Indian Journal of Radio & Space Physics
Vol 44, December 2015, pp 177-186

Spread F at tropical latitude stations in India

R G Rastogi & H Chandra[$,*]

Physical Research Laboratory, Ahmedabad 380 009, Gujarat, India
[$]E-mail: hchandra@prl.res.in

Received 30 July 2015; revised received and accepted 11 January 2016

Regular radio soundings of the ionosphere over Ahmedabad were started in 1953 and several studies describe the various features of the ionosphere close to the equatorial ionization anomaly crest. Finer characteristics of the spread F echoes could not be studied earlier due to the very wide pulse of the transmitter. The characteristics of the spread F at Ahmedabad are described in the present paper using the recordings of recently installed Digisonde during June - July 2012. The spread F echoes at Ahmedabad are not due to the *in situ* produced irregularities as at an equatorial station Thumba. The spread F echoes at Ahmedabad during the June solstices of 2012 are due to reflection (not scattering) from the off-vertical direction that produce multiple traces from off-vertical direction overlapping over the main (vertical) h'-f trace, sometimes giving an appearance of diffuse echoes near the critical frequencies. Presence of medium scale traveling ionospheric disturbances (TIDs) could be a possibility to account for such off-vertical reflections.

Keywords: Equatorial electrojet, Equatorial ionization anomaly, Night airglow, Spread F, Traveling ionospheric disturbance (TID)

PACS Nos: *94.20.dt*; 94.20.Vv; *92.60.hw*

1 Introduction

The ionosphere at low latitudes is characterized by several distinct features.

1.1 Equatorial ionization anomaly

The first ionospheric sounder near the magnetic equator in the world was established at Huancayo, Peru in 1931. Berkner & Wells[1] observed abnormal daily variation of the critical frequency of the F-layer, foF2, with a bite out around noon and maxima in the morning and afternoon. Appleton[2] showed that when the noon values of foF2 are plotted as a function of latitude, a pronounced trough centred at the magnetic equator with crests at 15° - 20° north and south are observed. This was called as Appleton F-region Anomaly, now commonly referred to as Equatorial Ionization Anomaly (EIA).

1.2 Equatorial electrojet

Chapman[3] reported abnormally large daily variations of the horizontal component of the geomagnetic field H at Huancayo and other stations close to the magnetic equator and interpreted it as an intense eastward flowing electric current in the dayside E-region of the ionosphere within ±3° dip latitude over the magnetic equator and called it Equatorial Electrojet (EEJ). Baker & Martyn[4] suggested that the magnetic field H being orthogonal to the eastward dynamo atmospheric electric field, an upward Hall polarization field gives rise to an abnormally large eastward effective (Cowling) conductivity, as the cause of EEJ. They also showed that the Hall field leaks away along the inclined magnetic field lines beyond 3° latitude from the dip equator.

1.3 Equatorial Spread F

Booker & Wells[5] noted that following the rapid rise of the F2 layer after sunset by 100 km or more at Huancayo (dip, 0.6°N), diffuse and scattered echoes are recorded in the ionograms, which is now called Equatorial Spread F (ESF). Osborne[6] reported similar rise of the F-layer followed by spread F at an off equatorial station Singapore (dip lat 9°S). Lyon *et al.*[7] described the equatorial type of spread F at Ibadan (dip 8°S). Rastogi *et al.*[8] have described the occurrence of equatorial type of spread F at Kwajalein (dip 9°N) during a magnetic storm.

The first ionospheric sounder over the magnetic equator in India was established at Thumba Rocket Launching Station in 1964 by Physical Research Laboratory. The general features of the ionosphere at Thumba (8.5°N, 77.0°E, and inclination 0.8 ° N) were described by Chandra & Rastogi[9]. Features of spread F over Thumba during the years 1965-67 are described by Chandra & Rastogi[10]. They identified two clearly different types of ESF: (i) the first starting at post sunset period consisting of a number of horizontal layers of scattering in the base or at the lower levels of the F-region giving rise to an ambiguity in finding the range, named Range ESF; and (ii) frequency spread occurring during the post midnight hours, with maximum spreading close to the critical frequencies causing an ambiguity in determining foF2. Chandra & Rastogi[11] from a study of spread F over a solar cycle at Kodaikanal showed that spread F was more frequent during pre-midnight hours of equinoxes during high sunspot years while during low sunspot years, it was most frequent during post midnight hours of June solstice. Further, while the occurrence of spread F is inhibited during geomagnetic disturbed days during high sunspot years, it shows an increase during the post midnight period of disturbed days during June solstice of low sunspot years.

Comparing the modified range time intensity (MRTI) records of 50 MHz radar backscatter echoes at Jicamarca with the vertical incidence ionograms at Huancayo, Rastogi[12] showed that the range spread F is very efficient for back scattering of VHF radio waves. On the other hand, the frequency type of spread F does not seem to produce strong echoes. It was suggested that the range type of spread F is due to the scattering of radio waves from irregularities with structures as small as 3 m situated below or at the base of the F-region. The frequency type of spread F was suggested to be due to scattering from irregularities situated around the region of peak ionization density. Later, Rastogi[13] showed that the multiple layer of scattering in range spread F in Huancayo ionograms corresponded very closely to the levels of strong gradient of ionization in the corresponding MRTI records at Jicamarca.

Plasma density irregularities covering a wide range of scale sizes, extending from hundreds of km to a fraction of a meter are associated with the phenomenon of ESF. The generalized Rayleigh-Taylor instability (RTI), that includes the electric field and neutral winds along with gravitational term, is considered to be the primary process for the generation of intermediate scale irregularities. Large scale plasma depletions, thus, generated rise fast to cover entire F-region including topside. Steep plasma density gradients, then, provide seat for the generation of small-scale irregularities[14]. Eastward electric field gives rise to gradient drift instability (GDI) under upward plasma density gradients besides raising the F-layer to higher altitudes where growth rate due to gravitational term is higher. Depending upon the altitude to which plasma depletions reach, the N-S extent of the field aligned irregularities (FAI) is seen. The belt of equatorial spread-F as observed from VHF scintillation in the Indian region is shown to be solar cycle and seasonal dependent. It is widest during high sunspot years and narrowest during low sunspot years and seasonally widest during equinoxes [15].

1.4 Tropical spread F

Comparatively, little attention had been paid towards the study of spread F at latitudes near the crest of the equatorial ionization anomaly. An automatic ionospheric recorder was installed at Ahmedabad (23.0°N, 72.4°E, dip 33.4°N) in March 1953. The ionosonde had relatively low power transmitter and consequently, a wide pulse of radio waves were utilized to get enough return echo power. Rastogi & Kulkarni[16] described the characteristics of the spread F at Ahmedabad covering a solar cycle. The spread F was more frequent during equinoxes of high sunspot years and during J solstice of low sunspot years. The occurrences of spread F at other low latitude stations outside the equatorial latitudes have been reported at Taipei (Huang & Yeh[17]) and Nairobi (Skinner & Kelleher[18]). The characteristics of the mid latitude spread F at Brisbane was described by Bowman[19]. Spread F occured mainly after midnight and consisted of series of traces overlapping the first order h’-f trace. Rastogi[20] studied the data from a number of vertical incidence and oblique incidence ionosondes operated in an area of 2800 km in radius centering on the magnetic equator at 173°W longitude during the high altitude nuclear exploration experiment in October 1962. It was shown that the spread F at tropical latitudes consist of multiple h’-f traces from off-vertical ionization bubbles overlapping on the first overhead h’-f trace. The time of peak occurrence of spread F at a low latitude station Kodaikanal was 0000 hrs IST, at Hyderabad, located between the dip equator and anomaly crest region, it was 0200 hrs IST and at Ahmedabad it was 0300 hrs IST. Thus, the progress of spread F at low latitudes was analogous to the development of daytime EIA. Chandra *et al.*[21] compared the occurrence of range type and frequency types spread F at anomaly crest regions in India (Ahmedabad) and Brazil (Cachoeira Paulista).

2 Observations

The features of the F-layer over Thumba, a station near the magnetic equator in India, for the period 1965-67 have been reported by Chandra & Rastogi[9]. Here, mainly the seasonal mean daily variations of the critical frequency of the F2 layer (foF2), height of the base of F layer, h'F and the height of the peak ionization, hpF2 for a low (1965) and a medium (1967) sunspot years during the summer season (May-August) are discussed.

The value of foF2, during 1965 or 1967, decreases from midnight to a minimum around 0500 hrs IST, close to the sunrise at F-region of the ionosphere. With decreasing solar zenith angle after sunrise, foF2 starts increasing rapidly till 0800-0900 hrs IST. With increasing electric field E over the equator (and hence EEJ strength), the hpF2 also increases causing a cessation of the increase of foF2 resulting in bite out (depression) around 1100 hrs IST. Later, it increases again but after 1700 hrs IST due to increasing solar zenith angle foF2 starts decreasing throughout the evening and night time hours. The most significant difference in the daily variation of foF2 with season found was that the noon bite out is most predominant during equinoxes, less in summer and almost absent in winter. Further, the presence of the post sunset peak is evident during equinoxes of 1967.

The height of the base of the F-layer remains fairly constant during day time. It showed a small bump around sunrise due to the start of fresh ionization at higher heights and later, it continues to decrease till midday hours. With decreasing solar zenith angle, it increases and a clear maximum is seen around 2000 hrs IST. This post sunset peak was broad and weak in 1965 than in 1967. The post sunset peak in h'F was most predominant during equinoxes and least in summer and the peak was much stronger in 1967 than in 1965.

The height of the peak of the F-layer decreased slowly after midnight till 0500 hrs IST and started increasing with a broad maximum around midday, after which it started decreasing but showed a secondary sharp and large peak around 2000 hrs IST in 1967. The rapid increase of both h'F and hpF2 in the post sunset period is due to the uplift of the F-layer due to the pre-reversal electric field.

Some examples of range and frequency spread F at Thumba are shown in Fig. 1. The top two ionograms (2100 hrs IST on 21 January 2004 and 0215 hrs IST on 11 February 2004) show range type equatorial spread F where the scattering layers are at different fixed levels of the ionosphere. These are the scattering from very sharp gradients of the ionization separate from the ionization profile of the F2 layer. The two lower ionograms (0215 hrs IST on 12 February 2004 and 0045 hrs IST on 8 January 2005) show frequency type equatorial spread F wherein the range of the diffuse echoes increase with increasing frequency. It is to be noted that the bottom limit of the scatter is identical with the uniform first order p'-f reflection trace of the F2 layer. Hence, there are longer wavelength irregularities inside the F2 layer.

With the installation of Digisonde at Ahmedabad in June 2012, excellent ionograms have been recorded with fine resolution between adjacent traces and a need was felt to study the characteristics of spread F at Ahmedabad with the Digisonde records. This paper describes the characteristic of spread F at Ahmedabad during June - July 2012. The month of July was a geomagnetic quiet period except for

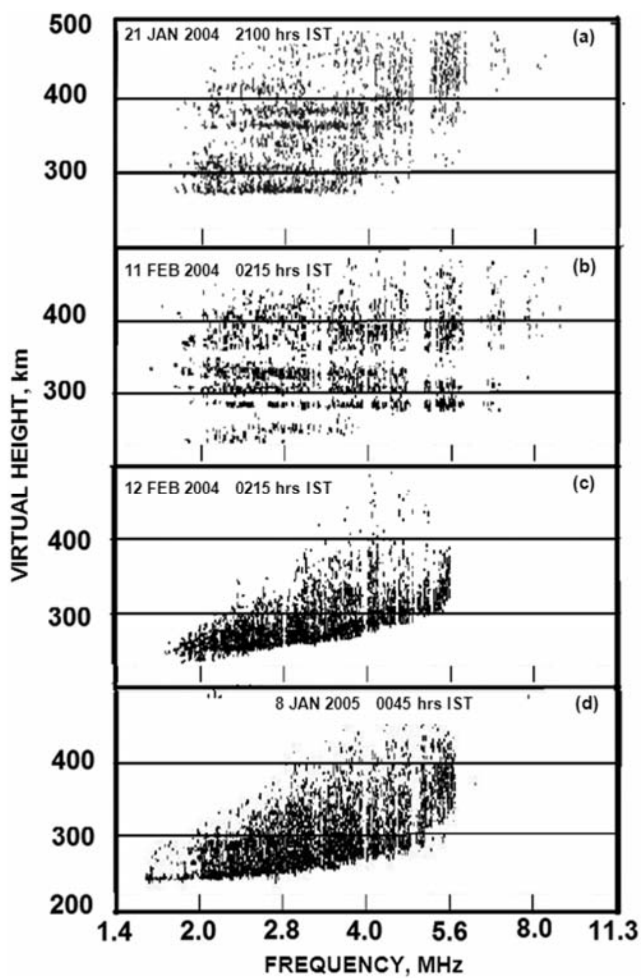

Fig. 1 — Ionograms at Thumba showing the range type of spread F (a and b); and the frequency type of spread F (c and d)

the days 14-16 July 2012 when K indices were 6. The monthly mean Ap index was 14.37 for July 2012. The monthly mean value of the sunspot number was 66.

The mean diurnal variations of the height of the base of F region h’F, height of the peak ionization density in the F2 layer hpF2, critical frequency of the F2 layer foF2 and the frequency of occurrence of spread F for June - July 2012 at Ahmedabad are shown in Fig. 2. Both h’F and hpF2 start increasing after sunset reaching a maximum around 0100 hrs IST and 0300 hrs IST, respectively. The variation of foF2 shows a sharp decrease, two hours after sunset and later assumes only a gradual decrease throughout the night. It is to be noted that the peak occurrence of spread F at Ahmedabad does not occur after sunset like in Thumba but reaches a peak well after midnight corresponding to the rise of h’F and hpF2.

Some typical isolated examples of spread F ionograms at Ahmedabad are shown in Fig. 3. The ionogram (1) at 2100 hrs IST on 16 July 2012 shows

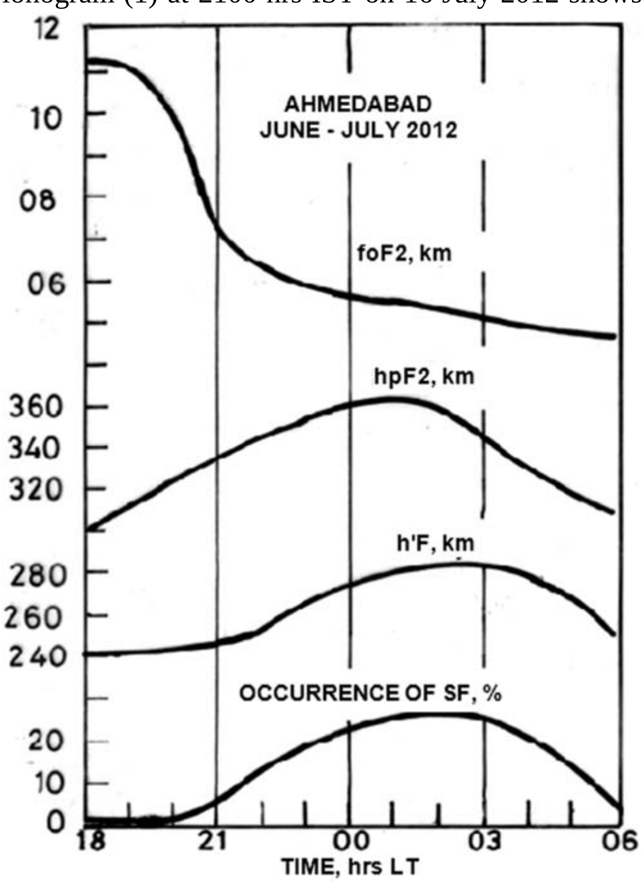

Fig. 2 — Mean diurnal variations of foF2, hpF2, h’F and the percentage occurrence of spread F over Ahmedabad during June - July 2012

the ordinary (red) and extraordinary (green) traces clearly separated. Some off-vertical echoes (blue) are seen in the second order reflection trace not corresponding to any first order trace. Week sporadic E trace at 100 km is also present. The ionogram (2) at 0215 hrs IST on 28 July 2012 shows clearly separated ordinary, extraordinary and off-vertical traces overlapping on the first order traces. It is to be noted that the off-vertical h’F is larger than the h’F of the main first order trace. The ionogram (3) taken 7.5 minutes later than ionogram (2) again shows the three types of traces. The ionogram (4) at 0100 hrs IST on 26 July 2012 shows some diffuse echoes with no doubling of multiple traces indicating the presence of irregularities in the overhead ionosphere. Sporadic E is also present. The ionogram (5) at 0300 hrs IST on 20 July 2012 shows a broader diffuse first order trace with clear second order traces separated. Presence of sporadic E is also seen. The ionogram (6) at 0500 hrs IST on 25 July 2012 shows clearly the vertical and off vertical closely separated traces. Sporadic E with three multiples is also present. The ionograms (7) at 0400 hrs IST on 28 July 2012 and (8) at 0115 hrs IST on 11 July 2012 show in time spread F some what resembling to the frequency type equatorial spread F. Strong sporadic E is also observed in the ionograms (8).

The ionograms on 1 July 2012 are reproduced in Fig. 4 showing the development of echoes overlapping on first order p’-f trace. The ionogram on 2000 hrs IST show very clear ordinary (red) and extraordinary (green) components of the first order overhead echoes. Second multiple and third multiple echoes are also seen. An additional (blue) trace from off vertical is also seen above the second multiple even though there is no off vertical trace for first order echo. A faint trace of sporadic E is also seen at 100 km. The ionogram on 2015 hrs IST show very clear ordinary (red) and extraordinary (green) components of the first order overhead echoes. Second multiple and faint third multiple echoes are also seen. There is additional blue trace from off vertical trace over the second multiple. In subsequent ionograms, a number of echoes from off-vertical are seen. At 2100 hrs IST extra traces are very clearly resolved and by 2107 hrs IST, the ionosphere is practically normal. This example shows that the range spread at Ahmedabad can be temporary for a period of less than an hour. It must be noted that sporadic E is present over this period of an hour and with multiple echoes at times.

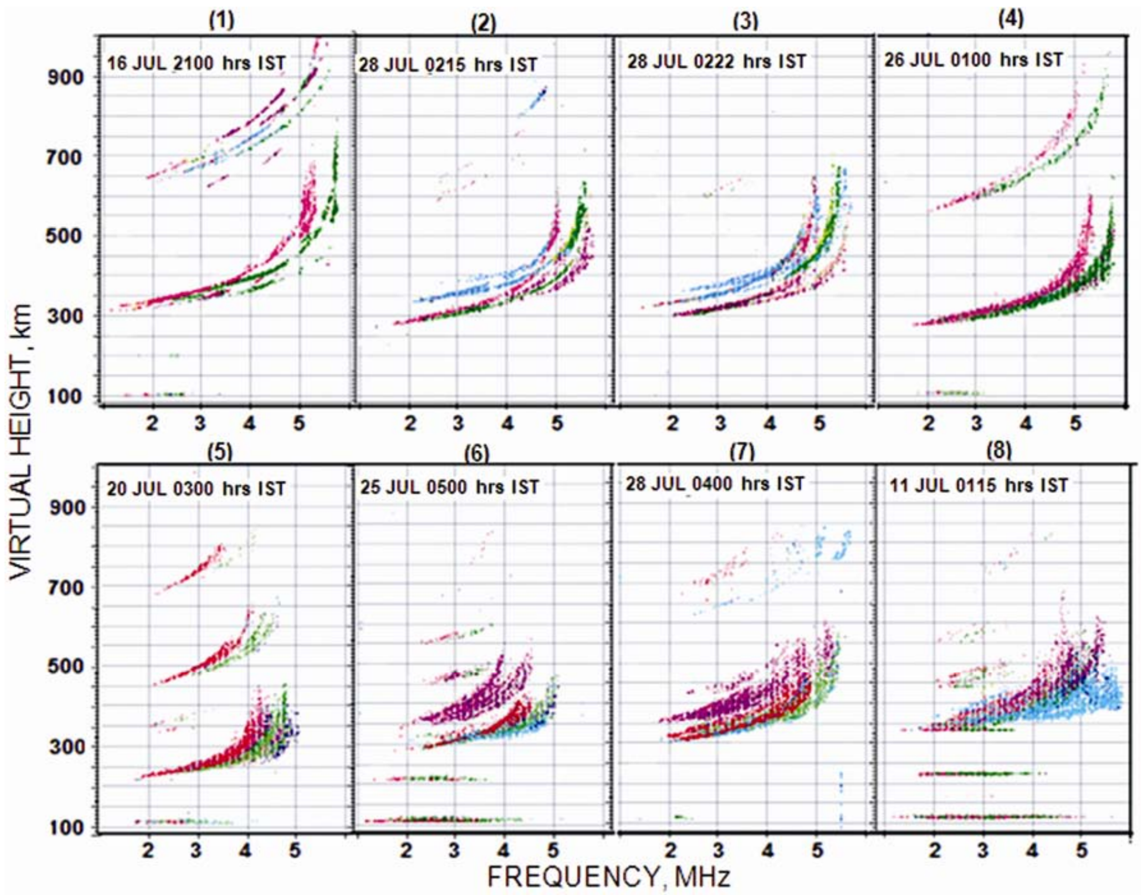

Fig. 3 — Typical ionograms over Ahmedabad showing different stages of spread

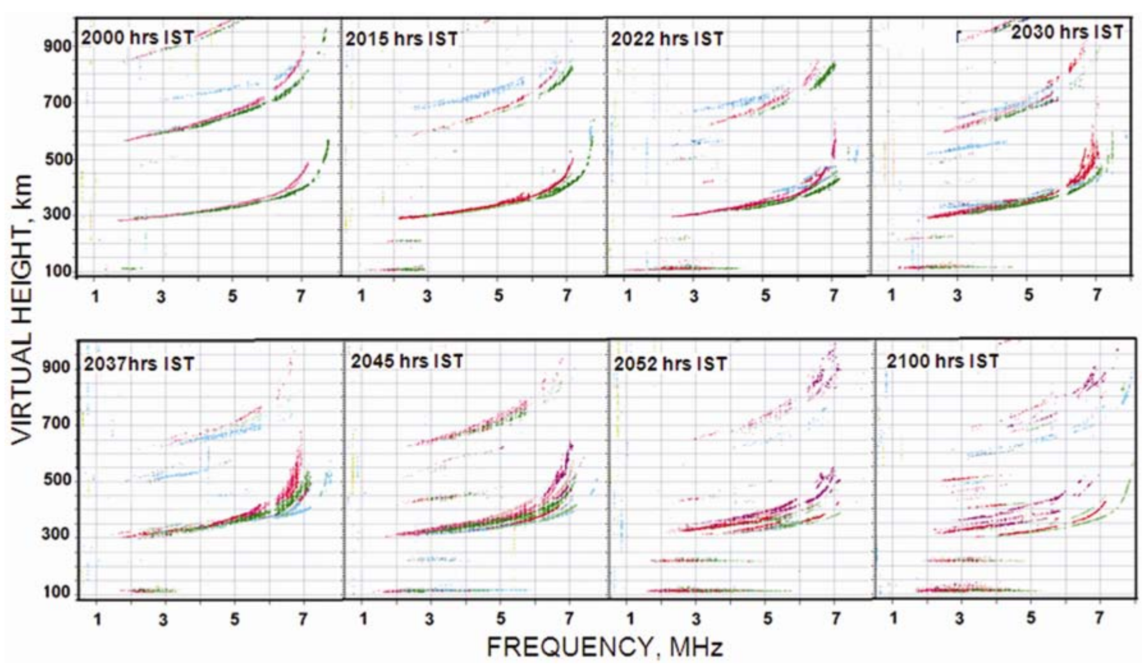

Fig. 4 — Ionograms over Ahmedabad on 1 July 2012 showing the development of multiple h-’f traces of spread F configuration

Ionograms on 28 July 2012 are shown in Fig. 5 wherein the additional traces can transform into bush type of spread F. The ionograms at 0237 hrs IST does not show any off vertical reflection but second reflection of the off vertical reflection is seen above the second reflection trace. At 0245 hrs IST off vertical reflection is clearly seen. The separation in range of the vertical and off vertical reflections narrows with time and transform into frequency type spread F (0337 hrs IST). Later, the separation between vertical and off vertical reflections increases (0330 hrs IST). Figure 6 shows short period changes in the character of spread F echoes at Ahmedabad recorded between 1745 and 1837 hrs IST on 5 July 2012. During this evening period, the separation between vertical and off vertical traces is quite large. Sporadic E is also seen during this period. Further, the onset of spread F over Ahmedabad in the early evening can not be of equatorial spread F origin.

3 Spread F and Night airglow

Plasma depletions have been detected by *in situ* measurements of electron density or the total electron content measurements. Optical signatures of the plasma depletions have been monitored by night airglow measurements using scanning photometers or imaging all sky camera. The plasma depletions in the night time ionosphere manifest as dark bands of reduced intensity in all sky airglow images, associated with the plasma depletion[22]. Several all sky imaging experiments have been conducted using 630.0 nm, 774.4 nm and 557.7 mm airglow emission[23]. The depletions extend from equatorial regions to lower and middle latitudes (pole ward extensions). The N-S and E-W extent, the degree of the plasma depletions and its zonal velocity can be estimated from the airglow pictures. Sahai ***et al.***[24] and Pimenta ***et al.***[25] have described the features of plasma depletions and their zonal drift in the Brazilian sector. Sobral ***et al.***[26]

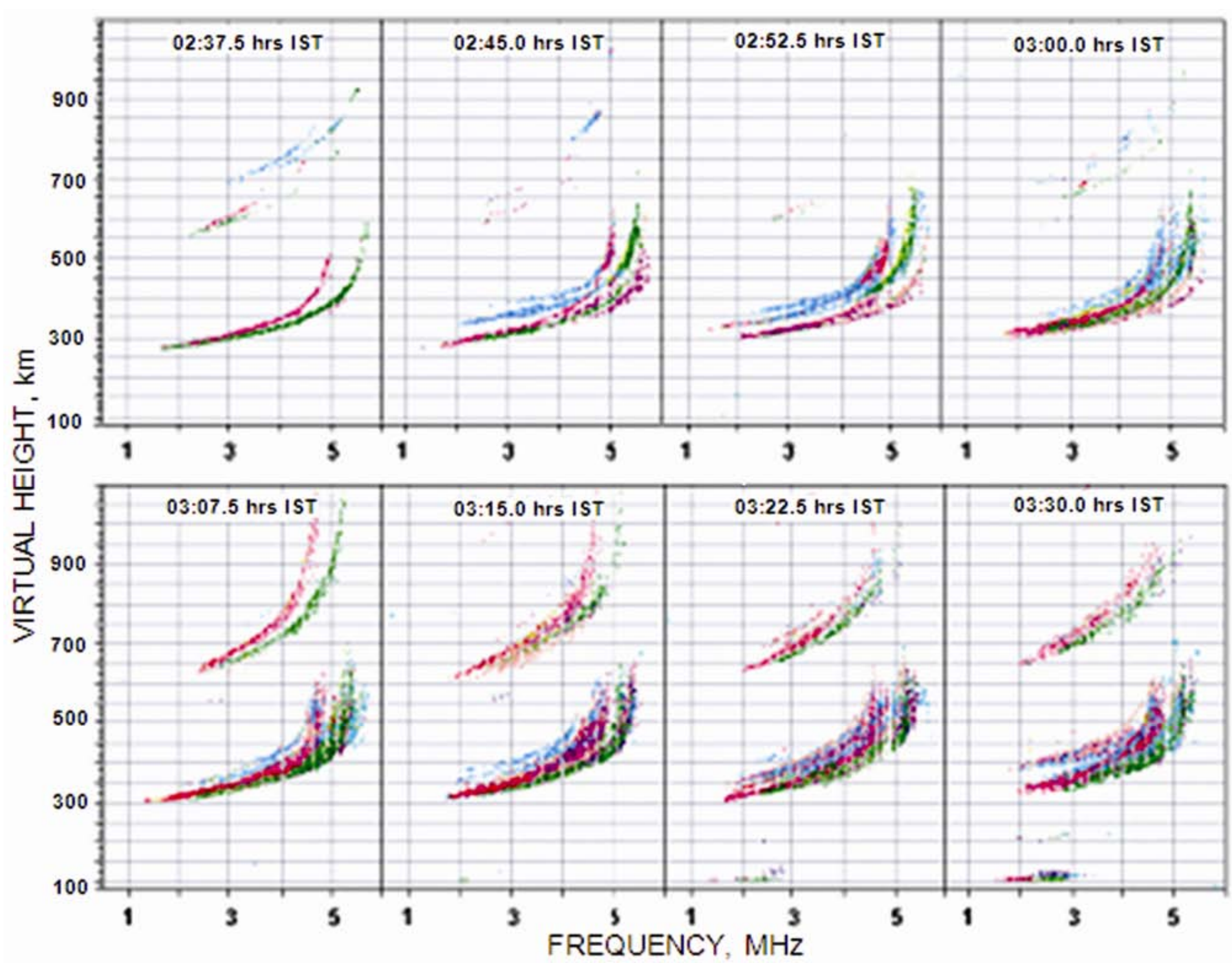

Fig. 5 — Ionograms over Ahmedabad on 28 July 2012 showing the multiple traces transforming into a bush type of spread F

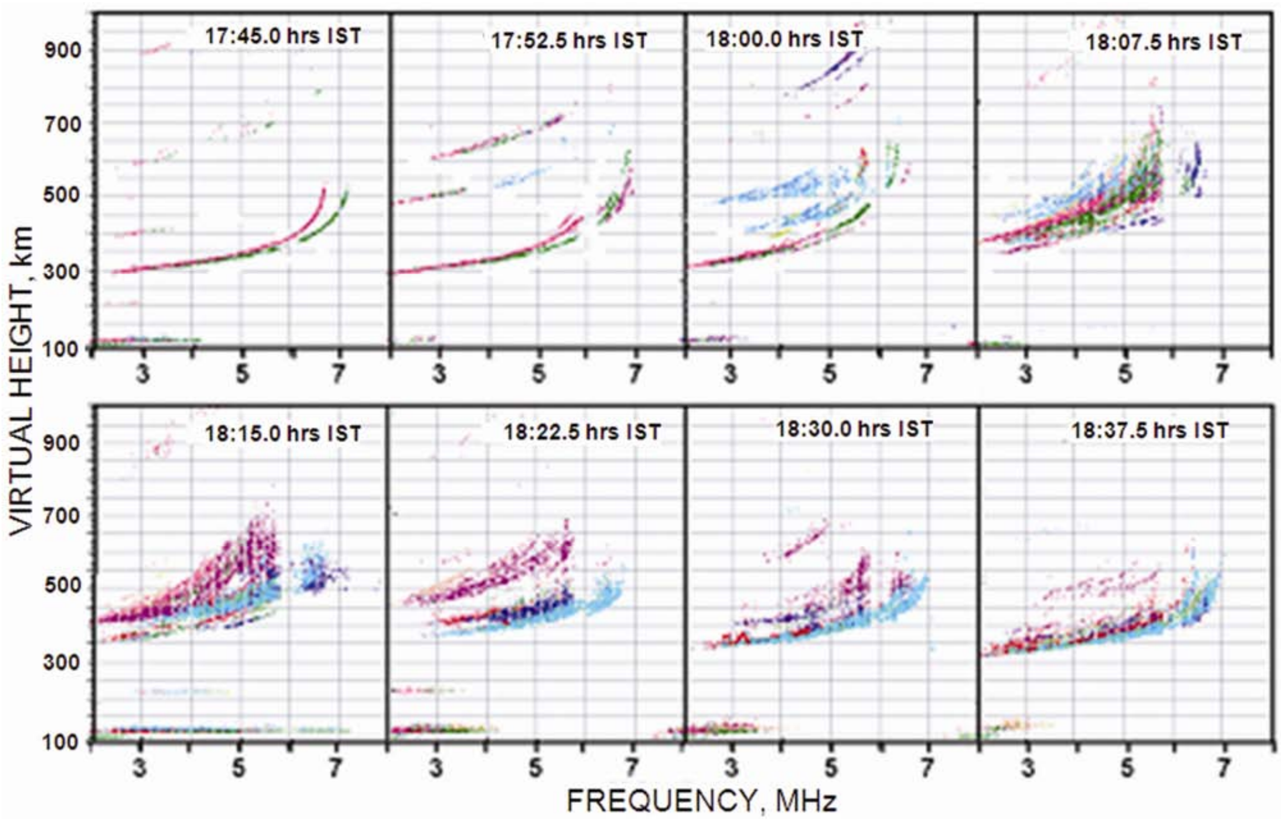

Fig. 6 — Ionograms at Ahmedabad on 05 July 2012 showing the development of bush type of spread F

have described the climatology of the plasma bubble over Brazil based on 22 years of airglow studies using scanning airglow photometers and complemented by air glow imagers for few years. In the Indian region extensive measurements have been made[27-29]. However, most of the observations in the Indian region are restricted to December solstices or equinoxes as rainy season during June solstices does not permit optical observations. Sales *et al.*[30] conducted a multiple instrument observations at the southern crest region of the equatorial ionization anomaly with CCD enhanced all-sky imaging photometer together with a Digisonde sounder operated as Doppler interferometer to locate individual scattering sources in the ionosphere. They found that the individual spread F traces in the ionograms were separated by hundred of kilometer off the vertical. Rajesh *et al.*[29] have reported simultaneous airglow and ionospheric observations from Kavalur (10.8°N, 79.2°E, dip 8.37) in India.

4 Discussion

The occurrences of spread F at equatorial and low latitudes are considered to be the manifestation of a single phenomenon. After sunset, rapid recombination of ionization at lower layer of the F-layer create a large vertical gradient of ionization at the base of the F-layer. If the normal day time dynamo electric field remains eastward for some time after sunset, the F layer experiences a rapid rise. The eastward electric field acting on the plasma gradient generates gradient drift irregularities at the base of the F-layer. The growth rate of the Rayleigh Taylor instability also increases with altitude and these plasma depletions rise up within the F-layer. Later, with the reversal of the electric field to the night time westward direction the F-layer starts coming down with the irregularities embedded in it. Rastogi[31] suggested a phenomenon of spread F as a fountain of plasma irregularities in the night similar to the phenomenon of day time equatorial ionization anomaly. During the high sunspot years, the post-sunset rise of F-layer at equatorial stations is large and the depleted regions map to anomaly crest region and even beyond. However, the post sunset height rise of the F-layer is not enough during the low and medium sunspot years and the high occurrence of spread F near anomaly crest region during June solstices cannot be explained by the field-aligned mapping of the plasma depletions. One of the possible mechanisms suggested is the role of traveling ionospheric disturbances (TIDs) as used to explain the mid-latitude spread-F by Bowman[19]. Other possibility suggested is the local generation of the irregularities. Candido *et al.*[32] studied the occurrence of spread F over Cachoeira Paulista, a low latitude station in Brazil in the midnight - post midnight during June solstice under geomagnetic quiet conditions and found inverse relation between the spread F occurrence and the sunspot number. Airglow imaging showed absence of plasma bubbles and presence of TIDs. F-layer dynamics and plasma densities suggested spread F likely to be associated with ionospheric disturbances caused primarily by TIDs originating from mid latitudes. In a recent study, Upadhyaya & Gupta[33] reported spread F occurrence over Delhi, a station beyond the anomaly crest region in India for the years 2001-2007. Maximum occurrence was found to be in June solstices for all the years and an inverse relationship was seen with sunspot number. Occurrence of spread F over Ahmedabad and Kodaikanal was also shown to be higher during low sunspot years for June solstices. Das *et al.*[34] studied scintillation from a network of GPS stations in the anomaly crest region in India during September 2011, April 2012 and September 2012. Post midnight scintillation was possibly associated with the interaction of TIDs from the mid latitudes to equator contrary to the evening hours when such movement are from equator to crest region. Zhang *et al.*[35] studied GPS scintillation and spread F from ionograms over Sanya, a low latitude station in China for the period December 2011 - November 2012. During June solstice, irregularities do not appear until late night. Absence of irregularities in the post sunset period is likely due to small pre-reversal electric field. Spread F during June solstice was suggested to be associated with the frequently observed sporadic-E and the medium scale TIDs (MSTIDs) could play an important role in triggering spread F. Haldoupis *et al.*[36] found a precise relation between spread F and patchy sporadic-E and concluded that enhanced electric field set up in unstable sporadic-E could easily map to F-region and trigger spread F. This is considered to work at low latitudes as well. Patra *et al.*[37] proposed that Es layer might be the energy source of RTI and GDI producing the post midnight field-aligned irregularities.

Local generation of the irregularities is the other possibility suggested for the spread F near anomaly crest region and beyond. Otsuka *et al.*[38] observed equatorial plasma bubbles and MSTIDs from the 630 nm all sky airglow imager from Shigaraki in Japan (dip 49°). Clear depletions were seen as the plasma bubbles moved eastward. MSTIDs moved southwestward and the airglow depletions disappeared when plasma bubble encountered the MSTIDs. It was suggested that the plasma depletions could be filled with ambient rich plasma that moved into depleted region by E×B drift associated with MSTIDs indicating that MSTIDs are associated with electric field fluctuations. Yokoyama *et al.*[39] reported both equatorial and mid latitude instabilities could be functioning in the ionosphere over Kototabang, a low latitude station (10.36° dip latitude). Mid latitude electric field fluctuations associated with MSTIDs were observed and simultaneous radar observations showed MSTID like striation[39,40].

Nishioka *et al.*[41] from radar at Kototabang in Indonesia and ionosonde at Chumphon in Thailand showed that F-layer altitude increased half an hour before FAI appeared at Kototabang. The velocity from radar was found to be downward. The FAI were frequent in the post midnight period of May-August. Uplift of the F-layer enhances the RTI growth and this uplift could be because of recombination or due to trans-equatorial winds.

5 Conclusion

The appearance of off-vertical reflection like echo traces in the ionograms observed during June solstices of 2012 could possibly be due to the presence of medium scale traveling ionospheric disturbances. However, in many of the spread F examples shown here sporadic E was also present. It will be important to have simultaneous digisonde, VHF radar and all sky night airglow imaging observations to ascertain the mechanisms operating under different seasons and solar activity conditions.

Acknowledgement

One of the authors (RGR) has been a Senior Honorary Scientist of Indian National Science Academy during the course of study. Thanks are due to Physical Research Laboratory for the facilities during the study. Thanks are also due to Prof D Pallamraju for the Digisonde data at Ahmedabad.

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