

## Some features of plasma bubble induced scintillations during the AICPITS campaigns of 1991

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The VHF scintillations were recorded at a chain of low-latitude stations in India as part of the All India Coordinated Programme of Ionospheric and Thermospheric Studies (AICPITS), using the 244 MHz radio beacon from the geo-stationary satellite FLEETSAT which was located at 73° E longitude. Data collected during the second campaign of September-October 1991 and analyzed jointly by the participating investigators are presented. The onset times of scintillation at pairs of stations at similar latitude but different longitudes can be used to estimate the eastward drift of the scintillation patches and its E-W extent. The maximum monthly mean occurrence for September 1991 is about 35% at Trivandrum and Tiruchendur, the stations close to dip equator. Occurrence is maximum for stations Annamalainagar, Payyanur and Anantpur (50 %), located slightly north of the dip equator. It decreases further north to 30 % at Nuzvid, Bombay, 20 % near anomaly crest region, 10 % at Agra and 8 % at Delhi, which is the northern most edge of the present observations. The occurrence frequency is slightly less than that observed during the campaign of March 1991. For the sake of completeness some very interesting features and dynamical characteristics of plasma bubble induced scintillations are included here based on digital records of scintillations made at Delhi during the two equinox data campaigns in March-April 1991 and September-October 1991.

**Keywords:** Plasma bubble, VHF scintillations, AICPITS, Equinox data campaigns

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### 1 Introduction

Radio beacons on-board orbiting or geo-stationary satellites provide a simple method of studying ionospheric irregularities. The fluctuations in the signal strength are related to the fluctuations in electron density. Temporal and spatial variations of

scintillation as characterized by scintillation index have been studied extensively. Globally there are two regions of strong scintillations – one centred over the magnetic equator and the other at high latitudes (Ref. 1 and references therein). Equatorial scintillations occur mainly at nighttime and are associated with equatorial spread-F. As strong scintillations often disrupt radio communications, the understanding of

the physical processes involved in the generation of ionospheric irregularities associated with equatorial spread-F/scintillation and forecasting is of considerable interest.

India provides a unique location for study of scintillation at low latitudes covering a region right from dip equator to F2 anomaly crest region and beyond. Scintillation studies were initiated in India using the radio beacons from orbiting explorer satellites. Detailed studies of multi-frequency scintillation in India were first attempted during the ATS-6 phase-II SITE experiment with observations made from Thumba and Ootacamund<sup>2-5</sup>. A chain of few stations<sup>6</sup> was set up during the total solar eclipse of February 1980. Extensive studies were made with the All India Coordinated Programme of Ionospheric and Thermospheric Studies (AICPITS) and a chain of 20 stations were operated. Their locations are indicated on the map of India given in Fig.1. The observations were made at 244 MHz using the radio beacon on-board the geo-stationary satellite FLEETSAT (73°E). The recordings were made using identical systems at most of the places, developed at the Indian Institute of Geomagnetism (IIG), Mumbai. There were 3 campaigns conducted during March-April 1991, September-October 1991 and February-March 1993. Workshops were conducted at Kolhapur,

Varanasi and Rajkot to analyze jointly the data collected during the three campaigns. Chandra *et al.* have described the details of the system used, and station coordinates with sub-ionospheric points along with the results for the first campaign. Scintillations at stations close to the dip equator occur almost continuously through the night with longer duration but break into more discrete patches at latitudes near the anomaly crest and beyond. There is a systematic delay in the onset time of scintillation away from the dip equator. Half width of the equatorial belt of scintillations was shown to be 15° before midnight and 6° in the post-midnight. Sushil Kumar *et al.* reported the results for the third campaign. From the time delay between the onset times of scintillation at different latitudes, estimate of the vertical velocity of large-scale plasma depletions was made. The results for the second campaign are described in the present paper.

## 2 Observations and results

The geographic coordinates of the stations with the dip angle at the sub-ionospheric point of the satellite to receiver path (at 400 km) are listed in Table 1. The chain covers the region from dip equator to about 44° N dip angle. The data from charts were scaled for the start time and end time of each patch of scintillation and the quarter hourly presence of scintillation.

An example of the recording of scintillation on paper chart at few selected locations is shown in Fig. 2 for the night of 5 Oct.1991. The pattern is almost identical at Trivandrum, Tiruchendur, Karur and Annamalainagar. There are 2 patches of strong scintillations (exceeding 20 dB). Further to north, two patches are seen at Anantpur, Goa and Bombay, but there are no scintillation at Ujjain. Thus, the N-S extent of the two patches is located up to north of Bombay and south of Ujjain.

Further, in Fig. 2 the first patch appeared at 2133 hrs IST at Trivandrum, 2147 hrs IST at Tiruchendur, 2151 hrs IST at Karur and 2207 hrs IST at Annamalainagar. The second patch appeared at 2147 hrs IST, 2201 hrs IST, 2203 hrs IST and 2218 hrs IST at the four stations, respectively. As both Trivandrum and Tiruchendur stations are close to dip equator the time difference (delay) of 14 min at Tiruchendur is because of the eastward drift of the scintillation patch. The difference of 1.3° in longitude between the two stations amounts to a separation of about 143 km and time delay of 14 min implies that the patch of scintillation is moving eastward with a velocity of

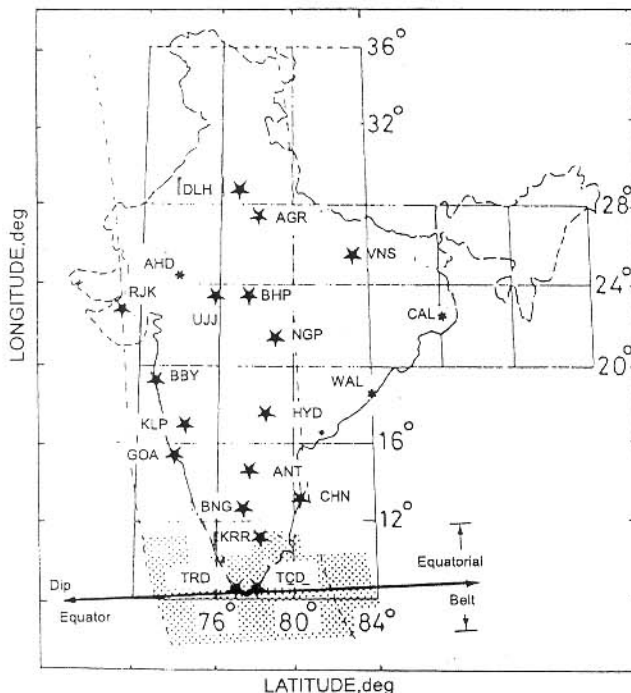


Fig.1 — Map of India showing the locations of the stations recording the 244 MHz radio beacon from FLEETSAT for scintillation studies during the AICPITS

Table 1 — Locations of the scintillations recording stations in India during the campaign of September-October 1991

Station name	Geogr. lat. deg	Geogr. long. deg	Dip angle deg	Sub-ionospheric dip deg
Trivandrum	8.4	76.9	0.6	-0.6
Tiruchendur	8.5	78.2	0.7	-0.5
Karur	11.0	78.0	6.8	5.4
Annamalainagar	11.4	79.4	7.6	6.0
Payyanur	12.0	75.8	8.9	7.1
Anantpur	14.7	77.6	15.7	13.4
Goa	15.2	74.0	17.2	14.9
Nuzvid	16.8	80.8	19.9	18.0
Waltair	17.7	83.3	21.9	19.3
Bombay	19.0	73.0	25.7	22.9
Nagpur	21.1	79.1	29.5	26.6
Rajkot	22.3	70.8	32.6	29.6
Ahmedabad	23.0	72.4	33.8	30.7
Bhopal	23.2	77.6	33.8	30.7
Ujjain	23.2	75.8	33.9	30.8
Calcutta	22.6	88.4	31.9	28.7
Varanasi	25.3	83.0	37.3	34.0
Agra	27.2	78.1	41.1	37.7
Delhi	28.8	77.2	43.7	40.7

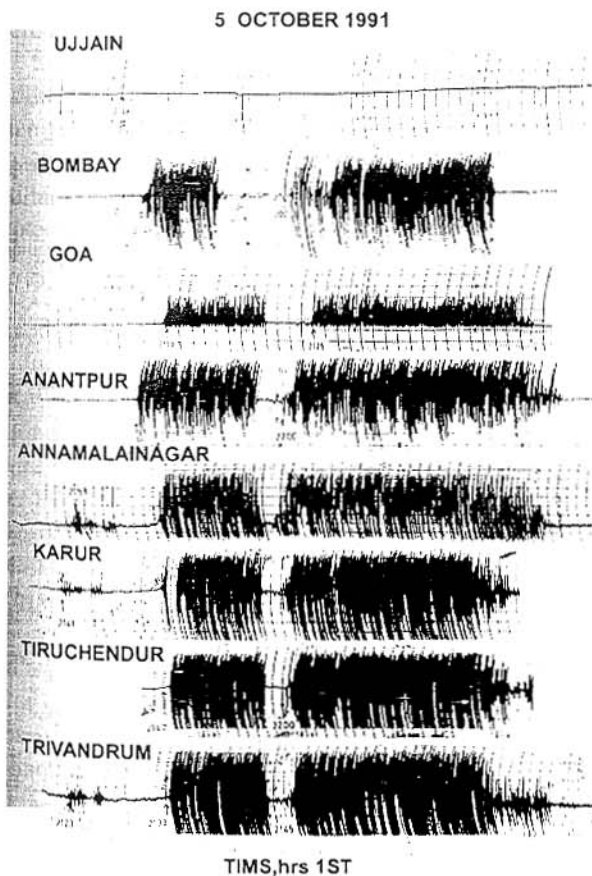


Fig. 2 — Examples of scintillations recorded at Trivandrum, Tiruchendur, Karur, Annamalainagar, Anantpur, Goa, Bombay and Ujjain (no scintillations) in the post-sunset period of 5 Oct. 1991.

170 m/s. The duration of patch is about 9 min, which will translate into an E-W extent of patch of about 90 km. The second patch is of 22 min duration and is equivalent to E-W extent of about 220 km. In addition to the two strong patches, there are two very short-duration patches of very weak scintillation (2 dB) preceding the main events. These patches are seen up to Annamalainagar only, implying that the N-S extent is smaller. The duration of these two events is about 2 min, and since one minute delay corresponds to about 10 km, the E-W extent, in this case, translates to 20 km. Similarly, the stations Karur and Annamalainagar have almost similar latitudes. The time delay of 16 min in the onset of scintillation and the longitude separation of  $1.4^\circ$  gives an eastward drift velocity of 160 m/s.

There is one difference that the time gap between the two patches, which was about 2.5 min at all stations from Trivandrum to Annamalainagar, starts increasing from Anantpur (3 min) to Goa (4 min) and Bombay (6 min). This, along with the observed fact that the patch duration is a little longer at Annamalainagar and Anantpur, points to the fact that the eastward drift velocity is becoming less at latitudes away from the magnetic equator. Further north, the patch duration appears to be less at Bombay. This is consistent with earlier results<sup>7</sup> that the patch duration becomes less as we move from dip equator to near anomaly crest region and beyond.

The longitudes of Tiruchendur and Karur are almost same. The delay of onset of scintillation at Karur is 3 min. Considering the longitude difference of  $0.2^\circ$  one will expect a delay of about 2 min due to the eastward drift of the scintillation patch. The delay of the onset of scintillation patch at Annamalainagar is 35 min. The longitude difference of  $2.5^\circ$  can account for about 25 min. Therefore, there is further delay, which could be due to the vertical drift of patch close to the dip equator and consequent spread of the scintillation patch along the geomagnetic field lines. Thus, the time delays in the onset of scintillation at stations with different longitudes but same latitudes can be used to provide eastward drift speed and E-W extent of the scintillation patches. Time delays at stations with different latitudes can provide vertical drift speed of the large-scale plasma depletions.

The mean nocturnal variations of the scintillation occurrence for the month of September 1991 at different stations are shown in Fig. 3. The maximum occurrence at Trivandrum and Tiruchendur (stations close to dip equator) is about 35 %. The occurrence is maximum for stations such as Annamalainagar, Payyanur and Anantpur (50%). It decreases further north with the values of about 40% at Goa, 30% at Nuzvid, Bombay, 20% near anomaly crest region, 10% at Agra and 8% at Delhi, the northern most station in the chain.

A comparison of the monthly mean occurrence of spread-F at Waltair and Ahmedabad for September 1991 is shown in Fig 4. Onset of spread-F occurs before 1900 hrs IST at Waltair and peaks with a value of 47% at 1930 hrs IST. The occurrence frequency decreases steadily with local time and is less than 10% at 0400 hrs IST. The onset of spread-F at Ahmedabad located near the anomaly crest is at 2000 hrs IST. The occurrence frequency remains between 10% and 12% from 2100 hrs IST to 0200 hrs IST. A comparison of the occurrence of scintillation recorded at Waltair (Fig. 3) with the occurrence of spread-F at Waltair for the month of September 1991 shows earlier onset of spread-F than that of scintillation. The occurrence of spread-F is also little higher than that of scintillation. Maximum occurrence of spread-F is 47 % around 1930 hrs IST as compared to 40 % at 2015 hrs IST for scintillation. Chandra *et al.*<sup>4</sup> examined the multi-frequency (40, 140 and 360 MHz) scintillations at Ootacamund near dip equator during the ATS-6 phase-II observations with ionograms recorded at Kodaikanal and showed that strong scintillations are associated with range type of spread-F, while the

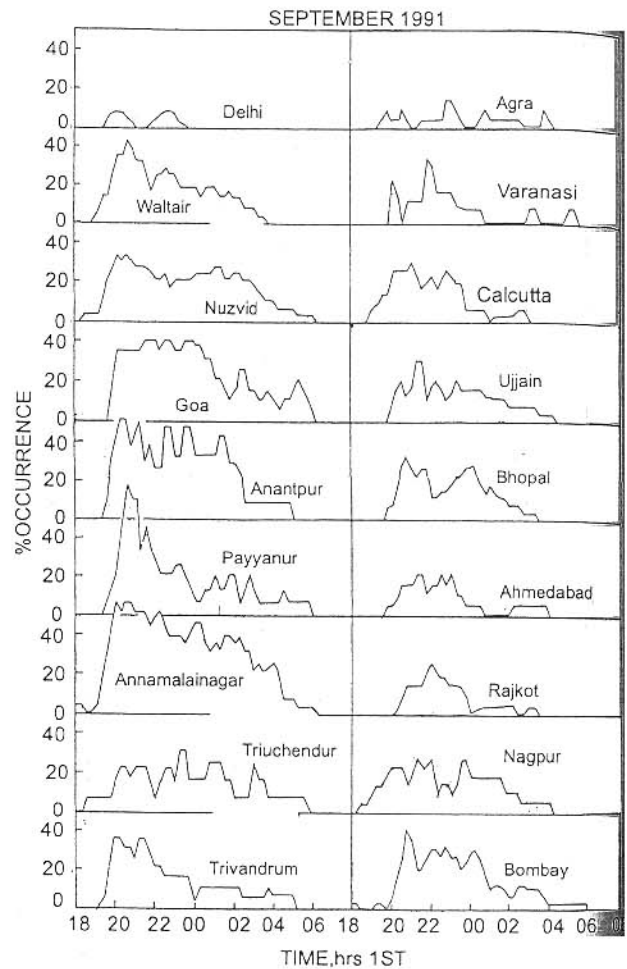


Fig. 3 — Nocturnal variations of the monthly mean percentage occurrence of scintillations at the chain of stations for the month of September 1991 based on quarter-hourly data

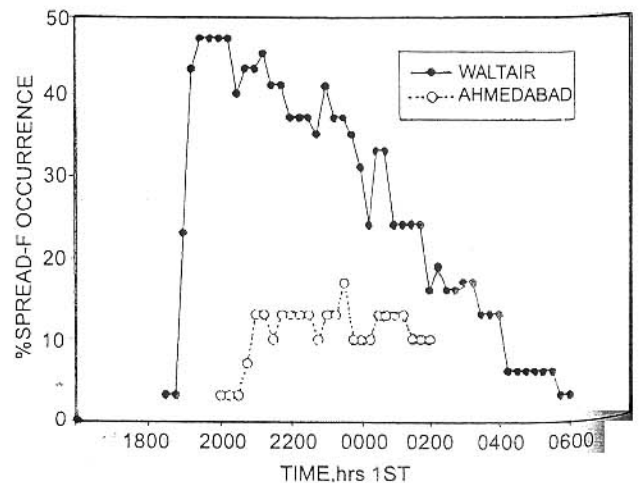


Fig. 4 — Nocturnal variations of the monthly mean occurrence of spread-F at Waltair (1900-0500 hrs IST) and Ahmedabad (2000-0200 hrs IST) for the month of September 1991 averaged for pre- and post-midnight hours during September 1991

scintillations associated with frequency type spread-F are weak and only seen at 40 MHz. Rastogi and Woodman<sup>9</sup> reported that VHF backscatter echoes at Jicamarca are associated with range spread only. It is well known that while range spread-F is predominantly a pre-midnight feature, the frequency spread-F is a post-midnight feature. Therefore, the extent of occurrence of spread-F to later periods in comparison to scintillation is understandable, because the scintillations are associated with range type of spread-F.

The daily plots of the occurrence of scintillations for the month of September 1991 at few selected stations are shown in Fig 5. Figure 5(a) shows the daily occurrence of the scintillations at Annamalainagar. The horizontal lines against each day of the month show the start time to end time of a scintillation patch observed. While NS denotes no scintillation, ND denotes no data (on that day). The scintillation activity was very low till 11 September, with small patches of scintillation occurring on 6-8 September. From 12 to 24 September, scintillations were observed every day and almost from 1930 hrs IST to 0430 hrs IST. Weak and intermittent scintillations were observed on 25, 27 and 29 September. Similar plots of scintillation recorded over Waltair are shown in Fig. 5(b). There were no scintillations till 11 September (except small patch on 8 September). From 13 to 24 September, scintillations were seen every day between 1930 hrs IST and 0300 hrs IST. Small patches were seen again on 25, 27 and 29 September. The trend is, therefore, similar to that seen for Annamalainagar with scintillations ending about 2 h earlier at Waltair. The occurrence of scintillation at Bombay [Fig. 5(c)] shows scintillation from 12 to 24 September only. Onset time is 2000 hrs IST or later and end time is 0100-0200 hrs IST except on 2-3 days when scintillations extended to morning hours. The plots for Ujjain and Calcutta [Fig. 6(a) and (b)] in the anomaly crest region, show still less duration of scintillation. Finally at Agra [Fig. 6(c)] scintillation occurrence is limited to few days and that also for duration of an hour or less. Also scintillation is observed at Agra only on days when strong scintillation (longer duration) is seen at stations in the equatorial region.

The latitudinal variations of the occurrence of scintillation for pre-midnight (2000-2200 hrs IST), midnight (2300-0100 hrs IST) and post-midnight (020-0400 hrs IST) are shown in Fig. 7((a),(b) and (c)). The best fit drawn from observed values shows

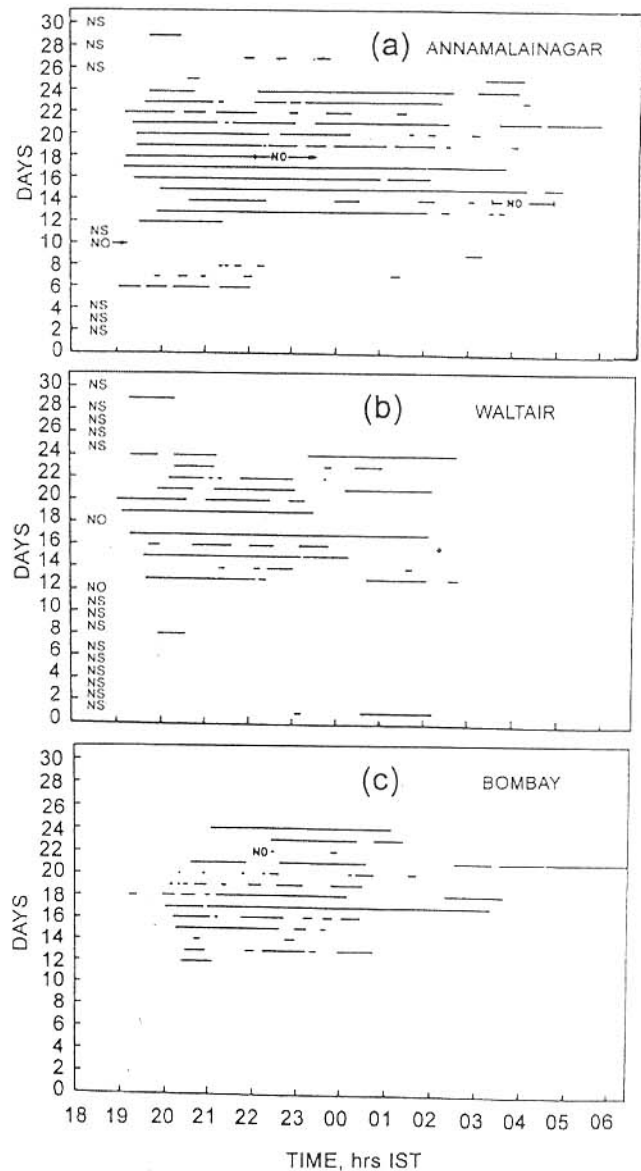


Fig. 5 — Daily plots of the start and end times of scintillations at (a) Annamalainagar, (b) Waltair and (c) Bombay for the month of September 1991 (NS: no scintillation; ND: no data)

maximum occurrence of scintillations around  $12^\circ$  geographic latitude with values of 50%, 40% and 25%, respectively, for the pre-midnight, midnight and post-midnight. The occurrence decreases steadily with higher latitude. The half-width of the equatorial belt of scintillation (defined as 50% of the maximum occurrence of scintillation) is  $10^\circ$ ,  $10^\circ$  and  $8.5^\circ$  for pre-midnight, midnight and post-midnight, respectively.

Though the recording of the signal was on paper chart at most of the stations, there were some locations where data were recorded in digital form. Digital data can be used to characterize the strength of scintillation as determined by the scintillation index  $S_4$

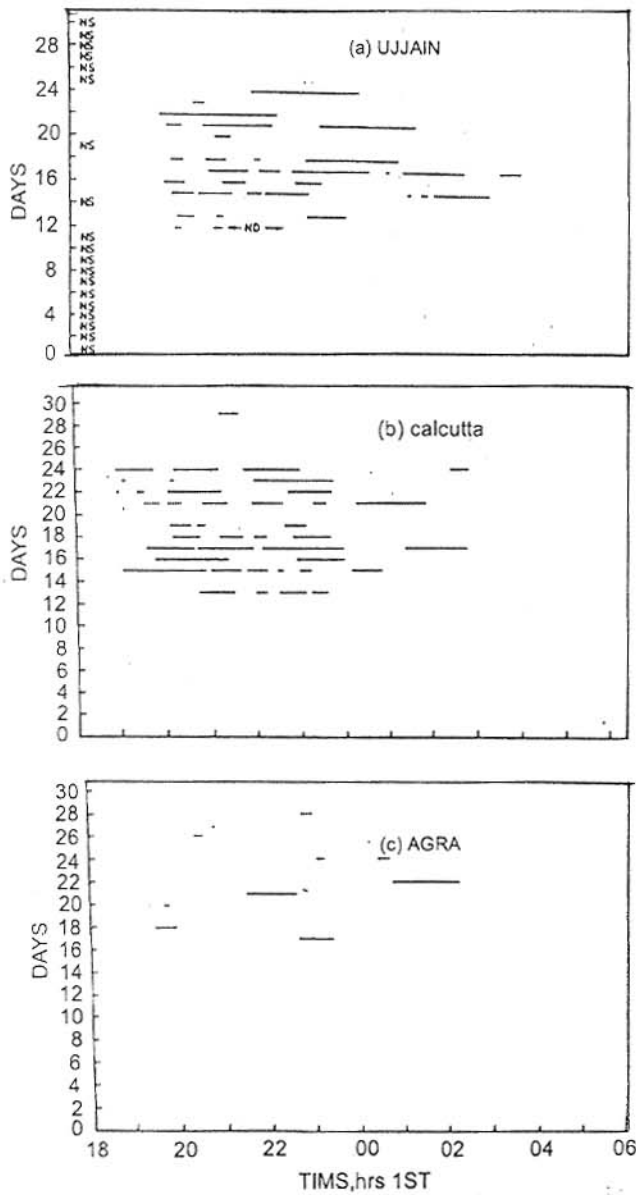


Fig. 6 — Daily plots of the start and end times of scintillations at (a) Ujjain, (b) Calcutta and (c) Agra for the month of September 1991 (NS: no scintillation; ND: no data)

and also to study the spectral features. As an example, here in Fig. 8, temporal variations of the  $S_4$  index and fading rate derived from digital data recorded at Bombay during the night of 17-18 Sep. 1991 have been shown. Though scintillation appeared as a large patch lasting for few hours, the variation of  $S_4$  shows strong scintillation with a value of about 1.2 for most of the time. However, there is periodic variation with value of  $S_4$  dropping to as low as 0.2 for brief moments. Thus, the scintillation patch itself has structures. This appears to be similar to the VHF radar plume structures that show different plasma bubbles

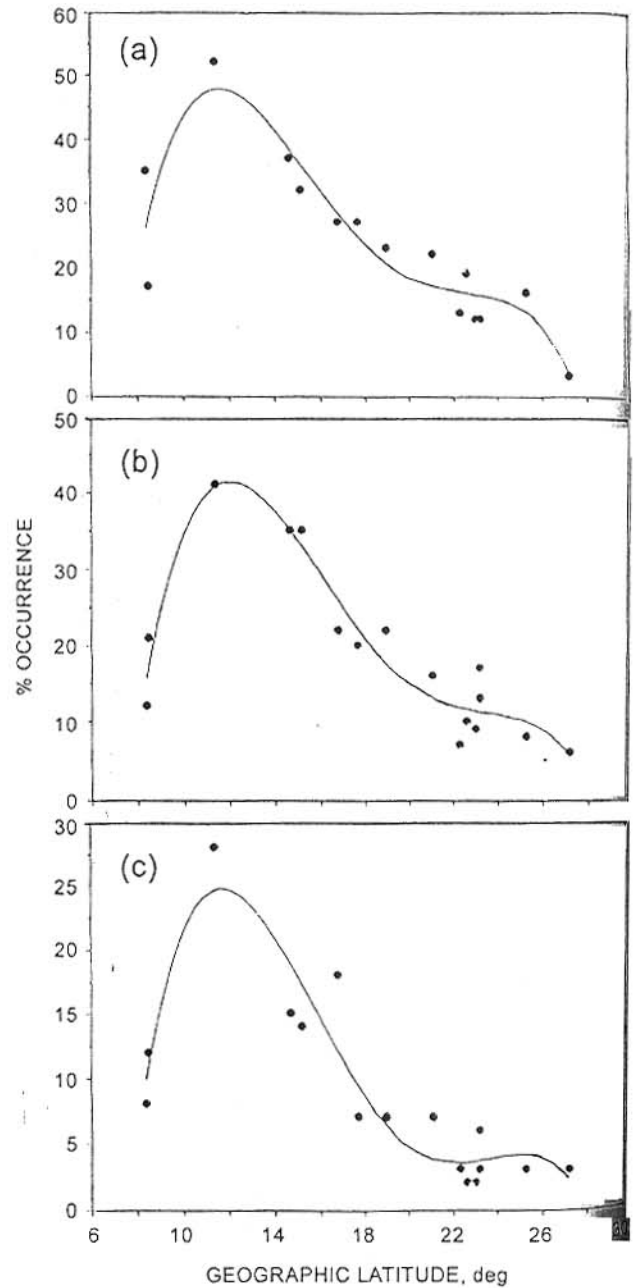


Fig. 7 — Latitudinal variation of the mean percentage occurrence of scintillation averaged for (a) pre-midnight hours (2000-2300 hrs IST), (b) midnight hours (2300-0100 hrs IST) and (c) morning hours (0200-0400 hrs IST) during September 1991 (The fit is represented by the solid lines)

appearing with periodicity. Temporal variation of the fading rate also shows similar structures with values ranging from about 80 fades per minute to about 100 fades per minute.

In Delhi, the post-sunset scintillations in the months of September-October 1991 present an interesting scenario and are very similar in nature to those recorded during March-April 1991.

similarities are that the scintillation occurrences are predominantly in the pre-midnight hours (2000-2345 hrs IST) and the extent of the patches are 10-25 min. The observed fading rates are 3-5 fades per second. Hence, 11 Hz sampling rate is employed in the digital data acquisition system. Using the digital data we are able to reproduce some very fine details of the plasma bubble-induced scintillations observed at Delhi at 244 MHz FLEETSAT signal. Using the digital data Vijayakumar and Pasricha<sup>10</sup> have earlier parametrized these plasma bubble induced (PBI) scintillations based on their temporal spectral features. A typical feature of plasma bubble-induced scintillation patch is shown in Fig. 9, which is reproduced from the digital record. This is the first 30 seconds of scintillation pattern seen at the start of patch recorded on 24 Sep. 1991. There are three distinct phases that are seen and

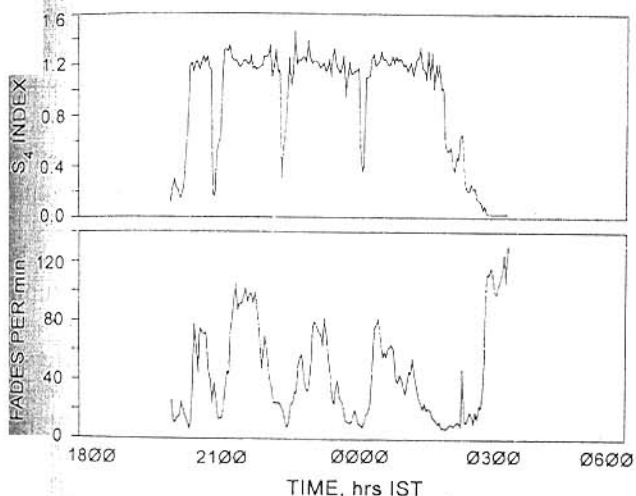


Fig. 8 — Temporal variations of the scintillation index  $S_4$  and fading rate recorded at Bombay during the night of 17-18 Sep. 1991

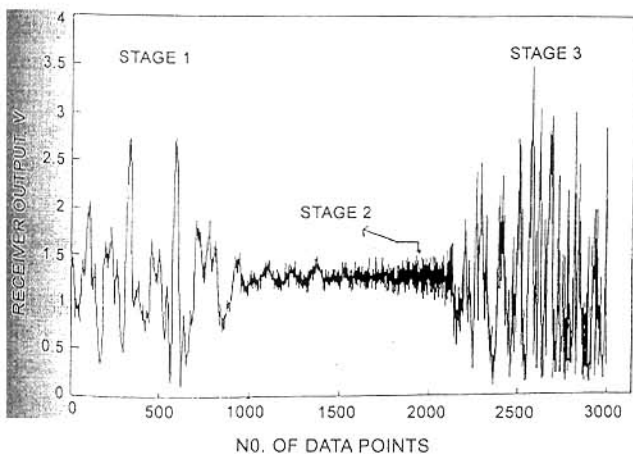


Fig. 9 — Typical initial phase of a scintillation patch associated with a plasma bubble recorded at Delhi on 24 Sep. 1991

marked as such in the Fig. 9 at the start of scintillations. Stage-I corresponds to weak Gaussian irregularities, stage-II corresponds to quasi-periodic scintillations and stage-III corresponds to scintillations induced by fully developed plasma bubble. Out of 31 scintillation patches recorded at Delhi during the two equinox periods (March-April 1991 and September-October 1991), 16 patches distinctly exhibit quasi-periodic fluctuations. These finer features of scintillations are not adequately resolved using conventional strip chart records. It is also interesting to note that towards the end of such scintillation patches the quasi-periodic scintillations reappear before the fluctuations finally die down to merge with the average signal level. In Fig. 10 is shown a fine example of a quasi-periodic scintillation occurring at the beginning of a strong scintillation patch, which was recorded on 15 Mar. 1991. A very exhaustive analysis of this has been performed using the well known technique developed by Titheridge<sup>11</sup> and Franke and Liu<sup>12</sup>, from which the eastward drift speed of the quasi-periodic scintillation patch, as close to 100 m/s, has been estimated within 2% error. Also, this drift value is further augmented by the two satellite scintillation observations, namely, FLEETSAT (73°E) and INMARSAT (63°E) at 1537 MHz. In this technique, since we know the distance separating the satellite sub-ionospheric points at 350 km height as 82 km, as seen from Delhi, it is quite simple to compute the drift speed of a scintillation patch by noting the delay in the onset time of scintillation on the two satellite signals. The distance of sub-ionospheric separation (in metres) divided by the delay (in seconds) gives the initial drift speed. The drift is always eastward as noted from scintillations.

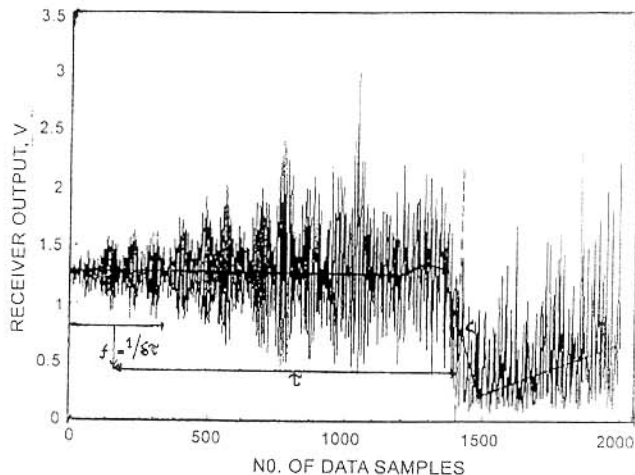


Fig. 10 — Quasi-periodic scintillations recorded at Delhi on 15 Mar. 1991

which are registered first on INMARSAT L-band and next on FLEETSAT VHF signals. The drift values are found to lie between 98 m/s and 140 m/s. Table 2 gives drift values obtained by using the two-satellite method. It is important to mention that there are many occasions when scintillations are observed on FLEETSAT VHF signal only and there are no corresponding scintillations seen on INMARSAT L-band signal. This is because the L-band scintillations are triggered by strong gradients embedded in the plasma bubble irregularities, while such is not the case with VHF scintillation production which are caused by much weaker plasma gradients.

Another important feature of these (PBI) VHF scintillations are that they help in identifying features of ionospheric irregularities much larger than Fresnel scale. In fact, the smaller (weaker) Fresnel size irregularities are often embedded in much larger scale irregularities, acting as either converging or diverging lenses for the satellite radio waves observed on ground, giving rise to strong focusing or de-focusing of the radio waves, as the case may be, at an observer's point on the ground. The saturated scintillation (marked as stage-III) in Fig. 9 has been analyzed for obtaining spectral features of the scintillation due to fully developed plasma bubble. In Fig. 11 is shown the long period fading component from FLEETSAT VHF scintillation filtered data which bears the foot prints of plasma gradients in the form of large signal excursions (close to 8 dB peak-to-peak) occurring at the start of the saturated scintillation phase. These signal excursions are due to focusing and de-focusing of the satellite signal. Further, these long period fading is subjected to spectral analysis to obtain the so-called lens scales.

Table 2 — Eastward drift of irregularities in the pre-midnight period during equinoxes of 1991 obtained from INMARSAT (63° E) and FLEETSAT (73° E) scintillations over Delhi

Date	Scintillation onset hrs IST	Time delay s	Eastward drift m/s
04 Mar. 1991	2105	656	125
11 Mar. 1991	2119	732	112
12 Mar. 1991	2059	640	128
15 Mar. 1991	2112	820	100
24 Apr. 1991	2028	577	142
09 Oct. 1991	2107	802	102
10 Oct. 1991	2056	494	166
12 Oct. 1991	2041	487	168
13 Oct. 1991	2057	684	120
15 Oct. 1991	2106	788	105

The result of such an analysis is shown in Fig. 12. The two spectral peaks marked as (a) and (b) in Fig. 12 obtained from the spectral analysis correspond to the outer scale points of 34 km and 15 km, respectively. These spatial scales are obtained by resorting to time-to-space conversion taking into account the drift velocities. The drift velocities were obtained from two-satellite observations described earlier corresponding to two scintillation events that occurred on 4 and 11 Mar. 1991.

An important aspect of any such coordinated scintillation observations is that it offers a simple means of estimating plasma bubble rise-velocities over the magnetic equator derived from the latitudinal extent of scintillation occurrence. However, the basic requirement is that the stations chosen are aligned in the magnetic meridian. In an earlier such experiment Somayajulu *et al.*<sup>6</sup> and Dabas and Reddy<sup>13</sup> obtained plasma bubble rise-velocities in the Indian sector by a

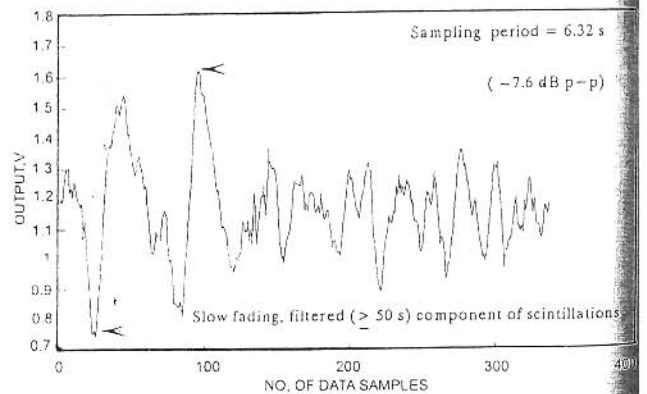


Fig. 11 — Long period fading component from VHF scintillation filtered data

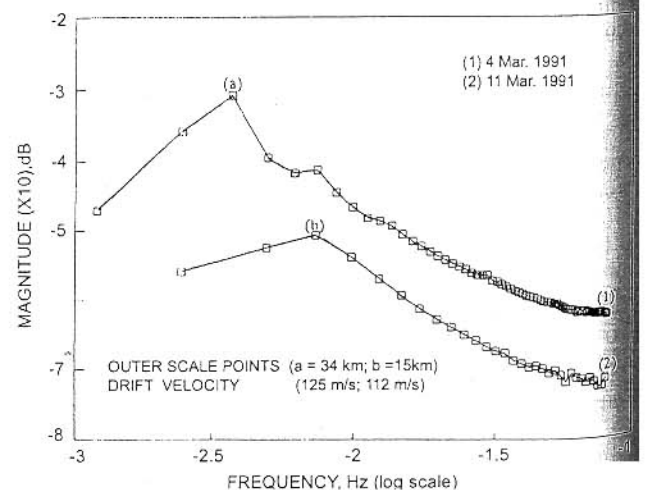


Fig. 12 — Temporal spectra associated with long period fading (Note that the scale sizes are much larger than typical Fresnel scale  $\approx 600$  m at the observing frequency)



simple technique. This is based on noting the monotonic increase in the time of scintillation onset, hence the delay in the onset time, as one moves away from the magnetic equator along a meridional chain of observing stations. Next, by knowing the field-line mapping geometry to the sub-ionospheric points (at 350 km), corresponding to the observing stations, it becomes a matter of simple computational effort to relate the delay in the onset time of scintillations to plasma bubble rise-velocities in the vertical plane over the magnetic equator. The field-line mapping gives the height to which the field-line maps in the vertical plane over the magnetic equator from a given sub-ionospheric point corresponding to an observing station. In the present campaign during September-October 1991, a limited data set is available, comprising 22 scintillation events of simultaneous scintillation observations made at Bangalore (6°N dip latitude), Hyderabad (11.1°N dip latitude) and Delhi (24.8° N dip latitude). The plasma bubble rise-velocities were computed using this data base and some preliminary results were reported by Vijayakumar *et al.*<sup>14</sup>.

Due to the field-line mapping, the observed onset of scintillations at Bangalore, Hyderabad and Delhi are initiated by plasma bubbles at the heights of 415 km, 520 km and 1245 km, respectively, over the magnetic equator. Further, this enables computation of plasma bubble rise-velocities between the two height regimes, 415-520 km and 520-1245 km. The bubble rise-velocities are small (large) when the F-region ambient (eastward) electric field is small (large). Since linear bubble growth rate is proportional to the ion-neutral collision frequency, the growth rate is high when the F-region is at a higher altitude where the collision frequency is small. Thus, day-to-day variations are seen in the plasma bubble generation and growth depending upon the height of the ambient F-region, which, in turn, depends upon the eastward electric field magnitude. In the present study, the vertical drift velocity in F-region (measure of eastward electric field) in the evening hours is derived from the rate of change of hourly  $h' F$  values ( $dh' F/dt$ ) at Kodaikanal, located close to the dip equator. Bittencourt and Abdu<sup>15</sup> have shown that in the evening hours the vertical drift velocity computed from the rate of change of  $h' F$  values from ionosonde is same as the vertical  $\mathbf{E} \times \mathbf{B}$  plasma drift velocity as long as  $h' F$  is above 300 km. Rastogi *et al.*<sup>16</sup> compared the nighttime vertical drift velocities obtained from the rate of change of  $h' F$  at Huancayo

(2° N dip) during post-sunset hours (1800-2200 hrs LT) with the vertical drift velocity obtained from Jicamarca (0.9° N dip) VHF backscatter radar and found very high correlation. During intense range spread-F the lower boundary of spread echoes can be used to determine vertical velocity. The onset of spread-F in ionograms shows echo traces, first appearing at the base of F-layer at lower frequencies and then extending to entire frequency range. The VHF radar maps also show the variation of the lower edge of echoing region as the variation of the base of F-layer. Thus,  $dh' F/dt$  from Kodaikanal is used in the present study for vertical velocity. In Fig. 13 are plotted  $dh' F/dt$  against bubble rise-velocities derived from the delay in the onset of scintillation at Bangalore and Hyderabad that corresponds to height range 415-520 km, because this range signifies early post-sunset scenario. It is seen from the Fig. 13 that there exist two distinct sets of bubble rise-velocities. The first set of values 50-100 m/s indicates only small differential velocity between the rising bubble and the ambient ionosphere. This is shown by a linear fit to the set of points marked (I). The next set of values 100-450 m/s indicates that there is a very large differential velocity existing between the rising plasma bubble and the background ionosphere. This range of values is fitted with a straight line marked (II) in Fig.13. One important point becomes very evident from Fig.13 that if plasma bubble growth rate is to be strong enough to cause scintillation at latitudes beyond the anomaly crest region, then it is required that the initial bubble rise-velocity in the height range of 415-520 km over the equator must far exceed 100 m/s. It is most unlikely that scintillations

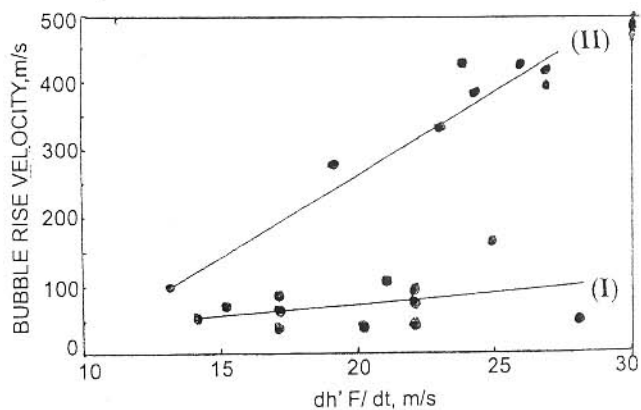


Fig. 13 — Bubble rise-velocity in the altitude range of 415-522 km plotted against the rate of change of  $h' F$  over Kodaikanal [The linear fittings in the two ranges of bubble velocity show correlation coefficients of 0.6 and 0.78 for lines I and II, respectively]

would be seen at higher latitudes if the initial bubble rise-velocity is 100 m/s or less. Thus, the present method offers scope for predicting scintillations over the Indian sub-continent.

Though no systematic study of the spectral features is made during the campaign period, it must be mentioned that the results of a systematic study on the spectral features based on scintillation data recorded at Tirunelveli, Pondicherry and Bombay have been reported by Banola *et al.*<sup>17</sup>

### 3 Discussion

Chandra *et al.*<sup>7</sup> reported the monthly mean occurrences of scintillation at different stations of the chain during the month of March 1991. Maximum occurrence of 50-60 % was noticed at Trivandrum and Tiruchendur located close to dip equator. Away from the dip equator, maximum occurrence of about 50 % was seen at Annamalainagar, Goa and Waltair. It reduced to 40 % at Bombay and further north to 30 % at Nagpur, Rajkot, Ujjain, Bhopal and Calcutta, all located near the anomaly crest region. It reduced further to 20 % at Delhi and 10 % at Agra. The scintillation occurrences were, thus, little higher during March 1991 as compared to the month of September 1991. One difference noted is that the occurrence of scintillation during September 1991 was maximum at stations little away from dip equator rather than at dip equator noted in March 1991. The results for the third campaign<sup>3</sup> of February-March 1993 also showed higher occurrence of scintillations at Madras, Anantapur and Nuzvid, all located little away from dip equator than at Tiruchendur located close to dip equator. Also the occurrence of scintillations was little less in this period compared to the campaigns of 1991 due to declining solar activity.

A comparison of the occurrence of spread-F at Thumba, Waltair and Ahmedabad during March 1991 showed that spread-F occurrence was more than the occurrence of VHF scintillations at each of the three stations. Present comparison at Waltair also confirms this. This is consistent with the fact that it is only range spread-F, predominantly occurring in pre-midnight, which is associated with scintillations. Also the spread-F traces in ionosonde recordings are due to comparatively larger scale size irregularities, which are generated first. The half width of the equatorial belt of scintillation is  $10^\circ$  for pre-midnight and midnight and  $8.5^\circ$  for post-midnight hours during September 1991.

One of the important problems of equatorial and low latitude ionosphere is the prediction of equatorial spread-F and scintillation. It is believed that spread-F is triggered because of the generalized Rayleigh-Taylor (RT) instability acting on the steep plasma density gradients in the post-sunset period. The vertical height rise of F-layer due to the pre-reversal enhancements of the electric field is considered one of the conditions favouring the growth of the instabilities. Apart from the vertical height rise of F-layer in the post-sunset period and the evening reversal time of electric field, the strength of ionization anomalies has been used by different workers<sup>18-23</sup> as a precursor in prediction of equatorial spread-F. The networks of ionosonde and scintillation currently operating in India will provide important inputs in testing the conditions required for the generation of spread-F during different solar and geophysical conditions.

In the present study the analysis of scintillation data (digital) at Delhi that signifies the plasma bubble characteristics has been incorporated in our foregoing observations and results obtained thereof. In a sense Delhi is at the very edge of the latitude coverage for estimating the mapping of equatorial plasma bubble-induced-scintillations over the Indian sub-continent during this campaign. As is established by the earlier results<sup>7</sup> too from the previous AICPITS-data-campaign based on March-April 1991 observations, scintillation patches seen at higher latitudes like Delhi signify some of the strongest plasma bubble events occurring over the magnetic equator due to the evening equatorial ionosphere, being subjected to large scale Rayleigh-Taylor (RT) instability both in space and in time. Thus, the strength of RT instability at the magnetic equator governs the latitude extent of scintillations. Also, since the satellite signals to Delhi propagate through the anomaly region where the background daytime electron densities reach their maximum, the satellite signals are likely to be scattered most by the scintillation irregularities produced in the post sunset periods in this region, giving rise to very strong scintillations observed at Delhi which is often the case.

### 4 Summary

This paper, being the third in the sequence of studies describing the results obtained during AICPITS campaigns, emphasizes further the main features of nighttime satellite scintillation in the Indian subcontinent<sup>7-8</sup>. However, it is important to

mention that some of the new results obtained here conform to general features of plasma-bubble-induced scintillations obtained elsewhere<sup>9, 18-23</sup>. The results are summarized as follows:

- (i) The ionospheric irregularities associated with range spread-F are mainly responsible for the satellite scintillation occurrence in the late evening hours during the equinoxes. Thus, just as range spread-F occurrence, the nighttime scintillation occurrence is influenced by solar activity. Hence, higher incidence of scintillation is seen during higher solar activity.
- (ii) The half width of the equatorial belt of scintillation is  $10^\circ$  for pre-midnight and midnight, and  $8.5^\circ$  for post-midnight hours during September 1991.
- (iii) In a qualitative sense, the spatial and temporal extent of scintillation patch observed at a station close to magnetic equator signifies the strength of the generalized Rayleigh-Taylor instability and determines the latitudinal and longitudinal extent of scintillation proliferation in the Indian subcontinent.
- (iv) If plasma bubble growth rate is to be strong enough to cause scintillation at latitudes beyond the anomaly crest region then it is required that the initial bubble rise-velocity in the height range 415-520 km over the equator must far exceed 100 m/s.
- (v) The long period fading component from FLEETSAT VHF scintillation filtered data bears the foot prints of plasma gradients in the form of large signal excursions (close to 8 dB peak-to-peak) occurring at the start of the saturated scintillation phase. The long period fading is subjected to spectral analysis to obtain the so-called lens scales much larger than the typical Fresnel scale (1 km).
- (vi) The  $S_4$  index for saturated VHF scintillation is of the order of 1.2. However, periodic variation is observed with value of  $S_4$  dropping to as low as 0.2 for brief moments. Thus, the scintillation patch itself has structures. This appears to be similar to the VHF radar plume structures that show different plasma bubbles appearing with periodicity.
- (vii) At Delhi, two-satellite scintillation observations have given very good confirmatory results of east-west movements of scintillation patches.

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## References

- 1 Aarons J, Global morphology of ionospheric scintillations. *Proc IEEE (USA)*, 70 (1982) 360.
- 2 Moorthy K, Reddy C R & Murthy B V K, Nighttime ionospheric scintillations at the magnetic equator. *J Atmos & Terr Phys (UK)*, 41 (1979) 123.
- 3 Rastogi R G, Deshpande M R, Vats H O, Davies K, Grubb R N & Jones J E, Amplitude scintillations of ATS-6 radio beacon signals within the equatorial electrojet region (Ootacamund, dip 40 N), *Pramana*, 8 (1977) 1.
- 4 Chandra H, Vats H O, Deshpande M R, Rastogi R G, Sethia G, Sastri J H & Murthy B S, Ionospheric scintillations associated with features of equatorial ionosphere. *Ann Geophys (France)*, 35 (1979) 145.
- 5 Rastogi R G, Koparkar P V, Chandra H & Deshpande M R, Multifrequency studies of equatorial ionospheric scintillations at Ootacamund, *J Atmos & Terr Phys (UK)*, 52 (1990) 69.
- 6 Somayajulu Y V, Garg S C, Dabas R S, Lakha Singh, Tyagi T R, Loknadhram B, Ramakrishna S & Navaneeth G N, Multistation study of nighttime scintillations at low latitudes: Evidence of control by equatorial F-region irregularities. *Radio Sci (USA)*, 19 (1984) 707.
- 7 Chandra H, Vyas G D, Rao D R K, Pathan B M, Iype A, Ram Sekran B, Tyagi T R, Vijaykumar P N, Lakha Singh, Iyer K N, Pathak K N, Gwal A K, Sushil Kumar, Singh R P, Singh U P, Birbal Singh, Jain V K, Navaneeth G N, Koparkar P V, Rama Rao P V S, Jayachandran P T, Sriram P, Santa Rao N Y S, Das Gupta A, Basu K & Rastogi R G, Coordinated multi-station VHF scintillation observations in India during March-April 1991, *Indian J Radio & Space Phys*, 22 (1993) 69.
- 8 Sushil Kumar, Gwal A K, Rama Rao PVS, Jayachandran P T, Prasad S V V D, Singh R P, Singh U P, Dasgupta A, Basu K, Sethuraman R, Pathan B M, Rao D R K, Banola S, Kesava Rao P S, Naidu A, Tyagi T R, Vijaykumar P N, Chandra H, Vyas G D, Birbal Singh, Chauhan P, Iyer K N, Pathak K N, Shalgaonkar C S, Vyas B M & Rastogi R G, Co-ordinated observations of VHF scintillations in India during February-March 1993, *Indian J Radio & Space Phys*, 29 (2000) 22.
- 9 Rastogi R G & Woodman R F, VHF radio wave scattering due to range and frequency types of equatorial spread-F, *J Atmos & Terr Phys (UK)*, 40 (1978) 485.

- 10 Vijayakumar P N & Pasricha P K, Parameterization of spectra of plasma bubble induced VHF satellite scintillations and its geophysical significance, *Ann Geophys (France)*, 15 (1997) 345.
- 11 Titheridge J E, The diffraction of satellite signals by isolated ionospheric irregularities, *J Atmos & Terr Phys (UK)*, 33 (1971) 14.
- 12 Franke S J & Liu C H, Analysis of long fading component in saturated VHF amplitude scintillation observed at Ascension Island, *J Atmos & Terr Phys (UK)*, 49 (1987) 421.
- 13 Dabas R S & Reddy B M, Equatorial plasma bubble rise velocities in the Indian sector determined from multi-station scintillation observations, *Radio Sci (USA)*, 25 (1990) 125.
- 14 Vijayakumar P N, Tyagi T R & Lokanadham B, Plasma bubble rise velocity using scintillation observations in the Indian zone, presented at X National Space Science Symposium, held at Ahmedabad during 25-28 Nov. 1997.
- 15 Bittencourt J A & Abdu M A, A theoretical comparison between apparent and real vertical ionization drift velocities in the equatorial F-region, *J Geophys Res (USA)*, 86 (1981) 2451.
- 16 Rastogi R G, Patil A & Alex, Post-sunset uplifting of the equatorial F layer of the ionosphere and the vertical plasma drift velocities, *J Geomagn & Geoelectr (Japan)*, 43 (1991) 607.
- 17 Banola S, Pathan B M, Rao D R K & Chandra H, Some characteristics of scintillations producing ionospheric irregularities in the Indian region, *Earth, Planet & Space (EPS) (Japan)*, 57 (2005) 47.
- 18 Raghavrao R, Nageswarrao M, Sastri J H, Vyas G D & Sriramarao M, Role of equatorial ionization anomaly in the initiation of equatorial spread-F, *J Geophys Res (USA)*, 95 (1988) 5959.
- 19 Alex S, Koparkar P V & Rastogi R G, Spread-F and ionization anomaly belt, *J Atmos & Terr Phys (UK)*, 51 (1989) 371.
- 20 Vyas G D & Chandra H, Ionospheric zonal drift reversal and equatorial spread-F, *Ann Geophys (France)*, 9 (1991) 299.
- 21 Sridharan R, Pallam Raju D, Raghavrao R & Ramarao P V, Precursor to equatorial spread-F in OI 630.0 nm dayglow, *Geophys Res Lett (USA)*, 21 (1994) 2797.
- 22 Whalen J A, Appleton anomaly increase following sunset: its observed relation to equatorial F-layer E $\times$ B drift velocity, *Geophys Res (USA)*, 103 (1998) 9497.
- 23 Alex S, Chandra H & Rastogi R G, Association between equatorial and tropical spread-F, *Indian J Radio & Space Phys*, 32 (2003) 83.