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Radio Beacon Studies at Physical Research Laboratory

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The study of ionosphere by recording the radio beacons from orbiting or geostationary satellites over Ahmedabad, Gujarat in the past five decades are reviewed. Results presented include both the total electron content of the ionosphere and the radio wave scintillation in the low latitudes, covering the region from the magnetic equator to beyond the ionization anomaly crest. Results from coordinated multi-station campaigns conducted for radio scintillation studies and also from other techniques are also covered. Some recent results obtained from studies conducted over the Indian region by other institutions/groups in India are also highlighted.

Keywords: Ionosphere, Radio Beacon Studies, Low latitude ionosphere, Total electron content and scintillations

1 Introduction

Radio beacons on-board satellites have been used extensively to study the ionosphere ever since the first sputnik mission. Total columnar electron content (TEC) measurements have been made by the simple recording of the Faraday rotation (Plane of polarisation) or by the recording of differential phase or group delay both of which require phase coherent transmissions. The amplitude or phase measurements at ground show fluctuations known as scintillations that are caused by the scattering of the radio waves by the plasma density irregularity structures in the ionosphere. Recording of these are used to study the spatial and temporal extent of the irregularities, strength of the irregularities as parameterised by suitable scintillation indices, power spectral features and the velocity of irregularities (in case of spaced receiver scintillations). Both the orbiting and the geo-stationary satellites have been used for radio beacon studies. The former suited specially for spatial studies while, the later give the temporal coverage.

Satellite radio beacon studies in India began with the recording of 20 MHz radio signals from the Russian orbiting satellite COSMOS-V in early 1962 at Delhi (28.6° N, 77.2° E) by the National Physical Laboratory[1]. Radio beacon studies were initiated at the Physical Research Laboratory (PRL), Ahmedabad, Gujarat in the early sixties with the recording of 20, 40 and 41 MHz signals from orbiting explorer satellites at Ahmedabad (23.0° N, 72.4° E) in October 1964 (BE-B) and May 1965 (BE-C)[2]. Recordings were started from Thumba (8.3° N, 76.9° E), near the magnetic equatorin 1966 and the data recorded at Kodaikanal (3.4° N, 77.5° E) observatory were also studied in collaboration with the Indian Institute of Astrophysics (IIA), Bengluru, Karnataka. A major programme of radio beacon studies was undertaken with the positioning of the geo-stationary satellite ATS-6, with multi frequency phase coherent transmissions with amplitude modulation, specifically designed for radio beacon studies, at 34° E for a year during 1975-76[3-4]. A sophisticated radio beacon receiver system with digital data recorder was moved from Boulder in the USA to Ootacamund (11.4° N, 76.7° E) in India under a collaborative programme between the NOAA and PRL. Measurements of the Faraday rotations at 40, 140 and 360 MHz; group delays (modulation phase) and the multi-frequency amplitude and phase scintillations were made for the first time in India. A chain of five stations was also set up by the PRL to record Faraday rotation at 140 MHz in collaboration with the Indian Institute of Geomagnetism (IIG) at Bombay (now Mumbai) (19.1° N, 73.0° E), Maharashtra, A V Parekh Technical Institute at Rajkot (22.3° N, 70.7° E), Gujarat, M L Sukhadia University at Udaipur (24.6° N, 73.7° E), Rajasthan, University of Jaipur at Jaipur, Rajasthan and the

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Punjabi university at Patiala (303° N, 76.4° E), Punjab. The chain of stations provided TEC measurements in India right from the magnetic equator to the region beyond the northern anomaly crest.

Radio beacon studies were continued in the post-ATS-6 period using the 136.1 MHz transmission from the Japanese satellite ETS-II positioned at 130° E. A spaced receiver scintillation experiment was conducted from Tiruchirapalli (10.8° N, 78.7° E) Tamil Nadu to determine the horizontal drift velocity of the ionospheric irregularities causing scintillations. Scintillation studies were also made from SHAR using a digital data logger during February-April 1986 and later during September-October 1988 as part of a rocket campaign when a comparison was also made between the power spectral features derived from simultaneous scintillations and in-situ rocket-borne Langmuir probe data. The PRL also participated, with the recording of the 244 MHz beacon from the geostationary satellite FLEETSAT (73° E), in the satellite scintillation network of the All India Co-ordinated Programme of Ionospheric and Thermospheric Studies (AICPITS) in which around 20 stations participated by recording scintillations at their respective locations thus providing spatial coverage from magnetic equator to the equatorial anomaly crest and beyond. Regular recordings of the GPS signals were started at the PRL since October 2009 to study TEC and scintillations.

The present paper reviews the ionospheric studies made at the PRL using the radio beacons and covers both the total electron content and scintillation. Salient features from later and current studies, carried out elsewhere in India are also highlighted.

2 Methods of Total Electron Content Measurements

For radio frequencies much higher than the maximum plasma frequency of ionosphere, the refractive index N is close to unity. However, the small departure from unity in the refractive index gives rise to changes in the characteristics of radio waves propagating through the ionised medium, so that features of the ionosphere can be studied from these changes. The more commonly used methods are the following.

2.1 Differential Phase

Presence of ionisation results in the reduction of the phase refractive index and consequently there is an increase in the phase velocity of the radio waves. This phase advancement is also frequency dependent, therefore if two phase coherent transmissions are used than the differential phase is a measure of the total columnar electron content from satellite to receiver. Neglecting the effect of collisions, the refractive index N for a radio frequency f, much higher than the plasma frequency f_p is given by

$$N = (1-X)^{\frac{1}{2}} \approx (1-\frac{X}{2}) \quad \ldots (1)$$

where $X = (\frac{f_p}{f})^2$

The phase change (ϕ) in traversing the medium from satellite to receiver is

$$\emptyset = -2\pi f \int \frac{ds}{V_\emptyset} \quad \ldots (2)$$

$$= \frac{-2\pi f}{c} \int N ds \quad \ldots (3)$$

$$= \frac{-2\pi f x}{c} + \frac{\pi}{f} \int \frac{ne^2}{4\pi^2 m\varepsilon_0} ds \quad \ldots (4)$$

$$= \frac{-2\pi f x}{c} + \frac{K}{f} \int n ds \quad \ldots (5)$$

where n is the electron density and $K = \frac{e^2}{4\pi^2 m\varepsilon_0}$ is a constant. Therefore if there are two phase coherent transmissions at frequencies f_1 and f_2, the differential phase changes are proportional to ∫nds or the total electron content (TEC). The TEC values derived from the differential phase measurements are relative and need calibration.

2.2 Group delay (Modulation phase)

The presence of ionisation also results in a decrease of the group velocity of radio waves propagating through the medium. The group delay of the radio waves from the satellite to receiver is given by:

$$t = \int \frac{ds}{V_g} \quad \ldots (6)$$

where V_g is the group velocity.

$$= \frac{1}{c} \int N_g ds \quad \ldots (7)$$

N_g is the group refractive index

$$= \frac{1}{c} \int ds + \frac{40.3}{cf^2} \int n\, ds \quad \ldots (8)$$

If the two frequencies are f_1 and f_2 then the differential group delay is proportional to the TEC. The method gives absolute measurements of the TEC.

For measuring the group delay phase coherent beacon signals with amplitude modulations are transmitted from the satellite and the modulation frequency compared with the corresponding phase difference on the modulated signal at the higher (reference) frequency.

2.3 Modulation phase

Consider a carrier wave with amplitude A_c, frequency ω_c and initial phase θ_c modulated by a wave with amplitude A_c, frequency ω_m and initial phase θ_m. The resultant amplitude A is

$$A = [A_c + A_m \cos(\omega_m t + \theta_m)] \cos(\omega_c t + \theta_c) \quad \ldots (9)$$

$$= A_c \cos(\omega_c t + \theta_c) + 2A_m \cos[(\omega_c + \omega_m)t + (\theta_c + \theta_m)$$

$$+2A_m \cos[(\omega_c - \omega_m)t + (\theta_c - \theta_m)] \quad \ldots (10)$$

where, the second and third terms are the upper side band (USD) and lower side band (LSD) respectively.

The general phase relationship is of the form:

$$\emptyset = \omega t - \left(\frac{2\pi f}{c}\right) \int N\, ds + \theta \quad \ldots (11)$$

Substituting the value of refractive index N as $(1-\frac{Kn^2}{2f^2})$ where the constant K is 80.6 in MKS units

$$\emptyset = \omega \left(t - \frac{R}{c}\right) + \left(\frac{\pi K}{cf}\right) \int n\, ds + \theta \quad \ldots (12)$$

where, R is the slant range. The phase relations for the carrier and side bands are therefore:

$$\emptyset_c = \omega_c\left(t - \frac{R}{c}\right) + \left(\frac{\pi K}{c f_c}\right) \int n\, ds + \theta_c \quad \ldots (13)$$

$$\emptyset_{c+m} = (\omega_c + \omega_m)\left(t - \frac{R}{c}\right) + \left\{\frac{\pi K}{c(f_c + f_m)}\right\} \int n\, ds + \theta_c + \theta_m \quad \ldots (14)$$

The modulation phase is therefore:

$$\emptyset_m = (\emptyset_c - \emptyset_{c+m}) \quad \ldots (15)$$

$$= \omega_m \left(t - \frac{R}{c}\right) + \frac{\pi K}{c}\left\{\frac{1}{f_c} - \frac{1}{(f_c + f_m)}\right\} \int n\, ds \quad \ldots (16)$$

If f_c and reference f_R are modulated with f_m with initial phase θ_m:

$$\emptyset_R^f = \frac{2\pi K}{c}\left\{\frac{1}{f_c} - \frac{1}{(f_c + f_m)} - \frac{1}{f_R} + \frac{1}{(f_R + f_m)}\right\} \int n\, ds \quad \ldots (17)$$

The differential modulation phase for carrier frequencies of 150 MHz and 400 MHz, each modulated by 1 MHz, is about 2 order of magnitude smaller than the differential phase from the carrier frequencies of 150 MHz and 400 MHz. Therefore, there is no ambiguity of initial phase and one can obtain absolute TEC.

2.4 Faraday rotation

The simplest of the techniques for TEC measurements is based on recording the change in polarisation (Faraday rotation). In this method use is made of the difference in the phase velocities of the two magneto-ionic modes of propagation. In case the angle between the radio wave propagation direction and the geomagnetic field direction is not close to $\frac{\pi}{2}$ (quasi-longitudinal propagation) the radio refractive index is given by the relation:

$$N^2 = \left(1 - \frac{X}{(1 \pm Y_L)}\right) \quad \ldots (18)$$

where

$$Y_L = \omega_e \frac{\cos\theta}{\omega}$$

Here ω_e is the angular gyro frequency:

$$= \frac{eB}{m\omega} \cos\theta$$

As the radio frequency is much higher than the gyro frequency,

$$N^2 = (1 - X \pm XY_L) \quad \ldots (19)$$

If linearly polarised waves are transmitted one can consider them to be a sum of two circularly polarised waves one with anti-clockwise rotation (ordinary wave) and other with clockwise rotation (extra-ordinary wave). The plane of the polarisation, Ω, will be:

$$\Omega = \frac{(\emptyset_O + \emptyset_E)}{2} \quad \ldots (20)$$

where, $\emptyset_O$ and $\emptyset_E$ describe the phase of the two components. If the refractive indices for the two modes are N_1 and N_2 then the phase difference is

$$\emptyset_1 - \emptyset_2 = \frac{2\pi f}{c}\int (N_1 - N_2)ds \qquad \ldots (21)$$

$$\frac{2\pi K}{cf^2}\int n f_B \cos\theta \, ds \qquad \ldots (22)$$

where f_B is the linear gyro frequency.

Assuming that $f_B = \frac{eB}{2\pi m}$ varies slightly with height the phase difference is given by:

$$\emptyset_1 - \emptyset_2 = constant \ \frac{B\cos\theta}{f^2}\int n \, ds \qquad \ldots (23)$$

$$= constant \ \frac{B\cos\theta \sec\chi}{f^2}\int n \, dh \qquad \ldots (24)$$

The polarisation angle therefore changes as the wave propagates. This is also known as Faraday rotation and has been extensively used in measuring the TEC. The Faraday rotation is dependent both on the electron density and the geomagnetic field and is heavily weighted by the electron density around the F-region peak and is insensitive at high altitudes. It has been shown that by taking the mean magnetic field value at an altitude of 50 km above the F-region peak, one can get TEC values within 2% of accuracy. The technique gives integrated columnar electron content up to about 2000 km in contrast to the differential phase or the group delay methods which give TEC values up to the satellite height. In case of radio beacons from geostationary satellites, the difference of the TEC from the phase or group delay methods and from the Faraday rotation method can therefore be used to find the protonospheric electron content, which lies above the ionosphere (above ~ 2000 km).

3 Scintillations

Radio waves traversing through the ionosphere suffer phase modulations due to the ionisation irregularities present in the medium. These phase modulations result in the fluctuations of intensity and phase at ground known as scintillation. A simple approach to calculate the scintillation statistics at ground has been the assumption of the equivalent thin screen[5-7]. Due to the finite distance between the screen (irregular medium in ionosphere) and ground, at a distance Z, the Fourier components of scale greater than the first Fresnel zone $(\lambda Z)^{\frac{1}{2}}$ do not contribute to the intensity fluctuations, also known as the Fresnel filtering effect. Another method to calculate the scintillation statistics for weak scintillations is to assume that the single scattering is applicable and thus the Born or Rytov approximation can be applied[8]. Power spectra under this assumption have been calculated[9-10]. Bramley[11] has shown that under practical ionospheric conditions, thin screen model gives results in very good agreement with those obtained from a single scattering model.

Following Wernik and Liu[9] amplitude (χ) and phase (S) variations at ground are given by:

$$\langle\chi\rangle^2 \left(\pi^2 k^2 \frac{L}{2}\right)\left(\frac{f_p}{f_t}\right)^4 \int_0 \ F_F \ (K)\emptyset_N(K)K \, dK \qquad \ldots (25)$$

$$F_F = 1 - \frac{2k}{K^2 L}\sin\left(\frac{K^2 L}{2k}\right)\cos\left(\frac{K^2}{k}\right)\left(Z - \frac{L}{2}\right) \qquad \ldots (26)$$

$$\langle S\rangle^2 = \left(\pi^2 k^2 \frac{L}{2}\right)\left(\frac{f_p}{f_t}\right)^4 \int \ F_\emptyset \ (K)\emptyset_N(K)K \, dK \qquad \ldots (27)$$

$$F_\emptyset = 1 + \frac{2k}{K^2 L}\sin\left(\frac{K^2 L}{2k}\right)\cos\left(\frac{K^2}{k}\right)\left(Z - \frac{L}{2}\right) \qquad \ldots (28)$$

where $\emptyset_N(K)$ is the power spectrum of electron density irregularities, K is the spatial wave number, f_t is the signal frequency, f_p is the plasma frequency of the background ionosphere, L is the slab thickness of ionosphere containing irregularities and Z is the distance between the transmitter and the top of the slab. Assuming the frozen-in irregularities, the temporal power spectrum of the received signal can be predicted. Umekiet al.[12-13] have shown the amplitude spectrum to be:

$$P_A(\Omega) = \left(\pi^2 k^2 \frac{L}{4V}\right)\left(\frac{f_p}{f_t}\right)^4 \int \ F_F \ (q)\emptyset_N(K)dK_Y \qquad \ldots (29)$$

The phase spectrum (Singleton 1974) is given by:

$$P_\emptyset(\Omega) = \left(\pi^2 k^2 \frac{L}{4V}\right)\left(\frac{f_p}{f_t}\right)^4 \int \ F_\emptyset \ (K)\emptyset_N(K)dK_Y \qquad \ldots (30)$$

where $\Omega = 2\pi f$, f is the temporal frequency and V the satellite velocity in case of orbiting satellites (in case of geo-stationary satellites the velocity of the irregularities) and $q^2 = \frac{\Omega}{V} r^2 + K_Y^2$.

Experimentally the observed scintillation spectra have been explained by power law type of electron density spectrum[14-15]. For a power law irregularity spatial spectrum $\emptyset_N(K) \propto K^{-P}$ proportional to f^{1-P} at sufficiently high frequencies. The temporal intensity power spectrum begins to roll off at Fresnel frequency $f_F = \frac{V}{\lambda_F}$ for the case of orbiting satellites, where λ_F is the Fresnel size). The temporal phase spectrum would be proportional to f^{1-P} for all frequencies.

The intensity of scintillation is generally characterised by an index S_4 as defined by Briggs and Parkins[16],

$$S_4 = \frac{[\langle I^2\rangle - \langle I\rangle^2]^{\frac{1}{2}}}{\langle I\rangle} \quad \ldots (31)$$

Similarly, the phase scintillation is characterised by the standard deviation of the phase fluctuations.

$$\sigma_\varphi = [\langle \delta\varphi^2\rangle - \langle\varphi\rangle^2]^{\frac{1}{2}} \quad \ldots (32)$$

In addition, auto-correlation function is a useful parameter to describe the scintillations statistically. The correlation interval, τ, the time for auto-correlation to fall to 0.5 is generally used to estimate spatial scale size. For a stationary radio source, knowledge of the velocity of the irregularities is required, while in the case of orbiting satellites the scan velocity in the ionosphere is required. Using spaced receiver mode of experiment, one can find the velocity of the ground diffraction pattern and hence the velocity of irregularities. In case of orbiting satellites, the temporal fluctuations of the intensity or phase at ground are primarily caused by the satellite motion. With two or more receivers spaced along the satellite track irregularity height also be determined[17]. For a flat earth model (overhead pass) the height of irregularity H_I is given by the relation:

$$\frac{V_S}{V_G} = \frac{(H_S - H_I)}{H_I} \quad \ldots (33)$$

where V_S is the satellite velocity, V_G the velocity of the ground pattern and H_S is the satellite height. However the method is not applicable near the magnetic equator due to the highly field aligned irregularities.

4 Studies using early orbiting satellites

4.1 Total electron content

The exploration of Indian low latitude ionosphere had started as early in 1962 using the Faraday rotation at 20 MHz from the COSMOS-V transmissions[1]. Using observations of Faraday rotation from the satellite explorer 22 (S-66) over Delhi (28.6° N, 77.2° E), Tyagi and Somayajulu[18] reported the diurnal and seasonal variability of TEC and its correlation with solar and geomagnetic activity. The TEC measurements were started at Ahmedabad in October 1964 by recording the Faraday rotation at 20 MHz, 40 MHz and 41 MHz transmissions from the BE-B satellite and later recording the signals of BE-C satellite from May 1965. The beacon from BE-B satellite with near polar orbit (inclination of 81°) was more suitable than of BE-C satellite for studying the latitudinal variations of TEC. Shirke and Ramakrishnan[2] reported the total electron content over Ahmedabad and Bombay obtained for the period October 1964 to April 1965 using the differential Faraday rotations at 40.01 and 41.01 MHz (closely spaced frequency method). Rastogi and Sharma[19] have described the results of TEC obtained over Ahmedabad for the period 1964-69 and also compared with the maximum ionization density, N_{max} obtained from ionosonde at Ahmedabad. Diurnal, seasonal and solar cycle variations of TEC and N_{max} were found to be similar. Equivalent slab thickness of the ionosphere, defined as N_T/Nmax, showed a peak near midday and another predawn peak, especially in winter. Both TEC and slab thickness showed an increase with the solar flux. Recordings of the beacons were also made from Thumba from December 1965 to August 1968. In addition to these measurements, data recorded by the Kodaikanal observatory were also analysed under a joint programme. The diurnal variations were obtained by combining the TEC data over the entire period. One of the most striking results that emerged from the measurements at Thumba, reported by Rastogi et al.[20], had been the absence of the diurnal anomaly in TEC. Figure 1 shows the diurnal plot of N_T, the TEC measured over Thumba and that of the N_{max} over Kodaikanal. The diurnal anomaly is clearly seen in the variation of N_{max} but not in the variation of TEC. This is in contrast to the earlier observations at other equatorial stations in Africa and South America[21-22]. To study the diurnal development of the anomaly, the latitudinal variations of TEC obtained by combining the data from satellite passes recorded over Kodaikanal and Ahmedabad were attempted. Rastogiet al.[23] examined the diurnal and latitudinal ionization anomaly in TEC from data recorded over Ahmedabad and Kodaikanal during the period November 1964 to December 1966. Figure 2 shows examples of the latitudinal variations of TEC at noon on four days. While there was no diurnal anomaly in TEC over Kodaikanal, latitudinal variations showed clear anomaly in TEC. Combining the simultaneous observations at Ahmedabad and Kodaikanal, the latitudinal variation of TEC from magnetic equator to the anomaly crest and beyond was further studied by Iyer et al.[24]. The development of the latitudinal ionization anomaly with local time was clearly seen. The strength of the anomaly as well as the crest of anomaly showed variability on day to day.

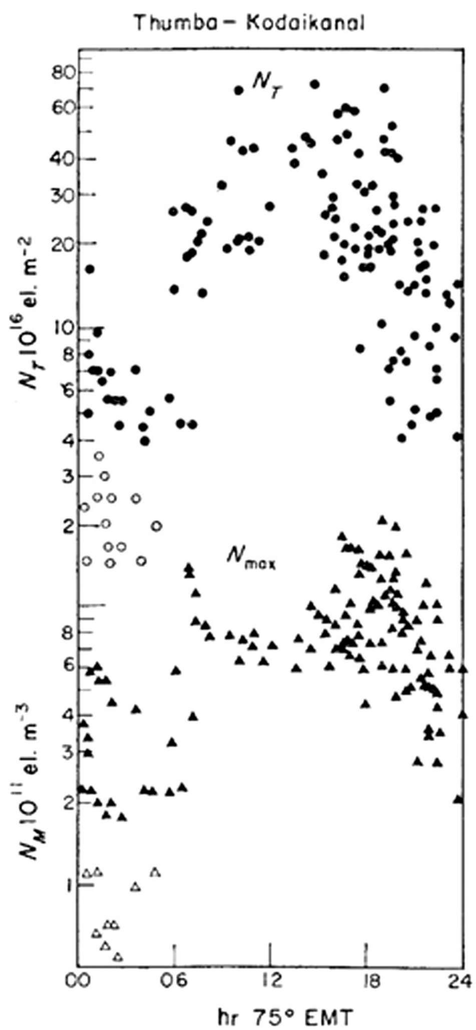

Fig. 1 — Diurnal plots of the TEC (N_T) measured over Thumba and N_{max} over Kodaikanal during the period December 1965 – August 1968. After Rastogi et al. 1973.

Development of anomaly as a function of the local time and latitude during high and low solar activity was clearly brought out and correlation with electrojet strength clearly seen. The vast amount of data collected by the observations made at Kodaikanal and Ahmedabad were also used to prepare a numerical model to describe the TEC at low latitudes in India[25]. The seasonal average values of TEC in a grid of latitude (every 2° interval) versus time (hourly) have been represented by 36 coefficients, four each to describe the latitudinal variation of the nine coefficients to describe the 4th order Fourier expansion by a third degree polonomial. Separate models have been prepared for low and high solar activity periods.

The latitudinal profiles of the electron content obtained from measurements from Ahmedabad were compared with profiles obtained from Hong Kong (22.2° N, 114.1° E) in East Asia during November 1964 - November 1965 by Walker et al.[26]. The two stations are separated by about 42° in longitude and showed appreciable differences. Day-to-day and longitudinal variability of the daily range of the geomagnetic H field (ΔH) and the ionization anomaly development were thought to have origin in the lower atmosphere.

4.2 Scintillation

The satellite passes over Thumba were also examined to study the phenomenon of scintillations. The nocturnal variations of the occurrence of scintillation at Thumba, spread-F index and

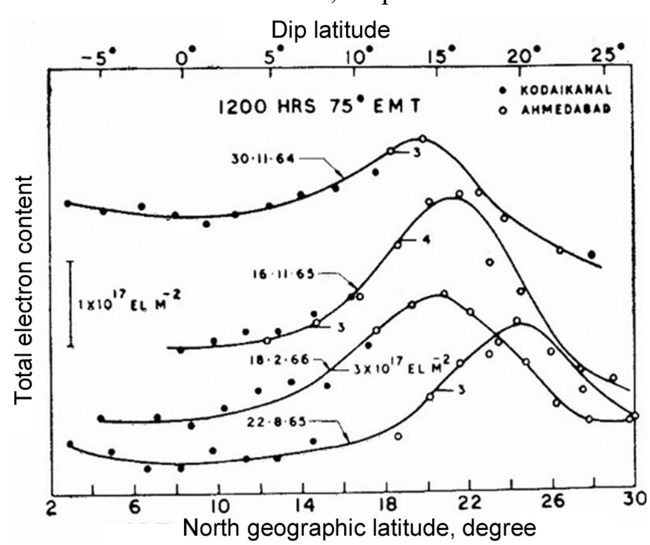

Fig. 2 — Latitudinal variations of TEC (N_T) at noon on few selected days obtained by combining the recordings at Ahmedabad and Kodaikanal during 1964-66. After Rastogi et al. 1975.

scintillation index (S_I) over Thumba were found to be similar[27]. Based on a few examples of the latitudinal variation of the scintillation index, Chandra and Rastogi[27] (1974) reported the width of the equatorial belt of scintillation to be about 10° in latitude during the low solar activity year of 1966 with the centre of the belt around 12-16° latitude. Later studies of Iyer and Rastogi[28] from the combined data sets from Kodaikanal and Ahmedabad also indicated the peak scintillation index around 14° latitude with northern limit around 28° latitude. Iyer and Rastogi[28] also found that most of the daytime scintillations at Ahmedabad were associated with blanketing type of sporadic-E and showed a linear increase in the scintillation index with increasing value of f_0E_S. Figure 3 shows a plot of the scintillation index (fluctuation in signal amplitude with respect to the mean amplitude in percentage) of the daytime scintillations and foEs over Ahmedabad, reproduced from Iyer and Rastogi[28]. The scintillation is seen around 30% for foEs value of 4 MHz and increases linearly to almost 100% for foEs of 15 MHz. Since scintillation depends on ΔN_e, larger foEs corresponds to larger ΔN_e so results in stronger scintillation.

5 ATS-6 Phase II

The ATS-6 was the first geo-stationary satellite with multi-frequency coherent radio beacons at 40, 140 and 360 MHz with amplitude modulations of 1 MHz/0.1 MHz. During the phase-II, ATS-6 was shifted to 34^0 E longitude on 1 August 1975 for a year. The NOAA-ERL ATS-6 receiving system was established at the Radio Astronomy Centre, Ootacamund, as a joint project between PRL and ERL, Boulder[3-4]. The radio beacons were received using short back-fire antennae at 40, 140 and 360 MHz. All data channels were digitised at a sampling frequency of 10 Hz and recorded on magnetic tape. Some of the data channels were also recorded on paper chart. Regular recordings were started at Ootacamund on 1 October 1975. The TEC values were obtained both from the Faraday rotation (N_F) and group delay (N_T) measurements at 140 MHz at Ootacamund. The Faraday rotation measurements at 140 MHz were also made at a chain of stations, set up by the PRL in collaboration with IIG at Bombay, A V Parekh Technical Institute at Rajkot, M L Sukhadia University at Udaipur and Punjabi University at Patiala, using the beacon receivers developed at the PRL.

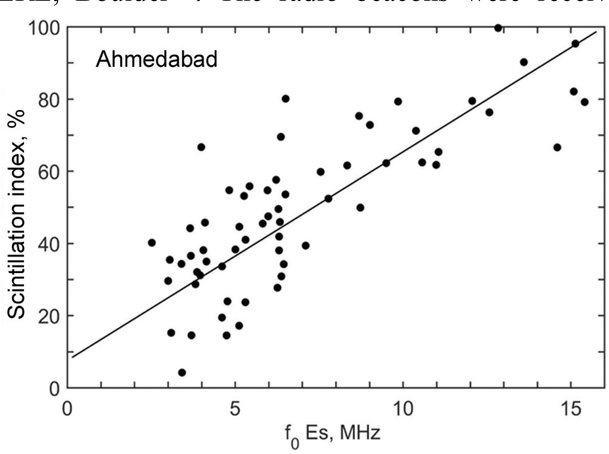

Fig. 3 — Plot of scintillation index (percentage fluctuation of signal with respect to mean) and foEs at Ahmedabad. After Iyer and Rastogi 1978.

5.1 TEC studies at low latitudes

The chain of stations set up to record Faraday rotation was unique in the sense that it covered the region right from the magnetic equator to well beyond the anomaly crest region. Thus the latitudinal variation of the ionospheric TEC (N_F) could be studied at different local times and different geophysical conditions for the first time in India. Figure 4 (a - c) (after Deshpande et al.[29]) shows examples of the latitudinal variations of N_F at different local times on 18 May 1976, a normal electrojet day with Ap index 3, 12 May 1976, a counter electrojet day with Ap index 7 and 3 May 1976, a geomagnetic disturbed day with Ap index of 94. The latitudinal variations are based on measurements made at Bombay, Rajkot, Ahmedabad, Udaipur, Jaipur and Patiala. The strength of the equatorial electrojet is also shown in the figure. On the normal electrojet day the anomaly was not developed at 10 LT and the value of TEC is highest at Bombay. The development of the anomaly was seen from the subsequent profiles at 12 LT which showed a flat maximum between Bombay and Udaipur and the anomaly was the strongest at 14 and 16 LT with maximum around 18 degree dip latitude and weakened at 1730 LT. On the counter electrojet day anomaly develops around 10 LT and was maximum at 14 LT with peak around 15 degree dip latitude. It weakened as seen from the variation at 16 LT and disappeared completely at 1730 LT. On the geomagnetic disturbed day, the anomaly was not seen at any of the daytime hours.

Singh et al.[30] described the daily and seasonal variations of N_F at the chain of stations from Bombay to Patiala. Sethia et al.[31] studied the daily variation of the N_F over Ootacamund and showed an absence of the midday bite out; however, there was a sharp decrease in the rate of increase in TEC around 11 LT. Thus, the absence of bite out in TEC reported earlier from the diurnal variation obtained by combining several months of data of orbiting satellites was confirmed. Rastogi et al.[32] studied in detail the diurnal variations of N_F, N_m and slab thickness of the ionosphere in the equatorial region by combining the TEC data over Ootacamund with the ionosonde data from Kodaikanal for geomagnetically quiet (strong electrojet) and disturbed days. There was no midday bite out in N_F seen on either of the quiet or disturbed days. From a detailed study on the effect of the electrojet strength on TEC at low latitudes, Sethiaet al.[33] showed a pronounced electrojet control. The effect of the electrojet was found to be strongest during equinoxes when electric fields are largest. The magnetic storms events in this period were studied by Jain et al.[34-35] and the observed changes attributed primarily to the electrojet behaviour. This was confirmed later by Rastogi and Klobuchar[36] from the daily contour maps of TEC at low latitudes plotted on a grid of local time and latitude. Chandra et al.[37] and Rastogi et al.[38] studied the lunar semi-monthly and lunar semi-diurnal tides in TEC at the chain of stations including Ootacamund and showed the maximum amplitude of both occurring in the anomaly crest region. The phases of the tides were however similar in the equatorial and the anomaly crest region. Thus, the phase reversal seen in the latitudinal variation of the phase of the tides in f_0F_2 was not observed in case of the tides in TEC. Based on the TEC measurements at the chain of stations during the period of October 1975-July 1976, a numerical model of TEC at low latitudes for low solar activity period was constructed by Sethia et al.[39].

The TEC data over Ootacamund obtained from group delay and Faraday rotation measurements were also used to find the protonosphere content. Annual mean daily variation of the plasmaspheric electron content was obtained. Sethia et al[40] examined data for the two magnetic storm events of November-December 1975 with large changes in the solar wind speed showed that, the daily mean N_P values on storm days with higher solar wind speed were lower. A linear relationship between the solar wind speed and plasmasphere content was also established[40].

5.2 Scintillation studies near magnetic equator

An extensive study on ionospheric scintillations was undertaken based on the digital recording of the multi-frequency amplitude and phase over

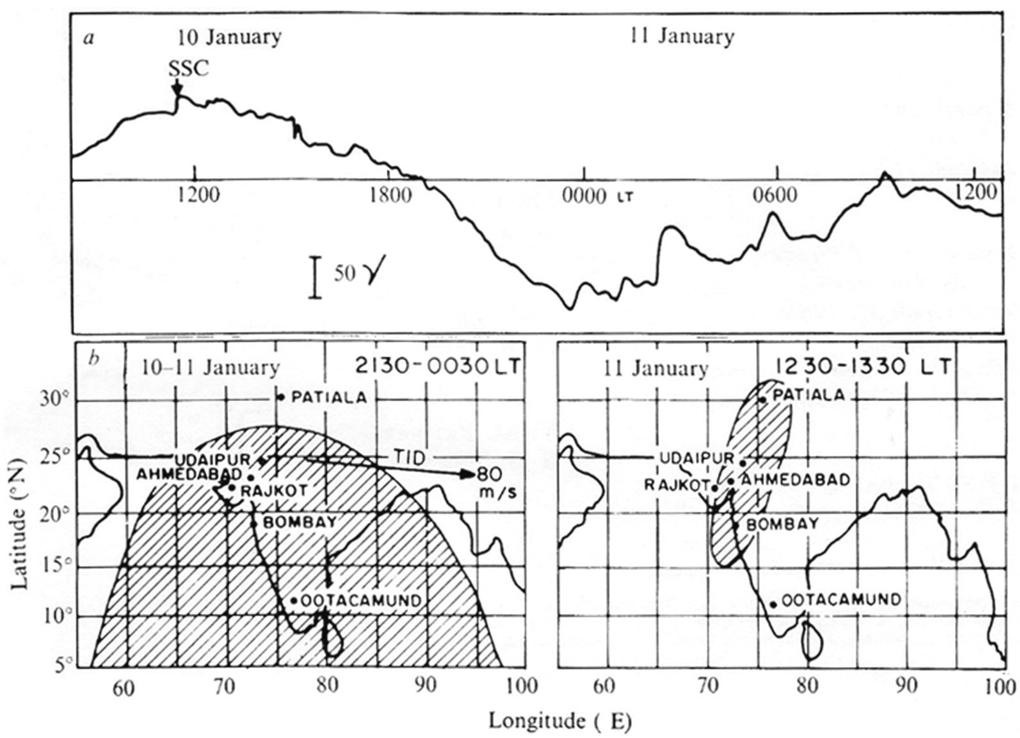

Fig. 4 — Latitudinal variations of N_F (TEC from Faraday rotation) at different local times: a, on 18 May 1976, a normal electrojet day; b, on 12 May 1976, a counter electrojet day and c, on 3 May 1976, a geomagnetic disturbed day based on measurements made at Bombay, Rajkot, Ahmedabad, Udaipur, Jaipur and Patiala. (After Deshpande et al. 1977).

Ootacamund[3]. Chandra et al.[41] examined the ionograms at Kodaikanal and scintillations at Ootacamund and showed that strong night time scintillations were associated with the range type of spread-F, while frequency spread-F was associated with comparatively weaker scintillations. Further the strong day-time scintillations were found to occur at times of blanketing type of sporadic E. The morphological features of the amplitude scintillations at 40, 140 and 360 MHz have been described by Rastogi et al.[42-43]. Large values of the scintillation index during 20-02 LT were associated with spread-F, while scintillations in the forenoon and afternoon were associated with blanketing type of sporadic E layers. A detailed study of the frequency exponent of the scintillation index, S_4, from the multi-frequency measurements, revealed that frequency exponent decreased monotonically with the increasing value of the scintillation index. Bhattacharya and Rastogi[44-45] have studied the temporal power spectral features from the multi-frequency amplitude and phase scintillations recordings over Ootacamund. Seasonally the scintillations were the strongest during equinoxes in the Indian zone as compared to the maximum during December solstice in the American zone[46].

One of the new results that emerged from the ATS-6 phase of observations was the detection of daytime scintillations in the polarization (Faraday rotation recordings) following the magnetic storm of 10 January 1976, with SSC at 1120 LT reported by Vats et al.[47]. It must be noted that the recordings of the amplitude and phase of the different radio beacons were recorded only at Ootacamund, while other stations of the chain recorded Faraday rotation at 140 MHz. Scintillation in the phase resulted in the scintillation in the polarization (Faraday rotation) also. The epoch 1975-76 being a low sunspot period, there was not a single occasion with scintillations present in the recordings made from Ahmedabad. However, during the main phase of the storm (2130-0030 LT of 10 January 1976) severe Faraday rotation scintillations were observed at all the stations except Patiala, the northern most station in the chain. Figure 5a shows the record of the horizontal component of the geomagnetic field at Kodaikanal near magnetic equator. Sudden Commencement with amplitude of 20 nT was seen at 1120 LT (75° EMT) and followed by decrease with a range of about 260 nT till midnight. Figure 5b shows the irregularity belt estimated from the Faraday scintillations at the chain of stations plotted as a function of latitude versus longitude (calculated from the time duration of Faraday scintillation and the Earth's rotation of 15° per hour of longitude. The presence of scintillations at Ootacamund was considered from the presence of amplitude scintillations at 140 MHz. The irregularity belt during the night of 10-11 January 1976 extended right from the magnetic equator to beyond Udaipur. On the following day in the recovery phase, strong Faraday scintillations were noted around mid-day

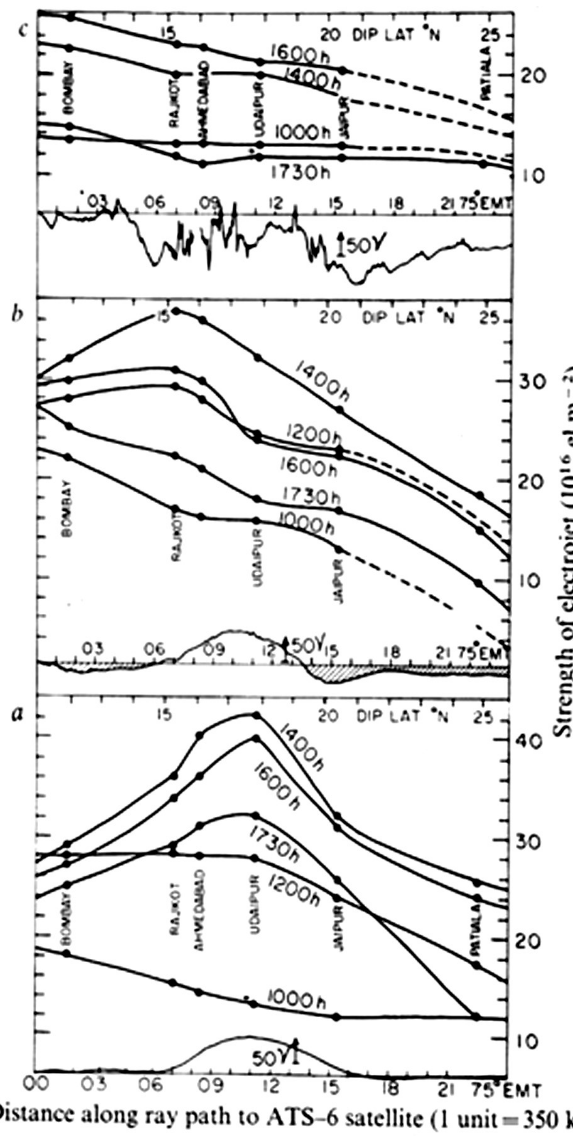

Fig. 5 — (a) Record of the horizontal component of the geomagnetic field at Kodaikanal near magnetic equator on 10 and 11 January 1976 and (b) Irregularity belt estimated from the time duration of Faraday scintillations at the chain of stations in India plotted as a function of latitude versus longitude during the main phase (2130-0030 LT) and recovery phase (1230-1330 LT) of the magnetic storm of 10 January 1976. After Vats et al. 1978.

(1230-1330) at all stations except Ootacamund. Later such cases of F-region scintillations extending into day-time were also reported at Huancayo in the American zone[48].

6 Scintillation studies using ETS-2

After the ATS-6 satellite was moved back to American longitudes, scintillation studies were continued using the 136.1 MHz transmission from the Japanese geo-stationary satellite ETS-2 (130° E). The ATS-6 receivers were modified for this purpose and a spaced receiver scintillation experiment was conducted from Tiruchirapalli for a year. Horizontal drifts of the irregularities were obtained by the similar fade method and the apparent velocities were found to be eastward with magnitudes ranging between 200 and 300 m/s in the post-sunset period and decreasing to 100-150 m/s at 02 LT[49]. The occurrence of scintillations showed equinoctial maxima as reported for the observations from Ootacamund also. Later the scintillation studies were made from SHAR during February-April 1986 using an indigenously developed digital data logger. Variation of the scintillation index computed at every five minutes of interval revealed fluctuations in S_4 index with periodicities of about 15 minutes and another of about an hour. Chandra et al.[50] also showed the temporal power spectral index to increase with the increasing scintillation index. Somayajulu et al.[51] studied night time scintillations during the high solar activity period of January-February 1980 at Bangalore, Hyderabad, Nagpur and Delhi, by recording Faraday rotation of the ETS-2 signal at 136.1 MHz. The chain covered from 3° magnetic latitude to 21° magnetic latitude at the sub-ionospheric point. The onset of scintillations was near simultaneous at Bangalore, Hyderabad and Nagpur but with a delay of 15 minutes to 4 hours at Delhi. The decay was found to be earliest at Delhi and progressively delayed at other stations. The occurrence frequency of scintillations was 90 % at Bangalore decreasing to 40% at Delhi.

7 Co-ordinated ionosonde, scintillation and rocket-borne measurements

A campaign of co-ordinated digital KEL ionosonde, 136.1 MHz scintillation (ETS-II) and rocket-borne in-situ measurements of ionospheric irregularities was conducted from SHAR during 15 September to 4 October 1988. The occurrences of spread-F and scintillations of 70% and 80% respectively, were very high in this solar activity epoch. The minimum virtual height of the F-layer rose to about 400 km in the post sunset period on days with spread-F but to only about 300-320 km on days with no spread-F. The electric field reversal as inferred from the h’F variations occurred around 1930 LT on spread-F days and around 1900 LT on no spread-F days. The spread-F days were marked with vertical drifts up to 70 m/s in the post-sunset period.

A RH-560 rocket instrumented with a Langmuir probe (electron density and fluctuations in it) and two pairs of double probe (fluctuations in electric field) was launched from SHAR at 2130 LT on 4 October 1988 during spread-F conditions as monitored by the ionosonde[50]. Electron density irregularities were seen in different altitude regions, 165-175 km, 210-250 km, 260-280 km and 300-320 km. The irregularities in the region of 295-320 km lied in the close vicinity of the radio wave ray path intersection and hence chosen to compare the power spectral properties by the in-situ and scintillation. Power spectra from in-situ observations were made from 1s data that covered range of 20 m to 200 m. Figure 6 shows the mass plot of the spectral index p against the scintillation index S_4. The spectral index showed a clear trend of increase with the increasing value of the scintillation index. Chandra et al. 1997[52] found the average temporal power spectral index of -3.8 obtained from the

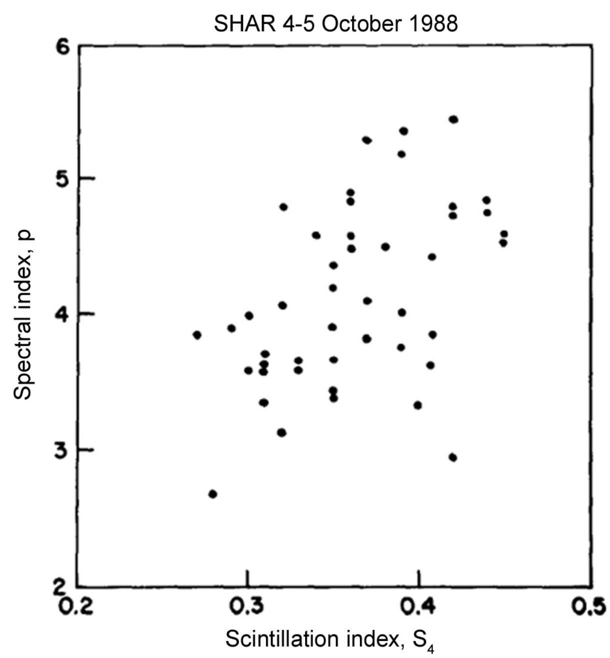

Fig. 6 — Mass plot of the spectral index p against the scintillation index S_4 obtained from the 136.1 MHz signal from ETS-2 satellite recorded at SHAR during the night of rocket launch (4-5 October 1988). After Chandra al. 1997.

temporal scintillation data, that corresponds to spatial one dimensional spectra of -2.8, and in good agreement with the one-dimensional spatial power spectral index (-3.4) obtained in the scale size range of 20-200 m from the in-situ data.

8. Scintillation studies from AICPITS campaigns

All India Co-ordinated Programme of Ionospheric and Thermospheric Studies (AICPITS) was initiated in the late eighties supported by the Department of Science and Technology, Government of India. As part of the program a chain of about 20 stations was operated in India, to record amplitude scintillation using the 244 MHz transmission from the geo-stationary satellite FLEETSAT. The receivers were provided to many of the stations by the Indian Institute of Geomagnetism, Bombay. The chain extended from magnetic equator to beyond the northern anomaly crest region. As part of the AICPITS satellite scintillation network, observations were also made over Ahmedabad. The scintillation observations recorded over Ahmedabad during 1991-92 were compared with the spread-F occurrence obtained from the ionosonde over Ahmedabad. Power spectral features were also studied from the digital amplitude scintillation data recorded over Ahmedabad, for the first time for the anomaly crest region over Indian longitudes[53]. Scintillation observations over Nagpur for the period of May 1989-January 1992 were also analysed to study the nocturnal and seasonal variation of the occurrence during this period of high solar activity. Equinoctial maxima with 35% occurrence and an occurrence of 15% during the winter and 10% during the summer were noted[54]. Mathew et al.[55] studied scintillations at Rajkot during 1987-89. Occurrence of scintillations was shown to increase with the sunspot number during the winter and equinoxes but decrease in summer. The occurrence of scintillations also exhibited a decrease with the magnetic activity in the winter and equinoxes but increased during the summer. A comparison of the scintillations observed at Bombay was made with the spread-F, observed by the ionosonde at Ahmedabad by Rastogiet al.[56]. Strong scintillations (exceeding 10 db) were seen at times of the range type spread-F, while weak scintillations were present at times of frequency type spread-F that occur mainly in the post-midnight period.

The unique feature of the satellite scintillation network was that about 20 stations distributed over India covered the entire region right from the magnetic equator to north of the anomaly crest. There were three campaigns when data were recorded and analysed jointly at workshops held after the campaigns. The campaigns were conducted during the equinoctial periods of March-April 1991, September-October 1991 and February-March 1993. Figure 7 shows the nocturnal variations of the monthly mean percentage occurrence of scintillation at different stations averaged over the month of March 1991 (After Chandra et al.)[57]. Results showed that in the equatorial region the scintillations occur earlier, were of a longer duration and with higher occurrence frequency. The occurrence frequency gradually decreased with increasing latitude with a time delay and scintillations occurred in patches of smaller duration at locations around anomaly crest[55, 57]. The half-width of the equatorial belt of scintillations, estimated from the latitudinal variation of scintillation occurrence, was also shown to be local time dependent.

Data collected during the second campaign of September-October 1991 showed small decrease in

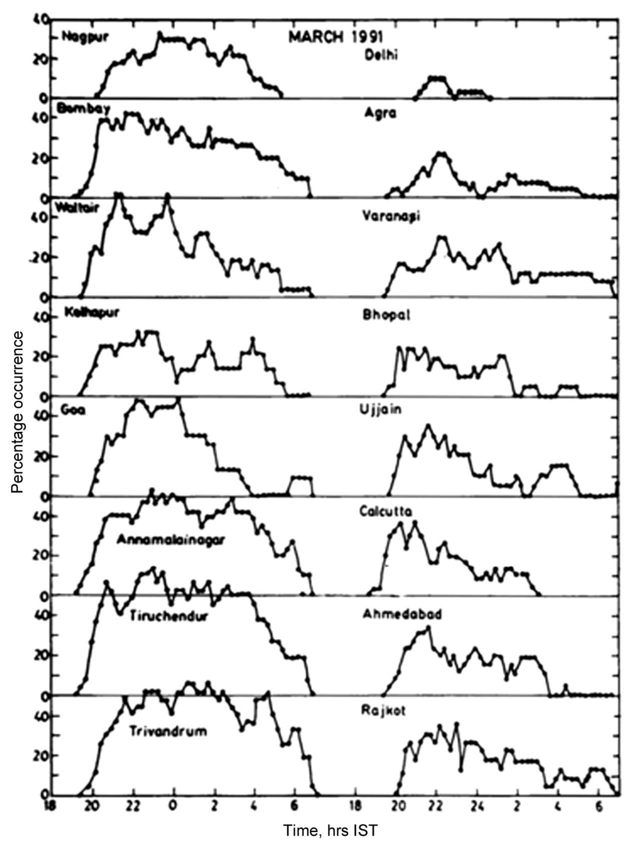

Fig. 7 — Nocturnal variations of the percentage occurrence of scintillation at different stations in India averaged over the campaign period of March 1991. After Chandra et al. 1993.

the occurrence frequency of scintillations compared to the first campaign period of March-April 1991[58]. The onset times of scintillation at pairs of stations at similar latitude but different longitudes were used to estimate the eastward drift of the scintillation patches and its E-W extent. From the time delay in the onset time of scintillations at different latitudes it was possible to compute the vertical bubble rise velocity over the magnetic equator and compare with the rise of F-layer.

The VHF scintillation observations made during February-March 1993 under the third campaign showed that, the occurrence features of scintillations were similar to those observed during the first campaign of March-April 1991[59]. The maximum occurrence was, however, reduced to some extent due to the lower solar activity. The latitudinal variations showed an increased occurrence in the region of about 17-18^{o} latitude. The data during the night of 19-20 February 1993 when an extensive ‘Ionisation Hole Campaign’ was undertaken from SHAR showed scintillations marked by earlier onset and longer duration at stations Waltair and Nuzvid than at the stations close to the magnetic equator. However, based on the average variations during February-March 1993 the onset at Tiruchendur, Anantapur and Waltair was at nearly the same time. The vertical rise velocity of the plasma depletions, estimated from the time delays in the onset of scintillations at latitudes away from the dip equator, was found to range from 40 m/s to 420 m/s in the altitude region 300-1350 km. The main results from the three campaigns have been described in a review by Chandra[60]. The scintillation observations at few stations in India for a solar cycle showed the latitudinal width of the equatorial belt of scintillations to be higher during December solstices and equinoxes than during June solstices[61]. Further there was a positive correlation between the width of the belt and solar activity, while it decreased with the magnetic activity. From an examination of more than 200 geomagnetic storms, it was shown that scintillation at low latitudes can be triggered or inhibited depending on the phase of the storm and the local time of occurrence of the SSC.

A major event of the strong F-region scintillations extending into daytime following a magnetic storm was also reported by Chandra et al.[62]. Figures 8 (a & b) show the amplitude scintillation records at Trivandrum and Bombay on 12 November 1991. Strong scintillations developed shortly before 05 LT

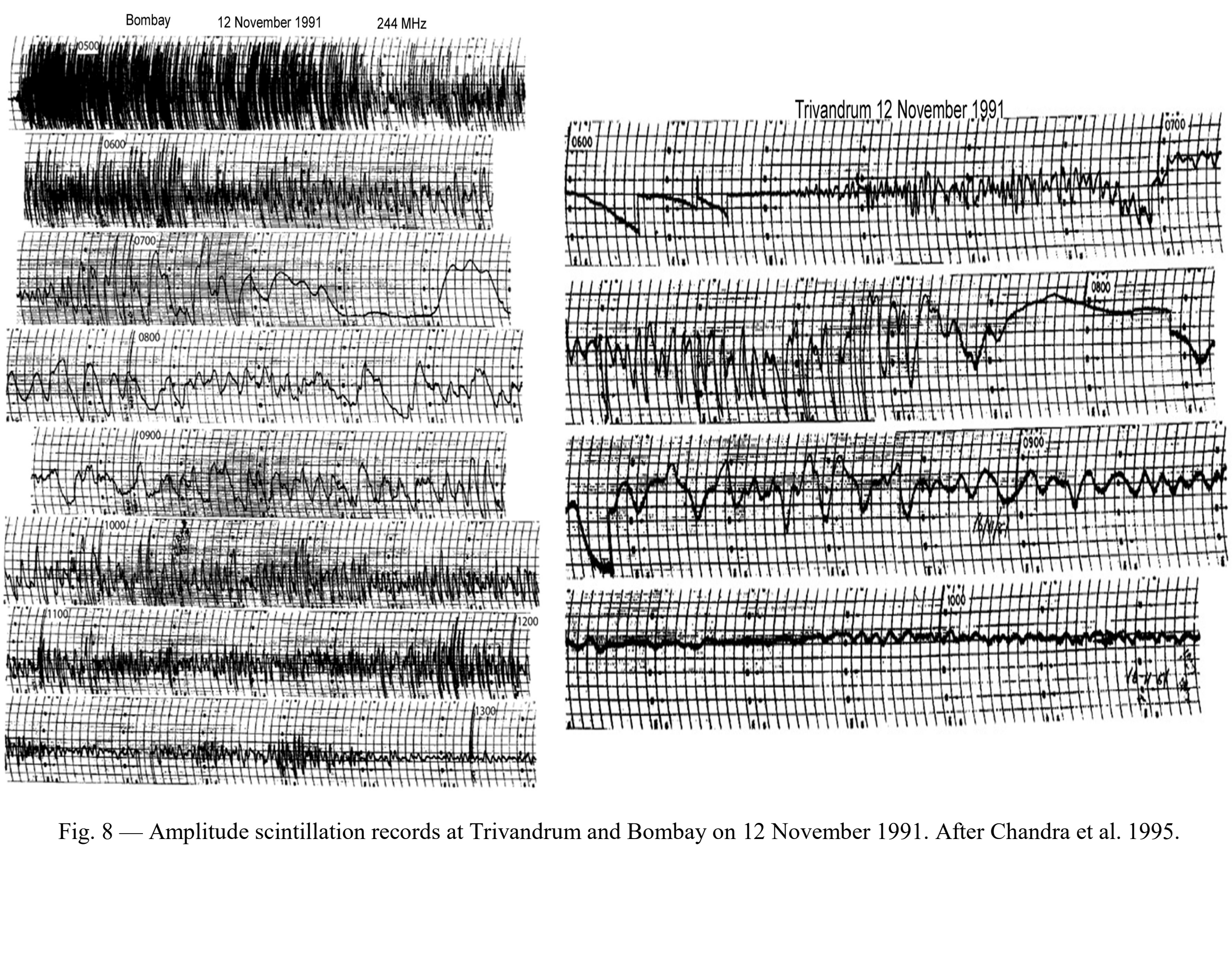

Fig. 8 — Amplitude scintillation records at Trivandrum and Bombay on 12 November 1991. After Chandra et al. 1995.

over Bombay and around 0620 LT over Trivandrum. Scintillations were present at Bombay till 1330 LT and till 1030 LT at Trivandrum. The ionosonde data at Kodaikanal and Ahmedabad indicating vertical drifts of about 50 m/s around 03 LT together with the earlier onset of scintillations at Bombay than at Trivandrum provided an evidence of the penetration of the electric fields of high latitude origin into low latitudes. The digital data recorded over Bombay showed power spectral features of the daytime F-region scintillations similar to those observed for the night-time F-region scintillations.

A case study of the day-time scintillations associated with E-region irregularities was attempted from the simultaneous ionosonde and the 244 MHz scintillation data over Ahmedabad using the beacon on-board FLEETSAT and the 103 MHz scintillations observed over the radio telescopes at Thaltej (Ahmedabad) and Rajkot. The observations provided the estimate of the patch of E-region irregularities with east-west spatial extent of around 400 km and north-south extent of about 80 km. A southward movement of the patch with a drift speed of about 60 m/s was also estimated from these observations by Vats et al.[63].

Iyer et al.[64] compared VHF scintillation and spread-F both at magnetic equator (Trivandrum and Kodaikanal) and at the anomaly crest region (Rajkot and Ahmedabad) during high solar activity and low solar activity years. The statistical pattern were similar at the two sites only during the high solar activity epoch. In the pre-midnight period scintillation and range type spread-F during equinoxes increased with solar activity. While in the post-midnight period the scintillation were predominant in the summer and decreased with solar activity.

The association of radio wave scintillation associated with the ionization in E-region associated with the Leonid meteor shower was observed during the night of 16-17 November 1998 by Paul et al. 2001[65]. Two cases of quasi-periodic scintillations characterised by a deep fade out in amplitude with regular ringing pattern before and after it were observed over Haringhata (22.6° N, 88.4° E) near Calcutta. The events were of about 2 minutes duration that occurred around 19.06 UT (00.36 LT) and 20.21 UT (01.51 LT). Figure 9 depicts the FLEETSAT carrier signal recorded at Haringhata from about 20.20 UT to 20.22 UT on the night of 16-17 November 1998. Ionosonde observations at Ahmedabad revealed two isolated peaks in the critical frequency of E-layer (measure of maximum ionization density of E-layer) during the same night (22.30 UT and 00.00 UT). Though no point to point correspondence between Ahmedabad and Calcutta was expected but the two bursts of ionization on two occasions during the peak meteor shower activity prompted to relate

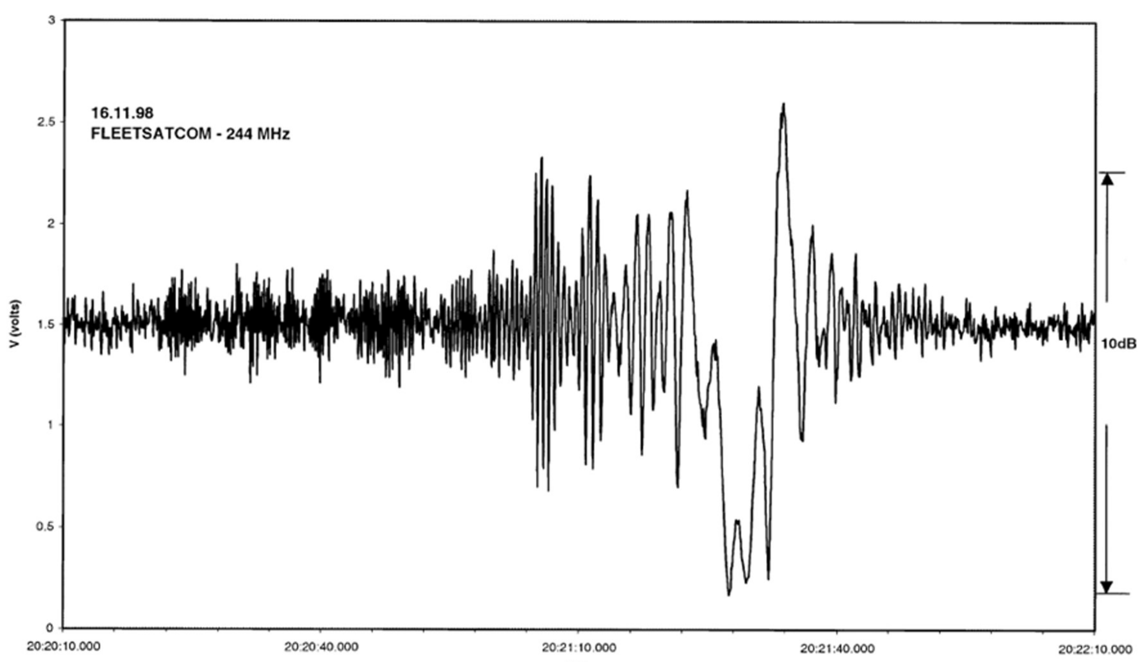

Fig. 9 — Record of the FLEETSAT carrier signal at 244.156 MHz recorded at Haringhata during the scintillation event on the night of November 16-17 1998. After Paul et al. 2001.

the satellite scintillations at two occasions over Calcutta to be associated with the sporadic-E ionization caused by meteor showers.

9 Solar eclipse studies from radio beacon data

Solar eclipse events provide unique opportunity to study several atmospheric processes. The solar flux decreases progressively as the solar disc is covered by the Moon. There is a decrease in the ionisation, the effect being delayed at higher altitudes. Another important feature associated with the solar eclipses has been the prediction that gravity waves would be generated by the shadow of the moon moving supersonically across the earth's atmosphere[66]. There have been a number of studies with every solar eclipse event. The observations during the ATS-6 phase provided an opportunity to study the eclipse-induced atmospheric gravity waves. The recordings at Ootacamund were analysed at every minute interval during the October 1976 partial solar eclipse event. However, there was no evidence of any eclipse-induced wave like feature in the TEC data over Ootacamund[67].

The total solar eclipse event of 16 February 1980 provided another opportunity to study the eclipse effects and polarimeters to record Faraday rotation using the beacon from ETS-2 were deployed at Rangapur near Hyderabad (17.4° N, 78.6° E) in the totality zone and at Ahmedabad and Rajkot away from the totality (75% obscuration). Decreases in TEC of ~ 8% over Ahmedabad and Rajkot and ~20% over Rangapur were observed with a time delay of 20 minutes[68]. There was no evidence of eclipse-induced TIDs. A receiver to record the differential phase between the coherent 150 MHz and 400 MHz radio signals from the orbiting navigation satellites was also set up at Rangapur, Telangana.

10 Recent studies in India using GPS and GAGAN network

There has been considerable work in the beacon satellite studies at low latitudes in India. The progress of the beacon work in India has been earlier reviewed by Iyer[69] and Rama Rao[70] respectively. The ionospheric effects on satellite based communication and navigation mainly depends on the TEC along the signal line of sight from the satellite to receiver. Now it is well accepted that a GPS-based navigation system provides accurate, continuous, all-weather, three-dimensional location of a user and in recent years the dependence on this navigation system has increased considerably. When GPS signals propagate through the ionosphere, the carrier experiences a phase advance and the code experiences a group delay mainly due to the total number of free electrons along the satellite-receiver line of sight. Therefore, the carrier phase pseudo-ranges are measured too short and the code pseudo-ranges are measured too long compared to the geometric range between the satellite and receiver. This degrades the GPS positioning accuracy[71]. Among the different sources of GPS positional errors, ionospheric delay, which is proportional to the TEC, is the highest contributor. The range error thus caused may vary from a maximum of hundreds of meters (at midday, during the period of maximum sunspot activity, with the satellite near the horizon of the observer) to less than a few meters (at night, during the period of minimum solar activity, with the satellite at the zenith). Therefore, in order to get better positional accuracy, it is necessary to have a near precise knowledge on the TEC variations at different geographical locations and under different geophysical conditions.

With the advent of satellite based augmentation system of GPS - aided GEO Augmented Navigation (GAGAN), the Indian low latitude ionosphere has been well re-explored using the network of GPS receivers installed under the GAGAN in addition to several individual GPS receivers and International Global Navigation Satellite System (GNSS) Service (IGS) receivers placed over the Indian region[72-78]. The northern EIA evolution using GAGAN TEC observations from Trivandrum (0.5° N Geomagnetic), Bangalore (4.58° N Geomagnetic), Hyderabad (9.2° N Geomagnetic), Bhopal (15.2° N Geomagnetic) and Delhi (20.38° N Geomagnetic) was studied by Bagiyaet al.[75]. All these stations are placed around the common longitude belt of 77–78° E. A typical result is shown in Figure 10 (top), where the contour plots of vertical TEC (VTEC) on a grid of geomagnetic latitude versus local time on 25 December 2005, 23 October 2005 and 20 October 2005 are presented. The three days represent a week, a moderate and a strong electrojet days respectively. The electrojet strength on these days are also shown in the figure (bottom). The EIA development depicted in the figure shows significant day to day variability and it is well correlated with the EEJ variations shown in the respective bottom panel. On morning counter electrojet day of 25 December 2005, the anomaly peak occurred with ~35 TECU only. The peak was delayed upto ~16:00 IST. On 23 October 2005, the EEJ peak occurred with ~31 nT. The anomaly peak occurred at ~14:00 IST with ~45 TECU and it extended up to ~10^o north. In last column of the Fig. 10, it is clearly seen that on the day of strong EEJ 20 October 2005, anomaly peaks with ~55 TECU and earlier at ~14:00 IST. The latitudinal extent is ~14^o north. In a more extensive study, Rama Rao et al.[72] have shown that the intensity and location of the EIA appears to be mainly dependent on the strength and duration of the equatorial electrojet. Figure 11 shows the correlation of EIA strength in TEC and of crest location in TEC to that of the integrated strength of the EEJ. It could be seen that EIA crest location in latitude varies positively with integrated EEJ strength. Similarly, EIA strength increased with the increase in EEJ. The scatter in Fig. 11 is attributed to the day to the day to day variations of local neutral and electro dynamical forcing.

In addition to this, GPS TEC variations over the Indian region could provide many new insights on low latitude ionospheric behavior during severe space weather, solar flare, solar eclipse as well as ground deformation events[79-88]. Specifically, Dasgupta et al.[86] presented the travelling ionospheric disturbances using the GAGAN GPS receivers located at Indian east coast during the Sumatra 2004 tsunami. These disturbances are observed ~90 minutes before the actual tsunami arrival. A recent and more detailed work by Bagiya et al.[87] focused on the origin mechanism of these disturbances. They presented for the first time a simulation study of tsunami-induced acoustic gravity waves (AGWs) in the atmosphere and its interaction with ionospheric plasma based on tsunami-atmosphere-ionosphere (TAI) coupling

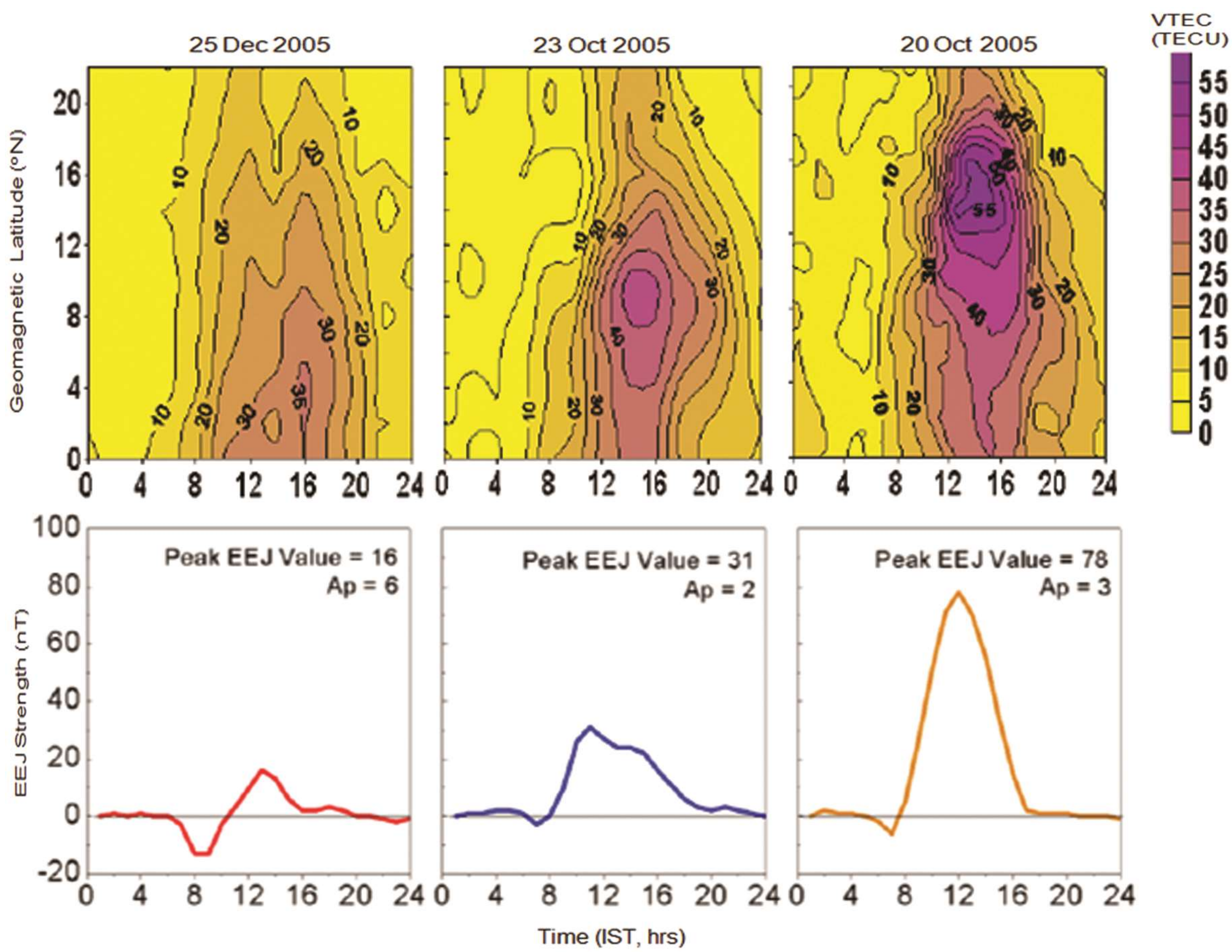

Fig. 10 — (top) Contour plots of vertical TEC (VTEC) on a grid of geomagnetic latitude versus local time on 25 December, 23 October and 20 October of 2005 based on observations from Trivandrum, Banglore, Hyderabad, Bhopal and Delhi. Three days correspond to week, moderate and strong equatorial electrojet strength days (bottom). The diurnal variations of the electrojet strength on these days are also shown. After Bagiya et al. 2009.

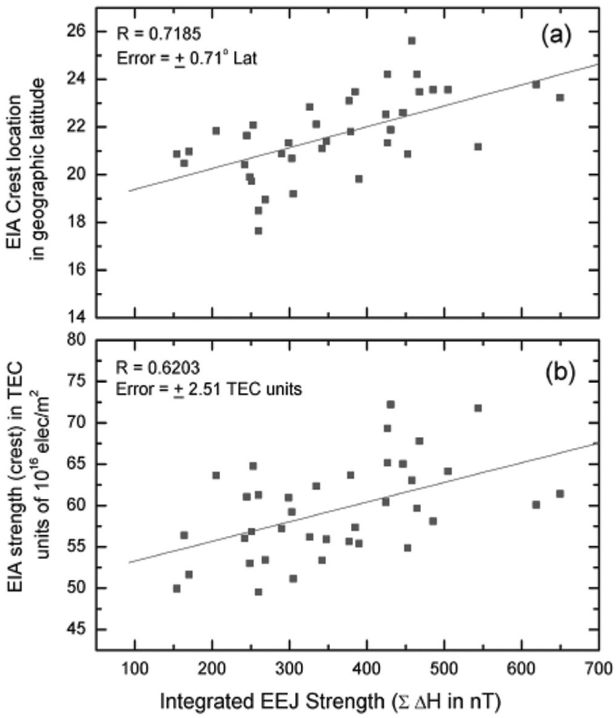

Fig. 11 — Plots of the EIA crest location and EIA strength (crest)as a function of the integrated EEJ strength. The least square fit and correlation coefficients are also shown. After Rama Rao et al. 2006.

mechanism, on similar lines proposed by Heki and Ping[89] and simulated by Kherani et al.[90]. Based on the reasonably good agreement between the observation and simulation, they termed the TEC disturbances as ahead of tsunami travelling ionospheric disturbances (ATIDs). Figure 12a depicts variations of TEC as a function of time with respect to Sumatra tsunami origin time at eight GAGAN stations located at the east coast of India, namely Aizwal (AIZ), Bangalore (BNG), Guwahati (GWT), Hyderabad (HYD), Kolkata (KOL), Raipur (RAI), Trivandrum (TRV) and Visakhapatnam (VSG) on 26 December 2004. The presence of ATIDs in absolute TEC recorded at eight Indian east coast stations is clearly seen. Variations of the de-trended TEC (using a 30 minute running mean) from the respective stations on 26 December 2004 following the Sumatra tsunami and on the previous day (25 December 2004) are shown in Fig. 12b. The observed delay of the ionospheric effects matches well with the simulated propagation time of the ATIDs from the source location. Thus, the real time monitoring of ATIDs may help for the tsunami early warning system.

In recent times, a novel method to forecast the occurrence and total duration of L-band scintillation over equatorial and low latitude region has been developed at PRL[91-92]. A critical evaluation of this method is made using the results from a special campaign conducted from Trivandrum (8.5°N, 76.91°E, dip latitude 0.5°N), India. After the evaluation, it has been noted that the forecasting capability of L band scintillation has remarkably improved and forecast success rate reached to 95% in total[93]. One should keep in mind that this forecast is in temporal domain while the scintillation has large spatial variability also. Thus, an attempt has been made to generate the spatial - temporal maps of the occurrence pattern of L-band scintillation over the Indian region. To start with, the day time fluctuations in electron density $[foF_2]^2$ were used to forecast the temporal evolution of perturbations during the course of the night over Trivandrum. Similar to our earlier studies, here too it is taken that the electron density perturbations retain their characteristics through-out night and traverse with a uniform velocity. This implies that when the integrity of wave train of electron density perturbations is retained, any particular feature that passes over Trivandrum would have crossed over another location west of Trivandrum at an earlier time only dictated by the zonal velocity. With this assumption it became feasible to generate the probable spatial and temporal pattern of L-band scintillation[94].

Further, the L-band forecast maps have been refined by duly accounting for the local time variation of the zonal velocity of density perturbations/fluctuations[95] and local time variation of vertical winds over the magnetic equator, while at the same time refining the earlier stipulated background ionospheric conditions[96]. The unique combination of two geostationary satellites (GSAT-8 and GSAT-10) over the Indian zone has been used to estimate the typical local time dependence of the perturbation velocities by closely following identifiable features in the scintillation pattern. The measured velocities, that registered a steady decrease with the progression of night, have been shown to significantly alter the forecast pattern of the scintillations with respect to longitude and local time. The significant improvement in the forecast pattern has been demonstrated through a case study putting the forecast method on a firmer footing[95]. The zonal velocity measurements for this exercise have been obtained under campaign mode during the year 2012 and thus the observations were available only for 10 days of March-April. It is

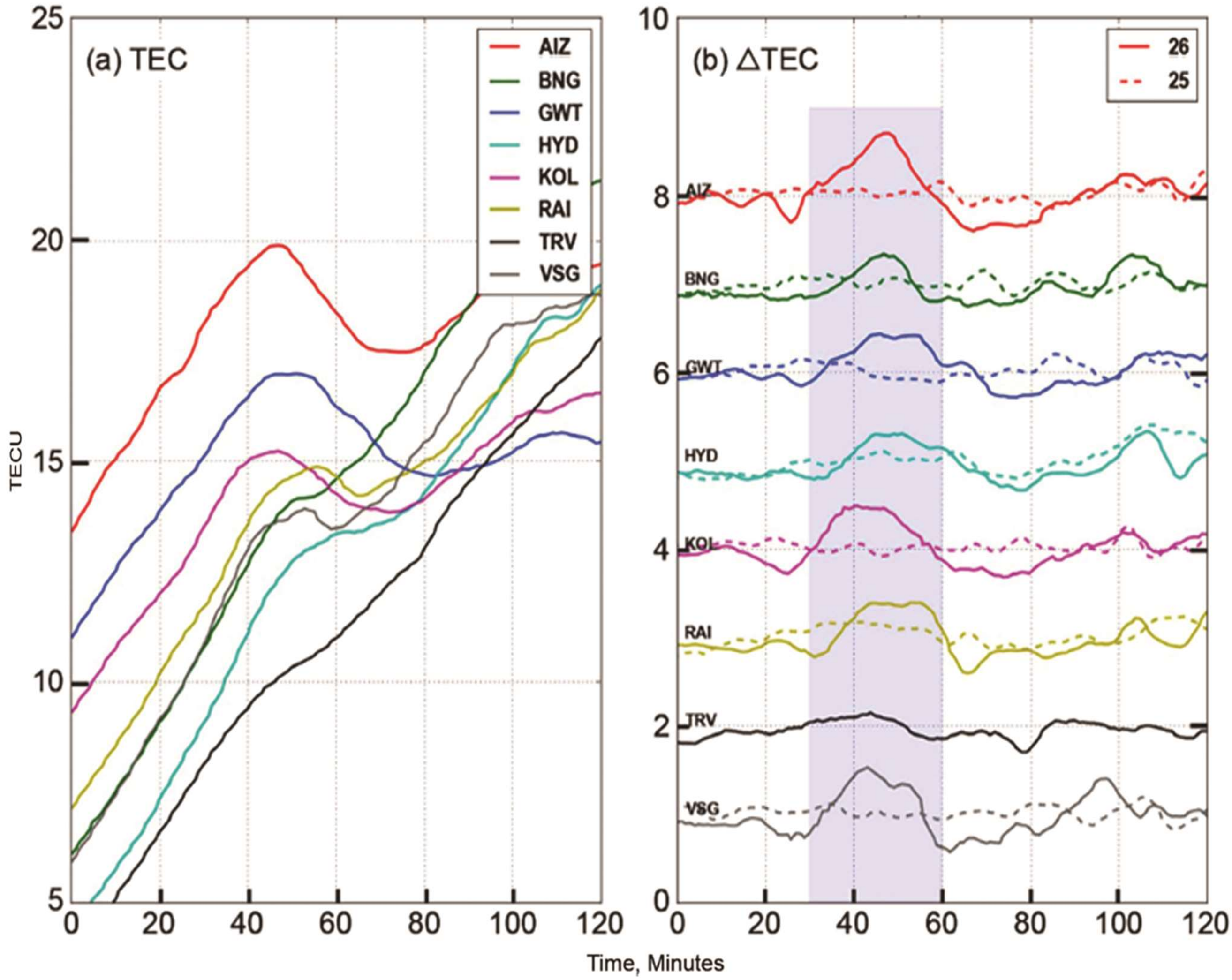

Fig. 12 — (a) Variation of TEC as a function of time with respect to Tsunami origin timeat eight Indian GAGAN stations along the east-coast, Aizwal (AIZ), Banglore (BNG), Guwahati (GWT), Hyderabad (HYD), Kolkata (KOL), Raipur (RAI), Trivandrum (TRV) and Visakhapatnam (VSG) on 26 December 2004 following the Sumatra Tsunami and (b) Variations of de-trended TEC at the eight stations on 26 December 2004 and on the previous day (25 December 2004). After Bagiya et al. 2017a.

believed that the results obtained by Bagiya et al.[95] hold enough potential to generate the reliable L-band scintillation forecast maps and provide the necessary alerts to the satellite based air navigation users. In light of the practical implications of L-band scintillation on GNSS based navigation forecasting the scintillation occurrence is always welcome so that necessary precaution could be taken to mitigate the subsequent effects.

Radio beacon studies have been made from Dibrugarh, a station in the anomaly crest region situated along 95° E longitude, for several years. Hazarika and Bhuyan[97] used data from a network of 10 GPS receivers in India for the year 2005 along a meridionalchain and along a zonal chain to study spatial distribution of TEC. The measurements showed a positive longitudinal gradient towards East. These are consistent with the longitudinal variations of electron density reported earlier from the satellite based critical frequency (electron density) and airglow measurements and attributed to longitudinal structure with wave number 4 (WN4). The peaks in electron density from satellite measurements were observed at around 10° E, 100° E, 190° E and 270° E. Therefore, zonal measurements along the anomaly crest region in India are important to understand more about the longitudinal structure. Another aspect studied in detail from Dibrugarh has been the comparison with IRI models. Bhuyan and Hazarika[98] reported GPS-TEC measurements from Dibrugarh along 95° E longitudes during the ascending half of solar cycle 24 (2009-2012) and compared with the IRI 2012 model values. It was shown that the IRI 2012 model underestimated the TEC values.

11 Future studies

Though there have been considerable work on ionospheric scintillations in the Indian region, the studies on TEC had been rather limited primarily due to the unavailability of suitable radio beacons. Transit satellites of the USNNSS with phase coherent transmissions at 150 and 400 MHz though available were never recorded except once for a total solar eclipse campaign. In recent times there has been a renewed interest in the TEC measurements due to the emerging field of 'Ionospheric –Tomography' which has great potential in future.

Tomography is the art of image reconstruction and has been used extensively in medicine. Scanning in different directions are used to construct image. The mathematical foundation of the image reconstruction dates back to very early in this century[99]. Tomography is also used in the study of ocean structures using acoustic imaging and also in radar imaging. However, the use of tomography for ionosphere is very recent following the landmark work of Austen et al.[100]. In tomography, measurements that give integrated effects along the ray path, are measured in along different directions and converted to give two dimensional maps. In ionospheric applications the TEC measurements provide the integrated columnar content along the ray path and measurements along different directions are obtained making use of the satellite movement along the orbit. A minimum of three receivers is required to give two-dimensional images along the altitude versus satellite track direction. Austen et al.[100] demonstrated the applicability of the technique to ionosphere by computer simulation studies. A background ionosphere was assumed described by a model and large-scale plasma depletion considered on top of the model ionosphere. Integrated columnar electron content along different scan directions were calculated for the assumed distributions for a given satellite geometry and receiver locations. The computed TEC values were later used to obtain altitude versus longitude maps of electron density by tomographic method and compared with the assumed values. A fairly good agreement was shown thus establishing the potential role of ionospheric tomography. A number of studies have been made since then. Kersley et al.[101] have made measurements in the Scandinavia and compared with the height versus longitude electron density distributions as measured by the EISCAT. The algorithm used to reconstruct image is very important and requires an initial guess to begin with. Recent works indicate use of the ionosonde data like the altitude of peak ionisation and the peak ionisation to greatly improve the results. Comparison of the results obtained from tomography and that obtained from incoherent scatter radar have also been made in the US.

The Indian Coherent Radio Beacon Experiment (CRABEX) was initiated around the year 2002, mainly to address the large scale features over the equatorial and low-latitude ionosphere. The day to day variability of the Equatorial Ionization Anomaly (EIA) and the large scale plasma depletions associated with the Equatorial Spread-F (ESF) were two of the problems that were identified to be studied using tomography. As part of CRABEX a chain of six coherent radio beacon receivers were set up at Trivandrum (8.5° N, 77.0° E), Banglore (13.0° N, 77.6° E), Hyderabad (17.3° N, 78.3° E), Bhopal (23.2° N, 77.2° E), Delhi (28.8° N, 77.2° E) and Henle (34.0° N, 78.0° E) to record coherent radio transmissions at 150 MHz and 400 MHz from the low earth orbiting satellites. The chain covers the region right from the magnetic equator (trough of the EIA) and beyond the crest of EIA. Simulation studies were made by Thampi et al.[102] to demonstrate the feasibility of tomographic reconstruction to study large scale features like the anomaly and plasma depletions at equatorial and low-latitude ionosphere. Based on the geometry of the five stations in the chain covering the region from 8° N to 29° N, reconstructions were attempted using Singular Value Decomposition (SVD) technique. The IRI model was used as input and large scale features introduced for ionization anomaly and plasma depletions. Reconstructed tomograms were compared with the input profiles of electron density. It was demonstrated that, large scale features at equatorial and low-latitudes can be studied. Errors varied from few percent to 50%.

Thampi et al.[103] reported the first tomographic profiles of electron density in the equatorial and low latitudes in India from observations made at the three stations Trivandrum, Banglore and Hyderabad during 29

September to 3 October 2004. Development of the EIA was shown and the role of strong EIA related to the ESF.

Radio beacon studies are important for navigation applications. In view of the Navik program, study of scintillations for both S band & L band in the Indian region is important. There have been some studies in this direction for the scintillation mitigation in the anomaly crest region where scintillation effect is strongest due to higher ambient electron density. Goswami et al.[104] studied scintillation on GPS L1, L2 and L5 frequencies for decorrelations during strong scintillation events over Calcutta. Results indicated maximum 40% of scintillation time during February-April 2014 and 33% during August-October 2014 that the signals are decorrelated. It is important to note that it is only during these time intervals that the principle of frequency diversity could be applied for scintillation mitigation.

Ionospheric corrections are also important for navigation applications like aircraft landing where precise location of aircraft is a must. In view of the large day-to-day variability, especially during space weather events, such studies are required to understand the processes involved and possibility of predictions. As the low latitude ionosphere is largely governed by the electrodynamics, knowledge of electric field in the equatorial ionosphere is an important parameter both on a geomagnetic quiet or a disturbed periods. In the absence of radar measurements of electric field, the strength of equatorial electro jet has been used as a proxy for day time. Ionization anomaly strength is another parameter, which is an indicator of the electric field. TEC measurements from GPS network are ideally suited for study of the dynamical features of the ionization anomaly.

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