregularity spectral index $a_z$ estimated from $n$. The top most curves in both figures, give the $a_z$ values, which are just one less than $a_z$. It is interesting to
Fig. 5.15: Histogram of 40 MHz scintillation spectral indices. At the top of each block is given the average $S_4$ at 40 MHz, estimated from the data used to obtain the spectral indices of the block.
Fig. 5.16: Temporal variations of parameters of daytime scintillations on two typical days, (a) Feb. 16, 1976 (b) Feb. 18, 1976. The right hand side ordinate scale in the bottom panels of (a) and (b) give $\alpha_3$ obtained from $\eta$ using equation (4.8) and that in the top panels give $\alpha_3$ obtained from $\alpha_2$. 
note that the features revealed by this comparison are in
good agreement with the general picture discussed earlier.

* follows the variations in scintillation strength. * is
higher for lower frequencies and for both the frequencies,
it follows the variations in * and * , roughly. * is
estimated from * are lower than those estimated from * ,
again as seen in the nighttime scintillation. It can also
be seen that the higher values of * at 40 MHz are not
entirely due to the fact that * at 40 MHz is higher than
that at 140 MHz. This is indicated by the large difference
in * at 40 and 140 MHz and the close-by values of * at
those frequencies during 1200-1300 hrs in Fig. 5.16.
Simultaneous observation of * at both frequencies for the
same range of * is difficult because * at 140 MHz is
normally much smaller than that at 40 MHz. However, a
general picture can be evolved if one selects the same
range of * for both frequencies using non-simultaneous
data. Selecting the range of * to be 0.1 to 0.2 for both
140 MHz and 40 MHz, the values of * obtained are listed in
table 5.3.
It can be seen that the average $S_4$ values at the two frequencies are roughly the same. Still $a_2$ is higher at 40 MHz. Thus the higher values of $a_2$ at 40 MHz are mainly due to the change in irregularity spectral index with scale size.

### 5.7. CORRELATED STUDIES ON SCINTILLATIONS AND VHF BACKSCATTER

#### 5.7.1. VHF Backscatter Radar Data

A coherent VHF backscatter radar at 54.95 MHz has been operating at Trivandrum. It provides information on the strength and drift velocity of the 2.7 m size electron density irregularities in the electrojet region (of 95 to 110 km altitude) through the signal amplitude and Doppler spectrum respectively. The signal amplitude has been recorded on paper charts while the spectrum on photographic films. The radar beam has been directed 30° west
of zenith. The height resolution was 9 km (Janardhanan et al., 1979; Viswanathan, 1979).

An exhaustive investigation of the equatorial electro-jet (EEJ) irregularities using the VHF backscatter radar at Jicamarca, has revealed two types of echoes in the radar Doppler spectra; viz., the Type-I and the Type-II (e.g., Balsley, 1969). The Type-I spectra are characterised by a sharp peak occurring at a frequency corresponding to the ion-acoustic velocity, while the Type-II spectra have a broad maximum and a weighted mean Doppler frequency less than the ion-acoustic frequency. Detailed features of these spectra have been given by many workers (e.g., Balsley, 1969; Balsley and Farley, 1971). Theoretical studies have also revealed that the irregularities responsible for these two types of echoes are produced by plasma instability mechanisms, distinct in nature. The Type-I irregularities are generated in the EEJ region when the electron streaming velocity in the jet exceeds the local ion acoustic velocity (Farley, 1963), by what is known as the two-stream instability mechanism. These irregularities show a narrow Doppler frequency spectrum peaking at the ion-acoustic velocity (Farley and Balsley, 1973). These are also found to be dominant at lower scale sizes corresponding to higher frequencies of radar (Balsley and Farley, 1971).
The Type-II irregularities are generated by the cross-field or the gradient-drift instability mechanism according to which plasma perturbations in presence of eastward electric field (Reid, 1968; Balsley, 1969) and the geomagnetic field with electron density-height gradient being positive will grow in strength. For a westward electric field, the electron density-height gradient has to be negative for amplification. This mechanism can account for larger scale irregularities (even those responsible for $E_{sq}$ on ionograms).

An examination of the radar Doppler spectra at Trivandrum also has revealed the presence of both the above types of spectra, during the data period (1975-1976). Mixed spectra have also been observed frequently suggesting the co-existence of both Type-I and Type-II. The radar data, available simultaneously with scintillation data have been used for the correlated study.

5.7.2. Correlated Study

The strength of radar backscattered echoes has been obtained from the signal amplitudes scaled at every 15 minute interval, from the paper chart records and then squaring them. Simultaneous strength of scintillation activity has been determined by estimating SI index at 40 MHz from the RBE amplitude records. Such estimates of radar signal strength and scintillation strength (SI) at 40 MHz have been made for all the days during which
both data were available simultaneous and continuous. The diurnal variation of these are then compared in Fig. 5.17 for four typical days. In the figure, the thick curves represent variations of radar signal power while the thin curves depict those of SI at 40 MHz. The duration of significant Type-I occurrence, as identified by the visual examination of the simultaneous radar Doppler spectra, are marked by horizontal lines with arrow heads on both ends, close to the abscissa in Fig. 5.17. It can readily be seen that except for the duration of occurrence of Type-I, (as indicated by the arrows) the nature of variation of SI and the radar signal power are in close agreement. But during the period of Type-I activity, the nature of variations is highly dissimilar. During such periods, SI shows a decrease, while radar signal strength shows a sharp increase. On 18 Feb., when there has been no occurrence of Type-I and the spectra are entirely Type-II only, the close association between SI and radar signal power is observed throughout the day.

This distinctive nature of the association between the two during Type-I activity has been investigated in more detail. For this, from the radar Doppler spectra the total echo power ($P_T$) and the weighted mean Doppler frequency ($\bar{f}_D$) have been estimated at regular intervals of 15 minutes.
FIG-5.17: TEMPORAL VARIATIONS OF RADAR BACK-SCATTERED SIGNAL STRENGTH thick line AND 40 MHZ SCINTILLATIONS thin line ON FOUR DAYS.
\[ P_T = \int P(f) \cdot f \cdot df \] and \[ \bar{F}_D = \int P(f) \cdot f \cdot df / \int P(f) \cdot df \]

where,

df is the frequency interval and f the frequency at which the power is P(f).

From \( P_T \), the contribution \( P_1 \) to \( P_T \) due to the Type-I signals are then removed by fitting a Gaussian curve centred around -115 Hz, with its peak coinciding with the spectral peak at -115 Hz. This frequency -115 Hz corresponds to the ion-acoustic velocity. (Typical Type-I echoes at Trivandrum are also found to occur with their peak centred at -115 Hz. The negative sign corresponds to the normal daytime westward motion of EEJ irregularities). The remaining \( (P_T - P_1) \) is considered as the echo power \( P_2 \), entirely due to Type-II. Thus

\[ P_2 = P_T - P_1 \]

Thus from a given spectrum the total power and the Type-I and Type-II power have been obtained separately. The diurnal variation of the thus obtained radar echo powers are compared with that of strength of scintillations at 40 MHz obtained from 15 minute SI values, in Fig. 5.18 (a and b) for two representative days. The x-axis represents time in IST (32.5°E) the ordinate at left 40 MHz SI and the ordinate at right the radar signal power in arbitrary units. The continuous and dashed curves represent the variations of Type-II and Type-I power respectively and the variations of
TEMPORAL VARIATION OF 40 MHz SCINTILLATION STRENGTH (SI) dotted lines WITH SIMULTANEOUS TYPE-I broken lines AND TYPE-II continuous lines RADAR SIGNAL STRENGTH AT 55 MHz, FOR TWO REPRESENTATIVE DAYS. Duration of significant Type-I activity is represented by the shaded region.
SI are shown by the dotted curve. Type-I power, exceeding 20% of the corresponding Type-II power is considered to be significant as far as the contribution to the total radar signal power is concerned. The duration of this significant Type-I activity is distinguished by the shaded region.

Fig.(5.18a), for Nov. 25, 1975, shows an onset of radar signals at -0900 and a rapid growth from 1000 hrs. By about 1100 hrs Type-I sets in and the signal strength built up very fast. Moderately strong scintillations are present even before the onset of signals in radar. However, the variations in SI are similar to those of Type-II/total power upto -1130, when Type-I power has become significant. The significant Type-I activity persisted until 1400 hrs and then slowly disappeared. From 1400 hrs till the final disappearance of radar signals, (-1500 hrs) a remarkably close association is seen again between radar signal strength and SI. In the shaded region of significant Type-I activity, SI appears to fluctuate about a mean value (~0.6) indicating some sort of a 'saturation'. In this discussion the word 'saturation' is used only to indicate the attaining of a steady level. In fact corresponding to the peak in the radar powers $P_2$ and $P_1$ at -1300 hrs., SI shows a dip similar to that observed in Fig. (5.17). It may also be noticed that the apparent 'saturation' of SI is dependent only on whether $P_1$ was significant or not, and not the value of Type-II power as seen from figure (5.18a). The 'saturation' appears at 1130 hrs, when $P_1$ has become
significant for the first time, and $P_2$ is then about 200. Finally in the afternoon when Type-I has just become insignificant and SI has started following variation of $P_2$, the value of $P_2$ is about 250, much higher than the earlier value. This clearly brings out that it is the significant Type-I activity, rather than the high value of Type-II power, that is responsible for the decline in the association between SI and radar signal strength. Further evidence to this is given in Fig. (5.18b) where scintillations and radar signals appear almost simultaneously. As usual, scintillations built up fast Type-I sets in immediately, and is quite comparable in power with Type-II even though the total power itself is small. This continues upto ~1030 and till then SI almost stays put around 0.45. (Here it is interesting to note that the total radar power is small as also is the value of SI at 'saturation'.) From about 1030, Type-II power shoots up very much so that $P_1$ power has become insignificant to the total power. SI also shoots up from the 'apparent saturation' and follows the variation of $P_2$ till the final disappearance. This brings out one more point that 'the apparent saturation level' in SI caused by significant Type-I activity need not be the maximum value for that day and SI can go much above this level, provided $P_2$ increases sufficiently and $P_1$ becomes insignificant.
To summarise,

i) SI and the total radar signal power (or the Type-II power) are well associated and depict similar diurnal variations, as long as contribution of Type-I power to the total power is insignificant.

ii) Occurrence of Type-I with significant power, causes some sort of a 'saturation' in SI irrespective of the value and nature of variation of $P_2$ or the value of SI itself. Once $P_1$ becomes insignificant, SI starts following $P_2$, irrespective of whether the value of $P_2$ is higher than its value at the time when $P_1$ became significant.

iii) The 'saturation' in SI depends only on the level of Type-I activity and not on the value of $P_2$ or the value of SI. The 'saturation' value of SI could be exceeded, once $P_1$ became insignificant and $P_2$ favours such a rise.

5.8. ONSET TIME DIFFERENCES

It has been noticed during the analyses described earlier that onset of scintillations is not simultaneous with that of $E_{sq}$ (Fig. 5.1 to 5.3) and with that of the radar signals (Fig. 5.17, 5.18). It is quite interesting to investigate this aspect when one considers the wide difference in the irregularity scale sizes involved
\( \sim 2 \) km for scintillations and 2.7 m for radar). The bar diagrams in Fig. (5.19) show the duration of scintillation activity and radar echoes from onset till the final decay for a few typical days. For each day there are two horizontal bars, the hatched one representing scintillations at 40 MHz. It can be readily seen that, onset of scintillations is generally earlier and occasionally simultaneous with that of the radar signals, but not later. Onset time differences as much as 30 min are observed frequently. During decay, it is found that generally the radar signals disappear earlier. On some occasions simultaneous disappearance of the two are also observed. However, on two days (23 June 1976 and 24 March 1976) the radar signals continued even after the disappearance of scintillations at 40 MHz.

Similar study has been made with the onset times of scintillations at 40 MHz, and \( E_{sq} \) also. Fig. 5.20 is a histogram representation of the onset time delays between scintillations at 40 MHz and \( E_{sq} \). A positive delay corresponds to an earlier onset of \( E_{sq} \). The onset times of \( E_{sq} \) have been corrected for the longitude difference of the sub-satellite point. As the ionograms are generally obtained at 15 minute interval, a maximum uncertainty of +15 minutes can be present in the delay time. Considering this also, it can be seen from the figure that onset
FIG-5.9: OCCURRENCE CHARACTERISTICS OF 40 MHz SCINTILLATIONS AND 55 MHz BACK SCATTER RADAR SIGNALS FOR FEW TYPICAL DAYS. The hatched bars represent scintillations.
Fig. 5.20: Histogram representation of onset time delays of scintillation at 40 MHz and Esq. Positive delays correspond to earlier onset of Esq.
of $E_{sq}$ generally precedes that of scintillations at 40 MHz by about half an hour to one hour even though delays as much as 90 to 100 minutes are not uncommon. The disappearance times do not present any consistent picture; some days scintillations may continue even after the disappearance of $E_{sq}$, while on other occasions they disappear prior to that of $E_{sq}$.

The above observations suggest that the generation and growth of large scale irregularities generally occur much earlier than the small scale ones. During the onset times, $E_{sq}$ could be caused by irregularities of the size of the first Fresnel zone (several tens of kilometers) and when finally becomes fully developed, corresponds to the exploring wavelength. Scintillations are mainly caused by kilometer sized irregularities and the radar echoes by much smaller meter scale (2.7 n) irregularities. Thus the present study also reveals that except for the differences during onset and decay periods, irregularities over a wide range from few kilometers down to 3 meters can co-exist in the electrojet region, for fairly long durations with significant power. These results are on par with observations at other equatorial stations like Huancayo. (Basu et al., 1977).
5.9. DRIFT SPEED OF IRREGULARITIES

As has been described earlier in Section 4.7, if a series of Fresnel minima can be identified in the scintillation spectrum of daytime scintillations, then the horizontal drift speed $V$ of the E-region irregularities can be estimated. It is known that as the thickness of the irregularity layer decreases the smearing of the Fresnel oscillations also decreases (Rufenach, 1972). As the EEJ irregularities are of short vertical extend (95-110 km), it is reasonable to expect more instances where such minima can be identified.

On examining the scintillation spectra, Fresnel oscillations with successive minima related through square root of natural numbers, have been observed during several occasions. Two typical spectra are shown in Fig. 5.21 where the minima are also identified. For the first case (16 Feb. 1976) the temporal Fresnel frequency $v_f$ is 51 MHz which corresponds to a horizontal drift speed of 153 m s$^{-1}$, considering the ray path geometry. For the second case of 26 May 1976 $v_f$ is 62 MHz and the corresponding speed is 185 m s$^{-1}$.

5.9.1. Comparison With Speeds Deduced From Radar

The drift speeds of the E-region irregularities have also been deduced from the weighted mean Doppler frequency obtained from the VHF radar spectra. It is interesting to compare the speeds deduced from the scintillation
Fig. 5.21: Representative scintillation power spectra (40 MHz) for two different occasions, depicting well developed Fresnel oscillations. The consecutive minima and $\nu_f$ are identified in the figure.
spectra with those obtained with the radar. For the radar beam geometry at Trivandrum and the signal frequency, the irregularity drift speed $V_R$ in the horizontal direction is given by

$$V_R = 5.46 \bar{f}_D$$

(5.4)

where,

$V_R$ is in $\text{ms}^{-1}$ if $\bar{f}_D$ is in Hz.

where $\bar{f}_D$ is the weighted mean Doppler frequency estimated using equation (5.2), by replacing $P(f)$ in the equation by $P_2(f)$, where $P_2(f)$ is the power at a frequency $f$ after removing the contribution due to Type-I to the total power. This is because the Type-II irregularity generation mechanism can support the large scale sizes relevant for scintillations (Reid, 1968), while Type-I have their maximum sizes up to a few tens of meters. The estimated hourly average values of the horizontal drift speed are then compared with those estimated by the scintillation technique for two typical days of distinctive Type-I activity.

The first case shown in Fig. 5.22, is for a day with strong Type-I activity. The relative strength of Type-I over Type-II is also shown in the figure by the variation of the dimensionless quantity $\sigma$.

$$\sigma = \frac{P_1}{P_2} \times 100$$

(5.5)
Fig. 5.22: Comparison of the variation of horizontal drift speed of irregularities estimated using scintillation spectra with the corresponding values estimated from VHF backscatter radar spectra, for a typical day with significant Type-I activity. Radar estimated values, during no Type-I activity are shown by circles, separated from the curve. Periods of $\tau$ exceeding 20% are considered to have significant Type-I activity.
where,

\[ P_1 \text{ and } P_2 \text{ are the Type-I and Type-II power respectively.} \]

\[ \sigma > 20\% \text{, then correspond to significant Type-I activity,} \]

following the earlier consideration. Accordingly for the
day represented in Fig. 5.22, Type-I activity is signifi-
cant throughout, except during onset and disappearance. It
is interesting to note that except at 0800 hrs and perhaps
at 1400 hrs, the speeds from scintillation data are consist-
ently and significantly lower than the estimates made with
the radar data. The differences are larger when the Type-I
activity is stronger. The second example shown in Fig. 5.23
for a day with no significant Type-I activity presents a
different picture. It is quite interesting to see that the
speed estimated by both the techniques are agreeing fairly
well within the uncertainties. (The uncertainty in estima-
tion of \( v_f \) is typically 5 mHz, which means uncertainty in
the scintillation estimated speeds of ± 10 m/s\(^1\)). This shows
that the drift speeds of EEJ irregularities estimated by
radar and scintillation techniques are fairly matching when
only Type-II irregularities are present. As significant
Type-I sets in, the radar estimated velocities become signi-
ficantly higher. Referring back to Section 5.7, where the
radar and scintillation activities are compared under dif-
ferent irregularity conditions, it is seen that this devia-
tion in scintillation estimated speeds under strong Type-I
Fig. 5.23: Comparison of the variation of scintillation estimated horizontal drift speed of irregularities with that of the radar estimated speed for a typical day with no significant Type-I activity. Periods of $\sigma$ exceeding 20% are considered to have significant Type-I activity.
conditions is in agreement with the earlier findings that there is a considerable deviation in the general association between the radar echo power and scintillation strength, in presence of strong Type-I.

5.10 DISCUSSION

The morphological features of daytime scintillations as revealed in the present analysis shows them to be rather weak (compared to the nighttime ones) with practically no occurrence at 360 MHz. Similar observations have been reported by Basu et al., (1977) from an analyses of ATS-6 data from another equatorial station Huancayo. In the present analysis it is found that scintillations (daytime) are closely associated with $E_{sq}$, but not always associated with $E_{sb}$. Based on ATS-6 scintillation data from the low latitude station Octacamuund (dip 50°N), Rastogi (1980) reported occurrence of scintillations associated with $E_{sq}$ and rather strong scintillations, even at 360 MHz, during $E_{sb}$ periods. Here it may be noted that ATS-6 to Octacamuund ray path crosses the $E$-region levels at the edge of EEJ, while the ray path to Trivandrum crosses near its centre. As has already been pointed out, $E_{sb}$ occurrences are more strong and frequent at latitudes away from EEJ (Reddy and Devasia, 1977). This probably accounts for the Trivandrum and Octacamuund observations, as far as their association with $E_{sb}$ is concerned.
Again for reasons already described earlier (Section 5.3) all blanketing $E_s$ layers need not produce scintillations. They produce scintillations only when the electron density height gradient in $E_{sb}$ layers and the ambient electric field are sufficiently strong to produce strong large scale ($\sim 1$ to $2$ km size) irregularities, and these irregularities intercept the satellite to ground raypath.

As far as the spectral features of the $E$-region irregularities are concerned, the present study reveals an average temporal variation for the three dimensional irregularity spectral index. It is steeper at around midday, when the scintillation activity also reaches the diurnal peak; or in other words there is a steepening of the irregularity spectrum as strength increases. The spectra become flatter in the evening when the irregularity power also decreases. These features of irregularity spectra are similar to those of nighttime C-II scintillations, which are also due to large scale irregularities (but in the F-region). Power spectral analyses have shown a value of $-2.8$ as most probable for three dimensional irregularity spectral index (varying in the range 2 to 4). Estimates made from frequency indices yield values in the range 0 to 4 with most probable value around 2. These values correspond to the large scale irregularities of the order of Fresnel dimension of
40 MHz (~2 km). Satyaprakasa et al., (1970) from rocket experiments reported an index of $3 \pm 1$ for irregularities in the range 1-15 m. Ott and Farley (1974), based on radar observations of 3 m irregularities and from dimensional analyses showed that the index should be at least 3. The values obtained in the present investigations are roughly agreeing with the above. The variation of the irregularity spectrum with scales size, shows that the spectrum is more steep at larger scale sizes (corresponding to 40 MHz).

This feature also is similar to that of nighttime C-II scintillation, which again lends support to the point that daytime scintillations could be caused by the large scale (Fresnel dimension) EBJ irregularities.

Correlated radar and scintillation studies have shown that irregularities over a wide range of scale sizes from ~2 km to as low as 2.7 m coexist in the EBJ region. A close association is found between the radar return signal power and strength of scintillations, when no significant Type-I irregularities are observed in the radar data. Basu et al., (1977) observed a good association between scintillations and Type-II irregularities, while with Type-I no significant association was found. Using radar observation at 3 wavelengths (9 m, 3 m and 1 m) Balsley and Farley (1971) found that the strength of Type-II irregularities decrease much more rapidly with wavelength,
than Type-I and consequently Type-II dominate at longer wavelengths and Type-I at shorter wavelengths. Theoretical investigations also support fairly large scale sizes for Type-II (Reid, 1968), of the order of hundred meters or more. Type-I irregularities are generally observed only at short wavelengths (below ~10 m).

Balsley et al., (1976) showed that Type-II irregularities are the most probable scatterers of $E_{\text{eq}}$ echoes on ionosonde and that Type-I irregularities are not detectable at ionosonde wavelength. All these are in line with present findings. It is also found in the present analyses that the drift speed of EEJ irregularities estimated by scintillations and radar measurements match well, when Type-II irregularities only are present. Occurrence of strong Type-I results in significantly higher values of radar estimated velocities.

Rastogi (1980) using daytime scintillation data for sunspot minimum reported fluctuation of 1 to 2 dB at American longitudes (Huancayo) and 4-5 dB at Indian longitude (Ootacamund), during periods of normal EEJ. This appears to be somewhat puzzling because, normally the EEJ is expected to be stronger over American longitudes (Suguiru and Cain, 1966). However, when viewed in juxtaposition with the present observations the follow-
ing picture emerges. As development of Type-I irregularities requires the electron streaming velocity to exceed the ion-acoustic speed, it is quite likely that Type-I is more common and stronger at American longitudes (than at Indian longitudes) as the EEJ current is stronger. It is found in the present study that scintillations are more associated with Type-II, and also that they remain somewhat 'saturated' during strong Type-I activity. Balsley and Farley (1971) also show that Type-II activity decreases as Type-I becomes stronger. These facts, explain qualitatively, the observation that daytime scintillations (which are mainly associated with Type-II irregularities) are weaker at American longitudes.

The present study also shows that, the onset of scintillations follows that of $E_{sq}$ but generally precedes the onset of radar signals. These indicate that the large scale irregularities occur first. The initial appearance of $E_{sq}$ in ionograms could be caused by irregularities in the sizes of the order of the Fresnel dimension and the later strong $E_{sq}$ by irregularity scales of the order of the wavelength. However, the observed time delays will not directly yield the growth times of different irregularities, as the time delay depends on the development of horizontal electric field also. The large scale size requires smaller value
of electric fields to grow (Krishna Murthy and Sen Gupta, 1973) than the smaller scales which grow when the electric field also becomes strong.