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Twenty-Five Years of Satellite Beacon Studies in India

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A comprehensive review of the highlights of the satellite beacon research in India during the past 25 years is presented.

1 Introduction

Satellite beacon research in India began when the first satellite beacon receiving system was set up in early 1962 at the National Physical Laboratory (NPL), New Delhi, to receive the 20 MHz radio beacon from the Russian orbiting satellite COSMOS-V. Faraday rotation of the 20 MHz beacon was recorded and used to derive the total electron content over Delhi for about a year until the beacon transmission ceased[1]. These results also provided the basis for deriving the topside electron density profiles by combining with ground-based ionosonde data[2].

Satellite beacon activity expanded with the launching of the Polar Orbiting Ionospheric Satellite Explorer-22 (popularly known as S-66 or BE-B) in October 1964, when additional groups set up satellite receiving systems to monitor the 20, 40 and 41 MHz transmissions. These observations continued using Explorer-27 (BE-C) beacons launched in 1965.

The first geostationary satellite became available to the Indian scientific groups with the repositioning of the geostationary satellite ATS-6 over the Indian ocean from May 1975 to July 1976 at the longitude of 35°E. During this period several additional groups established receiving systems to take advantage of this opportunity. Even after the moving of ATS-6, back to the western hemisphere in August 1976, work was continued at the NPL, New Delhi with the French satellite, Symphonie-2 when it was located over 45°E longitude from June 1977 to June 1978. Later the beacon work continued using the Japanese satellite ETS-II at New Delhi, Waltair and Calcutta. In addition, NPL in collaboration with groups at Osmania University, Hyderabad, Indian Institute of Science, Bangalore and University of Nagpur, Nagpur, set up receiving stations for monitoring the ETS-II VHF radio beacon. All these stations roughly lie along 77°E longitude, covering a geomagnetic (gm) latitude range of 4-19°, and are well suited for studying low latitude scintillation irregularities, their generation, growth, dynamics and decay. Later, the observations at NPL Delhi, were augmented with GHz scintillation using Insat 1-B and L-band observations using Marisat beacon.

Details of the various observing stations are given in Table 1 and displayed in Fig. 1. In this paper it is attempted to give the highlights of the 25 years of radio beacon research carried out in India.

2 Diurnal and Seasonal Variations in Ionospheric Electron Content (IEC)

Low latitudes—The diurnal variation in IEC at low latitudes is characterized by a predawn minimum, a forenoon increase of IEC, an afternoon maximum and a nighttime decay, as in mid-latitudes[3]. However, the results show some important differences in the behaviour of low latitude IEC in the northern hemisphere as well as differences between the northern and southern low latitudes[4]. One feature is the absence of the so-called winter anomaly in low latitudes

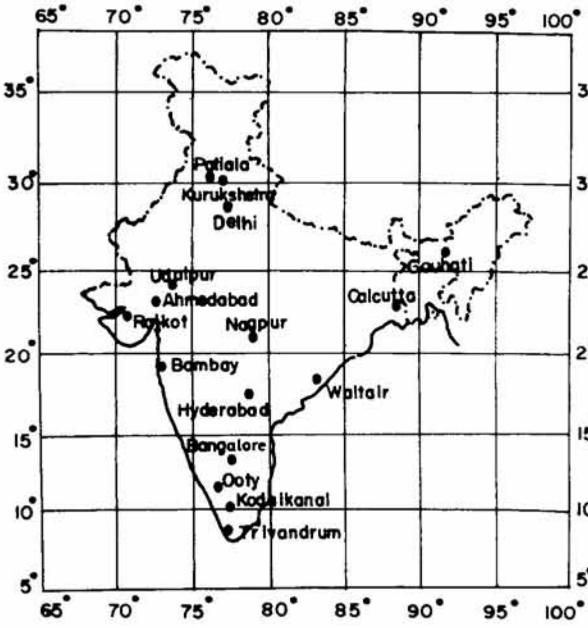

Fig. 1—Distribution of satellite beacon stations in India

Table 1 — Details of the Indian Observing Stations

S.No.	Location (Lat. Geogr., Lat. gm, °N °N Long °E)	Institution	Satellite: Orbiting	Satellite: Geostationary	Observation period	Solar activity	Remarks
1.	Patiala (30.3, 19.5, 76.4)	Punjabi University		ATS-6	Oct. 75-July 76	Low	In collaboration with NPL
2.	Kurukshetra (28.2, 19.3, 76.8)	Kurukshetra University	BE-B		June67-March 69	High	
			BE-C		June70-July 73		
				ATS-6	April76-Aug. 76	Low	In collaboration with NPL
				ETS-II	Dec. 79-June 80	High	
3.	Delhi (28.6, 19.2, 77.2)	National Physical Laboratory	COSMOS-V		July 62-July 63	Moderate	
			BE-B		Oct. 64-March 69	Low to High	
			BE-C		June 65-March 67	Low to Moderate	
					June 70-July 73	Moderate	
			INTASAT		Nov. 74-Oct. 76	Low	
				ATS-6	Sept. 75-Aug. 76	Low	
				Symphonic-II	April 78-April 79		
				ETS-II	June 79-to-date		
		Delhi University		ATS-6	Oct. 75-July 76	Low	In collaboration with NPL
4.	Gauhati (26.2, 17.0, 91.8)	Gauhati University		ATS-6	Nov. 75-July 76	Low	-do-
				ETS-II	Oct. 79-to-date		
5.	Udaipur (24.6, 14.0, 73.7)	Udaipur University		ATS-6	Oct. 75-July 76	Low	-do-
6.	Ahmedabad (23.0, 14.0, 72.6)	Physical Research Laboratory	BE-B		Oct. 64-March 69	Low to High	
			BE-C		June 65-March 69	-do-	
					June 70-July 73	Moderate	
				ATS-6	Sept. 75-Aug. 76	Low	Instrument shifted to Rajkot
				ETS-II	June 79-to-date		
7.	Calcutta (23.0, 12.3, 88.6)	Institute of Electronics & Radio Physics	BE-B		Oct. 64-March 69	Low to High	
			BE-C		June 65-March 67	Low to Moderate	
					June 70-July 73	Moderate	
				ATS-6	Oct. 75-July 76	Low	
				ETS-II	April 78-to-date		
8.	Rajkot (22.3, 12.4, 70.7)	Saurashtra University		ATS-6	Oct. 76-July 76	Low	In collaboration with NPL

—Continued

Table 1—Details of the Indian Observing Stations—*Contd.*

S.No.	Location (Lat. Geogr., Lat. gm, °N °N Long °E)	Institution	Satellite Orbiting	Satellite Geostationary	Observation period	Solar activity	Remarks
9.	Nagpur (21.1,11.4,79.1)	Nagpur University		ETS-II	Feb.80-Feb.81	High	In collaboration with NPL
10.	Bombay (19.0,9.0,72.8)	Indian Institute of Geomagnetism		ATS-6	Oct.75-July 76	Low	-do-
11.	Waltair (17.7,6.4,83.3)	Andhra University	INTASAT	ATS-6 ETS-II	Jan.75-Oct.76 May 75-July 76 April 78-to-date	Low Low	
12.	Hyderabad (17.3,7.7,78.5)	Defence Electronics Research Laboratory	BE-B BE-C		Oct.64-March 69 June65-March 67 June 70-July 73	Low to High Low to Moderate Moderate	
		Osmania University		ETS-II	May 79-to-date		In collaboration with NPL
		National Geophysical Research Institute		ETS-II	June 83-to-date		-do-
13.	Bangalore (13.0,3.3,77.5)	Indian Institute of Science		ETS-II	June 79-Nov.82	High	-do-
14.	Ootacamund (11.4,1.9,76.7)	Radio Astronomy Centre		ATS-6	Oct.75-July 76	Low	
15.	Kodaikanal (10.2,0.75,77.5)	Indian Institute of Astrophysics	BE-B BE-C		Oct.64-March 69 June 65-March 67 June 70-July 73	Low to High Low to Moderate Moderate	
16.	Trivandrum (8.6,-0.63,75.9)	Vikram Sarabhai Space Centre	BE-B BE-C		Oct.64-March 69 June 65-March 67 June 70-July 73	Low to High Low to Moderate Moderate	

as compared with mid-latitudes during solar minimum. Another way of describing this is to note that the semi-annual component is absent or practically negligible in comparison with the annual component in low latitudes during solar minimum. However, the semi-annual component increases in amplitude with respect to the annual component as the solar activity increases. As pointed out earlier, there is a difference between the northern and southern hemispheres. In the southern hemisphere the semi-annual component seems to be absent even as the solar activity increases[5]. It is believed that this is due to the different phase relationships between the annual and semi-annual components in the two hemispheres.

Equatorial latitudes—Studies of the equatorial IEC from orbiting satellites at Thumba and Kodaikanal, located within the electrojet region, reveal the following features[6-9]:

1. Absence of the noon bite-out in daily variations of IEC
2. Large ratio of topside to bottom side content in the presunrise hours
3. Very high values of slab thickness, particularly around noon

Equatorial anomaly—Electron content measurements using both orbiting satellites COSMOS V, BE-C and BE-B and geostationary satellites ATS-6, Symphonie and ETS-II have revealed the presence of equatorial anomaly in the electron content similar to that exhibited in f_0F2 (Refs 3, 10-12).

Equatorial electrojet and electron content—One interesting feature peculiar to low latitudes has been revealed, namely the influence of equatorial electrojet on the electron content[12-14]. The correlation between the equatorial electrojet and ionospheric electron content has been studied using the ATS-6 data from a chain of Indian stations spanning a dip range of 45°. The latitude of the crest of the anomaly was found to depend strongly on the integrated electrojet strength. During a normal electrojet day the anomaly is fully developed during the afternoon (Fig. 2a). During strong electrojet days the crest of the anomaly is formed even beyond the northern west station located at 40° dip (Fig. 2b), whereas in the presence of counter-electrojet the anomaly is reduced during the afternoon (Fig. 2c). They also show that while there is a midday bite-out in N_mF2 no such bite-out appears in electron content measured by both Faraday and different Doppler methods. The peaks in semi-annual variation of IEC are modified by an electrojet. On days of counter-electrojet a definite decrease was found in h_pF2 at the equatorial station Trivandrum, and also in the depth of the equatorial anomaly. This is interpreted as indicative of a reversal of the upward F-region drifts and a possibility of linkage between equatorial E- and F-regions.

Sudden increase in total electron content (SI-TEC)—Increases in electron content produced by EUV radiation from solar flares (SITECs[6]) have been reported by Deshpande *et al.*[15], Somayajulu *et al.*[16] and Tyagi *et al.*[17] which, on the average, amount to about 5% of the background electron content. SI-TECs are dominated by low-loss F2 ionization produced by 90-911 Å emission, and this part of the spectrum is mostly responsible for the impulsive effects.

Day-to-day variability—There is a large day-to-day variability in IEC which is not related to geomagnetic or other geophysical phenomena. Sometimes enhancements can be by a factor of 2 to 4 (Refs 3 and 17). The day-to-day variations appear to have short (2 days) and long term (45 days) periodicities[18]. The magnitude of fluctuations is found to be maximum at a station which is near the crest of equatorial anomaly belt[19].

Response to geomagnetic storms—The effects of magnetic storms on IEC were studied[20-22] using 140 MHz radio beacons from ATS-6. Results of major winter storms show the following features: (i) During early night hours following the onset of a major storm, large increase in IEC is observed at all the stations. (ii) Significant storm time changes occur predominantly during early night hours and the effects last for more than three days since the main phase onset. The increase in TEC is noticed more commonly during forenoon hours of day-1 and almost throughout on day-2. Negative phase is also noticed on afternoon hours of day-1 and also on day-3. Both positive and negative phases are largest at Ahmedabad and Udaipur, less at Bombay and least at Patiala. (iii) For one great storm which occurred during summer, a decrease in IEC is noticed at all stations near midday simultaneous with rapid decrease in H field. As in the case of winter storms, for this storm also positive phase is observed on day-2. (iv) The storm changes seem to be associated with the position of the station in the low latitude F2 region anomaly itself.

Qualitatively, variations in equatorial electrojet intensity are responsible for the significant daytime storm effects in IEC at these latitudes. Evidence of the 'fountain effect' on storm days is provided by (i) significant negative correlation between electrojet strength and N_mF2 for Trivandrum and (ii) significant negative correlation between changes in N_mF2 for Trivandrum and changes in the IEC at stations in anomaly region with diffusion time equal to 2 hr. The results suggest that changes in $\mathbf{E} \times \mathbf{B}$ drifts contribute significantly to daytime storm effects in IEC at stations in the anomaly region. Some abnormal increases in IEC which could not be explained on the

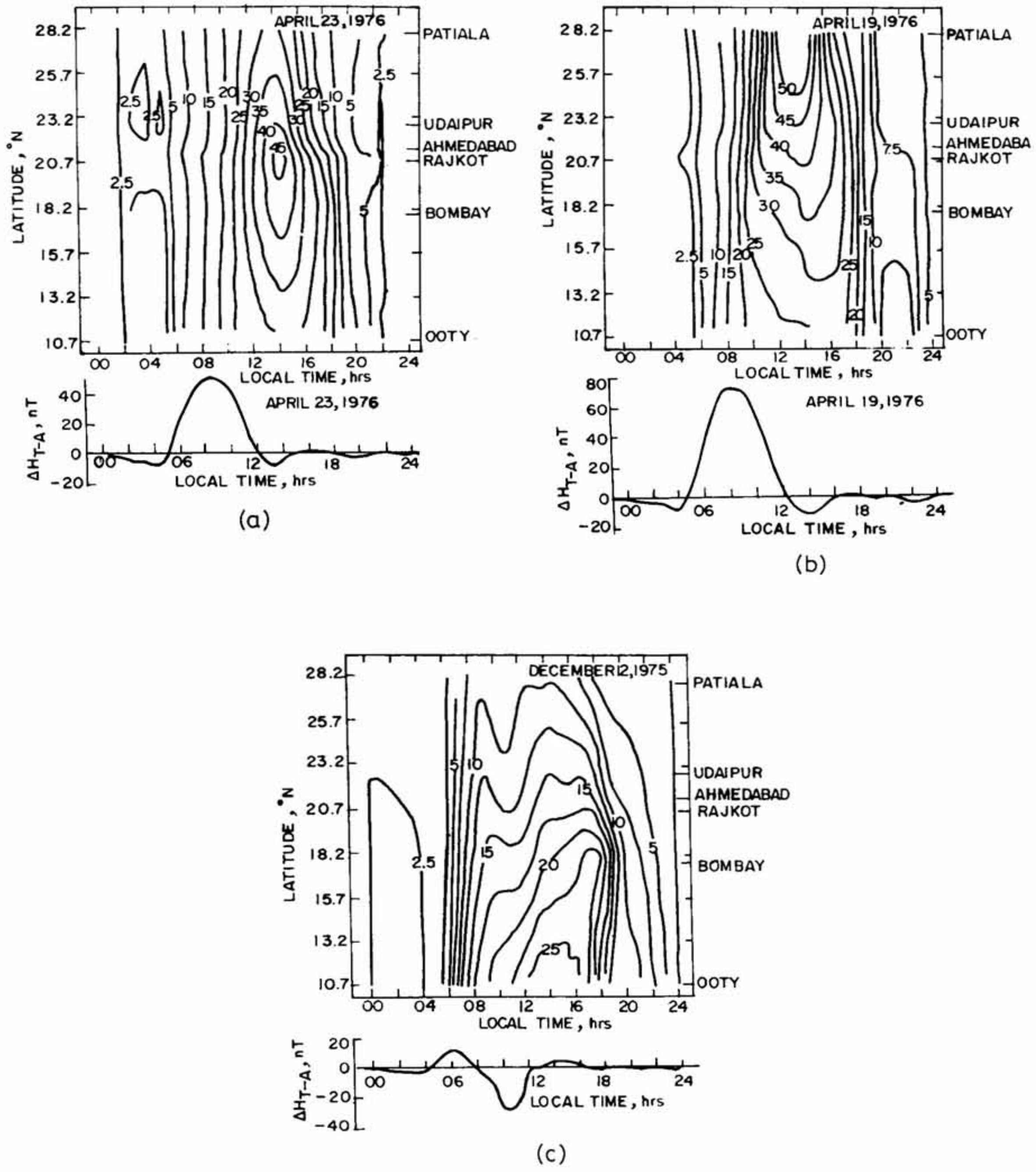

Fig. 2—Electron content contours illustrating the behaviour of IEC on (a) normal electrojet (b) strong electrojet and (c) a counter-electrojet day (after Rama Rao *et al.*[12b])

basis of $\mathbf{E} \times \mathbf{B}$ drifts are suggested to be due to the effects of equatorial winds from higher latitudes during the geomagnetically disturbed periods.

Other effects of geomagnetic storms are:

(i) Scintillations are triggered during the storm time at low latitudes with phase lags at different stations.

(ii) TIDs are induced during gm storms which appear to originate in high latitudes.

3 Solar Activity and IEC

Tyagi and Somayajulu[3] reported that a positive correlation exists between TEC and 10.7 cm solar flux values exceeding 80 units[5,23]. The following empirical relationships are given based on orbiting satellites and ATS-6 observations.

FOR DELHI

Winter IEC

Table 2—Summary of the TIDs Results

Period	Occurrence	Most probable speed (range)	Direction	Dimensions N-S E-W	Strength	Most common size (range)	Remarks	Reference
Non-Periodic irregularities								
	Equal by day or night	120 ± 20 ms^{-1} (30-500 ms^{-1})	Summer $270 \pm 60^{\circ}$ in Forenoon $45^{\circ} + 20^{\circ}$ in After-noon	60% have comparable dimensions in NS or EW; 16% elongated along NS; 24% elongated along EW	Upto $\pm$ 40%	400 km (15-3000 km)	Speeds are same as mid-latitudes, direction of travel different	Lakha Singh et al (1977)
Periodic disturbances								
8 min-2 hr		140 ms^{-1} (120-270 ms^{-1})	Generally S-W					Lakha Singh et al (1977)
		(54-314ms^{-1})	Winter S-SE				Jet Streams as possible source	Deshpande et al (1978)

The spectra of gravity wave fluctuation in N_F at Delhi with periods ranging from 10 to 100 min. exhibit a marked dip near 15 min in agreement with theory (Sengupta et al,1976).

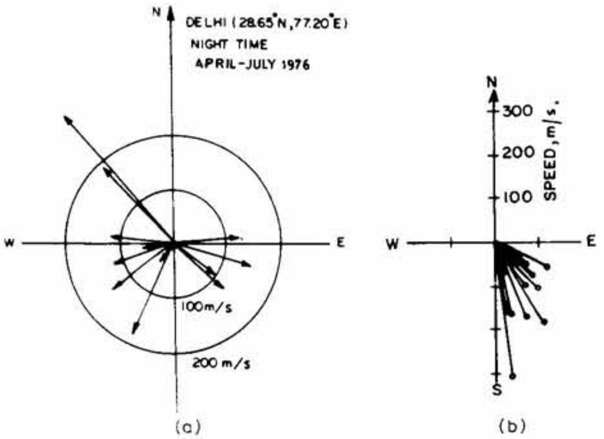

Fig. 3—Polar plot of TIDs around (a) Delhi (b) Ahmedabad in 1976 (after Deshpande *et al.*[30])

$$I_W = (1.20 + 0.03\,(s-70) \times 10^{17}\ \text{el/m}^2$$

(Tyagi and Mittal[24])

Summer IEC

$$I_S = (2.45 + 0.02(s-70) \times 10^{17}\ \text{el/m}^2$$

valid for $70 < s < 150$

$$I_S = (3.75 + 0.007(s-150) \times 10^{17}\ \text{el/m}^2$$

valid for $150 < s < 250$

FOR THUMBA

$$\text{IEC} = 134 + 6.49(s-50)1015\ \text{el/m}^2$$ (Reddi *et al.*[9])

valid for $50 < s < 90$

Bhuyan *et al.*[25] inferred from the analysis of IEC data from geostationary satellites ATS-6, Symphonie II and ETS-II, that though there is a linear relationship between TEC and solar flux up to about 200 units, there is a decrease in IEC with further increase of solar flux.

4 Ionospheric Irregularities

4.1 Medium Scale Irregularities

Medium scale irregularities have been studied in India using orbiting as well as the geostationary satellites. Both periodic and non-periodic type of irregularities have been observed[26-32].

The Faraday fadings of 40 MHz transmissions from the orbiting satellite Explorer-22 recorded at Delhi and Kurukshetra, 160 km apart along a N-S base line, during 1968-69 were utilized to study the irregularity characteristics. The most common height is around 350 km and irregularities content is in the range of 0.1 to 10% of the ambient content. The size of the irregularities varies from 10 to 250 km, and they are not field aligned. During daytime the direction of drift is north-west[26,28].

Two sets of observations, using triangulation, are available during the ATS-6 beacon visibility over India, one comprising Delhi, Kurukshetra and Pilani (Lakha Singh *et al.*[29]) and the other with Ahmedabad, Udaipur and Rajkot[30]). The results are summarized in Table 2 and Figs 3a and b.

Recently TID campaigns were conducted by NPL group during May and December, 1985 at Delhi and Hyderabad using 3-station network with base line less than 100 km. The short base line was chosen to make sure that base front of the TID is coherent at all the 3 stations. The results are shown in Figs 4a and b, which show that at Delhi the TIDs travel in all directions during daytime while at night the majority of them are directed towards the west. These results are in agreement with earlier results obtained from ATS-6 observations[29].

4.2 Fresnel Fading

Quite frequently, a particular type of quasiperiodic fading, known as Fresnel-type fading[33], occurs on satellite radio signals indicative of the presence of an isolated irregularity in the ionosphere (Fig. 5). This type of fading is characterized by a central minimum with wings of fast fading on either side of the minimum. Occasionally, a train of small fading pattern occurs suggesting several isolated irregularities in tandem. Fresnel-type fading patterns have been observed on recordings of signals from orbiting as well as geostationary satellites made at Delhi for over half a solar cycle[34].

Results show that the occurrence of Fresnel-type fading patterns is most frequent during low solar activity but less during high solar activity. These patterns are most frequently observed in the time interval between local sunset and midnight and mainly in summer months. The patterns occur mostly in groups with average periods ranging from 2 to 10 min. The orbiting satellite observations indicate a tendency of the patterns to occur at zenith angles greater than 45° but no azimuth preference is observed. The height of the ionospheric irregularities responsible for such patterns, is statistically associated with the occurrence of longlived or a shortlived blanketing type sporadic-E at Delhi with f_0Es values normally greater than 5 MHz whereas no correlation with the occurrence of spread-F is observed. It is also observed that in addition to high f_0Es value, a diffused nature of sporadic-E layer, indicated by range-spread on ionograms, is also one of the important factors associated with the production of these diffraction patterns[34]. In contrast, often at night, particularly around midnight, a train of such patterns appear followed by scintillations. Thus the irregularities causing these patterns may be located at the F-max or on topside since no correlation with spread-F is found.

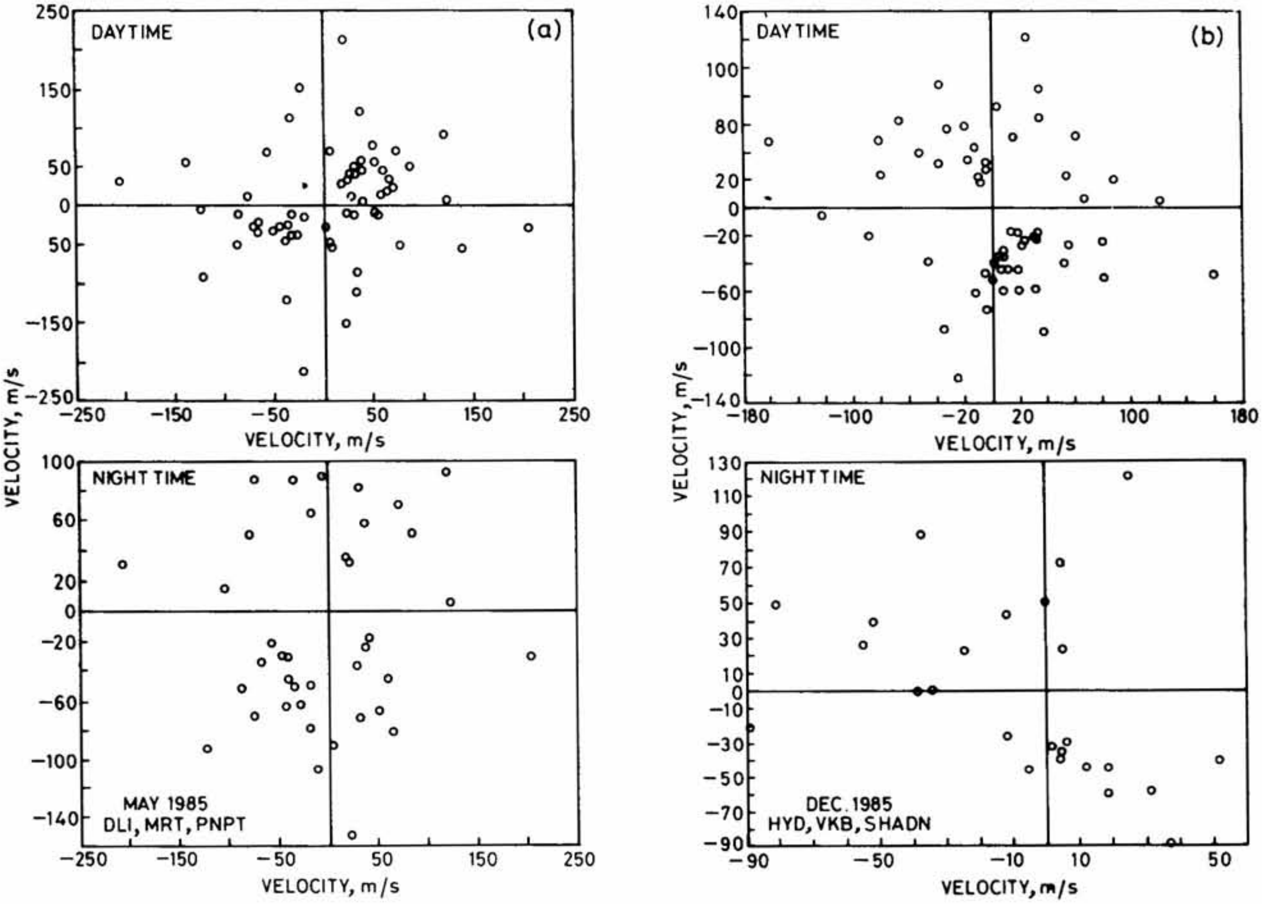

Fig. 4—Polar plot of TIDs around Delhi in May 1985 and Hyderabad in Dec. 1985 (after Lakha Singh *et al.*[29])

5 Scintillations

5.1 Tropospheric Scintillations

Anomalous enhancements of signal amplitude of radio beacons received from satellites have been reported in literature but whether they were of ionospheric or tropospheric origin was not clear. By using the recordings of INTASAT orbiting satellite beacons on 40 MHz and with coordinated set of observations from line of sight microwave link and acoustic sounding radar during a tropospheric event, the beacon signal enhancements and scintillations were clearly identified to be of tropospheric origin[35]. A systematic study[36] revealed that the tropospheric effects occur at elevation angles less than 15° and the most favourable elevation angle is 5°.

Also scintillations of tropospheric origin on VHF satellite beacon (137 MHz) have been detected and identified[37]. These scintillations are observed during monsoon period before the onset of rain. Usually, the scintillations start about 1 to 2 hr before the onset of the rain as clouds start gathering, the depth of signal fluctuation being 1-2 dB. After the commencement of the rain the scintillations gradually decrease in amplitude and scintillation activity completely disappears in about $\frac{1}{2}$ hr. These scintillations are attributed to scattering by irregularity structures in the tropospheric refractive index due to temperature and humidity irregularities, possibly of layered structures. These structures may also be moving upward due to convection. Soon after precipitation starts the convection subsides and the irregularities in refractive index are evened out, thus causing the scintillation activity to disappear.

5.2 Ionospheric Scintillations

Ionospheric scintillations have been observed and studied in low latitudes using HF and VHF beacons from orbiting and VHF, UHF and GHz beacons from geostationary satellites. Scintillations are most severe during nighttime but are mild when present during daytime.

DAYTIME SCINTILLATIONS

Daytime amplitude scintillations have been studied using the 20, 40 and 41 MHz beacons from orbiting satellites[3,38,39] and using VHF and UHF beacons

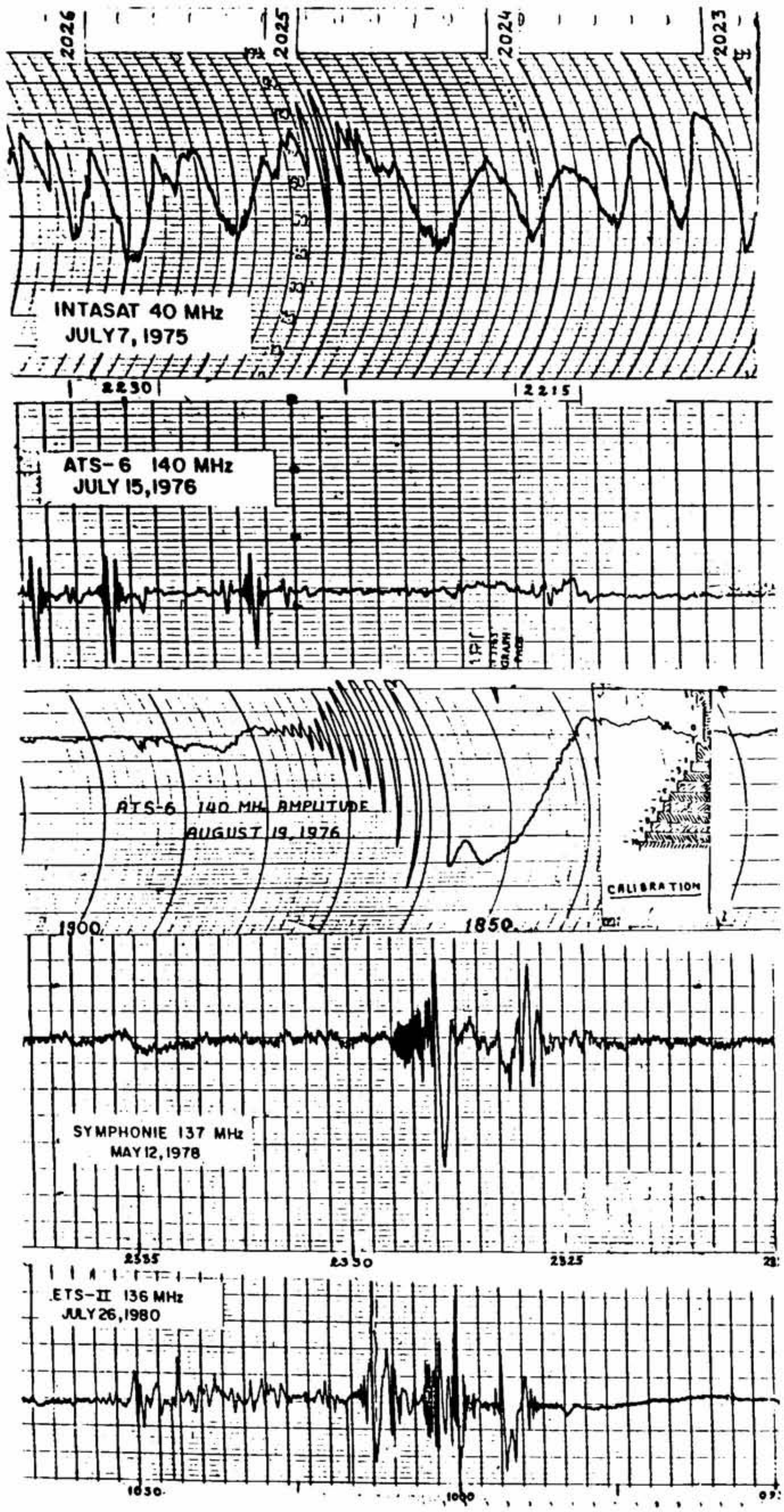

Fig. 5 — Fresnel fading patterns (after Dabas *et al.*[34])

from geostationary satellites[40-45]. These studies reveal the following features.

At Thumba on the geomagnetic equator, moderately severe daytime scintillations on 40 MHz are a regular feature with a fairly constant percentage occurrence between 0730 and 1400 hrs, with seasonal peaks during November, February and June. The frequency index of scintillations (n) was in the range 1.00-1.50. These scintillations are shown to be caused by electrojet irregularities.

At Ooty, slightly north of Thumba and the brink of the electrojet region, weak VHF scintillation (1-2 dB) occur with a peak occurrence around midday and are closely correlated with strong electrojet accompanied by q-type of Es. Strong daytime scintillations (10-15 dB) occur during strong counter-electrojet accompanied by non-q type or blanketing type of Es.

At the more northern latitudes, Calcutta, Delhi, Ahmedabad and Kurukshetra (gm lats 15-27°) the occurrence of daytime scintillations is generally[7] associated with the presence of Es with penetration frequency > 5 MHz. This is similar to the behaviour in mid latitudes[46,47]. However, they are also observed in the absence of Es or spread-F. It was suggested that some of the daytime scintillations might be caused by topside F-region irregularities. Another feature which lends support to this argument is that at Calcutta and lower latitudes, the scintillation rate is 20 fades/min or greater; at Delhi and northwards it is of the order of 3-5 fades/min.

At these latitudes a slight positive correlation between the daytime scintillation index and solar activity has been inferred.

NIGHTTIME SCINTILLATIONS

The earliest observations on ionospheric scintillations in low and equatorial latitudes were reported by Subba Rao and Somayajulu[48] using ionospherically reflected terrestrial HF-radio CW transmissions. They drew attention to the occurrence of a post-sunset "flutter fading" characterized by a deep and rapid fading with a fading frequency of the order of tens of cycles per second. The effect was that the quality of radio transmission was degraded and that of music transmissions ruined. When no modulation was present, variations in the carrier level were heard as a violent, semiregular rambling sound. Somayajulu[49] showed that this was essentially a low latitude phenomenon and that it was associated with the occurrence of spread-F echoes on pulsed-transmitter ionospheric reflections. Osborne[50] reported that, near sunset at Singapore on the geomagnetic equator, the F2-layer frequently disintegrated into clouds of ionization which was reported as spread-F by Booker and Wells[51] and that under these conditions radio waves show very intense and rapid fading. He further found that occurrence was most frequent at equinoxes and near the maximum of solar activity[52]. Bhargava[53] reported scintillations on radio waves received from radio stars at Kodaikanal in India near the geomagnetic equator. Koster[54] reported that in Ghana, near equator in Africa when the post-sunset flutter fading occurred, its presence seemed to coincide with an unusually severe type of radio star scintillation. Koster and Wright[55] pointed out that there was a high correlation between the occurrence of these two phenomena. Martyn[56] had suggested that electrostatic fields might be responsible for the formation of irregularities in the equatorial F-region. The theory was supported by the observations that the equatorial F-layer appears to rise by 50-150 km just after sunset and that irregularities often occur immediately thereafter[57-59].

The advent of radio beacon transmissions from artificial earth satellites provided an opportunity for a systematic study of scintillations. Amplitude scintillations on 20, 40 and 41 MHz radio beacon from orbiting satellites Explorers 22 and 27 have been reported[3,38,39]. These studies revealed that the scintillations are severe at night as expected and occur more frequently during summer months. These results are for low solar activity conditions and for locations in low latitudes north of geomagnetic equator.

With the availability of the geostationary satellite ATS-6 during 1975-76, there was a well coordinated and intensive study of low and equatorial latitude scintillations on 40, 140, 360 and 860 MHz, covering a latitude range from the geomagnetic equator to about 27°N gm latitude using more sophisticated reception techniques for phase and amplitude. Many of these studies are statistical, i.e. the data are reduced to a scintillation index and have provided useful information on the depth of scintillations, frequency of occurrence and the frequency dependence. Much of this information is summarized in Table 3.

The frequency exponent n was found to be 0.5 at Delhi[40] which is approximately the same (0.8) as that at the equatorial station, Thumba, reported by Krishnamurthy *et al.*[60] A relatively small value of n has been observed at Ootacamund by Rastogi *et al.*[43] and Deshpande *et al.*[61] who find that under certain conditions the scintillation on 360 MHz exceeds that on 140 MHz and 40 MHz. Both Rastogi *et al.*[43] and Krishnamurthy *et al.*[62] report that, in general, the nighttime scintillations start earlier on the lower frequencies and last longer than on the higher frequencies. The latter authors report that, at Trivandrum, the percentage occurrence of scintillations at higher frequencies was always less than that of spread-F which

Table 3—Results of Scintillation Studies in India

	Trivandrum (gm equator)	Ooty (gm 3°N)	Waltair (gm 8°N)	Calcutta (gm 13°N)	Delhi (gm 20°N)
Nighttime Scintillations					
Nighttime Max :	Premid-night (2200 hrs) Postmid-night 03-04 hrs	Premid-night (2200 hrs) Postmid-night 03-04 hrs	Premid-night	Premid-night	Around midnight extending to 0300-0400 hrs
Onset time	1900 hrs (in winter) 2000 hrs (in equi-nox)	1900 hrs (in winter) 2000 hrs (in equi-nox)	1900 hrs	1900 hrs	Around 2000 hrs (in summer)
Fading rates	C-I (>0.1Hz) associated with range spread C-II (>0.1Hz) confined to VHF (not associated with range spread sometimes associated with freq. spread).				>0.1 Hz, VHF
Freq.exponent of Scint.Index	(40,140 MHz) 046 (140,360 Mhz) 1.2	(40,140 Mhz) 1.0 (140,360 MHz).0.84			(40,140 MHz) 0.5
Daytime Scintillations		0900 hrs	1400 hrs		Around noon
Daytime		Not associated with Es-q- Closely connected with h or I type E_s which produces multiple M-reflections			
Freq.Exponent		>140 n = 1.15 (40,140) n=0.88			VHF
Fading rates	>0.1 Hz				

indicates that the two phenomena are caused by different types (sizes) of irregularities.

Based on the data at the geomagnetic equator (at Thumba), Krishnamurthy *et al.*[62] classified the scintillations into two types: the class I type of scintillations are characterized by fading rates greater than 6 fades/min and these seem to be associated with equatorial range type of spread-F (Fig. 6); the class II type have fading rates of 3-5 fades/min, are essentially confined to VHF and are associated with frequency spread. The class I type scintillations have maximum occurrence during equinoxes while class II occur with maximum during summer months. Thus it appears that what were observed at Delhi[40] and Calcutta[63] during summer are of the class II type[41].

Class I type are confined to much lower latitudes, during low solar activity which is the period of observation of ATS-6 beacon experiment. During high solar activity, scintillations at Delhi are apparently connected with equatorial spread-F (Ref. 64).

Phase scintillation observations within the equatorial electrojet region using ATS-6 beacons at 40 and 140 MHz at Ootacamund have shown that the r.m.s. phase fluctuations, at times, exceed well above one radian and also the spectrum of fluctuations shows high frequency components[43]. It is suggested that at equatorial latitudes thick-screen theory needs to be worked out.

GHz scintillations were observed at Delhi from the 4GHz beacon from INSAT-1 since 1984 (Ref. 65). These scintillations show maximum percentage occurrence during summer months and minimum in winter (cf. Ref. 40). The occurrence maximum is in the post-midnight hours during vernal equinox; an additional peak in pre-midnight hours occurs during autumnal equinox.

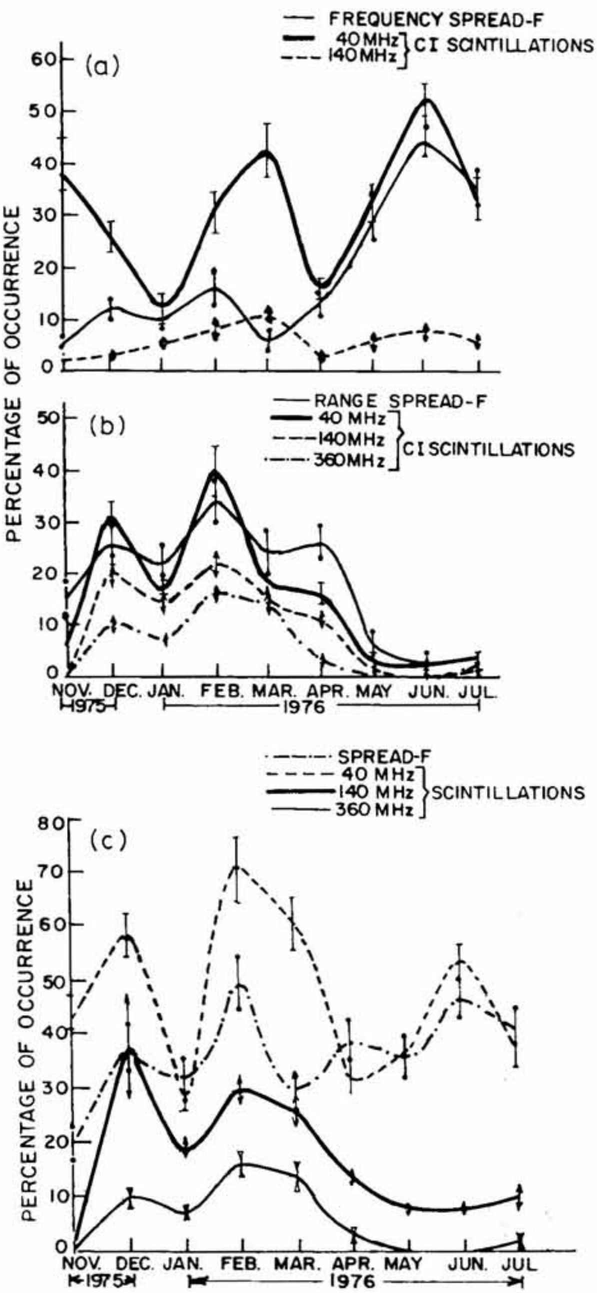

Fig. 6—Seasonal variation of (a) class II scintillations and frequency spread-F; (b) class I scintillations and range spread-F; and (c) seasonal variation of scintillations and spread-F (after Krishnamurthy *et al.*[62])

Detailed analysis of the data obtained from radio beacon experiments using orbiting and geostationary satellites established the following features of nighttime scintillations in equatorial and low latitudes in the Indian sector.

Frequency of occurrence—The equatorial and low latitude scintillations are severe at night, start an hour or two after sunset, and continue till midnight. Quite often there is a post-midnight activity till the early hours of the morning before sunrise. At the equatorial stations Thumba[62] (on gm equator) and Ootacamund[61] (1°gm lat.), the onset of scintillations is sudden with rapid build-up soon after sunset, around 1900-2000 hrs LT depending on the season. The scintillation activity peaks up around midnight during equinoxes; during other seasons there is a pre-midnight peak around 22 hrs LT and another post-midnight peak around 03-04 hrs LT. The maximum frequency of occurrence is around equinoxes. The pre-midnight scintillations are associated with range type of spread-F on the ionograms while the post-midnight scintillations seem to be correlated with frequency spread-F.

On the other hand Somayajulu *et al.*[40], from the observation of scintillations of ATS-6 beacon recorded at Delhi (gm lat. 18.9°N) reported that the nighttime scintillations are always of the slow fading type (similar to the class II type at the equator), and that their occurrence peaks up during local summer months. Similar results have been reported by Tyagi[66] for Delhi, Iyer and Rastogi[8] for Ahmedabad (gm lat. 15°N) from orbiting satellites, and Das Gupta *et al.*[67] for Calcutta (gm lat. 13°, 32°N dip) and Rama Rao *et al.*[68] for Waltair (gm lat. 7.7°N) from ETS-II and INTELSAT 2F2 geostationary satellite observations. Somayajulu *et al.*[40] further showed a pre-midnight and post-midnight peak moving closer in time during June and with only a pre-midnight peak occurring during July.

Seasonal dependence—It is generally believed that the nighttime equatorial scintillations are most frequent around equinoxes[43,62]. Results from equatorial stations using ATS-6 observations on VHF beacons and radio star scintillation at VHF generally confirm this seasonal behaviour. On the other hand, the observations of ATS-6 at Delhi (18.9°N gm) by Somayajulu *et al.*[40] clearly establish that the occurrence of nighttime scintillations peaks up during summer months and is minimal during equinoxes. Similar inferences were earlier made by Tyagi[66] for Delhi and by Reber[69] for Hawai and Walker and Chan[70] for Hongkong in the same latitude belt, using orbiting satellite observations. Similar behaviour was also observed at Calcutta (13° gm) by Das Gupta *et al.*[67]; these authors show that at this latitude the equinoctial maximum begins to show up as the solar activity increases and becomes more prominent at medium solar activity.

A close association between the occurrence of scintillations and spread-F in equatorial latitudes is known to exist[43,52,62,71-75]. Krishnamurthy *et al.*[62] had distinguished two types of equatorial scintillations: class I type are usually a pre-midnight phenomenon and are associated with range type spread-F, while the class II type are a post-midnight phenomenon associated with frequency spread. Rastogi[76] had also come to a similar conclusion. Krishnamurthy *et al.*[62] further showed that while the occurrence of class I (or fast fading) scintillations peaks up around equinoxes, the peak occurrence of class II (or slow fading type) is during local summer. This seasonal behaviour also correlates with the occurrence of the range and frequency type spread-F. Rastogi[76] had shown that the pre-midnight scintillations were always associated with range-spread, the post-midnight equatorial scintillations were associated with frequency spread-F. Both Rastogi *et al.*[43] and Krishmamurthy *et al.*[62] report that, in general, the nighttime scintillations start earlier on lower frequencies and last longer than on higher frequencies. Krishnamurthy *et al.*[62] further report that at the geomagnetic equatorial station Trivandrum, the percentage occurrence of scintillation at higher frequencies was always less than that of spread-F which is indicative of the fact that the two phenomena are caused by different types of irregularities.

Thus it would seem that there are two types of nighttime scintillations operating simultaneously with possibly two different mechanisms based on seasonal characteristics: one the so-called equatorial type confined to a narrow latitude belt of the order of ± 10° and another low latitude belt, extending to about ± 25°-30°, with maximum occurrence during local summer months and associated with range spread-F. This is further substantiated by the solar activity dependence of this scintillation type, as will be described later.

Extent of scintillation belt—The early orbiting satellite data show[3,28,62,77-79] that scintillations are observed from the geomagnetic equator to a gm latitude of 25°N. During low solar activity, the equatorial scintillation belt extends over ± 10° centred on around 5° from the dip equator. Latitudinally, the scintillation index decreases[8] with increasing latitude, finally levelling off beyond 28° gm latitude.

Solar activity dependence—At the equatorial stations such as Ootacamund[80], the scintillation occurrence is higher in year of higher solar activity than

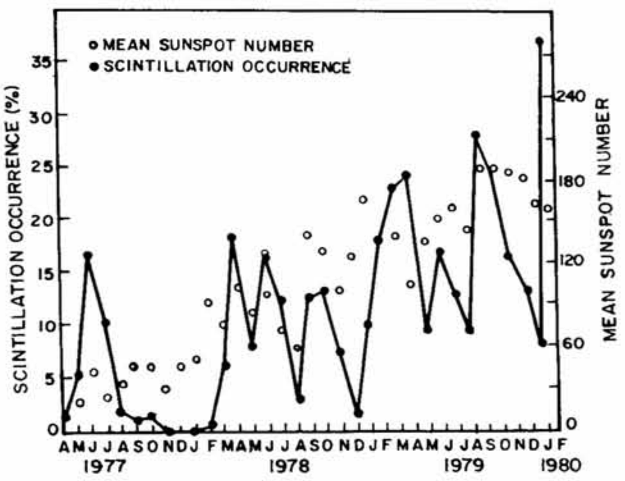

Fig. 7—Monthly variation of scintillation activity and sunspot numbers (after Das Gupta *et al.*[67])

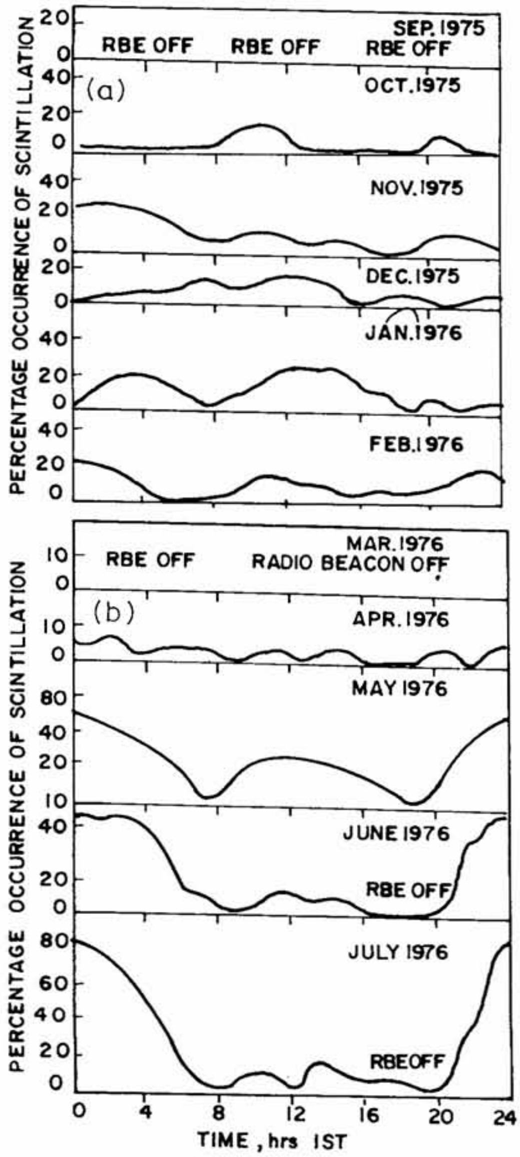

Fig. 8—Scintillation occurrence at Delhi during the period of stay of ATS-6 (after Somayajulu *et al.*[40])

during lower solar activity (Fig. 7). At Thumba also a similar trend is noticeable[62].

It was also noted that for Delhi latitude (20°N gm), there is an inverse correlation with solar activity[81]. The scintillation activity in the 15-25° gm latitude is more frequent in the low sunspot years compared with high sunspot years[8,66]. Similar results have been reported for Hawai[69] and Hongkong[70], at latitudes similar to that of Delhi (Fig. 8).

Taking into consideration the scintillation index fading rate, solar seasonal and magnetic activity dependence, it is necessary to divide the scintillation belt into two zones. The equatorial zone ± 10° centred on equator and the low latitude zone extending from 10° to 25° on either side.

Magnetic activity and scintillation—Chandra and Rastogi[82] showed that scintillation activity at Thumba decreases with magnetic activity, as also spread-F occurrence. This is also true for African zone while for American sector no clear relation is seen.

6 Modelling and Applications

6.1 Modelling

Ionospheric models are in demand for aeronomic studies and for predicting ionospheric characteristics for radio system applications. Satellite radio beacon systems are used to measure range, range rate and elevation angles for position fixing, satellite tracking, navigation and geodesy. In order to correct for the re-

Table 4—Modelling of Equatorial Nighttime Scintillations (from Ref. 62)

C-I

FEATURES	LOW SOLAR ACTIVITY	HIGH SOLAR ACTIVITY
NOCTURNAL VARIATION		
ONSET	1800 HRS IN JANUARY 2200 HRS IN JUNE	1800 HRS
MAXIMUM	2200 HRS IN JANUARY 2400 HRS IN JUNE	2200 HRS
DISAPPEARANCE	0300-0400 HRS	0300-0400 HRS
SEASONAL VARIATION		
PEAKS	EQUINOXES AND DECEMBER	EQUINOXES
NATURE OF TROUGHS	DEEP	SHALLOW

Nocturnal $(N) = 70.e^{-T^2/4} + F(e^{-T_1^4} - e^{-T_2^4})$

Seasonal $S = 1.4\ (F-60)\ (2-\cos\phi) + (L-1)\ (F-200)\ \cos^2\phi$

where

F is the 10.7 cm. solar flux $(10^{-22} W\ m^{-2}\ Hz^{-1})$

T is the local time (18-06) Hrs

D is the day number

$\phi = (D+31)\ /100$

$T_1 = (T-22)/12;\ T_2 = T_1 - L/6$

$L = \exp(-Q)$ and $Q = (D-165)/100$

$S_4 = C.\ (\ N).N.S.\quad f(k_o, n,\quad L, Z)$

where

N is the r. m.s. fluctuation in electron density

α the axial ratio

K_o the outer scale wave number of the irregularities
the operating wavelength

L the thickness of the irregularity layer centred around height Z and C a constant.

fraction effects, one has essentially to utilize a tracing of the ray path from receiver to satellite which requires a knowledge of the electron density distribution along the raypath. Building up of topside electron density profiles using electron content data was first proposed by Somayajulu *et al.*[2] and has been used in the development of a low latitude ionospheric model[83].

In order to facilitate the building up of low latitude ionospheric models where electron densities are strongly latitude dependent, electron content contours are first prepared for the Indian sub-continent based on the available electron content data[84]. Subsequently contours were published by Rastogi and Iyer[38] and Klobuchar *et al.*[80]

Modelling of nighttime scintillation for Thumba (gm equator) was done by Krishnamurthy *et al.*[85] The details are given in Table 4. Pasricha *et al.*[86] from radio star scintillations at Ootacamund, report that there was neither solar activity variation nor the presence of a post-midnight peak. These features are at variance with the SRI model.

6.2 Applications

Clock-synchronization experiment between the National Physical Laboratory (NPL) and Space Applications Centre (SAC), Ahmedabad via geostationary satellite Symphonie-II, stationed at 49°E longitude, was carried out during 1978. A crystal-based portable clock flown aboard an aircraft confirmed the clock-synchronization to within a microsecond[87].

Somayajulu and Ghosh[83] have developed a model for correcting refraction effects in satellite tracking and navigation in low latitudes. A numerical model of total electron content in low latitudes has been given by Klobuchar *et al.*[80] for use by satellite-tracking systems.

The cumulative probability distribution functions and scintillation indices were computed for the two classes of scintillations observed at the equator and compared with theoretical Nakagami-*m*-distributions by Raghava Reddi *et al.*[88] Fade margins have been studied by Deshpande *et al.*[61] for India; in the case of strong scintillations they recommend that for the signal to be received 100% of the time, one should design a system for about 12 dB fade margin on 40 and 140 MHz and about 7 dB on 360 MHz.

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