CHAPTER 3

EQUATORIAL SCINTILLATION AND SPREAD-F

3.1 Introduction

India lies wholly in the northern hemisphere extending from latitude 8°4' to 37°6' North and longitude 68°7' to 97°25' East of Greenwich. It is fortuitous that India lies under an extremely important part of the Earth’s ionosphere, the equatorial region and the anomaly region. Hence determining the morphology of F-layer irregularities in the equatorial region is vital for the design and operation of satellite communication systems that are effected by ionospheric irregularities upto the microwave bands.

Studies of ionospheric scintillations and spread-F at equatorial latitudes reveal the existence of an intense belt of ionospheric irregularities in the night time F-region. So the scintillation activity in the region covered by about ±20° magnetic latitudes around the magnetic equator (equatorial region) is remarkable. This region may further be sub-divided into two zones: the electrojet region (5°N – 5°S) and the non-electrojet region (5° – 20° North and South dip latitude). It has also be known for years that the electrojet controls equatorial anomaly in the F2 region.

3.1 Data Base Development and Method of Analysis

Indian Institute of Geomagnetism, Mumbai provided the data for the equatorial studies. The data which was recorded at Thiruvanathapuram and Tiruchendur, from
January 1988 to June 1993, is utilised in this validation study of scintillations. The above period encompasses the solar maximum year of 1989 and its decaying phase. The observations were taken during night time; the data from Tiruchendur is used only when no data was available from Thiruvanathapuram. Peak-to-peak fluctuation of amplitudes >1 dB, corresponding to a scintillation index $S.I > 10\%$, has been considered as the basis for this analysis.

For the stations Thiruvanathapuram and Tiruchendur the geographic and magnetic co-ordinates and sub-ionospheric points are:

**Thiruvanathapuram** (Geo.Lat. 8.3°; Geo. long.76.9°; Dip angle $-0.6^\circ$; Dip angle of sub-ionospheric points at 400 km $-0.6^\circ$) and **Tiruchendur** (Geo. lat. 8.3°; Geo. long. 78.7°; Dip angle $-0.7^\circ$; Dip angle of sub-ionospheric point at 400 km $-0.5^\circ$).

The solar data used is that in the previous Chapter. Only night time scintillations have been analysed to study variation of scintillation occurrences in different seasons, months and years. The months are grouped into three categories corresponding to December and June solstices (D-and J-Months) and Equinox (E-months). The occurrences of scintillation of every 15 minutes duration between 1800 to 0600 hrs (IST) has been noted. The monthly mean sunspot number during the observation period were also computed.

### 3.2 General Characteristics of F-layer Equatorial Irregularities

The Physics of F-layer irregularities in the equatorial region is very important. Generally the F-layer irregularities in the equatorial region originate at night in areas close to or on the magnetic equator.

Regular observations of scintillation at Thiruvanathapuram started nearly a decade ago and provide a long series of data at the magnetic equator. The first detailed studies of scintillation were made at Thumba during the ATS-6 phase II (August, 1975 to July, 1976).
At Thiruvanathapuram, scintillations generally start around 2100 IST with strong scintillation, which lasts till early morning in a single patch observed often during the period of solar maximum or sometimes with an absence of scintillation for a short duration. It is, however, reduced to patches of 3 to 4 hours duration during solar minimum. Ionospheric scintillations are known to be very severe around the magnetic equatorial latitude. They have been reported to occur both during day-and-night times (Basu et al., 1976; Aarons et al., 1977; Rastogi, 1980 & 1991) and are generally associated with spread-F (Dabas and Reddy, 1986; Krishnamurthy, 1993).

### 3.3 Morphology from Scintillation Measurements

The variation dominated by the rapid onset of intense scintillations just after local sunset is called diurnal variation. The data used in generating diurnal and seasonal distributions spanned a period from half an hour prior to local sunset to eight hours after sunset. The above time is further categorised into Post-sunset (1900-2100) Pre-midnight (2200-0000) Post-midnight (0100-0300) and Pre-sunrise (0400-0600) hours (IST), for effective analysis. We have also noted the apparent and real differences in scintillations data as a function of day of year, month and solar flux.

The morphology shows peaks at the equinoxes only during 1988 and 1992, both years being moderate sunspot years of the observation period. A dip in occurrence percentage was noted during June and July period of these years. The important features of the diurnal and seasonal variations for different years have been studied and plotted in the figures 3(a), 3(b), 3(c), 3(d) and 3(e).

A remarkable increase in diurnal variation was observed during 1989 and 1990. The percentage occurrence shows a similar behaviour during 1990 and 1991, figure 3(i). Pre-midnight time scintillation shows a higher percentage of occurrence and it mainly depends upon solar activity and seasonal changes, figures 3(f) - 3(h) depicts this fact. The monthly mean variation of pre-midnight and post-midnight scintillation is shown in figure.
Figures 3(a)-3(e): Plot of diurnal variation of percentage of occurrence of scintillation ≥ 1dB for equinox, winter and summer seasons. Solid curve indicates E-months, dashed curve indicates D-months and dotted curve, J-months. Figure 3 (a): depicts the seasonal and diurnal variation during 1988.; Figure 3 (b): depicts the variation during 1989.; Figure 3(c): depicts the variation during 1990; Figures 3 (d) and 3 (e): depict the variation during the years 1991 and 1992 respectively. Calculated from FLEETSAT Data sets.
Figure 3(f): Plot of annual comparison of scintillation activity of equinox (E-months) during consecutive years of the observation period (1988-1992).

Figure 3(g): Plot of annual comparison of scintillation activity of J-months during consecutive years of the observation period (1988-1992).
Figure 3(h): Plot of annual comparison of scintillation activity of D-months during consecutive years of the observation period (1988-1992).

Figure 3(i): Plot of annual average variation of percentage occurrence of scintillations calculated from the Thiruvanathapuram & Tiruchendur FLEETSAT Data sets.
3(o). The month-to-month variation of the percentage occurrence of scintillations along with sunspot number is also plotted in figure 3(n). The apparent and real differences in scintillations as a function of solar flux and planetary geomagnetic activity is shown in figure 3(p).

Comparing the seasonal variations of scintillations at the equator an apparent increase in percentage of occurrence is observed during equinoxial months except during the years of high solar activity or high sunspots number. The peak in the onset time occurs around 1930-2030 hrs IST, irrespective of seasonal variation. There is a marked reduction in the occurrence frequency of scintillations in J-months during low solar activity.

3.4 Characteristics of Internationally Quiet and Internationally Disturbed Days

The effect of magnetic activity on high frequency scintillations has been studied by selecting five International quiet days and five International disturbed days in each month as shown in the Solar Geophysical Data Bulletin. The data for the December solstices, June solstices and equinox months have been separated and hourly percentage of occurrence of scintillations have been computed and are shown in figures 3(j), 3(k), 3(l) and 3(m). Scintillations occured mostly on quiet days while it was suppressed on disturbed days, except for equinoxial months of low solar activity and J-months of high solar activity, for the above five years of observation. The plot during the high solar activity period is interesting: during 1989 except J-months all the other seasons showed a substantial reduction of 20 to 30 percent. This trend was repeated during 1991. The peak occurrence on quiet days lay at 2100 hrs IST; whereas for disturbed days the occurrence rate peaked at around 2200 hrs IST irrespective of seasonal variation. Years of high solar flux bring about higher occurrence of equatorial irregularities during disturbed days while during the years of moderate solar activity, a marked reduction in occurrence of scintillations during the post midnight period was noted.
Figure 3(j): Plot of seasonal and diurnal variation of percentage occurrence of scintillations as a function of international quiet and disturbed days. Top left shows J-months and right indicates D-months. Bottom left, E-months and right the average annual variation of 1989. Solid and dotted line stand for quiet and disturbed conditions respectively.
Figure 3(k): Plot of seasonal and diurnal variation of percentage occurrence of scintillations as a function of international quiet and disturbed days. Right bottom plots show the average annual variation of the year 1990 (Seasons are indicated in brackets). Solid and dotted line stand for quiet and disturbed conditions respectively.
Figure 3(I): Plot of seasonal and diurnal variation of percentage occurrence of scintillations as a function of international quiet and disturbed days. Right bottom plots show the average annual variation of the year 1991 (Seasons are indicated in brackets). Solid and dotted line stand for quiet and disturbed conditions respectively.
Figure 3(m): Plot of seasonal and diurnal variation of percentage occurrence of scintillations as a function of international quiet and disturbed days. Right bottom plots show the average annual variation of the year 1992 (Seasons are indicated in brackets). Solid and dotted line stand for quiet and disturbed conditions respectively.
3.5 Scintillation and Spread-F

Woodman and LaHoz (1976) presented strong evidence that equatorial spread-F (ESF) conditions and radio scintillations effects were due to plume shaped electron density irregularities or bubbles. Woodman’s study was based on Jicamarca radar data analyses. Spread-F and scintillations are closely associated with each other, based on their temporal variations. The association is found to be dependent on the type of spread-F; the range spread is thought to be due to extended frontal irregularities which give off vertical reflections, while the frequency spread is due to the irregularities giving near vertical reflections (Hajcowicz, 1977).

At the magnetic equator two distinct types of F-layer irregularities exist: a thin, long-lasting layer associated with frequency spread-F and plumes associated with range spread-F (Abdu et al., 1981; Das Gupta et al., 1983). Generation of perturbation electric fields suitable for triggering of equatorial spread-F by gravity waves, winds in the E-region producing electron density irregularities which in turn make the flux tube integrated Pederson and Hall conductivities non-uniform in this region. Since the phenomenon of equatorial spread-F is associated with the field-aligned irregularities, the altitude to which the F-region rises near the magnetic equator will determine the N-S extent of the latitude belt over which the irregularities will be seen. The night time equatorial distributions appear to consist of two very distinct populations (which means separated by four to five orders of magnitude). These are probably due to two source mechanisms; the most likely bottom side spread-F causing the lower population and large plume structures, the upper population. Some early observational work were complicated by the differences between the range and frequency type of equatorial spread-F. It was shown in Rastogi (1980) that the relationship between range spread-F and sunspot activity is positive for pre-midnight hours, and strongly negative for post-midnight hours. The frequency spread-F, however, showed relatively little sunspot activity variation. A comparison of spread-F with both radar and scintillation observations was made by Rastogi (1981 & 1986).
Night time scintillations are classified into two types namely, Class I and Class II depending upon their association with bottomside spread-F and fading rates (Krishna Moorthy et al., 1979). Vijaya Kumar et al. (1988), on the basis of a thorough study of association of scintillation with spread-F, showed that Class I scintillations are associated invariably with range spread-F and Class II with frequency spread-F. The percentage occurrence of Class I scintillations increases with an increase of solar activity and they peak in equinox, while the percentage occurrence of Class II scintillations decreases with an increase of solar activity and they peak in summer. Somayajulu (1987), in his review, inferred that Class I are confined to a narrow latitude belt of ±10°, called equatorial range-type of spread-F while the Class II types are confined to a low latitude belt extending to ±20 to ±30°.

Substantial progress has been made in recent years towards an understanding of instability processes that produce equatorial spread-F, particularly as a result of rocket and radar experiments. Much has been learnt regarding bubble growth occurrence (Dungey, 1956; Haerendal, 1973; Fejer et al., 1980) morphology (Chandra et al., 1972; Sastri and Murthy, 1975; Basu et al., 1976; Rastogi, 1980; Dasgupta, 1983; Aarons, 1991 and Dabas et al., 1992) and generation mechanisms of spread-F irregularities in the equatorial ionosphere (Krishna Murthy, 1993). The spread-F index was found to be directly related to the amplitude of pre-reversal enhancements in F-region vertical plasma drift. Along with this, the height of the F-layer is the parameter which plays an important role in the initiation and growth of the equatorial spread-F.

Since intense plasma density irregularities over the equator give rise to the phenomenon of equatorial spread-F which are also responsible for radio wave scintillations in trans-ionospheric propagation we consider, in the next section, the dynamics of these irregularities.
3.6 Equatorial Plasma Bubble Dynamics

Ionospheric plasma irregularities are direct manifestations of the electrodynamic coupling that governs the ionospheric-thermospheric system. However, at the magnetic equator, after local sunset, the bottomside electron density profile begins to steepen due to recombination. The eastward electric field at the magnetic equator during sunset shows an enhancement, before reversing in the westward direction. The enhanced $E \times B$ electrodynamic drift raises the F-region of the ionosphere to higher altitudes. Plasma density fluctuations begin to develop at the bottomside through $E \times B$ gradient drift instability processes which, in turn, forms density depletions in ambient plasma. These irregularities then develop in the form of plasma-depleted bubbles. The buoyant forces would then keep pushing the bubbles up until a region of equal or smaller density is reached. The initial bubble rise velocities would be a maximum due to the fact that maximum plasma density gradient exists at the bottomside of the ionosphere. Plasma bubbles are strongly aligned along the magnetic flux tubes extending on either side of the magnetic equator (Tsunoda 1980).

As the field-aligned plasma bubble and the associated irregularities rise in the equatorial ionosphere, the low-latitude extremities of the bubble should propagate away from the equator in such a way that the upper height limit of the irregularity would also define the latitudinal limit of the irregularity occurrence associated with the given event (Abdu et al., 1983). Multi-station observations of night-time scintillation occurrence along a common meridian plane reported by Somayajulu et al. (1984) and Dabas and Reddy (1986) support this hypothesis.

The $E \times B$ drift in the post-sunset hours at the equator plays a dominant role in the production of irregularities and in a re-distribution of ionisation over the equatorial region. It is generally accepted that Rayleigh-Taylor (R-T) instability mechanism in its generalised form which includes the cross-field instability mechanism and neutral wind effect and the various drift mode instabilities, account for the equatorial irregularities at different scale sizes.
The plasma analogy of the classical gravitational R-T instability occurs when the acceleration due to gravity \((g)\) is anti-parallel to the electron density gradient \((\Delta n)\) with both of them perpendicular to the magnetic field \(B\). Such a situation always exists in the equatorial bottom-side F-region. The growth rate of the instability is given by

\[
\gamma = \left[ \frac{\gamma_{in} - (\gamma_{in}^2 - \frac{4g}{L})^{1/2}}{2} \right] - \beta
\]

(1)

where \(\gamma_{in}\) is the ion-neutral collision frequency, \(L = N(\frac{\Delta n}{n})^{-1}\) with \(N\) as the electron density; \(h\), the altitude and \(\beta\), the attachment coefficient in the F-region.

\[
\gamma = \frac{g}{\gamma_{in}} - \beta \quad \text{for} \quad \gamma_{in}^2 > \frac{4g}{L}
\]

(2)

and

\[
\gamma = \left( \frac{g}{L} \right)^{1/2} - \beta \quad \text{for} \quad \gamma_{in}^2 < \frac{4g}{L}
\]

(3)

Equations (2) and (3) represent the collisional and collisionless R-T regimes respectively.

The different magnitudes of growth rate \(\gamma\) permitted by the ambient ionosphere-thermosphere conditions, such as conductivity distribution, neutral winds and electric fields are responsible for producing the different classes of irregularities. This theory holds good for equatorial spread-F as well as generation of equatorial scintillations.

3.7 Results and Discussions

Thiruvanathapuram shows remarkable variations during high periods of solar activity. 1989 June solstices shows a peak which changes to December solstices during 1990 and again shifts to June solstices during 1991. The peak during September-October and March-April are almost equal for the year 1988 with a medium sunspot number 98.
However during the year 1989, the September-October peak is higher than the March-April peak; for the year the sunspot number is 154. This trend is repeated for the year 1990 which is also a high sunspot year with SSN 149. So no systematic rule can be extracted from this data. However, the years 1988 and 1992 equinoctial maxima are seen; our results are in agreement with the suggestion that the equinoctial maxima is a general behaviour of this sector during the years of low sunspot numbers (Pathan et al., 1991).

Comparing the seasonal variations of scintillations at the equator and the anomaly region. Dabas et al. (1986) concluded that the equinoctial and December solstice nighttime scintillations, during the years of high solar activity are produced by ionospheric irregularities of equatorial region.

The station close to the magnetic equator (i.e., Thiruvanathapuram & Tiruchendur) show strong scintillation which lasts till early morning in a single patch or sometimes by an absence of scintillations for a short duration, during high solar activity. At the same time scintillations reduce to three to four hours during low solar activity periods. This leads to the conclusion that the electron density in the post-sunset time period may not be of sufficiently large magnitude during years of lower solar flux. This may be the main reason for a lower occurrence of scintillations during low sunspot periods.

The nocturnal variation shows a maximum percentage variation of scintillations of about 50% at the equatorial station (Thiruvanathapuram) while it drops to 20% in the anomaly crest station during 1992. This leads us to surmise that the increased scintillations activity is due to higher levels of ΔN i.e., there is more plasma (ΔN) available at the equatorial zones than at the anomaly crest zone. Therefore, the integrated density deviation associated with the irregularities should be much higher and give rise to more intense scintillations effect in the equatorial zone.
A spectral model of F-region electron densities at equatorial and low latitudes has been done by Singhal (1992). However, an extended period of observation may be needed to note the apparent and real differences in this case.

Basu and Kelley (1979) reviewed the equatorial scintillation observations and their relationships to the theoretical development of plumes and bubbles. Ossakow (1981) reviewed much of the theory and numerical scintillation results for plume structure development which strongly increased the understanding of the basic mechanisms of plume formation due to the Rayleigh - Taylor instability mechanism.

The percentage occurrence of scintillations tends to decrease with increasing geomagnetic disturbances at the equatorial station during the years of high solar activity. From observational evidence and discussions in literature a systematic behaviour is found: on quiet days the magnetic field is enhanced and thus scintillation activity increases, while on disturbed days the Earth's field is reduced and shows a lower occurrence of scintillation. Moreover, since Thiruvananthapuram is one of the electrojet stations, this in turn increases the Earth's magnetic field so naturally one can expect more scintillations to occur at this station.

Figure 3(n): Plot of monthly variation of scintillation occurrence with monthly mean sunspot number (S.S.N)
Figure 3(o): Comparison of pre-midnight and post-midnight occurrence of scintillations. Series 1 indicating premidnight and series 2 indicating postmidnight scintillations.

Figure 3(p): Plot showing the comparison of planetary magnetic activity (top), solar flux, and scintillation activity during the entire observation period.
3.8 Conclusions

At equatorial stations scintillations occur continuously throughout the night during the years of high sunspot number. It breaks up into discrete patches of 3 to 4 hrs duration during the time of moderate solar activity. The percentage occurrence consistently decreases with a decrease in solar activity. It has been observed that a major peak in the occurrence is around 2100 hrs IST. During 1992 a secondary peak was also observed in the post-midnight hours. All the data sets show a general increase in scintillation levels with increasing sunspot number. These observations are consistent with the conclusion that the overall ionospheric density is known to increase with increasing sunspot number.

Such studies will eventually lead to the underlying principle that embodies the basic reason for night time equatorial irregularities. The bubble development itself is actually the climax of a series of instabilities in the ionospheric and thermospheric systems. Geomagnetic variation (included in Chapter 4) makes the theoretical approach more difficult than the other control parameters. However we hope that a mixture of improvement in data, modifications in theory and large leaps in conceptual understanding would finally lead to a good model for equatorial scintillations in the Indian sector.